EVALUATING THE POTENTIAL ECONOMIC ADVANTAGES OF SMALL MODULAR REACTORS AND HOW THEY MAY CONTRIBUTE TOWARDS FUTURE EMISSION REDUCTION GOALS

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

According to the U.S. Energy Information administration (2022), around 60% of the electricity generated in the country in 2020 was produced through the burning of fossil fuels (¶ 3-4).). Given that 25% of greenhouse gas emissions were generated through power production that year, it is evident that, in order to reduce our overall emissions, transitioning to renewable and sustainable power sources as quickly as possible is of paramount importance in order to reach national and global climate change mitigation goals (U.S. Environmental Protection Agency, 2023). While wind, solar, and hydropower will certainly be part of the solution, they all come with their own shares of limitations and challenges, such as geographic and time constraints (Thoubboron, 2022).

Even though nuclear energy is zero-emission source of electricity, the U.S. has seen the closure of 13 commercial nuclear reactors since 2013 with several more announced in the next several years (Congressional Research Service, 2022). However, due to economic, political, and, of course, environmental factors, renewed interest in nuclear power has led to measures being taken to provide funding to extend the lifetime of aging powerplants and in some cases prevent the shutdowns of ones whose closure had already been announced (U.S. Department of Energy, 2022). One major motivator for this is the Biden Administration, who has set a goal of eliminating 50% of net greenhouse gas pollution from 2005 levels by 2030 (The White House, 2021). However, for nuclear power to contribute significantly to that end, more must be done than simply subsidizing an aging fleet of unprofitable reactors. In the past decade, the concept of Small Modular Reactors (SMRs) has gained increasing traction among those seeking solutions to challenges that larger, more conventionally sized reactors face, primarily regarding large upfront capital and financing costs (World Nuclear Association [WNA], 2023a). This paper will discuss how SMRs can potentially address these challenges, as well as their realistic potential to contribute towards meeting federal carbon emission reduction goals.

A Brief History of Nuclear Power in the U.S.A.

At the end of World War II, the U.S. government began looking into peaceful applications of nuclear fission under the Atomic Energy Commission. Possible applications included ship propulsion, medicine, and electricity production. The first nuclear reactor to produce electricity was started up in 1951 (WNA, 2020). With the passage of the Atomic Energy Act of 1954, development of commercial nuclear power became possible (U.S. Nuclear Regulatory Commission [NRC], 2021). The Shippingport Atomic Power Station, whose construction was initiated by President Eisenhower's "Atoms for Peace" initiative went online in 1957 and was the country's first commercial nuclear powerplant. The next couple decades would see the industry grow steadily, with 109 nuclear reactors online by the time the Shippingport station was decommissioned in 1989. However, due to economic, social, and political factors, demand for nuclear power in the country drastically fell off starting in the 1980s. Incidents at Three Mile Island and Chernobyl left a stigma on nuclear energy in the public eye regarding its safety that the industry has been struggling to rid itself of to this day (Duke Energy Nuclear Information Center, 2012).

According to the U.S Energy Information Administration (2023), nuclear electricity generation has stagnated over the past couple decades, peaking in 2012 at around 102,000 MW with 104 reactors (¶ 2). Currently there are 93 active reactors in the country, with one more under construction (Nuclear Energy Institute [NEI], 2022). For reference, China has over 20 reactors currently under construction (WNA, 2023a). The percent share of electricity produced by nuclear power in the U.S. has been maintained at around 19% largely due to a process called power uprating, which increases the capacity of existing reactors. The NRC (2022a) states that it has approved 171 power uprates since 1977, which has increased the output of existing reactors by 8,030 MWe in total ((¶ 2).). While this is fine for keeping pace with increasing overall electricity needs, to increase nuclear power's share, new reactors must be built.

Renewables and their Challenges

As Figure 1 illustrates, carbon dioxide emissions have by far the largest impact on atmospheric heating out of all greenhouse gases produced by humanity. As general awareness of climate change has increased in recent years, so too have calls to reduce emissions in all sectors, including electricity. As stated above, renewable energy sources, such as wind, solar, and hydropower, are still faced with persistent challenges that have yet to be solved. Hydropower is situational, as you need a source of running water to drive the turbines. Wind and solar both occupy large geographical footprints at utility scales and are intermittent sources of power, meaning that advances in electricity storage are required before they can be fully relied on to power our country 24/7 (Thoubboron, 2022). Another set of factors

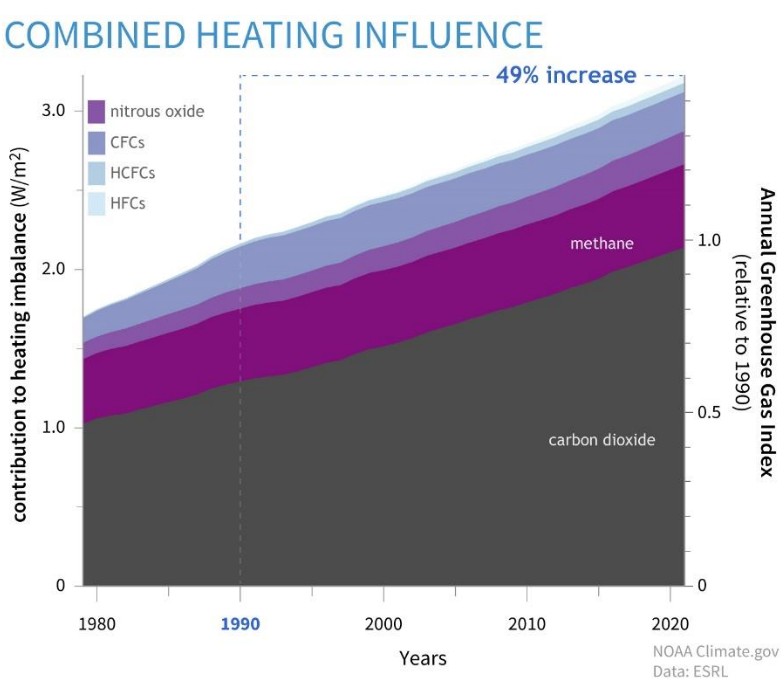

Figure 1:Graph of the heating influence of major human-produced greenhouse gases over the past 40 years (Lindsey, 2022).

that is often overlooked is the environmental impacts of sourcing raw materials, manufacturing, transporting, and disposing of solar panels and wind turbines. For example, solar power requires components composed of rare earth metals. So, despite solar power coming from a renewable source, it is still dependent on non-renewable resources with recycling rates currently under 1% (ClearWorld, 2022). Additionally, China mines 80% of rare earth metals. This dependence on a potentially adversarial country is obviously undesirable for the United States. One challenge facing wind power is the fact that we do not currently have an effective way to recycle wind turbine blades, with Stella (2019) reporting that researchers project the nation will have more than 720,000 tons of fiberglass-reinforced resin waste to deal with over the next twenty years, from 2019 ((¶ 1). This brief overview is by no means meant to argue against the continued development of renewable power. It is meant to explain why, given these challenges and increasing public awareness of the threats posed by CO2 emissions, the allure of 24/7 net-zero emission power generation has prompted renewed interest in nuclear energy.

Nuclear and the Future

A major challenge that nuclear reactors face in the U.S. is their ability to compete economically with other forms of power generation given their large upfront capital requirements. Notably, cheap natural gas has been a significant factor in the stymieing of new reactors being constructed. Nuclear power simply cannot compete currently. This has been further compounded by the fact that the nation's newest reactors, Vogtle 3 and 4, have overrun their original completion date by more than six years and at more than twice their original budget. They are projected to be completed this coming year. Construction on two nuclear powerplants in South Carolina was halted in 2017 after $9 billion of investment (Collins, 2023).

These recent incidents have left many in the country convinced that is no longer viable to build large nuclear reactors. Small Modular Reactors are a new class of nuclear reactor that is being developed with the hope of avoiding some of the major economic issues that large reactors face (WNA, 2023b). The World Nuclear Association defines them as "nuclear reactors generally 300 MWe equivalent or less, designed with modular technology using module factory fabrication, pursuing economies of series production and short construction times." For reference, larger reactors can exceed 1600 MWe in electricity generated. As illustrated by Figure 2, SMRs can range from ¼ to 1/10 the size of larger reactors and are characterized by the fact that significant portions of the reactor's systems or even entire reactors may be prebuilt in a factory, then transported to the site where they will be installed and operated. As the name suggests, modularity is a key feature of these reactors, which, in addition to series production advantages in time and cost, allows for powerplant output to be expanded or reduced simply by adding or removing modules while also significantly reducing construction time at the plant site. The combination of small, standardized designs and large portion of fabrication taking place in a factory are meant to significantly reduce the upfront costs associated with larger designs. Additionally, they are intended to offer several other economic, safety, and security advantages over larger designs.

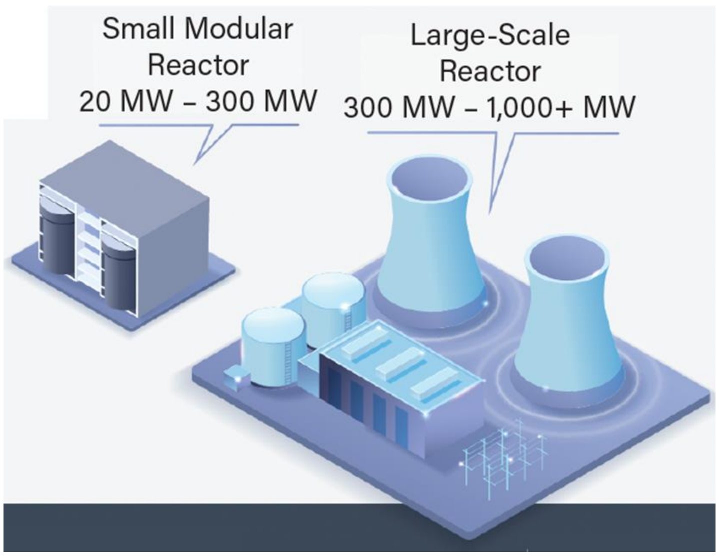

Figure 2: General comparison in size and power output between small modular reactors and large reactors (Kaustubh & Kasturi, 2022).

However, while advocates are enthusiastic about the potential of these new designs, critics have brought up concerns over their actual economic viability, on top of concerns over security, fuel requirements, and obtaining government certification (Ramana, 2021). In fact, Ramana argues that SMRs will only worsen the economic competitiveness of nuclear power due to ultimately having a higher specific cost of electricity. Ultimately, as these designs are unproven, it will remain to be seen if they can compete with other forms of power generation. It is important to note that, as there is much variation in different SMR designs, all these factors can significantly vary. For instance, variations in modularity will affect transportation, on-site installation, and the economy of factory production. Additionally, reactors using proven technology like pressurized water reactors will have lower development costs but may also produce more nuclear waste than more advanced designs. In-depth dissection of the variations in SMR design is not the purpose of this paper, but it should be noted that designs based on proven technology will likely require significantly less time and money getting approved by the NRC than more technologically advanced reactors.

Methodology of Research and Analysis

This research paper aims to discuss how SMRs may address the economic challenges that existing large reactors face in order to increase the share of electricity generated by nuclear energy in the nation and reduce carbon emissions in the U.S. To reach this end, research will be done on recent (within the past couple decades) government initiatives to promote industry growth, competing power sources, as well as public sentiments towards nuclear power and climate change. Recent closures and developments of nuclear reactors will also be covered. Additionally, the history of SMR development up through the present will be discussed, with a particular focus on their economic viability and when we can realistically expect construction of commercial reactors to be possible. Research will draw from a variety of sources, including government and other organizations' websites, scholarly and news articles, as well as radio programs featuring experts on the subject. Recognizing that a large barrier to nuclear power's growth is its lack of competitiveness with other cheap sources of power, economic and financial discussion of SMRs will be a major focus of this paper.

Most of the social groups relevant to nuclear energy and SMRs can be split into two broad categories: those looking at them primarily from an economic and financial point of view, and those who are concerned primarily with their influence on emissions and the environment. The latter category sees nuclear energy as a possible solution to the problem of emissions generated from burning fossil fuels, while the former category sees SMRs as a possible solution to the problem of nuclear energy not being competitive economically with other sources of energy. Another group that cannot be ignored is composed chiefly of the NRC, which prioritizes safety above all other considerations. In order for a new reactor design to be used commercially, it must first pass the NRC's rigorous certification process. This paper will first address the parties concerned with the economic advantages of SMRs by discussing their potential benefits and will then address the second group by discussing the realistic contributions that SMRs may make towards reducing emissions by the deadlines set by the Biden administration, with a particular emphasis on potential challenges posed by the NRC certification process.

Competitiveness of SMRs

As previously stated, nuclear energy is simply unable to compete in the current energy market. Two major reasons for this are access to cheap natural gas in the U.S. and large upfront capital requirements for building new nuclear powerplants. Figure 3 illustrates that the levelized cost of energy (LCOE), the average revenue per unit of power generated required to recover building and operating costs of a powerplant over the generator’s lifetime, of both large reactors and SMRs are not necessarily unable to compete with natural gas (NG), especially if the gas plant has implemented carbon capture (Asuega, Limb, & Quinn, 2023). Nuclear really struggles in its financing and capital requirements, which represent more risk than NG powerplants, which have relatively cheaper upfront costs and significantly higher fuel costs. Additionally, recent reactor construction projects in Georgia and South Carolina have seen massive delays and budget overruns, further decreasing the enthusiasm for new nuclear plants. Utility companies and investors, who are motivated by profit, will not pursue the nuclear option over less risky options. Taxpayers, whose money is also put into these projects, expect a return on investment in the form of low electricity costs. Budget overruns are ultimately paid for by the consumer, and in cases where the reactors are cancelled in

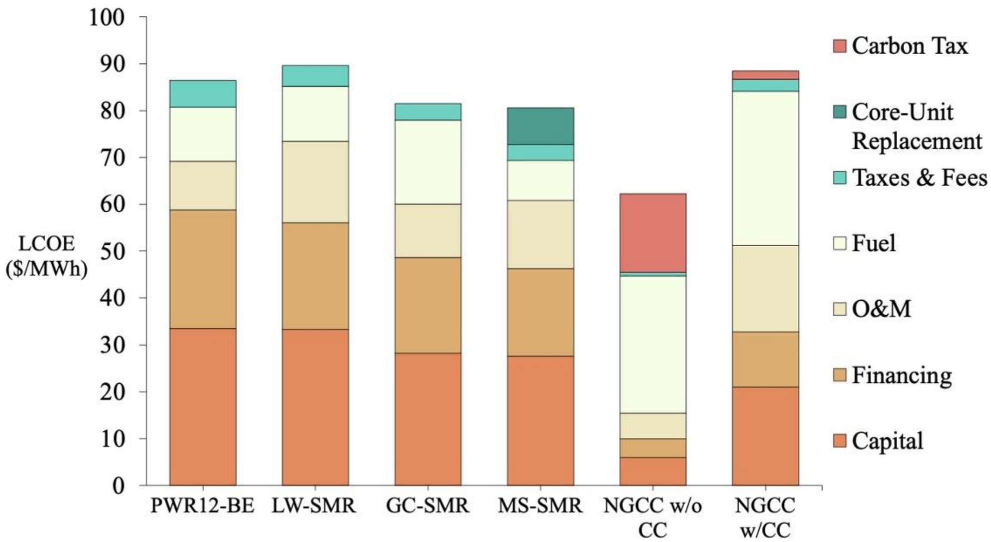

Figure 3: Comparison of the LCOE of a large pressurized water reactor, three different types of SMRs, a natural gas combined cycle plant (NGCC) without carbon capture, and a NGCC plant with 90% carbon capture. (Asuega et al., 2023)

the middle of construction, they will see zero benefit from the tax dollars put into the project. Naturally, for fossil fuels to be replaced, investment is required in other, cleaner sources of energy. Thus, nuclear energy must be made more competitive to be attractive to consumers, producers, and investors. Through their modular nature SMRs present some unique benefits over large conventional reactors that may help to reduce the capital and financing costs associated with the medium.

One major area of promise that SMRs hold is construction duration. This has significant implications on the overall costs, as reducing construction time results in a decrease in accumulated interest cost. So, a great way to reduce the financing cost of a project is to shorten the time it takes to build the plant. Figure 4 illustrates financing cost for construction times of 2, 3, 4, and 6 years based on 5% and 10% interest rates (Nuclear Energy Agency [NEA], 2011). So an SMR with a 4 year construction time can expect anywhere from roughly 5% to over 10% in savings compared to a large reactor with a 6 year construction time on the basis of build duration alone.

Figure 4: Cost of financing as a function of construction duration and interest rate with a uniform financing schedule (NEA, 2011).

Some cost savings may also be made in certain SMR designs by simplifying them relative to large reactors that utilize the same basic operating system. This may be due to simplification of safety systems and reductions in material requirements due to the smaller reactor size. For example, savings in overnight capital costs (OCC) of a couple small, pressurized water reactors (PWR) designs have been estimated to be around 15% (NEA, 2011).

Another important benefit that SMRs might offer is a significant reduction in per unit cost as series production takes place. This can occur due to experience gained over successive unit fabrications and installations, resulting in better, more efficient work practices (NEA, 2011). It is important to note that the first-of-a-kind (FOAK) reactor is usually significantly more expensive than subsequent units. Of course, for there to be a noticeable reduction in per-unit cost, multiple units must be built. It is also important for the intervals between unit construction to not be too long, otherwise the benefits of experience gained may be reduced or lost. Also, if plant sites vary significantly, this effect may also be reduced.

One other advantage of powerplants composed of multiple SMRs that should not be overlooked is that they can start producing electricity as soon as the first reactor is installed, connected to the grid, and activated, while a powerplant composed of a single large reactor can only do so after the entire project is completed (Mignacca & Locatelli, 2020). This means that investors and taxpayers will start seeing some return on their investments that much sooner.

A couple economic limitations of SMRs is higher transportation costs, as whole reactors must be moved from the factory to the plant site, and there is a minimum number of SMRs that must be sold to cover the cost of setting up the factory and supply chain for module production. Critics of SMRs also cite SMRs size as a disadvantage due to losing out on economies of scale compared to large reactors (LRs) (Ramana, 2021). Generally speaking, larger reactors are inherently more efficient on a cost per watt basis than smaller ones, so a simple comparison between an LR and a scaled down reactor of the same design one-to-one will favor the large reactor. Specifically, NEA (2011) states that, depending on the plant, "the specific (per kWe) capital costs of SMRs are expected to be tens to hundreds of percent higher than that for large reactors" (p. 85). However, there are some important caveats regarding this statement. First, it assumes that no significant design changes were made when scaling large reactors down. Additionally, the effects of scaling can vary significantly going from one component to another, meaning that accurately grasping an understanding of the overall scaling of a powerplant is by no means an exact science. SMRs promise several advantages over LRs by virtue of multiple units being onsite for the same power output as described above, that proponents argue will reduce capital and financing costs. However, whether these theoretical benefits will be enough to convince investors to take on the risk of investing in commercial SMRs over low-carbon sources of power remains to be seen.

SMRs and Carbon Emission Reduction

In the past, environmentalists may have largely taken stances against nuclear power on grounds of concerns over its potential to harm the environment due to accidents or improper waste storage. The fact that it is a zero-emissions source of power has made it much more attractive, given increasing public awareness of greenhouse gases and how they affect our planet. While the previous section discussed how SMRs are being developed in order to attract interest from those concerned with nuclear's market competitiveness, this section will discuss SMR implementation and its potential contributions to achieving decarbonization goals of the federal government.

Since 1996, only one new reactor has been built in the country, with two more expected to be completed in the coming year (Nuclear Energy Institute, 2022). Although SMRs have gained increasing support among proponents of nuclear energy, no commercial SMR projects have begun construction. Given that the federal government under the Biden administration has set the ambitious goals of achieving "a 50-52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution in 2030" and 100 percent carbon pollution-free electricity by 2035, the window for SMRs to contribute is rapidly closing (The White House, 2021).

A major bottleneck in SMR implementation is getting through the NRC's rigorous design certification process. This involves submitting an application for certification, which must then be reviewed by NRC staff to ensure that the reactor design is in accordance with the various safety rules and regulations set by the agency (NRC, 2022b). Any issues uncovered during this process must either be resolved through design revision or applying for an exception to the ruling. Zero nuclear reactors that applied for approval have gone through the NRC's licensing process from start to finish and commenced operation in the agency's 48-year history. When Georgia's over-budget and long-delayed Vogtle 3 and 4 are completed in the coming year they will be the first to have completed that long journey (Wesoff, 2023a). Critics attribute this to institutional problems in the NRC, that the commission solely prioritizes safety without considering other factors like commercial viability. This has greatly contributed to the stagnation of the nuclear industry, and only serves to hinder SMR implementation in the country.

In January 2023, a historic landmark was reached when the NRC certified its first SMR, a 50 MW power module design by NuScale Power (Wesoff, 2023b). While this is an important first step in commercial SMRs becoming reality, it should be noted that NuScale (2020) claims to have spent over $500 million dollars and 2 million labor hours to develop the information required to prepare its Design Certification Application (¶ 3). Keeping in mind that NuScale's design is a light-water reactor type, a familiar technology in large reactors, it can be assumed that designs that use more unproven technologies are and will continue to have a harder time getting through the process. Hopefully, this breakthrough will lead the way for other SMRs to reach approval. NuScale has an agreement to build its first SMR in Idaho utilizing six 77 MW modules. The reactor is expected to come online in 2029, although factors such as inflation and increased interest rates have caused them to increase projected energy costs from $58 per megawatt-hour to $89 per megawatt-hour (NuScale Power, 2023). Additionally, further NRC review is required, as the 77 MW modules have not been approved for commercial use yet (Walton, 2022).

Based on the evidence presented above, it does not seem likely that SMRs will make a major contribution towards meeting the Biden administration's 2030 emission reduction goals. While NuScale's Idaho reactor will hopefully serve as proof to investors that SMRs can be competitive, 462 MW is a drop in the bucket towards meeting the nation's electricity needs. SMRs do have a decent shot at helping to contribute to Biden's 2035 goal of having 100% carbon emission free electricity, depending on factors like how many reactors get certified in the next few years and how other renewable and low-carbon sources develop.

Whether nuclear energy even has a place in a low-cost zero-emissions future is up for debate. It is unlikely to completely disappear anytime soon however, as the federal government set aside $6 billion to ensure that existing reactors stay online and has additionally invested in advanced reactor research, education of nuclear-electric engineers, and producing high-assay, low-enriched uranium (HALEU), which is used by newer, more-efficient designs (Elbein, 2022).

Conclusion

Whether or not SMR's contribute towards the federal government's carbon reduction goals, their future will almost certainly be determined by whether or not they can prove themselves to be competitive with other low-cost sources of energy. In order to do so, the theoretical benefits described above must be proven in practice. SMR development still has merit in the eyes of many. Strong proponents of nuclear recognize that the significantly lower upfront financial risk may be much easier to stomach for potential stakeholders than the risk associated with large reactors. The federal government has demonstrated it still believes that nuclear energy has a place in the future through its dedication of funds towards advanced research and maintenance of old reactors.

There is much future research that can be done on SMR's and their potential. More detailed analyses of competitiveness of different SMR designs vs. renewable and low-carbon sources in the context of a realistic timeframe of commercial implementation would surely shed light on the issue. Additionally, revisiting the topic in a couple years will allow for reflection on this paper and its arguments, and will also allow for more accurate forecasting of where SMR development will be in 2035. Other worthwhile areas of study that this paper did not cover is SMRs in other countries and in other, non-electrical applications, such as heat generation.

If we as a species are to make progress in the fight against climate change, it is important to thoroughly explore all possible options available to us without holding on to unexamined prejudice. Understanding how others interpret technology and their problems concerning it will be vital in reaching a range of collegial solutions that will benefit the greatest possible number.

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