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Article

Small Modular Reactors for Enhancing Energy Security in Developing Countries

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Abstract: In recent years, small modular reactors (SMRs) have been attracting considerable attention around the world. SMR designs incorporate innovative approaches to achieve simplicity, modularity and speed of build, passive safety features, proliferation resistance, and reduced financial risk. The incremental capacity expansion associated with SMR deployment could provide a better match (than the large-scale reactors) to the limited grid capacity of many developing countries. Because of their lower capital requirements, SMRs could also effectively address the energy needs of small developing countries with limited financial resources. Although SMRs can have substantially higher specific capital costs as compared to large-scale reactors, they may nevertheless enjoy significant economic benefits due to shorter build times, accelerated learning effects and co-siting economies, temporal and sizing flexibility of deployment, and design simplification.

Keywords: nuclear power; small modular reactors; nuclear safety

1. Introduction

Increasing concerns related to energy supply security and widespread perceptions about the urgency of mitigating climate change are generating significant tensions in the global energy policy framework. A consensus is emerging on the need for: (i) a much longer term view of policy than that envisaged in the traditional debate about electricity restructuring, privatization, and deregulation; (ii) increased reliance on low-carbon generating technologies; and (ii) technological diversification.

According to the International Energy Agency (IEA), world primary energy demand in the Reference Scenario (in which government policies are assumed to remain unchanged), is projected to increase from 12,150 million tonnes of oil equivalent (Mtoe) in 2009 to 18,300 Mtoe in 2035, an increase of over 50 percent. Global electricity demand is projected to nearly double from 20,000 terawatt-hours (TWh) in 2009 to 39,400 TWh in 2035. More than 80 percent of the increased energy demand will come from developing countries, led by China and India. To meet these needs, the world's electricity generating capacity will have to double from about 4950 gigawatts in 2009 to 9150 gigawatts in 2035. In 2009, coal-fired generation accounted for 41 percent of world electricity supply; in 2035, its share is projected to rise to 43 percent. Coal is the most carbon-intensive of the fossil fuels—a 1 gigawatt coal-fired plant emits approximately 10 million tons of CO_2 a year. Without specific policies to limit greenhouse gas emissions, energy-related CO_2 emissions would rise from 30.2 billion tons in 2008 to 43.2 billion tons in 2035. During the same period, coal's share of CO_2 emissions is projected to rise from 43 to 45 percent—a scenario which, in the face of increasing concerns about climate change, could be deemed environmentally unsustainable [1,2].

As evidence mounts on global warming, pressures for curtailing carbon dioxide emissions from coal-fired electricity generation will escalate sharply. This gives rise to one of the central challenges in global energy policy: how to secure in the context of a carbon-constrained world, with coal and to a lesser extent natural gas (potentially) being limited in their future growth by restrictions on CO_2 emissions, the energy sources that will provide the estimated additional 4200 gigawatts of new electricity generation capacity the world is likely to demand by 2035. Since the bulk of that additional capacity will be needed in the developing world, whether and how this challenge is to be met is a dilemma of unprecedented complexity and magnitude. Failure to meet the increasing energy requirements of developing countries will exacerbate the already unacceptably high levels of energy poverty in many of these countries and stunt global economic growth. Moreover, given that most of this projected increase in demand will come from developing countries, any international agreement to slash greenhouse gas emissions from fossil fuels will affect their growth prospects—with serious implications for sustainable economic development.

Most recent research suggests that there is no obvious "silver bullet" for addressing the global energy challenge. The solution will be comprised of a variety of technologies on both the supply and demand side of the energy system. In the face of significant technological and market risks and uncertainties, prudence calls for technological diversification. A broad portfolio of technologies and energy sources needs to be considered and developed as part of a general strategy to confront the growing energy problems of both developed and developing countries. We simply do not have the luxury for excluding any option.

All energy sources and electricity generation technologies have benefits and drawbacks. Fossil fuels, particularly coal and natural gas, will remain important. Under the New Policies Scenario (NPS), fossil fuels are expected to still account for over 55 percent of electricity generated by 2035 (the NPS incorporates the broad policy commitments and plans that have been announced by countries around the world to tackle energy insecurity, climate change and local pollution, and other pressing energy-related challenges, even where the specific measures to implement these commitments have yet to be announced). However, their contributions to meeting the huge growth in electricity demand will have to be continuously reassessed in an increasingly carbon-constrained world. Renewable sources, by contrast, are abundant and produce little or no greenhouse gases. But renewable technologies typically provide intermittent rather than baseload electricity supply and are currently available only on a small scale—in 2009, they accounted for just 2 percent of electricity generated. Technological developments offer considerable promise for cost-effective scaling up of renewable sources. Still, it is not clear how rapidly non-hydroelectric renewables will become cost-competitive for large-scale production and thus they could continue to play only a limited role—under the NPS they are projected to account for 15 percent of total electricity generated by 2035 [2]. Widespread blackouts, melting glaciers, stronger hurricanes, and rising temperatures, on the other hand, could create a sense of unprecedented urgency—demanding rapid policy responses. Under those circumstances the scope for relying on the promises of visionary energy sources might narrow considerably.

Although nuclear fission represents a well-established technology for baseload electricity generation with very low CO_2 emissions, it has long been viewed as an unattractive option by environmental groups and ordinary citizens alike. These unfavorable public attitudes emanate from deeply-rooted apprehension about the potential hazard of reactor meltdown with catastrophic ecological and humanitarian consequences, the unresolved issues of nuclear waste disposal, and the potential problems of fissile material diversion and proliferation. The very word nuclear strikes fear into the hearts of many people. These fears have been exacerbated by the catastrophic events in Japan in March 2011.

For nuclear power to play a major role in meeting the future global energy needs and mitigating the threat of climate change, the hazards of another Fukushima and the construction delays and costs escalation that have plagued the nuclear industry during the past three decades have to be substantially reduced. The technical complexity, management challenges, and inherent risks of failure posed by the construction of new nuclear plants have been amplified considerably as their size increased to the gigawatt scale and beyond. And so have the financing challenges [3].

One potential solution might be to downsize nuclear plants from the gigawatt scale to smaller and less-complex units. New generations of nuclear reactors are now in various stages of planning and development promising enhanced safety, improved economics, and simpler designs. Small modular reactors (SMRs) are scalable nuclear power plant designs that promise to reduce investment risks through incremental capacity expansion, become more standardized and lead to cost reductions through accelerated learning effects, and address concerns about catastrophic events since they contain substantially smaller radioactive inventory.

The power grids in many developing countries that could consider nuclear power are not large enough to support deployment of very large units. Moreover, large nuclear plants entail massive fixed (largely construction) costs that are mostly sunk. In increasingly liberalized electricity markets, investors who must bear the bulk of the construction and other performance risks will favor less capital-intensive and shorter construction lead-time investments [4]. There are also some early signs of a potential paradigm shift in electricity markets, away from the large, centralized power stations and towards more decentralized, distributive generation systems that reduce the need for expensive regional or national electricity grids. New nuclear designs may be necessary to adapt to these changing commercial and social requirements. Thus, there may be considerable scope for SMRs which would permit a more incremental investment than the large units of the past and provide a better match to the limited grid capacity of many developing countries. SMRs could provide an attractive and affordable nuclear power option for many developing countries with small electricity markets, insufficient grid capacity, and limited financial resources. They may also be particularly suitable for non-electrical applications such as desalination, process heat for industrial uses and district heating, and hydrogen production. Moreover, multi-module power plants with SMRs may allow for more flexible generation profiles. Overall, SMRs could offer significant advantages in terms overall simplicity, modularity and speed of build, passive safety features, proliferation resistance, and reduced financial risk.

2. Design Status of SMRs

Small modular reactors can be classified according to the reactor technology and coolant. They include [5]:

- **Pressurized water reactors (PWRs).** Designs based on light water reactor technologies are similar to most of today's large pressurized water reactors and as such they have the lowest technological risk. Several are considered to be very close to commercial deployment. Still these designs incorporate innovative technologies and novel components to achieve simplicity, improved operational performance, and enhanced safety. They are typically less than 300 MW(e) and could be used to replace older fossil-fired power stations of similar size.
- **Gas cooled reactors (mostly high-temperature gas-cooled reactors (HTGRs)).** These designs provide broad flexibility in application and in the utilization of the fuel. One of the key advantages of HTGRs is the high outlet coolant temperatures compared to conventional reactors. Core outlet temperatures can range from around 650 °C to 1000 °C for very advanced reactors—these high operating temperatures allow for greater thermal efficiencies. The HTGR can be used with either steam cycle or gas turbine generating equipment, and as a source of high temperature process heat. High reactor outlet temperatures can also drive endothermic reactions to produce hydrogen. Fuel cycle options include: (i) low enrichment, where enriched uranium fuel is burned and Pu is recycled; (ii) Th-233, where enriched uranium and Th is burned and U-233 (and U-235) is recycled; (iii) Pu utilization in Th -U-233, where Pu and Th fuel is burned and Pu and U-233 is recycled [6].
- **Sodium-cooled fast reactors (SFRs).** The SFR design features a fast-spectrum, sodium-cooled reactor and a closed fuel cycle. It is designed for efficient management of high-level wastes—in particular the management of plutonium and other actinides. The reactor's key safety features include a long thermal response time, increased margin to coolant boiling, a primary system that operates near atmospheric pressure, and an intermediate sodium system between the radioactive sodium in the primary system and the water and steam in the power plant.
- **Lead and Lead-bismuth cooled fast reactors (LFRs).** The LFR design features a fast-spectrum lead or lead/bismuth eutectic liquid-metal-cooled reactor and a closed fuel cycle. Since it operates in the fast-neutron spectrum, it has has excellent materials management capabilities. The LFR can also be used as a burner to consume actinides from spent LWR fuel and as a burner/breeder with thorium matrices. An important feature of this design is the enhanced safety that results from the choice of molten lead as a relatively inert coolant. It does not react

with water or air exothermically and, therefore, the reactor needs no intermediate heat transport system. In terms of sustainability, lead is abundant and hence available, even in case of deployment of a large number of reactors. More importantly, as with other fast systems, fuel sustainability is greatly enhanced by the conversion capabilities of the LFR fuel cycle.

More than two dozen SMR concepts have been developed or analyzed worldwide during the past decade [7,8]. Several of these concepts have progressed to advanced design and licensing stages, and are near commercial as evidenced by established partnerships with the industry and on-going interactions with national regulatory authorities. All in all, these SMRs have a reasonable chance of being deployed, as a prototype or under a pilot plan, by 2020. In addition to the steadily progressing SMRs, there are some reactor concepts that are at very early stages of design. There is no detailed technical data available for these designs, some of which have been substantially slowed down or even stopped following the Fukushima accident.

In addition to the SMRs, there are several small and medium sized reactor designs. These represent conventional PWR or heavy water reactor (HWR) technologies. Some of these—e.g., the Indian Pressurized Heavy Water Reactors (PHWR), the Canadian CANDU6 or EC6, and Chinese QP300—have already been deployed. Finally, there are some SMR design concepts employing boling water reactor (BWR) technology, such as the Japanese CCR and IMR, or the Russian VK-300. For a variety of reasons, most importantly the Fukushima Daiichi accident, design development efforts for smaller boiling water reactors in the respective countries have either been stopped or brought to a standstill [5,9,10].

2.1. Pressurized Water Reactors

PWR are two-circuit, indirect energy conversion cycle plants. The primary coolant consists of pressurized light water. The heat generated in the reactor core is transferred to the secondary (power) circuit through steam generators. Boiling of water in the primary circuit is typically not allowed. The power circuit uses the Rankine cycle with saturated or slightly superheated steam for energy conversion [11]. PWRs account for 61 percent of the global reactor fleet and are also the design of choice among among the reactors under construction—56 out of 61 units in 2011. Table 1 summarizes the general characteristics and design status of SMRs based on PWR technologies.

The SMR design concepts presented in Table 1 can be classified into the following two groups:

- Compact modular designs based on the experience of the Russian marine propulsion reactors—KLT-40S and the VBER-300;
- SMRs with integral design of the primary circuit—all other SMRs in Table 1, except the HI-SMUR which combines the design features from both groups.

Table 1. General characteristics of small modular reactors (SMRs) (pressurized water reactors (PWRs)).

SMR name	**KLT-40S**	**ABV**	**VBER-300**	**RITM-200**	**CAREM-25**	**SMART**	**Westinghouse SMR**	**mPower**	**NuScale**	**HI-SMUR**
Company/ Country	JSC "Rosenergoatom", Russia	OKBM, Russia	JSC "Nuclear Plants", Kazakhstan, Russia	OKBM, Russia	INVAP, CNEA, Argentina	KEPCO, Republic of Korea	Westinghouse Electric, USA	Babcock & Wilcox, USA	NuScale Power Inc., USA	Holtec International, USA
Electric/ Thermal power, MW	2 × 38.5 (non-electrical applications disabled)/2 × 150	2 × 8.5/2 × 38	325/917	50/175	27/116	100/330	225/800	180/576 (per module)	45/160 (per module)	160/520
Non-electrical products	Heat for district heating: 2 × 25 GCal/hour, or	Heat for district heating: 2 × 12 GCal/hour, or	Heat for district heating: 150 GCal/hour, or	30 MW of shart power;	Potable water: 10,000 m^3/hour, as future option	Heat for district heating: 150 GCal/hour, or	No	No	Potable water or process steam, as options	
	Potable water: 20,000–100,000 m^3/day	Potable water: 20,000 m^3/day	Potable water	248 t/hour of steam at 295 °C, 3.82 MPa		Potable water: 40 000 m^3/day			No	
Plant configuration	Twin-unit for a barge-mounted NPP	Twin-unit for a barge-mounted NPP;	Single- or twin-unit land based plant;	Nuclear icebreaker reactor;	Single-unit land based plant;	Single-unit land based plant	Single-unit or twin-unit land based plant	Four-module land based plant;	Twelve-module land based plant.	Single- or multi-module plant
		Land based plant option.	Single-unit barge-mounted plant option.	NPP option to be considered.	Concentrated deployment possible.			Other NPP configurations possible.		
SMR name	KLT-40S	ABV	VBER-300	RITM-200	CAREM-25	SMART	Westinghouse SMR	mPower	NuScale	HI-SMUR
Construction period/ Refueling interval, months	48/27.6	48/288 (factory refueling)	48/24	48/84 (factory refueling)	60/11	<36/36	<36/24	36/48	36/48	Very short/>36

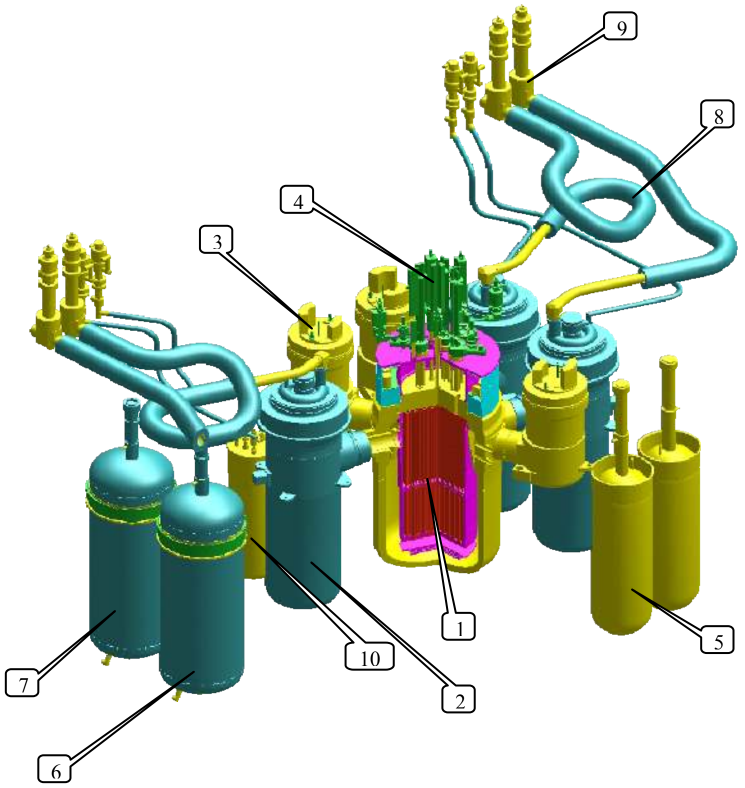
Table 1. *Cont.*

SMR name	**KLT-40S**	**ABV**	**VBER-300**	**RITM-200**	**CAREM-25**	**SMART**	**Westinghouse SMR**	**mPower**	**NuScale**	**HI-SMUR**
Design stage	Detailed design completed	Detailed design under revision for longer refueling interval	Detailed design in progress	Detailed design completed	Detailed design completed	Detailed design near completion	Conceptual design in progress	Conceptual design in progress	Detailed design in progress	Conceptual design in progress
Licensing stage	Licensed, construction being finalized	Previous design licensed	Not started	Detailed design approved by SAEC "Rosatom"	Licensing near completion	Licensing in progress	Pre-licensing negotiations/licensing initiation planned for 2012	Pre-licensing negotiations/licensing initiation planned for 2012	Pre-licensing negotiations/licensing initiation planned for 2012	Pre-licensing negotiations started in 2011
Targeted deployment date	2014	Start-up of construction: 2014 (no decision yet)	2020	2015-2015 (icebreaker)	Construction start-up: 2012; Designs for 150 and 300 MW(e) to be developed later.	2015	2018–2022	2018–2022	2018–2022	2018–2020 (target–2014)

The compact modular designs are backed by the approximately 6500 years of operating experience of the Russian marine propulsion reactors. They have steam generators, main circulation pumps and pressurizers all located in separate modules, as in conventional PWRs. However, the piping is short and there are special features incorporated to prevent or minimize potential leaks from the primary circuit. The whole primary system, including coolant purification and water chemistry systems, is very compact and is located within the primary pressure boundary (Figure 1). Thus the primary circuit design is often referred to as leak-tight [12,13].

Designs in the second group are characterized by an integral primary circuit layout in which the steam generators are located inside the reactor vessel (Figure 2). In most cases, the steam space under the top dome of the reactor vessel acts as a pressurizer. In some designs, the control rod drive mechanisms and coolant pumps are also housed inside the reactor vessel. This integral design of the primary circuit allows for the elimination of large-diameter piping and minimizes reactor vessel penetrations [11,13]. Thus it can effectively reduce the scope for loss of coolant accidents (LOCAs).

Figure 1. Layout of the KLT-40S reactor. Source: [11].



1 Reactor
2 Steam generator
3 Main circulating pump
4 CPS drives
5 ECCS accumulator

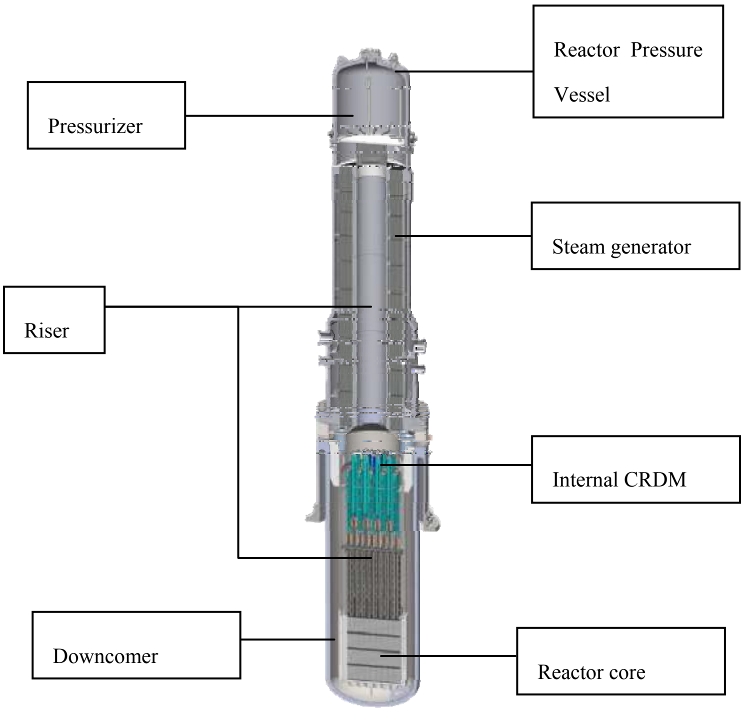
6,7 Pressurizers
8 Steam lines
9 Localizing valves
10 Heat exchanger of the purification and long term cooling system

The SMR designs that are based on light water reactor technologies (shown in Table 1) have power ratings that range from 8.5 to 300 MW(e). In many cases, the design calls for twin units or multi-module plants. There is always the option to build several units on one site, as in the case of conventional reactors. With a cluster of modules, the overall capacity of the SMR-based power station can be as high as that of a NPP with large reactors. However, the fundamental difference is that the overall SMR station capacity can be achieved in smaller increments. Except for the Russian designs, all other SMRs are being developed for land-based power plants. The reactor buildings in the Westinghouse SMR, mPower, NuScale and HI-SMUR designs are located underground [11].

Non-electrical applications, such as production of heat for district heating or seawater desalination, are included from the outset only in the Russian (KLT-40S, ABV, VBER-300) and Korean (SMART) designs. For all other SMRs, such applications are considered as an option for future NPPs. Regarding nuclear fuel, KLT-40S and ABV incorporate fuel based on uranium dioxide dispersed in the silumin (Al-Si alloy) matrix [12,13] or uranium dioxide based cermet fuel [5]. The initial enrichment is slightly below 20%. All other SMR designs in Table 1 incorporate uranium dioxide fuel with the enrichment less than 5% by ^{235}U.

Of the designs presented in Table 1, a barge-mounted plant with the two KLT-40S reactors has been licensed and is in the final stages of construction. It will be deployed in the bay area near the city of Vilyuchinsk in the Russian Far East. In 2013, the plant will be towed to its deployment place, and the plant operation is expected to be commenced the following year. CAREM-25 and SMART are currently in the licensing process. Also licensing negotiations with the US NRC have been initiated for the Westinghouse SMR, mPower and NuScale designs [14].

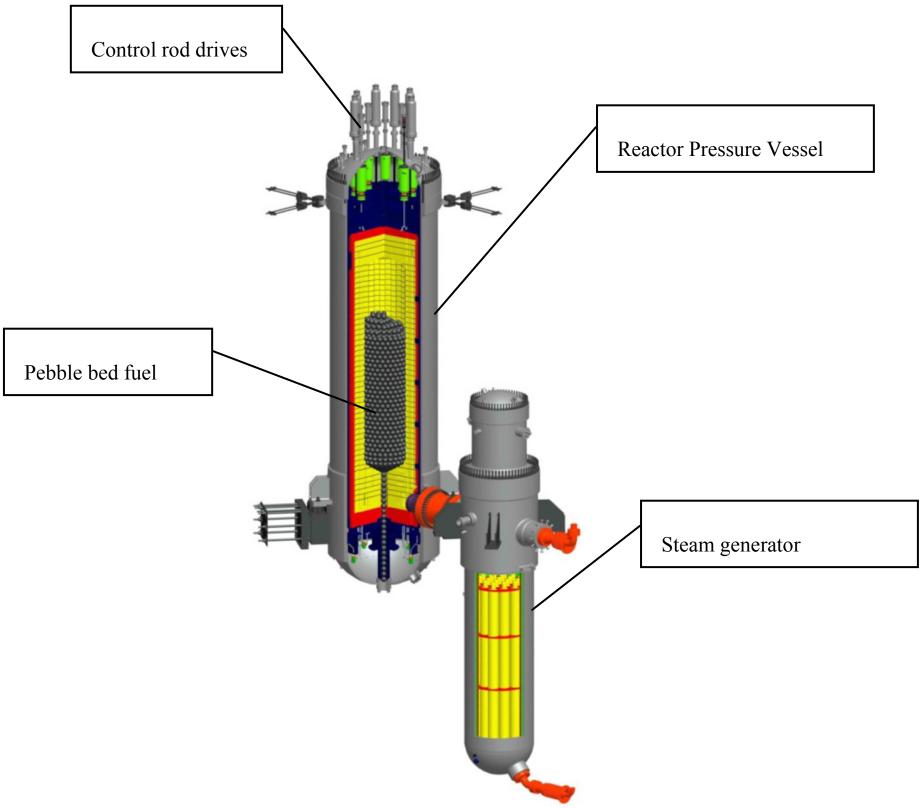
Figure 2. Layout of the mPower design with integral primary circuit. Source: [5].



2.2. Gas Cooled Reactors

Gas cooled designs are mostly related to High Temperature Gas Cooled Reactors (HTGRs). Historically, these reactors have been considered primarily for high temperature non-electrical applications, such as hydrogen production or coal gasification. For this purpose, all HTGR designs employ tri-isotropic (TRISO) fuel appearing as tiny (typically, 0.5 mm in diameter) ceramic fuel kernels with multiple ceramic coatings (typically, several pyrocarbon layers and a silicon carbide layer). TRISO fuel has a proven capability to confine fission products at high temperatures (up to 1600 °C in the long-term) and operate reliably at very high fuel burn-ups up to 120 MWday/kg [11,12,15].

Figure 3. Layout of the HTR-PM reactor module. Source: [5].



The traditional HTGR designs are employing the direct gas-turine Brayton cycle offering high energy conversion efficiency—up to 55% as compared to 32% in PWR. They incorporate provisions for multiple co-generation applications, such as hydrogen production and seawater desalination. However, deployment of these designs, which include the the Japanese GTHTR300, the Russian-U.S. GT-MHR, and the U.S. NGNP, is being anticipated within the timeframe of 2025 and beyond. One design that seems to be ready for deployment is the Chinese HTR-PM (Figure 3). The HTR-PM, uses the concept of a moveable pebble bed fuel (wherein the TRISO coated particles are embedded in graphite balls that move along the annular core in reactor operation) that is similar to that of PBMR (design development for PBMR has been stopped in 2010 owing to a financial collapse of the South African PBMR Pty). However, it employs an indirect cycle with superheated steam in the power circuit. The Rankine cycle that is being employed with multiple reheats of steam secures plant efficiency of about 42%. The HTR-PM provides for no non-electrical applications and is deemed for electricity production within a standard three module plant. It's design is backed by a decade long operation of a 10 MW(th) HTR-10 prototype at the Tsinghua University in China [5,11,12].

Table 2 summarizes the general characteristics and design status of HTR-PM. The kernels of TRISO particles in the HTR fuel contain UO2, UC and UCO. The enrichment of fuel is 8.9% by 235U [5]. The HTR-PM has been licensed for construction at the Shidaowan site in China in 2011. Should the project progress as scheduled, the pilot HTR-PM plant would be ready for operation around 2015.

In the United States, General Atomics is developing the EM^2 fast gas cooled reactor—a 240 MW(e) system designed to produce power from non-reprocessed spent fuel of conventional operating reactors. This development effort is linked to the Generation-IV program and the targeted timeframe for deployment is well beyond 2025. Few technical data are available for this design concept, although it is mentioned that to a large extent it will be based on the GT-MHR design.

Table 2. General characteristics of HTR-PM.

SMR name	**HTR-PM**
Company/Country	Huanheng Shandong Shidaowan Nuclear Power Co., China
Electric/Thermal power, MW	105.5/250 (per module)
Non-electrical products	No
Plant configuration	Standard 3-module land based plant; Pilot plant will be with 2 modules.
Construction period/Refueling interval, months	48/On-line pebble transport
Design stage	Detailed design completed
Licensing stage	License issued
Targeted deployment date	Construction start-up in 2012

2.3. Sodium Cooled Fast Reactors

Sodium has high heat capacity but reacts exothermically with air and water. For this reason all SFRs employ an intermediate heat transport system with secondary sodium as a working fluid. Primary sodium delivers heat generated in the reactor core to an intermediate heat exchanger located within the reactor vessel (pool-type reactor) or outside (loop-type reactor). Typically, older-design SFRs with small capacity are (or were) of the loop-type, while newer and higher capacity designs are (or were) pool-type. Secondary sodium delivers core heat to the steam generators that are located in a dedicated premise reasonably far from the reactor so as to localize the impacts of potential steam-sodium reactions. Indirect Rankine cycle on superheated steam is used for power conversion [11].

Table 3 provides a summary of the general characteristics and design status of SFRs. Both of the highlighted design concepts are modular pool-type reactors incorporating intermediate heat transport systems based on sodium coolant.

The PRISM design has been developed specifically for the purpose of burning the plutonium accumulated in spent fuel of the present day reactors. It is a dedicated reactor for plutonium burning, which also generates electricity. PRISM is designed to operate in a closed nuclear fuel cycle. It employs U-Pu-Zr metallic fuel with the initial plutonium content of 26%. As such, it is not being considered for deployment in countries that do not possess nuclear weapons. PRISM is designed to be a part of the advanced recycling center for spent nuclear fuel. Its design is backed by the technology and experience of the pool type EBR-II fast reactor operated at the Argonne National Laboratory between 1965 and 1994. Plans existed to build a larger capacity, pool type 1000 MW(e) EBR-III, but they never materialized [5,16].

Table 3. General characteristics of sodium-cooled fast reactors (SFRs)..

SMR name	**PRISM**	**4S**
Company/Country	GE-Hitachi, USA-Japan	Toshiba Corporation, Japan
Electric/Thermal power, MW	155/471 (per module)	10/471 (50 MW(e) option)
Non-electrical products	None	Potable water: 34,000 m^3/day (option); Hydrogen: 6.5 t/day; Process heat or steam (option).
Plant configuration	Standard 3-module plant configuration	Single-unit land based plant
Construction period/Refueling interval, months	No data/18	12, on the site/360 (whole core refueling)
Design stage	Detailed design	Preliminary design completed; Systems validation in progress.
Licensing stage	Original design licenses in 1994; Pre-licensing negotiations in progress for the updated design; Licensing application planned in 2012	Pre-licensing negotiations in progress; Licensing application planned in 2012
Targeted deployment date	Around 2020	First-of-a-kind unit after 2014

The PRISM system incorporates three reactor modules, each with its own steam generator, connected to a single turbine generator. The reactor modules are located underground while the turbine unit is located above ground. Passive air cooling is used as ultimate heat sink [5].

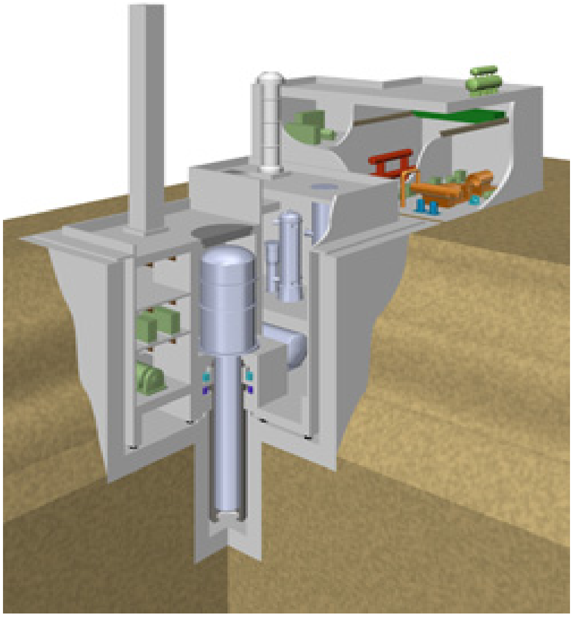
Over the past two decades, the 4S design has been developed first by CRIEPI and then by Toshiba Corporation (Figure 4). In its present version it is designed as a 10 MW(e) unit with 30 years of continuous operation without refueling. The 4S uses U-Zr alloy as fuel with initial enrichment of less than 20% of 235U by weight. A 50 MW(e) version with 10-year refueling interval is also being considered, but only at a conceptual design level [8].

4S uses passive air cooling as an ultimate heat sink. Burn-up reactivity change over a 30-year lifetime is compensated by pre-programmed upward movement of the graphite reflector. The 4S design provides for hydrogen and oxygen production by high temperature electrolysis method, and also foresees other non-electrical applications [8,11].

The 4S is at an advanced design stage and pre-licensing negotiations with the U.S. NRC have already been undertaken. Its formal licensing application was set for the second quarter of 2012. The vendor, Toshiba Corporation, is working with the city of Galena in Alaska regarding a potential 4S application as power and heat source for the city [5].

In addition to the design concepts presented in Table 3, the U.S. private company Advanced Reactors LLC has been promoting a 100 MW(e) small sodium cooled reactor with a 20 year refueling interval, named ARC-100. It is a pool type reactor with once-at-a-time core refueling on the site. The design has some similarities with the STAR family of lead cooled reactors previously developed in the USA [8]. The design concept is at pre-conceptual stage and, like the 4S, would require a long testing program in view of the adopted 20-year refueling interval.

Figure 4. Layout of the 4S plant. Source: [5].



2.4. Lead and Lead-bismuth Cooled Reactors

Lead and lead-bismuth eutectic cooled reactors could be considered together since they employ similar technologies—e.g., coolant purification and control of corrosion for both coolants are similar, although the details are different. Regarding implementation, progress has been achieved in the lead-bismuth eutectic reactors in Russia [11]. Presently, there are no lead cooled small modular reactors under development anywhere in the world, so this section is restricted to lead-bismuth SMRs [17].

Lead-bismuth eutectic is chemically inert in air and water. It has a very high boiling point of 1670 °C and a very high density enabling an effective heat removal at close-to-atmospheric gravity defined pressures. Due to its freezing point of 125 °C, it solidifies in ambient air. Thus it contributes to the effective self-curing of cracks if they ever appear in the primary lead-bismuth coolant boundary. For these reasons, a typical lead-bismuth cooled fast reactor (LBFR) design concept is that of a two-circuit indirect cycle plant. Contrary to SFRs, lead-bismuth cooled fast reactors do not employ an intermediate heat transport system.

One of the technical issues associated with the lead-bismuth eutectic is the corrosion of the fuel element claddings and structural materials in the coolant flow. Corrosion is temperature-dependent and, according to multiple studies performed worldwide, is easier to cope with at lower temperatures. In Russia the technology for reliable operation of stainless steel based structural materials in lead-bismuth eutectic was developed, allowing a reactor core continuous operation in the course of 7–8 years within a moderate temperature range below ~500 °C. The technology includes chemical control of the coolant [17].

Table 4 summarizes the general characteristics and design status of nearer-term SMRs based on the LBFR technology.

The SVBR-100 design is backed by 80 reactor-years of operating experience of the propulsion reactors in the seven Russian Alpha-class nuclear submarines [8,11]. In addition to the resolution of the corrosion problem, the Russian submarine program had succeeded in resolving the problem of volatile ^{210}Po trapping and developed a safe freezing/defreezing procedure for the lead-bismuth coolant (Polonium-210 is a strong alpha emitter that is lethally toxic to human beings if inhaled or digested; ^{210}Po is generated from ^{209}Bi under irradiation and has a half-life of ~138 days [11]).

Like all liquid metal cooled reactors, SVBR-100 operates at near-atmospheric pressure. As the coolant based on lead-bismuth eutectic is chemically inert in water and air, the plant has no intermediate heat transport system. The compact SVBR-100 module is immersed in a refillable pool with water at atmospheric pressure. Boiling of water in the pool helps remove the heat from the reactor vessel outer surface in accidents.

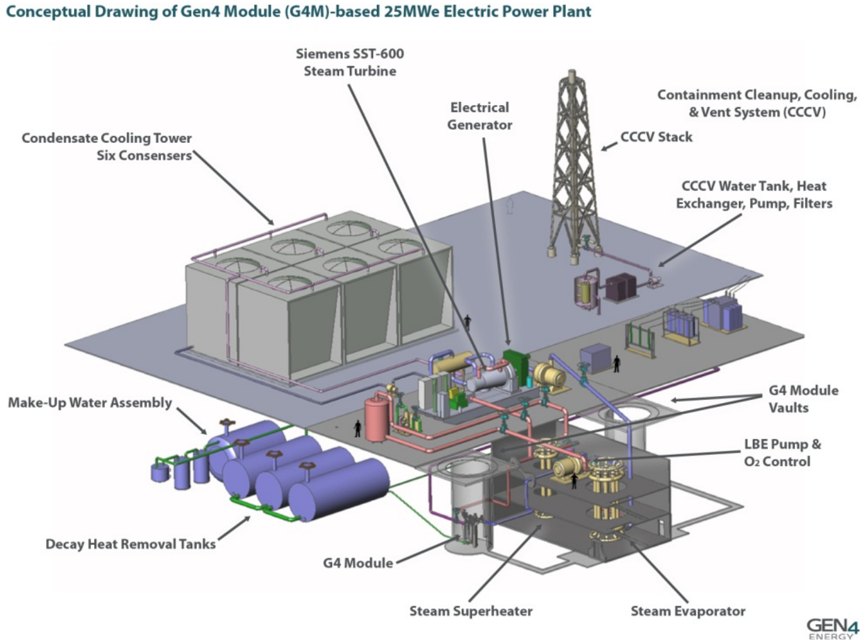
The SVBR-100 can operate with different types of nuclear fuel. For the near-term, uranium-dioxide based fuel load is considered with an average uranium enrichment of 16.3% by weight. The reactor is designed for continuous operation on the site in the course of 7–8 years, after which whole core refulling is performed on site. When operated in a closed nuclear fuel cycle, SVBR-100 will retain the effective fissile mass in the core, *i.e.*, will require no additional fissile materials to be added at a refueling [8].

Table 4. General characteristics of LBFRs.

SMR name	**SVBR-100**	**GEN4 Energy Module**
Company/Country	JSC AKME-Engineering, Russia	GEN4 Energy Inc., USA
Electric/Thermal power, MW	101.5/280	25/70 (per module)
Non-electrical products	District heating Potable water	Heat, potable water, hydrogen
Plant configuration	Single-unit and multi-module Land-based and barge-mounted	Single- or multi-module land based
Construction period/Refueling interval, months	42/(84-96)	21 on the site/(60-180) Refueling at the factory
Design stage	Detailed design in progress	Early conceptual design
Licensing stage	Not started	Pre-licensing negotiations in progress
Targeted deployment date	2017 (prototype plant)	First-of-a-kind unit in 2018

The GEN4 Energy Module (formerly known as the Hyperion Power Module) shares many common features with the SVBR-100. However, in contrast to the SVBR-100, it employs natural circulation of the primary coolant in normal operation mode—the SVBR-100 uses pumps for that purpose. Moreover, it is designed to be fueled and de-fueled at factory—the SVBR-100 design provides for whole-core on-site refueling). The GEN4 Energy design is based on the results of R&D carried out at the Los Alamos National Laboratory. Like SVBR-100, it is assumed to be used within single- or multi-module nuclear power plants (Figure 5).

Figure 5. Layout of the GEN4 Energy plant. Source: [18].



No matter how early the first-of-a-kind, non-commercial SVBR-100 or GEN4 Energy Module plants will be deployed, the long refueling intervals provided for by their designs (5-15 years) will necessitate long testing and demonstration programs. Thus, their promotion as exportable commercial products cannot be realistically expected before 2025.

3. The Economics of SMRs

In a deregulated global electricity marketplace, economics will be a key consideration in future decisions to build new nuclear plants. Thus assessing the forward-looking cost elements of nuclear power and the uncertainties underlying those cost estimates is key to evaluating its potential role in balancing the electricity supply and demand over the next several decades and mitigating the threat of climate change. Even if countries decide that the challenge of decarbonizing electricity generation requires more state control, economics will continue to be important, although the perceived costs of risk might then be somewhat lower.

One of the fundamental problems underlying the debate on the potential role of SMRs in meeting the future global energy needs relates to the continuing lack of consensus on what will be their costs under an expanded future deployment. Capital costs estimates for SMRs are very preliminary given that these systems are in the early stages of their development and there is lack of data regarding their construction cost [19]. Thus, it is very difficult to perform a credible comparative assessment of SMR competitiveness. This issue is only likely to be resolved with accumulating information about the full costs of SMR build.

3.1. Economies of Scale

Most of the nuclear reactors currently in operation are medium- to large-scale plants sized at 500–1500 megawatts, utilizing tested technologies. The first generation nuclear power plants had a capacity of about 300–500 megawatts. However, because of the general belief that nuclear power operations are characterized by significant economies of scale at the plant level, there was a definite trend toward larger units. By the mid-1960s, the industry scaled up to about 800 megawatts and, before those units were completed, new ones with capacities of over 1300 megawatts were planned and constructed.

Econometric evidence on economies of scale in nuclear power is scant and fairly mixed. The determination of how scaling-up affects unit costs has been marred by methodological uncertainties (e.g., whether overnight costs as commonly calculated can accurately represent economies of scale), the lack of an internationally agreed definition of the basic variables and standards for nuclear power plant costing (different cost assessments make varying assumptions that render direct comparisons among them very difficult), the growing divergence between good and poor nuclear plant construction performance, and the scarcity of new orders (especially in the United States) in recent years. The above difficulties notwithstanding, several studies from around the world have sought to estimate the savings in overnight costs arising from economies of scale when the size of power plants increases from 300 to the 1300 MW(e) range [20].

It can be plausibly argued that because of economies of scale, SMRs will suffer a significant economic disadvantage compared to large reactors in terms of their overnight costs per unit of installed capacity. Specific capital costs (*i.e.*, capital costs per unit of installed capacity) are expected to decrease with size because of fixed set-up costs (e.g., siting activities or earth works for connecting to the transmission grid), more efficient utilization of primary inputs (e.g., raw materials), and the higher performance of larger components (e.g., pumps, heat exchangers, steam generators, *etc.*). Several studies have employed the following scaling function to illustrate the effect of changing from a plant unit size P_0 to a plant of similar design with capacity P_1:

$$\mathrm{Cost}(P_1) = \mathrm{Cost}(P_0) \times (P_1/P_0)^n \quad (1)$$

where $\mathrm{Cost}(P_1)$ and $\mathrm{Cost}(P_0)$ are the costs of power plants of size P_1 and P_0 respectively, and n is the scaling factor for the entire plant (this is an overall scaling law for the entire plant—different components of the plant may have substantially different scaling exponents). Overnight cost estimates from France, Canada, and the United States point to a scaling factor in the range of 0.4 to 0.7, at the plant level [21]. These estimates imply that doubling the reactor size leads to a reduction in overnight unit costs roughly between 19 and 34 percent. It should be noted, however, that the above scale effects apply only if the reactors that are being compared have very similar designs and employ the same components. SMRs have several components that are scaled-down versions of larger rector designs. However, SMRs also eliminate the need for many components that are an integral part of the larger reactors. Moreover, they include components that are based on entirely different design concepts. Thus, all of these considerations have to be explicitly taken into account when comparing the capital costs of reactors with different sizes. Otherwise, the inference that smaller reactors have substantially higher capital costs per unit of capacity may be based on a misapplication of the economies of scale principle [22].

SMRs offer a number of advantages that can potentially offset the overnight cost penalty that they suffer relative to large reactors. Indeed, several characteristics of their proposed designs can serve to overcome some of the key barriers that have inhibited the growth of nuclear power. These characteristics include [23,24]:

- ***Reduced construction duration.*** The smaller size, lower power, and simpler design of SMRs allow for greater modularization, standardization, and factory fabrication of components and modules. Use of factory-fabricated modules simplifies the on-site construction activities and greatly reduces the amount of field work required to assemble the components into an operational plant. As a result, the construction duration of SMRs could be significantly shorter compared to large reactors leading to important economies in the cost of financing.
- ***Investment scalability and flexibility.*** In contrast to conventional large-scale nuclear plants, due to their smaller size and shorter construction lead-times SMRs could be added one at a time in a cluster of modules or in dispersed and remote locations. Thus capacity expansion can be more flexible and adaptive to changing market conditions. The sizing, temporal and spatial flexibility of SMR deployment have important implications for the perceived investment risks (and hence the cost of capital) and financial costs of new nuclear build. Today's gigawatt-plus reactors require substantial up-front investment—in excess of US$ 4 billion. Given the size of the up-front capital requirements (compared to the total capitalization of most utilities) and length of their construction time, new large-scale nuclear plants could be viewed as "bet the farm" endeavors for most utilities making these investments. SMR total capital investment costs, on the other hand, are an order of magnitude lower—in the hundreds of millions of dollars range as opposed to the billions of dollars range for larger reactors. These smaller investments can be more easily financed, especially in small countries with limited financial resources.

  SMR deployment with just-in-time incremental capacity additions would normally lead to a more favorable expenditure/cash flow profile relative to a single large reactor with the same aggregate capacity—even if we assume that the total time required to emplace the two alternative infrastructures is the same. This is because when several SMRs are built and deployed sequentially, the early reactors will begin operating and generating revenue while the remaining ones are being constructed. In the case of a large reactor comprising one large block of capacity addition, no revenues are generated until all of the investment expenditures are made. Thus the staggered build of SMRs could minimize the negative cash flow of deployment when compared to emplacing a single large reactor of equivalent power [25].
- ***Better power plant capacity and grid matching.*** In countries with small and weak grids, the addition of a large power plant (1000 MW(e) or more) can lead to grid stability problems—the general "rule of thumb" is that the unit size of a power plant should not exceed 10 percent of the overall electricity system capacity [11]. The incremental capacity expansion associated with SMR deployment, on the other hand, could help meet increasing power demand while avoiding grid instability problems.

- ***Factory fabrication and mass production economies.*** SMR designs are engineered to be pre-fabricated and mass-produced in factories, rather than built on-site. Factory fabrication of components and modules for shipment and installation in the field with almost Lego-style assembly is generally cheaper than on-site fabrication. Relative to today's gigawatt-plus reactors, SMRs benefit more from factory fabrication economies because they can have a greater proportion of factory made components. In fact, some SMRs could be manufactured and fully assembled at the factory, and then transported to the deployment site. Moreover, SMRs can benefit from the "economies of multiples" that accrue to mass production of components in a factory with supply-chain management.
- ***Learning effects and co-siting economies.*** Building reactors in a series can lead to significant per-unit cost reductions. This is because the fabrication of many SMR modules on plant assembly lines facilitates the optimization of manufacturing and assembly processes. Lessons learned from the construction of each module can be passed along in the form of productivity gains or other cost savings (e.g., lower labor requirements, shorter and more efficiently organized assembly lines) in successive units (Figure 6). Moreover, additional learning effects can be realized from the construction of successive units on the same site. Thus multi-module clustering could lead to learning curve acceleration. Since more SMRs are deployed for the same amount of aggregate power as a large reactor, these learning effects can potentially play a much more important role for SMRs than for large reactors [26]. Also, sites incorporating multiple modules may require smaller operator and security staffing.
- ***Design simplification.*** Many SMRs offer significant design simplifications relative to large-scale reactors utilizing the same technology. This is accomplished thorough the adoption of certain design features that are specific to smaller reactors. For example, fewer and simpler safety features are needed in SMRs with integral design of the primary circuit (*i.e.*, with an in vessel location of steam generators and no large diameter piping) that effectively eliminates large break LOCA.

Clearly one of the main factors negatively affecting the competitiveness of small reactors is economies of scale—SMRs can have substantially higher specific capital costs as compared to large-scale reactors. However, SMRs offer advantages that can potentially offset this size penalty. As it was noted above, SMRs may enjoy significant economic benefits due to shorter construction duration, accelerated learning effects and co-siting economies, temporal and sizing flexibility of deployment, and design simplification. When these factors are properly taken into account, then the fact that smaller reactors have higher specific capital costs due to economies of scale does not necessarily imply that the effective (per unit) capital costs (or the levelized unit electricity cost) for a combination of such reactors will be higher in comparison to a single large nuclear plant of equivalent capacity [22,25].

In a recent study, Mycoff *et al.* [22] provide a comparative assessment of the capital costs per unit of installed capacity of an SMR-based power station comprising of four 300 MW(e) units that are built sequentially and a single large reactor of 1200 MW(e). They employ a generic mode to quantify the impacts of: (1) economies of scale; (2) multiple units; (3) learning effects; (4) construction schedule; (5) unit timing; and (6) plant design (Figure 7).

Figure 6. Reduction of equipment fabrication and installation costs in serial production of nuclear propulsion plants. Source: [27].

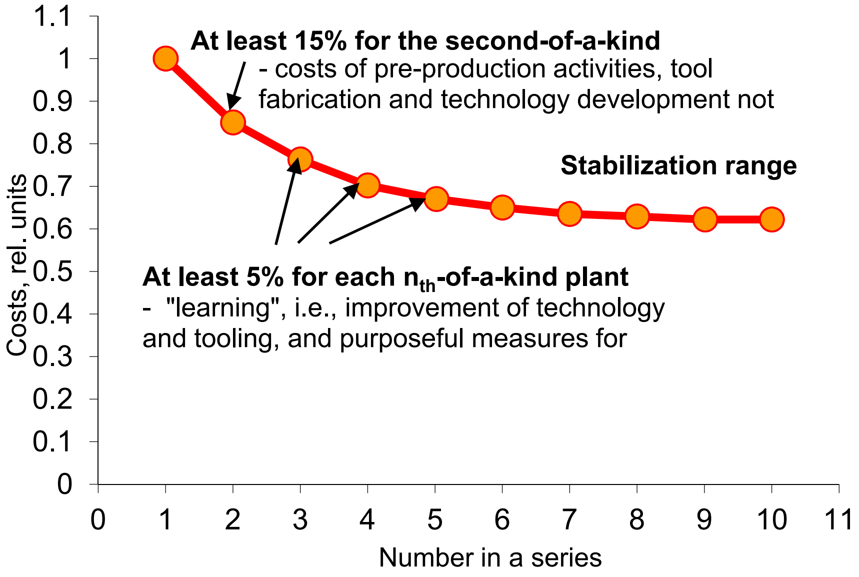
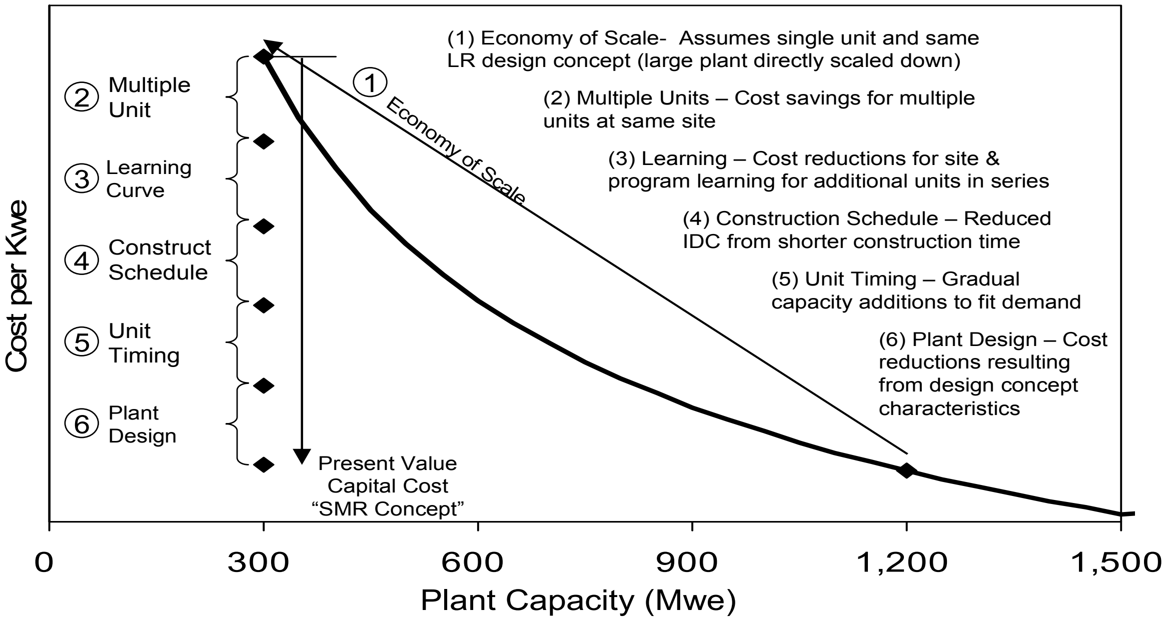


Figure 7. Factors affecting the competitiveness of SMRs. Source: [22].



To estimate the impact of economies of scale, Mycoff *et al.* [22] assume a scaling factor n = 0.6 and that the two plants are comparable in design and characteristics—*i.e.*, that the single large reactor is scaled down in its entirety to ¼ of its size. According to the standard scaling function, the hypothetical overnight cost (per unit of installed capacity) of the SMR-based power station will be 74 percent higher compared to a single large-scale reactor. Based on various studies in the literature, the authors posit that the combined impact of multiple units and learning effects is a 22 percent reduction in specific capital costs for the SMR-based station. To quantify the impact of construction schedule, the authors assume that the construction times of the large reactor and the SMR units are five and three years respectively. The shorter construction duration results in a 5 percent savings for the SMRs. Temporal flexibility (four sequentially deployed SMRs with the first going into operation at the same time as the large reactor and the rest every 9 months thereafter) and design simplification led to 5 and 15 percent reductions in specific capital costs respectively for the SMRs. When all these factors are combined, the SMR-based station suffers a specific capital cost disadvantage of only 4 percent as compared to the single large reactor of the same capacity. Thus, the economics of SMRs challenges the widely held belief that nuclear reactors are characterized by significant economies of scale [19].

3.2. Investment Perspective

While bringing the specific investment costs of a SMR based plant to the level typical of the state-of-the-art NPPs with large reactors appears to be a challenge, the absolute overnight capital costs of small reactors are much smaller compared to those of NPPs with large reactors (Table 5).

Table 5. Overninght capital costs for SMRs (2009 US$) *. Source: [11,28].

SMR (Country)	Unit power, MW(e)	Plant configuration	NPP power, MW(e)	Overnight capital cost, US$ billion
		PWR		
KLT-40S (Russia)	35	Twin unit, barge	70	0.259–0.294
ABV (Russia)	8.5	Twin unit, barge	17	0.155
VBER-300 (Russia)	325	Single unit, barge Twin unit, land	325 650	0.910 barge 2.275 land
RITM-200 (Russia)	50	Twin unit, icebreaker	100	0.231–0.262 icebreaker
CAREM-25 (Argentina)	27	Single unit	27	0.097
SMART (Republic of Korea)	100	Single unit	100	0.497
Westinghouse SMR (USA)	225	Per unit **	225	0.668 Per unit**
mPower (USA)	180 (per module)	Twin unit	360	1.07**
NuScale (USA)	45 (per module)	12-module	540	1.600**
HI-SMUR (USA)	160	Single unit	160	0.480
		HTGR		
HTR-PM (China)	105.5 (per module)	Twin unit	211	<0.317
		OECD-NEA projections for large LWRs		
VVER-1150 (Russia)	1070	Twin unit	2140	6.276
APR-1400 (Republic of Korea)	1343	Twin unit	2686	4.180
APWR, ABWR (USA)	1400	Twin unit	2800	8.316
EPR (France)	1630	Single unit	1630	6.292
ABWR (Japan)	1330	Twin unit	2660	8.002

* LWR—light water reactor; barge—barge mounted; land—land based (default, if not specified);
** Plant configuration not defined.

As it can be seen from Table 5, the overnight capital costs of typical configurations of Generation III and III+ large plants are in the range of 6.28–8.3 US$ billion for the range of overall plant capacities from 1630 to 2800 MW(e). For the near term SMRs, the corresponding cost range could be from 0.097 to 2275 US$ billion for plant capacity range from 27 to 650 MW(e). For the plants below 300 MW(e) the overnight capital costs are below US$ 1 billion.

Small absolute overnight capital costs make the SMRs attractive to a broader range of investors, including a variety of private companies (not necessarily affiliated with nuclear sector) and the utilities whose own funds are insufficient to finance a large reactor project. SMR partnerships between utilities and industrial enterprises have already emerged in the USA and elsewhere. In the case of NuScale, the Fluor Company has partnered with NuScale Power and is providing direct financing for the design development and licensing of the NuScale SMR project [29].

On March 22, 2012 The U.S. Department of Energy issued a Funding Opportunity Announcement entitled “Cost-Shared Industry Partnership Program for Small Modular Reactors” This program seeks to facilitate development and deployment of two U.S.-owned SMR designs at domestic locations. It is expected that an award of up to $452 million will be given to each the two winning vendors by the end of 2012.

In the Russian Federation, a public-private joint venture company named “AKME Engineering” is drivings forward the project of the SVBR-100 reactor that is expected to be constructed by 2017 (AKME Engineering Web-site). “AKME Engineering” is a joint venture of the “Evrosibenergo” JSC (a non-nuclear company) and the “Roatom” State Atomic Energy Corporation. Within this partnership, financing is provided exclusively by the “Evrosibenergo”, while the “Rosatom” contributes its intellectual property and workforce and facilities to carry out design development and licensing of the SVBR-100.

4. Opportunities and Challenges for SMR Deployment in Developing Countries

We summarize below the opportunities and challenges for SMR deployment in developing countries, and also highlight the pathways for the resolution of the identified challenges and issues.

4.1. Opportunities for SMRs

By and around 2020, about 11 SMRs developed in Argentina, China, Republic of Korea, Russian Federation and the United States could be deployed as first-of-a-kind plants in their countries of origin. In case of success, these reactors could later be considered for export to developing countries starting from the mid-2020s.

As Table 5 indicates, there is a significant diversity of SMR designs including land-based as well as barge-mounted (Russian only) plants. Unit power varies from 8.5 to 300 MW(e) with twin-unit or multi-module plant options available in the majority of cases. Thus, SMRs would provide for greater siting flexibility and be a better fit for many developing countries with small electrical grids where they could facilitate incremental growth of the grid.

The siting and temporal flexibility of SMR deployment would naturally leave more time for developing and streamlining the requisite human resources and technical expertise. Moreover, the smaller size and greater simplicity of SMR components and plant design might eventually facilitate greater national industry involvement in the recipient developing countries. Regarding financing, SMRs may offer substantial advantages owing to their smaller absolute capital outlay, better scalability and reversibility of SMR projects, shorter construction periods and the resulting minimal financial risks. It should be noted that the absolute capital cost of SMRs is always much smaller compared to that of large reactors. Specifically, for the plants in the range below 300 MW(e) the overnight capital costs are below US$ 1 billion—an important consideration, especially for small developing countries.

Projects with small capital outlay are typically more attractive to private investors operating in liberalized markets where indices like the net present value (NPV), the internal rate of return (IRR) and the payback time are of critical importance. Incremental capacity additions would generally lead to a smoother debt stock profile—*i.e.*, lower financial distress of the project. For particular scenarios of SMR deployment interest during construction could be as low as half of a large reactor based project with equivalent total capacity.

4.2. Capping Safety Hazards and Proliferation Risks

Compared to large conventional reactors, SMRs are better able to "respond" to lessons of the 9/11 and Fukushima disasters. They can do so by moving the nuclear islands underground and/or surrounding the reactor vessels or small containments with water, as well as by exploiting their relatively higher potential for passive decay heat removal—they can achieve grace periods of 72 hours and well beyond and eliminate the need for continuous emergency electrical supply on the site.

One of the key concerns regarding nuclear deployment in developing countries is that those countries generally have a less mature regulatory regime in place compared to the advanced industrial countries. These considerations place very stringent requirements on power station reliability and safety performance. The need for enhanced levels of safety can be more easily met by SMRs with design options that maximize the use of inherent and passive safety features and incorporate additional layers of "defense in depth" [13]. These safety features can be more easily and effectively implemented in SMRs because of these reactors' larger surface-to-volume ratio, reduced core power density, lower source term, and less frequent (multi-year) refueling. For example, large surface-to-volume ratios facilitate the passive (with no external source of electrical power or stored energy) removal of decay heat.

The extent to which nuclear power will prove an acceptable and enduring option for meeting the future energy requirements worldwide will depend in part upon the ability of the international community to minimize the associated proliferation risks. A major nuclear expansion program, unless is accompanied by adequate technical and institutional safeguards, could increase the risk that weapons-usable fissile materials, facilities, technology, or expertise might be diverted or stolen. The common fear is that such an expansion will make it easier for countries to acquire technology as a precursor to developing nuclear weapons capability or for terrorist groups to obtain nuclear materials. This risk could be further compounded by the likelihood that plutonium-fueled breeder reactors will be widely used to stretch uranium resources under expanded nuclear power deployment. Enhanced capacity and institutional arrangements to prevent proliferation and diversion of nuclear technology to non-peaceful purposes are challenges that will need to be overcome if nuclear energy is to be expanded in developing countries

One potential way of mitigating the proliferation risks of expanded nuclear deployment in developing countries might be through the adoption of hub-and-spoke configurations that restrict all sensitive activities (such as isotope separation of uranium or reprocessing of spent fuel) to large, international/regional energy parks that would export fuel, hydrogen, and even small (40–50 megawatts) sealed reactors to client states [30,31]. These reactors would be assembled and fueled at the central nuclear park, sealed (so that individual fuel assemblies could not be removed) and delivered as a unit to the power plant cites of client countries. At the end of their core life (say 15–20 years) the reactors would be returned to the central park unopened. Thus, during the 15–20 years of operation there would be no refueling and consequently the client countries would need no fuel fabrication facilities and management capabilities. To the extent that such modular reactors would operate almost autonomously, the hub-and-spoke architecture could reduce substantially the rationale and opportunities for countries to develop nuclear research laboratories and train technical specialists and scientists whose know-how could later be diverted to weapons activities [32]. It should be noted that providing attractive alternatives to the buildup of indigenous facilities is a good idea. However, trying to restrict knowledge diffusion is arguable futile and non-sustainable.

Although international energy parks and the hub-and-spoke nuclear architecture are technically feasible, they could prove politically difficult to implement. Countries might reasonably view these arrangements as threatening their sovereignty and encroaching upon their so energy independence. Moreover, the hub-and-spoke system would normally require the spoke countries to accept restrictions on their nuclear activities that might not be similarly imposed on the larger countries hosting the international or regional nuclear parks. Inevitably, such restriction will be viewed as being discriminatory, unless all countries (including the advanced industrial countries) were willing to accept a high degree of international control over their nuclear energy programs.

The analysis of options to reconfigure the developing world's energy supply architecture to exploit the innate features of nuclear power might include: a hierarchical hub-and-spoke energy supply architecture with regional energy parks handling both front- and back-end fuel cycle services; and reactor and plant designs that will enable incremental, time-phased market penetration to match the energy demand in the geographic areas circumscribed by the spokes and will efficiently mesh with existing energy distribution infrastructures.

Overcoming the political obstacles to regionalizing nuclear energy will require the identification and adoption of innovative institutional measures. It would be important to assess the scope for the following: creating regional energy parks owned by consortia of developing countries that have had a fair amount of success in regional cooperation and economic integration; providing the recipient (spoke) countries with guaranteed (legally binding) access to services from the regional energy park in exchange for their foregoing building an indigenous fuel cycle infrastructure; and creating regional regulatory authorities and regimes for governing the regional nuclear energy infrastructure.

4.3. Challenges and Issues for SMRs

The generally acknowledged challenge for SMRs is to provide levelized unit electricity cost that is competitive with comparable base-load electricity generation sources in a user country. However, aside from this important economic challenge, SMRs may face other deployment challenges in developing countries. These potential issues include:

- Proven technology requirements by developing countries suggest that several units of the plant should have a proven operating experience of 3-5 years. All current SMRs designs are expected to be deployed first in their countries of origin or in another developed technology holder country. Such plants would need to operate for several years before they are offered for export to developing countries.

- Requirements to plant design suggest that the design of equipment and components should allow for the supply of their replacement during the life of the NPP by manufacturers other than the original manufacturers. This may be an issue for SMRs, especially in the near-term, in view of diversity of the SMR design concepts and the unique technical features implemented in some of them.
- For small NPPs located in remote and isolated areas physical protection could be a challenge. Partial solution to this problem might be provided by a higher degree of intrinsic reactor security.
- Factory fueled/refueled reactors could substantially reduce the required infrastructure effort in a recipient country regarding nuclear fuel cycle and radioactive waste. However, the movement and exporting of such reactors would require resolving a number of important legal and institutional issues.

5. Summary

Small modular reactors offer a number of distinct advantages that might make them suitable for deployment in developing countries. These advantages include:

- small size and modular construction—this would allow these reactors to be manufactured completely in a factory and delivered and installed module by module, improving component manufacturing productivity through learning effects while reducing construction time, financing costs, and investment risks;
- substantially simpler designs (fewer systems)—this leads to a lower frequency of accident initiators and events that could cause core damage in comparison to the complex current generation plants;
- a diverse set of useful applications—low-carbon electricity generation in remote locations with little or no access to the grid, industrial process heat, desalination or water purification, and co-generation applications;
- an expanded set of potential siting options—their small size makes them suitable for small electric grids or for locations that cannot accommodate large-scale plants;
- capping safety and proliferation hazards—compared to large-scale reactors, SMRs have a larger surface-to-volume ratio (easier decay heat removal), lower core power density (more effective use of passive safety features), smaller source term relative to traditional large-scale reactors, and multi-year refueling so that new fuel loading is needed very infrequently.

Small modular reactors have compact designs—e.g., the containment vessels of 25 Westinghouse SMRs (225 MW(e) each) could fit into a single AP-1000 containment vessel—and could be manufactured in factories or other central facilities and then transported (along with the necessary containment walls, turbines for generating electricity, control systems, and so on) to the site of a future plant by track or rail. Building reactors in a factory could substantially decrease construction times and lead to savings on both construction and financing costs. Thus the small size and modularity of SMRs could make them more affordable to small utilities and developing countries by decreasing capital costs (*i.e.*, requiring less lumpy capital investments) and construction times [33].

In general, due to their significantly smaller size and simpler design, SMRs require smaller operator participation for both normal steady-state operations and responding to transients and postulated accidents. The potential radiological consequences of any accidents are much smaller than those of existing large-scale plants, due to the smaller source terms (the radionuclide inventory is orders of magnitude less). Moreover, the physical layout and reduced size of an SMR plant (the smallest SMRs will occupy less than one acre with perhaps three acres of land needed to support plant activities) also contribute to making management of an emergency simpler [34].

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Conflict of Interest

The authors declare no conflict of interest. The findings, interpretations, and conclusions are the authors' own and should not be attributed to the World Bank, its Executive Board of Directors, or any of its member countries.

References

1. EIA (Energy Information Administration). *International Energy Outlook*; EIA: Washington, DC, USA, 2011.
2. IEA (International Energy Agency). *World Energy Outlook 2011*; OECD/IEA: Paris, France, 2011.
3. Grubler, A. *An Assessment of the Costs of the French Nuclear PWR Program 1970–2000*; IIASA: Laxenburg, Austria, 2009.
4. Roques, F.; Newbery, D.; Nuttall, W. Investment incentives and electricity market design: The British experience. *Rev. Netw. Econ.* **2005**, *4*, 93–128.
5. IAEA (International Atomic Energy Agency). *Status of Small and Medium Sized Reactor Designs: A Supplement to the IAEA Advanced Reactors Information System (ARIS)*; IAEA: Vienna, Austria, 2011.
6. Schropshire, D.; Herring, J. Fuel-cycle and Nuclear Material Disposition Issues Associated with High-temperature Gas Reactors. In *Proceedings of the Americas Nuclear Energy Symposium (ANES 2004)*, Miami Beach, FL, USA, 3–6 October 2004.
7. IAEA (International Atomic Energy Agency). *Status of Innovative Small and Medium Sized Reactor Designs 2005: Reactors with Conventional Refueling Schemes*; IAEA: Vienna, Austria, 2006.

8. IAEA (International Atomic Energy Agency). *Status of Small Reactor Designs without On-Site Refueling*; IAEA: Vienna, Austria, 2007.
9. IAEA (International Atomic Energy Agency). *Heavy Water Reactors: Status and Projected Development*; IAEA: Vienna, Austria, 2002.
10. IAEA (International Atomic Energy Agency). *Design and Development Status of Small and Medium Reactor Systems*; IAEA: Vienna, Austria, 1996.
11. NEA (Nuclear Energy Agency). *Current Status, Technical Feasibility and Economics of Small Nuclear Reactors*; OECD: Paris, France, 2011.
12. IAEA (International Atomic Energy Agency). *Innovative Small and Medium Sized Reactors: Design Features, Safety Approaches and R&D Trends*; IAEA: Vienna, Austria, 2005.
13. IAEA (International Atomic Energy Agency). *Design Features to Achieve Defence in Depth in Small and Medium Sized Reactors*; IAEA: Vienna, Austria, 2009.
14. WNA (World Nuclear Association). Nuclear power in Argentina. Available online: http://www.world-nuclear.org/info/inf96.html (accessed on 30 June 2012).
15. IAEA (International Atomic Energy Agency). *High Temperature Gas Cooled Reactor Fuels and Materials*; IAEA: Vienna, Austria, 2010.
16. Stevenson, C. *The EBR-II Fuel Cycle Story*; American Nuclear Society: La Grange Park, IL, USA, 1987.
17. IAEA (International Atomic Energy Agency). *Liquid Metal Cooled Reactors: Experience in Design and Operation*; IAEA: Vienna, Austria, 2008.
18. GEN4 Energy. Available online: http://www.gen4energy.com/ (accessed on 10 August 2012).
19. Rosner, R.; Goldberg, S. *Small Modular Reactors—Key to Future Nuclear Power Generation in the U.S.*; EPIC, University of Chicago: Chicago, USA, 2011.
20. UofC (University of Chicago). *The Economic Future of Nuclear Power*; UofC: Chicago, USA, 2004.
21. NEA (Nuclear Energy Agency). *Reduction of Capital Costs of Nuclear Power Plants*; OECD: Paris, France, 2000.
22. Mycoff, C.; Carelli, M.; Petrovic, B.; Miller, K. Strategies to Demonstrate Competitiveness of SMRs in World Markets; In *Methodologies and Decision Criteria for Demonstrating Competitiveness of SMRs*; IAEA: Vienna, Austria, 2007. Available online: http://www.iaea.org/NuclearPower/Downloads/SMR/CRPI25001/2007_new/Mycoff.doc (accessed on 10 August 2012).
23. Carelli, M.; Garrone, P; Locatelli, G; Mancini, M; Mycoff, C; Trucco, P; Ricotti, M. Economic features of integral, modular, small-to-medium size reactors. *Prog. Nuclear Energy* **2010**, *52*, 403–414.
24. Kuznetsov, V. Overview of IAEA Project 1.1.5.5 "Common Technologies and Issues for SMRs". In *Proceedings of the4th INPRO-GIF Interface Meeting*, Vienna, Austria, 1–3 March 2010.
25. Kuznetsov, V; Barkatullah, N. Approaches to Assess Competitiveness of Small and Medium Sized Reactors. In *Proceedings of the International Conference on Opportunities and Challenges for Water Cooled Reactors in the 21st Century, IAEA*, Vienna, Austria, 27–30 October 2009.

26. Kuznetsov, V. Options for small and medium sized reactors (SMRs) to overcome loss of economies of scale and incorporate increased proliferation resistance and energy security. *Prog. Nuclear Energy* **2008**, *50*, 242–250.
27. Mitenkov, F.M.; Averbakh, B.A.; Antiufeeva, I.N.; Gureeva, L.V. Conceptual Analysis of Commercial Production Experience and Influence of Main Factors on the Economy of a Propulsion Nuclear Plant Lifecycle. In *Proceedings of the 2nd International Scientific and Technical Conference—Energy Strategy 2004 Power Development Planning: Methodology, Software, Applications*, Moscow, Russia, 25–27 October 2004.
28. IEA (International Energy Agency); NEA (Nuclear Energy Agency). *Projected Costs of Generating Electricity*; OECD: Paris, France, 2010.
29. UxC Policy Watch. U.S. Government support for small modular reactors. Available online: http://www.uxc.com/products/uxc_pw_updatelist.aspx (accessed on 30 June 2012).
30. Kursunoglu, B.; Mintz, S. *Global Warming and Energy Policy*; Plenum Publishers: New York, NY, USA, 2001.
31. Feiveson, H. The search for proliferation-resistant nuclear power. *J. Fed. Am. Sci.* **2001**, *54*, 1–9.
32. Feiveson, H.; Glaser, A.; Miller, M.; Scheinman, L. *Can Future Nuclear Power Be Made Proliferation Resistant?*; Center for International and Security Studies at Maryland: College Park, MD, USA, 2008.
33. Arness, M. Westinghouse SMR Product Development. IAEA Workshop, Vienna, Austria, 2011.
34. ANS (American Nuclear Society). *Interim Report of the ANS President's Special Committee on Small and Medium Sized Reactors (SMR) Generic Licensing Issues*; ANS: La Grange Park, IL, USA. Available online: http://www.ans.org/pi/smr/ans-smr-report.pdf (accessed on 30 June 2012).