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Small Modular Reactors – A Viable Option for a Clean Energy Future?

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With a growing number of states and utilities committing to a net-zero carbon future, attention turns to how best to craft a generation portfolio less reliant on fossil fuels that best meets local power needs. Wind and solar generation coupled with batteries are commonly looked to as a best vision of the future. Despite its track record for reliably generating carbon-free electricity, conventional nuclear power is often left out of the conversation.

For decades, nuclear energy has been the single-largest source of carbon-free energy in the United States. In 2018, more than 50% of all the carbon-free electricity was generated by nuclear. These plants can run 24 hours a day seven days a week, and most run reliably with capacity factors above 90%.

Conventional nuclear plants are large installations. It is not unusual for a two-reactor nuclear plant to generate more than 2,000 MWs—enough to power more than a million homes. With this size comes scale economies in operations. Existing nuclear plants can be cost competitive—Lazard studies show ongoing operating costs of $26/MWh, which compares favorably to new unsubsidized wind and solar.[1]

So why is an expansion of nuclear energy not a major part of the conversation for decarbonization plans? The answers lie in understanding what has happened to conventional nuclear over the last four decades and what remains to be proven by the new advanced reactor designs. This paper will explore the difficulties which have plagued conventional nuclear. It will then introduce small modular reactors (SMRs) and advanced nuclear reactors (ANRs) as possible answers to these difficulties. Finally, it will identify and discuss certain issues with these new reactor designs, which will need to be resolved if they are to deliver on their potential.

Conventional Nuclear

The lack of a market compensation for low-carbon electricity coupled with exceptionally low natural gas prices has hurt the economics of operating nuclear plants. Also, nuclear energy suffers from a disadvantage when it comes to government subsidies enjoyed by other low-carbon sources, but the overwhelming reason is a poor track record of performance in constructing new nuclear plants.

Even if carbon pricing and federal subsidies are addressed, there are some inherent disadvantages to conventional nuclear power plant designs, which are holding back the expansion of nuclear.

[1] Lazard Levelized Cost of Electricity - v14, October 2020

Cost Issues with New Conventional Nuclear Plants

The cost of unsubsidized new conventional nuclear is currently uncompetitive. Lazard estimates the levelized cost of energy (LCOE) of a new conventional nuclear plant ranging between a low case of $129/MWh and a high case of $198/MWh. The LCOE for new nuclear is critically dependent upon upfront capital costs, which comprise 80% of the Lazard LCOE low estimate.

Source: Lazard LCOE – v14

The wide range in Lazard's estimated LCOE is driven by uncertainty over the cost of construction. In the high-end estimate of $198/MWh, capital costs grow to 85% of the LCOE. The ongoing operating costs, by contrast, are fairly predictable and represent only $28-$31/MWh.

	Construction Cost ($/kW)			LCOE $/MWh
	Overnight Cost	Interest Carrying	Total All In	
High	$9,800	$2,700	**$12,500**	$198
Low	$6,025	$1,650	**$7,675**	$129

These estimates are in line with the new nuclear construction experience at Vogtle 3 and 4, currently under construction in Waynesboro, GA. Initial published estimates were for $6,000/kW. After construction delays and overruns pushing the total to nearly $30 billion, they will likely be completed at an all-in cost of approximately $13,000/kW. Such construction-funding issues doomed a similar project at VC Summer in South Carolina. It was cancelled in 2017 after $9 billion was spent and neither unit was completed.

Why, with their inherent operational scale economies, have conventional plants proven so difficult to achieve cost competitiveness? These plants are complex in **design**, difficult to **construct**, and resource intensive to **operate** while ensuring safety.

Conventional nuclear plant **designs** depend on a complex array of equipment that must function for both normal operations (e.g., reactor coolant pumps and steam generators) and shutdown safety (e.g., backup power and safety injection pumps). Even under best-case construction scenarios, the cost per kW of a new conventional nuclear plant will not be cheap because of this reliance on expensive active equipment. In these best-case construction scenarios, these designs require on-site construction and coordination of a complex supply chain (equipment and personnel) that will take 5 to 10 years. The paradox of new-build conventional nuclear is that it shows inverse economies of scale due to the size and complexity of these designs. There exist four primary issues with new conventional nuclear:

1. **Construction** performance for new conventional nuclear plants in the United States has been poor. Building a very large plant, like any mega-project, under any circumstances is difficult. The AP-1000 offered promise for more constructable design; however, construction at Summer and Vogtle began before the design was truly "shovel ready." As such, construction occurred concurrent with resolving design specifics—not a formula for efficient execution. Add to that the fact that in the United States, there had been no nuclear construction for decades. This meant that supply chain and construction capabilities had essentially withered away. Upon completion, the Vogtle plant will have regenerated some of this, but given its poor performance, the lessons learned will likely be lost if more plants are not built. An MIT study notes that traditional nuclear plant construction shows no improvement through the experience curve. This is not a surprise since most nuclear plants in this country were constructed by a fragmented set of different utilities, with slightly different designs, over 10 years, with overlapping timelines. None of this contributes to efficient lessons learned. Where we do see this experience curve is in countries, such as France and South Korea, where a single utility constructs a standard design several times, becoming better and better at it.

2. **Operational complexity**. The traditional power plant designs require active safety systems that add cost to the design and ongoing operational costs in order to maintain safe operation. While the industry has achieved high levels of safety, this has come at a cost in terms of equipment and staff to maintain and operate. Newer designs, such as the AP-1000, have improved on this, but they still require a large workforce to operate.

   Because a nuclear plant operator must continue to demonstrate safety to the regulator, the Nuclear Regulatory Commission (NRC), there is a burden of documentation and demonstration of continued compliance with safety standards.

   An example: In order to safely shutdown if off-site power is lost, a nuclear plant needs a very large and expensive backup diesel generator. For safety assurance, a second duplicate generator is required if the first is lost. During the year, both generators and the systems that support them must be maintained and tested periodically by plant staff.

A Note on Safety

When a nuclear reactor is at full power, an enormous amount of heat and energy is produced within the nuclear fuel. One of the advantages of a nuclear plant is how much energy is produced within a small footprint. When the plant is running, the heat is removed by generating steam to produce electricity. When the plant is shutdown, some residual heat must continue to be removed or there is a danger that the fuel will overheat and melt. The concentration of power in a small volume is good for electricity generation, but it creates more energy within that same small volume that must be dealt with after a shutdown.

3. **Grid location limitations**. The very **size** of these plants makes adding new capacity a major endeavor. While the size of these plants provides some economies of scale, spreading the cost of more MWhs, there are drawbacks. Adding 1,000 to 2,000 MWs onto a system with limited load growth is difficult for many systems to accommodate. In contrast, utility-scale solar can be added in increments of single-digit MWs.

4. **Lack of generation flexibility**. Traditional nuclear reactors are not designed to run with flexible, variable output. These plants work best when running at 100% power. They are not designed to ramp power levels up or down to adjust to varying demand. Natural gas has thrived in a role of filling in for the variation of output from intermittent renewables. Conventional nuclear does not fulfil this role.

These issues make for difficult utility executive decision-making. Even at best-case estimates of $5 to $10 billion per reactor, constructing a traditional nuclear plant involves capital costs and risks that equate to a "bet the company" wager for many utilities. Utilities must tie up that amount of capital for at least 5 to 10 years of construction before any revenue is realized. In a regulated environment, some commissions have allowed recovery to begin before completion; however, that has proven very controversial when customers see their bills increase for years before a plant provides any power. SCANA, a company with a market capitalization of approximately $5 billion, committed to building two Westinghouse AP-1000 reactors. After spending $9 billion, the project was cancelled, and SCANA was acquired by Dominion. The political fallout of this event on SCANA executives, state legislators, and public service commissioners represents a real consideration for other utility executives considering a new nuclear project.

Where Next for Nuclear?

In countries such as China and South Korea where the government drives the agenda, new nuclear is booming. In the United Arab Emirates (UAE), a four-unit nuclear plant is being constructed with a projected cost of $4,500/kW, drastically lower than in the United States. How? The UAE government has turned to the South Koreans to construct its standard design, and it is building four units delivering 5,600 MWs on a single site. The OECD has published a report that suggests conventional nuclear can be constructed for as low as $50–$60/MWh at 10% cost of capital. However, as demonstrated by the VC Summer experience, with our fragmented utility model and no single standard design, there is little hope of replicating this model in the United States.

There is, however, another hope for new nuclear in the United States. It comes in the form of SMRs. While definitions vary, a good synopsis is provided in a publication by Energy Northwest:

> "Small Modular Reactors are nuclear power plants that are smaller in size (300 MWe or less) than most current generation baseload plants (1,000 MWe or higher). These smaller, compact designs are factory-fabricated reactors that can be transported by truck or rail to a nuclear power site.
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> SMRs may be either light water reactor (LWR) or non-light water (non LWR) designs. LWR SMR designs come closer to current conventional power reactor designs in that water is used to cool the reactor, allowing well-known, proven technology to be the basis for the reactor's design. Non-LWRs use different coolants such as molten metals or salts, requiring technology that is less mature."

At the core of the case for SMRs is that the inherent safety and simplicity of the designs lead to cheaper construction and operations by obviating the need for safety-related equipment and staff required by conventional plants. Because of their smaller size and passive/natural circulation designs, SMRs do not rely on active shutdown and safety systems and actions characteristic of their conventional nuclear counterparts.

Both conventional and SMR plants have some of the same features, such as the need to manage used fuel, obligations for nuclear safety, and requirements for physical security. SMRs are promoted as having the ability to provide the carbon-free benefits of the current nuclear fleet and the inherent attributes that exist in current plants, while avoiding many of the downsides associated with building a conventional nuclear plant. Skeptics cite a range of safety, security, and cost issues as deterrents to early adoption. What follows is an overview of these SMR/ANR pros and cons.

Advantages of SMRs vs. Conventional Nuclear

SMR developers and advocates say they offer the following advantages vs. conventional nuclear plants.

Cost

Despite the smaller size, SMRs have the potential to be more cost effective than conventional nuclear. The Healthy Environment Alliance of Utah recently published a report with projections for NuScale's reactor at $65/MWh LCOE[2]. This would put SMRs at a distinct advantage to new conventional nuclear at $129-$198/MWh.

SMRs have significant potential advantages over traditional reactors in capital cost. Estimates of "overnight" construction costs are projected to be lower than for a conventional reactor—$3,600-$5,400/kW for NuScale's SMR according to the Breakthrough Institute. The simpler **designs** result in a less costly power plant. Another driver of lower construction costs is the more inherently safe designs, which will require fewer safety systems and equipment. While there is a loss of scale at the reactor level, the ability to build a multi-reactor facility allows SMRs to approach 1,000 MWs on site vs. 2,200 MWs for a typical two-unit, conventional U.S. plant.

SMRs will also have an advantage in **constructability**. The approach of constructing factory-built modules with its better control over the supply chain should yield shorter (approximately three years) and more predictable construction. The size of the plants will also provide more construction control—it is easier to build small than big. Most importantly, there is a much greater ability to take advantage of the learning curve in SMRs than in conventional plants. Stamping out multiple "factory-built" smaller reactors sequentially offers the potential for real learning-curve benefits.

While there is some loss of scale in operational and site costs, these have the potential to be offset by the inherently safer designs. These designs will require much less operations and maintenance. If the equipment does not exist, it does not have to be maintained. In addition, the placement of several smaller units on a single site can improve economics. The NuScale flagship plant consists of twelve 77-MW units providing 924 MWs on a single site. It is still half of a typical conventional two-unit plant, but it is creating some scale economies. Estimates published by the Breakthrough Institute indicate little difference in operations and maintenance cost per kW or MWh. Fuel costs are projected to be similar as well.[3]

Other Advantages

Financing

One of the biggest drawbacks to conventional nuclear plant construction is the risk of a schedule delay. The difficulty in building a mega-project brings with it the potential for significant schedule delays and cost overruns. In the case of plant Vogtle, the cost will ultimately be $15 billion per unit, double the initial estimate. There are very few utilities that can manage a $30 billion investment that takes 10 years to begin operation.

SMRs hold two great advantages. First, through standard and modular construction, these smaller reactors will have a much lower risk of schedule delays and cost overruns. Second, as capacity is added in increments of smaller reactors, a multi-reactor site can begin paying for itself long before the plant is fully finished. In addition, as reactors are completed in stages, this avoids the "bet the company" all-or-nothing risk.

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[2] NuScale - International SMR & Advanced Reactor Summit Atlanta, GA, April 2019

[3] NuScale, An Ideal Solution for Repurposing US Coal Plant Infrastructure and Revitalizing Communities, 2021

Operational Flexibility

SMRs are able to be added to the system in smaller increments, expanding flexibility for system planners. In addition, SMRs have load-following capability not available in conventional plants. This comes in two ways—the reactors themselves have better capability to ramp up or down, and with multiple small reactors, it is easier to turn on/off one of several reactors to vary output of the overall plant.

Safety

The smaller reactors with passive safety and reliance on natural circulation offer a more inherently safe design than traditional reactors. This inherently safe design means that SMRs do not require the same number of standby safety systems to be ready and operable to mitigate a potential accident. With far fewer operator actions required, there is also less potential for human error, which could make the SMRs even safer.

Market

Smaller reactors that are more inherently safe to operate can open the door for investment from companies without the capital or organizational capabilities to manage large-scale nuclear. Nuclear operations in the United States have consolidated into fewer fleet operators that have the organizational capabilities to run these plants safely and efficiently. There is a small subset of utilities with the ability to deploy large-scale nuclear. This could be markedly different for smaller reactors with operational support from an SMR developer.

SMRs could be installed on existing plant sites or shuttered fossil and nuclear plants to take advantage of transmission, substation, and site utilities. They could also be sited locally and coupled with industrial processes like combined heat and power, desalination, or hydrogen production.

Regulatory

The complexity and variability of conventional plant designs bring a complex regulatory environment. SMRs with simpler designs may bring a simpler set of regulations. However, in the near term, it will be a major effort to adapt the current regulations to a very different set of reactors. Many of these regulations evolved over decades as "prescriptive" rules to address specific issues with conventional plants. In rethinking these rules, the NRC will need to reevaluate based on a real understanding of the underlying risk. Merely applying existing rules to these new designs poses two different risks—it may be more costly through ultra-conservatism or conversely less safe by not emphasizing hazards not important in conventional plants. Creating new rules will take effort and courage on the part of the regulator.

Security

In conventional nuclear, there is more equipment spread out over a sprawling site that must be protected. In SMRs, the reactors are housed in one building and could shut down safely without support from other equipment. This offers a potential benefit in physical security in that there is a far smaller physical footprint to secure in case of an attack.

Used Fuels

The potential benefits of SMRs are mixed as compared to conventional reactors. The light water reactor SMRs promise no substantive benefits and, in fact, may produce slightly more used fuel per MWh as a result of less efficient fuel use.

Some of the more advanced designs offer the potential to reduce the amount of used fuel by separating and burning elements in used fuel. However, with that benefit, comes greater concerns for weapons non-proliferation because of this more open fuel cycle.

Potential Hurdles for SMRs

As noted above, there are safety and cost risks with conventional nuclear plants. Without delving further into safety and downsides of our current fleet, they should lead us to ask the question, "Will SMRs deliver at least as good or a better risk profile than current plants?"

As described earlier, at the core of the case for SMRs is that the inherent safety and simplicity of the designs lead to cheaper construction and operations by obviating the need for safety-related equipment and staff required by conventional plants. **The single biggest hurdle is to gain regulatory approval that the design will in fact deliver the safety benefits as put forth.** If approval is obtained in a way that satisfies concerns, the cost benefits can be realized, and construction should be able to proceed with limited risk of regulatory delay. If not, layered safety requirements could hurt the cost justification for SMRs.

For SMRs to realize this potential, there are a few concerns that must be satisfied.

Design Safety

Issues have been raised with an SMR's ability to deliver on the promise of passive safety. One high-profile example is with the NuScale reactor's ability to achieve shutdown with its borated water approach (see sidebar). Issues such as this must certainly be raised and resolved technically in the approval process to ensure SMRs can deliver on their inherent safety selling point. While NuScale is farthest along in regulatory approval, it still lacks the final design certification from the NRC. This design certification process must ensure that the design is sound.

Further, the industry must be careful not to repeat mistakes of the past and move too quickly to begin construction without having a "shovel-ready" design. SMRs with a solid design certification do have an advantage in that first-of-a-kind vs. nth-of-a-kind experience curve can be attained with less cost and risk than a conventional plant.

NuScale Shutdown Safety

The NuScale design relies on submerging its "fuel in water carrying boron, an element that absorbs neutrons and slows the fission chain reactions that generate heat and radioactivity." Concerns have been raised that if water boiled away, there would be a need to actively reintroduce borated water. NuScale asserts that "NuScale and the NRC have performed the needed analyses to demonstrate the plant reaches a safe condition and can be recovered safely."

Source: "NuScale Faces Questions on Nuclear Reactor Safety and Financing Its First Project," Greentech Media, October 27, 2020

Common Cause and Tail Risk

Even if the reactor designs are certified as functional, we must ensure that other failure modes are understood and addressed. While the Fukushima plant design could function as promised, a tsunami caused the backup diesel generators to fail leading to core melt. Issues have been raised by some questioning if the same level of understanding exists for SMRs. Are there "out of design" events that could overwhelm the inherent safety of these plants? Our understanding of these common causes and tail risks in conventional plants has evolved over time (loss of off-site power, earthquakes, intruders, tornados, etc.). Regulatory requirements and risk assessment approaches have evolved to better address them. The advent of probabilistic risk assessments uncovered insights into failure modes that were previously not well understood. Again, the design certification and construction/operating license reviews must ensure these are addressed in the context of new designs. This includes the tough task of ensuring the right evaluation framework is used. Failure to prove the safety profile could reduce the very advantages of the SMR designs and make them more costly.

Release Potential

Because of both the size (smaller amount of fuel and energy within a reactor) and the anticipated core melt timing, even if core melt occurs, SMRs put forth the promise that release of radioactivity will be much less likely or severe than from a conventional plant. This could impact everything from siting nearer population centers, emergency planning requirements, and physical security postures. The regulatory approvals will need to prove or disprove these assertions through objective analysis.

There have been unique issues raised in ANRs due to their different fuel designs. Molten salt, for example, introduces an issue with managing the radioactive gaseous releases that occur during normal operations. Unlike traditional solid fuel and metal fuel rod designs which contain these gasses, the liquid fuel will need to be managed and processed continuously. Regulatory reviews must ensure that the processing and sequestration can be done safely.

Operational Design

SMRs are not only advanced in their safety profile but also in their operating design. New designs function differently than conventional plants and can have different, more integrated equipment. Will the equipment function as promised in normal operations? A cautionary tale can be told of the San Onofre nuclear plant. In replacing steam generators, San Onofre opted for a new, more advanced design of a steam generator, which failed to perform and ultimately led to the shutdown of the plant. New technology comes with risk. However, the advantage of SMRs is that there is less risk on the first-of-a-kind than a conventional nuclear plant, and these issues could be addressed in the nth-of-a-kind.

Operating Costs

The simpler designs offer potential for far fewer staff and lower operating costs. There is less information published on what the true operating costs will be. A particular concern will be “site-level” costs, such as physical security and emergency planning, which may need to be spread over a smaller amount of capacity. In the review of the designs, the NRC will need to review the required positions, such as operators on staff. However, a very small percentage of the cost of conventional nuclear plants is NRC controlled (e.g., operators or security officers). Most is driven by the amount of work that comes with the plant equipment.

Used Fuel

LWR SMRs will not solve the current concerns with used fuel. As compared to conventional nuclear plants, there is little difference in the creation of used fuel. In LWR SMRs, there is potentially more created per MWh generated due to a less efficient burn. In more advanced reactor designs, there is a potential to actually reduce the volume by burning used fuel or by separation to reduce volume, but that brings with it heightened concerns with weapons non-proliferation.

Summary

If nuclear energy is to be a viable part of this country's clean energy future, it will likely come in the form of SMRs. To achieve this, SMRs still must prove their ability to deliver on their advantages and ensure that the safety and non-proliferation concerns are addressed. Decision makers must consider the following issues:

- Will these plants be able to deliver on their promises of simpler and more passive designs and constructability? They have not yet been proven in practice.
- Can the "inherent safety" of these plants be relied upon to justify the reduced need for some of the costly but effective equipment and approaches used in conventional plants?
    - Both accident risk and release potential
- Do the benefits of ANRs outweigh the new safety and non-proliferation concerns vis-à-vis well-understood LWR designs?
- Safety benefit aside, how many staff will these plants require under normal operation (e.g., operations staff, refueling costs)? Little is certain at this point.
- Will the site-level operating costs (emergency planning, physical security, etc.) reduce competitiveness?
- Can the regulations be adapted appropriately to these new designs? Can the process work to satisfy both SMR developers and concerned intervenors?
- Can energy policy and society provide a sustainable investment certainty needed to allow the technology to move from the laboratory to large-scale commercialization? The potential benefits are immense, but do policy makers have the courage and patience to allow the technology to mature?

Summary Comparison of SMRs vs. Conventional Nuclear Plants

Attribute	SMR vs. Conventional	Note
Capital Cost	**+**	▪ Strong advantage in constructability and potential for learning curve through modular construction vs. stick built ▪ Modular construction and repeatable construction will vastly improve cost and predictability of timelines ▪ Experience curve and better control of the supply chain through the ability to build higher volume ▪ The issue of fragmentation of designs and utilities constructing the plants will be better when a standard modular design is created and stamped out by a SMR company ▪ Standard design/construction will also improve supply chain performance with higher volume and predictable specifications
Operating Cost	**+/-**	▪ Loss of scale is likely offset by simpler and safer designs that require less ongoing operations and maintenance
Site Costs	**-**	▪ Fewer MWs on single site; some could be addressed by adding multiples or siting on existing nuclear plant locations
Financing	**+**	▪ Smaller increments mean less risk—no "bet the company" ▪ Shorter and more predictable timelines tie up capital less ▪ Ability to begin revenue collection as units are added incrementally
Safety	**+**	▪ Smaller reactors have less energy that needs to be managed post shutdown ▪ Advanced reactors, such as molten salt, can disperse the energy on shutdown in a way that does not lead to core melt ▪ Newer designs rely on passive heat removal (e.g., natural circulation) which are more reliable ▪ With multiple units on site, there is little improvement in overall source term should a common cause failure affect all the units at once ▪ Arguably, the need for emergency response may be less
Used Fuel	**-/+ Depending on technology**	▪ Smaller LWR designs are less efficient at burning fuel and may produce slightly more volume of used fuel ▪ Advanced designs have the potential to burn used fuel, reducing volume significantly ▪ Liquid fuel and reprocessing on site represents added non-proliferation, release, and failure risk
Operational Flexibility	**+**	▪ Ability to load follow ▪ Ability to add to the system in small enough increments
Regulatory	**-/+**	▪ Initially, licensing of SMRs will require effort to assess the level of safety vs. applying well-understood rules designed for a different technology ▪ Long term, simplicity of a standard design may provide a less complex environment
Market	**+**	▪ Potential applications for SMRs may open up siting and economies that currently cannot support a large conventional plant ▪ Through greater numbers and experience curve, this will benefit overall cost

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