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Economics of Small Modular Reactors: Will They MakeNuclear Power More Competitive?

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Abstract: Looking at the historical evolution of commercial use of nuclear power, the long-term trend so far has been to increase the size of the reactors to maintain their economic competitiveness through economies of scale. However, over the last five years, advanced reactor concepts, among which the SMRs (Small Modular Reactors), have progressed faster than anyone predicted ten years ago. It is likely that several FOAK (First of a kind) SMRs will be constructed and start operation over the next ten years, and a global supply chain will be developed to support them.

Benefitting from their architecture and the overall system simplification, SMRs could become one of the main drivers of deep decarbonisation of the global economy, an enabler of large-scale hydrogen economy, a solution for allowing growth of energy consumption in the developing world without relying on fossil fuels, a means to replace the heat source of hundreds of coal power plants around the globe.

The article analyses the main economic drivers to override the diseconomy of scale of SMRs – modularisation and factory build, design simplification, standardisation, and industrial and regulatory harmonisation – and discusses the advantages and challenges of different SMR designs in unlocking those drivers. Some publicly available studies on SMR CAPEX, OPEX and LCOE are reviewed to demonstrate the values the different vendors and developers are targeting to make SMRs competitive not only with respect to large nuclear reactors but also to other means of electricity and heat generation.

Keywords: SMR, safety, economics, competitiveness of nuclear energy.

1. Introduction

Small Modular Reactors (SMRs) are defined as nuclear reactors with a power output between 10MWe and 300MWe. Designs with power outputs smaller than 10MWe, often designed for semiautonomous operation, have been referred to as Micro Modular Reactors (MMRs).

The most mature SMR concepts are based on Light Water Reactor (LWR) technology. SMR deployment configuration can vary between single-unit installations, multi-units plants, or mobile power sets such as floating (i.e. barge-mounted) units. There are more than 70 different design concepts under development around the world with different technology and licensing readiness levels. The first SMR is now operational in Russia (Akademik Lomonosov, barge-mounted) and soon in China, at least five other SMR prototypes are expected to be built within the current decade.

A description of *Advances in Small Modular Reactor Technology Developments* (edition 2020) has been published by IAEA [1].

Due to smaller reactor cores, very large water inventories and lower power densities, LWR SMRs may benefit from reduced shielding requirements and reduced or eliminated offsite emergency planning zones which, in turn, will result in added flexibility for the siting of these reactors.

SMR designs often include an integral nuclear steam supply system and take advantage of overall system simplification. Inherent passive safety systems could also provide SMRs with greater and, in some cases

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indefinite (if long-term natural circulation of the coolant can be established), coping times in case of a loss of offsite power. Many SMRs are designed to be installed below ground level resulting in higher physical protection and protection from external hazards.

Advanced modular reactors use novel cooling systems or fuels (molten salts, liquid metals or helium gas) and bear the promise of "game changers" in terms of high intrinsic safety (walk-away safety), new functionalities, high proliferation resistance and, importantly, expected lower capital costs mainly due to design simplicity and the absence of high pressure and lower generation costs.

Looking at the historical evolution of nuclear power reactors, the long-term trend has been to increase the size of the reactors in order to maintain their economic competitiveness through economies of scale. This trend was driven by multiple factors, the most important of which were (1) significant improvement of efficiency and reduction of cost of coal and gas plants; (2) more stringent regulatory and safety requirements resulting in the reinforcement of safety-in-depth philosophy and the need to provide additional safety features and barriers, more redundancy, more complex designs; (3) growing complexity and cost and time burden of the licensing process; (4) the abandonment, in many countries, of regulated tariffs and shift to different models of electricity markets where long-term guarantees for off-take prices and volumes were no longer available.

Only projects involving large reactor unit capacities that would ultimately delivery large amounts of cheap and reliable electricity could compensate for the considerable costs associated with the above factors. Very large and safer reactors—the Gen III models, were designed in the late 1980's and expected to be able to cope with these challenges. However, the construction of most of the prototypes of these reactors has seen considerable cost and schedule overruns which have undermined the confidence of investors and decision-makers in these technologies and in nuclear power in general. Although the nuclear industry seems to be finally overcoming these challenges as the First-Of-A-Kind (FOAK) new builds have been finally completed and the lessons learned incorporated in the subsequent builds—still too low in numbers to allow for a true series effect though, Gen-III/III+ reactors will to some extent continue to be capital-intensive projects with significant labour costs and on-site work. Interest is therefore growing in more evolutionary concepts—"beyond" large Gen-III/III+ designs—that incorporate all the learning and techniques of previous projects to yield greater productivity and predictability per unit. A major stream of such designs is theSMRs.

2. The Fundamental Driver

While we observe a wave of enthusiasm in favour of SMRs in recent years, it should be noted that the concept has been around for several decades. The key potential advantages of SMRs have been known and described yet they have never taken off due to the multiple barriers facing their development (more on this in Section 3 below). Why do we see this new wave of interest and why should the outcome be different this time?

The fundamental driver behind the keen interest in SMRs is directly linked to the growing awareness that nuclear power will be indispensable for deep decarbonisation of the economy, that such decarbonisation relying exclusively on intermittent renewables like wind and solar would be extremely challenging and probably impossible without necessary dispatchable back-up plants(fossil-fuelled, hydro and nuclear). SMRs are very well suited to complement intermittent renewables in electricity generation through their high flexibility, in particular for high penetration of variable renewables where flexibility of dispatchable resources becomes crucial. Furthermore, many SMR designs can efficiently provide thermal storage to increase system flexibility, produce other forms of energy like low and high enthalpy heat to be used in for heating, water desalination, to produce competitively low-carbon hydrogen that could be used to decarbonise industrial sectors that are very difficult to decarbonise otherwise, like steel making, production of ammonia or cement. SMR designs offering high outlet temperatures could replace coal-fired boilers in existing coal plants, SMRs or MMRs[1] would fit to smaller electrical grids in many developing countries, in remote areas or operate with micro-grids or off-grid. The favourable non-proliferation and fuel sustainability and waste production characteristics of certain SMR designs make them easier and faster to adopt for smaller countries as well as countries wishing to embark on nuclear energy. Most SMR designs rely on higher levels of intrinsic safety and/or passive safety systems compared to Gen III/III+ LWRs[2]; this will facilitate their acceptability by the public and allow their operation within existing industrial sites or closer to large cities.

Humanity will have to do without fossil fuels in not-so-distant future. Apart from renewable energies, with their own lot of challenges and drawbacks, nuclear energy is the only low-carbon energy source that we have at our disposal, compensating for the two major drawbacks of renewables—their low power and energy density (and, as a consequence, their very high requirement of raw materials and land area) and their intermittency (for wind and solar). Most recent studies on deep decarbonisation of the economy conclude that massive increase of the use of low-carbon electricity and hydrogen will be indispensable to satisfy global energy needs[2](growing and expected to grow significantly in the developing world) if we want to abandon the use of fossil fuels, the reserves of which are anyway limited. Advanced reactors and SMRs can play a key role in scaling up of the production of these two energy carriers of the future—low-carbon electricity and low-carbon hydrogen.

3. The Promise and the Challenge

The attractivity of SMRs compared to traditional large-size Gen III/III+ reactors resides in their higher safety, versatility, flexibility, ability to provide a broader range of energies and energy services compared to pure electricity generation. Their value on the path to a decarbonised economy cannot be reduced to only assessing their overnight costs or comparing their Levelised Cost of Electricity (LCOE). Despite that, the SMR market will only take off if SMR designs can demonstrate costs that are competitive with all other solutions, and not higher than those of NOAK[3] large-size reactors[2,3]. The lower the costs of SMRs, the less reliance on public policies, supports and subsidies, the faster the SMR market will grow.

The key economic drivers of SMRs that have to override the diseconomy of scale factor are well known: (1) they need to be built in series (the larger the better) to maximise the benefit of the learning curve, (2) they have to be built quickly with minimised construction risks. From nuclear new build projects or fleet construction programmes the goal of SMR vendors is to move to delivering products (not only the reactor itself but the complete plant should be, to the extent possible, manufactured in factory and assembled on-site).

The key elements in achieving that are (see Fig. 1)[2]:

- Modularisation and factory build. Smaller SMR size means that transporting their modules would be easier than for large reactors, allowing for harmonised gauging for sea/train/road delivery of modules. In fact, the degree of modularisation increases considerably for power outputs of less than 500 MWe. It is estimated that 60-80% factory fabrication levels are possible for SMRs (with power outputs below 300 MWe). Factory fabrication would also facilitate the progressive implementation of advanced manufacturing techniques such as electron beam welding, diode laser cladding, powder-metallurgy hot isostatic pressing and additive manufacturing.

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[1] Micro Modular Reactors.

[2] See for example the IEA World Energy Outlook Special Report *Sustainable Recovery*, June 2016.https://www.iea.org/reports/sustainable-recovery.

[3] N-th Of A Kind.

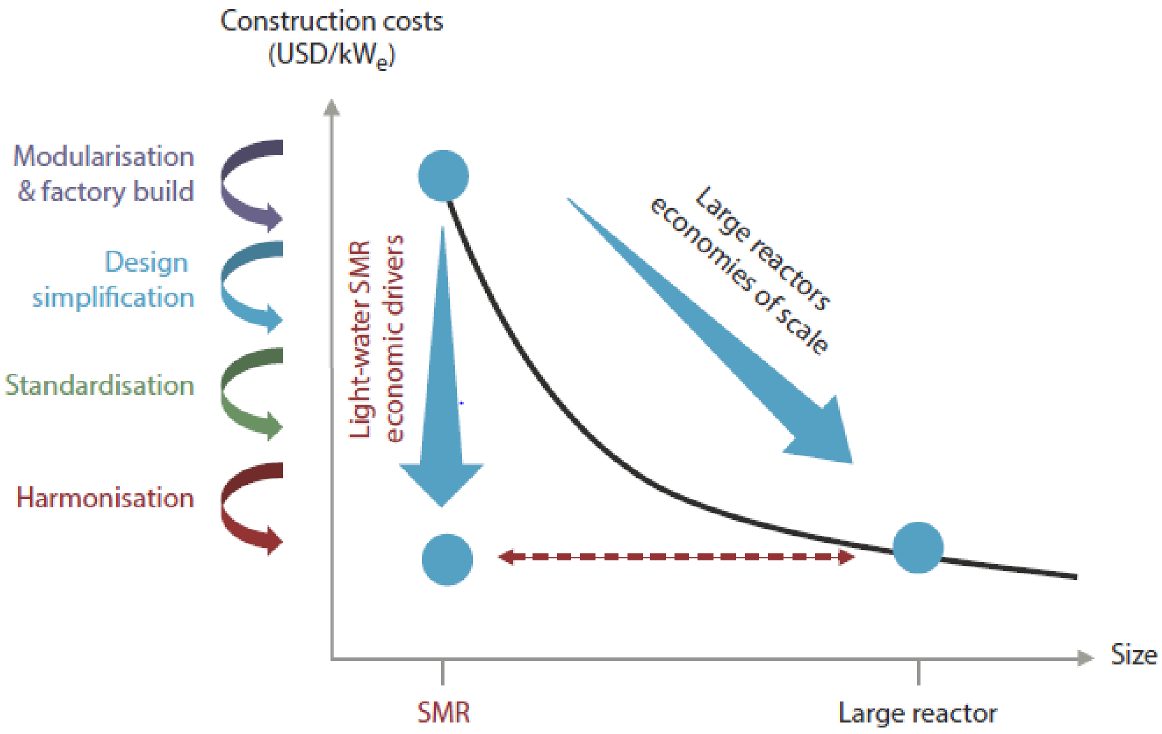

Fig. 1 **SMR economic drivers compensating the diseconomies of scale[2].**

- Design simplification. Passive mechanism improvements and greater design integration would reduce the number of components and result in containment building savings and facilitate ease of operation and maintenance.
- Standardisation. The lower power output of SMRs reduces the need to adapt to local site conditions, raising the level of design standardisation compared with large reactors.
- Harmonisation. Having access to a global market is necessary to foster series-production economies, but this is possible only with regulatory and industrial harmonisation.

From an economic and financing perspective, the small size of SMRs should largely facilitate the attractiveness of investment in SMRs and significantly reduce the real or perceived investment risks. The important characteristics of SMRs from an investment perspective are the following [4]:

- Lower capital costs.The smaller size of SMRs logically leads to lower per unit capital costs, and related lower financing costs. Further, the complexity and size of the on-site structures needed will be reduced; most of the SMR plant can be built in a factory or shipyard and delivered to site. This can reduce construction times by half or more, avoiding two years or more of significant plant financing costs. Light water SMRs will benefit from the large experience accumulated in marine propulsion and capitalise on modular construction experience and hundreds of reactor-years of operating experience. However, cost optimisation was not always the key objective of the designers of these reactorswhich are also very specific due to their own specifications, so considerable efforts will be needed to beat the diseconomy of scale and achieve competitive costs per MW installed. Non-light water SMRs bear the promise to reduce the capital costs significantly. They address the cost issue by eliminating water from the cooling process, using coolants with different characteristics and using inherent safety strategies, the need for pressurized containment and redundant cooling equipment is eliminated, eliminating as much as two thirds of the total plant mass of concrete and steel.

- Smaller upfront investment.The lower total overnight costs of SMRs will also result in lower upfront development costs, making project development easier and accessible to private and public developers with limited financial resources.
- Investment scalability.In stable market conditions or highly regulated environments, the SMR modularity translates into the possibility to decide between sequencing the investment (and the start of revenue earning of each module) over time or build multiple modules in parallel (higher one-time investment—similar to building a large reactor).
- Investment flexibility.In uncertain or highly volatile market conditions, SMR modularity translates into flexibility. The shorterconstruction and commissioning times of individual modules allow adapting more flexibly to the changing market conditions and adjusting further investment to reflect new market conditions.
- Shorter and more certain construction schedule. Less than 20% of the costs of a large Gen III reactor are connected to the cost of the nuclear reactor itself and power production equipment. Most of the cost comes from the construction of large containment structures, cooling equipment, site infrastructure, and financing costs for lengthy construction times. SMRs could be built in 3 to 5 years, their lower overnight costs resulting in reduced labour and site costs. The standardised SMR "product" will allow for much higher construction schedule certainty.
- Lower risks result in cheaper financing. The lower capital costs, standardised nature of the SMR, shorter construction times and lead times result in lower completion risks, lower interest rate exposures, reduced uncertainties of data entering the discounted cash flow model. The investor will be willing to accept lower internal rates of return on equity and lenders will offer lower interests on debt.
- Self-financing opportunity.Staggered deployment of SMR modules allows producing revenue from the first modules that can be used for financing of the subsequent modules, reducing the need of fresh equity and debt injections.

While the above elements may seem quite obvious and not fundamentally different from cost reduction strategies of other standardised industrial products, they represent at the same time an enormous challenge in the context of dozens of competing designs being developed in different countries:

- how to secure the sufficient number of units to trigger the process after the first prototype is build;
- how to guarantee large series of modules upfront, before sufficient experience feedback and lessons learned from construction and operation are accumulated;
- who will invest in the first factory to fabricate the modules;
- how to prepare a robust supply chain without long-term certainty;
- who will convince the global industry to adopt common norms and standards and the regulators to harmonise their licensing approach.

Public acceptance is another key challenge for SMR deployment, though it may differ significantly from country to country. The intrinsic safety and technical characteristics of SMRs are no doubt favourable to obtain public acceptance in an energy-constrained world. They have to be conveyed to the public by well-considered information and education strategies. Governments have an important role in proactively building public awareness and confidence.

4. Gen III Overpromised, Can SMRs Do Better?

Several GEN III/III+ FOAK projects were characterised by excessively optimistic initial cost and schedule estimates, with a final "as built" price tag representing multiples of the initial estimate. Many lessons have been learned and the importance of (1) design maturity before construction start, (2) improved project management practices, (3) regulatory predictability and stability, (4) supply chain maturity, (5) series effect and others are now well understood.

SMRs have unique design features that allow them to capitalise more extensively on some of the cost reduction strategies that have been developed based on the lessons learned from nuclear new build of large Gen III NPPs and which should further contribute to compensating the major economic drawback of SMRs: their inability to benefit from economies of scale.

Despite that we have seen the targeted LCOE of some of the most advanced SMR concepts rise as their technology readiness level and licensing readiness level increased.

With practically non-existent data on actual construction costs of SMRs, reliable cost estimates are difficult to obtain. Everybody keeps in mind the Gen III reactors case of costs inflating throughout the construction process. Consequently, we will see a lot of wait-and-see attitude from investors before actually jumping in and taking confidence from the cost estimates offered by the vendors and by independent studies. In-depth due diligence of the safety case, estimates of the design completion status, licensing progress and supply chain readiness will be an essential part of the decision-making process for investment in an SMR.

The fundamental philosophy of SMRs is based on the principle of large series. The difference in cost between FOAK, post-FOAK and NOAKwill be presumably more important than for large-size LWRs and the NOAK cost reduction will grow with the number of modules produced. Since the FOAK and NOAK risk profile is different, the discount rates will also be different, further penalising the FOAK overall cost. CAPEX and LCOE ratios between FOAK and NOAK indicated by vendors are typically between 1.2 and 1.6.

Vendors will adopt different selling strategies depending on a more or less favourable market outlook and amortise non-recurrent costs, such as research, development and design certification costs on one or several early modules sold.

Who will be the ultimate winners is difficult to judge today, it will depend on the availability of funding, government support, licensing process and its outcome and of course the cost. But it is clear that early investors will have to pay some kind of FOAK premium.

Not surprisingly, many SMR vendors focus their marketing efforts on developing countries. The SMR business models require serial production; serial production requires sustained demand growth which, in turn, is expected mainly in the developing world.

Most of the vendors' information and available studies about SMR economics and finance focus on SMR capital cost, component and subcomponents of the capital cost (i.e. overnight cost, base construction cost), indicators of economic and financial performances (LCOE, NPV[4], IRR[5]). There is still very little information available on operation & maintenance and decommissioning costs, and there is a gap in knowledge about the cost-benefit analysis of the "modular construction".

It is important to note that the main driver of many advanced SMR designs, in particular the non-light water design, is cost and cost-competitiveness with coal, considered as currently the cheapest source of electricity generation in many parts of the fast-growing developing world (India, South-East Asia, Africa). Early cost estimates of several designs of molten salt reactors indeed bring their NOAK costs in the range of 1,300-1,800$/MWe for the CAPEX and 30-50 $/MWh for the LCOE. This sounds excessively optimistic considering the low level of maturity of these designs.

If the SMR market does take off, it will do so with LWR SMRs that have the highest level of maturity. They will have to take up the challenge of competitiveness.

A recent study [5] (see Table 1) compared data on 8 advanced reactor designs under development, including one integrated PWR, one HTGR, one SFR and five MSRs.

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[4] Net Present Value.

[5] Internal Rate of Return.

Table 1 Eight advanced reactor designs under development.

Company	Reactor Type[a]	Country	Reactor Capacity (MWe)	Plant Capacity (MWe)
Elysium Industries	MSR	U.S.	1,000	1,000
General Electric[b]	SFR	U.S.	1,648	1,648
Moltex Energy	MSR	U.K.	1,000	1,000
NuScale Power	APWR	U.S.	47.5	570
Terrestrial Energy	MSR	Canada	288	288
ThorCon Power[c]	MSR	U.S.	250	1,000
Transatomic Power	MSR	U.S.	520	520
X-energy	HTGR	U.S.	75	600

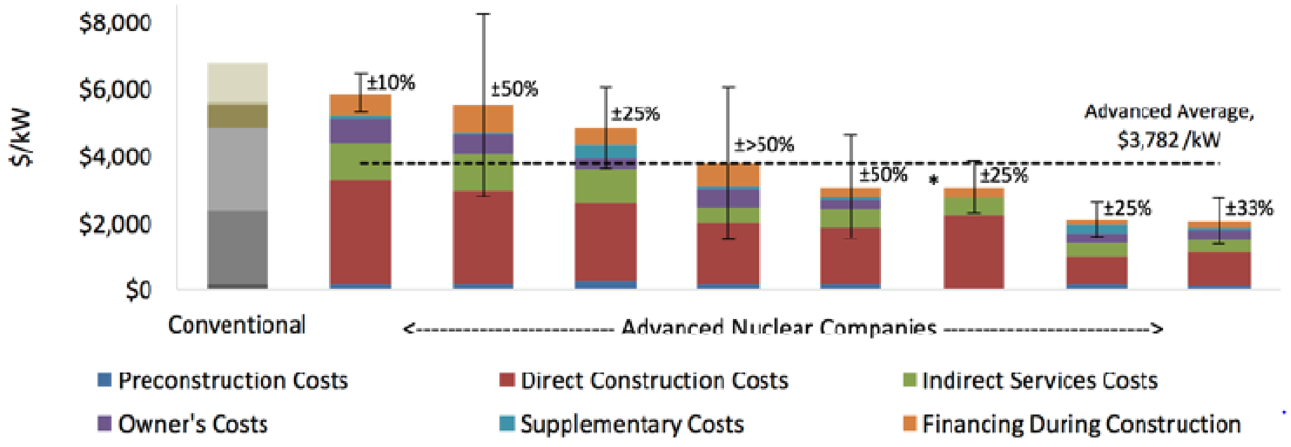

Fig. 2 SMR CAPEX as provided by the vendors participating in the study [5].

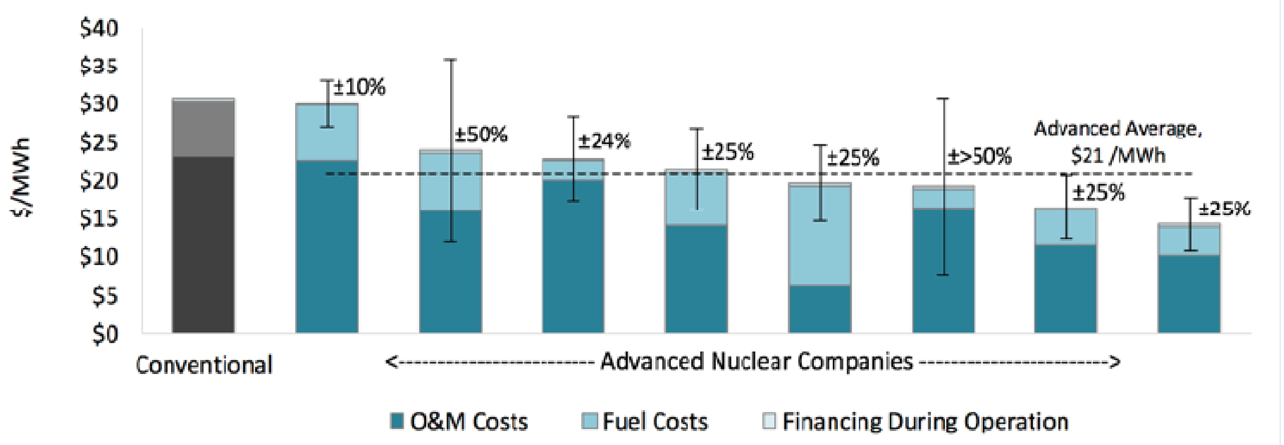

Fig. 3 SMR OPEX as provided by the vendors participating in the study [5].

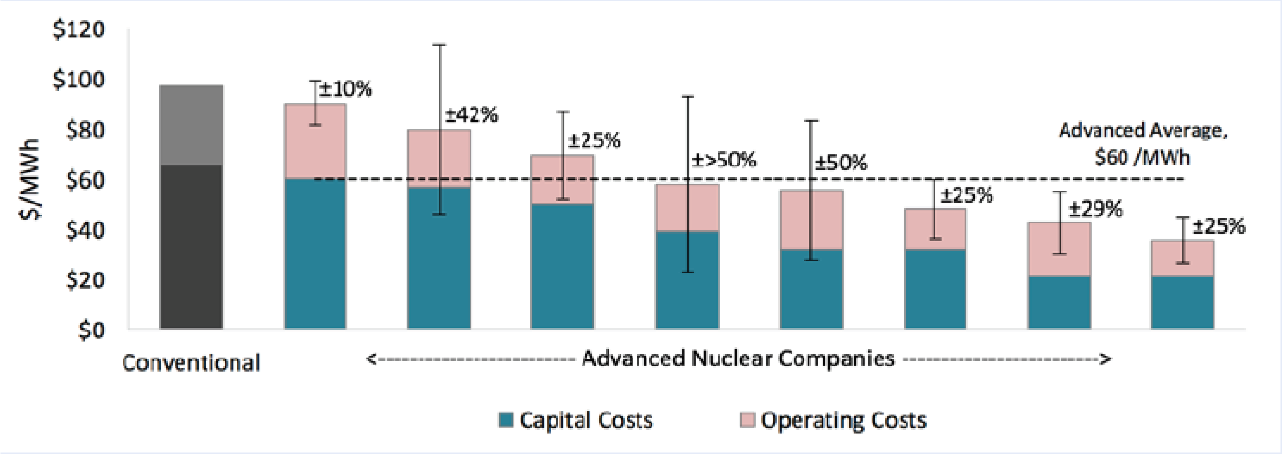

Fig. 4 SMR LCOE as provided by the vendors participating in the study [5].

The study compared the CAPEX, OPEX and LCOE of the 8 vendors of a NOAK reactor, using the same basic assumptions: capacity factor of 95%, discount rate 7%, discount period 25 years. The error bars on the charts are confidence bounds reported by the vendors. The results were presented for all 8 vendors; the cost information of the individual vendors was, however, not disclosed. We provide below the results of this study[6]. Multiple other studies and vendor estimates are available, including a recent meta-study with a systematic literature review of all published information on SMR economics [6]. The CAPEX, OPEX and LCOE figures from most studies lie within the confidence range of the results presented. Systematically, non-light water SMR designs promise significantly lower CAPEX and LCOE. The main reasons reside in significantly simpler designs resulting from the fundamental design choices and intrinsic safety, smaller numbers of components, low pressure (no need of thick-walled pressure vessels), factory (or shipyard) fabrication, standard “off-the-shelf” equipment for the turbine island of the plant. At the same time, the maturity of these designs is lower than that of light-water SMRs so they may need to be interpreted with higher precaution.

It is important to note that in competition with other low carbon energy sources, SMRs can provide additional services to energy systems which will further increase their value and hence allow higher capital costs while remaining competitive. Such additional value can come from, for example, providing thermal energy storage and flexible load following, cogeneration, providing ancillary services while producing hydrogen. A meaningful carbon tax will also increase the competitiveness of SMRs.

5. Conclusion

Advanced reactor technologies and SMRs in particular could become one of the main drivers of deep decarbonisation of the global economy, an enabler of large-scale hydrogen economy, a solution for allowing growth of energy consumption in the developing world without relying on fossil fuels, a means to replace the heat source of hundreds of coal power plants around the globe. They promise to be the technology allowing the necessary massive scaling up of low-carbon energy consumption that is required to replace the use of fossil fuels in the coming decades.

Over the last five years, advanced reactors have progressed more rapidly than anyone predicted and it is very likely that over the next ten years we will see the construction and operation of multiple FOAK advanced nuclear technologies and the development of a global supply chain to support them.

While there are still multiple open questions about the costs of FOAK SMR and about the scaling up of

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[6] The term “conventional” in Figs. 2-4 applies to a large-size PWR.

their development, multiple recent studies converge in their conclusion that light-water based SMRs, the most mature technology, can reach CAPEX and LCOE values similar or lower than current large-size reactors, in the range of 4,000-6,000 $/kWe and 50-80 $/MWh. Non-light-water design bears the promise of reaching CAPEX values below 2,500 $/kWe and LCOEs below 30 $/MWh. Such values would be quite transformative. However, it is important to underline that some innovative concepts still have to overcome significant technical hurdles in domains such as nuclear fuel reliability, materials behaviour and component manufacturing. Another challenge is the necessary close cooperation between the vendors and the regulators to review the existing regulatory frameworks and make them applicable to advanced reactor designs.

Strong government support and commitment is necessary to accelerate the deployment of advanced reactor technologies. Governments should support R&D programs, provide R&D and test infrastructure. Together with regulators they must foster international cooperation to harmonise international licensing to maximise transferability of the same designs. They also have an important role in providing consistent political and policy support to create a stable investment environment and to proactively build public awareness and confidence.

We expect clear, long-term energy policies from the governments. Decarbonization targets should include all clean energy sources and allow nuclear energy to play the role corresponding to its huge potential. This would help justify the long-term program of learning and improving cost efficiency through best practices in management, organizing manufacturing alliances and building efficient supply chains. The nuclear industry and the multitude of advanced reactors start-ups are convinced about the intrinsic competitiveness of SMRs. They are not looking for generation subsidies but for enabling policies and level-playing field with other technologies.

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