Replacement of Coal or Natural Gas Facilities with Small Modular Nuclear Reactors Operating by 2035

ENEC 698

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Contents

1 Abstract

Small Modular Reactors, SMRs, are factory-produced nuclear assemblies with an output of less than 300 megawatts of electricity. While not yet commercially available in the United States, SMRs have the potential to replace traditional large-scale expensive nuclear reactors currently operating in the United States. SMRs will offer a safer, cheaper, enduring, and cleaner energy production alternative to fossil fuels and can produce base load electrical output; an area where renewables struggle. Referencing the most up to date information regarding the various SMR designs, siting requirements, regulatory concerns, economic assessments, and potential environmental impacts, research was conducted in order to select the optimal SMR technology for replacing a coal power plant in North Carolina by 2035. After this encompassing analysis, it was concluded that the NuScale's Power Module is the ideal nuclear technology. After considering various sites in North Carolina, it was determined that the 727 MWe Mayo Coal Power Plant in Roxboro would provide a viable location for implementing SMR technology by 2035.

2 Introduction

The World Nuclear Association (WNA) defines a Small Nuclear Reactor (SMR) as producing less than or equal to 300 MWe, having modular technology and factory fabrication, and short construction times. The various types of SMRs offer several advantages over large, traditional reactors. These advantages incorporate mitigated financial risk, simplicity of design, improved production quality and efficiency, reduced siting costs, passive or inherent safety features, increased resistance to terroristic threats and natural disasters, scalability of multiple units at a single site, and lower cooling requirements (WNA 2019). It is for these reasons that, according to the Office of Nuclear Energy, "more than 50 U.S. companies are developing advanced nuclear reactor designs", such as SMRs (Office of Nuclear Energy 2018). Some publications are also estimating the amount of electricity produced by SMRs in the world to be as much as 21 GW by 2035 (NEA/OECD 2016).

SMRs are separated into four main technologies, these include: Light Water Reactors (LWRs), Fast Neutron Reactors (FNRs), High-Temperature Reactors (HTRs), and Molten Salt Reactors (MSRs). All of the different SMRs utilize a radioactive substance, usually uranium-235 at varying levels of enrichment, to power a fission reaction. The fission reaction releases large amounts of energy that can be harnessed to heat water into steam that then turns a turbine, producing electricity. Energy from the fission reaction, as well as the steam, can also be used for other industrial processes (WNA 2019).

LWRs in the United States of America are, for the most part, the furthest along in development out of all SMR types due to the fact that they are most similar to the large reactors currently in operation. Despite these similarities, they still claim enhanced safety features relative to their larger counterparts. Both common large reactors and LWRs are cooled and moderated by ordinary water, and often require fuel enriched to less than 5%. Some of the well known LWRs in development in the United States are Flour Enterprises' NuScale Power Module, the Holtec SMR-160, and the Westinghouse SMR (WNA 2019).

HTRs are also based on previous designs, primarily the experimentation of Germans in the 1960s and 1970s. HTRs that are not FNRs also employ graphite as a moderator and use helium, carbon dioxide, or nitrogen as a coolant. They may require specialized fuel in the form of TRISO (tristructural-isotropic) particles that are less than a millimetre in diameter. The TRISO particles include uranium that is enriched up to 20% and then surrounded by layers of containment materials to prevent the release of fission products. Spent TRISO fuel is often less radiotoxic than LWR waste but HTRs produce a larger volume of it. Newer HTRs are increasing their capability to reach high temperatures, opening up various industrial applications. Some HTRs in development in the United States include General Atomics' EM2, the X-energy Xe-100, and USNC's MMR5 (WNA 2019).

FNSMRs in the United States are largely at the conceptual stage of development but some are in use around the world with a few even producing electricity commercially. They are smaller and simpler than LWRs and do not require a moderator. Fast reactors are normally cooled by liquid metal that has a high conductivity and boiling point, but they can also be cooled by gas or molten salt. FNRs also have a reactivity feedback that slows the reaction during a loss of coolant flow, making the reactor inherently safer. Fuel for these reactors is generally enriched to between 15% and 20%. Some FNRs in development in the United States include GE Hitachi's PRISM, the ARC-100, and Gen4 Energy's G4M (WNA 2019). Some FNRs utilize natural uranium, depleted uranium, or spent nuclear fuel as their reactor fuel (WNA 2019).

MSRs are at various stages of development within the United States. The U.S. has proven the technology in the 1960s through a prototype at Oak Ridge. MSRs operate using molten salts as a primary coolant and can do this in two different ways: dissolving the fuel within the salt, or housing the solid fuel within graphite and using the salt solely as a coolant. Proponents of this type of SMR claim a multitude of benefits including less radioactivity of waste, less weapons-grade waste products, increased thermal efficiency, and low fuel use (WNA 2019).

3 Methodology

Initially, twenty-two small modular nuclear reactor technologies currently under development in the United States or by US companies were selected. Each technology was evaluated based on various attributes including MWe output, levelized cost of energy, coolant type, refueling window length, available safety features, module output scalability, operational lifetime, required construction time, and current phase of development. Reactor designs that were deemed underdeveloped or unlikely to be completed by 2035 were eliminated.

Remaining potential reactors were evaluated based on their predicted availability by 2035 and the feasibility of their costs. The most suitable options from each reactor technology were selected, yielding four potential SMR options to be compared and examined in depth.

3.1 Scoring Metrics

To compare the four selected SMRs, facets of each SMR technology were implemented into a weighted matrix scoring system. The NuScale Power Module, X-energy Xe-100, Martingale ThorCon, and ARC-100 reactors were all evaluated on the basis of their energy outputs, levelized costs of energy, refueling windows, safety features, expected lifetimes, commercial operation dates, estimated construction times, and siting feasibility. A score of 1-4 was assigned to each reactor based on its performance in each particular category. A score of 1 indicates the lowest relative performance and a score of 4 indicates the highest relative performance. The scoring numbers are estimates based on information from the various SMR manufacturers, International Atomic Energy Agency (IAEA), US Department of Energy, Nuclear Regulatory Commission (NRC), World Nuclear Association (WNA), and other relevant publications.

The two most critical factors under consideration were levelized cost of energy and commercial operation date. For the SMR technologies under consideration to be feasible in replacing coal and natural gas plants, they must promise LCOEs that are price-competitive with traditional, non-renewable sources. Also, equally valued was the date at which the SMRs plan to be operational, since this analysis concerns only designs that will be available by 2035. To evaluate the variables according to their importance, these variables were multiplied by a specifically weighted coefficient. The highest priority factors, LCOE and COD, were multiplied by a coefficient of 2.0.

When examining the factor of SMR siting, transportability of the reactors and size of EPZ zones were spotlighted within the metric. The accessibility of moving the SMR to the proposed site was compared to the physical size of the reactor and the logistical complications involved with transporting from the manufacturing facility to the final destination. While this was an important metric to be considered, it fell second in priority to the more pressing issues of LCOE, and COD. Examining the refueling window gave insight to frequency of potential refueling outages and the overall potential of proliferation during the refueling process. Again, while refueling window was an important facet under consideration, it was placed into the bin of second ranking priority. Because both siting accessibility and refueling window are still vital variables affecting the feasibility of SMR implementation and ranked of second priority, they have been multiplied by a weighted coefficient of 1.5.

Finally, electrical output in MWe, available safety features, operational lifetime, and predicted construction time were binned in the lowest tier of priority and thus a weighted scoring coefficient was not applied. Although output is undeniably important, the reactors under evaluation promised similar levels of scalability, thus reducing the comparability of the electrical output metric. Likewise, promised safety features among the considered technologies were largely similar, with each technology guaranteeing a degree of proliferation resistance, emergency cooling technologies, and passive walk-away safety. When examining operational lifetime and predicted construction time, there was negligible variation between the proposed technologies. Reactor lifetimes were all between sixty and eighty years, and predicted construction times all fell within two to four years. Due to the similar specifications these last facets were placed into the lowest bin of priority.

3.2 Scoring Breakdown

ThorCon Results

The ThorCon reactor was very promising in terms of its mid-2020s operational date and $26-34/MWh LCOE, but was hurt by its scores in siting feasibility and refueling (WNA 2019). ThorCon's refueling and siting feasibility scores are a direct result of ThorCon Power's proposed construction and assembly methods. ThorCon Power plans to build each reactor in prefabricated blocks at a shipyard and then transport these blocks to the plant site for assembly (ThorCon, 2019). Unfortunately, these blocks are too large to be transported by road or rail and virtually all of the eligible sites for a nuclear plant in North Carolina do not have sufficient river barge access. This drawback affects both siting feasibility and refueling, as the refueling process would also require barge access.

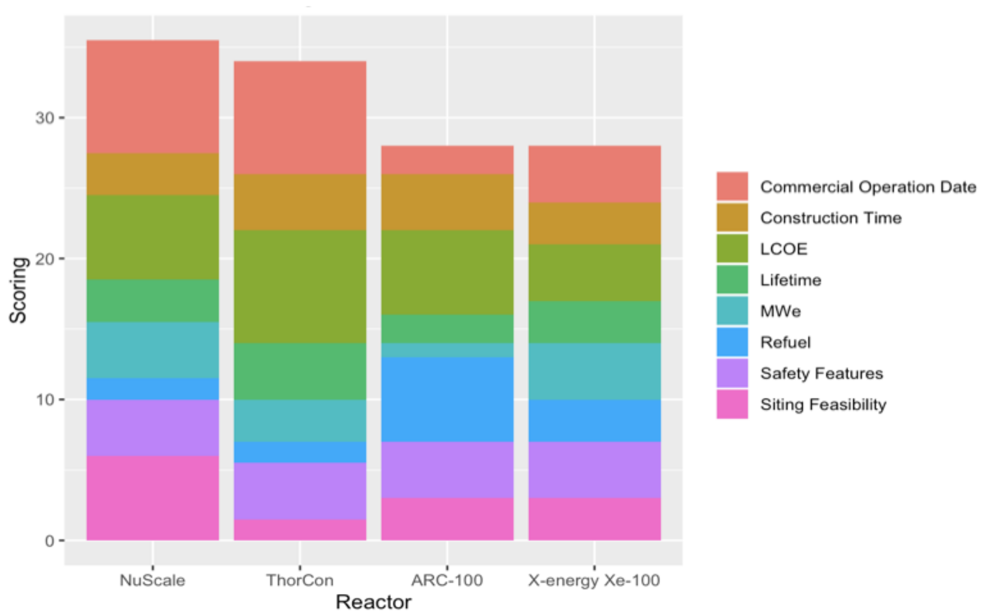


Figure 1: Final Reactor Scoring

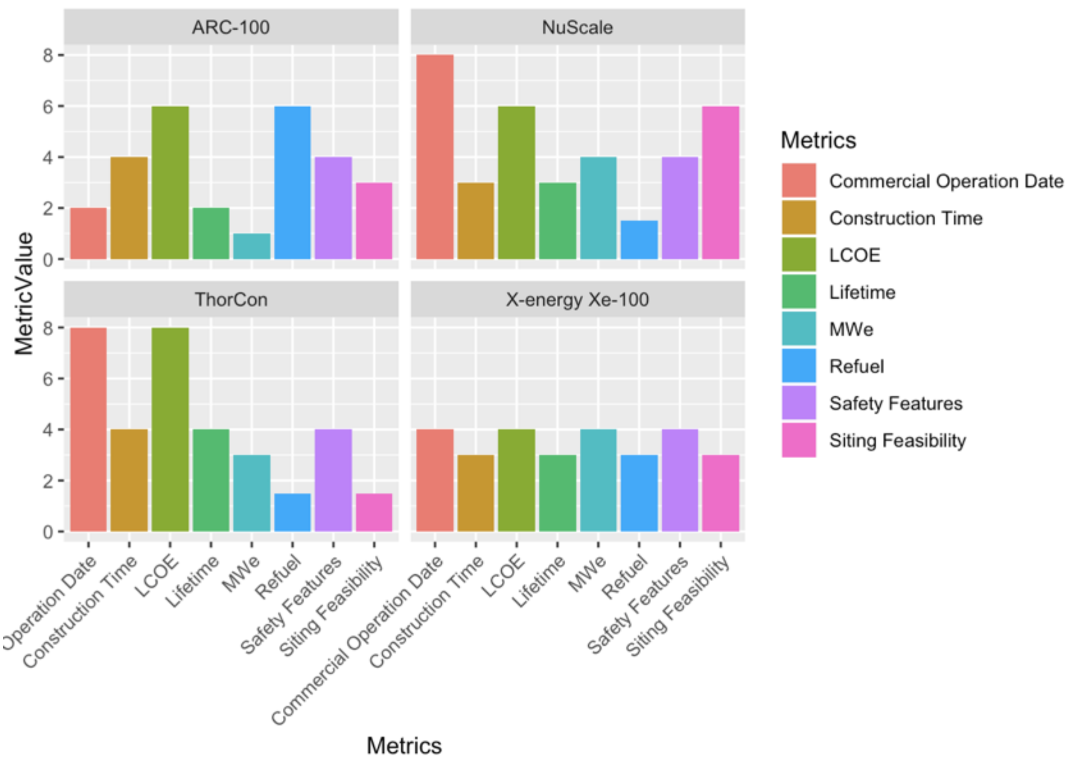


Figure 2: Individual Scoring Metrics

ARC-100 Results

The ARC-100 sodium-cooled fast reactor performed well in the categories of LCOE and refueling, with expected costs as low as \$50/MWh and a high refueling window of 20 years (WNA 2019).. However, this design was hurt by the lack of published information about its lifetime and potential MWe scalability. Still in its developmental stage, there exists a significant chance that the design will not be available for commercial operation by 2035 (WNA 2019). Most impactful, however, is the anticipated long lead time at the NRC and delays due to demonstrating the ARC-100's safe operation.

Xe-100 Results

The Xe-100 scored poorly in key metrics due to its \$84/MWh LCOE and speculative operational date. As of September 2018, X-energy claimed to have its design about 50% complete, with the full design "finalised by 2022 or 2023" (WNA 2019). However, the reactor is only expected to be available by "the late 2020s" (Office of Nuclear Energy 2018). Despite the design receiving average scores for most other attributes, its failure to perform in the weighted metrics yielded a third-place score equivalent to that of the ARC-100.

NuScale Results

The NuScale Power Module had the highest overall rating of the reactors under consideration. NuScale has an all-round balanced rating with high scores in LCOE, commercial operation date, and siting feasibility. With projected energy costs as low as \$65/MWh the NuScale would potentially be price-competitive with other forms of energy generation (Patel, 2018). For reference, the Intergovernmental Panel on Climate Change estimates the LCOE of utility-scale solar to start at \$56/MWh and the LCOE of onshore wind to start at \$35/MWh (IPCC 2014). Unsubsidized estimates from the U.S. Energy Information Administration place the LCOE of utility solar at \$60/MWh and onshore wind at \$55.9/MWh (EIA 2018). Private sector analysts from Lazard find these numbers to be even lower, estimating utility-scale solar to have an LCOE starting at \$40 and the LCOE of onshore wind to start at \$29 (Ray 2018). NuScale Power projects its reactors to be ready for operation by as early as 2024-2026, with the NRC on track to complete its review of the SMR design by September 2020 (WNA 2019). Unlike some of the other reactors discussed, the NuScale design also manages to incorporate impressive portability prior to construction. All of the required materials to build a NuScale plant can be transported via truck or rail, granting NuScale a favorable score in siting feasibility (NuScale Power Fabrication Assembly 2019). NuScale also earned the highest score of all the reactors in MWe output. Each individual NuScale reactor is reported to produce 60 MWe and each plant location can gang up to 12 of the reactors with no

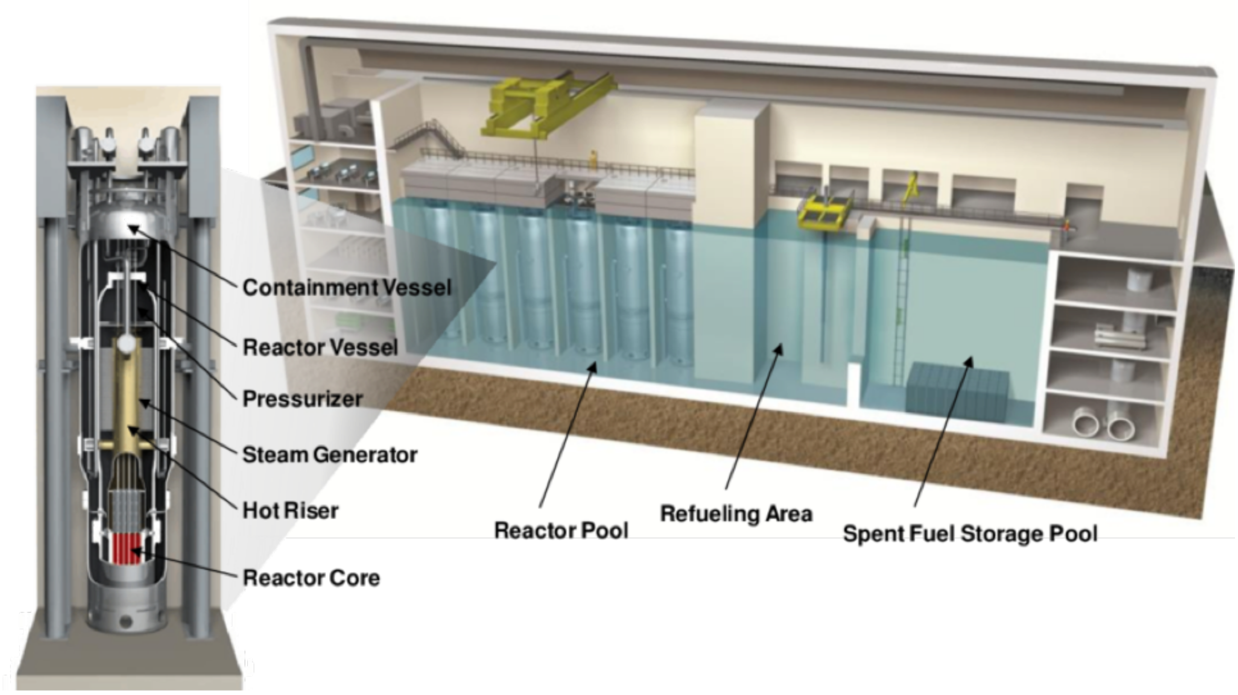


Figure 3: NuScale Power Module Reactor and Reactor Pool Diagram. Source: Ingersol 2014

additional capital investment outside the reactors themselves and their connectivity to the existing control room (NuScale Power Technology Overview 2019).

4 Specifications

4.1 Model

The selected technology is the NuScale Power Module (Figure 3), a culmination of over two decades of research by various entities into small modular nuclear reactors. The design started as a DOE-funded project at Oregon State University in the early 2000s working on a "Multi-Application Small Light Water Reactor" (NRC: Design Certification Application - NuScale 2019). These early designs were transferred from OSU to NuScale Power in 2007. Since 2007, NuScale has continued development on the Power Module design while adding partnerships with Fluor Corporation, Rolls-Royce, Enercon Services Inc., AREVA Inc., Ultra Electronics, and the Concurrent Technologies Corporation. These partnerships have helped expedite the NuScale

Figure 4: Five Ganged NuScale Power Modules. Source: NuScale Power 2019

design process, as well as improve the manufacturability of its modular reactors.

4.2 Output and Capacity

Each NuScale Power Module will produce up to 60 MWe of electricity, with the ability of having up to 12 modules operating at a single plant (WNA 2019). The operation of multiple modules is possible through ganging of the individual 60MWe reactors (Figure 4). Offering up to 720 MWe output on each site, NuScale's scalability makes it a viable option for replacing small and midsize coal-fired power plants. NuScale estimates that the plant's "capacity factor will exceed 95% - making it one of the most reliable electric generation systems available" (NuScale Power FAQs 2019). Aside from its electrical generation, each module will also produce up to 200 MWt of steam (2400 MWt for a fully-scaled unit) that can be utilized for cogeneration purposes (WNA 2019). Another key attribute of this SMR technology is its ability to load-follow, or fluctuate its power output to better meet varying energy demands and work in conjunction with intermittent renewable sources like wind and solar. NuScale claims to be able to do this in a number of ways, including taking one or more of the 60 MWe modules temporarily offline, which can take about a day, or adjusting an individual module's power over a period of a few hours (NuScale Power FAQs 2019). Another feature possible because of the NuScale's modular design is the ability to assign individual modules to hydrogen production or water desalination while maintaining electricity production.

4.3 Fuel

The NuScale Power Module will typically be powered by standard pressurized water reactor fuel: uranium-235 enriched to about 4.95% (WNA 2019). A NuScale reactor will only utilize less than 1/20th of the amount of nuclear fuel needed to operate a standard 1,000 MWe nuclear reactor (NuScale Power Comprehensive Safety Features 2019). This will result in lower decay heat, more overall stability of the reactors, and will require a much smaller containment vessel than standard nuclear reactors (Figure 8). A promising option for the NuScale Power Module is to use recycled fuel or mixed uranium-plutonium oxide (MOX) fuel. The company considers this to be "a suitable fuel for the NuScale reactors," which could mean that this SMR technology could contribute to saving uranium resources and reducing the toxicity of spent fuel (NuScale Power Storing Spent Fuel 2019).

4.4 Coolant System

The NuScale reactor is cooled with water and implements natural convection to circulate the water, making the pumps utilized in conventional reactors unnecessary (Cho 2019). The design calls for situating the entire containment vessel, with the NuScale reactor inside, into a pool of water that is below ground level (WNA 2019). This reactor pool acts as a passive heat-sink during any loss-of-coolant accident (LOCA) (NuScale Power FAQs, 2019) Furthermore, the NuScale Decay Heat Removal System (DHRS), a closed loop, two-phase natural circulation cooling system, provides secondary cooling for non-LOCA events where normal water feed is not available. (NuScale Power FAQs 2019) In extreme LOCA events, the Emergency Core Cooling System (ECCS) reacts by using reactor vent valves and reactor recirculation valves to rapidly remove heat from the containment vessel, reducing containment pressure and temperature. (NuScale Power FAQs 2019) The NuScale design also employs a system of Helical Coil Steam Generators (HCSG) that improves thermal efficiency by maximizing natural circulation flow without the need to use coolant pumps (NuScale Power Design Innovations 2019).

4.5 Safety Features

The primary advantage for the NuScale Power Module is its safety. NuScale intends for its SMRs to be the first "self-protecting reactors" through utilization of a new design coined "The Triple Crown for Nuclear Plant Safety™." This new design safely shuts down the facility and self-cools the reactors indefinitely without human intervention, AC or DC power, or additional water (NuScale Power Comprehensive

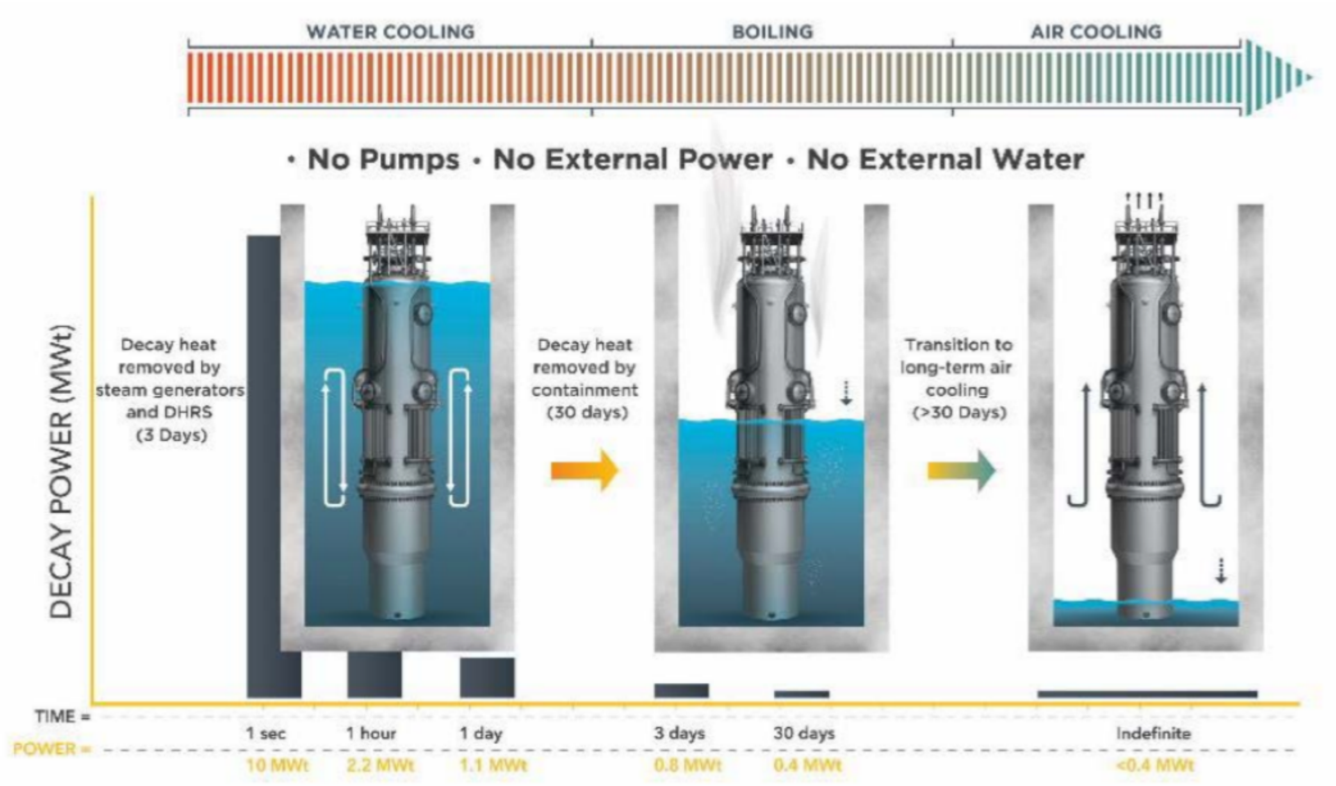


Figure 5: NuScale Emergency Passive Cooling Process. Source NuScale 2017

Safety Features 2019). The reactor itself boasts a “high-pressure containment vessel, redundant passive decay heat removal, and containment heat removal systems” that provide more foolproof cooling techniques than traditional reactors lacking passive safety features (NuScale Power Comprehensive Safety Features 2019). The containment vessel is housed in a below ground reactor pool located in a Seismic Category 1 building “capable of withstanding a Fukushima type seismic event, hurricanes, tornadoes, and floods (NuScale Power Comprehensive Safety Features 2019). Overall, NuScale offers a 7-layered defense preventing the release of nuclear material with its “oxide fuel pellets and cladding, reactor vessel, containment vessel, reactor pool, underground stainless steel lined concrete pool walls and floor, biological shield, and Seismic Category 1 building certification” (NuScale Power Multi-Layered Defense 2019). Outside attacks are no longer a concern with the NPM, which promises to deliver “resilience to solar-induced geomagnetic disturbances (GMDs) and electromagnetic pulse (EMP) events. Further, NuScale’s proprietary Field Programmable Gate Array-based digital Instrumentation and Control setup does not utilize a software operating system, making it impervious to outside cyber-attacks (NuScale Power Built For Resilience 2019).

4.6 Cogeneration Potential

The NuScale SMR is expected to have various cogeneration abilities, with a major advantage being that individual modules can be utilized for specific purposes in addition to generating electricity. The NuScale reactor will have the potential for desalination, oil recovery from tar sands and refinery power, hydrogen production by high-temperature steam electrolysis, and steam generation (WNA 2019). A single 60MWe Power Module is able to produce 200MWt of steam (NuScale Power Diverse Applications, 2019). When coupled to a desalination plant, a single module can produce 50 Mgal/day of clean water (NuScale Power Diverse Applications 2019).

4.7 Construction Time & Considerations

The construction of a NuScale Power Module will differ significantly from that of a conventional nuclear facility or even a coal/gas plant. Each module will be factory built off-site, then shipped and assembled at its eventual site (NuScale Power Fabrication Assembly 2019). All components will total about 700 tons, transported from the factory in three segments by ship, rail, or truck (NuScale Power Fabrication Assembly 2019; Technology Overview 2019). This will allow the SMR to be constructed off-site and then easily brought to any site in North Carolina. Another

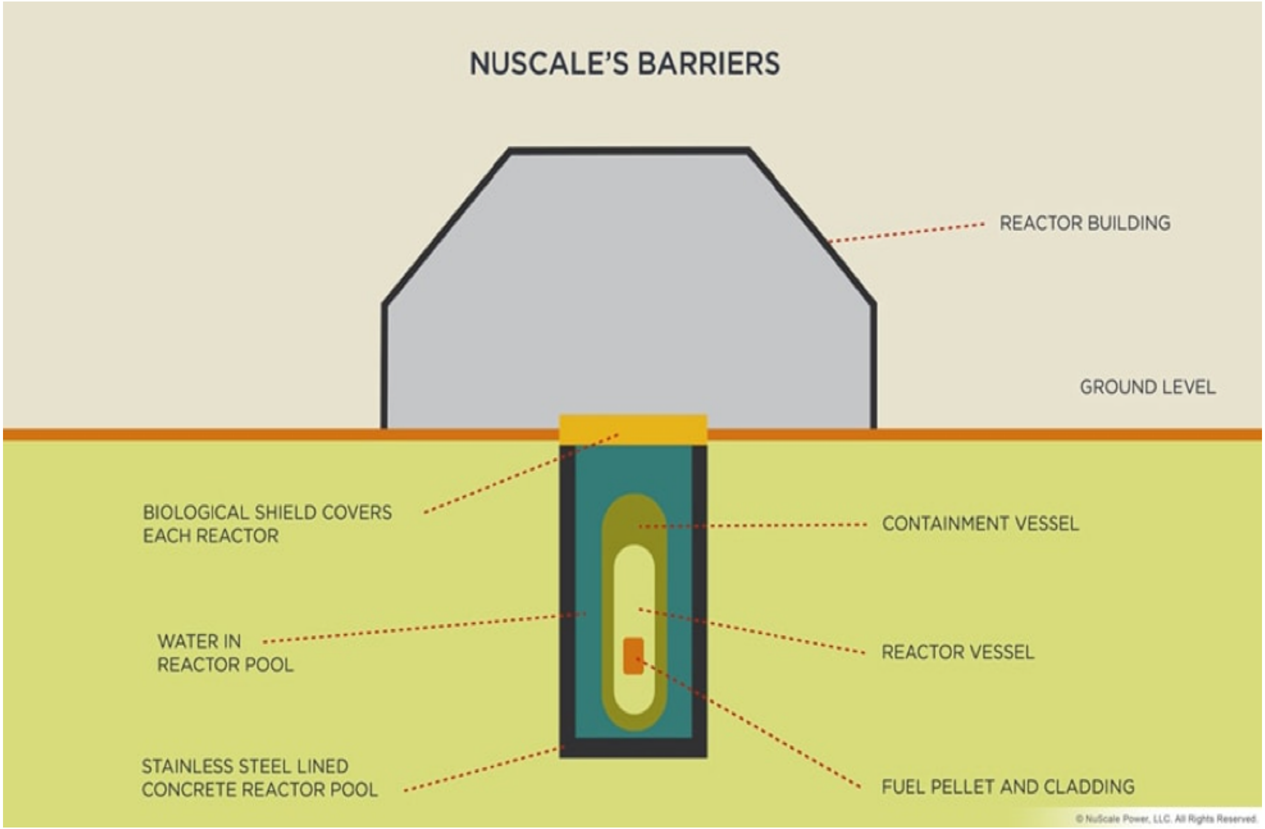


Figure 6: NuScale's Multi-Layered Defense. Source: NuScale Power 2019

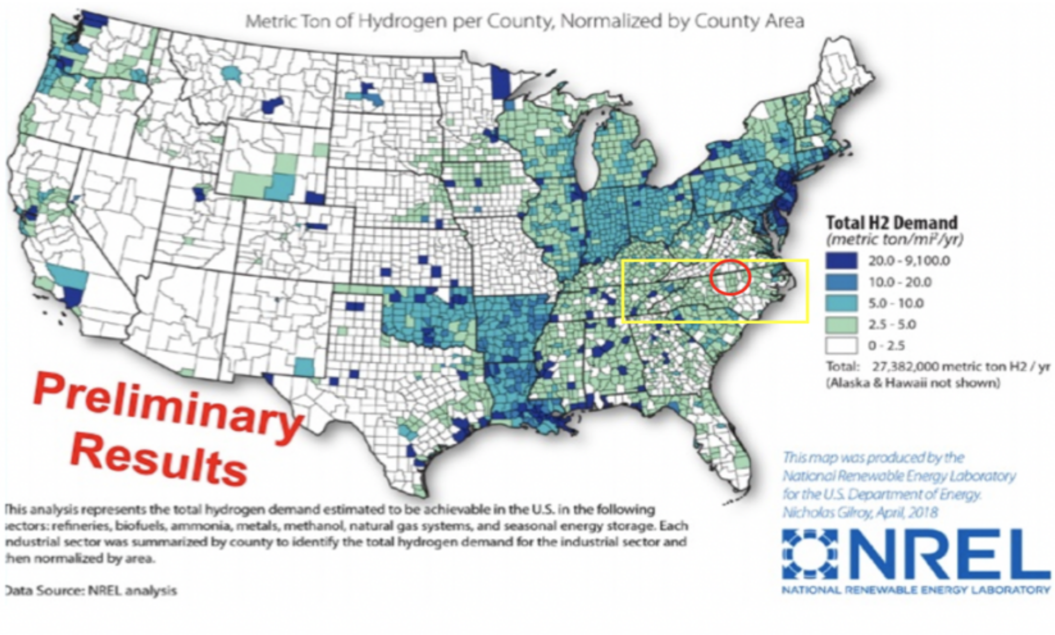


Figure 7: North Carolina Hydrogen Demand. Source: NREL 2018

consideration is that small modular reactors like the NuScale only require "medium-sized forges, something we still have here in the United States" (Conca 2018). The construction of a fully-scaled NuScale plant is estimated to take anywhere from 24 to 36 months after gaining full approval (NuScale Power Cost-Competitive Nuclear Technology, 2019). This is about half the time required to construct a conventional nuclear reactor (Conca 2018). The NuScale Power Module will require significantly less land for its siting when compared to traditional nuclear reactors; both because of its smaller EPZ and the reduced size of modular reactors. As displayed by Figure 8, at least 126 NuScale Power Module containment vessels and reactor systems could fit inside of the containment vessel of a traditional pressurized water reactor.

4.8 Refueling and Lifetime

The NuScale Power Module claims a 24-month refueling cycle, but it differs from many other SMR technologies in that refueling has been "turned into a routine task instead of a costly every two-year evolution" (NuScale Power Cost Competitive Nuclear Technology WNA, 2019). This is because a single NuScale module can be refueled without putting other modules offline. For a NuScale facility with 12 ganged reactors, this means the other 11 modules can continue to provide 92%

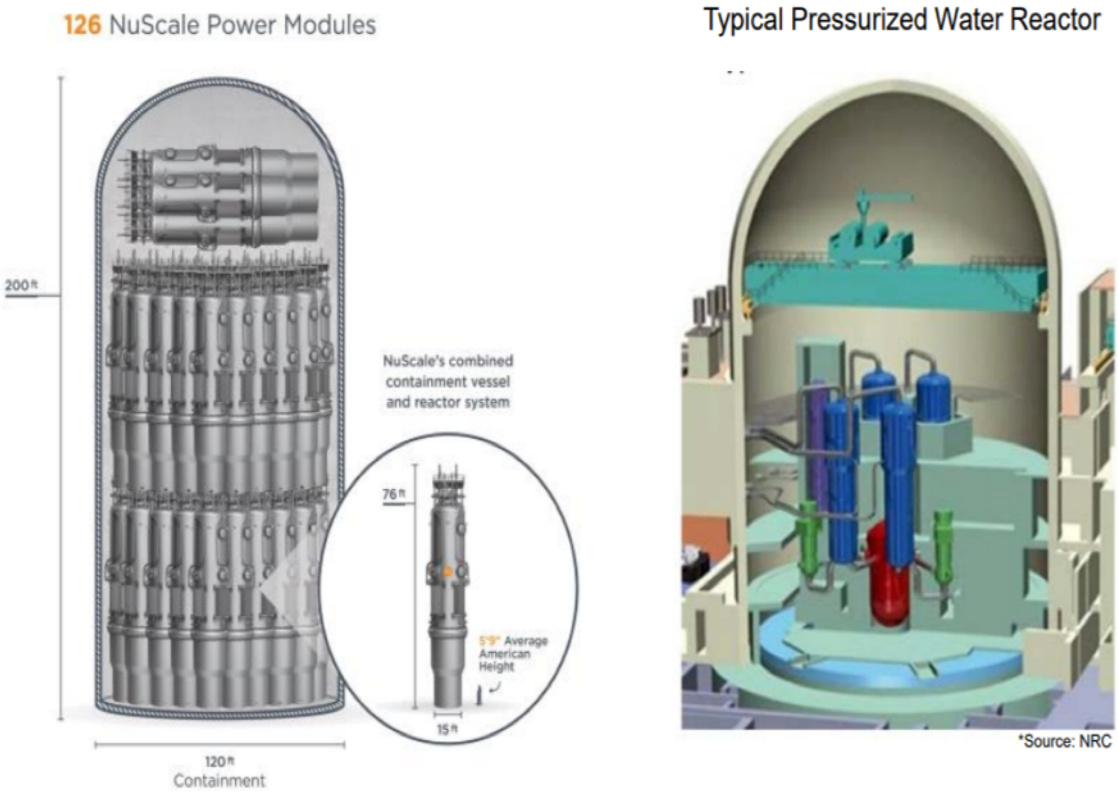


Figure 8: Size Comparison of NuScale vs. Standard Reactor Containment Vessels. Source: NuScale Power 2017

of the facility's electrical output while one is being refueled. (NuScale Power Cost-Competitive Energy 2019). Over the course of its lifetime, this SMR design promises 99.98% reliability, equating to "only four days in 60 years where there would be zero output" from a single 60 MWe module (NuScale Cost-Competitive Energy 2019). Each NuScale Power Module has a 60-year design operational lifetime, consistent with other SMR technologies and NRC 60-year operational permits (WNA 2019).

5 Siting

According to USA today, the United States is set to construct and implement 177 new natural gas power plants, complementing the already 2,000 natural gas facilities in the country (Weise 2019). North Carolina has 12 new plants planned to go into operation. Furthermore, there are 14 existing coal power plants in the state, some of which are already set to retire (NC State Government 2019). In this section, siting, and siting requirements, of NuScale SMRs in North Carolina will be explicitly examined on the basis of replacing a previously installed coal or natural gas plant. Factors to be explored include general locational reasoning and energy demand, surrounding grid analysis and interconnection viability, designed or potential use of 'waste' heat, and effectiveness of the services provided at suggested location.

5.1 Considered Location

The NuScale SMRs would be most suitable in a location with a relatively steady energy demand, and one that is in the vicinity of electrical substations and high voltage distribution lines. However, SMRs of this stature must be placed in a location where an assumed 40-acre emergency protection zone (EPZ) is not burdensome on the surrounding community (NuScale Power 2019). Yet, a location adjacent to a town or city is a vital consideration in regards to the usage of steam byproduct and cogeneration potential. Steam produced by the NuScale can be treated as a coproduct that can be directed to adjacent towns for heating during winter months, or for other various industrial (including hydrogen production or desalination) or medical uses throughout the year.

Retiring coal plants within North Carolina offer excellent locational options for the implementation of ganged/staged NuScale SMRs. These sites, owned by Duke Energy or Duke Energy Progress, are already connected to necessary grid infrastructure and electrical substations. This would ensure that the adequate transmission infrastructure for an SMR is available and would help to avoid high cost transmission upgrades or the addition of a new site-specific substation. Furthermore, high voltage transmission lines are already connected to coal power plants for distribution (Platts 2012).

Coal power plants, as previously stated, are no longer price competitive in a modernizing grid where levelized energy costs are quickly dropping for new technologies (IPCC 2014; EIA 2018; Ray 2018). Within North Carolina, a handful of the 14 operating coal power plants are already set to retire. Furthermore, language in Duke Energy's Integrated Resource Plan suggests a general transition to more price competitive and environmentally friendly generating sources (Duke Energy Progress 2019).

With these factors in consideration, the Mayo Plant, a 727 MWe coal plant located in Roxboro, North Carolina, has been selected as the most suitable location in the state to trial the replacement of a coal-powered facility with SMR technology. The power plant has been in operation since 1983, has faced multiple environmental lawsuits, and is set to retire in 2035. According to Duke Energy, the retirement may even be accelerated due to operating costs and the environmental cost of coal. In the following sections the logistics of selecting the Mayo Plant for replacement with NuScale SMRs will be explicitly explored.

5.2 Locational Reasoning

The Mayo Plant is located about ten miles northeast of Roxboro, NC, sited on the bank of Mayo Reservoir (See Appendix, Map A). The plant has traditionally used the lake as a water source for coal-steam generation. Due to the close proximity of the plant to the lake, there have been numerous environmental issues associated with metal discharge and runoff into the common recreational boating and fishing areas offered by Mayo Reservoir. On multiple accounts, various environmental and non-profit groups have targeted Duke Power in regards to their coal-ash runoff into Roanoke River Basin. In one instance, the Roanoke River Basin Association stated that the Mayo Plant violated the federal Clean Water Act. This particular group further claimed that, "6.9 million tons of ash at Mayo has illegally contaminated the popular fishing destination Mayo Lake," (Henderson 2016). This account, along with various others, demonstrates the detrimental activity that the current power producing coal facility exhibits on the surrounding natural area. With the implementation of NuScale reactors, power demand will be met all while having minimal impact on the surrounding environment.

An additional factor considered in the siting of NuScale reactors at the Mayo Plant focuses on the plant's geographical placement in relation to Emergency Protection

Zones, or EPZs. EPZs, established by federal regulators, are buffer-zones that protect surrounding populations in the event of severe nuclear accidents. Large scale nuclear operations typically require tiered levels of Emergency Protection Zones, with the largest buffer ring being 10-miles radius from the center of the plant. Because of EPZs, the siting process and legal barriers that large scale nuclear must face are cumbersome and laborious. Alternatively, according to NuScale, the SMR technology will only require an EPZ as large as 40 acres (Map A). Smaller EPZs will facilitate higher levels of siting flexibility and further establish Mayo Plant as an optimal location for an SMR, while still remaining close to the adjacent town of Roxboro to offer steady energy supply. To understand the scope of the minimal 40-acres EPZ zone versus that of the 5 and 10-mile EPZ, see appendix maps B and C. It's evident that the installation of a NuScale reactor would require less than one percent of the 10-mile EPZ zone for traditional large scale nuclear (Cho 2019). The Mayo Plant also conveniently sits on a roughly 1,000-acre parcel tract controlled and owned by Duke Energy and will have adequate access to a steady water supply via Mayo Lake, if necessary.

Adjacent to the Mayo Plant resides the small community of Roxboro, North Carolina, just ten miles southwest. The 727 MWe Mayo Plant has most recently been operating at only 21.8% of its capacity on average and never operated at over 50% during 2017 (Wamsted 2018). This is a strong inclination that the plant's full capacity has not been utilized due to the costs that Duke Power must face to operate the inefficient plant. However, Duke continues to operate the plant to supply the necessary generation to the town of Roxboro, and adjacent areas and manufacturers. Although energy demand and population are both not increasing in the area of Roxboro or Person County, the Mayo Plant still remains in an advantageous location in regards to distribution (Raynor 2019). Map D in the Appendix is an overview of the installed high voltage transmissions running from Mayo Plant, in Person County, to the Raleigh-Durham (RDU) area. There are multiple high voltage lines transmission lines that feed directly into the RDU region. The RDU area is a growing economic region with a positive population growth. The Mayo Plant is situated in a unique location to both supply reliable power to the local town of Roxboro and its surrounding industries, while still exporting surplus energy to the growing RDU area about 50 miles to the south.

5.3 Grid Analysis and Interconnection Viability

For all new generating facilities in the United States, developers must enter the project into an interconnection queue: a collection of feasibility and system impact studies. This is essentially the standard operating procedure that various grid op-

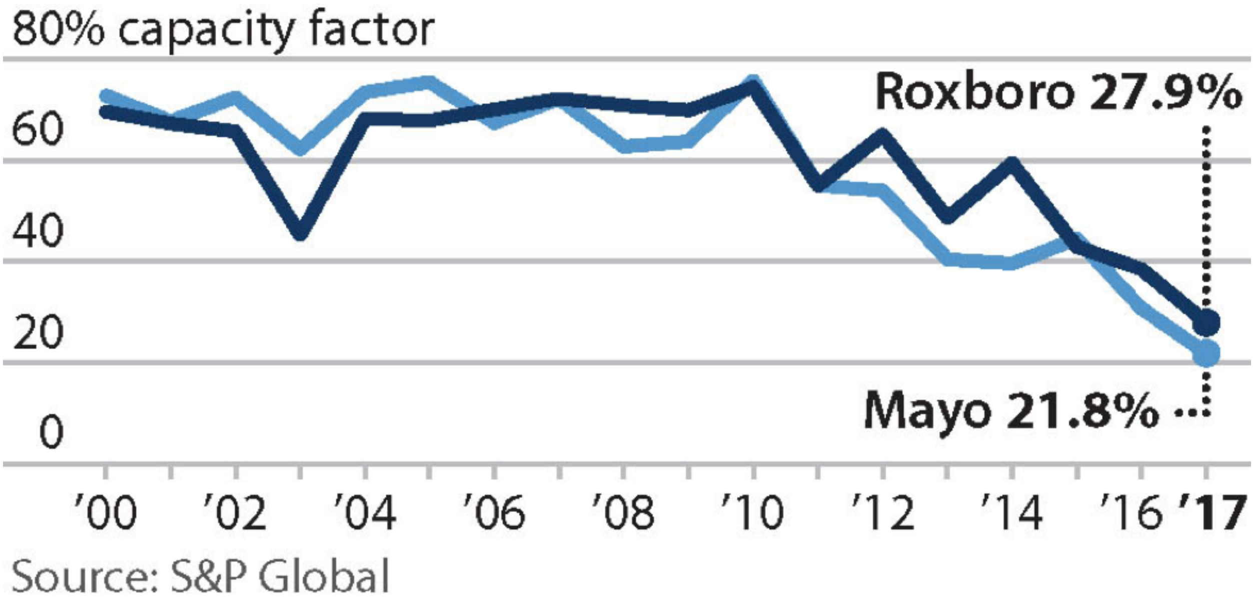


Figure 9: Mayo and Roxboro Plant Capacity Factors. Source: Wamsted 2018

erating entities take to analyze if the existing infrastructure can support additional capacity, and how the additional capacity will affect the rest of the grid. Interconnection studies are typically conducted by the entity of which the interconnection will be requested to. Since North Carolina is a regulated energy market, most requests go through Duke Energy, the state's regulated utility entity, rather than an Independent Service Operator (ISO). For the sake of a NuScale SMR replacement of the Mayo Plant, it is assumed that the plant would request interconnection into the Duke Energy interconnection queue. This is also the case as the Mayo Plant and surrounding infrastructure is owned and operated by Duke Energy. Furthermore, as this NuScale project will request a MWe capacity of over 700 MWe (comparatively a large-sized project), it will be assumed that the project will take precedence over smaller 1 to 5 MWe utility-scale solar or biomass projects that are becoming more common in the state of North Carolina.

A vastly important facet for the viability of a large-sized power generating facility is the effectiveness with which the plant can distribute the produced energy. The advantage of selecting the Mayo Plant to site a NuScale project is that the infrastructure for effective distribution is already in place and maintained by Duke Energy. The Mayo Plant site has both low and high voltage transmission lines, as coal power plants typically do to enable distribution. According to NuScale, "A NuScale plant could also utilize the existing water and transmission infrastructure of a retiring thermoelectric plant (e.g., a retiring coal-fueled plant)" (NuScale Power

Reduced Water Consumption 2019). Refer to the appendix for a view of the prolific high voltage transmission interconnecting the preexisting Mayo Plant. Most of the lines running to Mayo Plant fall within the 230 - 345 kV size, according to the PowerMap Electric Power Layer GIS Dataset, and provide excellent infrastructure to carry electricity throughout the grid (Engineering Notes 2017).

Lastly, substations are also paramount to the distribution and transport of produced electrical power. Electrical substations utilize step-up transformers to increase the voltage of current to a higher level in order to increase the efficiency of energy transportation. Higher voltage transmission lines, 230 kV or higher, are better equipped to transfer electricity with less electrical loss (Engineering Notes 2017). Map A (Appendix) is an overview of the existing electrical infrastructure at Mayo Plant. Mayo Plant has two on-site substations previously utilized for the step-up of the plant's own electricity distribution. These existing substations will allow for cheaper construction costs of a NuScale reactor and will provide for efficient, high voltage transmission to the RDU area.

5.4 Use of Waste Heat & Additional Services

Roxboro is an industry-centered town. According to the Roxboro Area Chamber of Commerce, the town's largest industries are manufacturing, veneer, and agriculture. A NuScale trial at the Mayo Plant site would provide a unique, price competitive, power supply option for these commercial and industrial customers. With cheaper energy production from a NuScale, CI energy rates will presumably decrease and will likely stimulate additional industry to the region. Furthermore, any of the industries, including nearby hospitals, that rely on the consumption of steam for heat or manufacturing would have steady supply from the ancillary steam generation of the nearby NuScale modules. Any surrounding manufacture that benefits from the raw hydrogen material is also viable to consume produced hydrogen from the modules. Refer to Figure 7 to observe industrial hydrogen demand in surrounding counties. Person County, notably, has a larger industrial hydrogen demand compared to many other surrounding North Carolina counties. Finally, in terms of residential heating, the retrofit modules would primarily benefit houses that live within one to two miles of the plant's vicinity.

6 Policy & Certifications

6.1 Traditional Nuclear Regulatory & Certification Process

The Nuclear Regulatory Commission (NRC) is in charge of licensing and regulating nuclear power plants in the United States. Traditionally, the licensing process has been done in two steps. These steps include obtaining a construction permit and an operating license. Initially, an applicant must provide safety, design, and siting information to the satisfaction of NRC staff (NRC Licensing Process 2019). Then, the applicant must cooperate with an independent reactor safety advisory organization called the Advisory Committee on Reactor Safeguards (ACRS), be subject to an environmental review in accordance with the National Environmental Policy Act, and ultimately listen to public concerns through a hearing in accordance with the Atomic Energy Act. Only then may an applicant be approved for a construction permit.

With a construction permit obtained, the applicant starts working towards an operating license. First, the applicant submits a Final Safety Analysis Report on the final design and safety features of the proposed plant, then the NRC must produce a Final Safety Evaluation that is assessed by the ACRS (NRC Licensing Process 2019). The NRC then once again gives the chance for public stakeholders to state their issues with the potential project. Finally, the NRC decides the fate of the operating license based upon their findings (NRC Licensing Process 2019).

In 1989, the NRC went on to develop two alternative licensing processes designed to improve efficiency: combined licenses and early site permits. As seen in Figure 15, combined licensing is aptly named as it essentially combines a construction permit and an operating license into one application. The purpose of an early site permit is to allow “for a limited work authorization to perform non-safety site preparation activities before a combined license is issued” (NRC Licensing Process 2019). The early site permit focuses on the safety of the location itself and potential emergency procedures without committing to a specific reactor design. Currently, these licensing processes are designed for and applied to large traditional light water reactors. Ideally, the safety improvements inherent to SMR designs will prompt the NRC to alleviate some of the licensing difficulty for companies like NuScale.

For traditional large scale nuclear siting protocol, the size and shape of each EPZ boundary is designed on a case by case basis by the NRC. However, establishing EPZs follow the same relative structure and jurisdictions. For each nuclear site, two EPZs are required. First, a Plume Exposure Pathway EPZ is created with a minimal radius of 10 miles from the reactor site. Within the 10 mile radius, concentric

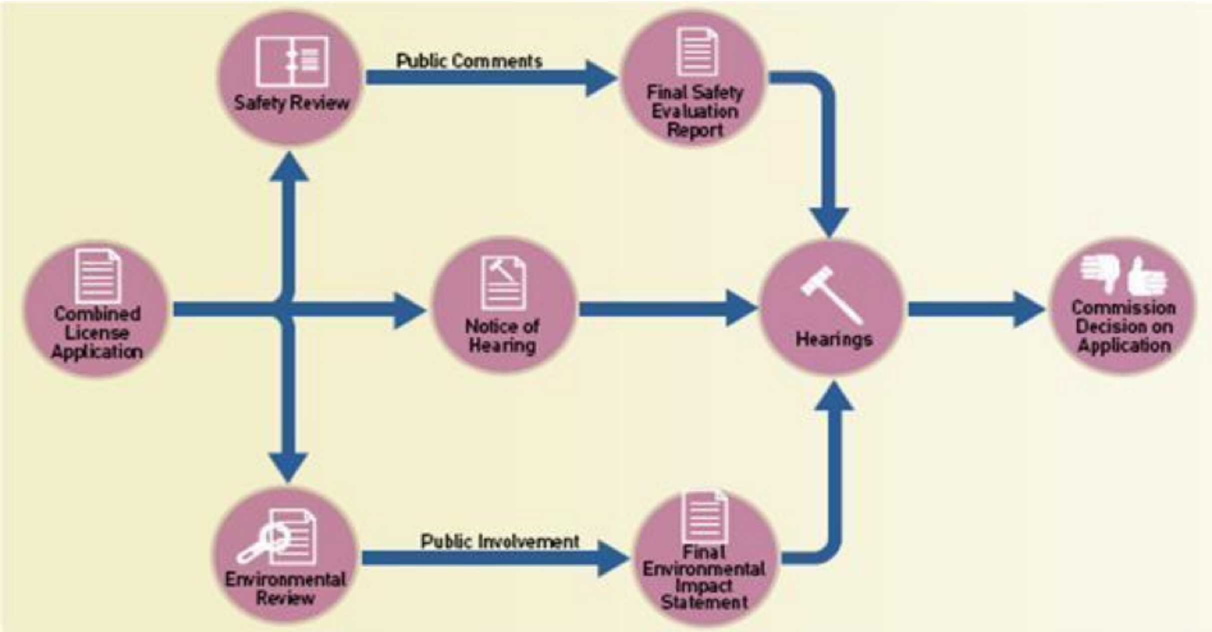


Figure 10: Combined Licensing Process. Source: NRC Licensing Process 2019

circles of 2 and 5 miles are established and are then subdivided into triangles and labeled into sectors. This is done to assess which sectors contain municipalities that may be affected by radioactive plume as it travels. The Plume Exposure Pathway are designed in order to avoid and reduce the frequency of doses from a potential exposure of radioactive materials in the event of an accident. Second, is the Ingestion Exposure Pathway. This EPZ is a predetermined 50 mile radius from the reactor site in order to reduce physical ingestion of potentially radioactive materials. This EPZ is accompanied with a ban of contaminated food (crops) and water (NRC EPZ, 2019).

6.2 Small Modular Reactor Regulatory & Certification Process

Regulatory bodies and the companies putting forth SMR designs have begun to agree that small modular reactor technologies must be evaluated differently than traditional reactor types. In 2019, the NRC proposed a new rule to address the fact that "current EP requirements and guidance," which were initially developed for large LWRs and non-power reactors, "do not consider advances in designs and safety research and their applications to existing or future operation of SMRs" (NRC Emergency Preparedness 2019). The major provisions of this new rule are new EP frameworks, a hazard analysis "of any NRC-licensed or non-licensed facility contiguous to an SMR," a scalable approach to designating EPZs, and a requirement to address ingestion response planning in the emergency plan (NRC Emergency Preparedness 2019). These new rules and approaches to SMR technologies are indicative of a greater acceptance among regulators that newer reactor technologies must undergo adjusted approval processes and safety analyses.

Additionally, the Nuclear Regulatory Commission recently published a statement agreeing with the Tennessee Valley Authority on a minimal Emergency Protection Zone that will be required for SMRs. Both parties acknowledge that the permitting and licensing process will be greatly simplified due to the enhanced safety features of SMRs (Charles 2018). Specifically, the smaller amount of fuel in the reactor cores, more simplistic systems, and reliance on built-in passive safety features eliminates several potential emergency scenarios. These unique features of SMRs mean that emergency planning requirements can be vastly scaled down and do not need to extend far beyond the SMR plants' actual physical boundaries. Altogether, the licensing procedure for SMRs is becoming increasingly established and simplified. This will hopefully allow later SMR technologies to avoid unnecessary portions of the cumbersome licensing process associated with traditional nuclear systems.

Overall, relevant regulatory bodies like the NRC, TVA, and IAEA agree that certain facets of small modular reactor designs will raise a number of issues in licensing and design certification. Many of the issues cited by the NRC and IAEA overlap, emphasizing "control room staffing, emergency planning, mechanistic source term, security requirements, multi-module licensing, issuing manufacturing licenses, and various economic issues such as annual fees, decommissioning funding, and insurance and liability" (Ramana 2013). Unsurprisingly, most of these issues relate to adjusting the traditional certification processes to better meet the needs and characteristics of small modular technologies.

6.3 Regulatory & Industry Collaboration

A driving factor behind the development of small modular reactor technologies, and especially the NuScale Power Module, has been collaboration between regulatory bodies and the companies developing SMR technologies.

The Memorandum of Understanding (MOU) is an October 2019 signed agreement between the DOE and NRC, which states that they will share their research and technical expertise with each other, thus advancing the knowledge of the nuclear community (DOE-NRC 2019). The DOE is an Agency responsible for informing other federal agencies about nuclear reactors in order to gain funding for nuclear testing and demonstrations, also helping to minimize the construction and operation times of experimental reactors. The NRC is an agency responsible for the licensing of nuclear technologies in order to demonstrate their feasibility and suitability for commercial use, as well as reviewing the safety and security measures of these types of reactors (DOE-NRC 2019). The DOE and NRC will collaborate through the DOE's Nuclear Reactor Innovation Center (NRIC), which was created under the Nuclear Energy Innovation Capabilities Act of 2017 to enable private developers to argue their reactor ideas at DOE-owned sites (Baranwal 2019).

Because of this agreement, the NRC will have access to the NRIC's high-performance computers and modeling codes, along with the DOE's facilities and nuclear research. This will allow the NRC to observe the development of nuclear reactors first-hand and make informative decisions with regards to their licensing processes (Office of Nuclear Energy 2019). This agreement will also authorize the DOE to be informed of the specific NRC regulations, guidelines, and licensing processes, thus being able to eliminate surprises and provide a greater understanding for nuclear applicants with their new or advanced technologies (Office of Nuclear Energy 2019). In an article by Dr. Rita Baranwal, the Assistant Secretary of the Office of Nuclear Energy for the DOE, she expresses her excitement and support for this collaboration by stating that she looks "forward to working with industry and the NRC to make advanced nuclear a reality, much sooner rather than later" (Baranwal 2019).

6.4 NuScale Power Module Regulatory Certification Progress

The NuScale Power Module is ahead of many of the other modular reactor designs in the United States due to the progress the reactor design has made in the regulatory approval process. The NuScale Power Module is the only SMR technology currently under design certification review by the NRC, and completed the "first and most intensive phase" of review in 2018 (NuScale Power Cost-Competitive Energy, 2019). By July of 2019, the design had cleared phases 2 and 3 of NRC review. The NRC and NuScale anticipate the complete review of design certification to be completed by 2020, with an agreement for a 12-module plant system to be brought online at Idaho National Laboratory by 2026 (NS Energy, 2019).

7 Economics

Small Modular Reactors are suitable options for both developing and developed countries. Developing countries have energy demands that are not currently being met due to a limited grid capacity as well as limited economic and financial support. SMRs are the cheaper, more viable solution to rerouting energy to these areas of need (IAEA 2018). Developed countries with growing populations and high rates of economic growth also have growing demands for energy that need to be met in the future. These countries have become more receptive to adopting new SMR energy sources to compensate for their increased energy needs (IAEA 2018). The United States fits this criterion and both government and industry have become financially invested in the development of different SMR types.

7.1 Financial and Economic indicators

The International Atomic Energy Agency (IAEA) is comprised of member states that have joined together in favor of promoting a peaceful use of nuclear energy. SMR deployment becomes more feasible for an IAEA Member State if their country is financially and economically sufficient. This means that they have the ability to support new investments, are open to international trade, and are fit for investment (IAEA 2018).

By evaluating a country's gross domestic product per capita (GDPPC), its ability to support new investments can be determined. Instead of assessing GDP as a monetary measure of all produced goods and services per year, this indicator divides GDP by the country's average population size for that given year. This allows each country to be compared with others around the world in terms of their individual purchasing power parity (IAEA 2018). In 2018, the United States had a GDP per capita of 54541.70 US dollars, approximating to 432 percent of the world's average (TE GDP 2019). This high GDPPC indicates a larger economy that is more capable of financing SMRs to resolve its increased power needs (IAEA 2018).

Financial and economic sufficiency can also be evaluated by a country's openness to foreign direct investment (FDI) and international trade (TRADE). FDI measures annual monetary inflows from foreign investors interested in domestic projects or businesses, as a percentage of GDP. The FDI indicator helps to demonstrate a country's openness to accept foreign investment as well as the amount of foreign entities that are inclined to invest in another country's economic activities (IAEA 2018). The TRADE indicator is a measurement of how much a country is intermixed with the global economy (IAEA 2018). As a country becomes more affiliated with foreign investors and international trade, they more than likely have a growing economy that is receptive to importing technological components for nuclear SMR configuration and deployment (IAEA 2018). Currently, the amount of FDI in the United States sits at 4.34 trillion US dollars and directly supports 7.1 million jobs

(ITA 2019). This indicates that foreign investments would likely help to financially support SMR deployment.

In order for SMR deployment to be a feasible option, a country needs to either have a low external debt or a high credit rating. This allows new energy production facilities to lower their risk premiums and interest rates, helping to alleviate the financial expenses that come along with any SMR deployment, on top of foreign investment (IAEA 2018). There are multiple different credit rating methods, including the Moody, Fitch, and DBRS methods, which can rate a country as negative, vulnerable, stable, or positive (TE Credit Rating 2019). Currently, they all rate the United States as stable, meaning that SMR deployment is a feasible option.

7.2 LCOE and Cost Comparisons

Regarding economic and financial feasibility, each SMR comes with an estimated LCOE, or "levelized cost of energy." As previously mentioned, the top four researched SMR types to fit our site (NuScale, Thorcon, ARC-100, XE-100) had a mid-2020s estimated projected range of LCOEs from $26-$84 per MWh. According to 2016 EIA estimations, LCOEs for all new generation resources could range between $43-$184 per MWh, with a first of a kind 12-module NuScale SMR having an estimation of $96 per MWh and an nth of a kind having an estimation of $85 per MWh (Figure 12). Meanwhile, NuScale Power is cost-competitive, aiming to produce electricity ata total cost of $65 per MWh. This is approximately 20% higher than the current cost of energy from a gas-powered plant. However, nuclear energy is cleaner for the environment and, "The price of gas isn't going to stay low forever"(Rosner) (Cho 2019).

Because the NuScale, Thorcon, and XE-100 SMRs are scalable to more than one module per unit, their capital cost per unit after the installation of the first unit also decreases. Thus, these added units increase the amount of energy routed and available to an area without having the same levelized costs as the initial SMR installation. Additionally, total overnight costs in regards to firm capacity are much lower for nuclear energy than they are for wind and even solar energy sources (Figure 11). As stated by a 2014 National Nuclear Laboratory report in Sellafield, U.K., "by 2035 SMRs could provide 65 to 85 gigawatts of power globally, a building spree worth between $320 billion and $510 billion" (Cho 2019).

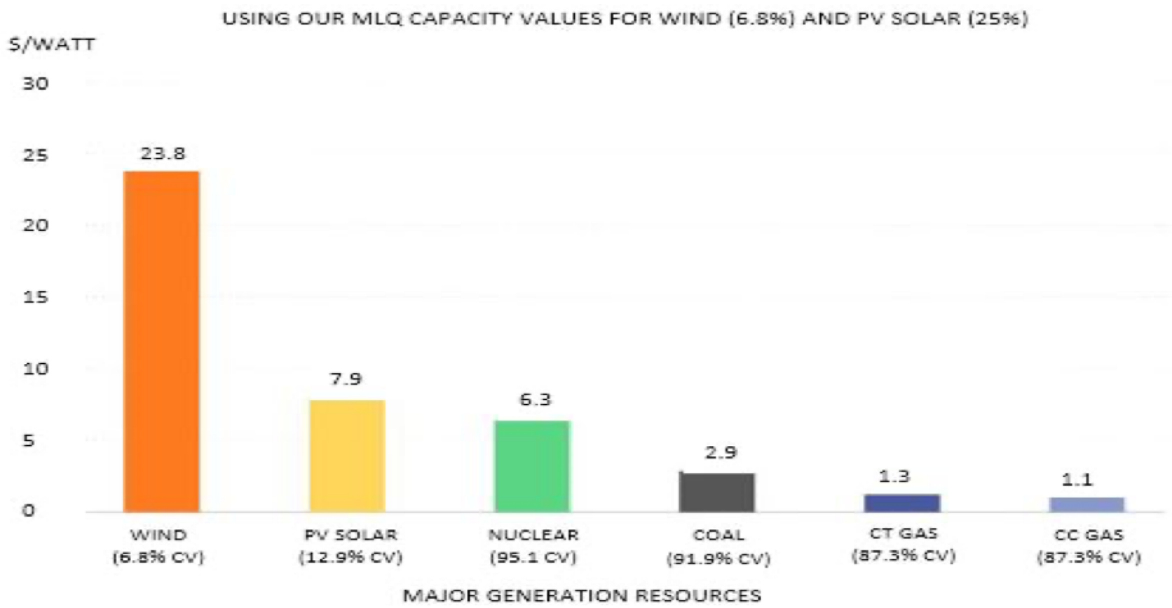


Figure 11: Total Overnight Capital Cosg for New Major Generation Resource (2018 $/watt of Firm Capacity Contribution. Source: Stacy 2019

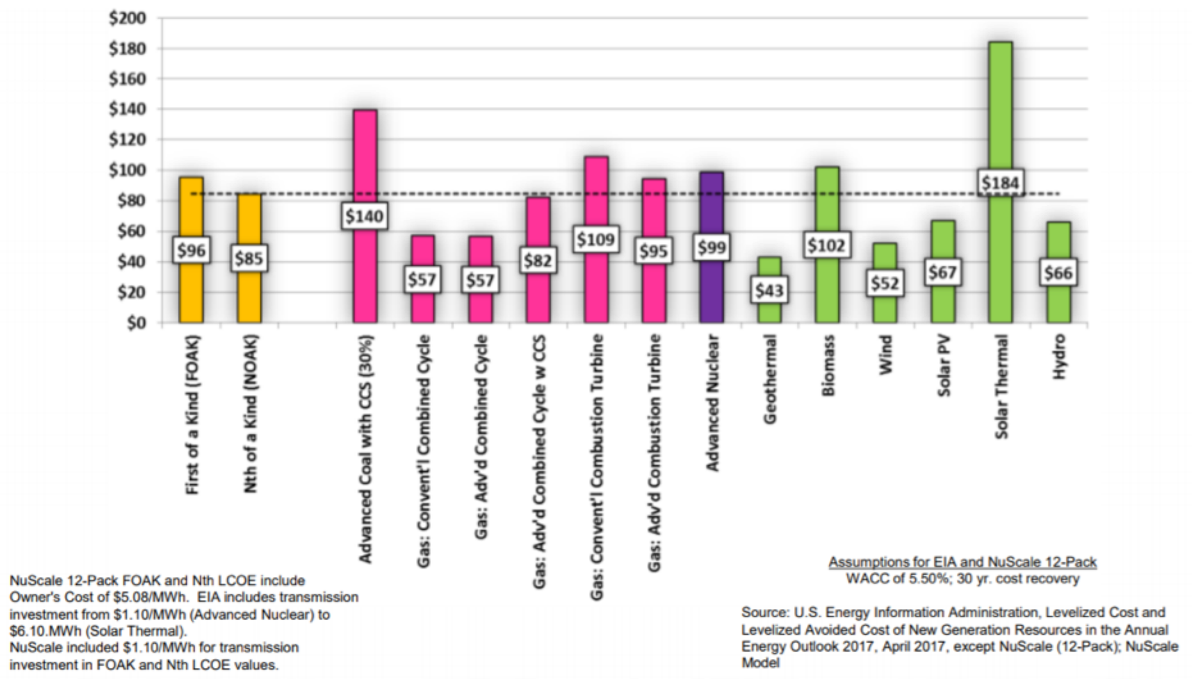


Figure 12: Estimated Average US Levelized Cost of New Generation Resources (2022 Costs in 2016 $/MWh). Source: U.S. Energy Information Administration 2018

7.3 Other Economic Benefits

The NuScale company has stated that in order to generate 1000MWe of power, “a NuScale SMR power plant would require less than one percent of the land area that renewables such as biomass, wind, solar, and hydropower need for the same amount of generation”, without taking into account their respective EPZs (SMR Start 2017). “A proposed 720 MWe NuScale SMR would have a 35-acre footprint, while a traditional nuclear plant generating the same amount of electricity would require nearly 600 acres” (SMR Start 2017). However, there has been some variability seen in these numbers, due to individual cell-efficiencies, wind-blade lengths, onshore and offshore wind availability, topography, and the specific technologies that are being used.

Nuclear SMRs can also have a positive impact on the economy by widening the job market. The NuScale SMR has the potential to support 4,000 jobs upon the manufacturing of a 12-modular, 720 MWe Nuscale SMR. These jobs become available due to the construction, assembly, installation, and commercial operation of the reactor (SMR Start 2017).

8 Climate and Security

8.1 Climate Change Indicators

Currently, the United States is one of the IAEA Member States concerned with CO2 Emissions Per Capita (IAEA 2018). Carbon dioxide is a greenhouse gas that is becoming more abundant within the Earth’s atmosphere. A higher CO2 ppm has correlated with an increased warming of the environment. The 2018 average concentration in the atmosphere was 407.4 ppm CO2, which is the highest it has ever been and continues to rise (Lindsey 2019). SMRs are a plausible solution to help reduce these effects of climate change. Unlike the fossil-fueled coal power plants, nuclear power reactors are associated with what is called ”zero-emission clean energy.” They do not directly produce carbon dioxide nor emit it into the atmosphere.

Another climate change indicator of concern is the Reduction of Fossil Fuel Energy Consumption (IAEA 2018). The consumption of fossil fuels comes from coal, oil, petroleum, and natural gas. As issues associated with their emissions of greenhouse gases continue to arise, countries that rely heavily on these fossil fuels have incentivized the reduction of these energy sources (IAEA 2018). These energy sources will also likely become more expensive in the future through greenhouse gas emission

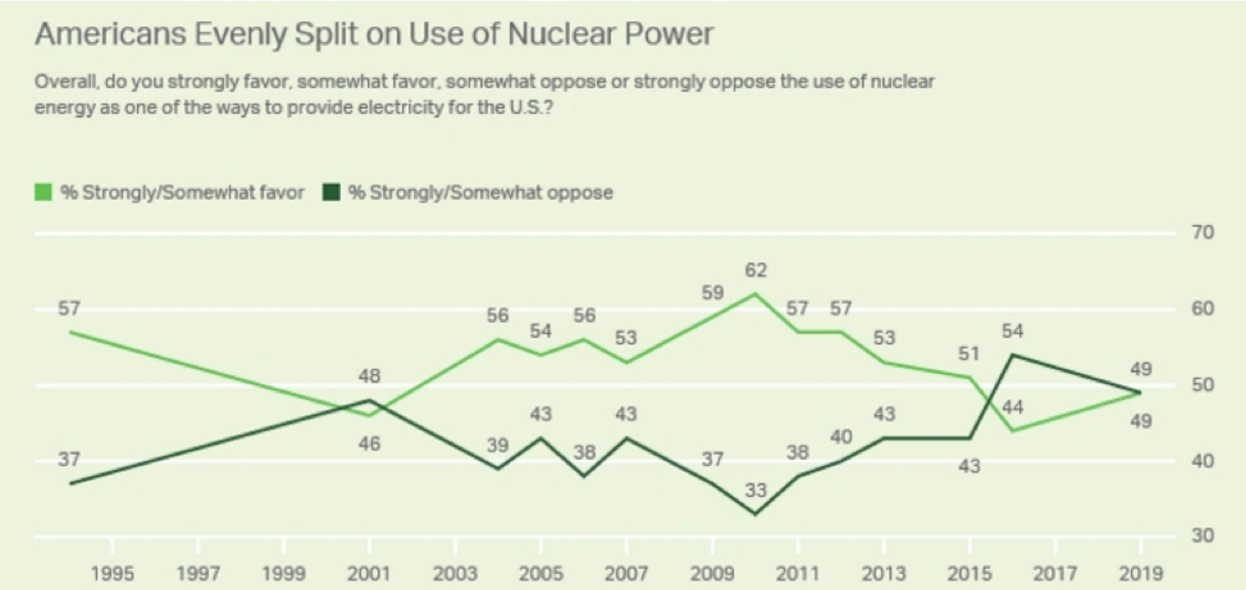


Figure 13: US Public Sentiment on Nuclear Power. Source: Gallup 2019 World Nuclear News 2019

taxes and storage requirements, leaving nuclear power to be the safer and cheaper option.

On March 19, 2015, an Executive Order was given by the White House stating that over the next decade, governmental agencies would work toward reducing greenhouse gas emissions by 40% (OPS 2015). The overall goal is to improve environmental performance through energy efficiency. Therefore, a third climate change indicator of concern is the Nationally Determined Contributions (NDC) of Carbon Reduction Goals. These reduction goals are to be achieved in part by "alternative technologies" including clean energy nuclear sources. SMRs such as the NuScale SMR would thereby work to improve the quality of the environment for future generations.

Favorability for and against nuclear power is evenly split amongst Americans today (Figure 13). Over the past two decades, fluctuations in favorability have stemmed from the instability of oil and natural gas prices (World Nuclear News 2019). More recent projections show that there has been a modest increase in support for nuclear power. This is speculated to be from increased oil prices, alike the peak support for nuclear power in 2010, or because of the emerging greenhouse gas concerns with the acknowledgement that nuclear power generates emissions-free electricity (World Nuclear News 2019). This information could sway opinions and generate higher support for the use of nuclear power in the near future.

8.2 Energy Security Motivators

In terms of energy production, a country can either be a net importer or exporter. Those that consume more energy than they produce are labeled as energy importers. Those that consume less energy than they produce are labeled as energy exporters. SMRs are more likely to be considered as alternative energy sources if a country is interested in increasing their energy security by developing a more domestic energy production (IAEA 2018). According to the Energy Information Administration, the United States has been an energy importer since 1953 (CNBC 2019).

Another energy security motivator is the domestic use of uranium resources. Reported by the International Panel on Fissile Materials, the 2015 global reserves of uranium extractable at an equal or lesser price of US$130/kg and at the rate of 2014 uranium consumption could supply the globe for the next 135 years (IPFM 2018). Some countries with larger uranium deposits or stockpiles have engaged in nuclear development and SMR deployment. Currently, the US has a highly-enriched uranium stockpile of about 600 tons. Of those 600 tons, about 500 is reserved for national security and military purposes, and the other 100 could be used for commercial nuclear reactor fuel (IPFM 2018). As previously mentioned, the NuScale reactor utilizes a considerably smaller portion of fuel in comparison to a 1,000 MWe reactor, and has the potential to use recycled or mixed uranium-plutonium oxide fuel, lowering the consumption rate of uranium and the toxicity of spent fuel. Also at an unknown recovery cost, there is an enormous resource of uranium in the oceans.

The United States' energy security could also be increased when trying to balance renewable energy sources. Renewable energy sources utilize water, wind, or solar radiation in order to produce energy that is clean and more sustainable in that it can not be depleted. However, there are daily as well as seasonal shifts that reduce the amount of available wind and sun. Daily variability in electricity production from solar exemplifies the issue with relying entirely on renewables and this can be seen in what is becoming known as the "Duck Curve" (Loutan 2015). The Duck Curve (shown in Figure 15) depicts energy demand minus solar energy production. It happens due to the highest levels of solar electricity production happening in the middle of the day (Figure 14), while peak electricity demand happens in the morning and the evening.

During these intermittent periods when renewables can not sustain a population, nuclear energy could account for an area's energy needs (IAEA 2018). The NuScale SMR has features that can turn wind and solar power Duck Curves into projections of stable baseload power, adapting to daily, seasonal, and weather conditions (Figure 14 15). It can backup renewable energy sources by varying its energy output through means of dispatchable modules, power maneuverability, and tur-

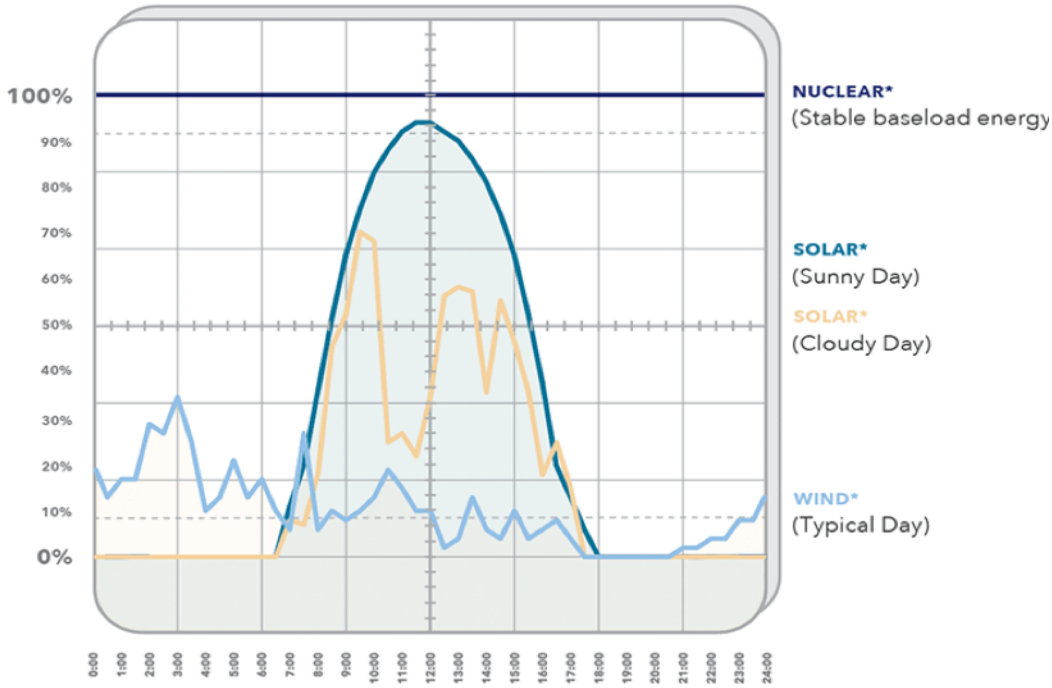


Figure 14: Diurnal Cycles of Wind and Solar (*Power Generated as a Percentage of Nominal Full Power. Source: NuScale Power Renewables 2019

bine pass. These "load following" processes initiate quick responses to intermittent generation by bringing modules offline during periods of low demand, maneuvering between modules to provide a consistent baseload power from the reactor, and bypassing steam turbines to maximize available energy at a faster rate (NuScale Power Renewables 2019). The unique "NuFollow TM" capability also complements renewables by promising the generation of safe, abundant, clean energy that can help to diminish the harmful factors contributing to climate change (NuScale Power Renewables 2019).

9 Discussion & Conclusion

After considering various specifications of 22 reactor designs currently under development in the United States, it was determined that the NuScale Power Module represented the best option for near-term SMR deployment in North Carolina. The NuScale design boasted numerous impressive features and advanced design specifications, with its competitive LCOE, mid-2020s predicted commercial operational date, and simplified siting requirements helping it to earn the best marks in the

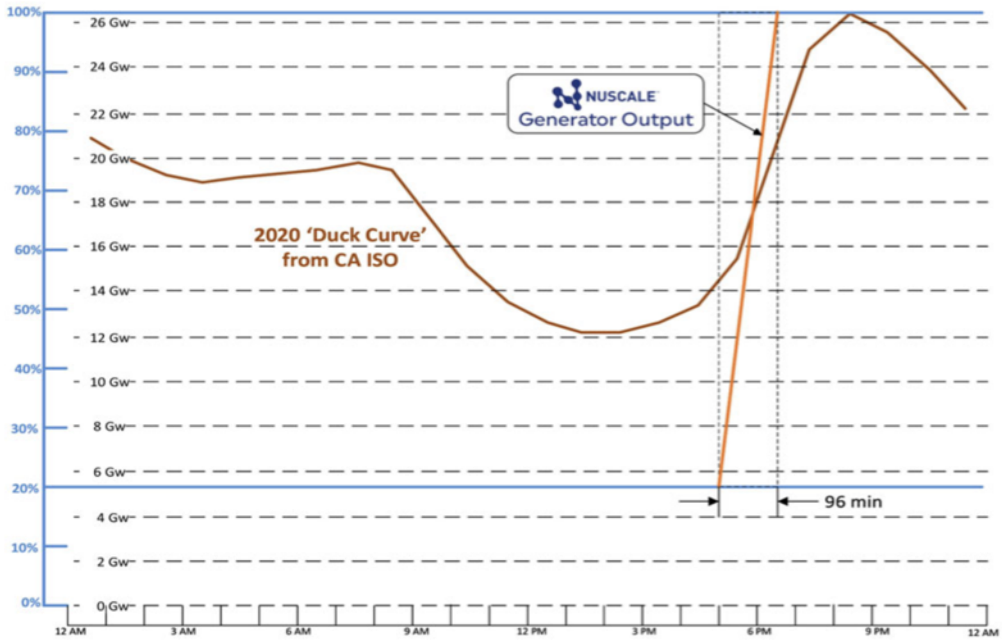


Figure 15: NuScale Solution to the 'Duck Curve'. Source: NuScale Solutions to the Duck Curve 2019 Loutan 2015

weighted scoring metric used to evaluate each considered design.

The 727 MWe Mayo Coal Generation Plant, in Roxboro, NC, is the optimal location for the implementation of a NuScale SMR system. Because of the ongoing environmental lawsuits, declining capacity factor, and increasing costs of operation, the plant is set to retire by 2035 or earlier. Furthermore, the Mayo Plant has the necessary electrical infrastructure paramount to the distribution of electricity. The surrounding energy demand of Person County, and the neighboring town of Roxboro, is relatively steady and fit to be met by baseload SMR electrical generation. For surplus energy production, existing high voltage (230 - 345 kV) transmission lines would be available to distribute the electricity to the Raleigh-Durham area. Lastly, the Mayo Plant is positioned in a strategic location for the distribution for ancillary services (steam hydrogen) to local manufacturers, hospitals, and adjacent residents for use.

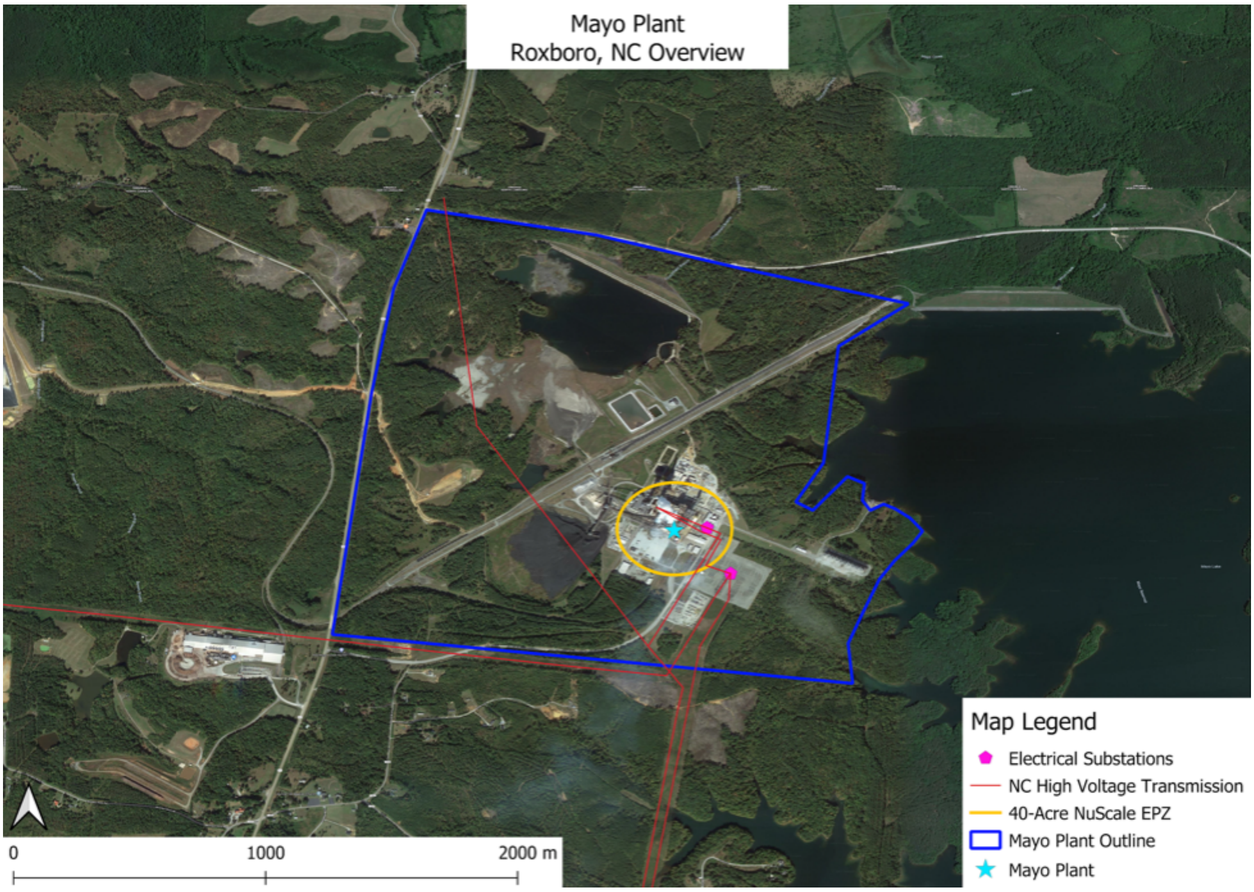
The NuScale Power Module SMR, and SMR technologies in general, promise greater reliability, reduced capital costs, and increased safety when compared to traditional nuclear reactors. Moving forward, the flexibility and base-load energy production capabilities offered by SMR technologies will become increasingly important. In order for North Carolina to avoid new investments in coal or natural gas, intermittent renewable energy sources like wind and solar must be coupled with more consistent base-load sources like small modular nuclear reactors.

As SMR technologies show increasing promise and commercial viability, public support for nuclear energy production continues to grow (see Figure 13). Garnering public approval for nuclear energy projects has traditionally been viewed as a significant impediment to furthering nuclear projects. With support growing among the public and those in charge of regulation demonstrating more flexibility, nuclear energy in the form of SMRs is increasingly attractive.

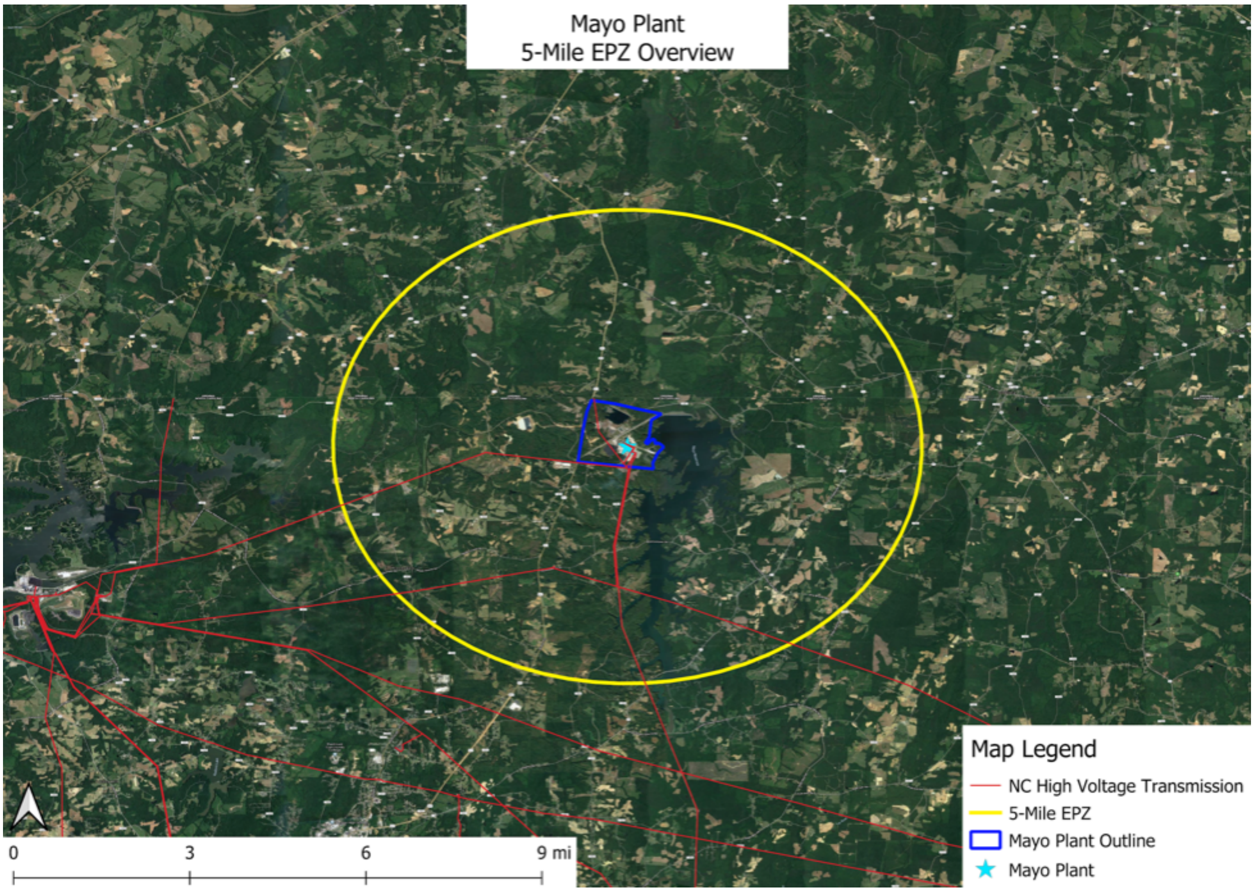
After considering each SMR's specific characteristics, the siting feasibility of various locations in North Carolina, and through conducting extensive economic, environmental, and certification process analyses, it has been determined that the NuScale SMR would be the most viable option to replace the coal-powered Mayo Plant located in Roxboro, NC, and be operational by 2035.

10 Appendix

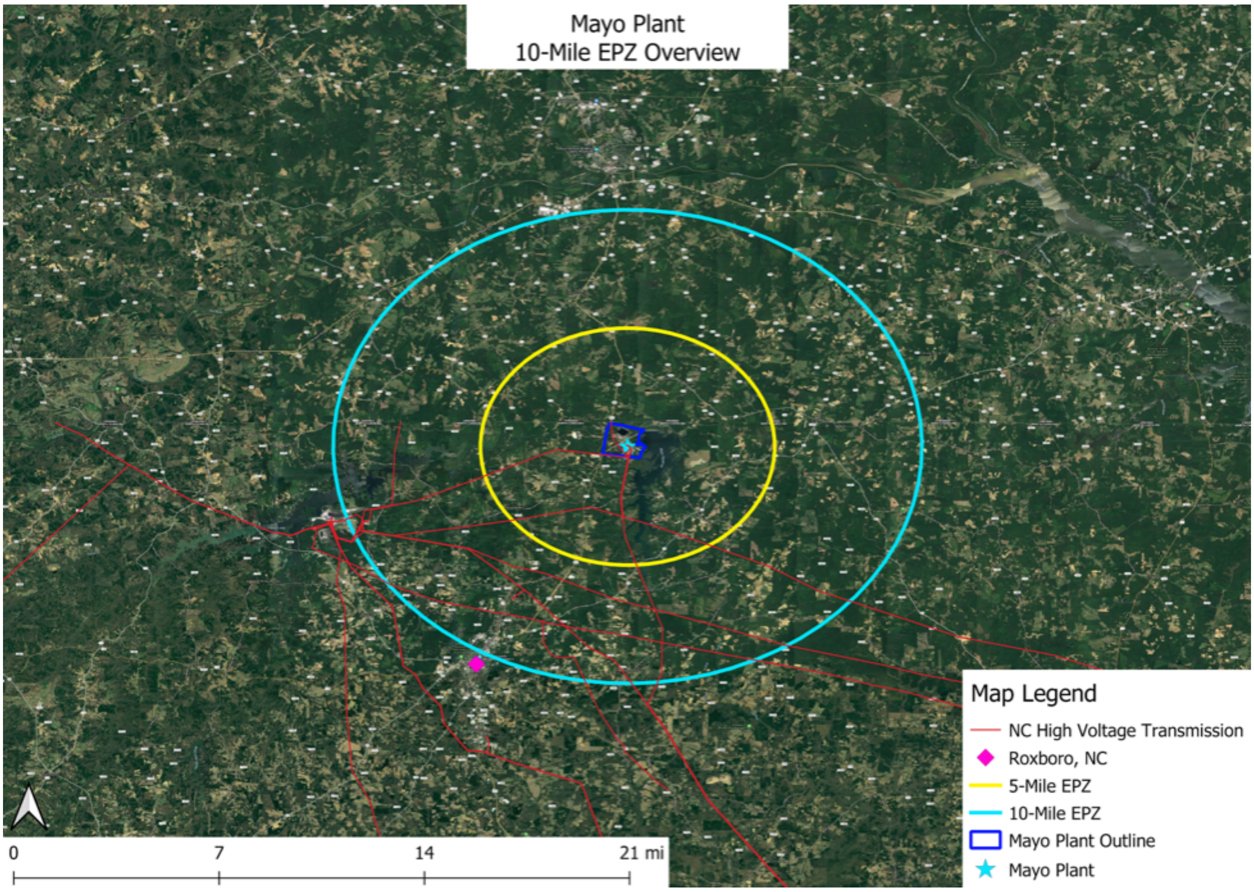
Map A - Mayo Plant Site Overview



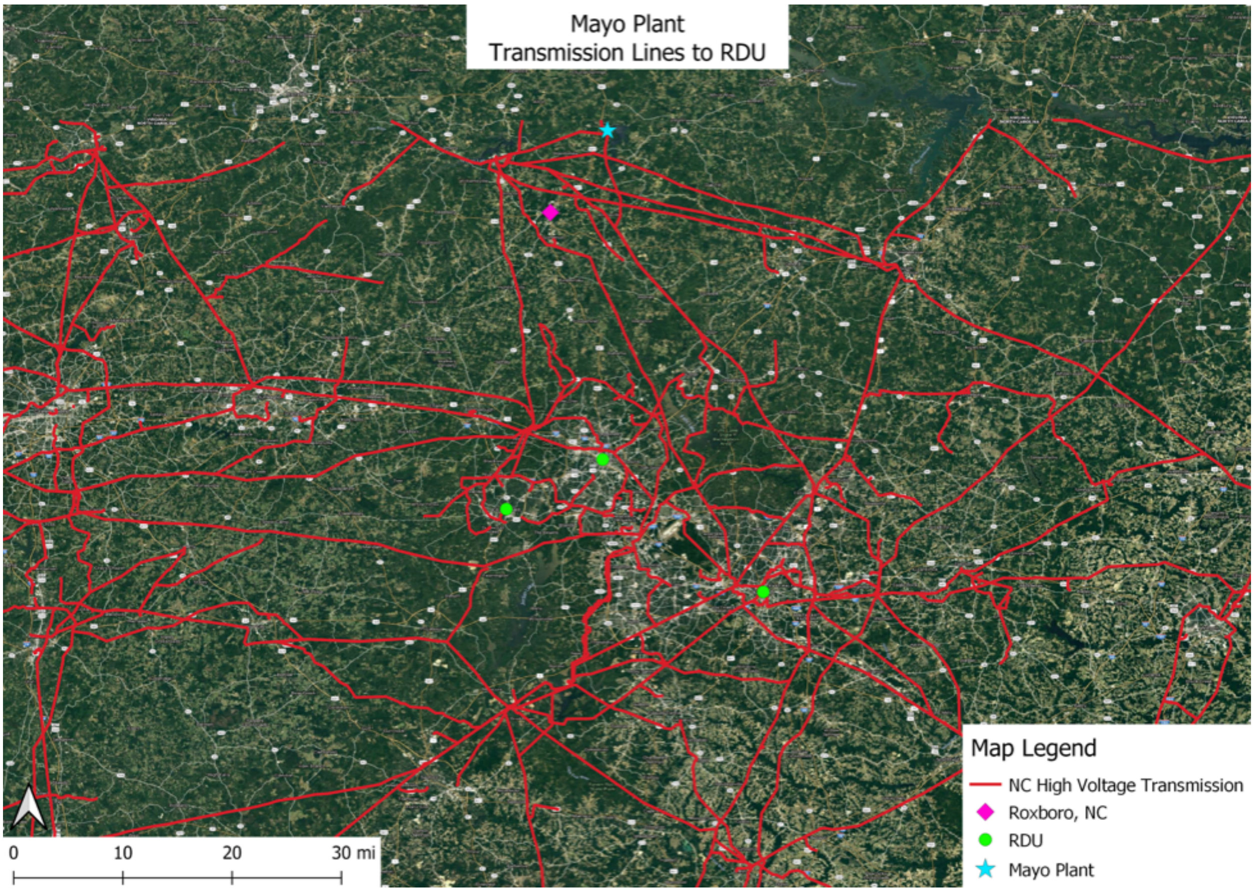
Map B - 5-Mile Mayo Plant EPZ



Map C - 10-Mile Mayo Plant EPZ



Map D - Mayo Plant Transmission to RDU



Map E - NuScale 40-acres EPZ

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