ANNEX IX

AN OPEN MODEL FOR THE EVALUATION OF SMRS ECONOMIC ATTRACTIVENESS

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IX-1. Introduction

This is an introductory document aimed at presenting an open framework for analysing the investment projects in nuclear reactors, to be implemented in an open model able to simulate and evaluate the economic features of small-to-medium nuclear power plants (NPPs).

The model means to support the comparative assessment of small-medium vs. large scale reactors (SMRs vs. LRs) as a final outcome, and it will allow to simulate the differential profitability of SMRs under several market and operating settings. The analysis is carried out at the plant level.

Before presenting the model architecture, special attention is devoted to a set of distinctive characteristics of SMR investments: replication, scalability, reversibility, standardization. These features have relevant effects in the following domains: generation costs (co-siting economies, learning economies, technical progress economies, mass production, and factory fabrication economies), market (market matching, market suitability, reduced entry barriers), financial costs (lower financial distress, reduced risk premium). At this stage of the research, selected elements of the generation costs are analytically modelled; moreover, the paper surveys pre-existing and relevant models of electricity market, financial costs, and external costs that can be adapted and integrated into the framework.

IX-2. Economic characterization of SMRs

Economies of scale are widely held to drive the generation cost structure of nuclear power plants. 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 can not be directly transferred into the investment analyses of small and medium sized reactors (SMRs) versus large size reactors (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 [IX-1], Schock et al. [IX-2] and Miller [IX-3].

Once the economies of scale have been modelled 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. LR is twofold:

– SMR ad hoc factors: Factors which are applicable to SMRs only or are critically affected by the difference in design and approach brought in by the SMRs.

– SMR-LR common factors: Factors which affect SMRs and large plants in a comparable way. Even for the common factors, a comparative quantitative evaluation might not be straightforward.

Those ad hoc and common factors are qualitatively discussed in the following sections. Presented here are the ones judged to have higher priority for a quantitative evaluation. This list of factors is by no means exhaustive and others might be considered. Furthermore the distinction between ad hoc and common factors is by now judgmental.

IX-2.1. Ad-hoc factors

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 is the net present value of the investment. For a given size, provided a sequenced construction of multiple modules, the 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 LR's) (market matching). The first scenario gives the best financial performance, with smoother cash flow profile during the project lifetime. On the contrary the parallel, concentrated construction of all the modules, generates higher overnight construction cost per kWe due to the loss of learning economies and consequently comparable or even worse financial expenses as compared to LR plant; still, shorter lead times lead to earlier revenues for the SMRs. Therefore for a given total plant size, the multiple SMRs allow to reap revenues that would be foregone by a LR.

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. 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 given 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 a expected loss of revenues with respect to SMRs for power not taken.

The latter effect translates in a higher net present value for SMRs, 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.

Easier plant-grid matching

Not only have the economic and financial requirements had 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 MW(e) 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 SMRs allow to reap profits that would be lost by a LR (market matching).

New design strategy and solutions

Even the technological choices on the design phase can directly affect the SMR v LR economics. 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 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 might decrease the levelized unit electricity costs[1].

Co-generation

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. 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

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[1] Levelized Unit Electricity Cost it is the present value of the total cost of building and operating a generating plant over its economic life, converted to equal annual payments, expressed as the value per unit of electricity and levelized in constant currency units (i.e. deflated to remove the impact of inflation). It takes into account both generation costs (i.e. production costs; see Section IX-4.) and financial costs (i.e. cost of capital; see Section IX-6.).

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 co-generation plants. Therefore, for a given size, the SMRs allows to reap profits that would be lost by a LR.

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 is possible having a heat bulk ordering process of components like valves. This aspect allows the SMRs to achieve the mass production economies and a more standardised procurement process.

IX-2.2. Common factors

Plant Size – Economies of scale

The size of a NPP is the first and most obvious of the common factor which, of course, generates the economies of scale. Other things being equal, the capital cost of a larger unit is significantly cheaper than for a smaller version.

Modularization – Factory fabrication economies

Generation IV International Forum (GIF), a framework for international cooperation in research and development for the next generation of nuclear energy systems, defines modularization as the process of converting the design and construction of a monolithic plant or stick-built scope to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies [IX-4]. 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 is possible having a greater percentage of factory made components, and investment costs are reduced (factory fabrication economies).

Modularity - Learning economies

Gen IV defines modularity like the idea of construction and deployment of a larger number of standardized units [IX-4]. Allowed by the smaller size and lower power of SMRs, the modularity approach reduces the requirements for more expensive and time consuming onsite 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 is a necessary condition, along with the smaller size of units, for supplier 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 MW(E)e 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 takes 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.

The mentioned technical benefits will hopefully allow the SMRs to experience smaller average investment costs, given the plant size.

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.

Multiple units at a single site - Learning economies and co-siting economies:

If the demand is growing locally, SMRs allow the investors to make incremental capacity additions in a pre-existing site. In addition to the mentioned learning economies, 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. Moreover, multiple units on a single site assure a higher average service factor than a LR unit, for a given total generation capacity, due to the lower probability of simultaneous, parallel failure of all the modules. And, finally, the higher number of units allows - through a smart refuelling outages scheduling – SMRs investors to require less replacement power during plant planned outages. 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 MW(e) do exist. Thus, while in principle this factor favours the SMRs, a case-by-case evaluation must be done.

Front end investment – Reduced entry barriers:

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 financial resources, therefore for a given size the multiple SMRs allows a larger number of investors than LR to enter the nuclear generation sector: a lower front-end investment for each module, together with a staggered construction produce a lower average capital employed. Table IX-1 synthesises the distribution of the mentioned benefits across the factors.

TABLES IX-1. NPP FEATURES AND THEIR EFFECTS: EXPECTED POSITIVE (+) AND NEGATIVE (-) CONTRIBUTIONS TO SMR DIFFERENTIAL PROFITABILITY.

NPP FEATURE	GENERATION COSTS	FINANCIAL COSTS	MARKET OPPORTUNITY
SMR Ad-Hoc Factors			
Scalability		Investment deferral (+) Better cash flow profile (+)	Market matching (+)
Investment flexibility		Reduced risk premium (+)	Market matching (+)

NPP FEATURE	GENERATION COSTS	FINANCIAL COSTS	MARKET OPPORTUNITY
Easier plant-grid matching			Market suitability (+)
New design strategy and solutions	Technical progress economies (+)	Reduced risk premium (+)	
Co-generation			Market suitability (+)
Mass production economies	Mass production economies (+)		
SMR&LR Common Factors			
Size	Economies of scale (-)		
Modularization	Factory fabrication economies (+)		
Modularity	Learning economies (+)		
Multiple units at a single site	Co-siting economies (+) Learning economies (+)	Reduced risk premium (+)	
Front end investment		Reduced risk premium (+) Lower average capital employed (+)	Reduced entry barriers (+)

All the above factors (summarised in Table IX-1) should be taken into account when comparing SMRs and LRs. In this chapter the focus is on factors with major effects on the generation costs.

The degree to which these unique features of SMRs are able to outweigh the reduction of average generation costs arising from LRs size economies is clearly dependent on the market and production setting. A parametric model will allow the user to analyze the sensitivity of SMRs differential profitability to a number of such exogenous elements.

IX-3. Description of the model framework

IX-3.1. General description

The model performs the economic and financial analysis of a new investment in nuclear power plants in the small-to-medium size range. The scope of the modelling is the investment in a given total power generation capacity, represented either by a multiple SMRs or by a single LR. A comparative methodology to evaluate the differential economic and financial advantages/disadvantages, offered by the two different plant configurations and technologies, is adopted. The investment model brings up all the main elements of an economic and financial analysis (revenues, operating and capital costs, financial costs) and relies upon a cash flow analysis over the plant lifetime. The output of the investment model is a set of indexes measuring the financial performance of the investment from the investor point of view: profitability for a private investor or economic soundness for a public stakeholder. The aim is to evaluate the project profitability for a private investor or for a public body (at governmental, ministry, public administration level) should a decision to invest in the construction of new SMRs be taken. By now the objective function of both public and public investors is assumed to be the profitability of investment, rather than its social value. In turn this is an acceptable assumption, and the investment profitability approximates its social value, if the wholesale electricity market is competitive, and energy and environment regulations induce the investors to take into account the external costs (e.g. by the means of carbon taxes for CO_2 emissions). A thorough discussion of this assumption is beyond the aim of present analysis, but further contributions about it are welcome.

A sensitivity analysis is performed by the investment model, to assess the impact of the key variable changes on the output values. Considering multiple SMRs on the same plant-site, a range of scenarios is considered varying from the staggered deployment of the power units to the parallel, concentrated construction of all the SMR modules.

The output of the investment model represent the input of a multi-attribute evaluation model, where the economic/financial performance is considered together with external, not fully quantifiable costs/benefits of the SMRs' concept, in a thorough evaluation to produce a synthetic assessment of the SMRs' vs. LR project attractiveness.

Since each scenario is country-dependent, the objective is not to evaluate in which countries the investments should be concentrated, but given a country, to evaluate the profitability in selecting the SMR technology. At the same time, the model is not assumed to demonstrate that SMRs are in any case more convenient than large NPPs, but under certain circumstances such technology can represent the optimal solution for the production of electricity and possibly other outputs (e.g. heat, desalinated water).

It has to be considered that several factors are specific of a country, e.g. the labour costs, the raw material (commodity) costs, the cost and the availability of capital, the electric grid (in terms of load capacity and interconnections). Hence some investment solutions could be optimal within a certain scenario and a certain country, but could not be simply transferred to others.

The general model for the evaluation of the investment is framed into a cluster of models. Figure IX-1 summarizes the overall structure.

The submodels to be adopted and linked are:

1. the generation cost model;
2. the revenue or market model;
3. the financial cost model;
4. the investment model;
5. the external factors model;
6. the multiattribute evaluation model.

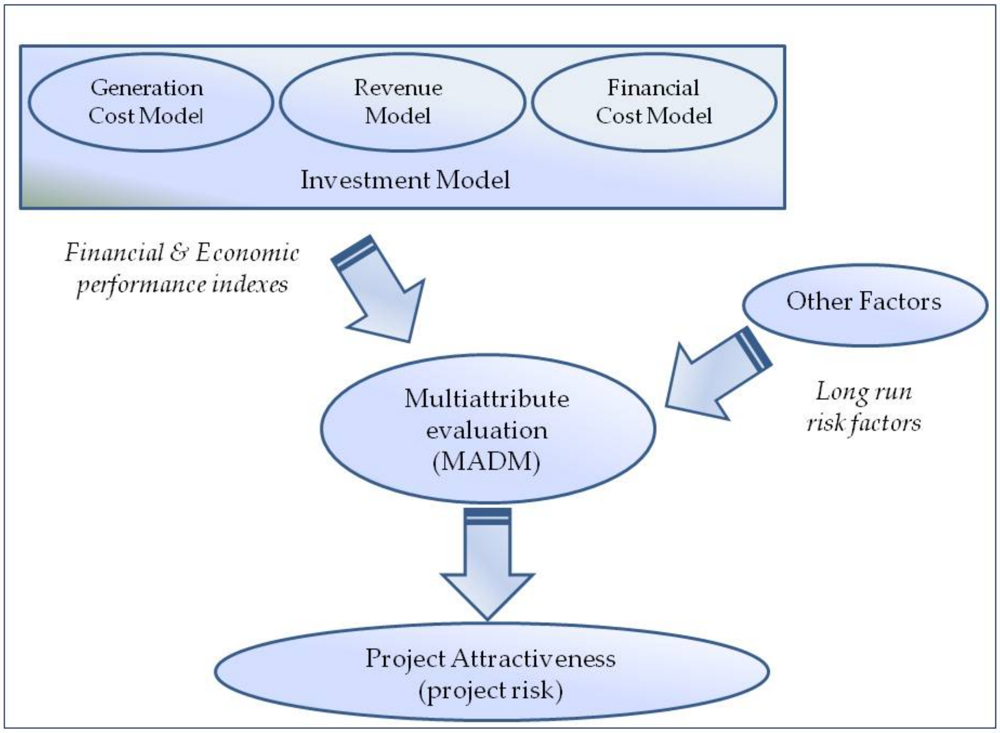

FIG. IX-1. Framework of the general model for the investment evaluation.

The following paragraphs deal with the hypothesis, the objectives and the main features each model should possess.

In the open literature, the most recent effort in developing an economic model appears to be that produced by the Economic Modelling Working Group of Generation IV [IX-4], devoted to next generation reactors but validated on GenIII and GenIII+ reactor data. The strategy [IX-5, IX-6]; is similar to that here proposed and the modules already prepared by EMWG are those related to the generation cost model. While this is a plant-based model, other enterprise models are available for multiple plants including fuel cycle plants and international scenarios evaluation, such as the DANESS code [IX-7 to IX-9]. Since the objective of the work is to prepare a plant-based, general-country economic model, all the items already available in the open literature, included those developed by the IAEA PESS/NE group, will be taken into account.

IX-3.2. Existing models in open literature

The open model is a contribution to a wide effort of modelling the economics of nuclear power generation. This subject shows a revamped interest on the back of a worldwide nuclear renaissance with plans for consolidating the nuclear power generation capacity of many developed and developing countries.

Several codes have been develop to deal with dynamic nuclear energy system strategies at regional or multi-regional level. All the following are based on the mass flow analysis (MFA).

- COSI (CEA, France),
- DANESS (ANL, USA),

- DESAE (UNK Group, Russia),
- ORION (NEXIA, UK),
- OSIRIS (NNC, UK),
- PROGNOSIS (Kurchatov Institute and Minatom, Russia),
- SuperStar (TEPCO, Japan),
- VISTA (IAEA).

They consider different types of reactors and are linked to exogenous detailed reactor physics codes. COSI, DANESS, DESAE, ORION, OSIRIS and PROGNOSIS calculate the LUEC; DANESS also involve a cash-flow analysis.

In Table IX-2 the main features of these codes are summarised.

TABLE IX-2. KEY FEATURES OF THE MAJOR CODES CURRENTLY AVAILABLE FOR ANALYSIS OF NUCLEAR RELATED SCENARIOS AND TECHNOLOGY.

Scope \ Code	COSI	DANESS	DESAE	DYMOND	NFCSim	ORION	OSIRIS	PROGNOSIS	SuperStar	VISTA
Equilibrium analysis										
Single reactor	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Reactor park	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Dynamic analysis										
Regional reactor park	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Multi-regional reactor park	✓	✓	✓		✓	✓	✓			✓
Mass-flow analysis										
Natural U/Th use	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Front-end capacity needs & use	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Reactor core loading	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Back-end capacity needs & use	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Separated material inventories	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Disposal needs	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Related functionalities										

Scope \ Code	COSI	DANESS	DESAE	DYMOND	NFCSim	ORION	OSIRIS	PROGNOSIS	SuperStar	VISTA
Isotopic composition	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Decay heat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Reactor core management	✓	✓	✓	✓	✓	✓	✓	✓		
Economics										
Levelized generation cost	✓	✓	✓			✓	✓	✓		
Investment needs		✓	✓			✓		✓		
Cash-flow analysis		✓								
Environmental										
Life cycle inventory										
Life cycle analysis										
Waste management										
Repository impact	✓	✓		✓					✓	
Socio-political										
Proliferation risk					✓					
Availability										
Free			✓							✓
License agreement	✓	✓		✓	✓			✓	✓	
Commercial						✓	✓			

In particular, COSI can take account of the investment, operating and decommissioning costs for reactors, fuel cycle facilities and the actualization rate, calculating a levelized generation cost per kWhe.

OSIRIS is an investment appraisal method to calculate a unit electricity generating cost, discounting the following costs given as input over the lifetime of a scenario: reactor first-of-a-kind, capital and decommissioning costs, fuel cycle front and back end costs, process plant capital and decommissioning costs, reactor operation and maintenance costs, raw material costs.

SuperStar is specifically used to assess the waste management aspects and has a built-in module, COST, that calculates the electric power generation cost.

Among the most recent efforts of economic modelling, the G4-ECONS model of the Economic Modelling Working Group of Generation IV International Forum [IX-5] is an excel-based code focusing on generation costs from next generation reactors; this model includes a highly detailed fuel cost module and is validated on GenIII and GenIII+ reactor data. Since the model's purpose is the technology comparison, such as the Generation IV and GNEP applications, it affords the cost estimation in levelized manner and calculates the LUEC as the main output. EMWG also provides detailed cost estimation guidelines in the attempt to set a uniform accounting standard.

Another important reference is the French SEMER [IX-10], a simplified code for the economic evaluation of nuclear based production systems; fossil-based systems are also included to provide a basis for cost comparisons. SEMER includes three types of model libraries: the global model, for a rapid estimation, the detailed models, for the finer cost evaluation of individual components and circuits in a PWR type of reactor and the fuel cycle models, for PWRS, HTRs and FBRs, allowing the cost estimations related to all the steps in the nuclear fuel cycle, including reprocessing and disposal.

Finally, the IAEA Planning & Economic Studies Section (PESS) of Department of Nuclear Energy, is active in the development of economic models; hereafter the available codes from IAEA-PESS with their purposes are listed:

- MAED (model for analysis of energy demand): evaluates future energy demands based on medium- to long-term scenarios of socioeconomic, technological and demographic development.
- WASP (Wien automatic system planning package): is used in developing countries for power system planning. It determines the optimal long-term expansion plan for a power generating system. Constraints may include limited fuel availability, emission restrictions, system reliability requirements and other factors. Optimal expansion is determined by minimizing discounted total costs.
- ENPEP (energy and power evaluation programme): is a program evaluation of energy system development strategies; it links to MAED and WIEN models, computes market clearing prices and balance energy demand / supply under market conditions and estimates environmental burdens from the energy system.
- MESSAGE (model of energy supply systems and their general environmental impacts): the code is able to formulate and evaluate alternative energy supply strategies for user defined constraints on, for example, new investment limits, market penetration rates for new technologies, fuel availability and trade, environmental emissions, as well as to analyze energy/electricity markets and climate change issues.
- SIMPACTS (simplified approach for estimating impacts of electricity generation): the code estimates the environmental impacts and external costs of different electricity generation chains, covering health, agricultural, forest and materials damage, airborne and water pollution as well as solid waste.
- GTMax (generation and transmission maximization) model: based on a mixed integer linear programming (LP) approach, it maximizes the net revenues of power systems by finding a solution that increases income while keeping expenses at a minimum. The model computes and tracks hourly energy transactions, market prices, and production costs.
- DEEP (desalination economic evaluation program): is an excel based simplified model that applies to the co-generation of desalination water and energy; it enables a side-by-side comparison of different design alternatives to identify the lowest cost technology option.

- FINPLAN (model for financial analysis of electric sector expansion plans): the code is intended as a tool for the assessment of the financial viability at plant-level or system-level. FINPLAN is used for comparative assessment of energy sector investment options (different energy sources) in competitive capital and electricity markets, based on financial performance ratios. In addition, FINPLAN helps to identify the selling price of electricity that would permit payback on investments. It was completed in 2001 and it has been mainly employed in country-scenario assessment. It was released on a pilot basis for the project 'Comparative studies of energy supply options in Poland for 1997-2020', using the results of GTMax as inputs.

It has to be highlighted that FINPLAN's architecture appears to be in line with some of the features of the open model here described. Both base their analysis on projected cash flows and give as output key financial ratios and other financial indicators. Both prescribe a sensitivity analysis of the output values: forecasts developed with the FINPLAN model take into account price sensitivity to exchange rates, fluctuations in demand, and foreseeable inflation rates for both domestic and foreign currencies. FINPLAN has been revised with input from commercial bankers and other experts to permit assessment of energy sector investment options in competitive capital and electricity markets.

SMRs' model purposes and features line up with FINPLAN model, but developing in detail the specific comparative economic assessment between SMRs' and LR technology options. In addition, SMRs' model is able to account for the main external, not-quantifiable factors affecting the investment attractiveness through a multi-attribute evaluation model, thus offering a comprehensive project evaluation that encompasses the mere financial profitability. Both FINPLAN and SMRs' model are intended as a strategic tool for both institutional and private investors in their investment decision.

To some extent, SMRs' model can be considered as a complement of FINPLAN's purposed investigation.

SMRs' model is intended as an open model with respect to the existing economic codes, to the extent that it has to be adaptable to be linked to some of them, to create a more comprehensive and flexible architecture to provide an exhaustive, detailed, customizable analysis tool.

On the base of the available information, Table IX-3 shows the links among the SMR's model and some of the codes presented in this paragraph; if such links could be set they could feed and strengthen the estimation capabilities of some modules of SMR's model.

In this framework, the open strategy allows the opportunity to co-develop the models with the aim to optimize, refine and coordinate the economic modelling effort.

TABLE IX-3. SMRs OPEN MODEL MODULES AND POSSIBLE LINKS WITH OTHER CODES

	MODULES OF SMRS' OPEN MODEL				
CODES	GENERATION COST MODEL	REVENUE MODEL	FINANCIAL COST MODEL	IINVESTMENT MODEL	OTHER FACTORS
COSI	✓				
DANESS	✓				
DESAE	✓				
DYMOND					

CODES	MODULES OF SMRS' OPEN MODEL				
	GENERATION COST MODEL	REVENUE MODEL	FINANCIAL COST MODEL	IINVESTMENT MODEL	OTHER FACTORS
NFCSim					
ORION	✓				
OSIRIS	✓				
PROGNOSIS	✓				
SuperStar	✓				
VISTA					
SEMER	✓				
MAED		✓			
WASP					
ENPEP		✓			✓
MESSAGE					✓
SIMPACTS					✓
GTMax	✓	✓			
DEEP					
FINPLAN			✓	✓	

IX-4. The Generation cost model

- Output: total generation costs over the economic plant life (input to the investment module), and front end investment (input to the revenue module)
- Inputs: reactor technology (LR vs. SMR), plant size, economic plant life time, construction time, degree of standardization, thermal efficiency, number of serial and on-site units, supplied quantities (output of the revenue module), …
- Parameters / forecasts: wages, retail price index, fuel price …
  Note: The parameters (and forecasts over economic the plant life) should be derived from pre-existing ancillary models and outlooks; they are country-specific, and common to LRs and SMRs.

It is the starting and basic model of the set. The main objective is the evaluation of the time series generation costs of electricity corresponding to the plant-scenario to be analysed, given a cash flow expenditure during the whole plant life. The module has to be flexible and sufficiently open to receive data from new reactor technology solutions (e.g. Generation IV, INPRO, GNEP). Moreover the module should consider both closed, partially open or open fuel cycles.

The module has to be applicable in the international scenario; hence the insurance, tax and account management rules should be customisable to the country.

The generation costs can be grouped into four main items:

i) Capital (construction plus interest) costs;

ii) Operation and maintenance (O&M) costs;

iii) Fuel and fuel cycle costs;

iv) Decontamination and decommissioning (D&D) costs.

The module should take into account also for the possible SMRs plant configuration strategies (e.g. size of the plant, multi-module on the same site; or centralised vs. distributed strategy) and for project planning and execution (e.g. staggered construction strategies).

The general features the module should maintain are clearly identified by the GenIV-Economic Modelling Working Group [IX-5] cit.:

- Simplicity: several SMRs are still in a design and development phase, hence the availability and quality of the information on costs could be still at an embryonic stage. This implies that complex economic models, as the USCEA (US Council for Energy Awareness) model or some models used by merchant banks or non governmental organizations to evaluate the competitiveness of the nuclear technology against other energy sources, are not suitable for the objective. The module has to be able to evaluate the cost of the produced MWh corresponding to different NPP solutions and to be integrated with the other modules for a global investment evaluation.

- Universality: since SMRs and several new generation reactors in general are designed to be built and operated even in developing countries [IX-11], the module has to be customisable in a simple way to the country-specific situation in terms of taxes, discount rate, labour cost, regulatory rules, etc. The G4-ECONS model handles this by discount rate selection.

- Transparency: the algorithms should be clearly identifiable and visible in such a way the user can comprehend how a certain value is calculated and the rule can be easily modified according to the country-specifics. A spreadsheet appears to be the most viable approach.

- Adaptability: it has to be allowed to link different parts of the model to other algorithms, models or specific data; e.g. in a specific NPP solution, some indirect cost values could be substituted by a link with an external model, evaluating that costs as a function of the reactor power (scale economy models) or other design variables.

The adaptability feature is of paramount importance since a large part of the SMRs are still in the design phase, hence detailed bottom-up costs are not yet available, but will be as the project develops. Thus a simplified top-down estimation of direct 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 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 life time;
- Thermal cycle efficiency;

- Labour cost;
- Load factor;
- Service factor.

Another study [IX-12] 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 generation cost module development, it seems reasonable to use simplification features similar to those adopted by the EMWG:

- the costs all over the plant life cycle can be broken down in two basic phase of the plant lifetime: 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, while an annual, levelised cost for the multi-year operational period over the economic life is obtained, taking into account the capitalised cost amortisation, the D&D fund growth, all the operational costs expenditure;
- at a preliminary stage, escalation cost factors or tables can be avoided;
- 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 and DANESS code could be adopted.

Hence the main macro-items for the costs splitting are [IX-6, IX-13]:

- R&D and design costs;
- License and permits;
- Construction;
- Interests;
- Operation and maintenance;
- Fuel;
- Decommissioning and decontamination.

The generation cost model will provide an estimated value for the levelised unit electricity cost (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.

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 a function of the supplied quantity q (MWh), the unit size S (MW(e)), the specific reactor technology T (e.g. whether LR or SMR) and a set 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 X and thus expanding the Eq. (1). The cost function is assumed to be separable into four components:

- the total capital cost function:
- the total operating cost function;
- the fuel cost function;
- the decommissioning cost function.

Once 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.

IX-4.1. The capital cost model

Nuclear power plants are known to be very capital-intensive, with long construction time and high IDC (interests during construction) costs; thus, in order to present a parametric and differential analysis of SMR reactors towards other nuclear power plants, it seems of a paramount importance to have them be deeply investigated. Some key factors have been identified and discussed in the following sections.

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)[2], 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 [MW(e)], 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 [IX-14]. The latter are investment costs in nature and should be included in construction costs.

Bowers et al. [IX-15] 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 IX-4).

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[2] See Table IX-5 for cost items that are included in investment costs.

Table IX-4.SCALE ECONOMIES IN INVESTMENT COSTS

AUTHOR	YEAR	N PARAMETER	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 economy 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 Mr. 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: Bower et al. [IX-15]

Economies of scale in investment activities are found to hold at a more disaggregated level, as shown by DOE [IX-16] (Table IX-5). 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.

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

TABLE IX-5. SCALE ECONOMIES IN INDIVIDUAL INVESTMENT ITEMS

COST ITEMS	N PARAMETER
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 [IX-16]

In their study of economies of scale at the plant level, Marshall and Navarro [IX-17] revise the widespread concept of overnight costs[3]. 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 [IX-19] 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

[3] 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 (say, 2007€) 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-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 borrowed funds and other factors working on the overnight cost cause the final capital cost of the plant to actually be more than the overnight cost.

far weaker (similarly to findings obtained by Rhine [IX-19], for a set of US electric utilities at the firm level)[4].

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.

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 [IX-20], David and Rothwell [IX-21, IX-22] and Carayannis [IX-23]. 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 [MW(e)], 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:

$$l^i = \frac{\partial TC^I / TC^I}{\partial N^i / N^i}, \text{for } N^i > 1 \tag{3}$$

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:

$$l^i \leq 0, \text{ and } \frac{\partial^2 (TC^C / TC^C)}{(\partial N^i / N^i)^2} \geq 0 \tag{4}$$

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

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[4] Since the pioneering econometric study by Christensen and Green [IX-24], 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 [IX-25] 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 [IX-26] confirm that differences exist and enlighten the role played by the region of plant location. Rhine [IX-19] 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.

First, the one co-siting economies, consisting in fix and semi fix 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, it is preliminarily proposed 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 IX-27 and IX-23].

$$l^S \leq l^U \leq l^W \leq 0 \tag{5}$$

where:

l^S= site learning economies

l^U = utility learning economies

l^W = world learning economies

Design strategies and innovative solutions

Shepherd and Hayns [IX-1], Schock et al. [IX-2] and Miller [IX-3] 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 IX-28 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 [IX-21 to IX-23].

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 components reduction and simplification of component allow to reduce the overnight cost thanks to both reduced labour and cheaper equipments.

IX-4.2. The operating and maintenance cost model

Operating and maintenance costs are the expenditures, fixed or variable, related to the decisions and actions regarding the control and upkeep of property and equipment of a nuclear power plant. These are inclusive, but not limited to, the following [IX-29]:

- Actions focused on scheduling procedures, and work/systems control and optimization;
- 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.

Synthesizing, O&M costs are all the costs of operating and maintaining the plant in keeping with the best practices available, excluding the fuel cost (which is considered separately): they start with commercial operation and continue through the operating life of the plant. More than 70% of them are labour-related costs [IX-30]: Generation IV Forum provides an annualized O&M code of accounts description [IX-4], as shown in Table IX-6.

TABLE IX-6. CODE OF ACCOUNT (COA) DESCRIPTION FOR THE O&M COSTS.

COA NUMBER	DESCRIPTION
710 Operation and maintenance staff	Includes all O&M personnel assigned to the plant site.
720 Management staff	Includes all management personnel assigned to the plant site.
730 Salary related costs	Cost of pensions and benefits, including worker's compensation insurance, provided for the on-site and off-site staff. The method of calculation will vary by nation. In some countries these are so-called social costs
740 Operations chemicals and lubricants	Can consist of a mix of variable and fixed costs. Includes non-fuel items such as resins, chemicals, make-up fluids. Includes costs of management disposal of operational radioactive waste
750 Spare parts	Purchased spare parts for operations of plant
760 Utilities, supplies, and purchased services	Consumables operating materials and equipments, rad-worker clothing, office supplies. Can consist of variable and fixed costs. Consists of materials and other unrecoverable items such, small equipment and tools required for maintenance. In the US these accounts include NRC annual fees and review costs, as well as other routine safety, environmental, and health physics inspections. Other nations' annual costs for this category will depend on their regulatory environment. Also includes purchased activities by personnel not assigned full time to the plant site; e.g. safety reviews, off-site training, environmental monitoring, meteorological surveys, power planning, fuel studies, and other owner home office activities directly supporting the plant. Some plants now use off-site crews for contract refuelling
770 Capital plant upgrades	Total cost of large capital item that must be purchased after commercial operation start (e.g. steam generator replacement), averaged per year over the economic lifetime of the system. Can be estimated as a % of the base cost per year
780 Taxes and insurance	Costs for commercial and government liability insurance, property damage insurance, and replacement power insurance. Includes property taxes, sales tax, and any other taxes that can vary by country
790 Contingency annualized O&M costs	Allowances for contingency costs for the desired confidence level of O&M costs.

The detailed account description could be particularly useful in a bottom-up approach: this is not the case of SMRs, since most of them are currently in an early stage of development. It looks more appropriate to focus on some cost drivers that lead O&M costs: one of them, i.e. economy of scale and technical saving, have already been described in the previous paragraph. Indeed, according to the common knowledge of power plants [IX-31 to IX-33], economy of scale is also the almost unique driver for O&M costs; to this end the same methodology used in capital cost can be assumed.

Further drivers specific for O&M costs are discussed in the following:

Multiple units in single site: the presence of one (or more) additional unit surely is a lever for the O&M cost competitiveness of SMRs. In fact some advantages can be obtained:

a) Sharing non-power structures and related staffing: all administrative and general expenses are not directly related to the number of units in the plant.
b) Reduction of licenses, taxes and insurance costs: some of them are 'una tantum' expenses not depending on the presence of one or more units in the site.

On the other hand, it should be considered that operating and maintenance costs depend on the compliance with staffing requirements and safety standards set by the Regulatory Commission: for this reason, the SMRs' O&M cost savings could be lower than expected.

Summarizing, it seems reasonable to assume that the cost reduction decreases with the number of units in the site. A power function, as proposed by Bowers et al. [IX-31], could be correctly applied:

$$O\,\&\,M = f(size) \times (\#units)^n \tag{6}$$

Reactor technology concept: the historical O&M cost performance of NPPs could be partly explained by the technological difference of the plants. In fact different designs have different safety requirements and different related costs. Some studies found a statistical relevance of the plant technology, specifically in the comparison of PWRs and BWRs. When appropriate, also this factor should be taken into account.

Plant outages: NPPs could be shut down either for planned outages (fuel substitution) or for forced outages (related to safety requirements violations). The effect of power plant outages can be observed on two sides: an additional cost and a time extension. In fact each stop requires on-site and off-site staffing to perform the maintenance operations and reduces the capacity factor with an associated opportunity cost (loss of power generation). The capacity factor (CF) is defined as:

$$CF = Availability \times Average\ Power\ Level \tag{7}$$

and

$$Availability = \frac{8766 - POH - FOH}{8766} \tag{8}$$

where:

- POH = planned outage hours per year for fuel substitution;
- FOH = forced outage hours, related to safety or public health requirements;

- Average power level = NPPs, to minimize the high investment costs, are used to work at full (100%) power level. This is surely not valid for other base load technologies such as coal or gas.

The SMRs, designed with unique technological solutions - not accessible to large size plants – can have a fuel cycle extension limiting plant outages with a reduction on the specific O&M annual cost in $/MWh.

Technical & design saving: the safety by design approach, described in the capital cost section, can provide advantages also in the O&M costs with a fewer number of maintenance operations. At this stage, as for the capital cost, the nature and role of standardization have still to be analyzed and modelled in detail.

Considering other non-differential factors, the O&M cost structure – mainly labour or labour-related – leads to different cost performances for different wage policies (according to the existing laws that are country specific). Thus, the plant location is particularly important for the total O&M cost of a plant, but not relevant in a differential competitiveness evaluation of SMRs towards Large size plants.

A further factor that seems important for a cost analysis is related to plant age, which is a controversial issue [IX-32 to IX-39]. Some of the operators argue that plant O&M costs dramatically grow after a 'break-in' point located at the very end of the plant planned life, when the major components begin to fall. On the other hand, some critics think that the aging process begins early in a plant's life and can be observed over most of its life. Actually, even an old plant, with the substitution of its vital components (e.g. steam generators) can mask its age and perform like plants at the early stage of their life. Anyway, this is not a differential factor for cost analyses on new plants with same design life.

Considering all the variables, the O&M cost function can be expressed as follows:

$$O\,\&\,M\ cost\left(\frac{\$}{MWh}\right)= f\left\{p(\$/kWe), q(CF)\right\} \tag{9}$$

where:

$$\begin{aligned} p\left(\frac{\$}{kWe}\right) &= g\,(size, units\ number, reactor\ type, ...) \\ q(CF) &= h\,(planned\ outage\ hours,\ forced\ outage\ hours) \end{aligned} \tag{10}$$

IX-4.3. The Fuel Cycle cost model

The third part of the Generation cost model includes an evaluation of the fuel cost for nuclear power plants, which covers about 10-15 % of the levelized unit electricity cost [IX-5, IX-32 and IX-40]. The operations associated with the nuclear fuel cycle and the corresponding waste typically extend of a period of between 50 to 100 years, from mining the uranium ore to finally disposing of the high level waste [IX-41]. The nuclear fuel cycle can be divided into three stages: front-end, at-reactor and back-end. These, in turn, can be sub-divided into more specific components [IX-42].

The front-end of the fuel cycle consists of the first four steps: uranium purchase (from mining or milling); conversion to uranium hexafluoride; enrichment; and fuel fabrication. Obviously, the at-reactor stage covers the use of new fuel assemblies into the core where the pellets can remain from 3 to 5 years, depending on the selected refuelling schedule. For an appropriate cost evaluation, two back-end options should be considered: the first is based on prompt reprocessing of the spent fuel and the recycle of recovered uranium and plutonium (open-cycle), while the second option is based on long term storage followed by direct disposal (closed-cycle).

As far as the evaluation of a new NPP investment is concerned, it seems appropriate to perform a more detailed analysis on the two major fuel cycle cost accounts, i.e. uranium purchase and enrichment cost.

Uranium markets: depending on the prices, uranium purchase can give a large contribution of the total fuel cost for a plant. Uranium spot prices apply to marginal trading from day to day and usually represent less than 20% of supply. Most trade is 3-7 year term contracts with producers selling direct to utilities, but with the price often related to the spot price [IX-43]. Thus, particular attention has to be paid to the volatility of the price, which in part depends on the perception of imminent scarcity of the material [IX-41].

Enrichment cost: the mass separation of U-235 from U-238 can be obtained with many different technologies: some of them – gaseous diffusion, gas centrifuges, jet nozzle / aerodynamic separation and electromagnetic isotope separation – are well-known, others (e.g. laser separation) are under development [IX-44]; anyway, since each of them requires a specific amount of energy and depending on the available technology, the enrichment cost will be different. Beside that, enrichment cost is mainly driven by the enriched U-235 percentage: the higher the U-235 percentage, the more expensive the enrichment process cost. Under this point of view should be taken into account that SMRs have been designed to have a slightly higher ratio of U-235 on U-238 than LRs.

Considering the impact of fuel cycle cost on SMRs competitiveness, some conclusions can be drawn:

- all fuel cycle cost accounts, except enrichment cost, are common factors also for evaluating the competitiveness of SMRs towards large size plants. Since SMRs have been designed to use more enriched uranium than LRs, useful information could rise up from a more detailed analysis of the specific uranium cost $/kg on the U-235 enrichment percentage.
- the total fuel cycle cost is significantly differential uniquely if the scope of the analysis is to evaluate the competitiveness of SMR towards other base load technologies such as coal or gas.

IX-4.4. The Decommissioning cost model

The process of dismantling a NPP, called decommissioning, is necessary because radiation hazard remains even after removal of the plant's spent fuel. Therefore the purpose of this section is to investigate the costs connected to the decommissioning.

From a general point of view the main frame structure of decommissioning cost estimation consists of 6 cost groups [IX-45]:

1. Preparation and project management: includes all the activities carried out during the preparation and management of the actual decommissioning.

2. Facilities shutdown: covers all the activities relating to the shutdown operations of the facility.

3. Decontamination and dismantling operations: covers all the activities relating to the activities relating to the decontamination and dismantling operations.

4. Waste processing and management: includes all the activities related to the treatment, processing, packaging and temporary storage of the decommissioning wastes.

5. Site restoration: covers all the activities related to the residual radiological characterizations and site restorations.
6. Other activities: covers all other activities costs that cannot be classified into the foregoing groups.

In order to estimate decommissioning costs, many aspects considered for the capital cost still apply. This aspect is consistent in particular with the NEA/OECD [IX-46] study indicating the 14 main cost drivers influencing the decommissioning cost. Considering the main goal of the open model, the cost drivers are divided into 2 groups: the ones affecting the evaluation Small vs. Large and the other not differential (Table IX-7). The firsts are briefly discussed.

TABLE IX-7. NEA/OECD COST DRIVERS, DIVIDED ACCORDING TO THE MODEL SCOPE.

DIFFERENTIAL FACTORS LARGE VS. SMR	NOT DIFFERENTIAL FACTORS
▪ Type of reactor	▪ Scope of decommissioning activities
▪ Size of reactor	▪ Decommissioning strategy options
▪ Number of units on the site	▪ Site re-use
▪ Operating history	▪ Clearance and classification levels
▪ Amount of waste	▪ Regulatory standards
▪ Availability of radioactive waste repositories	▪ Uncertainties and uncertainty treatment
	▪ Labour costs
	▪ Social and political factors

Type of reactor

Reactor types influence the decommissioning cost, because there are significant physically differences between them. For example the dimension of LWR reactors is smaller than the gas-cooled reactors; BWR reactors have steam turbines that are contaminated with radioactive substances whereas other reactor types do not.

Size of reactor - Economies of scale

The size of the reactor (combined with the Type of reactor) leads the quantity and the nature of the radioactive waste that results from decommissioning, as well as the scale of dismantling required. Here apply the consideration for the economies of scale already presented.

Number of units on the site - Learning economies and Co-siting economies

Also in this case all the considerations provided for the capital cost apply. Experience is essential in order to reduce the risks and costs. This embraces the adoption of a definitive strategy, the necessary planning and preparation, setting up the right organisation with defined responsibilities, and knowledge of the right technology for the job with access to the appropriate specialists. For example the BNFL approach is to set up a dedicated and experienced decommissioning project team. This is headed by a project manager who is responsible for all decommissioning work on site, and reports to the plant manager who is the client and retains responsibility for all regulatory and site safety issues [IX-47].

Operating history

The operating history might have an impact on decommissioning for three reasons.

1. if an incident occur on the site that resulted in damage or contamination spread requiring different or more extensive decommissioning effort;
2. other history related issues like fuel leakage and water chemistry events as well as fuel leakage events can result in the dispersion of alpha-emitting radionuclides within the primary circuit that will complicate the decommissioning and dismantling process;
3. reactor operating load factor during its lifetime influences the radioactivity level.

A safer reactor (as many SMRs could be) can drastically reduce the risks using the concept of 'safety by design'. This approach physically prevents accidents from occurring rather than coping, by active or passive means, with their consequences.

Amount of waste

The quantity and quality of radioactive waste resulting from decommissioning can vary significantly among different design type. In particular the SMRs seem produce a lower amount of waste. For instance, considering the IRIS case

> "… the reactor vessel can act as a sarcophagus for the reactor internals, (i.e., the irradiated internals, minus the fuel, can be left inside the vessel), thus greatly simplifying decommissioning and transportation"

and the internal shielding

> "…provide sufficient gamma shielding to limit the dose outside the vessel from activated internals (barrel, lower support plate) to make it easier and more economical to perform periodic in-service inspections and final decommissioning and disposal" [IX-48].

Availability of radioactive waste repositories

Decommissioning produces significant quantities, and different types, of radioactive waste that will ultimately require disposal in a suitable repository. Some repositories will be able to accommodate large packages, including whole reactor vessels, others will only accept much smaller packages. These will all affect the extent of dismantling and packaging work required. All these factors will have an impact on costs. Since the SMRs are smaller, both like overall dimension and components (modules), it seems reasonable to assume that will be easier to find more available repositories.

To get an order of magnitude of the decommissioning cost the NEA/OECD reports the cost estimates of 53 reactors, with sizes ranging from less than 10 MW(e) to more than 1000 MW(e). In order to quantitative asses the decommissioning cost of a generic NPP there are database such as PRICE [IX-49]. PRICE presents a hierarchical approach that can be used to identify costs in key areas. Estimates are produced at various stages in the lifecycle of a decommissioning project and these are related to the approach adopted for their study, planning and implementation.

The task of the decommissioning cost estimate is not a simple one, since at the moment only 5 reactors have been completely decommissioned, while 22 are underway, hence a historical database of real costs has not been yet established. Moreover, ex-post cost verification can be 20% to 70% more than ex-ante cost estimation. Nevertheless, a reliable estimate is essential for subject charged of the decommissioning cost, since a fundraising is required to cover all the cost which occurs during the decommissioning phase. In fact in nearly all countries, the operator/utility is responsible for the decommissioning costs. However, in cases where nuclear power plants are state-owned, the responsibilities may be distributed between the operator and the state as owner.

In the United Kingdom, the government was directly responsible only for the decommissioning liabilities of the non-commercial reactors, owned by the UKAEA (United Kingdom Atomic Energy Authority),but there were plans for major changes in the future management of nuclear liabilities.

In Switzerland, the owners of the nuclear facilities are required to make financial contributions to a joint decommissioning fund which is under the supervision of the government. The board of the joint fund is responsible for ensuring that the contributions are adequate to cover decommissioning costs in due course [IX-46]. In the USA, to finance the decommissioning, almost all utility owners and licensees, historically, have collected fees from their electricity customers over the life of the plant, and deposited these fees into separate funds managed by external financial managers [IX-50].

IX-5. The revenue model

- *Output*: Total revenues time series over the plant life (input to the investment model)
- Inputs: reactor technology (LR v. SMR), reactor co-generation capabilities, plant size and typical load and service factors, front-end investment (output of the Generation cost model), country-specific national grid infrastructure.

- *Parameters / forecasts*: electricity consumption and its spatial distribution (levels, growth rates, variance / standard deviation); wholesale electricity price and / or market structure (installed capacity, reserve margin and supply mix, concentration indexes and market shares, spot power exchange v. long-term bilateral contracts, …); consumption and price for other co-generated products. Note: The parameters (and forecasts over economic the plant life) should be derived from pre-existing ancillary models and outlooks; they are country-specific, and common to LRs and SMRs.

This component aims at modelling at a certain extent the electricity market of the country to be analysed. Given the complexity of a detailed model, the simulation of a domestic, competitive (not regulated) electricity market and its outcomes (price and supplied quantity) is beyond the scope of this effort. Some pre-existing outlooks and models of the wholesale markets for electricity and other co-generated products can be adopted and integrated.

First of all, the ancillary models and outlooks are expected to provide the revenue model with appropriate plant-life forecasts of the following country-specific variables, which are common to SMRs and LRs:

- consumption of electricity (MWh) at regional, national and local level over the economic plant life; one the one hand, one can refer to forecasts offered by the yearly electricity outlooks by IEA (International Energy Agency, Electricity Information or World Energy Outlook) or EIA (US Energy Information Administration, International Energy Outlook); on the other hand one can integrate pre-existing macro-econometric models that estimate the relationship between economic growth and electricity consumption from the public domain economic literature (among others, see [IX-51; on energy consumption and economic growth, see among others: [IX-52 to IX-54];
- wholesale market price for electricity (e.g. €/MWh) over the economic plant life; given the typical NPP time horizon, long-term price parameters and forecasts are likely necessary rather than short- or medium-term ones (that is, from some days up to a limited number of years); as a consequence it is worth refraining from a time-serie black-box approach; on the one hand one can limit to include parametric country-specific price trends (decrease/increase rates and variance), and to carry out sensitivity analyses and to calibrate them against the expert opinions and public domain outlooks;

on the other hand one can attempt to integrate pre-existing models of the wholesale electricity markets (see market structure drivers, infra)

- alternatively to electricity price, market structure drivers (total installed capacity, reserve margin, supply mix, concentration indexes and market shares, spot power exchange v. long-term bilateral contracts, etc.); the revenue model will elaborate the market structure variables and demand estimates to obtain the electricity price estimates; a computational approach that explicits the market structure and rules and conducts of national producers is [IX-55]; among other examples, see also the long run electricity market simulator developed for the spot Italian market [IX-56 and IX-57], the electricity pricing module of the US EIA's national energy modelling system [IX-58].

Finally, some simpler short- and medium-term models are also worth being surveyed, in order to understand whether an adaptation to a long-term horizon is feasible. On the one hand, the similar day or typical day approach allows the selection of the historical days closer in behaviour to those under forecasting. The system allows a high degree of configuration options for the typical day parameters, e.g. the season, the climatic data, etc. It is considered a reliable outlook system when a historical data set is available, even if the data are not very far in the time period. It is reliable even in the case auxiliary data are not available at all. It is adopted for short-term estimations (10 days) but it can be used for a preliminary estimation of the medium-long term, if historical data referred to 18-24 months backward in the market and forecasting for the climatic data are available. On the other hand, the linear regression statistical method can be applied when a limited data set is available, as well. It offers good results when data on environment and temperature are available for the market estimation. Other models are based on autoregressive moving average methods. These models produce the estimation series as a linear combination of the historical supply profiles and the profile of historical errors in the past estimations [IX-59].

Once the appropriate ancillary models and outlooks have been identified, and their integration has been proven to be feasible, the revenue module can import from these platforms the plant life forecasts for those variables that are country-specific and common to LRs and SMRs. Then the module should focus upon those factors that are potentially at the origin of SMR differential revenues.

The output of revenue or market model are total revenues at the plant level over the economic plant life (i.e. estimates of the total inward cash flows). The revenues R [€] are a function of the country- or local-level electricity consumption Q [MWh], the market price p [€/MWh] (or the mentioned market structure drivers, MS), the plant size S [MW], the specific reactor technology T (e.g. whether LR or SMR) and a set Y of other variables:

$$R = R(Q, p \text{ or } \mathbf{MS}, S, T, \mathbf{Y}) \tag{11}$$

The Y inputs include the load factors, the national electrical grid and the front-end investments; these variables, given the plant size S, the reactor technology R and the national or local consumption estimates Q (which are provided by the ancillary models and outlooks), allow the revenue component to work out an estimate of electricity quantities supplied by the plant (i.e. an intermediary variable q). Revenues are then computed as the product of plant electricity supply (i.e. q) and wholesale electricity price, which can be either directly offered by the ancillary models and outlooks (p) or elaborated by the revenue model given the market structure drivers MS.

Other revenues coming from non-electric products can be added up to the electricity revenues, e.g. hydrogen, desalinated water [IX-60], district heating [IX-61], given the selected NPP technology (i.e. T), its co-generation capabilities (to be included in the Y input vector), and price and consumption estimates for co-generated products (which should be provided by ancillary outlooks and models).

In order to gauge the role played by the Y variables in determining the plant-level quantity of supplied electricity (in particular, the reactor technology, plant size and load factors, the national electrical grid and the front-end investments), the departure point is the SMR market matching ability and market suitability implied by scalability, flexibility, easier plant-grid matching, reduced entry barriers, as discussed in Section IX-1.

First, shorter construction times and smaller size provide SMRs with more flexibility in incremental additions of capacity than LRs. This is at the origin of benefits under both certain and uncertain market conditions [IX-62 and IX-63]. In particular, under steady demand and price trends, the SMR scalability allows: (i) to defer investments and to save financial costs, if the demand growth rate is low; (ii) to stagger investments and not to lose early revenues, if the demand growth rate is medium; (ii) to anticipate investments (and to have financial costs) yet to reap anticipated revenues, if the demand growth rate is high. Under highly uncertain market conditions, the SMR reversibility allows the investors to save sunk costs and to reap revenues[5]. Second, new SMR investments are more suitable than LR counterparts to country transmission grids that are incipient, constrained or fragmented; in such cases, the easier grid matching of SMRs allows the investors to reap revenues that would be otherwise foregone. Third, a different entry-barrier is the huge size of front-end investments for LRs, which are likely to undermine the entry ability of several small-medium investors; the smaller front-end investments of SMRs allows exactly this class of investors to reap revenues that would be otherwise foregone.

At this stage of the research, the nature and role of independent variables in Eq. (11) have still to be analytically represented. In general terms, and similarly to the analytic approach described in Section IX-4 for the cost generation module, the interest is in the differential contribution of individual inputs to revenues; in particular the elasticity of revenues to individual Y variables for the specific NPP technology are worth being obtained:

$$n_T^Y = \left.\frac{\partial TR/TR}{\partial Y/Y}\right\|_T \qquad (12)$$

IX-6. The financial cost model

- Output: weighted average cost of capital (input to the investment model)
- Inputs: Investor-specific equity and front-end investment (output of the Generation cost module, financial gearing (debt / equity ratio), project and external risk estimates (output of External cost module)
- Parameters / forecasts: risk-adjusted rate of return required by shareholders (risk-free rate, market risk premium, industry asset beta) and risk-adjusted interest rates required by debt-holders (risk-free rate, spread on risk-free rate), inflation rate. Note: The parameters (and forecasts over economic the plant life) should be derived from pre-existing ancillary models and outlooks; they are country-specific, and common to LRs and SMRs.

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[5] As discussed in Section IX-4, over-capitalization with slack capacity is quite typical of electric utilities that have adopted LRs. This may well be a signal of the sunken nature of LR investments.

The module evaluates the cost of the capital for the private or for the governmental subject that is planning to build and operate the new NPP(s). The cost of each source of financing is weighted through the WACC (weighted average cost of capital) formula, here below in a post-tax approach:

$$WACC = K_e \frac{E}{D+E} + K_d (1-t) \frac{D}{D+E} \tag{13}$$

where the necessary inputs are:

- the equity amount (E) invested in the project;
- the financial gearing (D/E) of the project;
- the rate of return required by shareholders for the equity (K_e);
- the interest rate required by debt-holders (K_d);
- the tax rate (t).

The cost of capital is a critical parameter of an investment economic appraisal. Sensitivity analysis shows its dramatic impact on the value of financial performance indexes: e.g. it enters as a discount rate in the actualisation of expected cash flows in NPV calculations and affects the LUEC estimation through the amortization factor of constant cost annuities, etc.

In particular, the cost of debt generates financial interest costs, which are a significant cost item before (interests during construction) and after the commercial deployment of the plant. Therefore it has a significant impact on unit generation costs.

Several sources of financing can be employed in a technological and capital intensive project and each source of financing has its specific cost, set as a minimum rate of return required by each stakeholder to invest in the project.

Investors can be classified in the categories of shareholders or lenders and of private or public investors.

1) private funds can be provided by industrial companies (power and utilities), structured/project finance divisions from banks, private equity funds specialized in renewable energy. Institutional investor community (e.g. pension funds managers, etc.) is increasingly interested in renewables through specialized long term funds, but it can be assumed that they don’t invest at the level of individual project activities on the ground.
2) public funds: project development grants, public owned equity funds, etc.

The cost of capital depends on the financial risk perceived by the investor.

Construction and deployment of a new NPP presents very high risky factors and sector specific criticalities either in the upstream and downstream of the process: duration and outcome of licensing, innovative technologies behaviour, social acceptance, political climate, costs and liabilities in decontamination & decommissioning, waste treatment and disposal, etc.

These criticalities are emphasized by the capital-intensive nature of the project itself and the very long lifetime of the project as compared to other industrial technologies.

In some cases, private stakeholders of a project are able to build innovative and efficient investment schemes to lower the financial/industrial risk. In this framework it is worthwhile mentioning the Olkiluoto (Finland) current construction of a 1600 MW(e) EPR. In this case the shareholding base is formed by electricity producers, distributors and industrial users, in a sort of consortium where the absorption of the entire electricity production is assured at a fixed price through long-term sale contracts. Low-price electricity is supplied in exchange of low rate of return required for the equity invested. Moreover the reduced financial risk of the project on the revenue side, translates in a lower interest rate required by lenders.

In a more general case, in the free and competitive industrial and financial markets, the risks of a NPP project may be perceived as unacceptable by private investors or acceptable at an unrealistic investment yield required to cover them, thus resulting in an out-of-market unit generation cost.

From these considerations steam the opportunity of a public support to a NPP project, under different forms (Table IX-8), in accordance with international (OECD agreement), European (for intra-community contracts), and national regulations.

The public direct financial participation contribute to ease the financial distress of the project, while public indirect support aims to cap the financial liability of private investors and/or mitigate the risk factors to a limit acceptable by private shareholders and lenders, which reflects in a higher gearing and/or a cost of capital bearable by the project.

Compared to private stakeholders, the public investor's focus and goals are not primarily linked to the project financial profitability, but rather to social welfare (i.e. the development of a strategic industry, or the creation of qualified employment, etc.).

TABLE IX-8. POSSIBLE FORMS FOR A PUBLIC SUPPORT OF A NPP PROJECT

DIRECT	INDIRECT
▪ Co-financing of the project through soft loans	▪ Public guarantee on private lending
▪ Capital grants	▪ Public insurance on export financing
▪ Government taking equity stakes (Public-Private partnership)	▪ Tax regime: production tax credits (as in US), penalties on brown power such a s the UK's climate change levy ▪ Revenue support schemes: renewable portfolio standards with renewable electricity certificate (REC) trading; fixed price schemes (feed in tariffs); premium prices (on top of unit sale price
	▪ Public financial liability on waste treatment and disposal

Either as a shareholder or as a lender in the funding of the project, the public investor should aim to the financial soundness of the investment without burdening the cost of capital with an extra-profit requirement.

The literature offers two main views about the cost of public sources of financing, the 'financial theory' that identifies the cost of public financing with the risk free rate (profitability of a risk free asset as i.e. government bond of same duration than the project);

the ‘economic theory’ that focuses on the social preference rate as the most suitable rate or return for a public investor [IX-64]. This model assumes the financial theory.

IX-6.1. Factoring risks into the cost of capital

The country- and industry-specific interest rate and rate of returns should be estimated given the risk-free rate, the risk premium for equity markets, equity beta (an indicator which relates the industry-specific risks to the market risk premium) and industry interest rates.

The main risk sources for a NPP project (Table IX-9) may be identified and classified in the areas of:

- pure financial risk factors / risk of default;
- industrial/operational risk factors, stemming from operating and capital costs risk factors, revenues risk factors and external risk factors, some of the latter coming as an output from the other factors module.

TABLE IX-9. RISKS FACTORS OF A NPP PROJECT

FINANCIAL RISK FACTORS	INDUSTRIAL / OPERATIONAL RISK FACTORS		
	Cost (operating and capital) risk factors	Revenues risk factors	External risk factors
▪ Gearing ▪ Capital employed ▪ Interest coverage ratio ▪ Pay back time / debt duration	▪ Overnight construction costs overrun ▪ Plant failures: cost of repair / substitution ▪ Decommissioning costs uncapped ▪ Waste disposal liabilities uncapped ▪ O&M / fuel costs higher than estimated ▪ Design modification during licensing / construction / operation	▪ Construction time overrun ▪ kWe price trend ▪ kWe price volatility ▪ Revenues from co-generated products ▪ Service factor lower than expected ▪ Accident plant seizure ▪ Load factor lower than estimated ▪ Reduced operational life	▪ Regulatory changes once funds committed ▪ Social acceptance (e.g. NIMBY) ▪ Licensing duration and outcome

The exposure to the industrial/operational risks is as high as is the financial distress of the project, which is usually measured in terms of gearing, interest coverage ratio and pay back time. The risk aversion is increased by the amount of capital invested (either debt or equity), that represents a sunk cost for the entrepreneur in case of adverse conditions.

The risk perceived by each category of investor (i.e. shareholder or lender) is factored into the cost of the respective financing. In particular, the most credited theory to estimate the rate of return required by shareholders for their investment (equity funds) is the capital asset pricing model, that relates the cost of equity (K_e) to the risk free rate (R_f), the market average risk rate

(R_m) and the β parameter, that represents the risk of a specific industry versus the risk of a balanced market portfolio of industries:

$$K_e = R_f + \beta_E \times (R_m\text{-}R_f) \qquad (14)$$

The difference ($R_m - R_f$) represents the risk premium required to invest in a project with an average industrial risk.

A stock exchange index return is assumed to represent the market risk rate and the rate of return of a treasury bond of comparable duration to the project lifetime is assumed to represent the risk free rate. This risk free rate should refer to the country where the NPP project would be based, as to include the sovereign risk of the country, defined as the risk that a government will default on its loans or fail to honour other business commitments due to change in government or policy [IX-65]. The sovereign risk accounts for external risk factors that are common to all kind of business and not only to nuclear technology; sovereign risk can be measured considering Euro denominated sovereign debt yields of a specific country.

β is the most critical factor in the K_e estimation: it is calculated as the slope of the linear regression of dividend-adjusted stock returns against market returns.

For a private company or project, or a business unit, a reference can be set by an industry β, based on the assumption that the systematic risk is similar for all businesses in that industry [IX-65].

The industry asset β (unlevered β) should account for the underlying business risk of a project, e.g. operational risks stemming from the cost and revenue sides, and from the external factors mentioned in Table IX-9.

Nonetheless it is hardly possible to represent the risk of a specific NPP project through the industry assets β parameter because the sample of peers selected in the β estimation would hardly represent a reliable proxy of the specific project characteristics (i.e. innovative technology). The sample may run diversified activities in other related or unrelated industries, whose impact on the share volatility could tamper the risk analysis. Industry asset β should also account for external risk factors that are typically industry related and cannot be caught by sovereign risk: e.g. NPP licensing issues, the social acceptance of the project and the particularly controversial attitude of governments towards nuclear power generation.

Equity β_E is obtained by asset β_A through Eq. (15) and catches the project specific financial risk:

$$\beta_E = \beta_A \times (E + D) / E \qquad (15)$$

All else being equal, a highly geared project might be expected to have a higher financial risk, stemming from the fact that debt holders have a prior claim on the project's cash flows over equity holders (as in [IX-66], an analysis for regulated electricity distributors by the UK energy regulator). This results in a higher equity β and a consequent higher cost of equity.

The cost of debt, set as the interest rate required by lenders is defined by an interest spread (risk premium) over a risk free rate. The spread component of the cost of debt is designed to cover all the project risk factors (operational and financial) for the lenders.

The academic studies attempting to empirically explain corporate bond rates are sparser than for equities. Elton et al. [IX-67]find that risk aversion is responsible for most of the bond premium and that expected default premium is responsible for the least. Bond rating firms (e.g. Standard and Poor's and Moody) appear essentially to evaluate default probability.

The lack of widely accepted models relating debt premium risk letting the ground to case-specific negotiations between shareholders and lenders. Neither the industry bond rating can set a valid reference for the risk premium estimations, given the scarce data record for the nuclear power industry. Nevertheless, a correlation exists between financial distress indexes and risk premium. To estimate the financial soundness of the project, a sort of financial rating may be measured by some key financial indicators as:

- amount of the loan,
- gearing of the project,
- cash flow ratios: interest coverage ratio, cash flow from operations / debt amortization, etc.
- debt duration.

In general, the higher the amount of the loan and its duration, the higher is the risk aversion of the lenders. Indeed, the banks cover their risk of default by investing funds in a balanced mix of uncorrelated industry sectors, therefore a significant amount of capital invested would translates in a high risk exposure to the nuclear or the power generation industry, or to high technology, long term project.

Several studies have produced some estimations for the private sector risk-adjusted cost of capital: following Mackerron et al. [IX-64], it would not be less than the rates of return allowed on the regulatory asset base of the regulated electricity industry, that are set at 6.5% in real terms for a public electricity supplier. A 2-3% premium above this would be plausible for the market to finance a nuclear plant, (a lower premium of 1% in the long term, if a nuclear programme became established).

Oxera [IX-68] estimates the interest rate of debt during construction to 10% and 7.5% after refinancing, in the operating phase.

A study conducted by CESI Ricerche [IX-69] identifies a plausible value for the cost of equity and debt respectively in a 12% return rate and 7% interest rate.

Higher values are reported by Alemi [IX-70]: debt and equity return rates are assumed to be 12% and 15%.

Other sources (see [IX-4 and IX-71]) agree on defining two cases and two relating discount rate: 5% discount rate would be appropriate for LUEC calculation for plants operating under the more traditional regulated utility model where revenues are guaranteed by captive markets; 10% discount rate would better apply to a riskier deregulated or merchant plant environment where the plant must compete with other generation sources for revenues. CESI itself identifies a public supported investment case with an equity required rate of return on investment of nominal 5%.

The definition of an appropriate cost of equity and debt for an investment analysis in the nuclear industry remains a matter of bold judgement and a very sensitive parameter on the outcome of the analysis, which depends, among others, on a variety of country-specific and time-dependent factors (i.e. the capital market structure, the energy policy, etc.).

IX-6.2. Enhancement factors for SMRs versus Large Reactors (LRs)

According to the specific features the SMRs could have vs. LRs as addressed in Section IX-1, different costs of capital could arise, since risk enhancement / mitigation factors can intervene in the K_d, K_e and D/E ratio could change in the strategy of a company or a government towards a SMR vs. a LR project. The analysis will be centered around the reduction of financial costs implied by the SMR scalability, through investment deferral, and reversibility, through reduced risk premium, as discussed in Section IX-1.

In addition the financial cost model should integrate risk enhancement / mitigation parameters that are specific to SMRs and LRs and that can be provided by the external cost module or can derived by expert opinions. At this stage of the research, the analytic relationship between these risk factors and country- and industry-specific interest rate and rate of returns has still to be discussed and identified; see Gross et al. [IX-72] on the role of risk in investment decisions in the energy industries.

Several recent works illustrate the basic WACC model, or adapt it to the electricity industry; these models can be integrated or adapted within the financial cost model. See among others: the guidelines by the UBS investment bank [IX-65], the capital budgeting model of the US EIA's national energy modelling system [IX-73], and the analysis for regulated electricity distributors by the UK energy regulator [IX-66].

A comparative analysis may be developed considering a single LR or multiple SMRs, with the same total generation capacity of the site. Different scenarios may arise for the SMRs' case ranging from a best scenario of staggered construction of SMR modules, to a worst scenario of parallel, concentrated construction of all the SMR modules.

In the latter case, parallel construction of all modules causes the loss of important learning economies during construction and installation, leading to higher overnight construction costs per KWe installed of SMRs vs LR. Lower construction time still has a positive impact on IDC and early revenues come to relieve financial leverage, but the capital invested may be comparable or higher than LR plant.

Financial enhancement factors emerge in the staggered construction scenario, where the scalability of a cluster of SMRs allows a lower average capital employed and smoother cash flow time series over the construction period. Cash flows from early deployed units represent a financing source for the construction of later SMR modules in the site, thus relieving the financial distress of the project.

A more balanced cash flow profile produced a lower financial leverage of the project. Moreover, lower lead time for the deployment of each module accounts for a lower total interest during construction for all SMR modules.

Lower sunk cost coming from lower up-front investment and better cash flow profile mean a lower financial default risk of SMRs' project against external market or regulatory adverse conditions and mitigate the risk perception of both shareholders and lenders.

About the cost of equity it can be argued that the enhancement of the financial gearing of the SMRs project may reflect in a lower financial risk for the shareholders, thus allowing a lower rate of return required for the equity financing through a lower Equity β.

Nevertheless, from the shareholder perspective, a comparative assessment of the two projects' financial performance cannot be performed unless the same rate of return is set for the equity invested in the two projects.

In the shareholder point of view, the financial costs of the project are represented by the cost of debt. Here, the financial enhancement of a SMRs plant scenario may be expressed by the spread component of the cost of debt. The different merit of credit of the two projects would correspond to different risk premiums (spread on risk free rate).

The financial enhancement of SMRs may result either as a lower cost of debt or a higher gearing bearable by the SMRs' project vs. LR for a given cost of debt.

In addition to the financial risk-enhancement factors, other industrial/operational risk-enhancement factors can be identified, based on SMRs' concept specific features.

Investment flexibility, represents a valuable option for investors facing price uncertainty that characterize liberalized electricity markets, allowing a faster addition of generation capacity in market upturns and lower sunk cost in market adverse changes, where investment can be staggered/deferred.

Flexibility allows a more aggressive market strategy with a lower entry electricity price than required by a LR, thus reaping additional revenues (see [IX-63]).

Flexibility and market matching capability are of capital importance to cope with revenues risk factors, with nuclear generation technology being a price taker, base load resource, dispatched early in the merit order and therefore exposed to the revenues fluctuation of electricity price determined by peak-load technologies (i.e. gas and carbon).

TABLE IX-10. RISK FACTORS AND ENHANCEMENT FACTORS BY SMRS

	SOURCE OF RISK ENHANCEMENT FOR SMRS
Financial Risk Factors	
gearing	scalability: lower financial gearing with staggered construction
capital employed	scalability:
	(1) lower average capital employed with staggered construction
	(2) < financial exposure by the lenders
interest coverage ratio	scalability and shorter lead times: more balanced cash flow profile with staggered construction and deployment
pay back time / debt duration	(1) scalability: lower PBT / debt duration in case of parallel construction;
	(2) no enhancement in case of staggered construction
Cost (operating and capital) risk factors	
overnight construction costs overrun	modularization and modularity: higher standardization and better construction cost control
plant failures: cost of repair / substitution	multiple unit on a single site: higher availability factor
decommissioning costs uncapped	new design solutions, i.e. integral and modular approach: easier decommissioning process

	SOURCE OF RISK ENHANCEMENT FOR SMRs
waste disposal liabilities uncapped	new design solutions, i.e. integral and modular approach: easier high activity waste management
O&M / fuel costs higher than estimated	no enhancement by SMRs
design modification during licensing / construction / operation	higher standardization: lower ad-hoc design modification risks
Revenues risk factors	
construction time overrun	modularization and modularity: higher standardization and better construction time control
kWe price trend	scalability and flexibility: better market matching
kWe price volatility	investment flexibility: adaptability to uncertain market condition
revenues from co-generated products	reduced EPZ and plant size allow market proximity and increase opportunity for co-generation
availability factor lower than expected	multiple unit on a single site: higher availability factor: lower risk of loss of revenues
forced plant outages	multiple unit on a single site: higher availability factor: lower risk of loss of revenues
reduced operational life	new design solutions: higher expected operational life and plant quality of performance kept all along plant lifetime
External risk factors	
regulatory changes once funds committed	scalability: lower sunk cost in case of adverse conditions
social acceptance (NIMBY)	new design solutions: reduced scale of accidents and reduced EPZ
licensing duration and outcome	higher standardization may ease and speed licensing procedure

Higher modularization and modularity allowed by reduced size of components of a SMR may translate into a standardization of the construction/installation procedures and less ad hoc design modifications, granting a better control over construction time and costs overruns.

Integral approach and technical specific design solutions for SMRs are expected to have a positive impact on the extension of plant technical lifetime and of the quality of performance over the lifetime (i.e. load factor), thus resulting in an extended revenue base than LR.

For a given plant size, multiple units assure higher plant reliability due to lower parallel failure probability, while increased inherent safety features of SMRs account for a higher service factor and therefore a lower probability of loss of revenues due to plant stops or seizures. In addition, these features have a positive impact on the probabilistic risk assessment (PRA) of the plant: a lower scale of the worst accident scenario allows to reduce the emergency planned zone (EPZ) for a SMR plant. This may have a positive impact on social acceptance and may increase the market opportunities from co-generation capability of SMRs. Indeed, co-generation of product/services (i.e. water desalination, district/industrial process heating, hydrogen, ethanol production, etc.) benefit from proximity to users.

New design strategy for SMRs provide higher integral and modular approach, leading to an easier, more standardized plant decommissioning and spent fuel management, lowering the risk of costs overruns in this phase where the liability of the plant owner is often not clearly defined and capped.

Moreover, higher standardization, modularization, integral approach and increased inherent safety features of SMRs' could ease and speed the licensing procedure.

Factors increasing the industrial soundness of the project, also mitigate the risk perception of investors and thus may further lower the cost of financing.

The following table shows an outlook of the risk factors perceived by investors and the enhancements brought in by SMRs' vs. LRS' concept.

IX-7. The investment model

This module deals with the investment evaluation. The needed inputs are:

- the annual cash out-flows, coming from the generation cost model, and cash in-flows coming from the revenue model;
- the cost of capital estimated by the financial cost model.

The investment model performs a cash flow investment analysis to produce the following key performance indicators:

- the net present value (NPV);
- the internal rate of return (IRR);
- the pay back time (PBT);
- the profitability index (PI);
- the levelised unit electricity cost (LUEC).

Traditionally, the economic research on nuclear power generation focused on the generation costs and the LUEC calculation: the LUEC is a suitable reference value for a technology comparative assessment and is a traditionally referenced value to support policymakers' strategy for regulatory/subsidy design.

But it happens that industrial projects, even if proven as cost effective through the LUEC criterion, may not be undertaken if estimated financial return is not as high as to secure the market risks faced by private investors. In competitive, free electricity markets, investment decisions are made by private companies seeking to maximise return on investment, subject to acceptable levels of risk and regulatory constraints [IX-72].

Recent studies (see [IX-67]) and modelling efforts (i.e. FINPLAN and DANESS codes) approach the economic attractiveness of an investment not only from the generation costs point of view but from a broader perspective, estimating profitability indexes (i.e. IRR, PI) and other financial indicators (i.e. NPV).

The investment model here described provides private and public investors with a framework for a strategic assessment of an investment in SMRs vs. LR, based on a full set of financial performance indicators.

In particular:

- Pay back time is an important indicator of the financial soundness of an investment project and is a very sensitive parameter in the nuclear industry, where very long construction time and very high up-front investment produce a tight financial distress and typically long debt duration.
- The IRR represents an investment recovery rate that can be checked against a minimum, risk adjusted hurdle rate set by the investor, to evaluate the project financial attractiveness.

The public body either as an investor or a policymaker should either assess the financial viability of a direct investment intervention in an industrial project (i.e. SMRs vs. LR nuclear power plant) in order to assure a sound employment of public funds in the best economic-effective strategy, or check the efficacy of regulatory environment against the final investment criteria adopted by private investors (i.e. financial return and risk mitigation) basing its policy design strategy on a clear understanding on how investment decisions are made.

IX-8. The external factors model

A thorough analysis should entail not only the quantitative parameters directly connected to the costs and revenues, but also the external factors affecting the evaluation of an investment.

Among them the following can be cited:

- the risk offered by a change in the licensing rules/process and, in general, derived from political crises;
- the environmental laws (e.g. carbon tax, local emission constraints);
- a strategic security of supply;
- the degree of proliferation resistance;
- the level of physical protection, including that from terrorist attack;
- the trend in the macroeconomic parameters (tax rate, inflation rate);
- the confidence level in the social acceptance, e.g. enhanced by technical solutions as the emergency planning zone reduction or elimination.

Since a quantitative estimation of such a parameters is neither straightforward nor its link with the quantitative parameters is coming from the investment model, a suitable method for merging the information is necessary. The analytical hierarchy process (AHP) is able to address the issue of evaluating a global figure of merit for the different strategies and solutions to be analysed (e.g. a LR vs. SMRs at centralised level vs. SMRs at distributed level).

IX-9. The multiattribute evaluation model

The classical techniques for economical-financial evaluations, especially the DCF methods based on the analysis of the discounted cash flow rates, are in some cases not completely suitable in providing a thorough picture of the investment and its real value, since they do not take into account all the positive features and benefits of a project. This is anyway an obliged feature since they operate on parameters and variables that are quantitatively expressed, with no possibility to elaborate intangible elements.

The multiattribute or multicriteria techniques (multiple attribute decision making) have been set up to address this specific situation, where a choice within a number of alternative options is to be performed, given a set of attributes of different kind even of not tangible nature or not easily measurable in monetary term [IX-74 to IX-77].

One of the most adopted techniques, the analytic hierarchy process (AHP) one, has been selected for the evaluation of the project attractiveness of the NPP solution. The method represents an explicit way to quantify evaluation elements even of not tangible nature. The procedure organises the estimation process in a hierarchical way. This allows assigning a weight to each different attribute/criterion, by means of a systematic set of comparative evaluations among pairs of attributes/criteria [IX-78]. That means the decision is decomposed at sequential levels, where the first level represents the objective of the evaluation (e.g. the project attractiveness) and the second level and their following include the attributes and sub-attributes with significant importance for the goal [IX-79]. Each attribute and sub-attribute can be decomposed up to the suitable level of detail. The last level belongs to the different alternatives under examination (Fig. IX-2). This procedure is well structured with respect to other multiattribute techniques, and allows evaluation with a high degree of details. Moreover software packages are already available for the decomposition and the cross-checking evaluations.

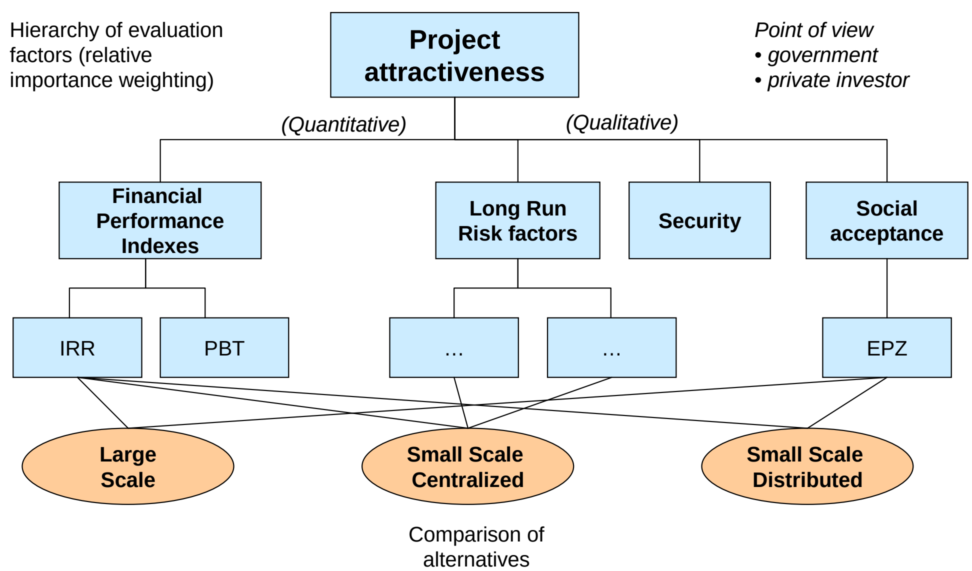

FIG.IX-2 – Analytical hierarchy process structure.

If compared against the score models, more easily readable and applicable but devoted to analyse homogeneous information sets, the AHP allows the examination of project alternatives characterised by highly heterogeneous evaluation elements and to reach sensitivity on the robustness of the final evaluations [IX-80 and IX-81].

IX-10. Conclusion

The open framework for analysing the investment projects in nuclear reactors, described in this paper, is at the moment being implemented in an open model able to simulate and evaluate the economic features of NPPs with SMRs and larger reactors. The updated versions of this code are being used in case studies of SMR competitiveness in different applications, carried out within the IAEA project ‘Common technologies and issues for SMRs’ .

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