EXAMINING THE FEASIBILITY OF SMALL MODULAR NUCLEAR REACTORS AS THE LEADING GLOBAL SOURCE OF ENERGY GENERATION

By

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A capstone submitted to Johns Hopkins University in conformity with the requirements for the degree of Master of Science in Energy Policy & Climate

Baltimore, Maryland

December 2021

ABSTRACT

Small modular nuclear reactors have emerged as a potential source of clean energy as the effects of climate change have become more severe, and the need to reduce greenhouse gas emission from fossil fuels is greater than ever. Nuclear energy has provided a significant amount of the energy for the United States and the rest of the world for the last 60 years, but it has inherent flaws that keep it from growing. Many have turned to renewable energy like wind and solar power even though they cannot meet global energy demands in their current state. SMRs are designed to address the issues that conventional reactors face to make nuclear energy more appealing.

This research uses quantitative and qualitative analysis to compare SMR technology with conventional nuclear reactors, fossil fuels, and renewable energy. The findings show that, in most categories, small modular reactors do improve upon conventional reactors. The size makes for more placement options and reduced costs through mass production. The modularity means that SMRs can be built to fit any project. Compared to wind and solar energy, SMRs are still expensive, but they offer efficiency and energy output that would require massive wind or solar farms.

Small modular reactors still have flaws that could keep them from reaching mass deployment. The inability for researchers to focus on one or two designs could lead resources being spread thin, and capital costs for manufacturing make many hesitant to in the early stages of SMRs. Some experimental SMR designs have shown promise, such as the Fast Neutron Reactor and the Molten Salt Reactor. If the technology continues to develop and SMRs can improve on conventional reactors, they could see increased usage for energy generation.

Primary Reader and Mentor: John Kyle Mitchell

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INTRODUCTION

Climate change due to increased greenhouse gas emissions has been a concern for decades. Still, it has become more prevalent in recent years as sea levels continue to rise and weather patterns grow more erratic and intense. In response, many nations across the globe have come together to create multilateral plans that reduce greenhouse gas emissions and limit the effects of climate change. The first of these major international agreements was the 1997 Kyoto Protocol, which set targets for renewable energy use and emissions reductions for six different greenhouse gases (UNFCCC, n.d.).

The Kyoto Protocol was largely flawed, and commitment levels were low because there were not many incentives for achieving the proposed goals. To remedy this, the Paris Agreement was created by the United Nations Framework Convention on Climate Change (UNFCCC) during a conference in 2015. The Paris Agreement set stricter enforcement processes than the Kyoto Protocol, requiring all nations to set emission-reduction targets and create nationally determined contributions (NDC) with the ultimate goal of keeping the global average temperature from rising 1.5˚C above pre-industrial levels. This ensured that nations would sign and implement the agreement. 175 parties signed the Paris Agreement at the convention, including 174 countries and the European Union (UNFCCC, 2016).

With this extensive commitment to reducing greenhouse gas emissions, nations are searching for a means to reach their proposed goals. One of the most popular methods is replacing high-emission fossil fuel power plants with zero-emission renewable energy. This can come in many forms. Wind, solar, geothermal, and hydropower are all promising forms of renewable energy, but they cannot currently meet the growing global energy demands.

Nuclear power plants have been used for commercial energy production since the early 1960s. Over the last 60 years, nuclear energy has proven to be reliable and able to meet energy demands. Currently, nuclear energy accounts for about 10% of the world's energy production and 20% in the United States (WNA, 2021c). This percentage has remained mostly stagnant in the US for many years due to the 20-year gap between 1996 and 2016 where no new reactors came online. At this same time, several existing power plants were being shut down and decommissioned.

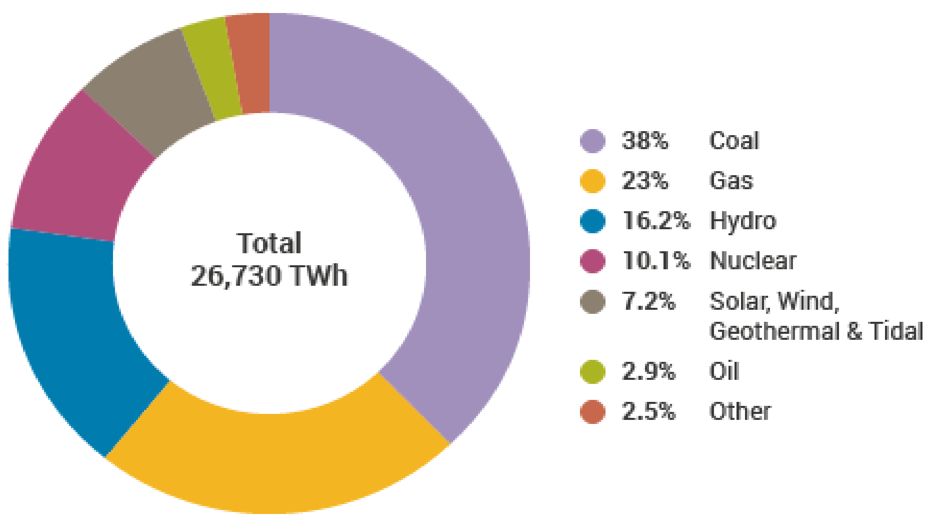

Figure 1: Global energy generation by source, 2018 (source: WNA, International Energy Agency)

Conventional nuclear energy has become an unfavorable choice for carbon-free power because it has some glaring flaws. Two of the most significant causes for the 20-year hiatus for new power plants are the sheer time and financial resources required to build a nuclear power plant. When considering all steps of the process, planning, licensing, building, and testing, it can take over a decade to build a single nuclear power plant, and the cost of a new plant can be upwards of $6 billion (Park, 2018). This leads to plans being scrapped and projects being abandoned during construction. Conventional nuclear energy also struggles with other issues pertaining to waste management, safety, and negative public perception.

Small modular nuclear reactors (SMRs) are being developed as a potential solution to the concerns that plague conventional nuclear reactors. Their small, standardized designs open up the possibility for mass production. In turn, this could significantly decrease the amount of time and money required to build new reactors. NuScale Power, the company building first SMR in the United States, originally estimated their plant would cost under $3 billion to construct (Conca, 2018). SMRs also build upon many of the other security, safety, and operational flaws that are hurting the nuclear industry.

While SMRs have improved on the designs of older nuclear reactors, they are not without their own flaws. Many have called the theoretical financial advantages into question, and a 2013 article from the Union of Concerned Scientists asserted that many of the enhanced safety features of small modular reactors have gone untested (Holt, 2017). Other critics have concerns about the ease of implementation, if SMRs can provide the same energy output as conventional reactors, and if this improved design is enough to overcome the negative perception that nuclear energy has developed.

Small modular reactor technology is still in its infancy, especially from a commercial standpoint, and massive amounts of money and research are being put toward future developments. As of November 2021, only one SMR is in commercial operation, four are under construction, and dozens more are in earlier stages of development. The future for SMRs is bright but full of unknowns. This paper will analyze data, both quantitative and qualitative, and compare different forms of energy in an effort to answer the question: *can SMRs be the leading source of global energy production?*

BACKGROUND

Small modular nuclear reactors are a Generation III/IV reactor design that aims to be a compact alternative to the large Generation II reactors that are typically found in the United States and other parts of the world. As the name suggests, SMRs are much smaller than their conventional reactor counterparts. Typical output for an SMR is under 300 MWe, compared to outputs over 1600 MWe for conventional reactors (WNA, 2021b). Their modularity means they can be built to specific requirements and come in "packs" to suit energy needs. This can be useful for making nuclear energy a viable option in remote areas or areas with space constraints that would not allow for a large nuclear power.

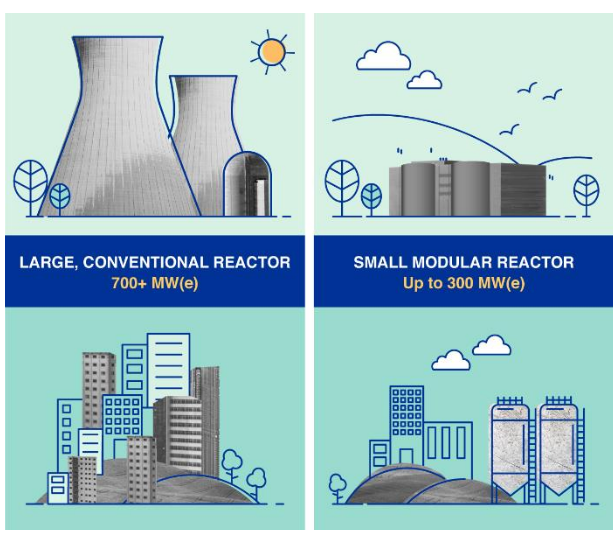

Figure 2: Conventional reactor vs SMR (source: International Atomic Energy Agency)

SMRs are still a relatively new technology for commercial use, but the United States military has used small reactor design for decades. In the 1950s and 60s, the US Army constructed five portable reactors that were sent to locations like Wyoming, Greenland, and Antarctica (WNA, 2021b). The idea for America's first commercial small modular reactor was born out of the failures of nuclear research in the 1990s. The Argonne National Laboratory researched the Integral Fast Reactor when the project had to be shelved in 1994 due to lack of funding. This led to a greater push in the nuclear industry for funding from the government. The Nuclear Energy Research Initiative was formed, and funding from this new organization was used to kickstart research on the Multi-Application Small Light Water Reactor (MASLWR). As a result of this project, NuScale Power was able to gain the rights to build America's first SMR (DOE, 2018a).

The four main types of SMRs that are currently being researched are light water reactors, fast neutron reactors, graphite-moderated high-temperature reactors, and molten salt reactors. However, in the 2020 edition of the International Atomic Energy Agency's (IAEA) book on SMRs, there are over 70 designs discussed. These designs are all in various stages of development, from conceptual design, to licensing, construction, and operation (IAEA, 2020).

Globally, there is only one small modular reactor operating for commercial use, the Akademik Lomonosov, stationed on a floating vessel off the coast of Russia. The United States has no SMRs in operation, but NuScale Power is in the process of building a 12-module plant at the Idaho National Lab. The project is in the final stages of licensing, with an estimated completion date in 2029.

METHODS

This research explores the possibility of expanded development on small modular nuclear reactors and their potential to be the largest source of global energy generation. There are numerous factors may lead to the success or failure of SMRs, both quantitative and qualitative, and this report considers all collected information. The analysis includes data on SMRs being compared with other forms of energy generation, including fossil fuels, conventional nuclear, and other sources of renewable energy.

Comparisons between SMRs and other energy sources will include qualitative analysis on issues like greenhouse gas emissions, public perception, and technological differences. The quantitative analysis will use data gathered on construction time and cost, levelized cost of electricity (LCOE), and capacity factor. These analyses will be used to draw a final conclusion on the state of small modular reactors.

This paper draws from several reliable sources in the nuclear industry to provide comparisons and analysis. Much of the data on nuclear reactors is pulled from the World Nuclear Association, which is an international non-profit organization with members representing 44 countries and all sectors of the nuclear industry. Other reputable organizations were referenced for opinions on the topic, such as the Union of Concerned Scientists and the Federation of American Scientists. The US Department of Energy and other government agencies also provided valuable incite into regional data and SMR history. Academic journals like Physics Open and Renewable and Sustainable Energy Reviews were utilized, as well.

RESULTS & ANALYSIS

Nuclear Energy vs. Fossil Fuels

To examine the feasibility of small modular reactors, one must first understand why nuclear energy is preferable to the fossil fuels, like natural gas and coal, that currently dominate the global energy market. Over the last 100 years, global carbon emissions from fossil fuels have risen from less than one billion metric tons in 1900, to nearly 10 billion metric tons in 2014 (Boden et al., 2017). This can be attributed to the increase in industrialization throughout the 20th century. For much of this time, options for mass energy generation were limited, so fossil fuels dominated the industry.

Fast forward to today, and there are a multitude of options for clean energy. Of these options, nuclear energy has proven to be one of the most reliable with the highest energy output. Nuclear energy has been used commercially since the early 1960s, and it has grown to generate around 2,500 terawatt-hours (TWh) each year since the turn of the century. That is more than all solar, wind, geothermal, and tidal energy combined (WNA, 2021c). Additionally, nuclear energy boasts the highest capacity factor of any energy source, which is an indicator of how often plants operate at full power. The estimated 92.5% capacity factor for nuclear power is nearly 1.5 to 2 times higher than estimates for natural gas and coal (DOE, 2021). This is due to the lower maintenance requirements of nuclear power plants and longer periods before refueling.

SMRs Improving on Conventional Nuclear

Conventional nuclear energy is a preferable alternative to the high emission fossil fuel that run the energy sector, but it still leaves a lot to be desired. Since the turn of the century, focus has shifted from nuclear energy to other sources like natural gas and even other renewables. The aforementioned monetary and time commitments that come with a new nuclear power plant have scared investors away and even stopped some projects mid-construction. Since 1974, over 40 U.S. reactor projects have been abandoned after receiving a construction permit from the Nuclear Regulatory Commission (NRC) due to rising costs, unexpected delays, and the withdrawal of financial backers (Reuters, 2017).

Nuclear energy saw a further decline after the disaster at Fukushima-Daiichi in 2011 capped off a string of three major nuclear power plant accidents that created a level of distrust between the public and the nuclear industry. The first of these three accidents, Three Mile Island (TMI), was the only to happen on U.S. soil. In March of 1979, a combination of operator error, machine malfunction, and design flaws caused one of the two reactors at TMI to lose coolant and overheat. An NRC study suggested that about 2 million people near the site received a dose of approximately 1 millirem above the typical background dose (NRC, 2018). While no one was injured and no negative health effects were recorded, this accident added fuel to the anti-nuclear crowd that already had their concerns.

The 1986 Chernobyl disaster and the Fukushima accident were much more severe and resulted in several casualties. Despite the NRC and other international nuclear agencies making changes to ensure that no more of these disasters happen, the world saw the deadly side of nuclear power, and it created a negative image that has been hard to reverse. Over the years, nuclear energy has been subject to many smear campaigns, protests, and negative depictions, even on popular television shows like the Simpsons.

Figure 3: Depiction of nuclear waste on The Simpsons (source: 20th Television Animation)

The introduction of small modular reactors to the commercial nuclear industry is an effort to solve the issues that have caused a decline in conventional nuclear energy usage. This next generation of advanced reactors promises to be cheaper, safer, and more portable than current designs. Once the SMR reaches the point of mass implementation, nuclear energy could potentially be the greatest source of power for the United States and the rest of the world.

The first major improvement that SMRs have over conventional nuclear is their claim that they will have quicker construction times and lower capital investments. Typically, nuclear power plants have unique designs that require specialized parts to be fabricated, but the small-scale reactors and modular parts of an SMR could be mass-produced in a factory. The global average construction time for a 1 GW conventional reactor is about 100 months, with more extreme cases like Angra 2 in Brazil taking about 300 months or 25 years (Carajilescov & Moreira, 2011). Standardizing the reactor design for SMRs will also lead to quicker licensing and procedural development for new facilities, as new SMR projects would not require a unique analysis during the licensing process that a specialized conventional reactors might.

Because of their size, SMRs also have more flexibility when choosing a location. A conventional 1-gigawatt nuclear power plant requires over one square mile of land for operation (DOE, 2019). To put this into perspective, that is larger than the entirety of the Disneyland theme park in California (~0.78 square miles). The massive amount of space needed for a nuclear power plant severely limits where one can be built. SMRs typically produce less energy than conventional nuclear reactors, but they come in at a fraction of the physical size. This means that they could be built closer to population centers with high energy demands, in remote areas that do not have access to the electric grid, on floating platforms in the water, and they could even be sent to space.

In January of 2021, President Donald Trump signed an executive order that would promote small modular reactors and consider them for use during future space exploration missions (Exec. Order No. 13972, 2021). The compact size of the SMR not only alleviates many of the issues that conventional nuclear plants have, but it opens the door for new developments that were never possible due to size constraints. Large cities could build SMRs just a few miles away and provide massive amounts of carbon-free energy. Coastal regions could even build SMRs out in the water like the Akademik Lomonosov, which provides about 60 MW of power to the port city of Pevek, Russia (Molinari, 2020).

With nuclear reactors potentially moving closer to cities and affecting more people, safety and security are important points to consider. Despite popular belief, nuclear energy is already one of the safest forms of energy, with hundreds of times fewer energy-related fatalities than fossil fuels like coal, oil, and natural gas. The death rate of nuclear energy appears to be in line with other clean energy sources.

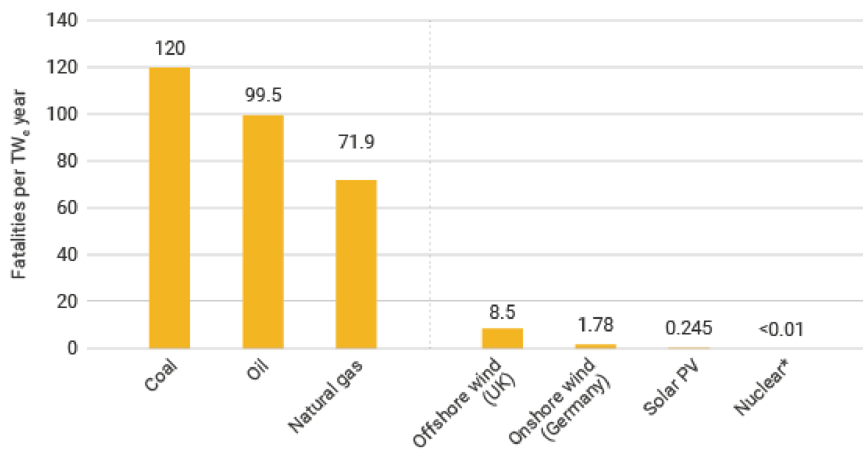

Figure 4: Deaths from energy-related accidents per TW.yr (source: WNA, Paul Scherrer Institute)

While the disasters at Chernobyl and Fukushima in the cumulative loss of hundreds of lives, the majority of nuclear energy history has resulted in minimal loss of life. Nuclear power plant regulations are some of the strictest in the energy sector, and many plants go above and beyond the recommended standards set by the Nuclear Regulatory Commission and international agencies. The design flaws and operator error that have caused nuclear reactor meltdowns, like the stuck-open relief valve that triggered the Three Mile Island accident, all led to new policies that ensure that the same incident would not happen again.

Small modular reactor designs build upon these standards and aim to be even safer than their predecessors. Because these reactors are smaller and provide less power, they require less fuel. This immediately reduces the risk of meltdown and lowers the severity in the case that one does occur, and it makes SMRs less desirable targets for theft and sabotage. Secondly, advanced reactors are designed with passive safety systems, like natural circulation, that can cool the reactor even in the event of power loss or equipment malfunction (Hussein, 2020). The mass production and standardization of design means that personnel training and safety protocols will be easier to develop and implement.

Lastly, SMRs will improve on the efficiency of nuclear energy, which already boasts the highest capacity factor of any energy source. Conventional nuclear's capacity factor of nearly 93% can be attributed to consistent uptime and required refueling once every two years or so, but some small modular reactor designs call for refueling every 3 to 7 years, and more advanced designs could operate as long as 30 years before having to refuel. Not only does this increase efficiency and the capacity factor, but this can also eliminate some of the issues associated with spent fuel storage (Chatzis, 2019). Spent fuel management has been a controversial topic in the last decade or so, with former President Barack Obama shutting down Yucca Mountain, the US's only permanent nuclear waste repository, in 2010.

Comparisons with Other Renewable Energy Sources

There is very little debate from climate activists and scientists on the future of fossil fuels. The United States and the rest of the world need to move away from coal, oil, and natural gas as soon as possible. The argument comes when deciding what source or sources of clean energy will replace the carbon-emitting fuels that make up over half of the global energy market. Wind and solar energy are popular options that have grown dramatically since the turn of the 21st century, but how do that compare to nuclear energy and small modular reactors?

Non-nuclear renewable energy is the fastest-growing energy source in the US, growing around 90% since 2000. About 20% of the US's energy generation came from renewables in 2020, with wind power providing the most at 8.4%, and solar power coming in at 3.3% (C2ES, 2021). This growth is powered by increases in efficiency, decreases in costs, and subsidies from the government to encourage clean energy, but there are still many issues that may keep wind and solar from overtaking nuclear as the main source for zero-emission energy.

One of the main concerns for renewable energy is the lack of reliability and efficiency during generation. As previously stated, nuclear energy has a capacity factor of over 90%. The capacity factors for wind and solar are significantly lower than that, measuring at 35% and 25%, respectively. This means that producing the amount of power typically generated by a 1 GW nuclear power plants would take three or four renewable energy plants of the same size. Renewable plants also have frequent down time, which would require large-scale storage or a reliable backup power sources (DOE, 2021).

Furthermore, the space needed for renewables to generate the same energy as a nuclear energy would be astronomical. A typical 1 GW nuclear power plant needs about one square mile to operate. A 2015 Nuclear Energy Institute (NEI) analysis found that a wind farm generating the same amount of energy would require nearly 360 times as much land, and a solar photovoltaic plant would need 75 times as much (NEI, 2015). At this time, no wind or solar farm in the United States produces even three-quarters of what a nuclear power plant produces.

Wind and solar farms are also limited in where they can operate. Wind turbines are most efficient in flat areas with high amounts of wind, and solar panels are most efficient in locations where insolation (amount of solar radiation) is adequate.

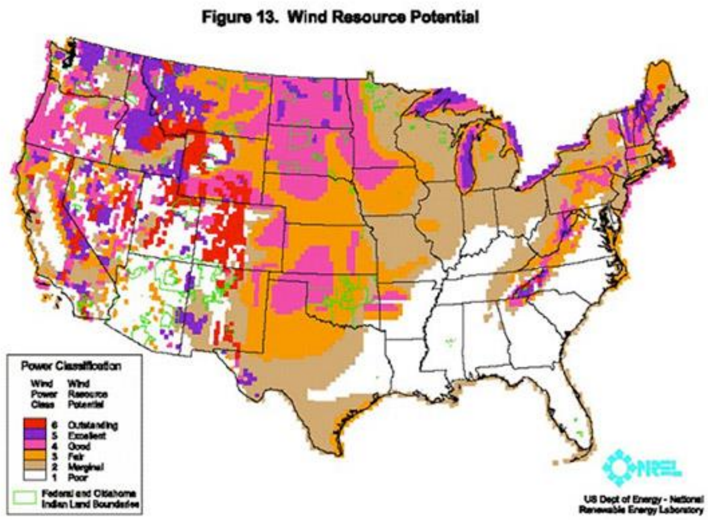

Figure 5: Map of best locations for wind energy. (Source: DOE - National Renewable Energy Lab)

This means they are often placed far from population centers that require the most energy. In order to get this renewable energy to cities, it would need to be transported over long distances, which can cause energy loss due to the low efficient rating of existing transmission lines in the United States. To fix this, the United States would have to invest in HVDC lines that have been estimated to cost between $1.17-8.62 million per mile (EIA, 2018).

Economics and Deployment of SMRs

One of the biggest draws for small modular reactors is the potential for lower capital and operational costs in comparison to current conventional reactors. Many nuclear projects have been shut down, and the nuclear industry as a whole has declined because of financial instability, so it is important to understand the economics behind SMRs and how it would affect the potential large-scale deployment of this technology.

An important piece of the SMR's identity is its ability to be scaled. While smaller projects of one or two reactors may require a lower financial commitment than a conventional reactor, recent studies show that an SMR with the same output as a conventional reactor can incur a similar cost (Mignacca & Locatelli, 2020). However, these analyses fail to take into account the unique characteristics that could potentially lower the cost of an SMR project.

The additions of modularization and standardization make factory fabrication a possibility. Parts that are mass produced in a factory can be made cheaper and potentially at a higher quality. Projects could then see a second wave of cost reductions with shorter construction times and reduced labor costs. Higher quality parts could potentially reduce accident-related costs and the cost of replacing failed components. Conversely, factory fabrication creates the need to ship parts and creates transportation and logistical costs that might not come with building a conventional nuclear power plant (Mignacca & Locatelli, 2020).

It is difficult to analyze the economics of SMRs because the technology is new in terms of commercial use, and there are zero operating SMRs in the United States. The project that is closest to completion in the United States is the collaborative effort between NuScale Power and Utah Associated Municipal Power Systems (UAMPS), which is expected to begin generating power by 2029.

The 12 module, 600 MW Carbon Free Power Project (CFPP) began in 2015 when the DOE awarded NuScale $16.5 million in funding. The initial cost assessment for the project was estimated to be about $3.7 billion in 2017, but over the last few years, this price has increased to $6.1 billion (Patel, 2020). For comparison, the Vogtle 3 and 4 conventional reactors being built in Georgia will cost $28.5 billion (Amy, 2021). The DOE was able to alleviate some of the financial burden from the CFPP by awarding NuScale an additional $1.4 billion in October of 2020 (Patel, 2020).

When comparing the economics of various energy sources, it is important to analyze the levelized cost of electricity (LCOE). LCOE is the cost at which energy must be sold to break even on a project. This measurement takes into account the entire lifetime of a plant or project, which is typically 20 to 40 years. Costs for construction, fuel, operation, and maintenance are all considered when calculating LCOE.

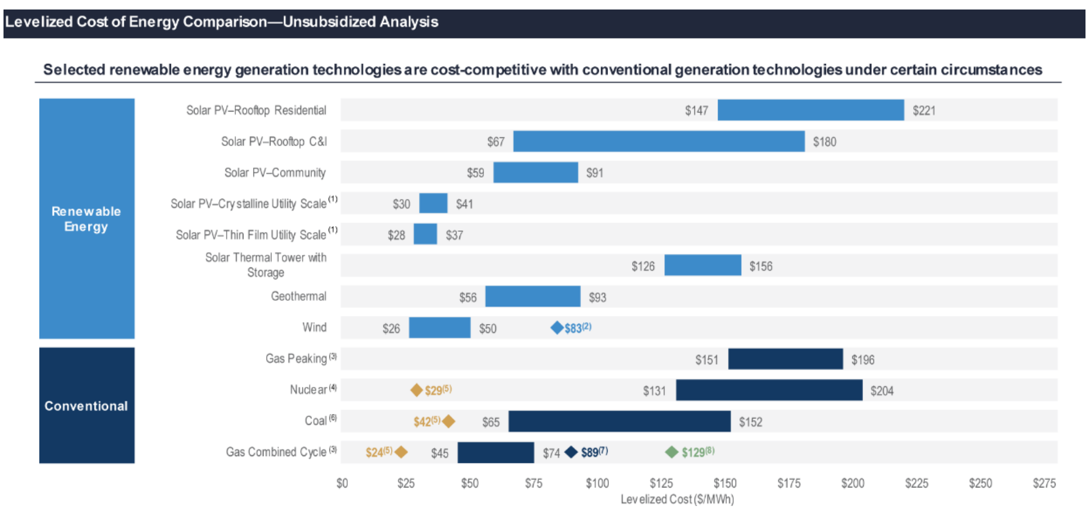

Figure 6: LCOE for Renewable and Conventional Energy Sources, 2021 (Source: Lazard)

The figure above shows investment firm Lazard’s 2021 LCOE analysis. Some important numbers to consider are the LCOEs for Solar PV-Crystalline Utility Scale ($30-41/MWh), Geothermal ($56-93/MWh), Wind ($26-50/MWh), Nuclear ($131-204/MWh), Coal ($65-

152/MWh), and Gas Combine Cycle ($45-74/MWh). These represent the main energy sources that are being used in the United States and globally. One of the main advantages of wind and solar energy is their respective LCOEs, which are about four times lower than that of conventional nuclear energy (Lazard, 2021).

Calculating the LCOE of small modular reactor plants is difficult because there is very little data on commercial SMR operation. In NuScale Power's Spring 2020 update, they stated that their target LCOE for the 12-module UAMPS project was $65/MWh (Patel, 2020), but more general analyses have estimated that the LCOE of SMRs could be in anywhere from $45 to $95/MWh (Energy Strategies, 2019). While this is not as low as the LCOE for wind and solar, it is an improvement over conventional nuclear and could make it SMR projects more appealing.

SMRs and the Electric Grid

A key concern when discussing energy across the world and in the United States is how it will affect the electric grid. It is no secret that the electric grid in the US is old and outdated. Grid infrastructure has been underfunded for several decades, and it is exhibited by antiquated transmission lines and frequent blackouts. In February 2021, Texas' power grid experienced a major blackout that led to the deaths of over 200 people. The unusually cold weather caused power plants to stop production, and the entire grid was just five minutes from total collapse (Largey, 2021). So, how can small modular reactors keep disasters like this from happening in the future?

SMRs are designed to have a few crucial features that aid in the resilience of the reactor and the electric grid. First, SMRs can "black start" in the event of an outage. This means that they do not require energy from the grid in order to start up. This is valuable during the process of recovering from a grid blackout because it helps the grid meet voltage, frequency, and other requirements. SMRs can also be completely detached from the grid and create what are called "microgrids." Not only can facilities connected to the microgrid maintain power in the case of a larger blackout, but the microgrid also helps in alleviating some of the stress on the main grid (DOE, 2018b).

One of the biggest factors in the 2021 Texas blackout what an inability for plants to operate due to the cold weather. SMRs are able to be built underground, which not only protects them from extreme weather, but also earthquakes and deliberate attacks like electromagnetic pulses and explosives. Moreover, the aforementioned fueling times mean that SMRs could run for several years without any reason to shut down. Lastly, the modularity of the reactor design reduces the need for electrical parts, such as in the passive cooling system (DOE, 2018b).

Dealing with Public Perception

Due to major disasters like Three Mile Island, Chernobyl, and Fukushima, nuclear energy has dealt with negative public perception for the better part of its existence. Anti-nuclear protests gained popularity in the 1970s and have continued to this day. It is nearly impossible to find a nuclear project that is not met with some sort of backlash. On a larger scale, states like California and even countries like Germany have vowed to cease nuclear energy generation and have been successful in doing so. California is in the process of shutting down its last nuclear reactor, and Germany has cut its nuclear energy consumption by over 50% since 2011 (WNA, 2021a).

Nuclear energy is in a unique position to receive major criticism from both sides of the political spectrum. On one side, conservatives lobby with oil and coal to keep the same carbon-emitting power plants that have been powering the world for decades. They argue over the loss of jobs, even though coal workers make up less than 0.02% of the US population (Kuykendall & Dholakia, 2020). On the other end, liberal climate activists contend that the risk of another nuclear accident is too high and that there are better clean-energy alternatives.

Reversing the negative public perception of nuclear energy is vital to its success in the future. Anti-nuclear citizens vote in anti-nuclear politicians that create anti-nuclear legislation. The keys to improving public opinion are pushing education that shows how nuclear energy adapted after notable accidents and proving that protocols and regulations work through safe operation.

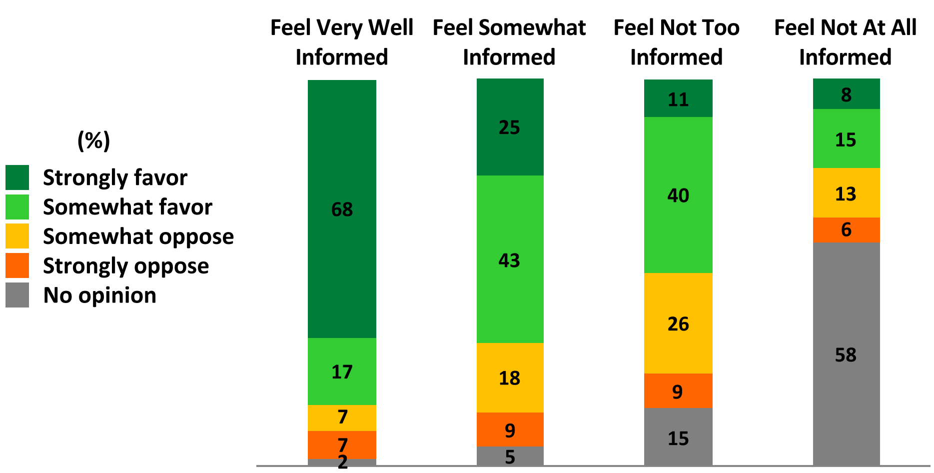

Figure 7: Survey of nuclear favorability based on information level, 2019 (Source: Bisconti Research, ANS)

Each year, Bisconti Research conducts a survey to gauge public perception on nuclear energy and is the only source of continuous data on this topic. One portion of the survey data analyzed public perception based on information level. Those that felt very well informed or somewhat informed were much more favorable to nuclear energy than those that were uninformed. The survey also offered this statement: "We should take advantage of all carbon-free energy sources, including nuclear, hydro, and renewable energy, to produce the electricity we need while limiting greenhouse gas emissions." Three-fourths of those polled agreed with the statement, with 40 percent strongly agreeing (Bisconti, 2019).

Education on nuclear energy should be a priority of all nuclear agencies and governments pursuing nuclear, with the primary target being youth education in schools. In 2018, the American Nuclear Society (ANS) started an initiative to ensure that nuclear science and energy curriculum could be taught in schools K-12. Over 1.2 million students were involved with the program in the first two years, and an even greater outreach is planned for the years ahead. ANS has also provided all 10,000 of its members with the resources needed to educate local schools and communities on nuclear energy (ANS, n.d.).

Disadvantages of SMR Technology

In order to advance SMR technology, the flaws must be analyzed, and improvements must be made. Just like any other energy source, SMRs have disadvantages that may keep them from reaching their full potential. With commercial SMR use in its infancy, there is still research and development to be done, analyses to be completed, and kinks to be worked out.

Many of the issues that SMRs will face during initial implementation involve the financial and logistical burdens that come along with emerging technology. Currently, there are over 20 different SMR designs being developed across the world. While most agree that only a few of these designs will pass the conceptual phase, there is still not a consensus on which of these designs will be developed and commercialized.

With no concrete plan to focus on, there are substantial resources potentially being wasted on creating more options, rather than diverting funds to support one or two strong designs. Furthermore, nuclear safety regulators lack the resources needed to analyze all the potential designs (OECD, 2021). Being unable to narrow down the design to one or just a few also hinders the fundamental capability of SMRs to be mass-produced in a factory.

As previously mentioned, there will also be a high cost associated with building the small modular reactor industry for mass deployment and implementation. The factories that would produce the SMRs do not exist yet. The transportation systems have yet to be designed. There would be a hefty price tag to employ and train all the new members needed to run power plants. The costs add up, and they make SMRs somewhat unappealing because of high capital costs.

Many SMR designs do not address the issue of permanent spent fuel storage. This is an ongoing problem with current conventional reactors due to the shut down of Yucca Mountain. The issue might not be as severe with SMRs because they are smaller, require less fuel, and operate for longer periods of time without refueling, but it is not completely solved. However, there is a potential solution, with some small modular reactor designs have the ability to reprocess spent fuel through breeding (WNA, 2021b).

Future Developments

The development of small modular reactors up to this point has shown major potential, so the Department of Energy has created a few programs to fund research and create new opportunities for SMRs. In 2019, the DOE created the Advanced SMR R&D program to expedite the development and implementation of US-based SMR technologies for commercial use domestically and internationally. This is the program that has provided financial support for the NuScale and UAMPS project. The program also works to alleviate licensing issues that hold back advanced SMR designs (DOE, n.d.).

In 2018, the DOE also announced, "U.S. Industry Opportunities for Advanced Nuclear Technology Development," which is a funding opportunity designed to support new and innovative nuclear technologies. Resources awarded from this program will be used to promote projects that help finalize SMR designs: "developing manufacturing capabilities and techniques to improve cost and efficiency of nuclear builds; developing plant structures, systems, components, and control systems; addressing regulatory issues; and other technical needs identified by industry" (DOE, n.d.).

Most small modular reactors in development are light water reactors (LWR). This means that they are both moderated and cooled by regular water. This is the safest of the SMR designs because the similar to existing conventional reactors, and they use fuel that is only enriched to about 5% U-235 (WNA, 2021b). Since this design is comparable to operating reactors, there may be fewer regulatory complications than a more experimental design might encounter. However, the experimental SMR designs, like fast neutron reactors, have the potential to address many of the issues LWR and conventional reactor designs.

Fast neutron reactors (FNR) are simpler than a typical LWR because they have no moderator, utilize passive safety features, and operate at or near atmospheric pressure. FNRs are much more efficient than conventional reactors, using the full potential of the uranium fuel rather than the 1% from LWRs. They also have longer fueling cycles that can last up to 20 years, and some can even produce more fissile material than they consume. They are typically cooled with liquid metal, but in the case of a loss of coolant accident, increasing core temperatures slow reactions and shut down the reactor (WNA, 2021b).

Small FNRs would be built in a factory and shipped directly to a construction site. They could also be disposed as entire units, eliminating complicated decommissioning steps. There are some proliferation concerns associated with FNRs, as they use highly-enriched uranium, and wide-scale deployment would require the production and handling of large amounts of plutonium (Grenêche, 2009). However, no facility in the US is designed to enrich fuels over 10% (WNA, 2021b).

Another feasible small reactor design is the molten salt reactor (MSR). As the name might suggest, MSRs use molten fluoride salt as a coolant, rather than water. This design was studied over 60 years ago at Oak Ridge National Lab, but interest has piqued once again due the ability to breed plutonium and uranium-233 through reprocessing. MSRs also operate at much higher temperatures than LWRs, opening up the possibility for better heat transfer and steam generation (Gen IV, 2021).

DISCUSSION & CONCLUSION

Interest in small modular reactor designs has increased dramatically during the 21st century, as the world desperately tries to find an alternative to the fossil fuels that dominate the energy sector and account for the majority of greenhouse gas emissions. There is a plethora of clean energy sources that show promise, but each has their own flaws. Wind and solar energy are popular choices for climate activists, having grown drastically over the last two decades, but issues with efficiency and ability to meet energy demands could hold them back. Nuclear energy has shown to be incredibly efficient, with an industry-leading capacity factor, but it is costly, and many are skeptical of the environmental impacts that nuclear energy may cause, such as the disasters at Fukushima and Chernobyl.

Small modular reactors aim to be a compromise that brings the energy production of conventional nuclear reactors while being safe, compact, and environmentally conscious. The modular design means reactors can be built to accommodate the energy and space needs of nearly any site. The possibility of factory fabrication could cut the costs and construction times that have left many nuclear plant projects abandoned. Enhanced safety features like passive shutdown systems and standardized training and lower risk of proliferation would help to address the negative public perception that nuclear energy has received.

Yet small modular reactor designs still have some flaws that could keep them from gaining traction. While SMR will improve upon construction times and costs, they will still more expensive than renewables like wind and solar. There could also be significant capital costs associated with initializing factory fabrication. Additionally, many SMR designs do not address the issue of spent fuel waste and storage.

Regardless of how safe or cost efficient SMRs can be, there will still be a widespread negative perception of nuclear energy. Major nuclear accidents combined with years of protests and anti-nuclear propaganda have made the public scared of nuclear power. If SMRs and entire nuclear industry want to grow and potentially become the leading source of energy generation, there must be a significant push to educate the population, especially the younger demographic, on nuclear energy and demonstrate the safety in nuclear power during operation.

Small modular reactors bring hope to an industry that has been stagnant for several decades, but there is still much work to do. The technology is new, and there are still significant hurdles to overcome before these reactors see mass implementation. If small modular reactor designs improve to address current issues, while still delivering on the promise to be a safer and more cost efficient form of nuclear energy, then SMRs can be the leading global source of energy generation.

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