Chapter 8: Small Modular Nuclear Reactors

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Abstract

Small Modular Reactors (SMRs) encompass a large number of technologies at different stages of development. A key challenge for SMR stakeholders is the evaluation of SMR competitiveness with respect to Large Reactors (LRs). SMRs are usually considered less competitive than LRs because of a misguided application of the economy of scale principle. However, several advantages of SMRs (e.g. suitability for cogeneration, modularization, reduction of the time to market, etc.) summarised in this chapter need to be considered in the comparison between SMRs and LRs. This chapter focuses on SMR economics and financing, concluding with a brief explanation on why no-one SMR has been built so far.

8.1 Introduction

The International Atomic Energy Agency (IAEA) defines Small Modular Reactors (SMRs) as "*newer generation reactors designed to generate electric power up to 300 MW, whose components and systems can be shop fabricated and then transported as modules to the sites for installation as demand arises*" [1]. IAEA also defines medium-sized reactors as "*reactors with an equivalent electric power between 300 and 700 MW*" [2]. Large reactors (LRs) are generally considered reactors with an equivalent electric power higher than 700 MWe. Regarding SMRs, which is the main topic of this chapter, [3] provides a summary of the innovative features and describes SMRs as "*reactor designs that are deliberately small, i.e. designs that do not scale to large sizes but rather capitalize on their smallness to achieve specific performance characteristics*". Furthermore, [4] explains the meaning of "Small" and "Modular" as follows:

"*Small refers to the reactor power rating. While no definitive range exists, a power rating from approximately 10 to 300 MWe has generally been adopted* […] *Modular refers to the unit assembly of the nuclear steam supply system (NSSS) which, when coupled to a power conversion system or process heat supply system, delivers the desired energy product. The unit assembly can be assembled from one or severe submodules* […]"

SMRs encompass a large number of technologies such as “Pressurised Water Reactors”, the most common technology used for LRs in operation and under construction, to more revolutionary designs based on Gen IV reactors that are mostly unproven [5]. [6] provides an overview of the different types of SMRs. SMRs, by their nature, are designed to be factory manufactured, transportable and for few designs even re-locatable. The term “modular” in this context refers to (1) a single reactor that can be grouped with others to form a large nuclear plant, and (2) whose design incorporates mainly pre-fabricated modules assembled on site. Whilst current LRs also incorporate factory-fabricated components or modules, a substantial amount of fieldwork is required to assemble components into an operational plant. SMRs are envisaged to require less work on site, and some extreme designs are expected to be almost “plug and play” when arriving from the factory.

One of the key challenges for the assessment of SMR advantages and disadvantages is the lack of empirical information, as no modern SMRs have been built yet, but only “traditionally built small reactors” like the CNP-300 (300 MWe) and the PHWR-220 (220 MWe) [7]. However, a key discussion about the competitiveness of SMRs vs LRs regards how SMRs might balance the “diseconomy of scale” with the “economy of multiples” [8]–[14]. [15], [16] analyse specific factors (such as grid characteristics, construction time, financial exposition, modularization, learning etc.) which distinguish SMRs from LRs in the evaluation of the capital cost. Once these factors are taken into account, the capital cost is comparable between the two technologies [10], [17]. Furthermore, [18] discusses the effects of ‘non-financial parameters’, such as electric grid vulnerability, public acceptance, the risk associated with the project, and licensing [19]. For many of these parameters, the authors explain how SMRs show an advantage with respect to LRs.

Another advantage of SMRs is the possibility to accelerate the learning curve [16]. According to [16], the learning curve flattens out after 5-7 units, determining that the nth of a kind is reached with less MWe installed for SMRs with respect to LRs [16]. Another key feature of SMRs is the possibility to split a large investment into smaller ones. The construction of a single LR is a risky investment [20]. The construction of SMRs is an investment decision with n degrees of freedom that allows hedging investment risks. The economic merit of flexibility can be calculated using the Real Options (ROs) approach [21]. SMRs, having the power fractionated, are also ideal for cogeneration, as presented in [20], [22], [23].

The rest of the chapter is structured as follows: section 8.2 provides an overview of economics and financing of SMRs; Section 8.3 summarises the “external factors” which have been identified from the literature about the differential characteristics of SMRs with respect to LRs; Section 8.4 concludes the chapter providing a brief explanation about why no-one SMR has been built so far.

8.2 Economics and financing of SMRs

8.2.1 Introduction to the economic evaluation of Nuclear Power Plants (NPPs)

The nuclear industry commonly clusters NPP life-cycle costs as: capital cost, operating and maintenance, fuel and decommissioning. Two broad cost estimation approaches can be used to calculate these, known as top down and bottom up [24]. Following the top-down cost estimation approach, a new project is compared to similar projects already completed (called “project analogs”). Cost and time needed in “project analogs” are adapted and used as predictors for the new power plant or parts of it (e.g. a turbine). In the bottom-up cost estimation approach, the power plant is divided into activities and, subsequently, the cost of each activity is estimated. According to [25], the bottom-up approach is most suitable for projects near construction where the design has been almost totally developed. On the contrary, in the early stages, when there is a lack of information, a top-down approach is preferred.

Furthermore, in the power plant cost estimation, it is fundamental to consider that “power plants do not exist in isolation”, but plants are interconnected with a wider system both from a technical and economic point of view. [26] focuses on this key point, highlighting how each electricity generation power plant is characterised by three cost levels:

1) Plant-level costs: the direct costs to build/operate/decommission a power plant;
2) Grid-level costs: the costs incurred to enhance transport and distribution grids, to connect new capacity to the grid, to maintain the long-term and short-term electricity supply;
3) Total system costs: this represents a broader set of costs, including effects difficult to monetise and beyond the power reactor itself, e.g. CO_2 emission, impact on the security of energy supply, country’s strategic position, etc. [18].

The following Figure 8.1 summarises these concepts.

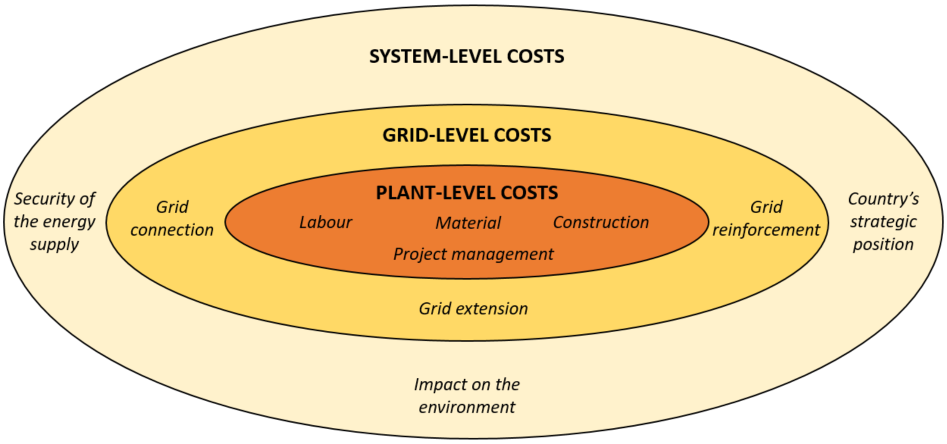

Figure 8.1: Plant Level - Grid Level - Total System Costs
Adapted from [26]

Several indicators are used to investigate the profitability of investing in an NPP for utilities. One of the most important economic indicators for policymakers is the levelised cost of the electricity produced by the NPP. This indicator, generally termed "Levelised Unit Electricity Cost (LUEC)" or "Levelised Cost Of Electricity (LCOE)" accounts for all the life-cycle costs and is expressed in terms of energy currency, typically [$ $(\mathrm{KWh})^{-1}$]. Net Present Value (NPV) and the Internal Rate of Return (IRR) are other two key indicators of financial performance. NPV measures absolute profitability [$], and depends by the discount value, i.e. the factor used to weight "present cost" vs "future revenue". The discount value usually depends on the source of financing and for many practical applications can be intended as the Weighted Average Cost of Capital (WACC). A low WACC gives the same weighting to present cost and future revenue (promoting capital-intensive plants such as nuclear power stations), while a high WACC is weighted more towards the present cost with respect to future revenues (promoting low capital cost solutions, such as gas-fired power plant). The IRR is a dimensionless indicator, i.e. the value of WACC that bring the NPV to zero. The greater the value, the higher the profit for the utility.

The NPP cost (both construction and operation) depends on how many identical (or at least very similar) units are planning to be built both globally, in the country and, most important, in the site. When the same identical plant is delivered more than one time (ideally several times), the economy of multiples is achieved and, therefore, a cost reduction. Economy of multiples in the construction of NPPs is somehow rooted in the idea of "mass production", a concept born in the automotive industry and later adopted in other fields, like aerospace (e.g. the production of aircraft), IT (e.g. the production of computers and smartphones) or even the food industry (e.g. the production of ready meals). For NPPs, the economy of multiples is achieved because of two key factors: learning process and co-siting economy. On the other hand, techno-economic analyses show that the average investment and operating costs per unit of electricity are decreasing with respect to increasing plant size (i.e. "economy of scale" principle).

Regarding SMRs, several papers discuss the competitiveness of SMRs vs. LRs and how SMRs might balance the "diseconomy of scale" with the "economy of multiples" [8]–[14]. The "economy of scale principle" cannot be directly transferred into the investment analyses of SMRs versus LRs, because it relies upon the clause "other things being equal". Effectively, this presumes that SMRs are the same as LRs except for the size. If the designs of large and small units are very similar, the unitary capital cost of a larger unit is significantly cheaper than for a smaller version. By contrast, SMRs exhibit several benefits that are uniquely available to smaller innovative reactors and can only be replicated by LRs to a very limited extent. The most important are: modularization, co-siting economies, learning and construction time.

8.3 Modularization

One of the key characteristics of SMRs, as their name emphasized, is the modularization. [25] defines modularization as the "*process of converting the design and construction of a monolithic or stick-built plant to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies*". Several papers and reports explain the costs and benefits of modularization. Most of these references are qualitative, like the review of modularization in the nuclear industry [27]. Factory fabrication is usually cheaper than site fabrication (see Section 8.0 for a more detailed explanation on the reasons), but the costs associated with shipping of modules to the site must also be considered. Smaller plants can take a better advantage of modularity since it is possible to have a greater percentage of factory-made components. In the nuclear sector, [28] were the first authors to illustrate why the technical solutions that are embodied by the small plant design might reduce the investment cost for a given plant. The most relevant elements of the small plant concept are the standardization of components and a broader safety by design approach. Standardization is at the origin of a more efficient supply, construction and operation (see [29] for a general discussion of the effects of standardization through design modularity) and it enables suppliers and utilities to more rapidly benefit the learning economies [30]. Although there are a number of works in the literature describing the qualitative advantages of modularization, only a few of them are able to quantify the underlying advantages. [31] focuses on the impact of modularization on cost and schedule in infrastructure, reporting quantitative information about schedule and capital cost saving determined by the transition from the stick-built construction to modularization. In particular, [31] reports a range of schedule saving between 7 and 20%, and a range of cost saving between 22 and 50%. Furthermore, [32] shows a methodology to evaluate the impact of modularization in the construction of a NPP, applying this methodology to Westinghouse SMR. In particular, [32] evaluates the TCIC (Total Capital Investment Cost) for three different construction strategies with different degree of modularization. The authors include in the definition of TCIC the cost of activities and components during construction and the time value of capital. The Westinghouse SMR design is characterised by 12 super modules which are assembled in five assembly areas on site. Three construction strategies are evaluated:

- Complete modularization: modules fabricated in factory, super modules in the assembly area and then installed creating the nuclear island.
- Lesser degree of modularization: modules fabricated in the assembly area, super modules in the assembly area and then installed creating the nuclear island.
- Stick built construction: no super modules.

The analysis shows a TCIC saving for the first and the second strategy respectively of 39% and 21% with respect to the stick-built strategy. Therefore, the analysis shows the positive impact of modularization.

8.3.1 Co-siting economies

Co-siting economies result from the cost saving of the set-up activities related to siting (e.g. acquisition of land rights, connection to the transmission network) which have been already carried out, and by certain fixed indivisible costs which can be saved when installing the second and subsequent units [14]. Therefore, the larger the number of NPP co-sited units, the smaller the total investment cost for each unit [16], [17], [33]. Operational costs would also be reduced because of the sharing of personnel and spare parts across multiple units [8] or the possibility to share the cost of upgrades on multiple units, e.g. the cost of upgrading software. In the literature, there are many statements about co-siting economies. For example, [34] suggests that "*the average cost for identical units on the same site can be about 15% lower than the cost of a single unit, with savings coming mostly in siting and licensing costs, site labour and common facilities. The 58 PWR in France built as multiple units at 19 sites are good examples*".

8.3.2 Learning and construction schedule

For the same power installed, SMRs can exploit two strong synergic advantages with respect to LRs: learning and construction time.

Regarding the first advantage, there are two key aspects [16]:

1) *Modularity - learning economies*

[35] explains what a learning rate is: "*A progressive increase in efficiency and effectiveness can be achieved by building experience and learning how to perform a process and use tools to deliver a product. The learning rate is the cost reduction realised in this way, for every cumulative doubling of production*". Learning rate increases through [35]: modularization and factory fabrication, high production rates, standardisation of design, a consistent delivery chain, in a stable regulatory environment. SMRs rely on the supply of standardized components and their assembly and maintenance within the plant site, with a reduction of investment and operating costs. The standardization of SMR design and components is a necessary condition for suppliers, along with the smaller size of units, to replicate in a factory the production of SMR units and to reap the learning economies. SMRs are characterised by an expected learning rate higher than LRs. The nuclear sector has always been characterised by a lower learning rate than the other industries, between 1 and 3% [35]. According to [35], the expected rate of SMR industry ranges between 5 and 10% (with a proportion of factory fabrication of 45-60%). Figure 8.2 summarises these information, providing also a learning rate comparison between different industries and between SMRs and LRs.

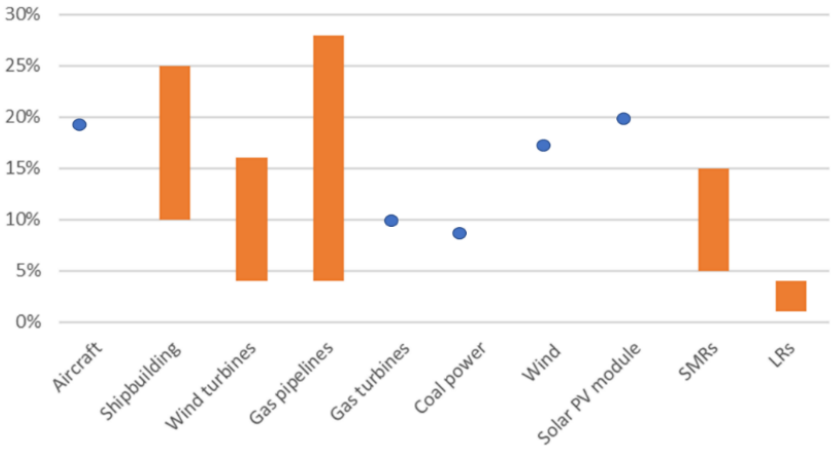

Figure 8.2: Learning rate comparison Data from: [35], [36]

2) *Mass production economies*

For a certain installed power, many more SMRs than LRs are required since the power provided by an SMR is a fraction of the power provided by a LR. Therefore, it is possible to have a large bulk ordering process of components, like valves, that are specifically developed for a certain reactor design. This aspect allows SMRs to exploit the economies of mass production and a more standardised procurement process.

Regarding the second advantage, construction time represents a critical aspect in NPP for two reasons:

1) *Fixed daily cost*

On a NPP construction site, there are thousands of people working and the utilization of expensive equipment (e.g. cranes). Consequently, each working day has high fixed costs.

2) *The postponing of cash in-flow*

Due to the postponing of cash in-flow, there are two negative effects. First, each year of construction delays the time when cash is expected to flow into the utility increasing the interest to be paid on the debt. Second, the present value of future cash flow decreases exponentially with time.

SMRs have an expected shorter construction schedule than LRs [16], [21], [35], [37]. The projected schedule is 4/5 years for the first-of-a-kind SMR and 3/4 years for the nth-of-a-kind SMR [35], [38], instead of the 6 years of LRs [38]. The SMRs characteristics which determine the shorter construction schedule are [16], [37]–[39]: smaller size, simpler design, increased modularization, a large fraction of components produced in a factory, serial fabrication of components and standardization.
Three key consequences of schedule reduction are:

1) Reduction of the time to market [3], [21];
2) Reduction of the Interest During Construction [16], [40];
3) Possibility to match the demand growth [3].

8.3.3 Life-cycle costs

- **Capital cost**

Firstly, it worth clarify the difference between capital cost and CAPEX (capital expenditure, also called overnight cost). Capital cost is the sum of the "overnight capital cost" and the "Interest During Construction (IDC)" [41]. [25] defines the "overnight capital cost" as "*the base construction cost plus applicable owner's cost, contingency, and first core costs. It is referred to as an overnight cost in the sense that time value costs (IDC) are not included".* Examples of owner's cost are land, site works, switchyards, project management, administration and associated buildings [42]. The capital cost is also defined as Total Capital Investment Cost (TCIC). [35] highlights that SMR CAPEX can be reduced up to 20% by way of: 1) modularization and factory fabrication, 2) advanced manufacturing, 3) BIM (Building Information Modelling), 4) advanced construction methods, and 5) co-siting of multiple reactors. Regarding BIM, it is defined as a "*combination of Computer Aided Design (CAD) tools and additional functionality, which gives a digital representation of the physical and functional characteristics of a facility. This can be used to collect and share facility information in order to improve decision making over the course of the life cycle*". The use of BIM might determine a CAPEX reduction for SMRs by 4% to 10% (consistently with saving in other industries) [43]. The same percentage of

CAPEX reduction is also envisaged for LRs [35]. Regarding the advanced construction method, open-top construction can determine a CAPEX saving of up to 2%. Parallel construction and crane optimisation can increase further the CAPEX reduction. These methods have to be considered early in the design phase. Considering the limited maturity of SMR designs, the possibility to achieve a CAPEX reduction is higher for SMRs than LRs [35]. Regarding the last point, the reasons because of SMRs can benefit from the co-siting economies is summarised in Section 8.0. However, [35] points out a CAPEX cost saving of 5% to 14% for SMRs (considering between 2 and 12 reactors on the same site).

[17] compares the 335 MWe IRIS reactor (SMR representative) and a 1340 MWe Generation III+ PWR (LR representative) evaluating six factors: size, multiple units at a single site, learning, construction time, match of construction schedule to demand and design related characteristics. The comparison shows how the economy of scale is a big disadvantage for SMRs if the two plants are comparable in design and characteristics. Indeed, by considering only the factor “size”, IRIS reactor has an average cost [€/kWe] 70% greater than a 1340 MWe Generation III+ PWR. This percentage changes if other factors are considered. [17] consider the following factors and the corresponding cost reductions (%) in the case of 4 versus 1 plant comparison: multiple units at a single site (14%), learning (8%), construction schedule (6%), design related characteristics (17%). When these factors are considered and combined, four 335 MWe SMRs have a capital cost [$\$(MWh)^{-1}$] 5% higher than a 1340 MWe LRs [17].

[40] considers four plant sizes (1600 MWe, 1200 MWe, 300 MWe, 150 MWe) to compare the “Economy of Scale” and the “Economy of multiples” paradigms and two scenarios: NPPs deployed by a big utility and two minors, NPPs deployed by a single utility. The main results are:

- By considering only the “economy of scale”, the overnight cost [€$(kWe)^{-1}$] of the first SMR (300 MWe) would be 89% higher than a single LR (1600 MWe);
- By considering not only the “economy of scale” but the “economy of replication” too, the gap reduces to 13%.
- If the “IDC” is considered, the gap between SMRs (300 MWe) and LR (1600 MWe) reduces to 7-10%.

- **Operating expenditure (OPEX)**

Firstly, it worth clarify the meaning of OPEX and O&M (Operation and Maintenance). [35] defines OPEX as *“the cost of maintaining a plant, including both the cost of keeping the plant available to generate (fixed opex) and the incremental cost of generation (variable Opex). Variable costs of operation include fuel, output related repair and maintenance, residue disposal and the incurring of charges that will fund the decommissioning costs after the operating life of the asset”*. Furthermore,

[35] defines O&M as "*all actions which have the objective of retaining or restoring an item in or to a state in which it can perform its required function these include the combination of all technical and corresponding administrative, managerial and supervision actions*".

The OPEX breakdown for LRs is usually characterised in this way: 50% fixed O&M, 25% fuel, 15% variable O&M, 10% decommissioning [35]. O&M costs are the "*most addressable areas*" of the OPEX [35]. SMR fuel cost is expected to be higher than the LR one, in particular with the single-batch fuel strategy adoption. SMR decommissioning cost is also expected to be higher than the LR one. Regarding the "*most addressable areas*", [35] highlight that they are expected to be higher for SMRs with respect to LRs. The main reasons are the expected higher workforce costs per unit of output (considering the lack of the economy of scale), and the expected higher manning costs. SMRs might reduce the expected higher OPEX through co-siting of multiple reactors, operational learning and shared control. In particular, co-siting of SMRs might reduce the fixed O&M costs by 10% to 20% (7% to 14% of the OPEX). The operational learning (determined through familiarity with the designs and a consistency of operations) might improve the capacity factor (potential increase by 5% to 10%) and reduce the variable O&M costs (potential saving of 5%). The shared control (single control for several reactors) staffing cost can be reduced [35] .

In another study, [17] compare the O&M costs of four 335 MWe SMRs (IRIS) with a 1340 MWe LR using a multiple regression analysis. According to the analysis carried out by [17], the O&M costs of four 335 MWe SMRs (IRIS) are 51% greater than a 1340 MWe LRs, if only the "economy of scale" factor is considered. This percentage becomes equal to 19% if the following factors and corresponding cost reductions are considered in the comparison: multiple units at single sites (15%), additional outage cost (3%), outage duration (4%).
Furthermore, [44], [45] highlights another two factors that might reduce the SMR O&M costs: the higher quality determined by factory fabrication and the fewer components with respect to LRs.

- **Decommissioning cost**

NPP decommissioning is complex, long and expensive [46], [47]. However, SMR decommissioning cost is the least life-cycle cost component analysed in both scientific and industrial literature. According to [48], [49], SMR decommissioning stage appears technically easier for full factory-assembled reactors, as they can be transported back to the factory in an assembled form. The dismantling and recycling of components of a decommissioned NPP at a centralized factory is expected to be cheaper compared to the on-site activity, in particular, due to the economies of scale associated with the centralized factory. However, estimates of decommissioning costs vary between authors. [50] compared one or two LRs (1340 MWe) vs four or eight SMRs (IRIS reactor, 335 MWe), both in the case of immediate and deferred decommissioning. The analysis shows if the economy of scale is considered as the only driver, the specific decommissioning cost [$\$(MWe)^{-1}$] of SMRs is three times higher, but if other factors are considered (site sharing and different technological solutions) the gap will be reduced.

8.3.4 SMR financing

Reduction of the investment risk with respect to the LRs is a key advantage of SMRs. SMRs are characterised by lower up-front investment, lower capital at risk during construction and lower financial distress than LRs, allowing the reduction of the investment risk [40], [51]. SMRs can be a solution to reduce the financial risk of NPPs (that are often taken by national government utilities or companies which already have several NPPs), and therefore the possibility to attract investment increases with respect to LRs [52], [53]. SMRs are also characterised by the successive addition of multiple units at the same site, determining that the revenue from completed units can help finance the construction of successive units and build investor confidence [51].

However, considering that some aspects of the technology feasibility have to be proven, and the commercial deployment might be long and complicated, few investors are inclined to take this early stage risks [53].

[13] evaluates the competitiveness of SMRs versus LRs from many points of views with the support of simulation software. The main results of the analysis are:

- The NPV of the LR option is higher than that for SMRs ($\$752\times10^{6}$ vs $\$110\times10^{6}$), (752 million US dollars vs 110 million US dollars) with an uncertainty range which may influence the profitability of the investment;
- SMRs are characterised by an average debt lower than LR ($\$825\times10^{6}$ vs $\$1,342\ 825\times10^{6}$), but by a duration higher (9 vs 13.3);

SMRs are characterised by an equity capital required lower than the LR. This happens because, though SMR capital cost is higher, SMRs benefits of the margin generated by the previous units in operation.

Furthermore, [54] compare the investment in LR with SMRs (4 SMRs of 335M MWe each and a LR of 1340 MWe) on the same site using the Real Option Approach (ROA), evaluating how the profitability of SMRs changes if ROA approach is applied instead of a DCF (Discounted Cash flow) approach. According to [54], the ROA permit to consider management's flexibility to adapt later decision. On the contrary, DCF ignores the management's flexibility, then resulting inappropriate in valuing the flexibility given to managers by the SMRs. Furthermore, [54] choice the following "state variables", which are the variable influencing the investor strategy: electricity price, equipment cost, licensing time and cost. The profitability is evaluated in terms of FCFO (Free cash flow from operation) both with an ROA and with a DCF methodology. The results show that the managerial flexibility has a value and it is higher in a modular project (more options to take advantage) than in one LR project. However, the profitability is higher for a LR project.

Furthermore, [55] point out that in energy generating portfolios small plants (therefore also SMRs) might provide a lower investment risk than LR (2GWe). The reason is that with SMR it is possible to increase the diversification in a portfolio, particularly in case of 2-3 GWe.

8.4 External factors

In the energy and nuclear field, most of the researches about the profitability of electrical power plants are focused on the generation cost (using indicators like the LUEC) and the financial performance of the investment (using indicators like IRR, NPV, etc.). Beside these important indicators, private or public investors must include in the analysis the so-called “external factors”. These factors are called external because they are not always monetary factors under the control of the investor, but they strongly influence the economic performance and the feasibility of the project itself. This section, elaborating the work of [18], provides an overview of several external factors which have been identified from the literature about the differential characteristics of SMRs respect to LRs.

8.4.1 Regulation

The licensing process (LP) is a key issue for the deployment of SMRs. [19] discuss SMR specific aspects of the LP, highlighting the following key topics.

Regulatory harmonization and international certification

One of the key debates concerning licensing SMR is the regulatory harmonization. In the nuclear industry, there are few major reactor vendors, contractors and “nuclear manufacturer suppliers”. However, the nuclear industry operates internationally (several countries are interested in SMRs) and LP and the nuclear regulations are country-specific [56]. Consequently, reactor vendors cannot “produce a standard plant” and simply ship/build identical units all over the world. A necessary precondition for the deployment of nearly identical/standard units in more than one country is the harmonization of law and LP. It is extremely difficult to make significant progress in this direction in the short-medium term because of the heterogeneity of [57]: legal systems and jurisprudence, institutional systems; and licensing process structures and underlying principles. Since each government has power over only its country, a short-term harmonization is unlikely.

Duration and predictability of the LP

The existing LP has been designed for LRs which are characterized by long construction periods. LRs require various assessments that take time and are performed in parallel with their construction. SMRs are designed for a shorter construction, and consequently, the “parallel” LP time could be longer than the SMR construction schedule time, preventing the expected time saving. Furthermore, [19] state that the SMR LP could be longer than the SMR construction time because: *“novelty of the design technology, issuance of different safety principles with respect the conventional Nuclear power plants,* *lack of experienced and specific regulatory framework, the multitude of institutions involved, and the various bureaucratic passages*".

Manufacturing licence

The manufacturing license was introduced by the US Nuclear Regulatory Commission for certifying the processes of critical nuclear suppliers. The manufacturing license does not substitute the LP, but it speeds up the LP because the manufacturers are known and certified by the regulatory body. Indeed, the plant must be certified onsite at the end of the construction because "*the reactor owner cannot get rid in any way of the nuclear operator liability, it is the ultimate and sole responsible for the nuclear safety*" [19]. Even if all the "mechanical components" would be certified in the factory, the LP apply to another unit of analysis: the system installed at the site; the LP relies on the NPP in a specific site and not on its parts. Even if the components are certified, the LP require the appraisal of the specific context: i.e. the site, the NPP, the interaction between the operator and the NPP, etc.

The need for a new and regulatory framework

Another issue is the need for the development of specific laws, regulations and licensing processes for SMR. This approach is already common for small nuclear research facilities. Three main challenges make difficult to develop a new legal and regulatory framework. Firstly, it requires a significant review of legal and regulatory frameworks. Secondly, it implies a complete rethink of licensing processes which in turn implies a redefinition of the institutional framework. Thirdly, it implies a reduction of licensing protections in institutional and democratic terms (e.g. exemption from public inquiry processes).

8.4.2 Electric grid characteristics/market dimension

This factor refers to the adaptability of the reactor size to the grid extension. Typical markets that will take advantage from SMR deployment are countries with a population requiring electricity in remote locations. A site for an LR must have an appropriate grid, on the opposite the SMR can fit where is not feasible an extension of the current electric grid for LR or the extension is very expensive. Two of the key purposes of SMR technology are the construction of NPPs in developing countries (with limited grid capability) and in isolated areas (as power or multipurpose energy) [58]. According to [59], the capacity of a single power plant should be lower than 10% of the grid's total capacity. Therefore, for instance, in countries like Jordan which has about 3400 MW of installed electricity capacity, SMRs are regarded as an option. Furthermore, the large vessels used in LRs limit the siting of the NPPs to coastal arear or along major rivers [3]. Conversely, SMRs use smaller vessel size leading to the opportunity for inland and remote sites [3]. [3] highlights another two SMRs features determining flexibility in plant location and the increased possibility of NPP construction. The first is the reduction of radionuclides produced by the fission process (the radionuclides produced are roughly proportional to the power level), determining a reduction of the site boundary leading to flexibility in plant siting. The second is the reduction of the water needed for the rejection of the waste heat. Smaller plants produce less power and, consequently, reject less power leading to the possibility of NPPs construction in countries where only small or low flow-rate rivers are available.

8.4.3 Public acceptance

The public acceptance of nuclear power is the attitude of the public towards the deployment of this technology.

Regarding SMRs, there are two different main points of view about public acceptance of SMRs:

- According to [60], [61], public acceptance of NPPs can be improved with SMRs for the following reasons: security improvement, environmental impact improvement, proliferation resistance improvement, passive safety system and massive deployment.
- [45], [62] considers the public acceptance of new concepts as one of the disadvantages of SMRs that must be overcome in order to develop SMRs in the near future.

8.4.4 Safety and security

Increased safety and security are two key advantages of SMRs with respect to LRs. Several papers highlight the increased safety as one of the advantages of SMRs with respect to the LRs [3], [45], [51]. The reduction of the type and number of the safety components and simplification of the remaining ones determine a dramatic increase in safety [16]. Furthermore, some SMR designs are characterised by an improved separation of systems and functions [51], determining a lower probability of compromising safety functions. [3] highlights three main reasons determining the enhanced safety as follows: 1) "*the reduced inventory of radionuclides produced from the fission process"*, 2) "*the potential to eliminate design features that introduce accident vulnerabilities*"; 3) "*the opportunities to passively respond to unexpected transients*". Furthermore, considering that SMRs are characterised by a smaller area of skyline than LRs leading to a reduction of terrorist air attack probability, NPPs security is improved [16], [40]. SMR security is further improved in the case of SMR designs characterised by an underground siting [51].

8.4.5 Emergency Planning Zone (EPZ)

The EPZ is the area surrounding a nuclear facility where special regulatory requirements apply (e.g. specific emergency preparedness procedures need to be available, the demographic density needs to be lower than a specific limit, etc.). Each country prescribes the regulatory requirements associated to their EPZ. The [63] suggests an EPZ radius between 5 and 25 km (for reactors having a power higher than 100 MWth). Many SMR reactor vendors advocate a smaller radius because of the improved safety concepts of SMRs (compared to LRs) and because of the limited radioactive material they store. [64] points out that the Nuclear Regulatory Commission agrees SMRs needs scalable EPZs.

8.4.6 Cogeneration

[65] provide an overview of the main challenges and opportunities related to the use of cogeneration for the load following of NPPs and highlight three most relevant technologies for the load-following (particularly with SMRs): district heating, desalination, and hydrogen. SMRs are more suitable for cogeneration than LRs because it is possible to switch some of the SMR fleet for the cogeneration, and, consequently, SMRs can run at the full nominal power and maximum conversion efficiency [23]. Furthermore, a specific requirement for the cogeneration is the siting of the heat or desalination plant near the end-user areas [3], [16].

In particular, [66] analyse “*the load following of SMRs by cogeneration of hydrogen*”, providing an assessment of the technical and economic feasibility of coupling hydrogen production facilities with SMRs, investigating three different hydrogen production electrolysis technologies: Alkaline Water Electrolysis, High-Temperature Steam Electrolysis and Sulphur-Iodine thermochemical. Alkaline Water Electrolysis is technically feasible and the investment can be profitable depending on the hydrogen and electricity price (hydrogen price >= 0.40 €$(Nm^3)^{-1}$ and the electricity price relatively low). For High-Temperature Steam Electrolysis, the coupling with an LWR SMR might be challenging because of the different temperature between the steam produced and the cogeneration process requirements. This coupling becomes profitable when the hydrogen price is in the range of 0.30-0.45 €$(Nm^3)^{-1}$ or above. For Sulphur-Iodine thermochemical, the coupling with an HTGR SMR is possible, but it is not feasible the coupling with an LWR SMR. This coupling results very profitably as far the hydrogen price reaches 0.30 €$(Nm^3)^{-1}$

[22], [67] analyse the coupling of a NuScale SMR plant with different desalination technologies. The analysis shows how the coupling is easy and effective.

8.5 Why has nobody built SMRs in the last two decades? And the way forward

Most SMRs have attractive characteristics of simplicity, enhanced safety and require fewer financial resources than LRs. However, they are usually not considered as economically competitive with respect to LRs because of the accepted axiom of “bigger is better” i.e. a misguided application of the economy of scale principle. The economy of scale principle applies if and only if the comparison is 1 Large vs. 1 Small and the reactors are of a similar design, as this has largely been the case in the past. This is no longer true today, however, where smaller, modular reactors have very different designs and characteristics from large-scale counterparts. Thus, assuming by definition, that because of the economy of scale principle, the capital cost of a smaller size reactor is higher than for a large size reactor is simplistic and not wholly applicable, and assuming that SMRs presents several advantages with respect to LRs (suitability for cogeneration, enhanced safety and security, increased possibility of NPP construction, reduction of the time to market etc.), a reasonable retort is “why has nobody built SMR in the last two decades?” There are a number of reasons, the most important being:

- In the nuclear industry, there is a strong belief in the economy of scale. However, this is not supported by the data. An example is analysed by [68] for the French case. In this instance, the author showed that with increasing the size came increased construction time without the economy of scale.

- In general, in the last two decades, relatively few reactors have been built globally, with most investors (mainly in South Korea, Japan and China) using “proven designs” i.e. the large GEN II reactors further developed in large GEN III reactors.

- To be fully competitive the SMR needs to balance size reduction with technical solutions that can only be enabled by a reduction in size; a typical example of which is an integral vessel, incorporating the heat exchangers, able to rely on natural circulation. Solutions like these are impossible to be fully implemented on LRs. It was not possible to implement these solutions in the 1970s because (quoting a senior engineer from an important nuclear vendor) “*to properly exploit passive solutions like natural circulation you need a great deal of computer simulations and codes. Twenty to thirty years ago those tools were not available, so the only option was to use a pump (plus the backup pumps). From an engineering perspective it is much easier to control fluids using several pipes and pumps than to rely and make sophisticated simulations with computer codes*”.

- One of the enabling factors to build cost competitive SMRs is the modularization (again expensive to implement in terms of software resources), and the availability of advanced technology and software (e.g. BIM) which have emerged only in recent years.

Very recently, the UK government commissioned several studies about SMR economics and financing, as [53] and [35]. The reports are publicly available and the authors encourge the reader to read them.

The authors also want to close the chapter echoing the wise words from Admiral Hyman G. Rickover, delivered in 1953: "*An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly. (6) It is very flexible in purpose. (7) Very little development will be required. It will use off-the-shelf components. (8) The reactor is in the study phase. It is not being built now. On the other hand a practical reactor can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It requires an immense amount of development on apparently trivial items. (4) It is very expensive. (5) It takes a long time to build because of its engineering development problems. (6) It is large. (7) It is heavy. (8) It is complicated*."

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