SMALL MODULAR REACTORS

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1. INTRODUCTION

'Small modular reactors' (SMRs) would have a capacity of under 300 megawatts (MW), whereas large reactors typically have a capacity of about 1,000 MW. Construction at reactor sites would be replaced with standardised factory production of reactor components (or modules) then installation at the reactor site. The term modular also refers to the option of building clusters of small reactors at the same site.

SMRs don't have any meaningful existence. Some small reactors exist, and there are hopes and dreams of mass factory production of SMRs. But currently there is no such SMR mass manufacturing capacity, and no company, consortium, utility or national government is seriously considering betting billions building an SMR mass manufacturing capacity.

With near-zero prospects for new large nuclear power reactors in Western countries, SMRs are being promoted to rescue an industry that even nuclear lobbyists acknowledge is in crisis. In essence, the nuclear industry's solution to its expensive and uncompetitive large reactors is to offer up even more expensive reactors. SMRs clearly fail the two economic tests set by Prime Minister Scott Morrison: they could not be introduced or maintained without huge taxpayer subsidies, and they would result in higher electricity prices.

Previous attempts to build SMRs have failed and there is no reason to expect success now. M.V. Ramana concludes an analysis of the history of SMRs:
"Once again, we see history repeating itself in today's claims for small reactors – that the demand will be large, that they will be cheap and quick to construct. But nothing in the history of small nuclear reactors suggests that they would be more economical than full-size ones. In fact, the record is pretty clear: Without exception, small reactors cost too much for the little electricity they produced, the result of both their low output and their poor performance."

No private sector SMR projects have reached the construction stage. A handful of SMRs are under construction, by state nuclear agencies in Russia, China and Argentina. Most or all of them are over-budget and behind schedule. None are factory built (the essence of the concept of modular reactors). Alarmingly, about half of the SMRs under construction are intended to facilitate the exploitation of fossil fuel reserves in the Arctic, the South China Sea and elsewhere. Moreover there are disturbing, multifaceted connections between SMR projects and nuclear weapons proliferation.

The prevailing scepticism is evident in a 2017 Lloyd's Register report based on the insights of almost 600 professionals and experts from utilities, distributors, operators and equipment manufacturers. They predict that SMRs have a "low likelihood of eventual take-up, and will have a minimal impact when they do arrive".

Likewise, American Nuclear Society consultant Will Davis said in 2014 that the SMR "universe is rife with press releases, but devoid of new concrete."

A 2014 report produced by *Nuclear Energy Insider*, drawing on interviews with more than 50 "leading specialists and decision makers", noted a "pervasive sense of pessimism" resulting from abandoned and scaled-back SMR programs.

Dr. Ziggy Switkowski – who headed the Howard Government's nuclear review in 2006 – noted in 2019 that "nobody's putting their money up'' to build SMRs and "it is largely a debate for intellects and advocates because neither generators nor investors are interested because of the risk." Moreover "the window for gigawatt-scale nuclear has closed", Dr. Switkowski said, and nuclear power is no longer cheaper than renewables with costs rapidly shifting in favour of renewables.

World Finance reported in October 2018 that "while SMRs are purported to be the key to transforming the nuclear sector, history has painted a troubling picture: SMR designs have been in the works for decades, but none have reached commercial success.

Former World Nuclear Association executive Steve Kidd wrote about SMR "myths" in 2015.:
"The jury is still out on SMRs, but unless the regulatory system in potential markets can be adapted to make their construction and operation much cheaper than for large LWRs [light-water reactors], they are unlikely to become more than a niche product. Even if the costs of construction can be cut with series production, the potential O&M [operating and maintenance] costs are a concern. A substantial part of these are fixed, irrespective of the size of reactor."

2. OPERATING AND UNDER-CONSTRUCTION SMRS

SMR projects won't be immune from the major cost overruns that have crippled large reactor projects (all recent reactor projects in the US and western Europe have gone at least A$10 billion over budget). Indeed cost overruns have already become the norm for SMR projects.

Only one SMR is operating – Russia's floating nuclear power plant with two 35-MW reactors (and since it did not involve modular factory production, it can only loosely be described as an SMR). Estimated construction costs for Russia's floating plant increased more than four-fold and amounted to over US$10.6 billion per gigawatt (GW) (US$740 million / 70 MW). An OECD Nuclear Energy Agency report said that electricity produced by the Russian floating plant is expected to cost about US$200 (A$258) per megawatt-hour (MWh), with the high cost due to large staffing requirements, high fuel costs, and resources required to maintain the barge and coastal infrastructure.

The Minerals Council of Australia has acknowledged that there will be no market for SMRs unless costs can be reduced to A$60–80 / MWh, yet the world's only operating SMR is producing power at an estimated cost of A$258 / MWh.

Cost estimates for the CAREM SMR under construction in Argentina have ballooned. In 2004, when the CAREM reactor was in the planning stage, Argentina's Bariloche Atomic Center estimated an overnight cost of US$1 billion / GW for an integrated 300 MW plant. When construction began in 2014, the estimated cost was US$17.8 billion / GW (US$446 million for a 25-MW reactor). By April 2017, the cost estimate had increased to US$21.9 billion / GW (US$700 million with the capacity uprated from 25 MW to 32 MW).

Construction of the CAREM reactor was suspended in 2019 due to a 'financial breakdown' but construction resumed in 2020. The CAREM project is years behind schedule and costs will likely increase further. In 2014, first fuel loading was expected in 2017 but the project remains incomplete as of March 2021.

The estimated construction cost of China's 210 MW demonstration high-temperature gas-cooled reactor (HTGR) has nearly doubled, with increases due to higher material and component costs, increases in labour costs, and increased costs associated with project delays. China reportedly plans to upscale the design to 655 MW but China's Institute of Nuclear and New Energy Technology at Tsinghua University expects the cost of a 655 MW HTGR to be 15-20 percent higher than the cost of a conventional 600 MW PWR.

3. FAILED SMR PROJECTS

Numerous SMR projects have been abandoned or scaled back in recent years.

The Generation mPower SMR project in the US was abandoned in 2017 by Bechtel and Babcock & Wilcox after the expenditure of US$500 million – including a US$111 million federal government grant.

Transatomic Power gave up on its molten salt reactor R&D in 2018.

Westinghouse sharply reduced its investment in SMRs after failing to secure US government funding. Westinghouse CEO Danny Roderick said: "The problem I have with SMRs is not the technology, it's not the deployment − it's that there's no customers."

Warren Buffet's MidAmerican Energy gave up on its plans for SMRs in Iowa after failing to secure legislation that would force rate-payers to part-pay construction costs. Instead, MidAmerican has invested over US$10 billion in renewables in Iowa and is now working towards its vision "to generate renewable energy equal to 100 percent of its customers' usage on an annual basis."

In the UK, Rolls-Royce scaled back its SMR investment to "a handful of salaries" in 2018 and threatens to abandon its R&D altogether unless massive government funding is provided and a suite of demands are met.

China's demonstration high-temperature gas-cooled reactor is behind schedule and over-budget and plans for additional HTGRs at the same site have been "dropped" according to the World Nuclear Association.

TerraPower abandoned its plan for a prototype fast neutron reactor in China due to restrictions placed on nuclear trade with China by the Trump administration.

The UK government abandoned consideration of 'integral fast reactors' for plutonium disposition in 2019 – and the US government did the same in 2015.

4. INEFFICIENCIES

SMRs would be more inefficient than large reactors in every respect, and hence more costly.

A 2016 European Commission report notes that decommissioning and waste management costs of SMRs "will probably be higher than those of a large reactor (some analyses state that between two and three times higher)."

The 2016 South Australian Nuclear Fuel Cycle Royal Commission report stated: "SMRs have lower thermal efficiency than large reactors, which generally translates to higher fuel consumption and spent fuel volumes over the life of a reactor."

An article in the *Nuclear Technology* journal notes that integral pressurised water SMRs (iPWRs) "are likely to have higher requirements for uranium ore and enrichment services compared to gigawatt-scale reactors. This is because of the lower burnup of fuel in iPWRs, which is difficult to avoid because of smaller core size and all-in-all-out core management."

Prof. M.V. Ramana notes that "a smaller reactor, at least the water-cooled reactors that are most likely to be built earliest, will produce more, not less, nuclear waste per unit of electricity they generate because of lower efficiencies."

5. DISECONOMIES OF SCALE

Power produced by SMRs will be more expensive than large reactors. SMRs will inevitably suffer diseconomies of scale: a 250 MW SMR will generate 25 percent as much power as a 1,000 MW reactor, but it will require more than 25 percent of the material inputs and staffing, and a number of other costs including waste management and decommissioning will be proportionally higher. It is highly unlikely that potential savings arising from standardised factory production will make up for those diseconomies of scale.

Cost *reductions* arising from mass production of SMRs are entirely speculative. Cost *increases* arising from diseconomies of scale are certain – they are built into the very concept of SMRs.

6. INDEPENDENT ECONOMIC ASSESSMENTS

Every independent economic assessment finds that electricity from SMRs will be more expensive than that from large reactors.

Renewables coupled with storage are cheaper than SMRs. The CSIRO provides these estimates in a 2020 GenCost report:

	Low and high estimates (2020) A$/MWh
Nuclear - small modular	258-338
Wind + 2 hrs battery storage	84-107
Wind + 6 hrs pumped hydro storage	92-117
Solar PV + 2 hrs battery storage	88-133
Solar PV + 6 hrs pumped hydro storage	101-151

A study by WSP / Parsons Brinckerhoff, commissioned by the South Australian Nuclear Fuel Cycle Royal Commission, estimated costs of A$180–184 / MWh for large pressurised water reactors and boiling water reactors, and A$225 / MWh for SMRs based on the NuScale design (and a slightly lower figure for the mPower design that was abandoned in 2017).

The Minerals Council of Australia has acknowledged that there will be no market for SMRs unless costs can be reduced to A$60–80 / MWh, yet the independent study commissioned by the Royal Commission estimated costs of A$225 / MWh.

The Royal Commission's final report identified numerous hurdles and uncertainties facing SMRs, including the following:

- SMRs have a relatively small electrical output, yet some costs including staffing may not decrease in proportion to the decreased output.
- SMRs have lower thermal efficiency than large reactors, which generally translates to higher fuel consumption and spent fuel volumes over the life of a reactor.
- SMR-specific safety analyses need to be undertaken to demonstrate their robustness, for example during seismic events.
- It is claimed that much of the SMR plant can be fabricated in a factory environment and transported to site for construction. However, it would be expensive to set up this facility and it would require multiple customers to commit to purchasing SMR plants to justify the investment.
- Reduced safety exclusion zones for small reactors have yet to be confirmed by regulators.
- Timescales and costs associated with the licensing process are still to be established.
- SMR designers need to raise the necessary funds to complete the development before a commercial trial of the developing designs can take place.
- Customers who are willing to take on first-of-a-kind technology risks must be secured.

The Royal Commission further stated in its final report:
"Advanced fast reactors and other innovative reactor designs are unlikely to be feasible or viable in the foreseeable future. The development of such a first-of-a-kind project in South Australia would have high commercial and technical risk. Although prototype and demonstration reactors are operating, there is no licensed, commercially proven design. Development to that point would require substantial capital investment."

A 2015 report by the International Energy Agency and the OECD Nuclear Energy Agency predicts that electricity costs from SMRs will typically be 50−100 percent higher than for current large reactors.

A report by the consultancy firm Atkins for the UK Department for Business, Energy and Industrial Strategy found that electricity from the first SMR in the UK (assuming one is ever built) would be 30 percent more expensive than power from large reactors, because of diseconomies of scale and the costs of deploying first-of-a-kind technology.

An article by four current and former researchers from Carnegie Mellon University's Department of Engineering and Public Policy, published in 2018 in the *Proceedings of the National Academy of Science*, considered options for the development of an SMR market in the US. They concluded that it would not be viable unless the industry received "several hundred billion dollars of direct and indirect subsidies" over the next several decades "since present competitive energy markets will not induce their development and adoption."

A 2014 study published in *Energy and Power Engineering* concluded that fuel costs for integral pressurized water SMRs are estimated to be 15% to 70% higher than for large light water reactors, and points to research indicating similar comparisons for construction costs.

The Institute for Energy Economics and Financial Analysis states:
"For all the hype in certain quarters, commercial deployment of small modular reactors (SMRs) have to-date been as successful as hypothesized cold fusion – that is, not at all. Even assuming massive ongoing taxpayer subsidies, SMR proponents do not expect to make a commercial deployment at scale any time soon, if at all, and more likely in a decade from now if historic delays to proposed timetables are acknowledged."

7. NO-ONE WANTS TO BUY SMRS AND NO-ONE WANTS TO PAY FOR SMRS

SMR enthusiasts envisage a large SMR market emerging in the coming years. However there is no market for SMRs. Thomas Overton, associate editor of POWER magazine, wrote in 2014: "At the graveyard wherein resides the "nuclear renaissance" of the 2000s, a new occupant appears to be moving in: the small modular reactor ... Over the past year, the SMR industry has been bumping up against an uncomfortable and not-entirely-unpredictable problem: It appears that no one actually wants to buy one."

No company, utility, consortium or national government is seriously considering building the massive supply chain that is at the very essence of the concept of SMRs – mass, modular factory construction. Yet without that supply chain, SMRs will be expensive curiosities.

In 2019, Kevin Anderson, North American Project Director for Nuclear Energy Insider, said that there "is unprecedented growth in companies proposing design alternatives for the future of nuclear, but precious little progress in terms of market-ready solutions."

A 2018 US Department of Energy report states that to make a "meaningful" impact, about US$10 billion of government subsidies would be needed to deploy 6 GW of SMR capacity by 2035. But there's no indication or likelihood that the US government will subsidise the industry to that extent.

Canadian Nuclear Laboratories has set the goal of siting a new demonstration SMR at its Chalk River site by 2026. But serious discussions about paying for a demonstration SMR – let alone a fleet of SMRs – have not yet begun. The Canadian SMR Roadmap website simply states: "Appropriate risk sharing among governments, power utilities and industry will be necessary for SMR demonstration and deployment in Canada."

Companies seeking to pursue SMR projects in the UK are seeking several billion pounds from the government to build demonstration plants. But nothing like that amount of money has been made available. An industry insider said in 2017: "It's a pretty half-hearted, incredibly British, not-quite-good-enough approach. Another industry source questioned the credibility of SMR developers: "Almost none of them have got more than a back of a fag packet design drawn with a felt tip."

William Von Hoene, senior vice-president at US energy and nuclear giant Exelon, has expressed scepticism about SMRs, saying they are "prohibitively expensive".

A 2018 article in the Proceedings of the National Academy of Science summarised private-sector investment in SMRs and other 'advanced' nuclear concepts:
"Often, proponents of nuclear power note that private enterprise is faring better than the government at advancing non-light water reactor concepts. Indeed, more than $1.3 billion has been secured by close to four dozen such companies. However, a dozen of these are working not on advanced fission reactors but on fusion reactors or nuclear fuels. Another dozen reactors either belong to bankrupt companies (e.g., Westinghouse) or are proceeding at a very low level of activity (e.g., the DOE's Next Generation Nuclear Plant and various university ventures that are very much in the conceptual design phase). Moreover, while $1.3 billion sounds impressive, that sum is dominated by one firm, TerraPower, which has found it remarkably challenging to build or secure access to the range of equipment, materials, and technology required to successfully commercialize its innovative design."

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8. STATE-RUN SMR PROGRAMS

Funding for state-run SMR programs – such as those in Argentina, China, Russia, and South Korea – has been minuscule compared to investments in other energy programs.

South Korea, for example, won't build any of its domestically-designed SMART SMRs in South Korea ("this is not practical or economic" according to the World Nuclear Association). South Korea's plan to export SMART technology to Saudi Arabia is problematic and may in any case be in trouble.

China and Argentina hope to develop a large export market for their high-temperature gas-cooled reactors and small pressurised water reactors, respectively, but so far all they can point to are partially-built demonstration reactors that have been subject to significant cost overruns and delays.

Russia planned to have seven floating nuclear power plants by 2015, but only recently began operation of its first plant.

9. CREATIVE ACCOUNTING

SMR enthusiasts point to questionable reports.

The Energy Information Reform Project (EIRP) purports to have conducted a 'standardized cost analysis of advanced nuclear technologies in commercial development'. But the EIRP doesn't have any credible cost data or estimates for the 'advanced nuclear technologies' it considers (none of which are in commercial development). Indeed, the EIRP just uses estimates provided by companies involved in R&D, despite their obvious interest in providing low estimates. The EIRP researchers heavily qualified their findings: "There is inherent and significant uncertainty in projecting NOAK [nth-of-a-kind] costs from a group of companies that have not yet built a single commercial-scale demonstration reactor, let alone a first commercial plant."

The Minerals Council of Australia claimed in its submission to the federal nuclear inquiry that SMRs could generate electricity for as little as $60 per megawatt-hour (MWh). That claim is based on a report by the Economic and Finance Working Group (EFWG) of the Canadian government-industry 'SMR Roadmap' initiative. Yet the EFWG paper takes a made-up, ridiculously-high learning rate and subjects SMR cost estimates to eight 'cumulative doublings' based on the learning rate. That's creative accounting and one can only wonder why the Minerals Council would present it as a credible estimate.

Here are the first-of-a-kind SMR cost estimates from the EFWG paper, all of them far higher than the figure cited by the Minerals Council:

300-megawatt (MW) on-grid SMR:	C$162.67 / MWh
125-MW off-grid heavy industry:	C$178.01 / MWh
20-MW off-grid remote mining:	C$344.62 / MWh
3-MW off-grid remote community:	C$894.05 / MWh

The EFWG paper used a range of estimates from the literature and vendors. It notes problems with its inputs, such as the fact that many of the vendor estimates have not been independently vetted, and "the wide variation in costs provided by expert analysts". Thus, the EFWG qualifies its findings by noting that "actual costs could be higher or lower depending on a number of eventualities".

The 'Bright New World' nuclear lobby group promotes a 2016 study in support of its claims about nuclear construction costs but the study was widely criticised for cherry-picking, with one such critic being a former World Nuclear Association executive.

US company NuScale Power is said to be an SMR front-runner even though it has not begun construction of a single reactor. NuScale is targeting a cost of just US$65 / MWh for its first plant. But the WSP / Parsons

Brinckerhoff study commissioned by the South Australian Nuclear Fuel Cycle Royal Commission estimated a cost of A$225 (US$174) / MWh, 2.7 times higher than NuScale's self-serving estimate.

10. MORE INFORMATION

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