



The Economics of Small Modular Reactors

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Executive Summary

This report evaluates the market opportunities, commercialization timeframe, and cost competitiveness of light-water, small modular reactors (SMRs) in the U.S. The analysis concludes that SMRs are commercially viable and needed in the marketplace before 2030.

The market needs SMRs: SMRs will be needed as large retirements of baseload generation and an increase in intermittent renewables have negative impacts on the electric grid. SMRs can match demand growth at lower upfront capital costs, provide flexibility to integrate with renewables, repower (replacing the fossil combustion technology with nuclear technology) retired fossil fuel plant sites, and can generate highly resilient baseload power. SMRs will become even more important if the market demand for decarbonization of industrial heat and hydrogen continues to increase.

More integrated resource plans are predicting a carbon-free grid by 2050. According to many climate experts, this goal is not feasible without contributions from nuclear energy. Several studies have concluded that the lowest cost carbon-free generating portfolio is one that includes SMRs, which are currently the lowest cost resource that are reliable, dispatchable, and zero carbon. SMR capacity additions in the U.S. are conservatively expected to exceed six gigawatts-electric (GWe), while more aggressive targets could see more than 13 GWe by 2035.

Progress to commercialize SMRs continues: Private companies continue to invest in SMRs – billions to date –with support from the Department of Energy accelerating the pace of development. The first SMR design approval was issued by the U.S. Nuclear Regulatory Commission (NRC) in 2020, and several other entities are in different stages of engagement with the NRC. Designs are mature enough today for potential owners to begin moving forward with projects. The recent SMR Start *Opportunities for Small Modular Reactors in Electric Utility Resource Planning*¹ discusses how utilities can plan for SMRs.

SMRs are cost-competitive: The analysis of various policy and market conditions shows that there are scenarios where SMRs are economically competitive in comparison with other generation sources, especially when the value of nuclear energy is considered. SMRs are strong candidates for providing firm clean electricity as partners with renewable generation and storage. The first SMRs are expected to be within the range of the lowest cost alternatives, assuming appropriate private-public partnerships address typical first-of-a-kind challenges, which have been provided historically for other new technologies.

By 2035, after the first few plants begin operation, SMRs can be cost-competitive without the need for private-public partnerships. For several scenarios, the costs of SMRs are within the range of natural gas plants and renewable generation sources. This means, that a utility could choose an SMR based on intangible factors such as long-term price stability and fuel diversity. The tremendous potential for SMRs justifies further investment and private-public partnerships to support first movers. Successful commercialization of SMRs – a critical addition to the nation’s energy infrastructure – is essential to a resilient, low-carbon energy system, growing jobs and the economy, and to strengthening national security.

¹ <http://smrstart.org/wp-content/uploads/2020/02/SMR-Start-Public-SMRs-in-IRPs-APPROVED-2020-02-28.pdf>

Introduction

Light-water small modular reactors (SMRs) are one of the most promising new nuclear technologies to emerge in decades. A few pioneering companies see specific market opportunities and recognize the tremendous potential for SMRs inside and outside of the United States. SMRs continue to overcome challenges facing SMR commercialization, such as regulatory efficiency, slow electricity demand growth, and the fact that markets do not appropriately value the attributes of nuclear energy generation. There is growing customer interest in SMRs to meet market needs for reliable, clean, and flexible baseload electricity.

For decades, the U.S. has operated a fleet of nuclear reactors, which today generates nearly 20 percent of the nation's electricity – more than half of the nation's carbon-free electricity – and provides a uniquely valuable set of attributes. Nuclear power plants produce large quantities of electricity around the clock. They operate in all weather conditions and do not require a continuous supply of fuel arriving by truck, barge, rail, or pipeline. Nuclear plants provide price stability, and, without nuclear generation, retail rates would be about six percent higher on average.² They provide “reactive power” – essential to controlling voltage and frequency for the grid. Nuclear power plants have portfolio value, contributing to the fuel and technology diversity that is one of the bedrock characteristics of a reliable, resilient electric sector. Finally, nuclear power plants provide clean air compliance value. In any system that limits emissions of the so-called “criteria” pollutants or carbon dioxide, the emissions avoided by nuclear energy reduce the compliance burden that would otherwise fall on generating capacity with regulated emissions. Other sources of electricity have some of these attributes, but none of them, other than carbon-free nuclear energy, has them all.

SMRs, together with currently operating nuclear power plants and other advanced non-light-water reactors, are part of the all-of-the-above nuclear energy portfolio needed to meet national, regional, and local goals on carbon-free pledges, energy independence, economic growth, national security, and environmental protection. SMRs are uniquely positioned to provide a large share of new nuclear generation capacity over the next several decades. SMRs are among the most mature advanced reactor technologies, with relatively low technology and licensing risk, and are near-term deployable. Although large light-water reactors (LWRs) are available today, the market trends for small capacity additions at lower up-front capital costs. With reasonable government policies, SMRs can overcome the first of a kind hurdles and be competitive with other low-cost electricity generation sources to begin operation in the U.S. in the late-2020s.

This study looks at the economics of SMR deployment in the U.S. Global demand for SMRs is expected to exceed the demand in the U.S. Although this report may serve to inform the prospects for cost competitiveness in other countries, it is not intended for this purpose, as many country-specific factors, such as financing, current electricity costs, and policies on carbon would need to be considered.

² Source: Nuclear Energy Institutes *Nuclear by the Numbers*, 2019/0

The market opportunity for SMRs

According to the Energy Information Administration's (EIA's) 2020 Annual Energy Outlook (AEO) reference case, U.S. new electricity generating capacity additions are expected to be approximately 60 GWe between 2030 and 2035 (roughly the first 5 years during which new SMRs would begin operations) to cover demand. Using the assumption of SMRs capturing 10% percent of total new capacity additions, the demand for SMR plants in the U.S. would exceed six gigawatts by 2035. The market potential for SMRs, with an aggressive target and more favorable market conditions, could be 13 GWe or more by 2035, for example by also capturing retiring coal and nuclear. Various factors, including the policies toward new nuclear plants, market compensation for attributes that are not appropriately accounted for today, and the ability to achieve lower costs for SMRs, will influence the rate of SMR deployment.

In current projections from the EIA, nuclear generation is decreasing due to nuclear power plant retirements and a lack of new nuclear builds. However, this could change with cost competitive SMR plants that will help meet carbon reduction goals. Today many government policies, electricity suppliers, and commercial customers target carbon-free electricity production by 2050—a goal that will be difficult to achieve without a larger percentage of nuclear generation. EIA expects that more than half of the capacity additions will come from renewables, with most of the rest from combined cycle natural gas plants (partially covering for coal and nuclear baseload retirement), and a sizable addition of gas turbine generation capacity will cope with the volatility added by renewable generation. At the same time, coal and nuclear plants will make up most of the capacity retirement. This trend would result in a dramatic change to the generation mix. For example, in 2035 the baseload installed capacity will be 16% (down from 30% today), and non-dispatchable intermittent capacity will be 34% (up from 24% today). These changes will have negative impacts on the reliability and resiliency of the electricity supply. The replacement of firm capacity with non-dispatchable variable renewable generation would need to be compensated for with an increase in combined cycle and simple cycle generation turbine.

Under current policies, as reflected in the EIA reference case, it is unlikely that the U.S. will see additions of new nuclear generating capacity by 2035 to reach the over 40 GWe that would maintain the nearly 20 percent nuclear electricity that is generated today. The tremendous benefits provided by nuclear power plants will be greatly diminished in the coming years without new nuclear builds, and this does not include replacement of premature nuclear retirements due to market effects. Nuclear has the highest capacity factor of the technologies, currently above 93% and an even higher reliability factor. If market dynamics are not changed, such that they value and allow monetization of attributes other than short term prices – reliability, resiliency, carbon avoidance, and long-term price stability – it will be difficult for the industry to build the new nuclear generation needed to maintain a healthy mix of carbon-free generating capacity.

Benefits of Small Modular Reactors

Deployment of SMRs would help maintain the beneficial supply of nuclear energy and baseload generation. The SMR value proposition is particularly strong for the following applications:

Matching Demand Growth and Affordability – Modular plants allow generating companies to better match construction of new capacity with electricity load growth. This is particularly important in parts of the country where load growth may have slowed for decades and also in areas where the electricity grid is not developed enough to support larger nuclear power plants. Capital investments

can also be staged as modules are constructed. This could be particularly important for smaller companies such as rural electric cooperatives, or municipal agencies that may not be able to afford the high up-front costs associated with a 1,000-megawatt reactor.

Repurpose Retired Fossil Fuel Plant Sites – SMRs can repurpose retired fossil fuel sites, even those that are close to population centers. Safety advances in SMRs are expected to provide public health and safety assurance without the need for large emergency planning zones. Replacement of retiring coal generation alone represents more than 100 GWe of the total capacity reductions between now to 2040. Replacement of retired coal power plants with SMRs helps to preserve the important baseload and grid stabilizing benefits, and it preserves local jobs, with the potential for former coal plant workers to be retrained at an SMR facility.

Integration with Renewables – SMR power plants offer flexible baseload capacity which integrates well with intermittent renewables. A phenomenon connected to higher penetration of intermittent renewables is the tendency toward low or negative electricity prices during periods of excess sun and wind availability, and higher electricity price spikes when not available. This situation is especially acute in the state of California, where excess solar energy has created the “duck curve.”³ This conundrum of pricing variations over the course of the day is also attributable to the inability of other generating sources to quickly respond to rapid additions or removal of electricity supply from intermittent wind and solar generation. SMRs can solve this problem with their capabilities to rapidly change power output, which in turn helps to flatten the price of electricity over the day, and ultimately lower overall cost to consumers. One way to mitigate this phenomenon connected to the penetration of variable renewable generation would be to deploy large scale, grid-size batteries at large scale. Unfortunately, such a strategy can only be successful, while maintaining a reasonable price of electricity, if future battery prices drop to 10% of today’s costs⁴. Moreover, batteries may be able to deal with diurnal cycles, but it is unlikely that they can cope with weekly or seasonal cycles. SMR deployment can mitigate this situation in two different ways: (1) as part of an integrated energy system that is capable of modulating its energy consumption and/or (2) modulating power output, SMR suppliers have the capability to load-follow variable wind and solar generation. The integration of SMRs with renewables will result in a more reliable and resilient supply of electricity at lower costs to the end-user. The integration of SMRs and intermittent renewables in the U.S. provides a zero-carbon solution, without the need to add expensive battery storage options. These options are poor at addressing the intermittency of renewables, since they can only store electricity over short time periods. In addition, battery storage options are expensive, and resource limited. It is currently difficult to establish whether there will be adequate resources (and at reasonable prices) to supply the batteries required to maintain reliable output.

Integrated Energy Systems - Additional demand, and better integration with renewable energy generation, could come from an integrated energy system (IES) or cogeneration where heat is

³ https://en.wikipedia.org/wiki/Duck_curve

⁴ Micah S. Ziegler, Joshua M. Mueller, Gonçalo D. Pereira, Juhyun Song, Marco Ferrara, Yet-Ming Chiang, Jessika E. Trancik Storage Requirements and Costs of Shaping Renewable Energy Toward Grid Decarbonization Joule, Volume 3, Issue 11, 20 November 2019, Pages 2867-2869

directly taken from the nuclear power plant. For example, a large production of hydrogen as foreseen by some IES scenarios, would require more installed nuclear capacity. The production of hydrogen and other chemicals is usually very capital intensive. To maintain low production costs, they would require a large electric baseload supply and possibly process heat directly generated by an SMR nuclear power plant. SMR nuclear power plants can also revert to production of electricity for the grid during periods of high demand. SMR nuclear power plants would play the role of peaker for the grid, while supplying highly reliable, consistent energy to the IES. This new paradigm would favor the penetration of variable renewable energy (VRE), avoiding the need for expensive storage systems and ensuring a high-capacity factor for nuclear power plants.

Resilient and Highly-Reliable Micro-Grids – Some SMRs are being designed with an electric power system that is entirely self-sufficient with all power sources required to perform safety functions, startup, shutdown, and operations located on-site providing black start capability. These self-sufficient designs will have independence from the grid by eliminating the need for power from offsite sources. These plants may not need to be connected to the electric grid at all. These designs would be ideal for providing secure, resilient, and highly reliable power to Department of Energy (DOE) and Department of Defense (DOD) facilities that perform national security and mission critical activities. These designs would also be ideal for remote locations and other areas with small or no electric power grids.

SMR Commercialization Pathway

The path to the first commercial operation of an SMR at the end of the 2020s depends upon steady progress in developing the design, licensing, supply chain, and owners’ projects. SMR plants could range from one reactor unit to twelve units with generation capacity, depending on the number of units, ranging from 160 to over 1,000 MWe. The majority of plants are expected to produce between 160 to 924 megawatts-electric.⁵ The following table depicts U.S. SMR designs from SMR Start members.

Table 1: U.S. SMR Design

Companies	Design	Standard Plant Capacity ⁶
GE Hitachi Nuclear Energy	BWRX-300	300 MWe (1 module)
Holtec SMR LLC	SMR-160	160 MWe (1 module)
NuScale	NuScale Power Module	77 MWe (1 module); scalable up to 12 modules per plant for a total of 924 MWe

Licensing of SMRs continues to proceed smoothly, although improvements in the NRC licensing process to enable reviews in less than 3 years would support accelerated deployments. NuScale Power received

⁵ SMRs are defined as nuclear power plants that contain one or more reactor modules that produce less than 300 megawatts-electric per module and make greater use of factory construction.

⁶ SMR plants can scale their capacities by deploying fewer or more than the standard number of modules on a given site.

the first-ever SMR design approval by the U.S. Nuclear Regulatory Commission in August 2020. GE Hitachi Nuclear Energy (GEH) and Holtec are also interacting with the NRC on their designs. In addition to a market need and a cost competitive product, successful commercialization depends on a sufficient number of customer commitments, as well as the existence of government policies supporting first movers. As in the development of any new technology, there is reluctance in the market to be the first adopter, due to the first-of-a-kind risks inherent in these new technology projects⁷. Incentives are needed for early adopters to address the new technology risks and pave the way for broader adoption of SMRs.

The first-mover SMR projects in the U.S. are being led by UAMPS (Utah Associated Municipal Power System) and TVA (Tennessee Valley Authority). UAMPS partnered with NuScale Power, the technology provider, and Energy Northwest, the power plant operator. As part of their Carbon Free Power Project, UAMPS is locating the first NuScale SMR power plant at the Idaho National Laboratory site. TVA's early site permit application for a generic SMR (representative of the available designs) at their Clinch River Site in Tennessee was approved by the U.S. Nuclear Regulatory Commission in December 2019.

There are also several other utilities actively considering becoming first movers to deploy an SMR. Some have included SMRs in their integrated resource plans (IRPs), and others are considering to do so in future IRP updates. Though most have not revealed their interest publicly, there are more potential customers interested in SMRs once the technology risk has been addressed by the first movers, Table 2 summarizes the SMR designer's ongoing licensing efforts.

SMRs are attractive to utilities that previously never considered owning a nuclear power plant (e.g., municipal utilities). This is because SMR power plants are more affordable, have smaller up-front capital costs, and have capacities that are more aligned with market needs. Current U.S. customer interest in SMRs, including the first movers, is estimated as five SMR plants in operation by 2035. This equals a total of 3 GWe of generating capacity (based on a nominal 600 MWe per SMR facility). It is expected that this critical mass, along with fair markets and competitive prices for follow-on SMR plants, will achieve a breakthrough for the technology that will lead to broad adoption. To achieve a total of 6 GWe of new SMR capacity by 2035 (which captures 10% share of new capacity), an additional five SMR plants at 600 MWe each would be needed. This equates to an average of two SMR plants per year that would begin commercial operation between 2030 and 2035. Although these SMR plants could be expected to be built in as little as three years⁸, it is expected to take 8 to 10 years from the time a company begins an SMR project until the plant begins commercial operation. This includes the three to five years it takes to gain regulatory approvals before construction can begin. Considering the timeline for the deployment of new SMRs, to maximize their impacts, risk reducing policies need to be in place by 2021.

⁷ In fact one of the cost drivers penalizing nuclear technology is the high discount rate imposed to these projects, which is in excess of what is usually adopted in the power sector. The main reason for such a practice is the high risk that the construction of a nuclear reactor represents from the point of view of project cost and schedule overrun. Having government support to move to N-th of a kind would remove this source of cost.

⁸ This is based on expert judgment of the member of the SMR Start NEI task force.

Table 2: [NRC SMR related current applications](#) (updated February 2021)

Design or Site	Application Type	Applicant
Clinch River Nuclear Site	Early Site Permit (approved) based on a Plant Parameter Envelope	Tennessee Valley Authority (TVA)
NuScale	Design Certification (standard design approval issued August 2020; Design certification follows in 2021)	NuScale Power, LLC
NuScale720	Standard Design Approval (SDA) Pre-Application ongoing Target Application submittal 2022	NuScale Power, LLC
SMR-160	Pre-Application	SMR, LLC, a Holtec International Company
BWRX-300	Topicals being submitted and approved.	GE Hitachi Nuclear Energy

Figure 1 depicts the major project planning, licensing and construction milestones to deployment of the first SMR and establishes a foundation for companies to pursue deployment of additional SMRs. Figure 2 depicts the projection of SMR generation capacity through 2040 for low, reference, and aggressive deployment targets, overlaid with existing nuclear generation capacity and nuclear capacity needed to retain a 20 percent share of generation. The existing nuclear retirement timeline can be strongly influenced by policies and market conditions.



Figure 1: SMR First Mover Commercialization Timeline

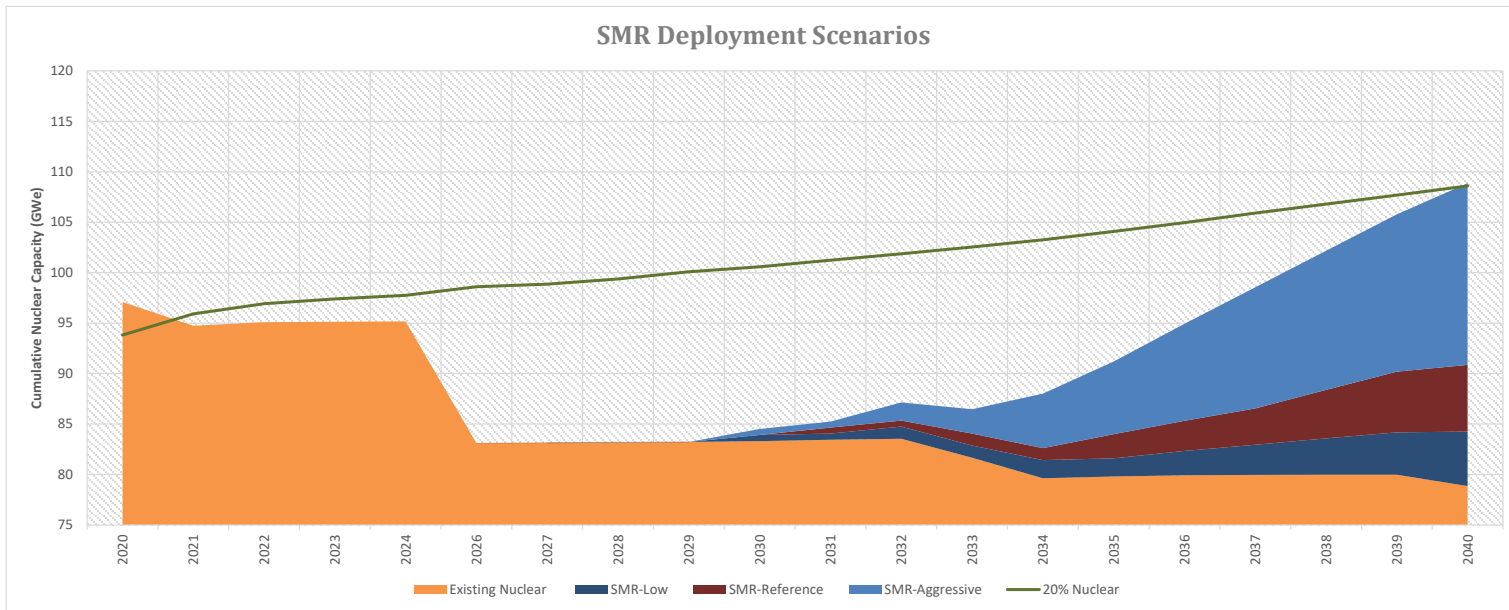


Figure 2: Projection of SMR Deployments through 2040

SMRs are cost competitive

Traditionally, nuclear developers have been building increasingly larger designs to overcome high up-front capital costs through economies of size. SMRs take advantage of the economic benefits of simpler design, standardization, smaller components, and greater use of commercial-off-the-shelf parts to more than offset the loss of economy of size. Repetition that reduces costs through applying learning curves is an important benefit. SMRs are modular and factory-fabricated, improving the quality and costs, and taking safety-related work out of the field. A cost analysis was performed using a proprietary model based on a nominal 600 MWe SMR plant consisting of four 150 MWe reactors, and compared to costs of other generation sources. The following is a discussion on the results of the analysis. Inputs and assumptions are provided in Attachment A.

Two different types of possible ownership are considered; investor-owned utilities (IOU) and municipal utilities (Muni), the latter of which represents any government-backed utility.

Overcoming First-of-a-Kind Challenges

Typical first-of-a-kind (FOAK) challenges create unique regulatory, technology, and financial risks that most companies are unable or unwilling to accept. These risks translate into higher costs for the first SMRs that exceed other lower-cost generation sources creating a fundamental barrier to technology adoption. A classic challenge exists in which companies are unwilling to construct new technologies because of the perception that FOAK costs are more than the lowest cost alternative in the market. It is common for government to help bridge this gap for capital intensive long-timeframe technologies like SMRs.

The comparison of the costs of first mover SMR plants without any private-public partnerships in Table 3 shows that SMRs are not expected to be the lowest Levelized Cost of Electricity (LCOE) for investor-owned utilities (IOU) or for municipal utilities. These first-of-a-kind plants have technology and regulatory risks not associated with more established generation sources like natural gas, wind, or solar. These factors make it difficult for owners to choose an SMR, even if it would be the best technological fit. It is interesting to notice how the government is still heavily investing in other generation technologies, even as some are the least cost in the market. This is clearly connected to a widespread desire for carbon emissions reduction. Nuclear can be part of the carbon emission reduction strategy with a competitive pricing point.

Table 3: Comparison of Costs for First Of a Kind SMRs with and without Partnership and Natural Gas Plant (2020 dollar). Ranges account for gas price ranges.

	Investor-Owned Utility (LCOE)	Municipal Utility (LCOE)
Dispatchable		
First of a kind SMR \$/MWh (no government partnership)	98	76.7
First of a kind SMR \$/MWh (full government partnership)	48.4	43.4
NGCC \$/MWh	38.6-43.4	35.9-40.6
Variable		
Wind ⁹	41.6	33.5
Solar ⁹	51.7	40.8

Utilities face a financial challenge when considering potential first deployments of SMRs. The SMR Start Policy Statement on U.S. Public-Private Partnerships for Small Modular Reactors identifies a combination of private-public partnerships that would encourage customers that want to adopt FOAK SMRs. Some of these policy tools are better implemented at the Federal level and others at the State level. Federal policies include Production Tax Credits (PTCs), Loan Guarantees (LG), power purchase agreements for high resiliency for federal facilities (PPAr), and direct cost-shares (CS). State Incentives include Advanced Cost Recovery (ACR), which is also known as Construction Work in Progress (CWIP), and tax incentives for facilities and manufacturing, such as sales and use tax exemptions, property tax abatements, and investment tax credits. These policies were evaluated to determine their impact on deployment of the first SMRs. Attachment A details the values of these private-public partnerships on the LCOE for both investor-owned and municipal utilities.

Figure 3 through Figure 5 show examples of how the private-public partnerships may be used by utilities with differing constraints. Actual projects will differ based on applicable conditions. The investor-owned utility example utilizes PTCs, LGs, CWIP, PPA, and CS (only FOAK). The municipal utility utilizes PTC, and tax incentives (no taxes), PPA, CS, and CWIP.

⁹ LCOE computed using data from EIA for 2025 technology, same discount rate of the nuclear case, no subsidies

The results show that, with a combination of policy tools available, the costs for FOAK SMR plants will be comparable to the costs for the current lowest cost option of NGCC. Specifically, Federal production tax credits, loan guarantees and power purchase agreements for resiliency, and State advanced cost recovery and tax incentives are all needed to accomplish the goals of deploying the first SMRs. Additionally, Federal support for finalizing FOAK engineering and manufacturing is needed to keep costs low and reduce technology risk.

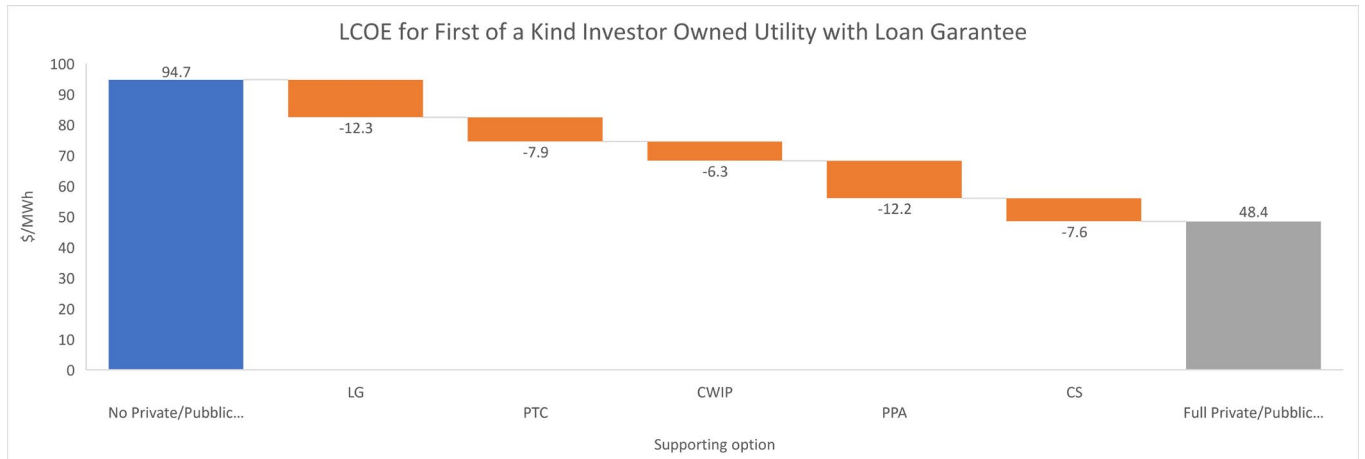


Figure 3: LCOE benefits for FOAK IOU SMRs with loan guarantee

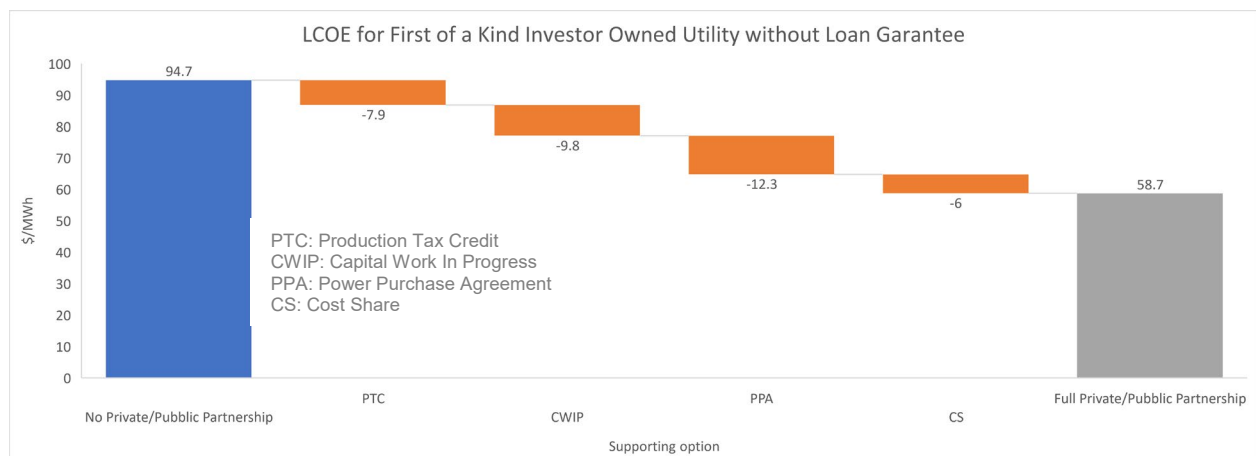


Figure 4: LCOE benefits for FOAK IOU SMRs without loan guarantee

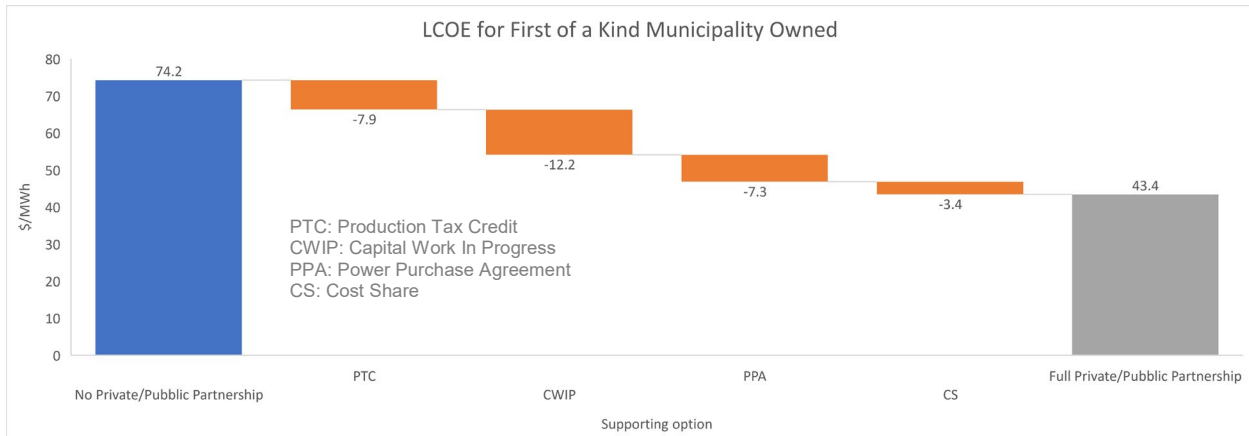


Figure 5: LCOE benefits for FOAK Muni owned SMRs

Long Term Cost Competitiveness

Starting around 2035, after lessons learned through deploying the first few facilities are incorporated, SMRs can be cost competitive without private-public partnerships. This occurs by applying a learning curve that achieves cost reductions – a well-established phenomenon where repetition leads to improvements in productivity resulting from the experience gained. As production and construction increase, government support would no longer be needed to be cost competitive in the market.

Figure 6 and Figure 7 summarize the NOAK for IOU, starting from the reduced capital cost and O&M as described in Appendix A. Figure 6 assumes a learning rate (LR) of 15% and Figure 7 assumes a learning rate of 10%. The Muni case has only the CWIP cost reduction option as summarized in Figure 7.

The costs of an SMR and an NGCC, both becoming operational in 2035, are reflected as ranges of LCOE, due to the uncertainty of future conditions. Uncertainties that affect the future costs of SMRs include a longer operating lifetime (60 years instead of 40 years), material escalation, and opportunities to further reduce upfront capital costs by achieving higher rates of learning and incorporating advanced manufacturing and construction technologies, and policies or market dynamics that value nuclear energy’s attributes such as resiliency, reliability, and zero carbon emissions. Uncertainties that affect the future costs of NGCC include future natural gas prices, carbon sequestration requirements and technology maturation.

Figure 7 presents the range of costs expected in 2035 for an SMR and current alternative technologies. The min max ranges are including/excluding the possible cost reduction strategies discussed before as also the 10/15% bracket in the learning rate and possibility to benefit, in the case of IOU of a 1% reduction in the cost of equity due to a decrease in the risk of the investment profile. For most scenarios, the costs of SMRs are within the range of natural gas plants; a utility could therefore choose an SMR based on qualitative factors such as long-term price stability and fuel diversity. Although there are some scenarios that place SMRs at costs higher than NGCC, there are also many scenarios where SMRs would cost less. Therefore, SMRs are a valuable option for utilities in the future.

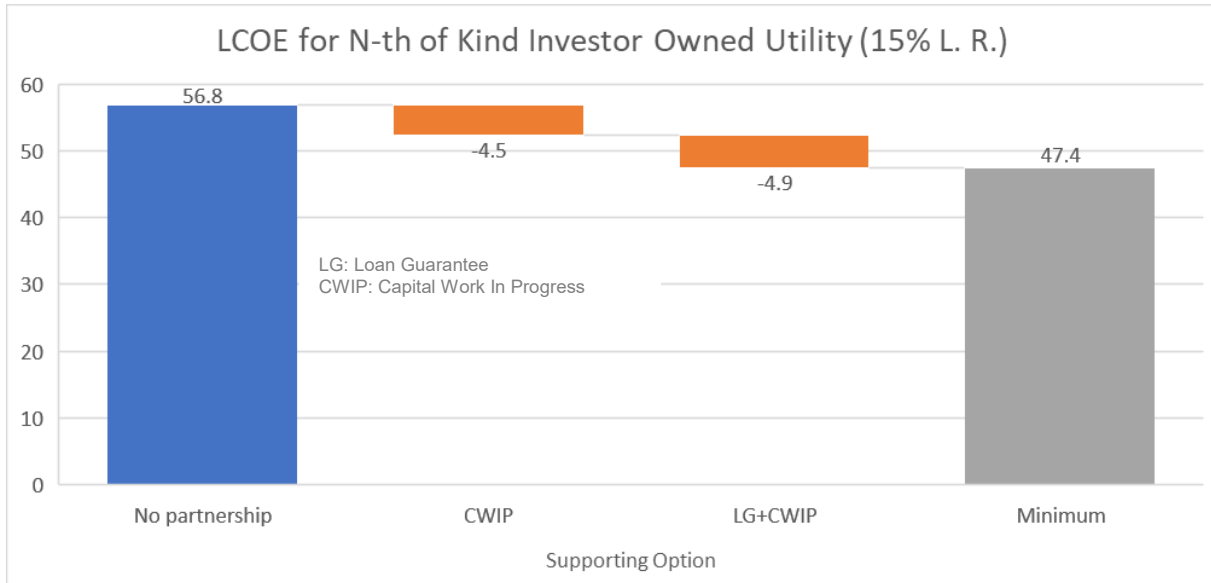


Figure 6: LCOE benefits for NOAK IOU SMRs (15% learning rate)

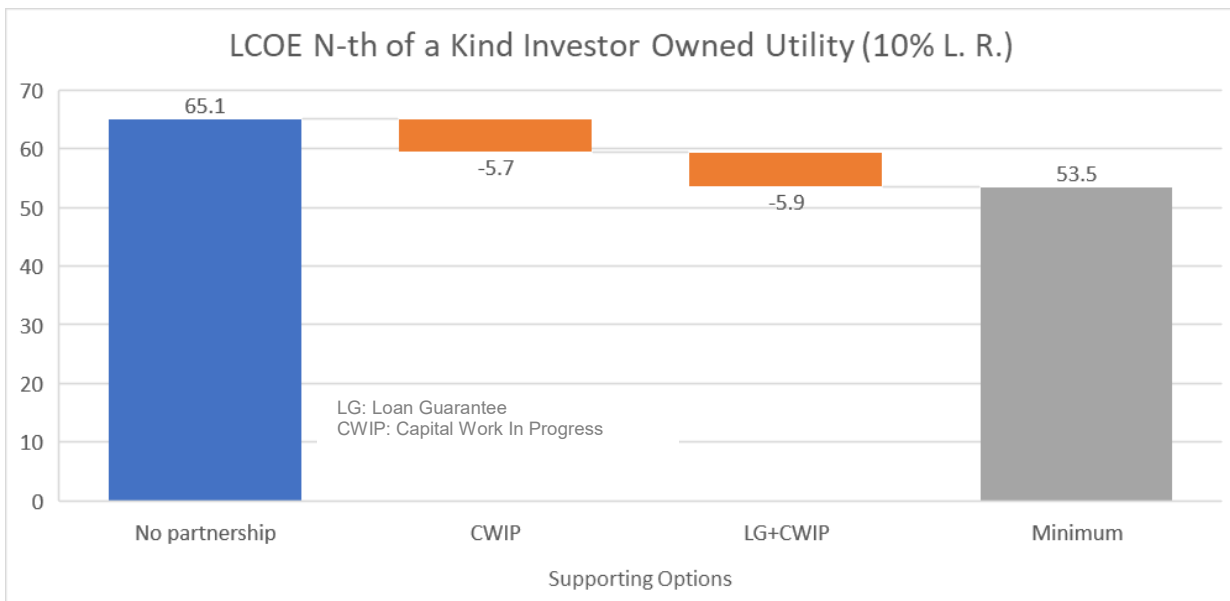


Figure 7: LCOE benefits for NOAK IOU SMRs (10% learning rate)

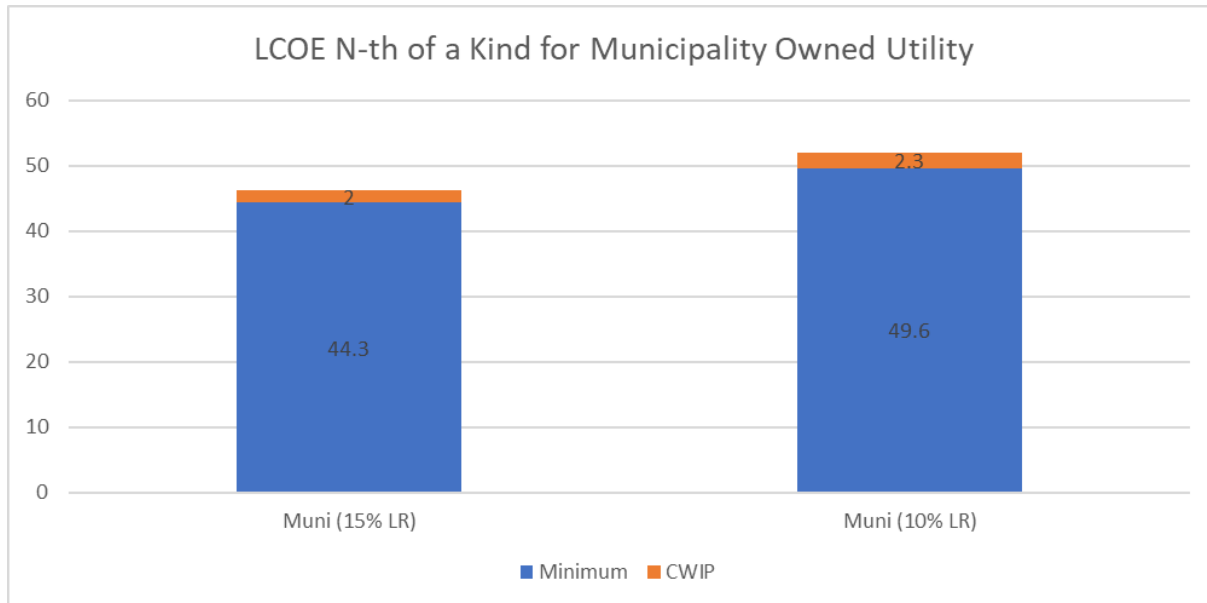


Figure 8: LCOE benefits for NOAK SMRs (10%/15% learning rate)

If CWIP and LG (LG for IOUs only) are used to decrease the cost of the electricity produced by an SMR, SMRs should be competitive without further government support in a CO₂ free grid. In Figure 7 for NGCC, low/high refers to low and high gas prices scenarios, for wind and solar Muni/IOU refers to types of ownership, Muni or IOU. It is worthwhile noting that wind and solar do not provide the same level of dispatchability as do SMRs and NGCCs. To be a fair comparison, the system cost derived from ensuring the right amount of firm capacity should be added to the LCOE of variable non-dispatchable electricity sources as wind and solar. It is also worthwhile to highlight the findings of Ziegler et. al (2019),¹⁰ study, which demonstrated that the cost to cover baseload with a mixture of wind, solar, and batteries (estimated to cost \$150/kWh/\$700/kW) will exceed \$100/MWh.

A potential factor that could further decrease the cost of electricity produced by SMRs is a reduction of the discount rate. Currently SMRs, or nuclear projects in general, are more negatively impacted by higher discount rates compared to other technologies. At the corporate level, investing in nuclear technology is considered riskier than other conventional technology. This seems to be related to overrun in time and budget of recent nuclear projects. This additional risk is reflected by higher discount rates applied to nuclear projects. If NOAK project will meet expectation in cost and construction time a further saving could be gained from a reduction of the discount rate. For example, for IOU a reduction of 1% of the discount rate would lead to a LCOE decrease of ~\$2/MWh.

¹⁰ Micah S. Ziegler, Joshua M. Mueller, Gonçalo D. Pereira, Juhyun Song, Marco Ferrara, Yet-Ming Chiang, Jessika E. Trancik Storage Requirements and Costs of Shaping Renewable Energy Toward Grid Decarbonization, Joule, Volume 3, Issue 11, 20 November 2019, Pages 2867-2869

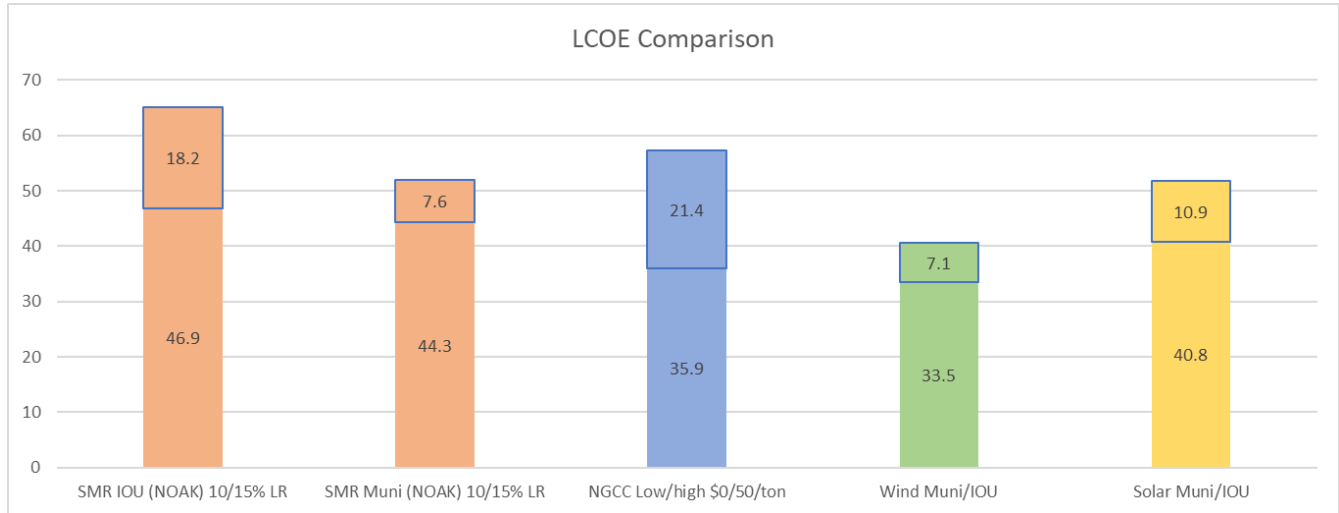


Figure 9: LCOE comparison of NOAK SMRs and Other Generation Sources

Systems Considerations

When deciding on a generation technology, utilities must consider a variety of additional factors that have not been considered in this report. Table 4 provides a comparison of some of these factors, based on 1,000 MWe capacity (not the electricity generated). Note that values for nuclear are based on data from operating nuclear plants and SMRs are expected of achieving higher capacity factors and lower usage of land and water. Additionally, local community opinions should be considered. According to a 2015 survey by the Nuclear Energy Institute, current operating nuclear plants enjoy an 83% local community favorability rating in the U.S.

Table 4: Additional Factors Considered in Selecting Generation Technology (per 1,000 MWe)

	Nuclear SMR	NGCC	Wind	Solar
Max. Capacity factor (%) ¹¹	>95	90	35	25
Land requirements (acres) ^{12, 13, 14}	50 ¹⁵ see below	343	85,240	7,900
Jobs during operation	500	50	50	-
Plant lifetime (years)	60 to 80	40 to 50	20 to 25	20 to 25

¹¹ 2018 Average capacity factors were used. SMRs are expected to be able to achieve capacity factors that are higher than the 92% achieved by today’s nuclear power plants. NGCC plants are able to achieve higher capacity factors if operated as baseload plants. U.S. Energy Information Administration, [Electric Power Monthly](#)

¹² STRATA, [The Footprint of Energy: Land Use of U.S. Electricity Production](#)

¹³ U.S. Department of Energy, [Wind Vision - A New Era for Wind Power in the United States](#)

¹⁴ National Renewable Energy Laboratory, [Land-Use Requirements for Solar Power Plants in the United States](#)

¹⁵ It is expected that the land usage for SMRs will be less than current nuclear power plants, which have larger owner-controlled areas. [our reactor comparison data has NuScale at about 95 acres per 1000MWe and BWRX at 87.5 acres for 1000MWe].

When comparing nuclear with Variable Renewable Energy (VRE), it is important to remember that nuclear is a dispatchable resource and firm capacity, while VRE is generally non-dispatchable and only part of the installed capacity can be considered firm. A typical electrical grid can use a certain amount of non-dispatchable resources, but when they exceed a certain level of penetration, mitigation is necessary. This mitigation for excess unpredictability of supply might include an increase of installed gas capacity or batteries. For example, ERCOT uses Seasonal Peak Average Wind Capacity as a Percent of Installed Capacity (SPAWCPIC), for reliability purposes, to estimate how much the installed capacity of wind can be counted toward the coverage of peak demand. For Panhandle wind resources, for the period 2012-2020, the average was 26% for summer and 30% for winter. A similar statistic is available for solar and for the period 2012-2020 the average Seasonal Peak Average Solar Capacity as a Percent of Installed Capacity (SPASCPIC) is 68% (summer) and 8% (winter). For reference, the LCOE (2020 EIA Annual Energy Outlook) of wind is computed using a 40% capacity factor and solar instead using 30%. A grid with only wind to cover both the summer and the winter peak, which are respectively 170% and 141% of the mean demand (2019 data) would have an effective cost of covering load of \$71.57/MWh (Muni) to \$79.7/MWh (IOU), driven by the cost of covering the summer peak¹⁶. The analysis is done using the best combination for the NOAK scenario. For the same situation but using solar, the effective cost of covering load would be \$216.4/MWh to \$274/MWh, driven by the cost of covering the winter peak. In the case of nuclear, given that its capacity factor is not affected by any fluctuation, the effective cost of covering load is just the LCOE time the scaling factor of the larger peak (summer). The NGCC, as it can be seen in Figure 9 is the one with the lower increases in costs. This is of course due to the NGCC having a sizable component of variable costs contributing to the LCOE, which are not affected by the increase in idle capacity requirements necessary to cover peaks.

In conclusion SMRs can be price competitive with other generation sources in many scenarios and their characteristic of dispatchability and reliability make them a necessary component of future energy production portfolios.

¹⁶ The calculation is done assuming that the capacity installed is the one needed to cover both peaks. Initial LCOE cost are first scaled by the peak to mean demand ratio, then by the ration EIA assumed capacity factors to effective capacity factor toward peak coverage.

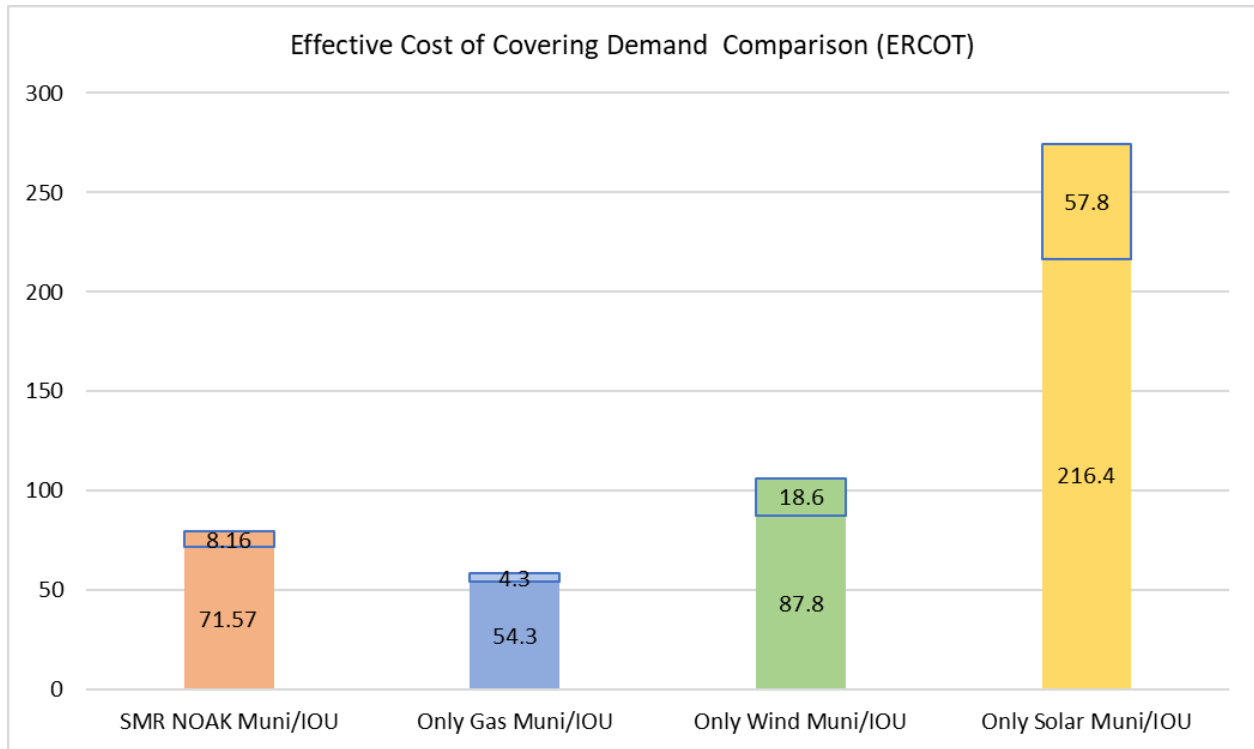


Figure 10: effective cost of covering load for summer and winter peak in the ERCOT region.

SMRs are important for the nation

Successful commercialization of U.S. SMR technology is important to the nation and depends upon private-public partnerships. The benefits are the creation of a critical piece of the nation's future infrastructure that strengthens national security, provides high paying jobs, furthers economic growth, and provides the benefits of a resilient, affordable low-carbon energy system.

National security

The U.S. has historically been a leader in nuclear technology, driving the export of nuclear technology to other countries, which led to strong domestic job creation and strong global relationships. Unfortunately, nuclear energy policies over the past few decades have led to an erosion of U.S. nuclear leadership and commercial competitiveness. Today China and Russia supply 55% of the reactors planned or under construction globally, compared to only 5% by the US¹⁷.

U.S.-led commercialization of SMRs would increase credibility and our engagement as suppliers of new advanced nuclear power reactors around the world. Other countries are already seeking U.S. SMR technology, which represents a golden opportunity to improve U.S. leadership in advanced nuclear technology, along with renewed geopolitical influence.

Economic growth

Construction and operation of a 600-megawatt SMR plant, with multiple reactors (based on a 1,000 MWe nuclear facility), is estimated to employ approximately 900 manufacturing and construction workers for about four years, as well as around 300 permanent positions for the 60-year operational life of the SMR power plant. The data shows that each permanent position creates a multiplier effect, resulting in 1.66¹⁸ additional jobs in the local community and 2.36 additional jobs in the rest of the state. Nuclear jobs pay 20 percent more¹⁹, on average, than jobs supported by other energy sources. Nuclear jobs pay 36 percent more than average salaries in the local area.

Based upon experience with a 1,000 MWe nuclear facility, a 600 MWe SMR plant is expected to generate over \$500M in direct and indirect economic output annually²⁰. This includes over \$270 million in the plant's electricity sales and spending generated at the local, state, and national levels of \$10 million, \$48 million, and \$236 million, respectively. The SMR plant is expected to pay about \$10 million in state and local taxes and \$40 million in federal taxes annually.

¹⁷ <https://www.world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide.aspx>

¹⁸ Nuclear Energy Institute, [Jobs](#)

¹⁹ Oxford Economics, [Nuclear Power Pays](#)

²⁰The Brattle Group, [Nuclear Industry's Contribution to the US Economy](#)

Deployment of the first five SMR power plants could create up to 1,500 permanent jobs and \$250 million in local, state, and federal taxes per year by 2035. By 2040, 12 GWe of SMRs in operation could support 6,000 permanent jobs and \$996 million in local, state, and federal taxes per year. At a more aggressive target of 24.6 GWe from SMRs, this increases to 12,300 permanent jobs and \$2 billion in local, state, and federal taxes per year. This does not include manufacturing and construction jobs, which could reach 4,500 workers around 2040s, assuming five SMRs are under construction simultaneously.

The United Kingdom National Nuclear Laboratory estimates that the global market potential for SMRs at about 65 GWe to 85 GWe by 2035. Assuming that the U.S. captures just one-third of the global market – more than 28 GWe – SMRs would create (or sustain) tens of thousands of high-paying American jobs, in addition to generating billions of dollars in domestic economic activity and tax revenues.

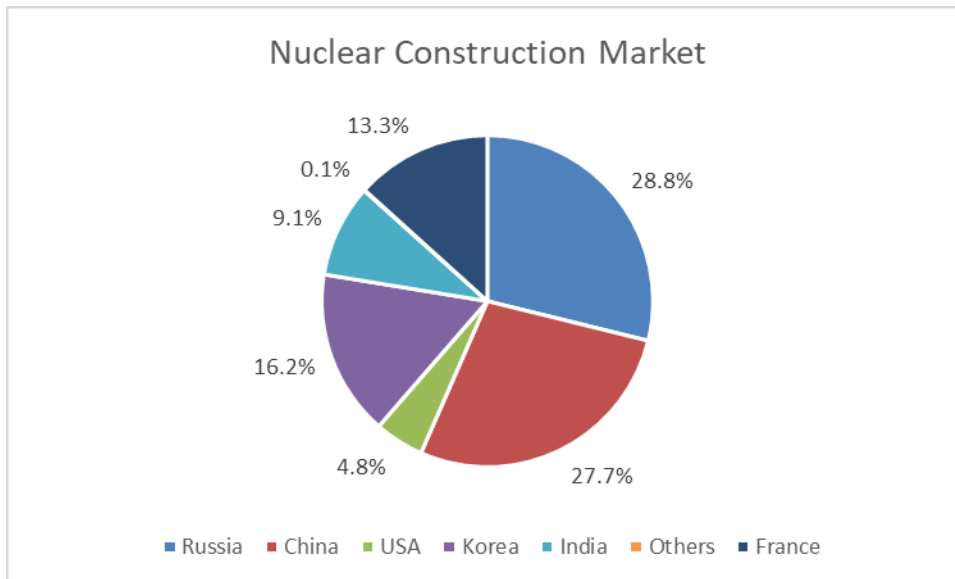


Figure 11: Market Share for New Construction

Attachment A – Input Assumption

Small Modular Reactor Modelling Assumption

Table A-5 reports the cost, size, and deployment timeline for the prototypical chosen SMR reactor. This choice is representative of current industry expectation.

Table A-5: SMR's info in 2020 \$

	First of a Kind SMR	Nth of a Kind SMR (after 36 cores, ~10% learning rate)	Nth of a Kind SMR (after 36 cores, ~15% learning rate)
Facility Size	600 MWe (150MWe x 4 cores)		
Construction Time (including 6 months start up)	36 months	30 months	30 months
Deployment Year	2030	2035	2035
Overnight Capital Cost	\$3800/kWe	\$2500/kWe	\$2000/kWe
O&M Costs (2020\$)	22\$/MWh	15\$/MWh	15\$/MWh
Fuel (includes costs of used fuel disposal at \$1/MWh)	\$8/MWh		
Heat at Turbine	2,000 MW-thermal		
Availability / Capacity Factor	up to 95%		
Design Life	60 years ²¹		
Staffing	200 to 300		
Time between 1 st and 2 nd unit	3 months		
Time between nth units	3 months	2 months	

Discount Rate

The determination of the proper discount rate for the investment can be done following a purely market-driven approach, or a more project specific risk-driven approach. The U.S. Energy Information Administration uses a standard, market-driven approach in combination with the Capital Asset Pricing Model (CAPM), which estimates a discount rate of 6.6% for the 2020 Annual Energy Outlook. This is the discount rate that has been used to compute the LCOE for the NGCC IOU plant.

For the nuclear power plant, a slightly more conservative approach is taken, using the data in Table A-6. The discount rate used is conservative with respect to a straight application of the CAPM approach for the current market. It is worth noting that the last decade has been a low interest rate environment for advanced economies, which would be conducive for undertaking capital-intensive projects such as a nuclear power plant. In fact, financing the project in 2020, at the current cost of equity and bonds, would lead to a discount rate as low as 3.8%. However, using historical data, a 7% rate is more appropriate

²¹ The initial operating license from the U.S. NRC is 40 years. The 60-year design life is based on an expectation for a 20 year license without any significant plant modifications. Additional license extensions in 20 year increments are possible.

given the long lead time to deploy the first reactor. For example, for IOU a reduction of 1% of the discount rate would lead to a LCOE decrease of \$4.6/MWh.

Table A-6: Discount Rate for SMRs

Data	IOU (FOAK)	IOU (NOAK)	Muni
Equity Share	45%	45%	0
Equity Return	10.5%	10.5%	N/A
Debt Rate	5.5%	5.5%	4.5%
Tax Rate	25.6%	25.6%	N/A
Discount Rate (Weighted Average Cost of Capital -WACC-)	7%	7%	4.5%

Natural Gas Combined Cycle (NGCC) Modelling Assumption

NGCCs are more and more used as baseload supply given the low cost of natural gas. This is a mature technology, which is not subject to risk premium in the determination of discount rate but is also not subject to any detectable decrease in cost due to learning. The two discount rates used, 6.6% and 4.5%, respectively reflect the current market requested discount rate for an Investor-Owned Utility (IOU) and the discount rate for a municipality utility (MUNI). For this technology, we refer directly to the Energy Information Agency 2020 outlook data. The data in Table A-7 are used in the calculation of the \$/kWh. LCOE calculation was done with a simplified approach (with 2 years construction time using EIA representative parameters). Gas prices were chosen as representative values based on the EIA projection of prices for the power sector.

To perform an equitable comparison, few options to incorporate the cost of CO₂ have been considered. This is due to the fact that SMRs are a clean energy source and that states and the ISO are striving for carbon-free electricity production by 2050. For this purpose, Table A-8 provides electricity cost mark-up for different options. CO₂ costs are computed using carbon tax or Carbon Capture and Sequestration (CCS) data²²

Table A-9 summarizes the electricity price ranges for IOU and MUNI with CO₂ penalties. The CO₂ has been capped to 16.7 to consider that FOAK CCS is not likely marketable without some form of government support.

²² <https://www.globalccsinstitute.com/archive/hub/publications/201688/global-ccs-cost-updatev4.pdf>

Table A-7: Technology-Economic data for NGCC

Technology	Combined-cycle—single shaft		Combined-cycle—multiple shaft	
Size (MW)	418		1,083	
Overnight cost (\$/kW)	1,079		954	
Financial Lifetime (years)	30		40	
Capacity Factor	90%		90%	
Fixed O&M \$/MW/year	14,040		12,150	
Heat rate (mmBTU/kWh)	643.1		637.0	
Variable O&M (\$/MWh)	2.54		1.86	
Fuel cost (\$/mmBTU)	3.75	4.5	3.75	4.5
LCOE \$/MWh @6.6 discount rate (IOU)	41.3	46.1	38.6	43.4
LCOE \$/MWh @4.5 discount rate (Muni)	38.1	43.0	35.9	40.6

Table A-8: Carbon Cost for NGCC

CO ₂ penalty option	Additional levelized cost for NGCC \$/MWh
\$25/ton CO ₂ emission penalty	8.3
\$50/ton CO ₂ emission penalty	16.7
NGCC+CCS FOAK	29.7
NGCC+CCS NOAK	14.4

Table A-9: LCOE ranges for NGCC

Ownership	Electricity cost reference (Combined-cycle— multiple shaft, \$25/ton CO ₂ penalty, gas price avg among the one considered)	Electricity cost ranges \$/MWh (not including FOAK CCS)
MUNI	48.8	44.2 – 59.7
IOU	52.0	46.9 – 62.8

Private-Public Partnerships for First of a Kind Deployment

This analysis evaluates the value of the following private-public partnerships to address first-of-a-kind (FOAK) costs to incentivize utilities to deploy the first SMRs.

Production Tax Credit (PTC): The PTC in this analysis is modeled on the PTC for renewables that has been effective in promoting those new technologies for decades. This methodology was used instead of the existing nuclear PTC from the Energy Policy Act of 2005 so that the value reflects escalation since the original Act was passed. The PTC is currently available to stimulate SMR deployment beyond 2020, given the extension of the previous 2020 deadline signed into law in 2018. Currently, PTCs are transferable and sellable on secondary markets from private and public entities. The value of PTCs on secondary market is diminished in a proportional fashion to the likelihood of the production will take place in a given amount of time. For nuclear, the discount would probably be minimal. Given the transferability of the PTC to be sure that an eventual lack of large enough tax liability would jeopardize fully capturing its value, it is preferable to model the PTC as an energy credit. The PTC is modeled as an energy credit of \$23.6/MWh for 10 years, escalated for inflation, which equals \$7.9/MWh in the LCOE reduction.

Loan Guarantee (LG): The LG modeled in this analysis is based upon the current Department of Energy Loan Guarantee program. It is assumed that the utility with a loan guarantee finances the project with 80% debt. Depending on the financial credit rating of the company, the debt interest will be different. For a BBB rated company, the markup in addition to a Treasury bond (T-bond) rate for the same tenor is 0.71% while for AA and above it is 0.375%. The historical rate for the 30-year T-Bond is quite high, and the last 20 years average is significantly lower. Table A-10 reports the cost of capital using the LG program in different cases. Notice that in case of the Muni, the LG does not provide any benefit using the last 20-year average T-bond return. This is due to the current low rate of the current cost of capital for Muni vs. the long-term rate of the 30-year T-bond; therefore, the analysis will be highly sensitive to the time in which the project is initiated. The rate assigned to

municipality bond is not far from the T-bond, and depending on the time, fees and markup can make up the difference, in which case the LG program would not be viable for the Muni. If choosing financial terms today, it would be advantageous due to the very low rate of the current 30-year T-bond, but in a long-term analysis it does not seem suggested.

Table A-10: Discount Rate for SMRs with Loan Guarantee

Data	IOU	Muni
Bond Rating	BBB	AA and above
Markup bond rating	0.71%	0.375%
Historical T-bond 30-year rate (last 20-year avg.)	4.08%	4.08%
Loan fee (this is an additional capital cost not accounted in the WACC)	0.5%	0.5%
Tax Rate	25.6%	N/A
Equity Return	10.5%	N/A
Equity Share	20%	0
Discount rate using historical data (WACC)	4.82%	4.45%

Advanced Cost Recovery (ACR): The ACR (also known as Construction Work in Progress – CWIP) modeled in this analysis is based upon the authorities granted in Florida, Georgia, and South Carolina. The ACR is modeled as recovery of 100% of the financing charges as they are incurred.

Power Purchase Agreements for Resiliency (PPA): The PPA modeled in this analysis is a broad contractual vehicle between the SMR owner and a Federal entity (e.g., DOE) receiving services from the SMR owner. Under this PPA, the Federal entity provides compensation to the SMR project annually in an amount that is sufficient to compensate for the value of those products and services (e.g., high reliability of 99.9999%). SMRs can efficiently provide these benefits when compared to the level of resiliency provided by diesel generators, fuel oil, and maintenance for dozens of MWe of backup power that would be neither economical nor carbon-free. The PPA is modeled as a capacity credit of \$60 million per year for 40 years.

Department of Energy (DOE) Cost-Share (CS): The DOE entered a cost share agreement with UAMPS and has established the Advanced Reactor Demonstration Program (ARDP), to support the engineering, procurement, and construction of one or more of the first SMRs. This program would directly address the near-term aspects of technology uncertainty in deploying a first-of-a-kind (FOAK) SMR and could be an attractive value proposition for the government and first mover customer. This analysis models a direct investment at \$350M in the SMR plant as a ‘buy down’ of the overnight capital cost to \$3,375/kWe for the FOAK.

While the values of other private-public partnerships are not calculated in this report, they are included in the assumptions for SMR costs as well as for the deployment rates. These include:

Manufacturing and Supply Chain Support: A DOE program to support SMR manufacturing of innovative first-of-a-kind components (e.g., the integral reactor pressure vessel and containment module) during the licensing phase. This will demonstrate advanced manufacturing techniques and

allow for the fabrication of commercial units at lower costs and shorter delivery schedules, while incorporating lessons learned via repetition. Support also includes investment tax credits to incentivize a domestic supply chain for SMR deployment in the U.S., as well as for export. Manufacturing and supply chain support is important to achieve the expected cost and schedule of SMR construction, as well as to reduce cost and schedule uncertainty.

Deployments in 2030 and Beyond

This analysis evaluates the following uncertainties around the cost of SMRs after lessons are incorporating lessons learned from FOAK deployment.

Operating Lifetime: The analysis assumes that the operating lifetime of an SMR is 60 years, but the tenor of the loan is kept at 30 years to compare to an NGCC and offer a risk-free reference for investment the 30-year T-bond. However, it is expected that several of the current fleet of nuclear plants will operate for 80 years. The extension of the lifetime of the plant from 60 to 80 years would decrease the LCOE by about \$1/MWh for the current rate considered, and at the same time it would be fair also to consider additional capital expenditure to increase the plant lifetime to 80 years. But in this analysis, these additional benefits are not accounted for.

Overnight Capital Cost: Two factors could reduce the overnight capital cost in 2040 below from \$2,500/kWe to the \$2,000/kWe in Table A-5: (1) advancements in manufacturing and construction, and (2) technologies and higher learning curve rates. A more focused effort by both industry and the Department of Energy to develop advanced manufacturing and construction technologies could significantly reduce the materials, labor, and time needed to construct SMRs. The nth-of-a-kind estimation of the costs assume either 10% or 15% reduction in cost due to learning, which is applied with every doubling of the number of SMRs deployed, so the mentioned \$2,500/kWe or \$2,000/kWe are achieved after approximately nine units, with four core each, built. For comparison, the learning curve reduction seen in the building of large light-water reactors by (Korea Hydro & Nuclear Power) KHNP is estimated to be 15% with every doubling during construction of 16 reactors. Figure A-11 shows the expected reduction to overnight capital costs when applying a 10% and 15% learning curve.

Material Escalation: Part of the reason the overnight capital cost of SMRs is so high compared to NGCC is because they require a lot of commodity materials, such as concrete and steel. Commodity material prices can be volatile. The possible impact of an increase of \$100/MWe in the overnight costs has been considered. For both MUNI and IOU, the impact would be less than \$2/MWh.

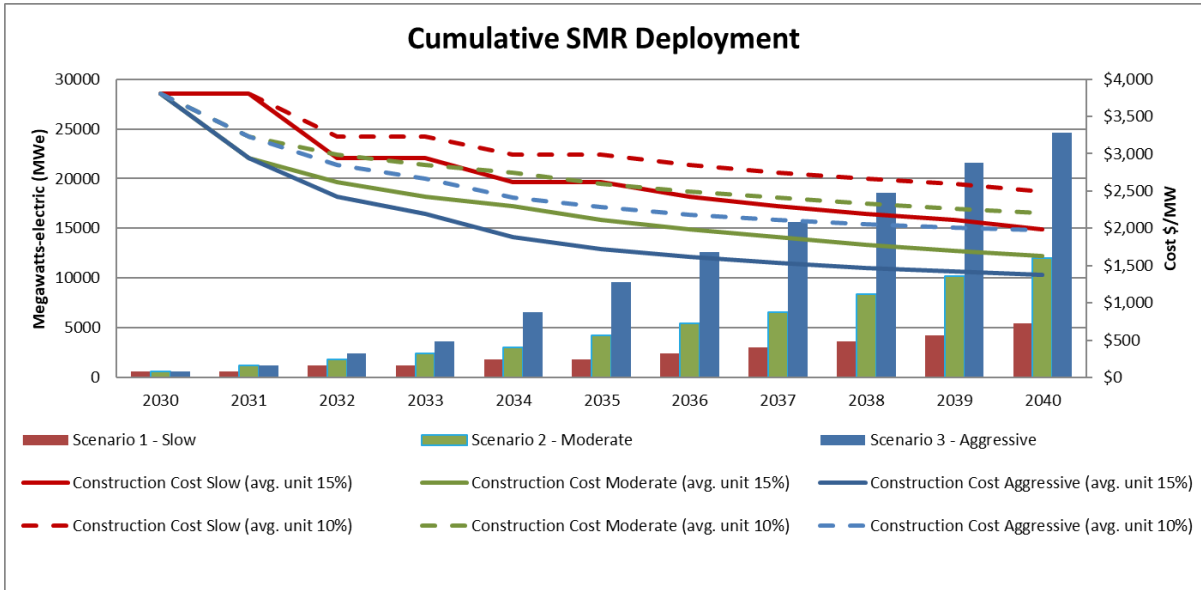


Figure A-12: Decrease of overnight costs for different deployment scenarios as derived from a 10% learning rate