Virginia's Nuclear Energy Solution

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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

The world was introduced to an unimaginable source of energy nearing the end of the Second World War—the energy held within atoms. The first use of this energy was destructive, as seen in the leveling of Nagasaki and Hiroshima by atomic bombs. However, once the war ended, scientists turned their attention toward harnessing this immense power for peaceful purposes. In 1953, President Eisenhower promoted research into nuclear energy through his "Atoms for Peace" program, ensuring that the United States remained at the forefront of this technological revolution (World Nuclear Association, n.d.).

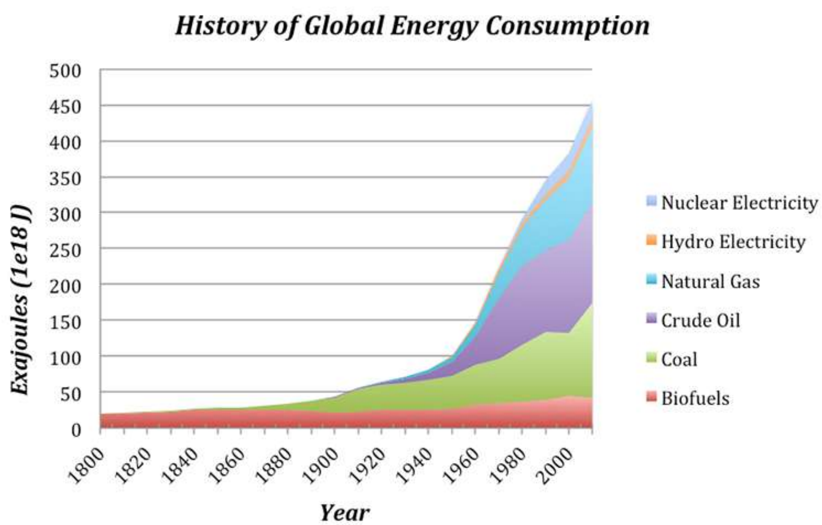

Figure 1: Plot of energy usage from 1800 – 2010 by category of fuel (Bice, n.d.).

As reactor technology matured, governments across the globe invested heavily in nuclear power, seeing it as a safe, reliable, and clean energy source. However, a series of high-profile nuclear accidents—Three Mile Island, Chernobyl, and Fukushima—shifted public perception, creating fear and uncertainty around nuclear energy. This led to reduced investment, supply chain instability, and halted progress, keeping nuclear power in a state of stagnation for decades. Meanwhile, as seen in Figure 1, global energy demand has continued to rise, driven by industrialization, the growth of data centers and tech companies, and increasing electrification. This surge in energy consumption has been met primarily by fossil fuels, contributing to deforestation and greenhouse gas emissions, with detrimental effects on the environment (Union of Concerned Scientists, n.d.).

In response to climate change concerns, governments worldwide have begun implementing policies aimed at reducing carbon emissions. The green energy movement has pushed for a transition to sustainable energy sources, including solar, wind, hydropower, and geothermal energy. However, as policymakers, researchers, and energy companies seek viable solutions, nuclear power has re-emerged as a potential cornerstone of decarbonization strategies. The state of Virginia, for instance, aims to achieve carbon-free energy by 2050, with nuclear energy playing a key role in this transition.

Virginia's push for nuclear energy is shaped by a combination of public perception, government policy, technological advancements, and economic needs. This paper uses Social Construction of Technology (SCOT) to analyze how these factors interact in shaping Virginia's energy future. This paper will investigate the viability of implementing nuclear energy as a primary solution to the decarbonization of Virginia's power grid. Analyzing the risks posed by this technology, the technological limitations currently restricting it, and the social impacts that may arise.

Background

In 2020 the Virginia General Assembly passes the Virginia Clean Economy Act (VCEA). This act mandated that the state implement a goal of 100% carbon free energy generation by the year 2050. This would require the state to phase out any energy production sites running on fossil fuels and find a way to continue generating that energy without emitting carbon. Reaching this goal is not without its own challenges. While revamping the energy landscape of the state a few factors need to be considered. The grid needs to continue being affordable and reliable, the technology used has to be economically and technologically viable, and energy production needs to increase rather than decrease in order to match a growing economy (Virginia Department of Energy, 2022).

As of 2020, the majority of the energy production in Virginia was via fossil fuels with the majority of the total energy being produced by natural gas alone. Figure 2 demonstrates a percentage breakdown of power generation by fuel source. The implementation of the VCEA would eliminate over 65% of our current energy production, this can be further split into two types of energy; base load and intermittent load generation. Base load generators operate continuously and consistently such as fossil fuels plants, nuclear plants, and hydropower stations. Meanwhile intermittent load generators refer to sources such as wind and solar which depend on the conditions to generate a specified load.

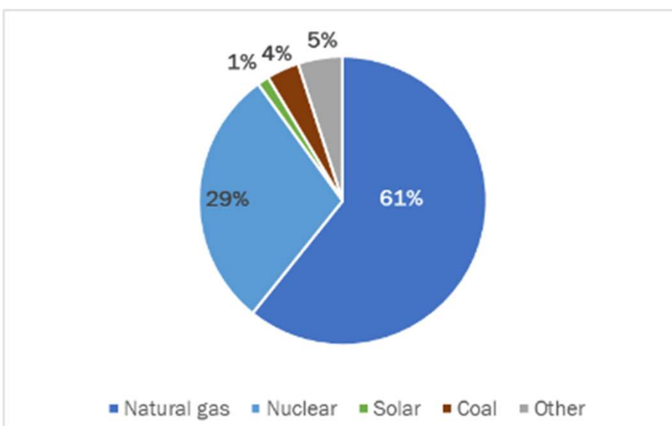

Figure 2: Generation Output by Fuel Source (Virginia Department of Energy, 2022).

With the removal of fossil fuels in order to meet the carbon free energy generation goal, that serves to remove the entire bas load generation production outside of nuclear power plants. In order to compensate new base load generation plants will need to be implemented. While renewables such as solar and wind have a huge push for them, they are currently not viable due to the fact that their energy producing capacity is dependent on the environment around them. They would become a viable option in the event that improved battery technology becomes available, that is a field that still requires further research. The existing batter technology is far too expensive to be commercially viable or competitive. Intermittent sources would extend the price of energy to the consumers, solving the reliability aspect but preventing the goal of affordable energy from being achieved. Solar is still a great supplemental energy source whose viability should be investigated when constructing new buildings and remodeling existing buildings (Virginia Department of Energy, 2022).

The requirements for affordability and reliability end up limiting the possible power generation methods. Especially considering the fact that new infrastructure will need to first cover the phased-out fossil fuel plants accounting for the majority of the current generation and secondly manage all the expected growth in energy demand that Virginia is planning on. This expectation comes from increased electrification of transportation systems, projected increases in population, more companies and jobs moving into the state, and the proliferation of energy intensive industries such as data centers. Figure 3 below shows Dominion Energie's expected energy consumption forecasts as predicted in the last few years, it's notable that as time passes the forecasted amount increases. This means that if Virginia plans to keep to the VCEA it is crucial that tried and tested technologies are implemented as opposed to gambling on unproven technologies.

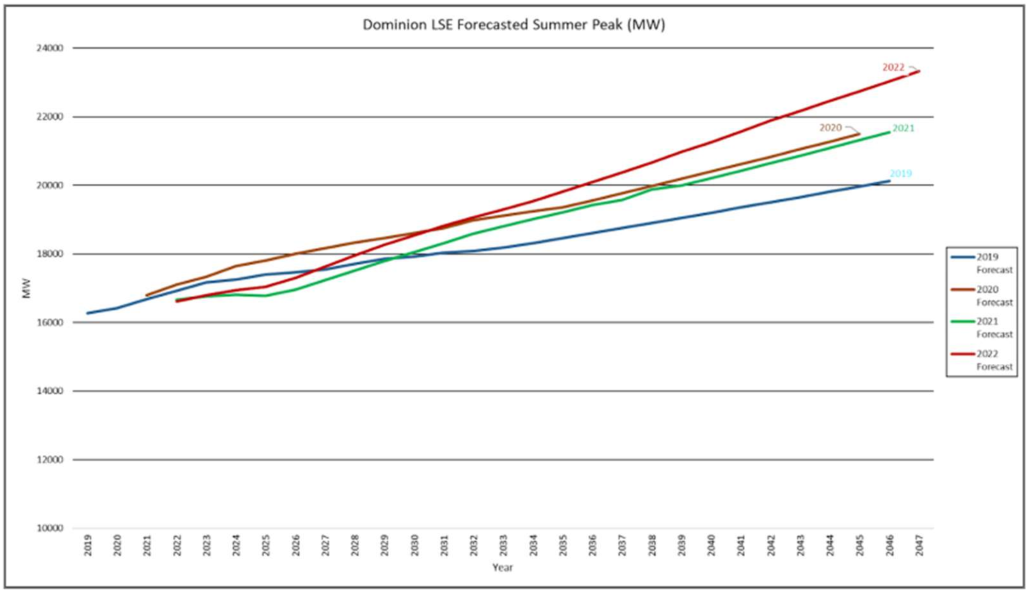

Figure 3: Forecasted peak energy demand (Virginia Department of Energy, 2022).

The potential solutions outlined in the Virginia Energy Plan emphasize the need for R&D and further innovation. Of these proposed solutions, nuclear power comes out on top in terms of technology readiness, and reliability while maintaining affordability. Virginia is no stranger to nuclear power, currently it houses two nuclear power plants accounting for 32% of the total power generated, North Anna in Louisa County and Surry in Surry County. Additionally, Virginia is home to Newport News, one of the two naval shipyards responsible for producing the entire nuclear-powered fleet (Virginia Nuclear Energy Consortium, n.d.). One promising technology is the Small Modular Reactor (SMR), these are defined as small nuclear reactors generating less than 300 Megawatts of power. This technology allows for decentralized power generation limiting the need for widespread power transmitting infrastructure, or the ability to replace fossil fuel plants without expanding the amount of land required.

From the energy usage side there are various reasons to increase the capacity of clean energy production. As outlined in Youngkin's energy plan, the increase of energy production will allow growth in population, career opportunities, and quality of life. Youngkin desires to turn the state of Virginia into not only a nuclear tech hub, but an overall technological center for the United States. The reasoning is that the increased quantity of energy production will allow for energy prices to remain stable and low. In turn more manufacturing, data driven companies, research labs and overall, any industry can move into the Virginia area without worrying about their high usage of energy. This will supply economic growth in the form of jobs designing, building, and occupying facilities among a vast variety of fields.

In order to achieve this energy landscape in Virginia, nuclear power seems to be the technology with the most potential. Notably promoting a carbon free energy generation process, reliability comparable to existing fossil fuel plants, delocalized production through SMR's, and the ability to take advantage of existing infrastructure. Throughout this paper I will be investigating the current limitations of nuclear energy and propose a plan to move forward. I will be considering the societal impacts on technological developments through the SCOT framework.

Methodology

Nuclear energy was a topic of interest, from personal experience I had noticed that the opinions on nuclear energy tended to be strong weather positively or negatively. Originally this paper was going to be an investigation to understand how and why the opinions had become so polarized. However, in stumbling across the Virginia Clean Energy Act (VCEA), this question evolved into investigating the concerns held by those opposed to nuclear energy and determining if it could potentially be an energy solution moving forward. As such, the question this paper seeks to answer became "Is nuclear power generation a viable solution for Virginia to meet the VCEA's goal of providing carbon free nuclear energy?"

In order to gather the subtopics in nuclear energy to analyze I searched though news articles and interviewed Dr. Kory Burns. Dr. Kory Burns is an associate professor in the Materials Science & Engineering department. Dr. Burns has had experience working on the research side for developing materials for nuclear reactors and other irradiated environments, specifically semiconducting materials. Through the news sources and the interview with Dr. Burns, I defined the largest hurdles that face the development of nuclear energy technology to be - public perception, safety concerns, and technological limitations. After defining the hurdles, a literature search and review proceeded.

Starting with public perception, nuclear energy is a concept recognized in many households not for its benefits but for its accident and dangers. It's association with nuclear bombs and large-scale disasters has skewed the negative perception. For this reason, I thought it important to seek out papers that compare the threat to life that has been posed by nuclear energy compared to other energy production technologies. The sources for this section comparatively analyzed the normalized death rate per unit amount of energy produced and the greenhouse gas emissions as well.

With the failure of nuclear reactors having potentially highly dangerous and widespread effects on the surrounding regions the safety considerations become a very important aspect of its design. The paper reviewed concerning the safety of nuclear reactors is focused on pebble bed reactors. These reactors are designed to prevent catastrophic accidents from occurring even in accident prone conditions. The paper goes through the technological developments that pushed forward the possibility of a reactor that can't meltdown or burn.

Finally, the technological limitations of nuclear power technology. Identifying said limitations was mostly based off of an interview with Dr. Kory Burns. In the interview Dr. Kory

Burns said that in his opinion the largest technological limitations for nuclear fission technology were the degradation of the reactor due to the extreme environment created (high pressure, high temperature, and radiation) and the management of the waste products. In this paper the primary focus is on the management of the weapons-grade waste since it ties most closely with the other concerns of safety and public perception. That said the other aspects of waste management are also crucial in proper implementation of nuclear reactors.

The analysis in the results section looks to answer the research question posed; “Is nuclear power generation a viable solution for Virginia to meet the VCEA’s goal of providing carbon free nuclear energy?” This will be done by first addressing the obstacles that stand in the development of nuclear energy technology and then focus on the implementation of said technology to replace the existing system. Throughout this analysis the SCOT framework will be utilized to draw conclusions.

The SCOT framework is a framework that analyzes the relationship between society and technology with an emphasis on societal influences of technological developments (Klein & Kleinman, 2002). There are four key components to the SCOT framework; interpretive flexibility, relevant social groups, closure and stabilization, and wider context. Interpretive flexibility is the idea that the method in which technology develops is open to the influence of various interpretations among varying social groups. Relevant social groups emphasizes the role of social groups with a common interpretation of the technology and the interplay between different social groups. Closure and stabilization is the idea that a technology reaches a “stabilized” form when the disagreement among social groups are all resolved. Finally, wider context includes the broader societal conditions that influence the way in which a technology is developed and adopted.

Literature Review

Public Perception

Nuclear energy has been plagues with a negative public perception since the initial demonstration of its potential – the atom bombs. This public perception was further diminished by large scale accidents, most notably Fukushima, 3 Mile Island, and Chernobyl. Yet, an estimate of the total amount of human deaths caused by nuclear power globally from 1971 through 2009 is 4900 total deaths (Kharecha & Hansen, 2013). Of these 4900 deaths about 25% are attributed to occupational accidents and another 70% are accounted for by air-pollution related effects, presumed to be fatal cancers resulting from radiation fallout. From this 70% only 43 deaths can be conclusively attributed to radiation fallout from a nuclear power plant as reported in the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) – all of which were a result of Chernobyl. The UNSCEAR also reported that of the workers who survived, some even receiving some high doses of radiation, saw no increased adverse health effects when compared to the general population aside from the increased probability of cataracts.

It has been found that nuclear energy is in fact among the safest sources of energy. Currently the worlds leading energy sources are the fossil fuels; coal, oil and gas. When comparing a normalized number of deaths per kWh of energy produced nuclear energy ranks among the lowest as visualized in Figure 4 (Ritchie, 2020). This data accounts for three of the major ways that energy production can have adverse effects on human health and on the environment. The first of these effects is from air pollution, the two main sources being from mining and combustion of fossil fuels specifically. The mining process releases microscopic particles into the air that can be hazardous to human health and have been found to have the potential to kill. The combustion process similarly releases microscopic particles; however, these particles tend to be incompletely combusted fuel and any contaminants the fuel may have had. The combination of these two air pollutants is responsible for the deaths of millions every year. The second effect accounted for is from accidents – most if not all of nuclear energy deaths fall into this category. The types of accidents that are considered in this data include hazards posed by the mining/extraction process of the fuel, transportation of said raw materials, and the infrastructure required for the conversion of raw materials into energy; including but not limited to the power plants and pipelines. The third and final effect considered is a result of greenhouse gas emissions. While it can be a common misconception, this differs from the air pollution in the fact that air pollution is the particulate matter that escapes into the atmosphere while the greenhouse gas emissions are the gas portion as implied by the name.

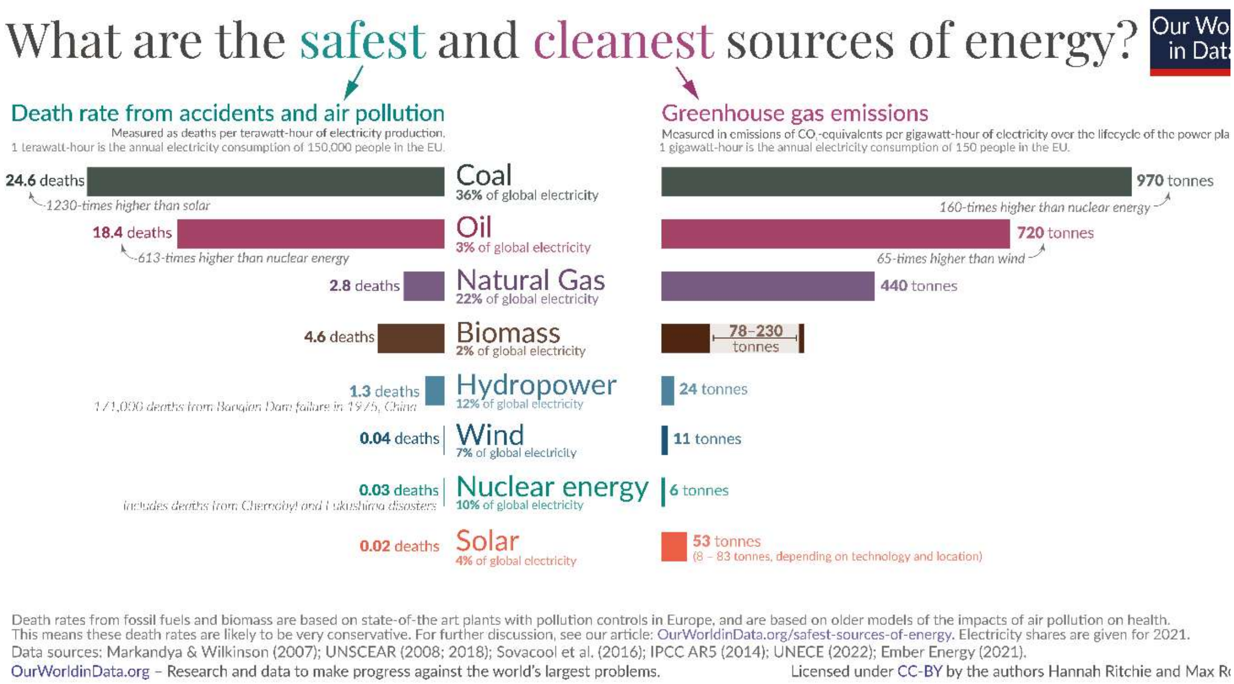

Figure 4: A visualization of various energy sources and their impact on deaths and greenhouse gas emissions (Ritchie, 2020).

From figure 4 it becomes apparent that nuclear is a much safer alternative to many of the common place energy production methods currently used. Being nearly 100 times safer than the safest fossil fuel in terms of deaths per kWh and nearly 10,000 times safer than coal and oil. The prior study that estimated the total amount of deaths by nuclear power production to be 4900 also estimated the total amount of lives saved by the production of nuclear energy during the same time period, 1971 – 2009. Utilizing historical data of power production and maintaining the ratio of types of energy production throughout this time period the same, they found that the implementation of nuclear power as opposed to other more traditional methods of energy production has saved an estimated 1.84 million lives from just the air-pollution related deaths (Kharecha & Hansen, 2013).

Safety

With much of the negative outlooks on nuclear energy being a result of accidents and meltdowns, this signifies the importance of safer reactor designs. This is where pebble bed modular reactors (PBMR) come into play. Pebble bed modular reactors are reactors designed to utilize spherical tennis ball sized fuel pebbles as opposed to the traditional fuel rod design. This design stands out due to the fact that safety lies at the core of it's design, utilizing inherent safety features as opposed to engineered safety features. MIT's design was analyzed and is praised on its safety due to a handful of features; low power density, fuel design, passive helium cooling, and modular build (Kadak, 2005).

Pebble Bed Modular Reactors (PBMRs) are high-temperature gas-cooled reactors that use graphite-coated fuel pebbles containing TRISO particles. Designed for modular deployment, each unit operates independently, which enhances safety by isolating failures. If one module experiences a malfunction, it does not compromise the performance or integrity of others. This modular approach also allows for scalable construction and simplifies emergency response.

A central safety advantage of PBMRs is their low power density, which results in slower temperature increases during accidents. In a complete loss of coolant, it can take 70–80 hours to reach peak temperatures—still below levels that would damage the fuel. Passive heat removal via conduction and radiation is effective even without active cooling systems. The use of helium as a coolant further improves safety, as it is inert, non-flammable, and does not become radioactive.

The TRISO fuel design adds another layer of protection. Each particle has multiple containment layers, particularly a silicon carbide shell that retains fission products. Even assuming a small fraction of defects, releases remain negligible due to the tiny amount of fuel in each particle. While graphite oxidation from air ingress is a concern, the process is slow and not capable of reaching combustion temperatures. The design avoids problematic materials like water or zirconium, reducing risks seen in earlier reactor accidents.

Nonetheless, PBMRs face some safety challenges. Air ingress could still cause gradual graphite degradation, and the system relies heavily on high manufacturing standards for fuel integrity. Additionally, while modularity limits the scale of incidents, coordinating multiple units may pose operational complexity. These factors emphasize the need for rigorous testing and oversight as PBMRs advance toward broader use.

Technological Limitations

Currently the technological limitations can be split into two categories, waste management and degradation. The degradation of materials is a result of nuclear reactors being harsh environments operating with a combination of high temperatures, pressures, and radiation fluxes.

That said, this issue has been constantly addressed and improved on with each new generation of reactors. The other limitation, waste management can be further split into two similar yet very different concerns; enriched fissile materials that has the potential to be used in nuclear bombs, and radioactive waste left over by incomplete use of fuel rods.

Addressing the potential production of weapons-grade materials; the materials required are either the isotope Pu-239 or U-235, both of which would need to be in a high purity state. While these materials are produced in the process of preparing nuclear fuel rods, they would need to be deliberately separated from the other isotopes through a highly specialized process. Additionally, it is reassuring to know that there is currently no commercial nuclear power reactor operating that has in its lifetime been utilized for production of weapons-grade materials aside from the RBMK-type reactor that was designed with a dual purpose and constructed in the Soviet Union (van Leeuwen, 2014). The reason for this is that in order to be economically feasible as a power station the fuel need to have a high percentage of these materials to undergo fission and release their energy as part of the nuclear reaction.

Another approach to this concern while tackling the nuclear waste concern is to fully consume the fuel rods. Currently a large amount of existing nuclear power plants use a once-through fuel cycle which doesn't recycle or reuse spent fuel products. These spent rods are stored in specially designed holding pools or encased in "dry containers" made of radiation blocking materials (Kharecha, Kutscher, Hansen, & Mazria, 2010). However, there has been research into alternative reactors that generate little to no nuclear waste, one example being the Integral Fast Reactor (IFR) which was developed at Argonne National Lab in the 1980s – 1990's. Throughout this development three key features were proven distinguishing it from existing once through fuel cycles. Firstly, it was capable of making highly efficient use of the fuel, generating nearly 100 times more energy from Uranium fuel rods than conventional reactors. Secondly, it's design had passive safety features that prevented the possibility of a meltdown left to its own devices. It also proved to consume essentially all of the weapons grade materials during the fuel cycle preventing any of it making it into the nuclear waste pipeline. It was expected this technology would eventually reach the stage where it would produce zero waste, but the project was shut down by congress at the request of the Clinton administration before it could be realized.

Currently there is also work being done with alternative fuel sources, most notably Thorium. The use of thorium serves two purposes, it prevents the existence of any weapons grade material being present in the nuclear power industry and decreases the radiation half life of nuclear waste products [(Kharecha, Kutscher, Hansen, & Mazria, 2010). Thorium has various additional benefits, for one, thorium is a more abundant element than uranium and exists in higher concentrations. These potential mining locations additionally span the globe including sites in each of the top five energy producing nations. This is an additional benefit in terms of preventing any bottlenecks in the raw material pipeline.

Discussion

The literature and evidence examined in this paper suggest that nuclear energy, especially SMR's, can play an important role in Virginia's decarbonization strategy, aligning with the state's goal of 100% carbon-free energy by 2050. Nuclear power, with its high-capacity factor and low emissions, could significantly complement renewable sources like wind and solar, helping to stabilize the grid and meet decarbonization targets. However, public perception and historical concerns about safety and waste management remain significant challenges. The SCOT framework provides valuable insight into how nuclear energy's acceptance is shaped by both technical features and societal interpretations, which are influenced by historical events and various social groups.

A key finding is that SMRs, with their enhanced safety features and modular design, present a promising pathway for improving public trust in nuclear energy. SCOT emphasizes that public perceptions of technology are shaped by how different social groups (Klein & Kleinman, 2002)—such as policymakers, environmentalists, and local communities—interpret the risks and benefits. Although nuclear power's safety record is strong and its carbon reduction potential significant, the public often perceives nuclear energy through the lens of past accidents like Chernobyl and Fukushima. SMRs, with their passive safety mechanisms and smaller scale, could address these concerns by providing a safer, more flexible solution that aligns with community and environmental expectations.

Another critical issue highlighted in the literature is waste management. While advancements in reactor design reduce operational risks, nuclear waste disposal remains a contentious issue. SCOT helps explain why different groups, particularly environmental and local communities, view nuclear waste as a major challenge. A statewide, government-managed waste management system could provide the necessary infrastructure and transparency to mitigate these concerns. By addressing waste management upfront, Virginia can build the social trust needed to support nuclear energy development.

Additionally, integrating larger-scale reactors like Fast Reactors into existing infrastructure, such as decommissioned gas power plants, could minimize the need for new infrastructure and accelerate the adoption of low-carbon nuclear technology. This approach, discussed in the literature, could reduce costs and enhance grid reliability by leveraging existing sites. This flexibility also reduces public resistance by repurposing already established infrastructure rather than building new plants from scratch.

Finally, public education and engagement are critical to the success of nuclear energy in Virginia. SCOT highlights the importance of framing technology in a way that resonates with societal concerns. Addressing fears about safety, waste, and environmental impact in a transparent and proactive manner will be essential in shifting public opinion. By providing clear, evidence-based information about modern reactor designs and their role in a low-carbon future, Virginia can foster a more informed dialogue about the potential of nuclear energy.

Conclusion

In conclusion, this paper demonstrates that nuclear energy, particularly through Small Modular Reactors and innovative reactor designs, holds significant potential to support Virginia's decarbonization goals. By complementing renewable energy sources and enhancing grid reliability, nuclear power can play a pivotal role in achieving the state's target of 100% carbon-free energy by 2050. However, the successful integration of nuclear energy into Virginia's energy mix will depend not only on technological advancements but also on addressing the public's concerns around safety and waste management. The SCOT framework underscores the importance of public perception and highlights that nuclear energy's acceptance will require effective communication, transparent policy decisions, and a robust infrastructure for waste management.

Looking ahead, the next steps for Virginia—and other regions considering nuclear energy—should include continued research and investment into next-generation nuclear technologies, such as SMRs and Fast Reactors. Additionally, efforts to engage the public, educate them on modern nuclear technologies, and address key concerns will be essential in shifting perceptions and fostering greater social trust. Policymakers must also focus on developing a comprehensive waste management strategy, possibly involving government oversight, to ensure that nuclear energy is a viable and sustainable option in the long term.

Ultimately, while nuclear power is not a one-size-fits-all solution, its role in Virginia's clean energy future cannot be overlooked. The state has the opportunity to be at the forefront of nuclear innovation, building a cleaner, more resilient energy system for future generations.

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