Small Modular Reactors (SMRs) - A Future Nuclear Power Option

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Abstract

Pakistan is facing energy deficiency for the last three decades, to overcome this deficiency Pakistan plans to expand its nuclear energy sector on large scale. The Small Modular Reactors (SMRs) is a futuristic technology and considered to be the game changer in decade to come. It will help to overcome the deficiencies of nuclear power production while bringing the initial capital cost down. The SMRs technology can help to overcome many problems such as the financial requirement by lowering initial cost investment, beside this usage of very less space, easily transportable, easy increment in power capacity, with more safety and security and ease of dismantling with less cost after completion of life span. The article discusses the energy scenario of Pakistan, mentioning nuclear energy as a solution, the benefits of SMRs technology, development and deployment stages of various type of SMRs under construction worldwide, their advantages and benefits.

Keywords

Nuclear Energy, Nuclear Power Plants, Small Modular Reactors

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Introduction

Pakistan is a medium sized country with an area of 307,374 square miles and a population of over 210 million according to the provisional available data of the sixth population census enumeration of 2017.[1] Almost 50% of Pakistanis live in urban and semi-urban centres and more than 25% of people, roughly 6.3 million, are estimated to be in middle-income group earning over $11-12 per day. The World Economic Forum (WEF) study ranks Pakistan's economy on 52nd position among the world's emerging economies ahead of India which is ranked 62nd by the WEF.[2]

Being ahead of its arch rival, India, among the emerging world economies, should only be a small consolation for Pakistan as a large proportion of its population is still below the poverty line earning less than two dollars a day. This segment of population, have insufficient or no health coverage, no access to clean drinking water and almost 22.6 million children in the country are out of school. Additionally, according to some reports, over 140 million Pakistanis do not have access to the necessity like electricity or have to endure long hours of electricity outages during summers.[3]

Non-availability of electricity particularly in the industrial sector not only has affected industrial output and exports but also resulted in job losses resulting in increased poverty because of curtailment of new employment opportunities. The situation can be retrieved by sustained high economic growth for at least two decades. Fortunately, Pakistan has the potential to achieve it, as it has done so in the past. The country had recorded rapid industrialization in 1960s when cheap electricity became available to the industry from the newly constructed hydro-electric power plants. The momentum of growth however could not be maintained subsequently owing to external geopolitical environment and domestic factors, though high GDP growth was achieved for a few years in 1980s and from 2002-2007 as well. A former finance minister, Dr. Salman Shah, believes that the country has the potential and can be among ten biggest world economies by pursuing prudent policies and implementing economic reforms.[4]

Besides other factors, two major hurdles that have impeded Pakistan’s economic growth at a faster pace are its security problems, both internal and external due to geopolitical situation, and non-availability of cheap energy for the country’s industrial sector as mentioned before.

This paper aims to discuss Pakistan’s energy challenges and why Nuclear Power and Small Modular Reactors (SMR) could be a feasible option for meeting Pakistan’s future energy and security needs. SMRs are the latest technology that can overcome the existing hurdles in the way of nuclear power generation.

Pakistan Electricity Supply and Demand Scenario

Pakistan did not have energy sufficiency at the time of independence in August 1947. It is still struggling to meet its growing electricity demands even 70 years later as sufficient efforts are not directed to achieve self-sufficiency in this sector which is vital for this economy and country's social sector development. The country produced only 60MWe of electricity from a small hydro-electric dam built in the north of the country and a few small thermal power plants in some urban centres. Thermal plants operated only for few hours at night. The country has come a long way since then and adopted different methods to produce electricity. It now has an installed capacity of 29,573MWe.[5] Meanwhile, demand for electricity has also increased manifold. It now stands at 123,188GWh. The gap between the supply and demand increases to 12 hours during the peak summer month when the temperature rises to almost 48 to 50 degrees Celsius.

Table 1: Electricity Consumption by Sector (Public Utilities Only) Unit: GWh TOE

Sector	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	ACGR
Domestic	35,589 2,898,379	36,116 2,941,308	39,549 3,220,860	41,450 3,375,647	44,486 3,622,967	48,698 3,965,972	6.5%
Commercial	5,754 468,612	6,007 489,207	6,375 519,195	6,512 530,331	7,181 584,855	7,856 639,808	6.4%
Industrial	21,801 1,775,501	22,313 1,817,171	24,356 1,983,592	24,979 2,034,309	25,035 2,038,889	24,010 1,955,361	1.9%
Agriculture	8,548 696,122	7,697 626,827	8,290 675,099	8,033 654,221	8,526 694,395	9,221 750,993	1.5%
Street Light	478 38,888	457 37,231	458 37,274	441 35,925	459 27,410	484 39,4301	0.3%
Traction	81						
Bulk Supplies	4,502 366,676	4,137 336,931	4,313 351,271	4,334 352,929	4,666 379,990	5,018 408,662	2.2%
Other Govt.	88 7,161	61 4,999	68 5,503	69 5,648	76 6,197	242 19,714	22.5%
Total: GWh TOE	76,761 6,251,421	76,789 6,253,675	83,409 6,792,794	85,818 6,989,011	90,431 7,364,702	95,530 7,779,939	4.5%
Annual growth rate	-0.44%	0.04%	8.62%	2.89%	5.38%	5.64%	

Source: Pakistan Energy Outlook, Ministry of Energy (Petroleum Division), HDIP

Electricity Installed Capacity as on June 30th, 2017

Type/Power Station	**2017**
A. Hydel (WAPDA)	7,129
B.1 Thermal (WAPDA)	5,688
B.2 Thermal (K-Electric)	2,295
B.3 Thermal (IPPs)	12,505
C. Nuclear	1,335
Renewables	1,237
Grand Total	30,178

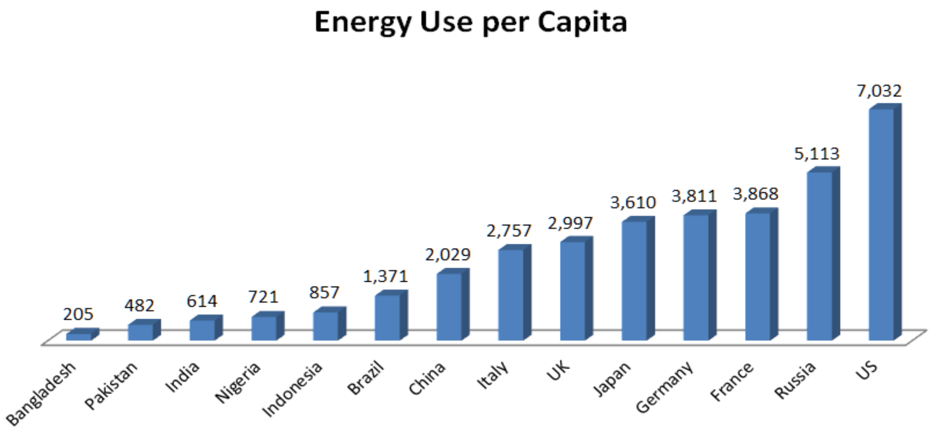
Source: Pakistan Energy Outlook, Ministry of Energy (Petroleum Division), HDIP

Pakistan's Energy Vision-2035, prepared in 2014, aims to add substantial quantum of electricity produced from diverse sources including hydro, coal, nuclear, solar and wind projects.[6] According to Ahsan Iqbal, the then Planning Minister, a total of 2500 to 3000MWs electricity was to be added to the national grid by May 2018[7].

Per Capita Consumption of electricity of a country is considered an indicator of its economic strength. Pakistan's per capita consumption of electricity is one of the lowest in the world.[8]

Pakistan's energy use per capita in 2011 stands at 482 in comparison to other countries, the highest per capita use being that of the US.[9]

Even after completion of planned electricity projects, if completed in time, which is seldom, country's per capita consumption will only increase by a small margin. The country, therefore need to continuously direct efforts to increase electricity supply. With a population growth recorded at 1.89% in 2016 and with a developing economy, Pakistan will require many new electricity projects for years to come before the supply situation equals the per capita consumption of the developed economies.



Source: ("Energy use per capita", *The World Bank*), 2011

The supply of additional electricity to the national grid would certainly be an important contributor to the country's socio-economic growth but the cost at which it is available to the consumers, particularly to the industry, is equally important. Expensive energy becomes a hindrance in industrial growth. Pakistan's industrial sector has suffered because of high cost of electricity, in the last decade or so. Electricity provided to the industrial consumers during this period was at a higher rate than its regional competitors. Resultantly, a large number of Pakistani industries were either closed or shifted their businesses to countries where cheaper and assured electricity supply was available. Pakistan's economic managers are therefore giving now particular importance to this aspect in order to incentivise industrial growth in the country.

The energy shortage faced by Pakistan is alarming and growing day by day and resulting in serious challenges such as load shedding of electric power, water shortage, low agriculture productivity, food shortage and food security etc. Pakistan's energy mix at present is 46% Oil & Coal, 19% hydel, 28% gas, 5.1% nuclear and 1-2% renewable. Pakistan beside increasing production of energy is facing two other problems, one of energy distribution and second of energy theft and line losses as the national grid is neither sufficient nor efficient.

Role of SMRs in Pakistan Nuclear Energy Scenario

Pakistan has an installed electricity generation capacity of 22,797MW. The average demand is over 20,000 MW and production between 15,000 and 16,000 MW,[10] with the shortfall lying between 4,000 and 5,000 MW.[11] Thermally produced energy, i.e. that produced from natural resources, most importantly oil, coal and gas constitutes about 74% of the energy production sources in Pakistan, while nuclear power as a source for energy production constitutes only 5.1 %.[12] Hence, nuclear power can potentially play a bigger role in the energy production in Pakistan to meet the country's needs.

Pakistan has a Nuclear Power Production Capacity of about 1335MWe[13] and the government is trying to increase it with the help of Chinese Government. The Pakistan Civil Nuclear program was slow for two reasons; first Pakistan is restrained from the trade of Nuclear Power Plant material as it is not a member of Nuclear Supplier Group(NSG) and second large initial capital cost required for Nuclear Power Plants(NPPs). Which Pakistan can not afford the development of SMRs technology would be of great importance to Pakistan, as it is trying to increase its capacity of producing nuclear energy and the target set by Planning Development & Reforms, Planning commission, Government of Pakistan is 8800 MWe by 2030 and 40,000 MWe by 2050 from nuclear sources. Recently the share of nuclear energy in Pakistan has increased from 3.6% to 5.1% in January 2017 by addition of C-3 and C-4 the two of 340 MWe reactors at Chashma. Pakistan is working to increase its nuclear energy share in the overall energy mix upto 16%, about the same as of the developed countries. The other two reactors Hualang-1PWR, each of 1100 MWe KANUPP-2 and KANUPP-3 are under construction at Karachi. But it is getting very difficult economically to build these two and the other proposed NPPs in the future to achieve the targets set for 2030 and 2047 or 2050 because of the high cost of such plants. Beside that ageing and dismantling of existing power plants will need to be funded in due course.

Keeping the economic situation in view the next big step in nuclear energy may be to adopt the technology of the "small modular reactors" (SMRs). Promoters of SMRs, argue that their smaller size will lower construction and initial costs, thus overcoming one significant barrier of building new reactors. They further maintain that cost savings can be achieved through mass production of modular components.

Small Modular Reactors (SMRs)

According to International Atomic Energy Agency (IAEA) definition the SMRs are called small as they generate less than 300MWe of electric power, which is about 30% of the generation capacity of currently available commercial nuclear power reactors.[14] Their importance for power generation was first confirmed in 1991. Besides that, a sub-category of 15MWe are defined as very small Modular Reactors (vSMRs). They are also in the research and development stage. Smaller nuclear reactors have however been in use for decades for research and power generation, but these designs lacked modular features; they were designated as small and medium reactors but not characterized as modular. Modular refers to the concept that the units would be small enough to be manufactured in the factories and transported to the reactor sites, thus saving construction on site time.

Subsequently the generation capacity of the plant can be enhanced any time by adding additional units.

SMR Designs under Consideration

Currently several types of designs of infrastructure, generators, turbines, fuel storages are under consideration in several countries to overcome the high cost. Their common characteristic however remains their small size and the simplicity of design. At present about 20 small modular reactors are at design stage in China, Canada, Russia, UK, USA and *World Association of Nuclear Operators* (*WANO*), IAEA published a report on small modular reactors, in 2006, which discusses the designs of 13 water cooled, 6 gas cooled, 6 liquid metal cooled and conventional high temperature reactor designs.[15]

SMR designs currently under consideration will be as compact as 16 meters high and 4 meters in diameter. Its size would be 40,000m^2 as compared to 400,000m^2 of a conventionally designed nuclear power plant, which would be just one-tenth of the size of a typical large scale reactor. It will take almost 5 years from start of construction to the generation of the electricity and will have a life span of about 60 years. SMRs can be transported in a truck or by train.

China National Nuclear Corporation (CNNC) engineers and scientists are working on designs of floating NPPS, which can be installed on aircrafts as well. CNNC has already designed a reactor named Ling Long or Nimble Gragon having floating design features. China has also shown willingness to cooperate and share its expertise and designs with other countries which are yet in initial stages of SMR research. Talks are in progress with several countries including Pakistan, Iran, Britain, Indonesia Mongolia, Brazil, Egypt and Canada as potential partners.

United Kingdom has recently taken a policy decision to adopt SMR technology and to replace the older nuclear power plants with SMRs when the older plants have completed their life and are decommissioned. It is presently engaged in evaluating the prospect with vendors like Rolls Royce, NuScale, Hitachi and Westinghouse.[16] It is expected that the Small Modular Reactors are going to deliver electricity at a cost of 60 pounds/megawatt hour almost same as that of wind i.e. 58 pounds/megawatt hour.[17]

American vendors are also working on the development of SMRs and other advanced nuclear reactor designs. Several other countries are also pursuing this technology, with around 50 SMR designs being under consideration worldwide according to IAEA.[18] The first three SMRs are expected to begin commercial operation in Argentina, China and Russia between 2018-2020.[19]

IAEA is continuously helping and providing cooperation and collaboration in the design and development of small modular reactors. IAEA in this regard has formed a Technical Working Group (TWG) to share information on SMRs design. Many designs are in various development stages and some are very near to deployment in different countries.

Argentina is working on CAREM-25 prototype reactor which involves technical-engineering solutions and several innovative design features resulting in a highly cost effective and safe reactor. It is being built by the Argentine National Atomic Energy Commission (CNEA), with considerable input from INVAP. It is an early design first announced in 1984 with 27MWe gross integral pressurized water reactor (PWR). It has 12 steam generators within the pressure vessel and is designed to be used for electricity generation, as a research reactor, or for water desalination with 8MWe in cogeneration configuration. The IAEA lists it as a research reactor under construction since April 2013, though first concrete was poured in February 2014. CAREM has its entire primary coolant system within the reactor pressure vessel which is 11m high, 3.5m in diameter, with axial coolant pumps driven electrically. Fuel is standard 3.1 or 3.4% enriched PWR in hexagonal fuel assemblies, with burnable poison, and is refueled annually.

The Chinese SMRs under construction is HTR-PM. It was approved in principle in November 2005 but the preparation for first concrete began in mid-2011 and full construction started in December 2012. It is also based on the German HTR-Module design originally envisaged as a single 200MWe unit. It will now have twin reactors, each of 250MWe driving a single 210MWe steam turbine. Each reactor has a single steam generator with 19 elements and 665 tubes. Fuel pebbles are 60 mm in diameter which are 8.5% enriched. Core outlet temperature will be 750ºC for the helium, steam temperature will be 566°C and core inlet temperature will be 250°C, with a thermal efficiency of 40%. Core height is 11 meters, diameter 3 m in a 25 m high and a 5.7 m diameter reactor vessel. There are two independent reactivity control systems: the primary one consists of 24 control rods in the side graphite reflector, the secondary one of six channels for small absorber spheres falling by gravity. Pebbles are released into the top of the core one by one without shutting the reactor and are removed from the bottom. Broken ones are separated, the burn-up is measured, and spent fuel elements are screened out and transferred to storage. Fuel pebbles in the plant were loaded in September 2017 and start-up is expected in 2018. Plant operating lifetime is envisaged as 40 years with 85% load factor.

The other Chinese SMRs under construction by China Nuclear Group are two small ACPR100 and ACPR50S designs, both with passive cooling for decay heat features and 60-year life. Both have standard type fuel assemblies and fuel enriched to <5%, giving 30-month refueling time. ACPR100 is an integral PWR, 450MWe, 140MWe, having 69 fuel assemblies. Reactor pressure vessel is

17m high and 4.4 m inside diameter, operating at 310°C. It has a modular feature which can be added to enhance plant capacity. The reactor would be installed underground. The off shore ACPR50S is 60MWe with 37 fuel assemblies and four external steam generators. Reactor pressure vessel is 7.4m high and 2.5 m inside diameter, operating at 310°C. It is designed for mounting on a barge as floating nuclear power plant (FNPP).

The Russians are also working on two designs; one is KLT-40S from OKBM Afrikantov which is derived from the KLT-40 reactor. It has proved its usefulness in icebreakers ships. With low-enriched fuel – it is proposed for wider use in desalination plants and, on barges, for remote area power supply. Burn-up is 45 GWd/t. Units are designed to run for 3-4 years between refueling with on-board refueling capability and used fuel storage. All fuel assemblies are replaced in each refueling. At the end of a 12-year operating cycle the whole plant is taken to a central facility for overhaul and storage of used fuel. Operating plant lifetime is 40 years. The reactor core is normally cooled by forced circulation (four-loop), the design relies on convection for emergency cooling. Fuel is Uranium Aluminum Silicide with enrichment levels of up to 20%. The plant is now expected to be completed in late 2018 and will become operational in 2019.

OKBM Afrikantov is also developing another compact icebreaker reactor – RITM-200 – to replace the KLT reactors and to function in floating nuclear power plants. This is an integral 175MWe PWR (also quoted at 210MWe, 55MWe) with four coolant loops and external main circulation pumps. It has inherent safety features, using low-enriched (<20%) fuel in 199 fuel assemblies. Refueling is every seven years at 65% capacity factor, over a 40-year total operating lifespan. It is designed to provide 30MW shaft power for an icebreaker, and the LK-60 design will be powered by two of them.

Proliferation Risks and Safety Features of SMRs

IAEA, in various reports, has discussed safety features, economic feasibility and proliferation issues pertaining to SMRs. The proliferation risk increases in case of deployment of small modular reactors as they are likely to be installed at remote locations and in countries which have not had experience of handling nuclear power plants. Even smaller reactors use significant amount of nuclear fuel. To safeguard against nuclear fuel theft and proliferation issues, SMRs will be so designed that the proliferation risks are minimized. Proliferation issues are, therefore, being catered for in SMR designs.

A few features covering these risks are discussed here:

a) SMRs are being developed with longer core lives. This would mean that fuel once loaded will be accessed less frequently than a conventional nuclear reactor which will enhance fuel safety. Other designs will not have permanent fuel handling equipment available on site, thus reducing the chances of unauthorized access to nuclear fuel.
b) Some SMR designs are characterized by longer core life time and higher burn up. With higher burn up, the usefulness of the leftover fuel for weapons is reduced, rendering it less suitable for making weapons.
c) In the new technology of SMRs with the above mentioned features (a) and (b) the fuel is less than 20% enriched and the burnup is maximum, second a fuel change is required after 30 years or loaded for a life time makes the fuel management, waste management and storage easy.
d) Digital integrated circuits may be featured in some designs to ensure monitoring of the complete fuel cycle. Digital integrated circuits are being developed for sealed reactors. Fuel will be sealed in the reactors by the manufacturers, in certain designs, ensuring safer supplying to the users. It will

only be unsealed again by the manufacturers when the fuel is to be replaced.

Economic and Security Implications

The initial cost of production of the first-of-a-kind (FOAK) SMR is projected to be 30 percent more than that of large, next-of-a-kind (NOAK) reactors[20] in some studies, and 15-55 percent more in other estimates[21] . The cost is likely to reduce only with serial production as a result of "learning" that would occur in a "controlled, efficient and productive factory environment,"[22] with the process of serial production aimed at optimizing the design of the SMR. It is estimated that not less than 10 SMRs would have to be produced in a production unit annually, in order to achieve cost reduction and improvements in design. However, the levelized cost of production (LUEC) or cost of generating electricity per unit by SMRs is projected to be higher (as compared to large power plants) in some studies, and lower in others, depending on the design of the SMR and demand for energy.[23] In a case scenario where the capacity requirement would be 1-2 gigawatts of energy, the LUEC could be reduced to upto 10-25%.[24] Moreover, although the production time of SMRs is less than that of large nuclear power plants, serial production would depend on demand. Unless sufficient demand exists, SMRs cannot be manufactured serially.

The cost of SMRs depend on many factors such as capital cost, operating and maintenance cost, fuel cost and decommissioning cost. Initially the factory fabrication will be much cheaper than site fabrication and beside that putting multiple units will bring it further down (expected 20% cheaper), beside that fuel used is about 20% or less enriched which also contributes to bringing the cost down. Third the operation and maintenance cost is also calculated 15-20% less than the cost of larger reactors and the decommissioning cost is also estimated to be about 15% less[25]. All these factors along with large scale factory production will bring cost down to consider SMRs as potential replacement of small and medium size fossil fuel plants on completion of life cycle[26].

In order to be able to play their role effectively, armed forces in the contemporary era have become increasingly more dependent on reliable supply of energy. CNA Military Advisory Board in its 2017 report stated, "The strength of a nation's economy underpins its trade and diplomacy and enables it to maintain a military robust enough to protect national interests."[27] Besides state's security, non-traditional security factors are being included in the security policies of states. National security strategy of countries in future would focus on traditional state-centric security and non-traditional security whose focus is on human security. The latter aims at strengthening a nation's human resource which, in indirect and subtle ways, contributes to the security of a state.

SMRs can help address security issues faced by a country like Pakistan in a number of ways. Pakistan, being an energy starved country, can benefit from this technology by installing SMRs on military bases located in remote areas where supply of electricity from national grid is not possible or may be difficult or expensive. Similarly, in mountainous northern regions of the country and sparsely populated areas of Balochistan where laying transmission lines from the national grid to the consumer centers may pose financial and technical difficulties in this situation, SMRs can ensure uninterrupted supply of electricity.

Conclusion

Shortage of energy has impeded Pakistan's economic and social development for several decades and affected its citizens' lives in multiple ways. Successive governments have struggled to overcome this problem. The Vision-2025 was chalked out in 2014 by the then government in power. The Vision expects to achieve electricity generation capacity of 42,000MWe by 2025. Several projects are presently in different phases of completion. These include hydro-electricity dams, coal and gas fired thermal projects and commercial nuclear projects, K-2 and K-3 being constructed with China's help near Karachi.

Besides shortage of electricity, cost of available electricity has been a problem for the country. The cost had increased as the generation mix is 67 percent is thermal, most of which is produced from expensive imported fuel. Pakistan, therefore, is planning to produce electricity at lower rates. This can be achieved by reducing dependence on imported fuel for operating generation plants. The vision-2025 also aims at reduction of electricity production cost to half of the rate of presently available. Planners are working on several options to achieve it.

One of the options can be installation of Small Modular Reactors. Pakistani nuclear scientists and engineers have had a long experience of handling and maintaining nuclear power plants. Some of them have also been part of the teams that have installed these plants in the country. Pakistani engineers successfully upgraded and extended the life span of CANDU-PHWR (K-1), a 137 MWe power plant, whose life was to expire in 2002.

Light Water Small Modular Reactors is most promising technology for Pakistan as it is easy to adopt and Pakistan has along experience of operating PWR Light Water Reactors There is no chance of misuse of nuclear fuel as the plants will operate under the IAEA safeguards.

Pakistan having a large and competent workforce of nuclear engineers and scientists, now has initiated steps to explore the feasibility of installing SMRs for electricity generation. SMRs could be a suitable option for a country like Pakistan to meet its growing electricity needs. Chinese are reportedly willing to share this technology with other states. Given the excellent relations China and Pakistan enjoy, Pakistan could benefit from the Chinese expertise in overcoming its perennial electricity shortages.

End Notes

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