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Small modular reactors: A comprehensive overview of their economics and strategic aspects

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ABSTRACT

A key challenge for engineers and scientists over the coming decades is to develop and deploy power plants with sufficient capacity and flexibility to meet the growing demand for energy (mainly electrical) whilst simultaneously reducing emissions (primarily greenhouse gases). With fusion-based power plants not currently being considered viable for large-scale deployment for at least 40 years, other technologies must to be considered. Renewable and high efficiency combined gas-fired plants, along with nuclear solutions, are regarded as the most suitable candidates, with Small Modular Reactors (SMRs) developing as a favoured choice. However, two main impediments to the current deployment of SMRs exist: (1) safety concerns, particularly following the Fukushima accident, and (2) their economic models, with high capital costs only being available through a limited number of investors. The goal of this paper is to provide a review and a holistic assessment of this class of nuclear reactor, with specific focus on the most common technology: the Light Water Reactor (LWR). In particular, the paper provides a state-of-the-art assessment of their life cycle, along with a comparison of their relative merits with other base-load technologies. It is shown that SMRs are a suitable choice when the power to be installed is in the range 1–3 GWe and the social aspects of the investment, such as the creation of new employment positions, is a goal of policy makers. The paper thereby provides governments and stakeholders with key economic and social boundaries for the viable deployment of SMRs.

1. Introduction

According to the DOE/EIA (DOE/EIA, 2011) the world energy consumption in 2035 will be more than double that of 1995, mainly due to increasing requirements in non-OECD countries.[1] Moreover, global electricity generation and energy consumption will increase by a factor of 3 over the same timeframe with non-OECD countries increasing their consumption by 5–6 times; mainly due to an expected exponential growth in China. Specifically for nuclear power plants, it is forecasted that electricity generation will increase from 2.6 trillion kWh in 2008, to 4.9 trillion kWh in 2035, and with many nuclear reactors approaching the end of their productive life (Schneider et al., 2011) the market is expected to expand significantly. Although the Fukushima accident has directly prevented an immediate deployment of nuclear power in some countries (e.g. Germany, Switzerland and Italy), other nations (China, Emirates, Russia, India and to some extent the USA and UK) are still pursuing their programs vigorously.

Since nuclear power provides zero greenhouse gas emission electricity (if correctly managed at affordable prices), the construction of new reactors is now also being considered in many “new-comer countries”. According to World Nuclear Association (WNA) (WNA, 2013), 53 countries including Poland, Turkey, Vietnam, Kazakhstan are at various stages in the development of their nuclear infrastructure. In particular:

- Contracts signed, with a well-developed legal and regulatory infrastructure: UAE, Turkey.
- Committed plans, with a legal and regulatory infrastructure being developed: Vietnam, Jordan, Belarus, Bangladesh.
- Well-developed plans but full commitment still pending: Thailand, Indonesia, Egypt, Kazakhstan, Poland, Lithuania, Chile.

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[1] The OECD (Organisation for Economic Co-operation and Development) is an international economic organisation of 34 countries founded in 1961 to stimulate economic progress and world trade (www.oecd.org). The 34 countries are mainly form Europe, North America and Australia. Non-OECD countries are from Africa and Asia (with the exception of South Korea and Japan), including Russia, India and China.

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- Developing plans: Saudi Arabia, Israel, Nigeria, Malaysia, Morocco, Ghana.
- Under discussion as a serious policy option: Namibia, Kenya, Mongolia, Philippines, Singapore, Albania, Serbia, Croatia, Estonia, Latvia, Libya, Algeria, Azerbaijan, Sri Lanka, Tunisia, Syria, Kuwait, Qatar, Sudan, Venezuela.

In all such countries, governments are required to create (i) a suitable environment for investment, including professional and independent regulatory regimes, (ii) policies on nuclear waste management and decommissioning, (iii) involvement with international non-proliferation measures and (iv) insurance arrangements for third party damage (IAEA, 2007a). This article aims to show to what extent a particular type of nuclear reactor, termed the "Small Modular Reactor" (SMR) might provide a candidate solution to fulfil the energy needs in these emerging nuclear markets. Specifically, the paper focuses on the Light Water Reactor (LWR), predominantly the Pressurised Water Reactor (PWR), since more advanced Generation IV (GEN IV) reactors will not be available for commercial deployment for at least two decades (IAEA, 2006; Locatelli et al., 2013). GEN IV designs still need a great deal of research and development to be sufficiently reliable and economic to justify their commercial large-scale deployment, as demonstrated by the recent experience with the PBMR reactor (Thomas, 2011). Therefore, because of the dramatic difference between GEN IV reactors and commercial GEN III/GEN III+ reactors, GEN III + LWR will be the only SMRs considered in this paper.

2. Why SMRs

From annex IV of IAEA (2007b), which is considered a seminal text on SMR technology, small sized reactors are defined as those with an equivalent electric power less than 300 MWe, while medium-sized reactors are those with an equivalent electric power between 300 and 700 MWe. More often, the two are combined into the commonly termed "Small and Medium-sized Reactors" or "Small Modular Reactors" (SMR) representing those with an electrical output less than 700 MWe. For the purposes here, it will be assumed that a "Large Reactor" (LR) counterpart has a power output >700 MWe. The term SMR includes the nuclear options along with the remainder of the plant support infrastructure and equipment, namely the steam generator, turbine and fuel storage facilities, if necessary, and can be deployed as multiple units on the same site to increase total power output. Several SMR designs (detailed in Khan et al., 2010) are currently at different stages of development around the globe. Ingersoll (2009) provides a good summary of the innovative feature of these; "*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.*".

SMRs usually have attractive characteristics of simplicity, enhanced safety and require limited financial resources. However, they are usually not considered as economically competitive with LR because of the accepted axiom of "bigger is better" i.e. a misguided application of the economy of scale principle. According to the economy of scale, the specific capital cost (currency/KWe) of a nuclear reactor decreases with increasing size, due to the rate reduction of unique set-up costs in investment activities (e.g. licensing, siting activities, or civil works to access the transmission network), the more efficient use of raw materials and the exploitation of higher performances characterizing larger equipment (e.g. steam generators, heat exchangers, pumps, etc.). Thus, when the size and the power increases, in the specific capital cost expression the numerator (currency) increases less than the denominator (KWe). Consequently, in large developed countries, during the last four decades, the reactor size has steadily increased from a few hundred MWe to 1500 MWe and more today. However, the economies of scale apply if and only if the comparison is 1 Large vs. 1 Small and the reactors are of a similar design, as 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 (Carelli et al., 2004). 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. Despite this, a reasonable retort is "why has nobody built SMR in the last two decades?" There are a number of reasons, the most important being:

1. In the nuclear industry there is a strong belief in the economy of scale. However, this is not supported by data. An example is analysed by Grubler for the French case (Grubler, 2010). In this instance the author showed that with increasing the size came increased construction time without the economy of scale.
2. 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.
3. 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 large reactors. 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 30 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".
4. One of the enabling factors to build cost competitive SMRs is the modularisation (again expensive to implement in terms of software resources) and the availability of heavy lift cranes which have emerged only in recent years.

In particular, SMRs by their nature, are designed to be factory manufactured, transportable and/or re-locatable, and be suitable for the production of heat, desalinated water and other by-products that industrial sectors require (I. M. A. Dominion Energy Inc., Bechtel Power Corporation TLG, 2004). 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 limited on-site preparation as they are expected to be "plug and play" when arriving from the factory. Kuznetsov (2008) stresses these aspects by underlining how small reactor size allows transportation by truck, rail or barge and installation in close proximity to the user, such as residential housing areas, hospitals, military bases, or large governmental complexes. Fig. 1 presents a typical PWR with a loop configuration, i.e., large primary circuit piping and components external to the reactor vessel, whereas SMR as IRIS features an integral configuration, i.e., all major primary system components are placed inside the reactor vessel ("integral vessel"), and external piping is eliminated. While the vessel size is increased in integral configuration, the

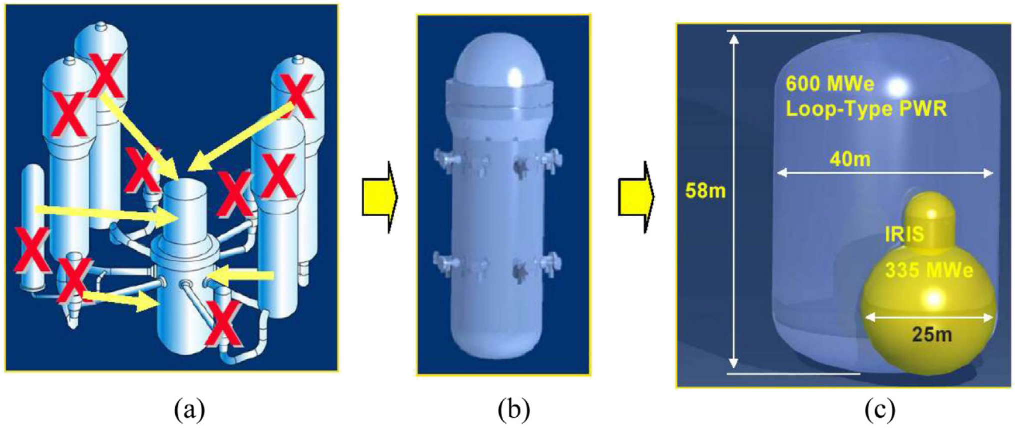

Fig. 1. Comparison of Large LWRs with loop configuration (a) and SMR (IRIS) integral primary circuit configuration (b), and the overall containment size (c) (Carelli et al., 2005).

containment and overall NPP size is decreased, with a positive impact on safety and economics (Carelli et al., 2005).

Fig. 2 highlights the transportability of SMRs.

The US Secretary of Energy, Dr. Steven Chu, has highlighted the importance of SMRs for the USA (Chu et al., 2010) *"[…] one of the most promising areas is small modular reactors (SMR). If we can develop this technology in the U.Staffing and build these reactors with American workers, we will have a key competitive edge. […] Their small size makes them suitable to small electric grids so they are a good option for locations that cannot accommodate large-scale plants. The modular construction process would make them more affordable by reducing capital costs and construction times. Their size would also increase flexibility for utilities since they could add units as demand changes, or use them for on-site replacement of ageing fossil fuel plants. Some of the designs for SMR use little or no water for cooling, which would reduce their environmental impact. "*

Notably, the world nuclear organisation lists 20+ SMR designs. However, according to the IAEA database the only SMRs under construction are in Russia: the Akademik Lomonosov 1 and 2. These are based on a reactor design used for several years on icebreakers and now - with low-enriched fuel, are used on barges for remote area power supply. For the most part, the primary candidates to be a First Of A Kind unit (FOAK) land-based counterpart are the Korean SMART (System-integrated Modular Advanced ReacTor) reactors. These are 330 MWt units designed for electricity generation and seawater desalination. The construction of SMART will be a significant test of the technology, since South Korea is the country that has recently demonstrated the best capability in construction of nuclear plants. Importantly, successful construction will form the basis for best practice guidelines.

Because of the growing interest in these technologies several papers and reports have been published. The following section provides a critical appraisal of the most relevant of these.

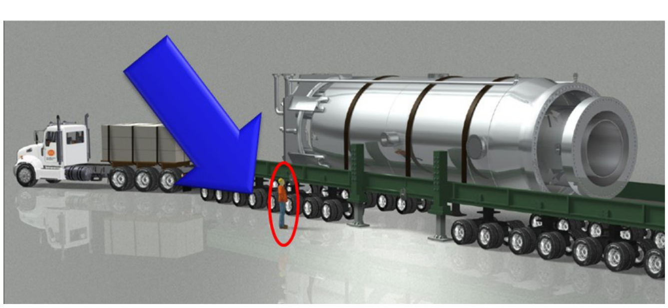

Fig. 2. NuSclare reactor (45 MWe). This reactor has been designed by explicitly considering constraints in transportability. The figure shows the containment of the reactor that includes the vessel and a number of other components such as steam generators and pressuriser that in large reactors (such as EPR and AP1000) are connected to the vessel via large pipes [figure from www.nuscalepower.com].

2.1. Reports and publications

Several research institutes see the SMR as a credible technology for supporting electricity production. NEA/OECD (OECD-NEA, 1991) provides one of the earliest reports, focussing on an assessment of their suitability for electric power production, heat generation (both for industrial process and space heating) and co-generation of both heat and electrical power in OECD countries. However, most of the SMRs described are actually scaled versions of the LR, and not the modular SMR concept. More recently, IAEA (2006) provided a milestone report (more than 700 pages) on the "modern" SMR. It reviews their main concepts and provides an extensive review of water cooled variants (13 designs), gas cooled reactors (6 designs), liquid metal cooled (6 designs) as well as one "unconventional" advanced high-temperature reactor. Their economics and strategic implications are qualitatively discussed, and have been recently updated. The main conclusion of the report is that GEN III + SMR can rely on the successful experiences in building large GEN II and GEN III LWRs. However, regarding their commercial deployment, there remain several challenges.

IAEA (2007b) investigates safety features, economics and other important factors such as proliferation resistance and other challenges (always with qualitative approaches). Nevertheless, a later report (IAEA, 2009) is devoted to explaining the superior safety features of SMRs, with a further short paper (IAEA, 2010) summarising the status and near-term prospects of SMRs. Two others UOC/EPIC (Rosner and Goldberg, 2011) and NEA/OECD (OECD-NEA, 2011), review different designs and underpinning technologies, economics, safety aspects and licensing issues. It is the implications of the outputs of these reports that are used as a basis for much of what follows. Nevertheless, much recent work has also been published looking into issues surrounding SMRs and their relative merits. Although each of these focuses on different aspects, key recurring concluding remarks from the literature are as follows.

- SMRs have enhanced safety attributes primarily due to them being "passive systems" that impede the effects of any human error and perform well and predictably in extreme circumstances.

- SMRs can be divided in two categories: Gen III+ Light Water Reactor (LWR), and GEN IV reactors. GEN III+ SMRs are based on the same physical principles of current LRs, and can be deployed rapidly in around 2–3 years. GEN IV SMRs require greater research and development effort, and if adopted most could only be available for commercial operation from 2030.
- Current GEN III+ SMRs are suitable for electricity production and low-temperature co-generation, while GEN IV SMRs will add the capability to burn nuclear waste from GEN III+ reactors, to produce high grade heat.

Here, the most relevant economic and strategic information related to SMRs is now considered, comparing them with other technologies and discussing their relative merits under various scenarios.

3. The economics of the SMR

3.1. Introduction to the economic evaluation of power plant

The nuclear industry commonly clusters NPP life cycle costs as: capital cost, operating and maintenance, fuel and decommissioning. Two broad cost estimation techniques can be used to calculate these: top down and bottom up. The first merges different cost drivers and escalation coefficients. Regarding the power plant industry, these drivers are size, technology, location etc. With the bottom-up analysis, “resources level” elements identify quantities and unitary cost. The final cost is their sum.

The most important indicator for policy makers is the levelised cost of the electricity produced by the power plant. This indicator, usually 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 [$/KWh].

To investigate the profitability of investing in a power plant for utilities, several indicators are used, with the two most popular being Net Present Value (NPV) and the Internal Rate of Return (IRR).

NPV measures absolute profitability [$], and is significantly affected by the discount value, i.e. the corrective factor used to weight “present cost” vs. “future revenue”. This indicator usually depends on the source of financing and can be forecast 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 high WACC is weighted more towards the present cost respect to future revenues (promoting low capital cost solutions, such as gas-fired power plant).

The IRR is a specific dimensionless indicator, usually presented as a percentage that represents the return. The greater the value, the higher the profit for the utility.

3.2. Economy of scale

Economy of scale is widely employed to drive the generation cost structure of LWR. Traditional techno-economic analyses show that the average investment and operating costs per unit of electricity are decreasing with respect to increasing plant size. However, this result cannot be directly transferred into the investment analyses of SMRs versus LR, because it relies upon the clause “other things being equal”. Effectively, this presumes that SMRs are the same as LRs except for size. If the design is only marginally different, the capital cost of a larger unit is significantly cheaper than for a smaller version. The reasons are geometrical (volumes increase to the power of 3 and areas – and so material and cost – to the power of 2) and economic (sharing of fix or semi fix cost e.g. licensing on more MWe).

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 factors are (The Economic Modeling Working Group Of the Generation IV International Forum, 2007; Carelli et al., 2010).

Modularization: the process of converting the design and construction of a monolithic plant to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies. The factory fabrication is cheaper than site fabrication, but the limit is the possibility of a cheap shipping of modules built off site. The SMRs can take a differential advantage since it is possible to have a greater percentage of factory made components.

Multiple units at a single site: SMRs allow the investors to make incremental capacity additions in a pre-existing site. This leads to co-siting economies: the set-up activities related to siting (e.g. acquisition of land rights, connection to the transmission network) have been already carried out; certain fixed indivisible costs can be saved when installing the second and subsequent units. The larger the number of SMR co-sited units, the smaller the total investment costs for each unit.

New design strategy and solutions: 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. This also positively affects the safety of the plant via a reduction of the number of safety systems and a simplification of those remaining.

3.3. Learning and construction time

SMR can exploit two strong synergic advantages: learning and construction time.

Regarding learning, there are two key aspects (Carelli et al., 2010).

1 *Modularity – learning economies*. 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. 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.
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 an LR. Therefore it is possible to have a large bulk ordering process of components like valves. This aspect allows the SMR to exploit economies of mass production and a more standardised procurement process.

A fundamental precondition for the industrial learning is a stable regulatory environment allowing the utilities to “standardise the design”. According to The Economic Modeling Working Group of the Generation IV International Forum (2007) N-Of A Kind (NOAK) costs are achieved for the next plant after 8 GW (GWe) power installed, before that costs decline with each doubling of experience. 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 mature. 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” offers a significant advantage for SMRs when, using a similar power comparison, a site with one LR is compared with a site with many SMRs.

Aside from learning economies related to a high cumulated number of supplied SMR units, the mentioned technical benefits

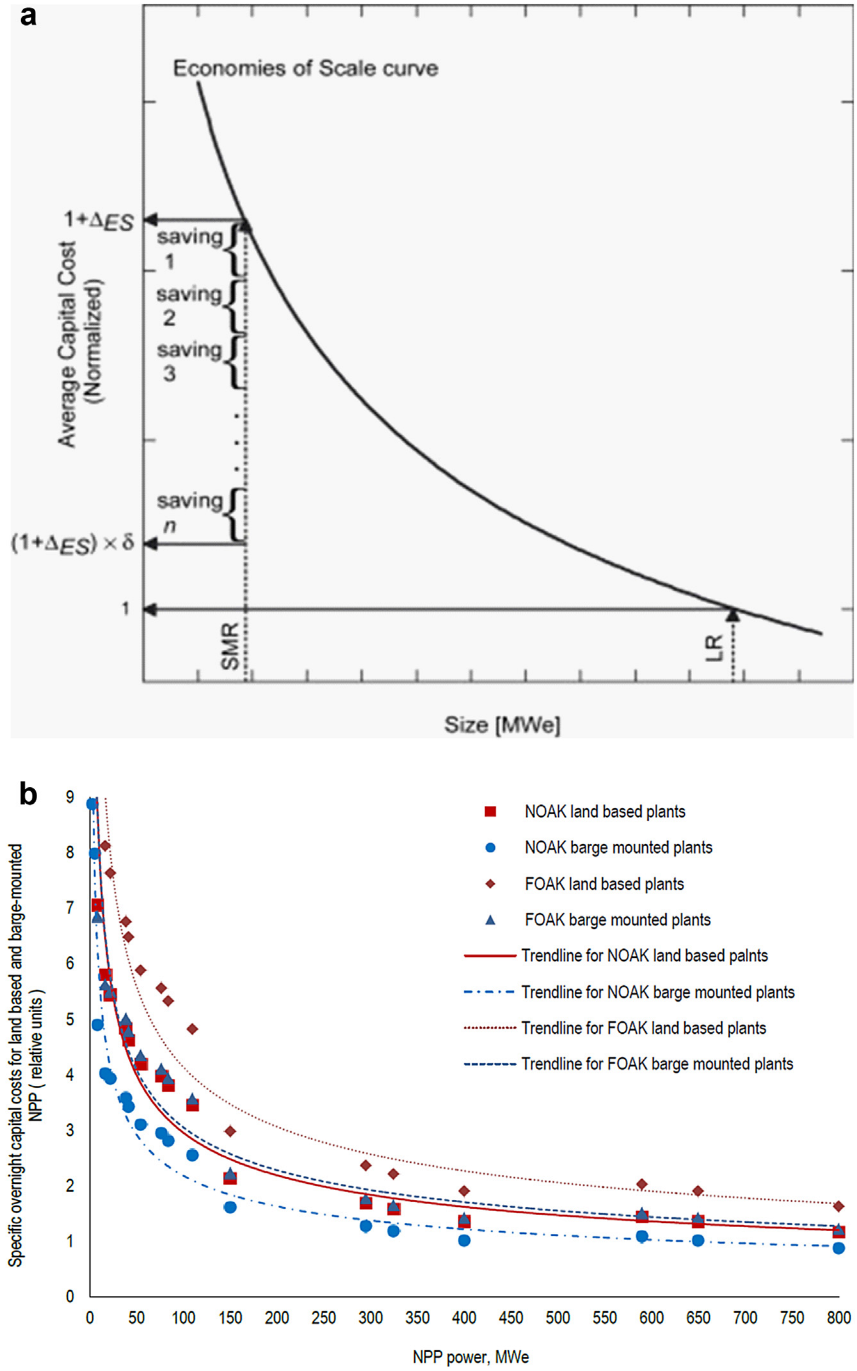

Fig. 3. (a) Parametric approach for estimating the capital cost of SMRs (Carelli et al., 2010). (b) Cost reduction from the economies of multiples (Rosner and Goldberg, 2011).

will hopefully allow the SMRs to experience smaller average generation costs, for a given plant size (technical progress economies).

The construction schedule is another very critical economic aspect in nuclear power plant for two reasons:

1. *Fixed daily cost*. On a nuclear construction site there are thousands of people working and the utilisation of expensive equipment (e.g. cranes). Consequently each working day has high fixed costs.
2. *The postponing of cash flow*. Each year of construction postponement (or delay) of inbound cash flow for the utility increases the interest to be paid on the debt. It is possible to argue that, since the life of the reactor is fixed, e.g. 60 years, this makes no difference. However, this is not true since the present value of a cash flow that is received 60 years from the present, is negligible. Consequently, for each year of delay the revenue has to be considered as lost.

The Economic Modeling Working Group of the Generation IV International Forum (2007) presents a very detailed analysis of FOAK schedule vs. NOAK schedule. Being an SMR, the smaller FOAK units weigh less that the equivalent for LR, therefore the extra time of the FOAK has less impact. Moreover, as previously discussed, there is a reduced construction time for SMR delivery due to reduced size and assumed design simplification.

3.4. Life cycle costs

3.4.1. Capital cost

Hayns and Shepherd (1991) show that investment in SMRs could be potentially attractive for 300–400 MWe PWRs, with specific capital costs [$/MWe] of co-siting being of the same order as a single LR. Carelli et al. also provides a parametric methodology to calculate the capital cost of an SMR, based on the application of dimensionless coefficients related to the main differential aspects between SMR and LRs in terms of size, number of units on the same site, and differences in their design. It is concluded that the capital costs of 1 × LR and 4 × SMRs, are commensurate. However, NEA/OECD also provides a detailed analysis, and concludes that the SMR may cost the same as the LR, or up to 50% more, depending on the number of required units and assumptions based on the economies of scale. Fig. 3 provides a summary of the conclusions of the two studies. An alternative, bottom-up cost estimation is provided by UOC/EPIC (Rosner and Goldberg, 2011), and shows that the cost of a 600 MWe FOAK is around $5000M, although the cost drops to $3000M for NOAK units. Most of the savings are attributed to reductions in direct costs.

3.4.2. Operation and maintenance (O&M) and fuel

Considering O&M, Carelli et al. (2008) considers all differential factors (economy of scale, multiple units, outage additional cost, outage duration), and the overall difference in capital costs between a large size reactor of 1340 MWe and a suite of 4 SMRs, of 335 MWe each, is 19%, with SMR being the more expensive. According to NEA/OECD (OECD-NEA, 2011) the corresponding O&M and fuel costs (combined) for LRs vary from 16.9 to 25.8 [$/MWh], while the costs for SMR vary between 7.1 and 36.2 [$/MWh]. According to UOC/EPIC (Rosner and Goldberg, 2011) the O&M cost for the 600 MWe FOAK is 16.54 [$/MWh], although the cost falls to 12.05 [$/MWh] for the NOAK. Fuel cost is always 8.53 [$/MWh].

3.4.3. Decommissioning

Estimates of decommissioning costs vary between authors. Locatelli and Mancini (2010a), using a multi-regression analysis calculated the specific decommissioning costs of 4 × 335 MWe SMRs to be double that of 1 × 1340 MWe LR. According to NEA/OECD (OECD-NEA, 2011) and the IAEA (2007c) the decommissioning 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.

3.5. Overall life cycle economics

The paper of Hayns and Shepherd (1991) is the first in investigating the whole life cycle of SMRs. It presents a bottom-up cost estimation model for a 300–400 MWe PWR that also considers the IRR indicating a positive economic attraction for this model of plant. In an alternative formulation, Shropshire (2011) focuses on scenarios more in line with EU expectations, with an indication that the actual competitiveness of SMRs for these markets is yet to be fully demonstrated, but that they show potential to achieve competitive costs in other electricity market areas. Evidence is also given that greater benefits are afforded by their combined usage with wind turbines to stabilize the power grid, with an additional impact on sustainability measures from deployment. UOC/EPIC

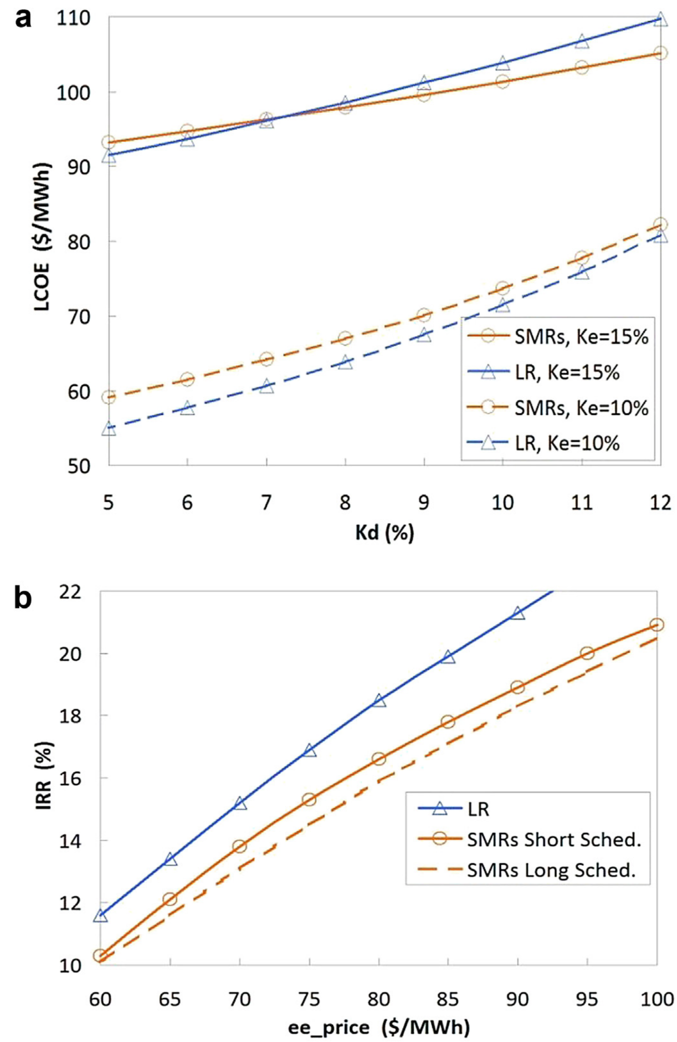

Fig. 4. (a) LCOE trend at increasing cost of debt Kd, at different cost of equity Ke (i.e. for "Merchant" case – solid lines – and "Supported" case – dotted lines) and (b) Project profitability (IRR) with different levels of price of electricity (ee_price) and construction schedule – "Supported" case (Boarin et al., 2012).

(OECD-NEA, 2011) stress the importance of the 'learning effect' and economy of multiples (or mass production). The "*SMR economics is strongly dependent on the degree of cost savings achievable through off-site factory manufacturing of the reactors and the subsequent learning-by-doing achieved after production of multiple modules*". A NOAK unit could provide an LCOE that is around half that of a FOAK, and be comparable to the Natural Gas Combined Cycle (NGCC) (Rosner and Goldberg, 2011).

Boarin et al. (2012) compares the use of the INCAS model ("INtegrated model for the Competitiveness Analysis of Small modular reactors") for the SMR and LR. Four SMR units on a single site are compared to the use of a single LR unit, with the total power installed being equal. They assess LR and SMR technology with two business cases: a "Merchant" case, based on the rules of the liberalised electricity and capital markets; and a "Supported" case, referring to special risk-mitigation policies and conditions. The "Merchant" case has a higher cost of financing while the cost of the "supported" case is lower due to external support (e.g. from the state).

The economic performance of the two alternatives (i.e. LR and SMR) is shown to be broadly similar, but with SMRs having lower capital risk and lower upfront capital investment requirements. For similar reasons, the financial risk of SMRs is lower than LRs due to lower sensitivity of financial profitability to changes in operational conditions. The reader is referred to Fig. 4 showing examples of profitability characteristics. It is important to notice that the NOAK units of SMR bear less risk than the NOAK of LR, mainly because of the simpler design and lower upfront investment requirements. Consequently, the remuneration expected by the investors (both Debt and Equity) is lower.

3.6. *Economics of SMR vs. other sources*

According to NEA/OECD (OECD-NEA, 2011), the use of nuclear power, in general, is directly competitive with other technologies (coal-fired plants, gas-fired plants, renewable plants of the various types) in Brazil, Japan, the Republic of Korea, the Russian Federation and the United States – though notably not in China. SMRs, including twin-unit and multi-module plants, generally have higher LUEC than NPPs with large reactors. As shown in Locatelli and Mancini (2010b), similar to large NPPs, some SMR are expected to be competitive to several coal-fired, gas-fired and renewable plant projects, of various types, including those of small to medium-sized capacity (below 700 MWe).

Locatelli and Mancini (2010b) show a Montecarlo analysis comparing SMRs with coal and gas-fired plants, and stress the fundamental role played by the carbon tax (or the sequestration cost). Without accommodating this cost, it is clear how coal and Combined Cycle Gas Turbine (CCGT) are, for a 335 MWe Power plant, more attractive than nuclear (Fig. 5). Coal has the lowest LUEC, and the highest NPV, CCGT the higher IRR. In these scenarios, SMRs do not appear as attractive options due to the low NPV for the shareholders, and the high uncertainty of the ultimate output. This is very consistent with the policy in EU and USA. In these countries,

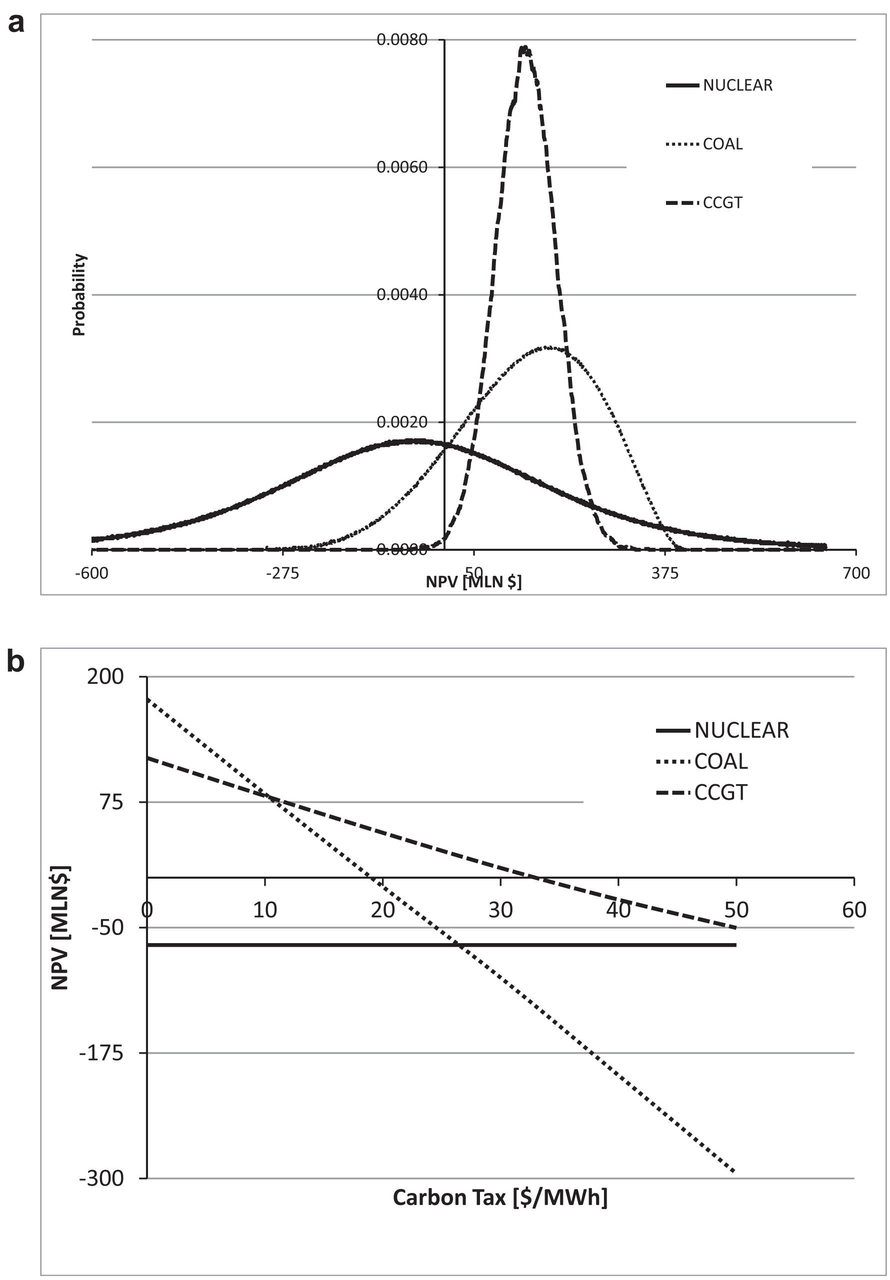

Fig. 5. (a) NPV to the shareholders probabilistic distribution, no carbon tax. (b) Impact of carbon tax on the NPV (Locatelli and Mancini, 2010b).

most of the base-load power installed in the last decade is CCGT. Those plants have small upfront cost and are very reliable. The low risk in the investment and the short payback time are therefore key factors that have pushed their adoption in liberalised markets.

UOC/EPIC (Rosner and Goldberg, 2011) focuses on a comparison of SMR and NGCC. According to their analysis, the cost of SMR is higher than NGCC, but the long-term market competitiveness of SMR, measured as LCOE, will need to be benchmarked to new NGCC capacity. The exploitation of learning and "economies of multiples" in general is a key element in this respect.

4. SMRs from a "system's" perspective

4.1. Portfolio analysis

A classical method for utility companies to reduce the overall risk to their business is to differentiate investments by building a portfolio of power plants based on different technologies. Due to their smaller size, SMRs can provide a means to increase this diversification, even for utilities with a small market share. Locatelli and Mancini (2011a) present a detailed analysis of this. The adopted mathematical approach demonstrates that portfolios composed of larger power plants have a lower LCOE than those of small plants (including SMRs). However, in the case of the small-scale market (2 GWe), portfolios of small plants are able to provide a lower investment risk than large portfolio counterparts, both for IRR and LUEC indicators, due to their diversification, which is not otherwise applicable to large plants.

4.2. Non-electrical sectors

Other than for the generation of electricity, other application sectors are also appropriated for SMR consideration. Fig. 6 summarizes the most important, comparing their temperature range with that required for various sectors.

In the short term, the most relevant non-electrical applications are concerned with district heating, where the extracted steam from high and/or low-pressure turbines is fed to heat exchangers in order to produce hot water/steam, which is delivered to the consumer. Heat transportation pipelines are installed either above or belowground. Steam from low-pressure turbines is usually used for the base heat load, while steam from high-pressure turbines is used, when needed, to meet peak demand. The portion of steam retrieved for heat production represents only a portion of the total steam produced by the reactor, the remaining being used to produce electricity (IAEA, 2002). Co-generation plants, when forming part of large industrial complexes, can be readily integrated into an electrical grid system. In turn, they serve as a backup to providing energy security and a high degree of flexibility (IAEA, 2007d).

Energy Policy Institute (2010) reviews three possible co-generation options: (1) desalination (because of population growth, surface water resources are increasingly stressed in many parts of the world), (2) hydrogen production and (3) process heat for industrial applications and district heating. Regarding GEN III+ SMRs, process heat for industry and district heating, provides the most attractive applications. GEN III+ SMRs can be used to provide heat at temperatures ranging from 100 to 200C – more than half of the heat generated is rejected at low temperature. This residual heat is available for other uses. District heating is an existing low temperature application provided by nuclear plants in cold regions. Given the modular nature of SMRs, they offer advantages in areas or applications where heat is needed but where the large heat output, and the expense of a large nuclear reactor, makes their use impractical.

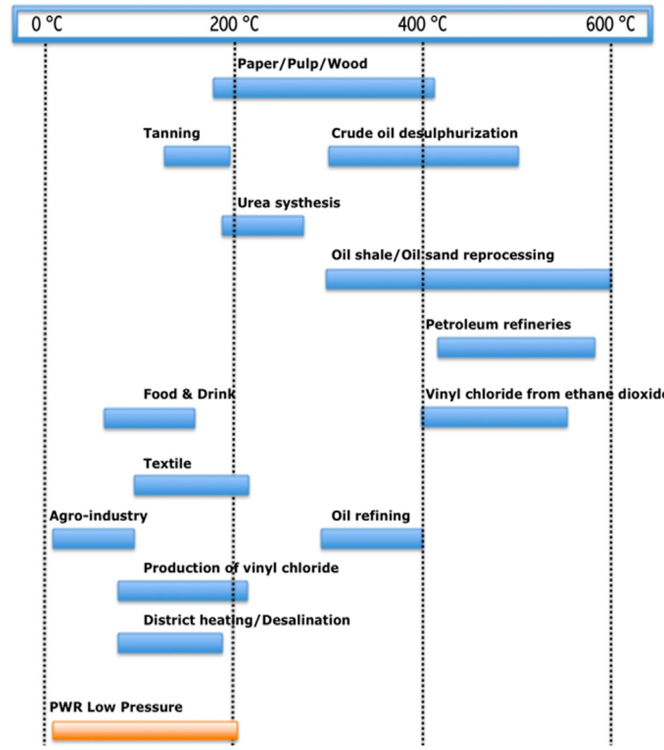

Fig. 6. Required temperature for industrial processes (adapted from IAEA, 2002).

NEA/OECD (OECD-NEA, 2011) stress the relative advantages of using SMRs compared to LR counterparts for cogenerative applications. Specifically:

- Many SMR designs are considered for replacement of ageing power plant in the range of 250–700 MWth. The cost of upgrading the distribution infrastructure for an LR can be very substantial.
- SMR sites are expected to be located closer to the final consumer than large reactors (due to improved safety), and thus energy losses and the associated costs due to long-distance transport of hot water or desalinated water, can be significantly reduced.

Shropshire (2011) suggests that SMR may be well suited to support process heat markets. The smaller SMR align well with the capacity requirements of process industries, and reduced exclusion zones may allow SMRs to be located near industrial parks. The economies of heat production are process industry dependent (e.g., temperature requirements for primary and secondary heat cycles, availability requirements, capacities, processing durations, etc.). Considering specifically GEN IV reactors, they can also recycle waste from other reactors to produce electricity (Triplett et al., 2012). One of the most promising designs is the molten salt reactor. Cammi et al. (2012) present a detailed review of this technology and specifically allude to its unique characteristics in terms of actinide burning and waste reduction.

4.3. Non-financial factors

The nature of an investment in energy production requires enlarging the range of parameters influencing strategic decisions, moving from technical, economic and financial, to social, environmental and political. For these reasons, non-financial factors are important in assessing the overall suitability and configuration of a site for energy production (technology, size, output, interconnection with existing network). Mancini et al. (2009a) provide a list of these parameters (risk of severe accidents, EPZ preparation, security of fuel supply, volatility of fuel price, environmental aspects and public acceptance), guidelines and algorithms for their quantification and integration to support the identification of a long-term investment decision. Results show that nuclear power plants present a promising alternative to improve a country's sustainability and energy independence, even when the adverse impact of nuclear options have been accommodated – i.e. including Not In My Back Yard (NIMBY) social aspects (Tanaka, 2004). Focussing on the nuclear choice, and in particular on the impact of plant size Mancini et al. (2009b) and Locatelli and Mancini (2011b) propose a set of differential qualitative and quantitative measures to help the identification of suitable deployment scenarios: spinning reserves management, electric grid vulnerability, public acceptance, technical siting constraints, risks associated to the project, impact on national industrial system, time-to-market, competences required for the operations, impact on employment, incremental design robustness and historical and political issues. The results clearly show that the greater flexibility afforded by the use of SMRs, from technical, managerial and economic standpoints, can be the critical factor for many emerging countries.

4.4. Cost management aspects

The cost escalation of nuclear power plant has been one of the major issues preventing their construction in the USA, where costs have risen by 300% (Schneider et al., 2011). However, this is not always typical, for example, the (previous generation) French and (current) South Korean programs present more successful economic cases, while the 2 LRs under construction in the EU (Olkiluoto 3 and Flamanville 3) are expected to require a doubling of their budgets and schedules (Locatelli and Mancini, 2012a). Much of the delay is due to the project size, FOAK issues and the complexity of design. SMRs, due to their inherently modular approach, are easier to build and, because of their smaller size, the FOAK impact on cost escalation has a limited effect. Shorter construction times imply an important economy in the costs of financing, and are particularly important when discount rates are high (the specific capital costs could be reduced by up to 20%).

5. Evaluation of scenarios

Locatelli and Mancini (2012a,b) have previously shown how to integrate financial, economic and non-monetary factors to evaluate their suitability on a country-by-country basis. The authors discuss the different algorithms available and apply their own methodology to an Italian scenario, finding that LRs are still preferable to SMRs in a number of situations. However, Boarin et al. (2012) describe an important option embedded into the investment model of proposing several SMRs: so-called "self-financing", typically encountered in modular investments. It represents the capability of the project to finance itself by re-investing the income from early-deployed Nuclear Power Plants (NPP) operation into the construction of later NPP units. This approach is common in many other sectors, e.g. in the transportation industry with the toll roads used to finance the construction of further highways (Small, 1992) or in the civil sector where residential complexes construction is performed sequentially, in order that the first build covers the cost of the second build. If short-term positive income exists for an NPP, after covering debt obligations, it is diverted to cash-deficit NPPs under construction, to an extent defined by the user (from 0% to 100%), the rest being earned as "shareholders' dividends". That gives the shareholders an option to reduce upfront equity investment, re-investing self-generated equity resources in the project, at an appropriate *IRR*.

Energy Policy Institute (2010) has assessed the possibility of building SMRs in the USA. Besides the main advantage quoted by Chu et al. (2010) and reported in Section 2, they discuss how factors such as licensing, public acceptance, and supply chain issues may hinder significant SMR deployment in the future.

From a more global perspective it is clear that SMRs should not be considered an alternative to LRs, but a solution for niche markets that are normally not suitable for LRs. For instance:

- When SMRs are competitive with LRs and the power required is 1–3 GWe: since the economies of scale are compensated by the "economy of multiples".
- Where the power required is about 300 MWe–1 GWe: since there is not enough market space to justify the construction of an LR. Here, SMRs can also be competitive with coal and CCGT. Typical scenarios are islanded plants for isolated towns etc.
- Where the environment presents a challenge in terms of water availability, earthquakes etc. (IAEA, 2009; Carelli et al., 2004)
- SMRs can represent the ideal solution for "nuclear newcomers" without significant prior experience in building and operating nuclear reactors: to build and operate an SMR requires much less prior knowledge than LR counterparts (Locatelli and Mancini, 2011b).
- Replacements for the decommissioned small and medium-sized fossil fuel power and heat plant. Typical scenarios are the replacement of an old coal power plant, jeopardized by the carbon tax and tighter environmental legislation, or an old oil plant that is no longer allowed to operate.

6. Conclusions

The aim of the paper has been to summarise the main features of SMRs; predominantly from the perspective of investors and policy makers. Given the extreme relevance and complexity of the field, this paper aimed to bring together the contributions of scholars and practitioners with state-of-the-art papers and report. Senior managers, policy makers, practitioners and the wider community of scholars are the target audience.

Modern SMRs are a relatively "new product" in the nuclear industry since they are not a scaled version of more traditional LRs, but a new concept in nuclear power generation. They aim to take advantage of a smaller size to implement new technical solutions and easier construction. SMRs exploit the "economy of multiples" rather than the "economy of scale". The strengths and weaknesses of an investment in SMRs allow an identification of market conditions where they are more economically viable than LRs. From an investment perspective, the IRR remains one of the most important differential indicators, particularly when utilities are owned by private sector companies tasked with maximizing the return. However, the "added extra" from LR investment is reduced when the electricity price and overnight costs are not stable, and mainly decrease: the lower the electricity price, the smaller the difference in the IRR among the reactors. It is concluded that SMRs are attractive in scenarios with limited financial resources, where the utilities can add modules to exploit the self-financing options. With this approach, shareholders receive a lower remuneration of their equity in the short-term, in favour of higher income at a later date. Moreover, SMRs, because of lower upfront investment requirements, present a promising choice in cases of limited resources, and "wait and see" (real options) strategies. However the SMR must be built sequentially, with an ideal delay of 1 year between a “first concrete” and the following to reap the advantages from “learning” and “self-financing” i.e. from the “economy of multiples”.

Considering non-financial factors, preliminary results indicate that SMR perform better or at least as well as LRs. However, NIMBY limits the possibility of using SMRs on many sites to exploit the advantages of grid stability and site availability. Nevertheless, even if a proposed solution is to focus many SMRs on a reduced number of sites (quasi-distributed) they may still present with regard to life cycle costs. For instance, during the planning and construction phases, more sites can be exploited (than for LRs), and the time to market is shorter with less risk associated with construction issues. During the operational phase, SMRs provide more employment positions and require lower spinning reserves.

We expect that SMR will play an important role in nuclear industry in the next decades.

SMRs are cost competitive with LRs when the power required is 1–3 GWe, since the economies of scale are compensated by the “economy of multiples”. This is very important when 1–3 GWe is the total power to be installed in a country, where the specific regulatory requirements and the local project delivery chain push for an ad-hoc national design. Moreover, the investment project flexibility, in terms of time and placement, is one of the greatest strengths of SMRs. With a smart schedule (a delay of about 1.5–2 years between the start of the construction of each module) is possible to achieve the maximization of learning and co-siting economies and self-financing to minimize the upfront investment. Where the power required is less than 1 GW the situation has to be carefully evaluated. They can be viable where there is not enough market space to justify the construction of an LR, and SMRs can be competitive with coal and CCGT. However, the long licence process if often not justified for small projects. SMRs can represent the ideal solution for “new comers” without experience in building and operate nuclear reactors: to build and operate SMRs is easier than LR counterparts.

In conclusion, regarding the future of LWR, it appears clear as there are now two well established categories of reactors: LR (1100 MWe or more) and SMR (350 MWe or less). The first group, LR, exploit the economies of scale and targets markets requiring several GWe where few utilities (usually owned by the national state) have large availability of capital able to sustain the deployment of a fleet of standard LR. Such countries include China, Russia, Korea, and UAE. SMRs are intended for newcomers (like Kenya) or private utilities (like in USA) willing to reduce the risk and the upfront investment and are keen to exploit learning and prefabrication. The “middle ground” of 700 MWe LWR does not appear to have a promising future at this time: those reactors are too big for “factory builts” but too small for recouping the benefits afforded by the economies of scale. For instance the AP600 received the NRC’s final design certification 1999 but no orders were ever placed, while the AP1000 is under construction in USA, China and regarded as viable options in several other countries.

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