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New to Nuclear Countries: Considerations for Adoption of Small Modular Reactors – A Guide to Future Adopters

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Abstract

Small Modular Reactors (SMRs) are under development in a number of countries. This class of reactors, with enhanced safety and security inherent to their design, can potentially offer advantages to countries adopting nuclear power for the first time. This includes countries considering expanding existing nuclear power capability using the benefits of Generation III+ and Generation IV technological advances. For example, public perceptions and engagement in relation to nuclear safety and security are important and need to be addressed. The regulation of nuclear power plants and the management of the nuclear fuel cycle are also important considerations. For some countries, an industrial strategy linked to participation in the nuclear fuel cycle could be a priority, associated with the development of a sophisticated workforce to support the design, construction, commissioning and operation of a fleet of reactors. Some countries will choose to be early adopters of SMRs. Others may prefer to wait until the technologies are more established. This paper will focus on the potential appeal of different SMR designs in relation to the considerations that new to nuclear countries must address and how this underpins effective decision making.

Keywords: Small modular reactors, nuclear power, national strategy, public engagement

Introduction

The history of civilian nuclear power can be summarised somewhat by the simple axiom of 'bigger is better'. From the early days of Shippingport's 60MWe nuclear power plant (NPP) to today's 1650 MWe European Pressurised Reactor (EPR), reactor engineers have steadily increased the power output of each NPP design, benefitting from the accumulated 50+ years of pressurised water reactor (PWR) operational experience and assisted by increasingly sophisticated computational tools for simulating reactor dynamics and material degradation. However, the problem with 'bigger is better' is that it invariably locks out those countries without the means to provide the $5-7 billion USD outlays required for implementing gigawatt-scale large reactor (LR) energy solutions. Such countries, like so many, aspire to improve the standard of living of their people but are constrained by the lack of electrical capacity. This is evident by an examination of statistics which show the daily per capita usage of electricity in developing countries to be less than 4 kWh, in contrast to the developed world which uses on average more than 12 kWh per person per day.

The search for greater electrical production in the face of diminishing hydrocarbon resources, price volatility and expensive renewables is difficult. However, nuclear can make a contribution for small nations and utilities alike if reactor systems are made with lower build costs, enhanced safety, improved build quality, pre-licensed conditions, non-proliferation safeguards and reduced build-time. Understanding these needs, a consortium of companies, national laboratories and universities initiated the International Reactor Innovative and Secure (IRIS) program to develop the basis of what is now widely known as the light water Small-Modular-Reactor (LW-SMR), also known as the integral Pressurised Water Reactor (iPWR). The design for a safer, smaller, modular-build / low-initial-cost reactor will alleviate some of the challenges facing nations looking to introduce nuclear power.

Challenges include:

1. the need to develop a regulatory body in new nuclear nations.
2. the need for public engagement on nuclear technology and public familiarisation with the nuclear regulatory process.
3. the need to develop a specialised technical workforce
4. the usually high initial cost of building a gigawatt-output large reactor (LR) that may be alleviated by SMRs.
5. the need for financial structures catering for the initial high cost of reactor-build but relatively lower operational & maintenance (O&M) and fuel costs during its 60-year lifecycle.
6. the risk associated with a usually prolonged process for attaining a site-license to build and license to operate.
7. the need for a spent fuel repository, a re-processing facility or a buy-burn-return agreement from fuel suppliers.

Nuclear power in the Pacific Rim

Table 1: Major electricity producers of the Pacific Rim

Country	Installed Capacity* (GWe)	Electricity usage* TW.h / yr	Nuclear power as % of domestic electricity**
China	1,100	4,491	2.1%
United States	1,053	4,048	19.4%
Japan	287	963	0% - 26%
India	238	975	3.4%
Russia	232	997	17.5%
Canada	139	644	16.0%
Korea, South	85	495	27.6%
Mexico	62	278	4.6%
Australia	60	255	no nuclear installed
Taiwan	49	235	19.1%
Indonesia	41	173	no nuclear installed
Asian countries	N. & S. America	Oceania	

Sources: *US Energy Information Administration, 2013

**World Nuclear Association, 2013

Although many developed economies have adopted nuclear power, smaller nations face many challenges as outlined above. Furthermore experience has demonstrated that sustained public engagement is necessary to ensure people are aware of the benefits of nuclear power. These benefits should be presented along with a practical understanding of the risks involved in reactor operations which are small, given the multi-decade effort of reactor engineers and nuclear regulators to continuously improve reactor safety.

Table 1 displays the top 11 Pacific-basin countries for electricity usage including India for comparison. It can be seen that the top 8 countries with large GDPs are nuclear power capable but those without include smaller nations of lower GDPs, such as Indonesia, Thailand and Malaysia (table 2). However this is set to change as most new-builds are occurring in the Asia-Pacific region, where there are concerns with pollution, carbon emissions, increasing fuel prices and energy security.

Table 2: Medium sized electricity producers of the Pacific Rim

Country	Installed Capacity (GWe)	Elec. Usage (TW·h/yr)	Population ('000)	daily kWh per capita	Plans for NP?
Australia	59.130	255.00	23,061	30.30	none
Taiwan	48.750	235.00	23,316	27.61	NPP operational
Indonesia	39.900	173.00	247,425	1.92	Developing Plans
Thailand	32.600	131.60	66,720	5.40	Developing Plans
Vietnam	26.300	101.00	90,388	3.06	Committed Plans
Malaysia	25.390	93.80	28,334	9.07	Developing Plans
Chile	16.210	56.35	17,403	8.87	Developing Plans
Philippines	16.360	54.40	103,776	1.44	Under discussion
Singapore	10.250	41.20	5,312	21.25	Under discussion
Bangladesh	10.260	39.10	161,084	0.67	Committed Plans
New Zealand	9.679	38.56	4,468	23.65	none
Sri Lanka	2.685	9.27	20,278	1.25	Under discussion
Papua New Guinea	0.700	2.76	6,310	1.20	none

Sources: US Energy Information Administration, 2013; CIA Factbook.
Data from years 2010 - 2013; NPP deployment data: Locatelli (2014)

An examination of the fifth column in table 2 tells a story of disparity between energy rich and energy poor nations. Wealthy, industrialised countries including Australia, Taiwan, Singapore and New Zealand have daily per capita energy usage of over 20 kWh. Of these four lead countries in electricity production, neither Australia nor New Zealand has nuclear power. Taiwan operates a number of nuclear power plants. On the other hand, nearly all developing South East Asian nations have plans at various stages of development, to implement nuclear power despite its characteristically high upfront cost.

As set out by Locatelli et al. (2014) [6], countries committed to the introduction of nuclear power include Vietnam which is securing four Russian VVER-1000s. Bangladesh have also committed to a nuclear power program - two VVER-1000s. Thailand, Indonesia, Malaysia and Chile are in the process of developing plans for nuclear. Finally, in the phase of public discussion for nuclear power are the Philippines, Singapore and Sri Lanka.

Surveying the S.E. Asian region of growing nuclear power needs, there is ample opportunity for smaller output SMRs to contribute towards green energy demand. The options for SMRs span from Integral Pressurised Water Reactors (iPWR) to High Temperature Gas Reactors (HTGRs), Sodium Fast Reactors (SFRs) and even Molten Salt Reactors (MSRs) but in the near future it is the integral PWR (iPWR) which will have the most impact because of its 8-10 year timeframe [10] to market as opposed to the 20 year time scales of most advanced designs. Two leading iPWR designs mPower and NuScale are in the process of NRC review for licensing, while Russia has a variety of marine-reactor derived LW-SMRs and the Argentinian CAREM and Korean SMART SMRs are either under construction or in advanced development. The Chinese CNNC / NPIC's ACP-100 has finalised its preliminary design and has submitted a preliminary PSAR.

Table 3: Small Island States

Small Island States	Installed Capacity (MWe)	Elec. Usage (TW·h/yr)	Population ('000)	daily kWh per capita	Pop. density (person/sq. km)
Fiji	250	0.87	858	2.76	47
Maldives	62	0.27	338	2.19	1,136
Samoa	41	0.10	194	1.39	68
Solomon Islands	36	0.09	550	0.45	19
Vanuatu	28	0.06	247	0.66	20
Tonga	12	0.05	103	1.39	138
Nauru	1	0.03	9	8.69	447

Sources: US Energy Information Administration, 2013; CIA Factbook.
Data from years 2010 - 2013

Nuclear Power and Small Island States

Small Island States (SIS) face the combined challenges of a growing population, rising fuel costs and a small and possibly shrinking landmass resulting from rising sea-levels. Unfortunately for reasons of economics, most SIS burn hydrocarbons for electricity using combustion plants that are cheap to build but expensive to fuel. Renewables are attractive in theory but difficult to implement for reasons of siting and economics. Table 3 shows high population densities for SIS, highlighting the issue of land scarcity for siting of power plants. To address this need barge-mounted-nuclear reactors could be a valid option. Russia is nearing completion and commissioning of the ship-borne KLT-40s PWR which produces up to 70 MWe with additional heating capacity, sufficient for supplying a population of 200,000. The floating nuclear power station designed by OKBM Afrikantov is envisioned as a turn-key system which will return to Russia for decommissioning, returning the SMR host country to a 'green-field' state. However logical nuclear power may seem for small-island states, local public sentiments have historically remained anti-nuclear. A reversal of this position will require sustained community engagement and public discourse.

Financing for SMRs

The high up-front costs of LRs are a major impediment to the introduction of nuclear power. Early studies by Hayns and Shepherd [3] concluded that the capital costs of 1 x LR are equal to the cost of 4 x SMRs of equal aggregate electrical output. A recent study by NEA / OECD [7] concluded that 4 x SMR would cost somewhere between 100-150% of a single LR of equivalent output. Prices provided by SMR vendors are more conservative with mPower and NuScale estimating an SMR overnight cost (ONC) between \$4000-\$5000/kWe. In comparison EPR ONC is $ 3860 / kWe and VVER-1150 ONC is $2930/kWe [5], resulting in a SMR/LR cost ratio between 1.03 and 1.70.

The point to note here is that the initial cost of building a SMR, though slightly higher than one quarter that of a LR, is a significant reduction in up-front costs and that this could sway the argument for green-lighting a SMR construction. The large price tag of LRs may not be of significance for national utilities but for private utilities operating in a deregulated energy market the lower price tag of a smaller reactor with shorter lead-times and faster cash-flow generation will make a significant difference.

More importantly, SMR's shorter timeframes to operate gives utilities the option of using the operational plant as collateral for financing the next stage of modular build. The next module would cost less as a result of lessons learnt from the first install and from the possible cost reduction of co-siting subsequent units with the first. [6]

Sub-contracting work for building SMRs to new nuclear countries could be an added incentive for boosting local employment and know-how. A similar business strategy has been adopted by other multi-billion dollar projects, such as the Boeing 787 commercial airliner which sources not only parts but entire sub-sections from the countries that are also 787 customers. Such a strategy not only improves the host countries' skills and R&D but also strengthens global economic trade and co-operation.

The recent strike-price deal of 92.5 GBP / MWh between UK and EDF [9] shows a trend for governments to externalise NPP build-risks to large utilities and reactor vendors. The structuring of such deals allows the EDF group to charge electricity at a higher price to recover build costs. An alternative approach is the the Finnish 'mankala model' which gathers multiple utilities and end users to finance NPP construction. Both the UK-EDF deal and Finnish model are examples of reduced government exposure to NPP construction cost overruns. Considering the lower build costs and lead times of SMRs, SMR financing could become even more attractive to utility and commercial based financing; thus allowing SMRs to be built at a higher rate than LRs.

Power plant replacements and appropriate capacity sizing

Many Asian-Pacific countries like Malaysia, Indonesia and Australia are coastal-dwelling nations with long power-grid structures requiring vast distances of transmission. A network of distributed SMR power stations can serve to distribute energy production more efficiently, minimising transmission losses with the added benefit of bringing employment to more regional areas. Moreover, the modest output of SMRs at less than 300 MWe allows their deployment on electrical grids without upgrades to existing transmission infrastructure.

Industrialised and developing nations alike face the prospect of replacing aging coal fired power plants. The lower power outputs of SMRs make them an ideal solution for replacing the dispatchable and high-capacity generation of coal fired power plants but without the associated pollution which comes from burning coal. Nuclear has always been designed to operate as a concentrated, clean, low-emission energy source.

Finally, some SMRs like mPower are designed with air cooled condensers which allow their installation in dry remote locations where water is scarce [1]; mPower quotes a power reduction from 180 MWe for water-condensed cooling to 155 MWe for air-condenser cooling as a result of reduced thermodynamic efficiency but this allows the SMRs great flexibility for deployment, especially near inland mining operations.

Smaller reactors for smaller initial outlays

Light Water Reactor (LWR) based NPPs are a mature industry with over 50 years of experience. Nuclear technology, developed by leading industrial economies, is well understood and nuclear power utilities have enjoyed profitable operations. The general trend of increased size, power and electrical output has been driven by the need to achieve greater economies of scale alongside steadily increasing costs in labour and resources. As such, large outlays are often beyond the means of small-nations or private utilities without government financial assistance.

From this perspective, the advantages of small modular reactors come into play. Designed to be factory-fabricated, small modular reactors use assembly-line and batch-production techniques to deliver the scale-of-multiple advantages achieved in the mass-production of aircraft and cars. In addition, their small size allows ease of transportation to remote locations for installation.

Smaller reactors for safer operations

Smaller is also synonymous with safety. By integrating the pressuriser, heat exchanger, control rod assembly and reactor core in the same pressure vessel, SMRs eliminate the large-pipe-break Loss Of Coolant Accident (LOCA) scenarios of large PWRs. This reduces the probability of a SMR core breach by a magnitude or more compared to today's already very safe Gen III+ PWR designs. Also, many SMRs under development have passive safety systems which require no external electrical supplies or pumps for emergency cooling; thus making them defensible against a Loss of Electrical Power (LOEP) accident scenario as experienced in Fukushima.

Innovative designs like NuScale and CAREM use passive natural-convection primary cooling systems that operate during reactor-operation and shut down conditions. The lack of primary coolant pumps greatly simplifies the primary cooling system and introduces new inherent safety factors. With passive physics-driven systems, these SMRs do not require the active pumping systems of LRs. It's important to note the passively driven primary loops of SMRs are only feasible on account of their small sizes and lower power outputs which are not possible for the large powers of LRs.

There are however features from LRs which are kept for SMRs. To capitalise on the experience gained from LR operations with standard 17 x 17 fuel assembly bundles, NuScale, mPower and SMART will use similar fuel bundle layouts albeit at a half-height of 2 meters. The neutronics and thermohydraulic characteristics of standard 17 x 17 fuel bundles have been thoroughly documented and characterised through rigorous reactor engineering design, testing and operation, and approved by regulatory processes, leading to confidence by operators, regulators and the public. Utilising standard fuel is a conservative and risk minimised approach to engineering, which will expedite the process of reactor licensing.

Longer burn, higher plant capacity

Refueling schedules of SMRs like mPower have been extended to 4 years as opposed to the 18 – 24 month cycle typical of current LRs. Longer reactor cycles translate to higher plant capacity. Current NPPs already operate at very high capacity of +85%, SMRs aim to have a higher capacity factor of 90 - 95%.

Given both the mPower and AP1000 use the same type of fuel with the same level of enrichment of 5% but with a longer core residence time , the mPower fuel would be burnt at a lower power density when operating which translates to lower fuel operating temperatures. Also, the lower power density results in a lower rate of fission product production which reduces the passive cooling requirements of normal and accident-initiated shut down conditions.

Maintaining proliferation resistance

Current LWRs replace 1/3 of their fuel bundles at approximately 18-24 months intervals. As the uranium-dioxide fuel is burnt, U-238 is converted to Pu-239 via neutron capture which is subsequently burnt as fuel. To ensure non-proliferation is maintained, the IAEA tracks fuel movements of LWRs so that fuel is not extracted from the reactor for anytime less than 6 months. This ensures further neutron capture by Pu-239 to produce Pu-240 which renders the overall content of the plutonium unsuitable for weapon making purposes. By extending the length of time the reactor fuel spends in the core and maintaining similar burn-up percentages, the non-proliferation qualities of SMRs are maintained.

Fuel leasing

New-to-nuclear countries without established nuclear fuel cycle infrastructure could benefit from a buy-burn-return scheme for the lease and return of reactor fuel. This scheme pioneered by the Global Nuclear Energy Partnership (GNEP; now evolved to IFNEC) will help to alleviate the technological hurdles facing new-to-nuclear countries when establishing a nuclear power program and will enhance nuclear-non-proliferation by centralising the distribution and recovery of spent fuel.

The vendor country leasing and receiving spent fuel should be signatories to the Nuclear Non-proliferation Treaty (NPT) to ensure spent fuel is not diverted. The buy-burn-return scheme could be especially suitable for iPWRs which are designed with a ‘cassette-core’ that can be completely swapped out without fuel reshuffling. For some small countries or countries located in areas of geopolitical instability the benefits of fuel leasing would offset the higher embedded cost of this option.

The solution may be for countries with established fuel fabrication, radioactive waste reprocessing and waste repositories to facilitate the leasing and recovery of spent fuel, in a manner similar to the U.S. leasing of TRIGA fuel to research reactor overseas.

SMR licensing for nuclear countries new and old

Despite the focus of enhanced safety for novel and LWR-based SMRs, all new SMRs will require thorough and lengthy licensing review by their respective national nuclear regulatory authority. Of the many SMR designs under various stages of development, SMRs licensed by the US NRC under 10 CFR Part 52 could be internationally regarded as one of the most stringent and comprehensive of licensing processes. As explained by Ramana et al. (2013), 10 CFR Part 52 combines the traditional two step approach of authorisation to construct and license-to-operate under a single license. The UK Generic Design Assessment also has attractive features that could be considered for an international licensing framework.

The benefits of smaller NPPs with lower initial capital investments, smaller site exclusion zones, smaller core power and safer passive systems, can do much to sway the energy debate of many countries in favour of nuclear power. For countries with established nuclear regulatory structures, new SMRs would be assessed under local regulatory frameworks. For countries new to nuclear power, it is possible that the host countries may adopt the US NRC licensing procedure or strengthen multilateral approaches to generic design assessment.

Licensing SMRs under an adopted US NRC or UK regulatory framework could bring overall improvements to reactor safety assessments for new-to-nuclear countries. Such an approach would introduce uniformity and cohesion to safety analysis, in-line with global-best-practice methods. Also if the licensing of SMRs by the US NRC was internationally recognised, it would reduce the delay and uncertainty of SMR new-builds in countries unfamiliar with nuclear power regulation. However, such an approach would require a very thorough analysis of each SMR design as recommended by the IAEA which include:

1) a detailed assessment of first-of-a-kind technologies of new SMR systems: e.g. natural convection primary loop dynamics and passively driven decay heat removal.
2) the viability of multi-modules on a single site
3) control room staffing for multiple modules
4) determination of radiological source term for the modelling of accidents for SMRs
5) assessment of a reduced emergency planning zone (EPZ) size for SMRs
6) proliferation resistance
7) the use of risk-informed licensing methods and
8) the potential for technology transfer to other nations.

There will be a difference between a first-of-a-kind licensing framework for SMR first-builds and a global licensing regime when a significant global fleet has been built.

Under a global licensing regime, one possible set up is:

1. Licensing the SMR once from the country of origin, and
2. Installing a monitoring regime for the operation of the SMR in its host country

Potential SMR host countries, such as small-island-states, are limited in manpower and technical resources for nuclear regulation. An international licensing arrangement would allow the adoption of nuclear power for these countries under the guidance of international surveillance teams assisting local personnel in the operation or monitoring of reactor operations. This would require careful design and development as well as new arrangements negotiated in international agencies.

Small modular reactors for smaller environmental footprint

Smaller implies a reduction in environmental impact. Current PWRs in the United States of America, are licensed on the condition that the site is surrounded by a 10 mile radius emergency planning zone (EPZ) and is in line with IAEA [4] recommendations for traditional gigawatt-output LWRs to be bounded by a recommended 25 km radius around the reactor site.

The NRC may allow a reduction of a SMR EPZ to below 2 km radius (Ramana et al, 2013), based upon the smaller probability of a containment breach event and smaller radiological source term in accident analyses. SMR developers in America, Russia and Korea are making their cases to regulatory bodies for reduced EPZ radii via justifications of intrinsic passive safety and defence-depth design features. Russian SMR EPZs for KLT-40S, VBER-3000 and ABV are at 1 km [7] and SMART designers are requesting an EPZ radius of 1.5 km with a low population zone radius of 2 km [8]. Thus, a smaller EPZ for SMRs is not improbable, given their enhanced passive safety characteristics and would assist in presenting an attractive economic and regulatory case for building SMR reactors.

Conclusion

Global demand for affordable, clean and sustainable energy will continue to rise. Many S. E. Asian countries striving to improve their standard of living are deploying electrical capacity that is usually driven by coal or gas which comes at the cost of pollution, CO_2 emissions and fuel price volatility.

Nuclear power provides an alternative source of energy that is clean, dispatchable and affordable but large scale implementation is hampered by high up-front costs and lengthy regulatory processes. Small modular reactors of the integral PWR variety are an engineering solution to the questions of finance, safety and deployment timescales that comes with nuclear power.

Synthesizing the lessons learnt from 50+ years of PWR operations, small integral PWRs are designed to have order-of-magnitude improvement in reactor probabilistic safety analyses and also designed to be defensible against Fukushima-type events. The simplification of design brings advantages in safety and their smallness allows mass-production, improving manufacturing efficiency, quality and reduces per unit costs.

SMRs' limit (< 300MWe) in electrical output places them as an ideal candidate for replacing coal fired power plants, serving as dispatchable and affordable electricity sources. The smallness of SMRs' size also allows substantially lower costs of construction relative to large reactors. By operating a longer burn-up cycle with a smaller fuel load, the likelihood and severity of iPWRs' radiological release is reduced; allowing the reduction of the Emergency Protection Zones (EPZs) from 16 km to below 2 km.

As noted by the Energy Policy Institute[1], SMRs should not be regarded as an alternative to gigawatt-scale Large Reactors (LRs) but as a category of reactors designed for niche markets unsuited for LRs. Integral SMRs show clear advantages in safety and affordability which increase the attractiveness of nuclear power and have the potential to contribute to growing energy demand.

References

[1] Chu, S., *America's new nuclear option - small modular reactors will expand the ways we use atomic power*. Wall Str. J.; March 23, 2010. http://online.wsj.com/news/articles/SB10001424052748704231304575092130239999278.

[2] Energy Policy Institute, Centre of Advanced Studies, USA, *Economic and Employment Impacts of Small Modular Reactors*; 2010. http://epi.boisestate.edu/media/3494/economic%20and%20employment%20impacts%20of%20smrs.pdf.

[3] Hayns, M.R., Shepherd, J., *SMR-reducing size can reduce cost*. Nuclear Energy 30, 85-93; 1991.

[1] Energy Policy Institute, Centre of Advanced Studies, USA, *Economic and Employment Impacts of Small Modular Reactors*; 2010. http://epi.boisestate.edu/media/3494/economic%20and%20employment%20impacts%20of%20smrs.pdf.

[4] IAEA. *Method for developing arrangements for response to a nuclear or radiological emergency*. Vienna, Austria: International Atomic energy agency; 2003.

[5] IEA/NEA, *Projected Costs of Generating Electricity:2010 Edition*, OECD, Paris, France, 2010.

[6] Locatelli G., Bingham C., Mancini M., *Small modular reactors: A comprehensive overview of their economics and strategic aspects*. Progress in Nuclear Energy, v 73, p 75-85; 2014.

[7] OECD-NEA, *Current Status, Technical Feasibility and Economics of Small Nuclear Reactors*; 2011.

[8] Park KB. SMART: an early deployable integral reactor for multi-purpose applications.Vienna, Austria; 2011.

[9] WNN, *Strike Price deal for Hinkley Point C*, October 21, 2013. http://www.world-nuclear-news.org/NN_Strike_price_deal_for_Hinkley_Point_C_2110131.html

[10] Kessides I., Kuznetsov V., *Small Modular Reactors for Enhancing Energy Security in Developing Countries*, Sustainability 4, pp 1806-1832, 2012.