Small Modular Reactors in an Uncertain Nuclear Power Future

By Ioannis N. Kessides*

The future of nuclear power remains clouded in uncertainty and controversy. The Fukushima Daiichi disaster in March, 2011 has heightened public apprehension about nuclear safety, as after the disasters at Three Mile Island and Chernobyl. Consequently, public opposition to nuclear power has intensified in Europe and in a number of developing countries. Great debate also exists over the cost-effectiveness of nuclear energy, and about current and future technical advances that could address economic and safety concerns.

Nevertheless, several developing countries (larger and smaller, middle and lower-income) are actively considering nuclear power in their national energy mix. This interest in nuclear power is driven primarily by energy security concerns—the level and volatility of fossil fuel prices, and the availability and reliability of other sources of supply. While many developing countries are also making major commitments to renewable energy, all large-scale (grid-connected) renewable investments require considerable subsidies given the current state of technology, implying a long-term financial burden. Although there have been significant cost reductions driven by technological change, wind, solar and other renewable generating technologies are still more expensive (per unit of electricity delivered) relative to conventional fossil fuels. An overly rapid uptake of renewables in developing countries could have significant implications for their competitiveness.

Recent research indicates that there is no obvious "silver bullet" for addressing the challenges of energy security and the need for massive increases in electricity supply in developing countries, while also curbing global emissions of greenhouse gases leading to climate change. A number of energy sources and technological options exist. However, there are highly divergent views on the environmental, social, and economic tradeoffs associated with all of these options. In the face of significant economic and technological uncertainties, prudence calls for energy supply diversification. A broad portfolio of low-carbon technologies and energy sources (larger and smaller-scale) needs to be investigated and developed, in addition to major improvements in energy efficiency. Over the longer term, in particular as technology advances, nuclear power may need to play an important role in managing the costs of transition to a low-carbon economy with scalable and affordable electricity supplied to meet the projected large absolute increase in electricity demand in developing countries.

For nuclear power to play a major role in meeting the future global energy mix and security, the hazards of another Fukushima and the construction delays and costs escalation that have plagued the industry in recent years 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 (perhaps non-linearly) as their size increased to the gigawatt scale and beyond. And so have the financing challenges. 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. They can also address concerns about catastrophic events since they offer passive safety features and contain substantially smaller radioactive inventory. Thus, 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.

Small Modular Reactors

In recent years, small modular reactors (SMRs)—350 MWe or less, compared to a typical nuclear power plant of 1000 MWe—have been attracting the attention of government officials, regulators and energy leaders around the world. These designs incorporate innovative approaches to achieve simplicity, improved operational performance, and enhanced safety. They offer a number of distinct advantages:

---

* Ioannis Kessides is the Lead Economist in the Development Research Group of The World Bank. The findings, interpretations, and conclusions are the author's own and should not be attributed to the World Bank, its Executive Board of Directors, or any of its member states.
See footnotes at end of text.

- 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 (e.g., in the petrochemical industry);
- 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 core inventory 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 MWe 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 truck 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 (Aness, 2011).

Design Status of SMRs

Small modular reactors can be classified according to the reactor technology and coolant: They include (IAEA, 2011):

- 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 MWe 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 (Schropshire and Herring, 2004).
- 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 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 (IAEA, 2006).[1] 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.

Capping Safety and Proliferation Hazards

There are currently only 435 nuclear power plant units operating worldwide, and 68 plants are under construction (WNA, 2013). For nuclear power to make a significant contribution to the future global energy mix, and if SMRs are to comprise the bulk of expanded nuclear deployment, then the number of deployed SMRs could be in the thousands or even tens of thousands. Indeed, most SMR concepts envision widespread deployment of a large number of small nuclear plants sited in diverse environments and frequently in close proximity to users. These considerations place very stringent requirements on SMR reliability and safety performance—arguably even more exacting relative to traditional large-scale nuclear plants. The hazard created per SMR deployed must be maintained exceedingly small in order for the cumulative hazard of the global SMR fleet to remain acceptably small. Two cumulative hazards that scale with the number of deployed plants are safety and nuclear weapons proliferation. These have been specifically addressed in the designs for SMR plants and their supporting fuel cycle architecture.

In general, due to their significantly reduced size and simpler design, SMRs require smaller operator participation for both normal steady-state operations and responding to transients and postulated accidents. Most SMRs employ passive or inherent safety features that place reliance on natural laws of physics. Thus, they add an additional layer of "defense in depth"[2] to back up traditional engineered safety systems and operator action. This increases the level of reliability for achieving a safe response to accident initiators and reduces the safety hazard per deployed SMR. Moreover, because they have a smaller power rating but the same fuel burnup limit as larger reactors, the SMR radioactive source term is smaller than in large reactors—in fact, their radionuclide inventory is orders of magnitude less. So on top of reduced hazard of core damage, the potential radiological consequences of any accidents are much smaller than those of existing large-scale plants, due to the smaller source terms. Finally, 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 (ANS, 2010).

The effectiveness of passive safety features can be illustrated by comparing outcomes from probabilistic risk analysis (PRA). In 1991, a Level-2 PRA was developed for the EBR-II fast neutron spectrum experimental breeder reactor—a 21 MWe plant—to compare its operational risk to that of commercial LWR's for which PRA's were available. EBR-II employs an extensive array of passive and inherent safety measures to back up traditional active safety systems. This PRA exercise showed that for EBR-II the risk of simply violating a fuel pin technical specification (with no core damage) is less than the risk of significant core disruption for the LWRs of the time. The point of the PRA comparisons is that application of passive and inherent safety measures as incorporated in SMRs can help to overcome the increase in numbers of SMRs needed to deliver the same societal energy provided by a smaller number of large-sized LWRs. Similarly, preliminary Level-1 PRA results for the NuScale reactor indicate a total single-module mean core damage frequency of 2.8x10-8/reactor-year, well below that of existing nuclear plants. And for the direct cycle boiling water reactor VK-300, the probability of severe core damage has been estimated to be less than 2.0x10-8/reactor-year (Hill et al, 1998; Kuznetsov and Gabaraev, 2007; Modarres, 2010).

As to the proliferation hazard, a tension has always existed between the expanded deployment of nuclear technology to provide abundant low-C energy and the risk of the technology being diverted instead to the development of nuclear weapons. The proliferation hazard of nuclear energy mainly arises from the fuel cycle facilities—both at the front end of the fuel cycle, during which natural uranium is enriched to make reactor-grade fuel, and at the back end of the cycle to extract fissile material from spent fuel (Richter, 2008). In the past, for energy security reasons, countries that relied heavily on nuclear energy often emplaced indigenous fuel cycle infrastructure facilities along with their nuclear power plants. Under indigenous fuel cycle infrastructure deployment, the proliferation hazard scales with the number of countries embracing nuclear energy for a significant share of their energy supply.

Most SMRs have been designed for multi-year refueling so that new fuel loading would be needed very infrequently. With long intervals available to secure fuel delivery, the risk of supply disruption is reduced. Moreover, the proliferation hazard of expanded SMR deployment could be substantially reduced 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 MWe) sealed reactors to client states (Feiveson, 2001). 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. 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 arguably futile and non-sustainable.[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 (Rosner and Goldberg, 2011). 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. Still, 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.).

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 (Carelli et al, 2010; Kuznetsov, 2010):

- Reduced construction duration.
- Investment scalability and flexibility.
- Better power plant capacity and grid matching.
- Factory fabrication and mass production economies.
- Learning effects and co-siting economies.
- Design simplification.

Summary

One promising direction for nuclear development might be to downsize reactors from the gigawatt scale to less-complex smaller units (with substantially smaller radioactive inventory) that are more affordable. SMRs are scalable nuclear reactor designs that could: (i) enhance component manufacturing productivity while reducing construction time, financing costs, and investment risks; (ii) cap safety hazards because of their passive or inherent safety features and reduced radioactive inventory; (iii) more effectively address the energy needs of small developing countries because of the lower capital requirements and suitability for small electric grids.

Footnotes

[1] These include the: mPower Reactor; Holtec Inherently Safe Modular Underground Reactor (HI-SMUR) 140; NuScale Power Reactor; The Westinghouse SMR; KLT-40S; RITM-200; VBER-300; VK-300; ABV reactor variants; CAREM-25; SMART; GT-MHR (Gas-Turbine Modular Helium Reactor); ANTARES (AREVA's New Technology Advanced Reactor Energy System); Pebble Bed Modular Reactor; HTR; HTTR; Hyperion Power Module (HPM); Power Reactor Inherently Safe Module (PRISM); EM2 (Energy Multiplier Module); 4S (Super-Safe, Small and Simple Reactor); BREST-300; SVBR-100.

[2] An approach to designing and operating nuclear facilities that prevents and mitigates accidents that release radiation or hazardous materials. The key is creating multiple independent and redundant layers of defense to compensate for potential human and mechanical failures so that no single layer, no matter how robust, is exclusively relied upon. Defense-in-depth includes the use of access controls, physical barriers, redundant and diverse key safety functions, and emergency response measures (http://www.nrc.gov/reading-rm/basic-ref/glossary/defense-in-depth.html).

[3] 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.

References

Aness, M. 2011. "Westinghouse SMR Product Development." IAEA Workshop, Vienna, Austria.

ANS (American Nuclear Society). 2010. "Interim Report of the ANS President's Special Committee on Small and Medium Sized Reactors (SMR) Generic Licensing Issues."

Carelli, M., P. Garrone, G. Locatelli, M. Mancini, C. Mycoff, P. Trucco, and M. Ricotti. 2010. "Economic Features of Integral, Modular, Small-to-medium Size Reactors." Progress in Nuclear Energy 52: 403-414.

Feiveson, H. 2001. "The Search for Proliferation-resistant Nuclear Power." J. Fed. Am. Sci. 54: 1–9.

Hill, D., W. Ragland, and J. Roglans. 1998. "The EBR-II Probabilistic Risk Assessment: Lessons Learned Regarding Passive Safety." Reliability Engineering and System Safety 62: 43-50.

IAEA (International Atomic Energy Agency). 2002. Heavy Water Reactors: Status and Projected Development. IAEA: Vienna, Austria.

IAEA (International Atomic Energy Agency). 2006. Status of Innovative Small and Medium Sized Reactor Designs 2005: Reactors with Conventional Refueling Schemes. IAEA: Vienna, Austria.

IAEA (International Atomic Energy Agency). 2011. Status of Small and Medium Sized Reactor Designs: A Supplement to the IAEA Advanced Reactors Information System (ARIS). IAEA: Vienna, Austria.

Kuznetsov, V. 2010. "Overview of IAEA project 1.1.5.5 'Common Technologies and Issues for SMRs SMRs'." 4th INPRO-GIF Interface Meeting, 1-3 March, VIC, Vienna, Austria.

Kuznetsov, Y. and B. Gabaraev. 2007. "Non-electricity Application of Nuclear Energy: Some general Issues and Prospects." IAEA Conference, Oarai.

Modarres, M. 2010. "PRA Overview." U.S. Nuclear Regulatory Commission, Pre-Application Meeting, June 2, Rockville, MD.

Richter, B. 2008. "Reducing Proliferation Risk." Issues in Science and Technology Fall: 45-52.

Rosner, R. and S. Goldberg. 2011. "Small Modular Reactors—Key to Future Nuclear Power Generation in the U.S." EPIC, University of Chicago: Chicago, USA.

Schropshire, D. and J. Herring. 2004. "Fuel-cycle and Nuclear Material Disposition Issues Associated with High-temperature Gas Reactors." In Proceedings of the Americas Nuclear Energy Symposium (ANES). Miami Beach, FL, USA, 3–6 October.

World Nuclear Association. 2013. "World Nuclear Power Reactors & Uranium Requirements." http://www.world-nuclear.org/Nuclear-Basics/