Viability and Deployment of Small Modular Reactors

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I. INTRODUCTION

Small Modular Reactors (SMRs) are economically competitive nuclear power reactors within the 300 MW range aimed to provide sustainable clean safe and reliable nuclear energy free from the risk of fissile material proliferation and to bring in, in Dr. Alvin Weinberg's words, "the second nuclear era". SMRs address Gen-IV requirements including non-proliferation and passive safety in Low Enriched Uranium (LEU) reactor systems [1-3].

The IAEA reports that Member States have significantly increased their programs for the technology development of SMRs driven by their potential to meet, among other factors, flexible power generation with more affordable and enhanced safety features. With over 45 SMR designs under development, ready for deployment over the next decade, it is clear that they have several advantages, such as small size and modularity and hence easier siting, over the present large-sized nuclear reactors [4-6]. However, counter arguments have been given to conclude that major vendors in the US (Westinghouse and Babcock and Wilcox) have dramatically reduced SMR development efforts [7] due to the large "book of orders" required, to the tune of 30-50 reactors with an assembly line requiring investment of $ 36-45 b.

It may be closer to the truth to speculate that the future of SMRs is still an open topic with scientists and technologists from academia and industry taking a point of view that needs to converge with that of economists, policy-makers and the public at large. Like any new technology, this new face of nuclear energy is bound to face a wide spectrum of questions, issues and challenges. One of the vital issues that will determine the future of SMRs, and hence the future of nuclear energy as a whole, is the viability of SMRs globally. Yet, factors that favor SMRs in one region of the world (*e.g.* large deployment and proximity to demand) may be looked at unfavorably in another region of the world.

The purpose of this paper is to consider the factors that determine the viability of SMRs in developing countries.

This paper is organized as follows: The status and technological aspects of SMRs are briefly reviewed in Section II. A generic Gen-IV SMR is used to comment on some features that strongly contribute towards a new paradigm for nuclear technology in the global energy scenario particularly compared with fossil fuels and other renewables. Non-technological aspects including the construction and levelized costs of SMRs in comparison with costs of competing technologies is discussed in Section III. The deployment of nuclear reactors, large and small, in the specific environments of developing countries is discussed in Section IV. The viability of SMRs in the specific context of Pakistan is discussed in some detail in Section V covering a broad social science perspective followed by the technological aspects of SMRs, their economics, integration, viability, safety and overall utilization for national requirements. Finally, conclusions are presented in Section VI.

II. THE TECHNOLOGY OF SMRs

The technology of SMRs is mostly well-known and derived from the earlier designs of the 1970s and 1980s. As of Dec 2016 there were 110 small and medium operational reactors with gross capacity less than 700 MW (out of 448 worldwide). The rationale to develop SMRs includes specialized applications, such as powering of production facilities, desalination, hydrogen production, district heating, reaching off-grid remote locations, and providing incremental demands to large nuclear reactors. Out of the 45 SMR designs being pursued, most are in the conceptual or detailed design phase and none of the innovative SMR designs are commercially available. Some designs (*e.g.* NuScale 50MW/module; mPower 125 MW; Westinghouse 200 MW; PRISM 311 MW; SMART 100 MW; 4S 10 MW; HTR-10 10MW; HTR-PM 250 MW) are moving towards licensing with the first-ever SMR design certification accepted in the US being for NuScale Power expected to be ready for deployment by the 2020s. The design features of SMRs, some of which are listed in Table I, are based on innovative designs with scaling-down of large NPPs essentially integrating all primary components inside a reactor vessel resulting in a small size, in addition to passive safety systems.

TABLE I. Selected SMRs

SMR	Country	Type	Fuel/Mod/ Coolant	Power
4S	Japan	Fast reactor	17%/19% ^{235}U (U 9.2708t)	30MWth /10MW
NuScale	United States	iPWR	<4.95% ^{235}U	160MWth /50MW
mPower	United States	iPWR	<4.95% ^{235}U	530MWth /180MW
SMART	South Korea	iPWR	LEU	330 MWth /90MW
ACP-100	China	iPWR	4.2% ^{235}U	385MWth /125MW
KLT-40S	Russia	iPWR	LEU	300MWth /70MW

For example, the 4S 10MW reactor (which is actually a vSMR *i.e.* a very Small Modular Reactor), consists of a cylindrical core, shown in with active core height: 2.5 m, and diameter 1.16 m. Since core size is small, the relatively small fuel inventory (e.g. 1.273t U with 179 kg ^{235}U for the 150MW KLT-40S) leads to lower source terms for radiation release in case of an accident.

Similarly, enhanced safety features of SMRs such as a passive residual heat removal system in SMART give a "20-day grace period against a Fukushima type accident.

The reactors listed above can be considered as candidates for near-term deployment. Both the 4S designs (30 MW and 50 MW) are small and address Gen-IV requirements including non-proliferation, essentially due to the absence of blanket breeders typically incorporated in fast reactors, and passive safety in Low Enriched Uranium (LEU) reactor systems. One of the most attractive features of the 4S reactor is that re-fueling is not required in the entire 30-year operation.

Key design and technology issues of SMRs are based on their inherent features which include:

- Small factory-built systems leading to reduction in on-site work
- A single (integrated) pressurized vessel containing steam generator so that a large break LOCA is eliminated from DBAs.
- A small core will have less risk due to less accident radioactive release
- Passive safety systems e.g. natural gravity-driven circulation in LWR SMR's

The above factors lead to reductions in the Emergency Planning Zone (EPZ) from 5-25 km, suggested by IAEA for 100-1000 MWth reactors, to possibly 1000 feet as listed by Babcock and Wilcox for its mPower reactor [2]. SMRs can thus be shifted closer to the location requiring power in contrast to present-day NPPs. Thus resilient and isolated microgrids of high reliability can be set up.

One issue of concern for SMRs is the amount of plutonium production [10] which over the 30 year operation period of 4S could be as high as 11 kg after 2 years, 82 kg after 15 years and 159 kg after 30 years). Unfortunately, this is a negative aspect of a SMR of the 4S type which means that proliferation resistance is an issue that would require careful security standards and practices.

III. THE ECONOMICS OF SMRs

While the investments involved for SMRs (hundreds of millions of dollars) will be less than that for large reactors (billions of dollars) the cost per kW would be higher due to "diseconomies" of scale (*e.g.* SMART has a construction cost~ $5000/kWe but a low O&M cost of 6.1 c/kWh; NuScale has a cost ~ $ 5100/kWe). In comparison with competing conventional technologies, with risks and acceptance barriers associated with SMRs, the cost for the First-of-a-Kind (FOAK) SMRs is expected to be higher [8] than that for Nth-of-a Kind (NOAK) SMRs steadying as the installed power is large (1-3GW) and job creation is a goal of policy makers. Comparisons for 335MW SMRs, coal and CCGT plants show that coal has the lowest "Levelized Unit Electricity Cost" (LUEC) and the highest NPV, while Combined Cycle Gas Turbine (CCGT) has the higher IRR and thus, SMRs do not appear as attractive options for the shareholders. However, the NPV decreases with the carbon tax where coal levels with nuclear at about $25/MWh and CCGT at about $50/MWh. This is very consistent with the policy in EU and USA. Several other factors considered by utilities are the capacity factor, land and water requirements, jobs created during operation and plant life (SMR START) each of which put SMRs above natural gas, wind, solar and even hydroelectric.

Cogswell et al. [9] have compared, in the Indonesian scenario, the generation costs of SMRs with solar PV to demonstrate competitiveness. These costs include capital, O & M, fuel and decommissioning costs. They conclude that a large NPP is 2.5 times and a SMR 3 times costlier than solar PV which is calculated to be [2015]$ 73.25/MWh, the main difference out of the large capital costs of nuclear reactors ($ 6500/kW for NPPs and $ 9100/kW for SMRs). With so many uncertainties for SMR costing, it would be discouraging to consider factors such as overnight costs within technologies, for PWR technologies in France and the US [7], showing linear increases steepening further for pre- and post-TMI years and worsening for the "renaissance designs" EPR and AP1000 crossing $ 7000/kW and $ 6000 respectively by 2012. This is in contrast to the findings of Locatelli et al. [8] that the cost of the FOAK SMRs will be higher than that for NOAK SMRs due to the learning from experience as the installed power becomes large. For all US and French PWRs cost estimation and cost escalation data showed that learning leads to bigger sizes and delays while for a subset of reactors it can have a positive, though small overall, beneficial effect.

IV. SMRs FOR DEVELOPING COUNTRIES

In the last five years, the growth in the number of NPPs in Asia is evident from new connections to the grid in 2013: 3 in China and 1 in India; in 2014L 3 in China, 1 each in Argentina and Russia; in 2015: 8 in China, 1 Russia, 1 Rep. of Korea; 2016: 5 in China, 1 each in Russia, USA, India and Pakistan; in 2017: 2 in China and 1 in Pakistan. It is clear that Asia will have the largest number of NPPs in the near future.

At present, the number of reactors in USA (the largest single country NPPs) is the same as that in China, Russia, India and Pakistan combined. Further, considering new NPP orders, it is also clear that China and Russia will have a great lead over the US which historically has been the leader in nuclear technology. The same trend appears to be true for SMRs whose number, according to IAEA estimates could be 96 by 2030 in the 'high' case and 43 in the 'low' case with none in the USA. With this pace of growth in the number of NPPs, together with typical grid size in developing countries, it is probable that SMRs would be preferred over larger NPPs. At present, in Asia, SMRs are in operation in China, Pakistan (Section V) and India only. However, potential markets are likely to emerge in developing countries such as Saudi Arabia, United Arab Emirates and Indonesia extending to Iran, Turkey, and Egypt. The perception of SMRs appears to be favorable due to a mix of financial and infrastructure constraints. As an example, Saudi Arabia is to acquire 16 reactors (22 GW) by 2030 to meet the growing requirements for energy to generate electricity, produce desalinated water and reduce reliance on depleting hydrocarbon resources with an investment of $ 100 billion. Saudi Arabia has also opted for a SMR, the Korean 100MW SMART (System-Integrated Modular Advanced Reactor) which will in addition to electricity produce 40,000 tonnes of desalinated water per day. Further, the plant can produce H_2 by electrolysis. The UAE has however opted for four large APR-1400 reactors, operational by 2020, at a cost of $20 billion in an agreement with a Korean consortium.

V. SMRs FOR PAKISTAN

Pakistan embarked upon its nuclear program in 1965 with its first research reactor PARR-1, a 5 MW HEU (~93% enriched ^{235}U) Materials Test Reactor (MTR), gifted by the United States of America under the "Atoms for Peace" program announced by the then US President Eisenhower. Since this beginning in 1965, Pakistan has developed a fleet of four operational power reactors, KANUPP-1 (Canadian PHWR commissioned 1972) and CHASNUPP-1,2,3 (Qinshan Chinese PWRs commissioned 2000, 2011, 2016 costing ~US$ 3.27 b) while one is under construction. Two CNNC "Hualong" ACP1000 NPPs, 1100 MWe each, are planned for the Karachi Coastal power project at an estimated cost of US$ 9.116 b. At present, the total nuclear capacity is 1355 MWe which is ~6% of the total installed capacity. By 2030, NPPs will be gradually added to the grid bringing the nuclear energy component to 8800 MWe.

New economic opportunities in the country are emerging with the China Pakistan Economic Corridor (CPEC) with an influx of megaprojects worth US$ 46 b in several sectors including energy and infrastructure development. In this scenario, it is likely that China will play a lead role in the nuclear energy landscape of Pakistan with management and operations of nuclear reactors carried out by the Pakistan Atomic Energy Commission (PAEC).

With a population of 210 million, a total installed capacity of ~21GWe and an energy mix in which thermal ~60%, hydroelectric ~35% and nuclear ~5%, the per capita electricity consumption is 405 kWhr/yr (compared with the global average of 2674 kWhr/yr) and Gross Domestic Product: Purchasing Power Parity GDP (PPP) of US$ 5235 per capita ranks Pakistan 126 out of 175 countries. With urban and rural electrification of 91% and 62% respectively, 49.5 million people remain without access to electricity mainly due to the off-grid populations far from the north-south electricity grid shown in Fig. 1. Pakistan's serious difficulties in funding large energy projects is due to lack of resources which, compounded with a foreign debt of ~$ 89 b against an annual budget of ~$ 45 b, is leading to a progressively worsening unemployment gap mainly due to a shrinking industry base. The GDP by sector (agriculture: 20% industry: 20%, services: 60%) has a work force of~ 61 million with an unemployment of ~6%. This workforce is mostly placed in the agriculture sector (~42%) while industry and services account for 35% and 23% respectively. The economic challenge thus translates to the establishment of industrial zones in off-grid locations. Such an endeavor would require energy in remote locations with possibly low water availability.

www.geni.org/globalenergy/library/national_energy_grid/pakistan/pakistaninationalelectricitygrid.shtml

Fig. 1. Electricity grid of Pakistan

The enormity of the energy gap, just to attain world average consumption statistics, gives an estimate of an additional 120 GW requirement. Compounded with this, is the requirement of water to Pakistan's major cities. Karachi, for example, classified as a mega-city with a population of 20 million has a requirement of 20 GW while only ~2.3 GW are presently supplied. Similarly the water requirement is 1778 million gallons per day while the supply is a mere 36% of the requirement. Thus, water desalination is an urgent requirement for the country at present as well as for the foreseeable future.

CONCLUSIONS

The technology of SMRs makes them easier for deployment and suitable for a more diverse range of applications than large NPPs. However, evidence is hard to present on a global level to support their market acceptance and indeed they carry the questions of spent fuel waste management and proliferation concerns. Clearly, at the moment the nuclear industry is neither posed for a "renaissance" nor for a revolutionary replacement of large NPPs by SMRs. That said, they still offer the advantages of suitability to small grids and financial affordability which can become over-riding factors to favor their deployment.

It is these factors, in the environment of developing countries, which could make SMRs a "first choice" out of all modern technologies. Present oil-rich countries like Saudi Arabia, mindful of the consequences and possibility of a post-oil production wealth, would eagerly commit huge financial resources towards acquiring SMRs and the technology with the hope that knowledge too would be acquired. Thus, 'big' markets, of the sort that major international vendors would find attractive, are available in developing countries. It is however uncertain whether political considerations, based on concerns of security during deployment and the spread of nuclear technology, would influence a decision of not to participate in such an undertaking. Pakistan's SMRs are in operation and have integrated well into the national grid. With CPEC and the opening of a major trade corridor linking the Gwadar port to China, Central Asia and beyond, the availability of energy especially to off-grid populations is bound to create a new economic environment with a potential to significantly uplift the overall prosperity.

With factors specific to developing countries, SMRs are a viable option and offer the potential for boosting economic development not just restricted to urban centers but widely spread to remote locations which would otherwise remain deprived of the modern amenities of life such as health facilities, access to education, and opportunities for industrial development.

Nomenclature

CCGT	=Combined Cycle Gas Turbine
CHASNUPP	=Chashma Nuclear Power Plant
CNNC	=China National Nuclear Company
CPEC	=China Pakistan Economic Corridor
EPZ	=Emergency Planning Zone
HEU	=Highly Enriched Uranium
IAEA	=International Atomic Energy Agency
IRR	-Internal Rate of Return
KANUPP	=Karachi Nuclear Power Plant
LEU	=Low Enriched Uranium
MTR	=Materials Test Reactor
NPP	=Nuclear Power Plant
NPV	=Net Present Value
PAEC	=Pakistan Atomic Energy Commission
PARR	=Pakistan Atomic Research Reactor

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