The state of progress and associated challenges in the global deployment of small modular reactors

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Abstract: Small Modular Reactors (SMRs) represent an innovative class of reactors with the advantages demonstrated through the reliable history of the current fleet coupled with a unique operational paradigm that may facilitate their deployment. This paradigm refers to new markets: nuclear hybrid energy systems; baseload generation to back intermittent renewable sources or process heat applications; decentralised electricity grid generation, where electricity demand may not support large reactors or the water supply is limited; and construction of single modules at a time, allowing new investors to enter the market with lower investments risks. With the increase in wind and solar generation worldwide, the inherent electricity grid and market fluctuations must be addressed. SMRs offer one potential solution; however, the social, political, and economic challenges must be overcome in regions where nuclear power is already prevalent. Other obstacles exist in new nuclear markets, including the development of a regulatory body and supply chain.

Keywords: small modular reactors; regulatory challenges; new nuclear deployment; market potential; international standards; energy security; hybrid energy systems; combined heat and power; intermittent renewable energy; electricity market fluctuations; availability; fuel cost.

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Li (Emily) Liu is an Associate Professor in the Nuclear Engineering and Engineering Physics Program at Rensselaer Polytechnic Institute. As a Physicist and Nuclear Engineer by training, her research is focused on solving high-impact problems associated with energy and the environment through fundamental investigations into the structure-function relationships of materials. For this purpose, she is developing a variety of experimental and computational tools based on neutron, X-ray, and light scattering as well as molecular dynamics (MD) simulations. More importantly, her work focuses on direct nanoscale experimental validation of simulation results as well as the integration of simulation, experiments, and theories at various length scales.

1 Introduction

The global development of new nuclear reactors is progressing, with 70 reactors currently being constructed and an additional 190 reactors in the planning or proposal stages (IAEA, 2014). The current fleet of large commercial reactors has demonstrated stable, long-term fuel costs, low greenhouse gas emissions, and baseload generation with high availability and long refuelling intervals. Although large commercial reactors are capable of supporting industrial process heat applications or intermittent renewable technologies, Small Modular Reactors (SMRs) are particularly well-suited to these scenarios, especially with reactors of many different types under development, including light water, heavy water, gas, metal, and molten salt-cooled technologies (Boldon et al., 2015). The flexibility in reactor type and design, colocation of modules at a single site, and the potential for mass manufacturing of standardised modules all lend themselves to an international SMR marketplace, which will allow for new nations to reap the environmental benefits and electricity security offered by nuclear energy. Although each SMR design will inherently exhibit distinct risks, the fundamental drivers of their development will be economics and marketability, social and political acceptance, and environmental concerns. This paper provides an overview of the economic and political considerations for SMR deployment and explores key distinctions in the financial, regulatory, and licensing needs for developing and developed nations.

2 Marketability

The electricity market is influenced by competition, the political and public environment, and environmental concerns. Several factors should play a role in determining which energy options are more economically competitive. The first is the stability of long-term fuel prices, which allows for better cost-estimates over the lifetime of a facility. Fossil fuels have exhibited large fuel cost fluctuations, while uranium prices have been relatively constant over the last 20 years (illustrated by the electric utility's monthly cost for heavy oil, natural gas, coal, and uranium shown in Figure 1) (NEI, 2013a). A second factor is the proportion of total costs that is comprised of fuel costs. According to the Nuclear Energy Institute (NEI), approximately 86% of natural gas production costs in the USA are comprised of fuel costs, while only 31% of nuclear production costs are associated with fuel; thus, any natural gas price fluctuations will be more directly translated to the end-users of the electricity (NEI, 2013b). A final factor is the availability or capacity factor of the technology. Figure 2 illustrates the availability of several distinct energy sources over a three-year period (EIA, 2013). The high availability of nuclear technologies is beneficial to both the electricity grid and market stability. Furthermore, the reduced availability of energy technologies may be directly related to shorter refuelling intervals and greater fuel use.

Figure 1 Electric utility monthly fuel cost (₵/kWh) for oil, natural gas, coal, and nuclear energy from 1995 to 2012 in $2012 (NEI, 2013a) (see online version for colours)

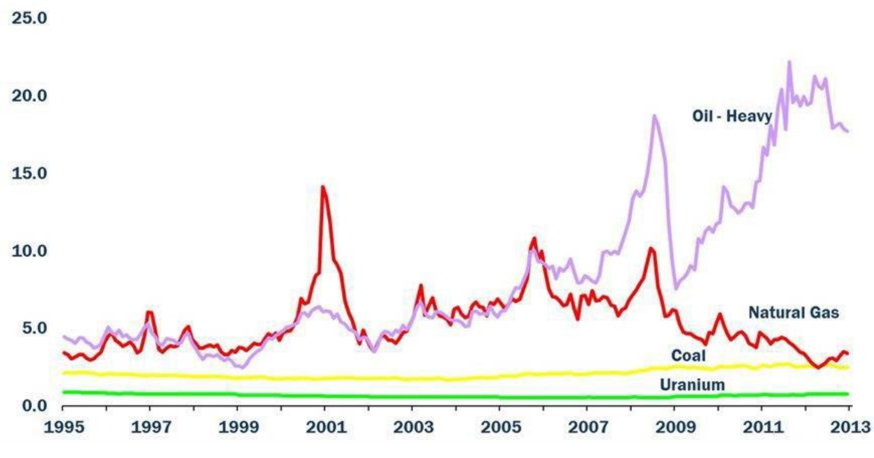
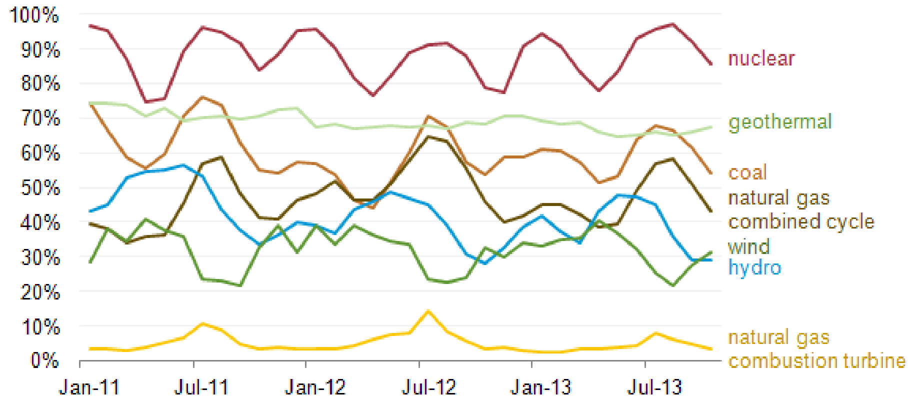


Figure 2 Capacity factors for distinct generating technologies from January 2011 to October 2013 (EIA, 2013)



According to the Environmental Protection Agency and the US Department of Energy, there is substantial market potential for combined heat and power facilities – approximately 40 GW domestically (DOE/EPA, 2012). This is one potential deployment paradigm that may further SMR deployment, especially in regions where desalination is necessary for clean drinking water. SMRs may also be paired with process heat facilities that require heat production similar to the output of smaller SMR designs. Flexibility in supporting either electricity demand or process production would also be economically beneficial. These types of facilities would support the move towards more sustainable energy systems. For example, if 40 GW of available combined heat and power in the USA was utilised, an estimated one quadrillion BTUs would be conserved and 150 million metric tons of carbon dioxide would not be emitted into the environment (DOE/EPA, 2012). As environmental regulations become more stringent in regards to greenhouse gas emissions, nuclear energy may become more economically viable. Although nuclear energy could help reduce greenhouse gas emissions on a long-term scale, climate change alone will not help increase the energy market share of the technology unless government policies (such as carbon taxes) are implemented and these policies force energy producers to internalise the effects of harmful emissions (IAEA, 2007).

3 Political acceptance and deployment

The political environment and nuclear regulatory framework will directly influence the ability to deploy SMRs in a reasonable time frame through licensing capability, incentives, and environmental regulations. To obtain a license, a particular SMR design must demonstrate reactor and radiation safety, as well as plant security (Magwood, 2001). The primary differences in SMRs and typical large commercial reactors are staffing requirements, the emergency planning zone, and siting of multiple units on a site. Once licensing is obtained for a design, it will be necessary to manufacture modules to reap the economic benefits. This is the only method of improving major construction delays, cost overruns, etc., which increase the financial risks associated with nuclear power plants. The present, near-term SMR landscape is limited to a handful of integral pressurised water reactor designs. To further development of manufacturing facilities, SMRs must initially penetrate the market with a single SMR type. This allows for standardisation and mass production of components in assembly-line facilities. Furthermore, it allows for improved construction and operational learning within a skilled workforce, all of which improve SMR safety and economics. A manufacturing licence may also help establish the mass manufacturing of SMR modules that would support extensive deployment. Government involvement at multiple stages of deployment will also be essential to promote nuclear technologies. The first stage is through economic incentives such as the carbon tax to internalise pollutants and emissions, loan guarantees, cost sharing, asset allocation, etc. These economic incentives reduce some of the investment burden (IAEA, 2008). Inclusion of nuclear energy in sustainability and renewable energy policies is also significant and will promote future development.

There is strong agreement that electricity and human development are highly integrated and that human development factors often increase with electrical system development (Pasternak, 2000; Abdel-Aziz et al., 2009). Therefore, to support human development within these nations, it is necessary to enhance energy reliability, economy, and security. Developing countries are often highly dependent on fossil fuels and are subject to supply changes, price fluctuations, and significant climate change effects. Nuclear power may provide a method of mitigating some of these negative impacts. However, nuclear integration in developing nations will require methods for introducing nuclear training and education. This requirement will result in a supply chain to maintain the technologies. Similarly, standardised design, construction, and manufacturing must be established so that licensing may reference widely applicable international standards and codes.

SMRs may provide energy security through stable, long-term fuel and market prices and flexibility in operations through renewable energy support, process heat applications, potential operation in smaller electricity grids, and siting in regions with limited water availability (Carelli and Ingersoll, 2015). Developing countries like Jamaica and Ghana are highly susceptible to oil price supply and fluctuations, which drastically effect electricity availability and prices. Historical fuel prices (shown in Figure 1) clearly demonstrate the stability of nuclear fuel and the instability of fossil fuels. SMR designs may utilise significantly less water resources than large reactors and some fossil fuel technologies reduce the downstream pollution associated with fossil fuel plants (Carelli and Ingersoll, 2015). They may also be paired with desalination to supply clean water to a region. Baseload production offers a stable and predictable power supply and will ultimately support human development without the negative environmental problems of fossil fuel technologies. Many developing nations contain megacities, with some of the largest populations in the world. Air pollution and other negative climate change impacts are prevalent in these locations and will only get worse as fossil fuels are continually used (Zhu et al., 2012). SMRs may be deployed flexibly as fossil fuel plants are replaced and retired or as electricity demand increases; therefore, fewer additional fossil fuel plants must be constructed. They may also be located closer to the megacities than typical light water reactors due to enhanced safety systems, particularly if developing nations have culturally different perspectives on nuclear power than many developed countries (IAEA INPRO DF 5, 2012; Hecht, 2012).

When exporting nuclear energy technology, a licence is obtained within the country of deployment, regardless of the particular regulatory body and oversight in either the country of origin or the destination (Carelli and Ingersoll, 2015). This often creates problems because standards and codes are adopted for one country and do not promote international deployment. Another concern is that developing counties may not have an internally established nuclear program that includes the manufacturing supply chain through construction, operation, and regulation. Thus, any deployment in developing countries is subject to the regulatory requirements of the country exporting the good (Carelli and Ingersoll, 2015).

International development of codes and standards will be necessary to facilitate further deployment of SMRs in an international market place. The Nuclear Energy Standards Coordination Collaborative was created to provide a forum for international collaboration to amend current international standards and establish new ones where needed for future progress in nuclear design, licensing, fabrication, etc. (Carelli and Ingersoll, 2015). The Nuclear Energy Standards Coordination Collaborative aims to develop technology-independent standards for materials and methods. These standards could be utilised by a new regulatory body that lacks technical expertise or experience to independently analyse new applications for licensing. Furthermore, operators, manufacturing facilities, equipment, processes, and standardised operation and maintenance may even be issued an SMR international certification (Carelli and Ingersoll, 2015). Many developing countries may receive aid from developed countries to support new energy deployment; SMR deployment may prove difficult if aid nations promote the use of non-nuclear energy technologies (World Bank, 2010). Revisions to the lending policies for aid nations may promote SMR deployment, particularly if they take emissions or other externalities into account (World Bank, 2010).

4 Conclusion

New nuclear energy deployment will require substantive investment and the assumption of risks in terms of policy and regulation, marketability, and social acceptance. For scenarios such as combined heat and power or hybrid energy systems to become feasible, licensing must be further studied, along with the ability to obtain long-term agreements between utility companies and process heat users. Proximity to another facility may change the conditions of widely accepted and practised regulations and would likely impact the accident scenarios required for licensing. In developed nations with prior nuclear experience, the investment risks are mitigated because a regulatory body may already exist and may be capable of assessing the technical aspects and safety. Furthermore, the necessary capital for investment and the capacity for government support through risk sharing or loan guarantees may be present. In developed nations with no prior experience, the financial capabilities may be present, but the regulatory body and supply chain have yet to be established. Therefore, the required expenses and associated deployment delays will make such projects less economical. Similarly, developing nations may lack the expertise, workforce, and infrastructure to support nuclear development. Because of the financial situation of the country, nuclear energy may not be an option, particularly if aid is received from a nation that does not favour nuclear energy.

The world's megacities are often located in developing nations, where electricity demand will continue to increase and influence the production of greenhouse gas emissions. If options are not put in place to support nuclear and renewable development within these countries, it is more than likely that greenhouse gas emissions will exceed any energy conservation or reduction measures put in place in other developed nations. As a result, new nuclear deployment must be made on an international scale, utilising international standards and providing an alternative to nations that cannot sustain their own regulatory body and/or supply chain. International standards would further facilitate the export of technologies between countries and provide a sound basis for safety analysis. Furthermore, standardised designs would provide a more efficient and effective manner of training a new workforce and introducing a nuclear supply chain. These designs would also make the licensing process simpler for faster deployment. SMRs offer a unique opportunity, with simpler designs that may exhibit shorter refuelling intervals, enhanced proliferation and sabotage resistance, passive cooling systems, and remote siting capabilities, all of which lend themselves to both developing and developed nations.

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