The Social Construction of Nuclear Energy in the United States and its Prospects in Net-Zero Emissions Pathways

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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: Energy Sector Risks to Climate Change

There is unequivocal evidence that Earth is warming at an unprecedented rate, and the scientific consensus is that human activity is the principal cause. The planet's average surface temperature has risen about 2 degrees Fahrenheit since the late 19th century, and the ocean has absorbed much of this increased heat, with the top 100 meters of the ocean having warmed by more than 0.6 degrees Fahrenheit since 1969. Between 1993 and 2019, Greenland and Antarctica lost an average of 279 billion and 148 billion tons of ice per year, respectively, and global sea levels have risen about 8 inches in the last century. Since 1950, the number of record high temperature events has been increasing, while the number of record low temperature events has been decreasing (Shaftel, 2022). Furthermore, the effects of human-caused global warming are only expected to worsen in the decades to come, leading to an increase in the intensity of hurricanes, more frequent droughts and heat waves, a longer wildfire season and more land consumed by wildfires overall, and an ice-free Arctic Ocean before mid-century if current projections hold (Callery, 2022). There is agreement that climate change presents immediate concerns for the global community.

The primary mechanism behind climate change is the greenhouse effect, whereby the release of aptly named greenhouse gases (GHGs) like carbon dioxide, methane, and nitrous oxide into the atmosphere creates an insulating layer which traps the sun's heat and causes global temperatures to rise (European Commission, 2021). The energy sector is responsible for approximately two thirds of global CO_2 emissions, representing by far the largest source of greenhouse gas emissions in the world with fossil fuels being the primary contributor (European Environmental Agency, 2021). Within the energy sector, burning fossil fuels like oil, coal, and natural gas generates 84.3% of global primary energy and is therefore a massive contributor to climate change; for comparison, nuclear energy accounts for 4.3% of global production, and only 11.4% of global energy demand is met by renewable sources like hydropower, wind, and solar (Ritchie et al., 2020). Without significant changes to the global energy mix, the effects of climate change will only become more severe and widespread. Global warming of 2 ºC above the pre-industrial average was established by the Paris Agreement in 2015 as the upper limit to prevent "large and escalating risks to human life as we know it on Earth" (Fendt, 2021). However, with global energy demand expected to double by 2050, current climate forecasts built assuming the current trajectory of the energy production landscape continues predict warming even above the 2 ºC upper limit (UNECE). It is clear from these projections that decarbonization efforts must not only be maintained but rather further accelerated, and due to its overwhelming contribution to GHG emissions, the energy sector has been widely identified as the priority for these efforts.

Deep decarbonization of the energy sector will require rapid investment in low-carbon alternatives to fossil fuels as the global community's reliance on coal, oil, and natural gas diminishes. Nuclear energy has emerged in recent years as one candidate technology to facilitate the curtailment of fossil fuels, being safer than fossil fuels without the weather-dependent variability or large land requirement of many renewables and all without producing any GHG emissions during operation. However, despite these seemingly apparent advantages over alternative energy sources, nuclear technology has not been widely adopted by the United States nor the global community at large. This thesis will assess the influence of print media coverage of nuclear disasters on the low level of adoption of nuclear energy in the United States through the framework of the social construction of technology.

Case Context: Nuclear Energy and Trends in its Historical Adoption in the United States

A single nuclear reactor produces enough energy to power 100 million LED light bulbs, equivalent to the production of more than three million photovoltaic panels, all while producing one-third of the emissions per unit of electricity as solar energy sources (U.S. Office of Nuclear Energy, 2021). Indeed, in 2021, the United States avoided more than 476 million metric tons of carbon dioxide emissions—equivalent to the yearly emissions of more than 100 million cars—by producing clean energy from nuclear power plants across the country (Nuclear Energy Institute, 2022). Historical utilization of nuclear power in the U.S. has cumulatively prevented more than 20 gigatonnes of CO_2-equivalent GHG emissions which equates to more than triple the total emissions from the U.S. in 2021 (Kharecha & Hansen, 2013). Another advantage of nuclear energy is its incredible reliability. In 2020, nuclear power plants operated at their maximum capacity more than any other energy source with nuclear producing maximum power for 92.5% of the year as compared to 56.6% for natural gas, 35.4% for wind, and 24.9% for solar (U.S. Energy Information Administration, 2023).

Nuclear energy is also much safer than fossil fuels: Whereas a few nuclear disasters have produced a strong negative perception of the safety of nuclear energy, the air pollution generated from the burning of fossil fuels and the resulting millions of premature deaths from heart ailments, lung disease, and cancer make fossil fuels the much deadlier option. In fact, nuclear energy causes only 0.03 deaths per terawatt-hour of electricity generated compared to 32.72 for brown coal, 26.42 for coal, and 18.43 for oil, making nuclear at least 99.7% safer than fossil fuel alternatives (Ritchie, 2020). However, despite nuclear energy's ability to reliably generate dispatchable, clean, and safe energy on a large scale, only 92 commercial reactors currently operate in the United States, accounting for just 18.9% of U.S. energy production today (U.S. Office of Nuclear Energy, 2022).

The generation of commercial nuclear power in the United States began in 1958 with the opening of the Shippingport Atomic Power Station as part of President Eisenhower's Atoms for Peace program which aimed to promote the peaceful use of nuclear energy worldwide. Shippingport broadened opportunities for atomic research and paved the way for new nuclear plant construction (Duke Energy, 2012). During the 1960s, nuclear power achieved the status of a technically proven and commercially viable energy source, and electric power utilities began placing orders on a routine basis (Char & Csik, 1987). By 1966, U.S. utilities had ordered 40 reactors with an aggregate electric capacity of 25.5 GW (U.S. Energy Information Administration, 1991), larger than that of all orders for coal and oil-fired plants at that time (International Atomic Energy Agency, 2004). In 1967, the Atomic Energy Commission (AEC) anticipated that more than 1,000 nuclear plants would be operating in the United States by the year 2000 (Cohn, 1997), and from 1967–1974 utilities ordered an additional 196 nuclear reactors, appearing to confirm the AEC's projection. However, by the end of the 1970s, it had become clear that nuclear energy would not experience nearly the growth projected.

Nuclear adoption began to slow in the late 1970s as inflation and rising energy costs depressed electricity demand growth and new regulations were introduced, resulting in high construction costs. The National Environmental Policy Act of 1969 established new requirements, notably an environmental impact statement, and created the Environmental Protection Agency (EPA) and Council on Environmental Quality. These events, in combination with the growing environmentalism movement, ultimately increased the numbers, opportunities, and credibility of nuclear opponents. These mainly environmentalist nuclear opponents prolonged licensing and construction times, complicating financing, delaying cost recovery, and escalating capital costs for building reactors (International Atomic Energy Agency, 2004). Whereas unit costs for technology typically decrease with volume of production due to scale factors and technological learning, the case of nuclear power has been seen largely as an exception that reflects the idiosyncrasies of the regulatory environment as public opposition grew, regulations were tightened, and construction times increased (Hultman et al., 2007). For these reasons, more than 70% of all nuclear reactors ordered from 1970–1978 were eventually cancelled, and seven others (4.5%) were either rejected by New York State in 1980, indefinitely deferred, or completed but not operational. All 41 reactors ordered from 1974–1978 were cancelled or rejected (U.S. Department of Energy, 1991), as shown in Figure 1.

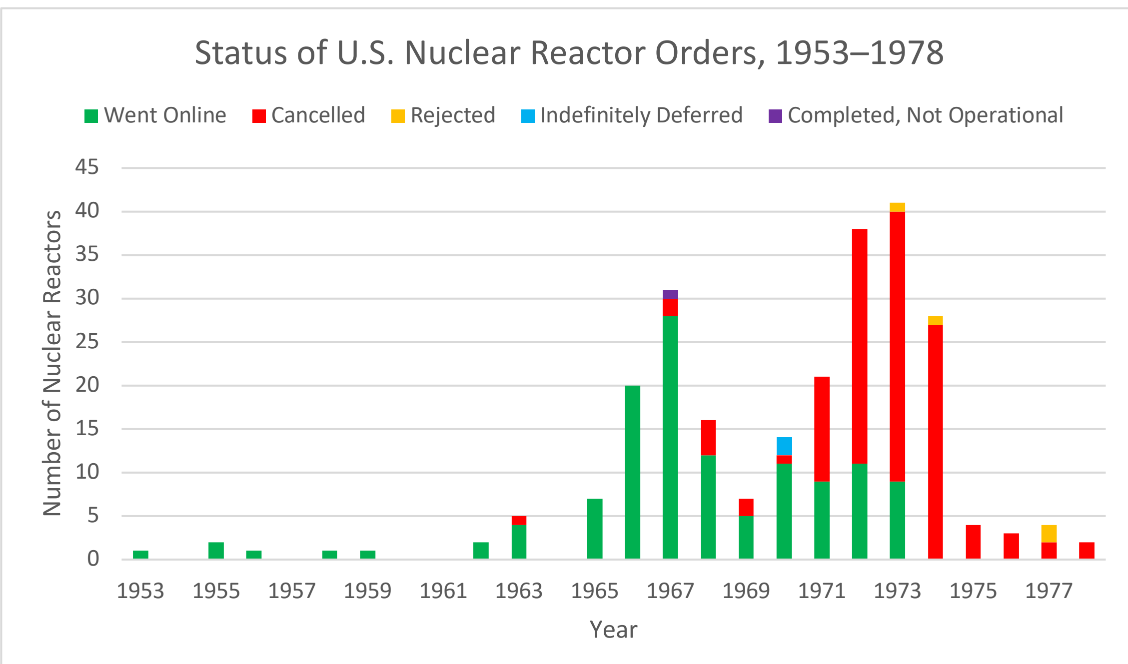

Figure 1. The status of nuclear reactors ordered in the United States from 1953 to 1978 (U.S. Department of Energy, 1991).

The Nuclear Regulatory Commission (NRC) did not issue a new combined license (COL) to construct a nuclear reactor until 2012 (U.S. Department of Energy, 2011; U.S. Nuclear Regulatory Commission, 2022a). As of April 2023, there are five licensees with COLs for eight new reactor units, two of which are to be placed into service in the coming months (U.S. Nuclear Regulatory Commission, 2022b; Clark, 2023).

Applying the Social Construction of Technology to Study Current Trends in Nuclear Adoption in the United States

The adoption of nuclear energy in the United States depends upon its perception by those with the power to effect change within the U.S. energy sector, whether it be directly through policy or innovation or by indirect means such as public demonstrations and the election of representatives. In this paper, I employ the framework of the Social Construction of Technology (SCOT) to assess the perceptions of various energy sector and nuclear power stakeholders, describe the mechanisms underlying their interactions with one another, and characterize the influence of these perceptions and interactions on current trends in nuclear adoption in the U.S. The basis of the SCOT approach was developed by Trevor J. Pinch and Wiebe Bijker in 1987 through their pioneering book titled *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*. The thirteen essays in the book, taken together, affirm the fruitfulness of an approach to the study of technology that gives equal weight to technical, social, economic, and political questions and can be understood as a concerted effort to disprove the idea that technology is deterministic.

The SCOT approach provides a theoretical framework for explaining technological development as a social process. It contends that technology is not developed in isolation but rather as part of a much broader socio-technical system which includes various social groups, each with distinct values, interests, and influence, who uniquely ascribe meaning to technology. Here, the essential delineation between social groups is that all members of a certain group share the same set of meanings attached to a particular technology. Generating a social constructivist account of a technology relies upon a multidirectional model in which development occurs through the alternation of variation and selection. Both phenomena are driven by the concept of interpretive flexibility which allows for the construction of alternative interpretations of a technology by various social groups. These differing interpretations of a technology then create various problems to be solved and distinct prioritizations of tradeoffs in the features of solutions to those problems by each social group. The selection of features in solution designs is facilitated by the networks of communication and exchange inherent in socio-technical systems. The SCOT methodology lastly details two primary mechanisms through which interpretive flexibility may collapse as technologies are developed: rhetorical closure and closure by redefinition of the problem. Rhetorical closure refers to relevant social groups perceiving their problem as being solved, whereas closure by redefinition of the problem is achieved when the meaning of a technology is translated to constitute a solution to another problem (Pinch & Bijker, 1987).

Applying the SCOT framework to the adoption of nuclear power in the United States, I demonstrate the interpretive flexibility of nuclear energy as a socio-technical system by identifying four relevant social groups: (1) Nuclear industry professionals, (2) elected policymakers, (3), journalists and media analysts, and (4) anti-nuclear activists. It may be impossible to homogenize the meanings ascribed to nuclear technology for each of these social groups in a country as diverse and individualistic as the U.S., so I make several generalizing assumptions for the purpose of their descriptions.

Industry professionals and anti-nuclear activists hold nearly opposite interpretations of nuclear energy: For one, it represents their livelihood and perhaps even the future of renewable energy, and for the other, a destructive force capable of environmental damages and ending lives. However, whether it be for economic, political, or moral reasons, the two groups share a value for the safety of the general public. For policymakers, the nuclear industry is yet another divisive issue to contend with, and whichever political position they adopt must both be popular enough to be reelected and best fulfill the needs of their constituents; these pursuits are not always aligned. The media may perceive two conflicting duties with respect to nuclear energy. The apparent obligation is that of accurately representing the full extent of available information, although profit-driven incentives may instead encourage the publication of news which simply achieves the widest reach.

Many of the solutions to the identified problems of these social groups directly oppose one another. An ideal solution for nuclear industry professionals points in the direction of less stringent regulations, fewer decommissioned plants, and the issuance of new COLs. For anti-nuclear activists, it is the opposite. Similarly, elected officials seeking to appeal to a broad base may favor nuclear development which decreases controversy surrounding the issue, whereas journalists would benefit from heightened controversy bringing more eyes to their coverage of the issue. Therefore, with the debate over the future of the technology still very much alive, no form of closure has yet been reached for nuclear energy.

Research Question and Methods

This research addresses the following question: What are the root causes of the low level of nuclear energy adoption in the United States, and how does its perception by relevant social groups limit its prospects for future investment despite being a low-carbon, load-balancing energy source? To perform this analysis, I review current U.S. emissions reduction commitments and efforts to achieve those targets through energy policy. I then compare projections for the energy sector which stem from current energy policies to the 2050 energy mixes projected in decarbonization pathway studies conducted by the Breakthrough Institute, Princeton University, Vibrant Clean Energy, and Williams et al. (2021) to find discrepancies between current trends in nuclear energy adoption and those needed to achieve net-zero emissions by 2050. Lastly, I review several studies which identify barriers to increased nuclear energy deployment and apply the SCOT framework to demonstrate the emergence of a reinforcing loop through which nuclear energy is perceived as an unattractive investment by relevant social groups.

Results

Analysis of the United States' energy policy and stated climate goals reveals a strong commitment to decarbonization in pursuit of mitigating the effects of climate change in the coming decades. Importantly, however, these policies do not proportionately prioritize future investment in all low-carbon alternatives in accordance with several studies which model the most cost-efficient energy transition pathways. The Biden administration has pledged to achieve a 50-52% reduction from 2005 levels in economy-wide net GHG pollution by 2030, an ambitious target in line with the goals of the Paris Agreement and significantly higher than the previous U.S. pledge to cut emissions 26-28% by 2025 (World Resources Institute, 2022). This target builds upon Biden's existing goals to create a carbon pollution-free power sector by 2035 and a net-zero emissions economy by 2050 (The White House, 2021). In pursuit of these goals, President Biden signed into law the Inflation Reduction Act (IRA) in 2022 which is estimated to accelerate the decline in U.S. GHG emissions to 26-42% below 2005 levels, assuming no further policies are implemented (Climate Action Tracker, 2022). Another legislative gain for decarbonization efforts came with the Infrastructure Investment and Jobs Act in 2021 which realizes incremental progress in emissions reduction and technological advancement in some sectors (Higman et al., 2021).

Whereas these policies as well as regulatory pressure being imposed by the EPA (Storrow, 2022) help facilitate an expected more than 247% increase in electricity generation from renewables like solar, wind, and hydropower by 2050, nuclear electricity generation is expected to decline by at least 19% in the same period; this stems from the loss of 21.1 GWe of generating capacity from projected plant retirements (U.S. Energy Information Administration, 2023). Moreover, this projected decline in nuclear capacity to 75.9 GWe by 2050 significantly diverges from the levels modeled by the most cost-efficient net-zero energy pathways in prominent decarbonization studies. By 2050, the Breakthrough Institute's *Advancing Nuclear Energy* report (Stein et al., 2022) finds that the U.S. power grid will operate between 247 and 489 GWe of installed capacity of advanced and conventional nuclear reactors across four scenarios of varying initial costs and learning rates. Models that permit advanced nuclear construction in Vibrant Clean Energy's *Zero by Fifty* report (2022) similarly anticipate between 293 and 473 GWe of nuclear capacity. In both studies, the deployment of advanced nuclear reactors forms part of a least-cost pathway to a decarbonized power sector, and total electricity system costs decrease over time relative to initial 2020 system costs in scenarios which include advanced nuclear (Figure 2).

Other net-zero studies such as Princeton University's *Net-Zero America* (Larson et al., 2021) and Williams et al.'s "Carbon-Neutral Pathways for the United States" (2021) only consider traditional nuclear power plants as an option for new generating capacity, and their models therefore only build new nuclear capacity when costs are competitive with renewables. In scenarios where renewable capacity is limited by land or deployment rate constraints and new nuclear construction therefore becomes economical, the Princeton NZA and Williams et al. (2021) studies project 310 GWe and 150 GWe of nationwide installed nuclear capacity, respectively. In both studies, the scenarios which prohibit new nuclear power plants lead to higher total system costs and nationwide land use, demonstrating the valuable role of traditional nuclear energy in energy system optimization even at present-day costs (Figure 2).

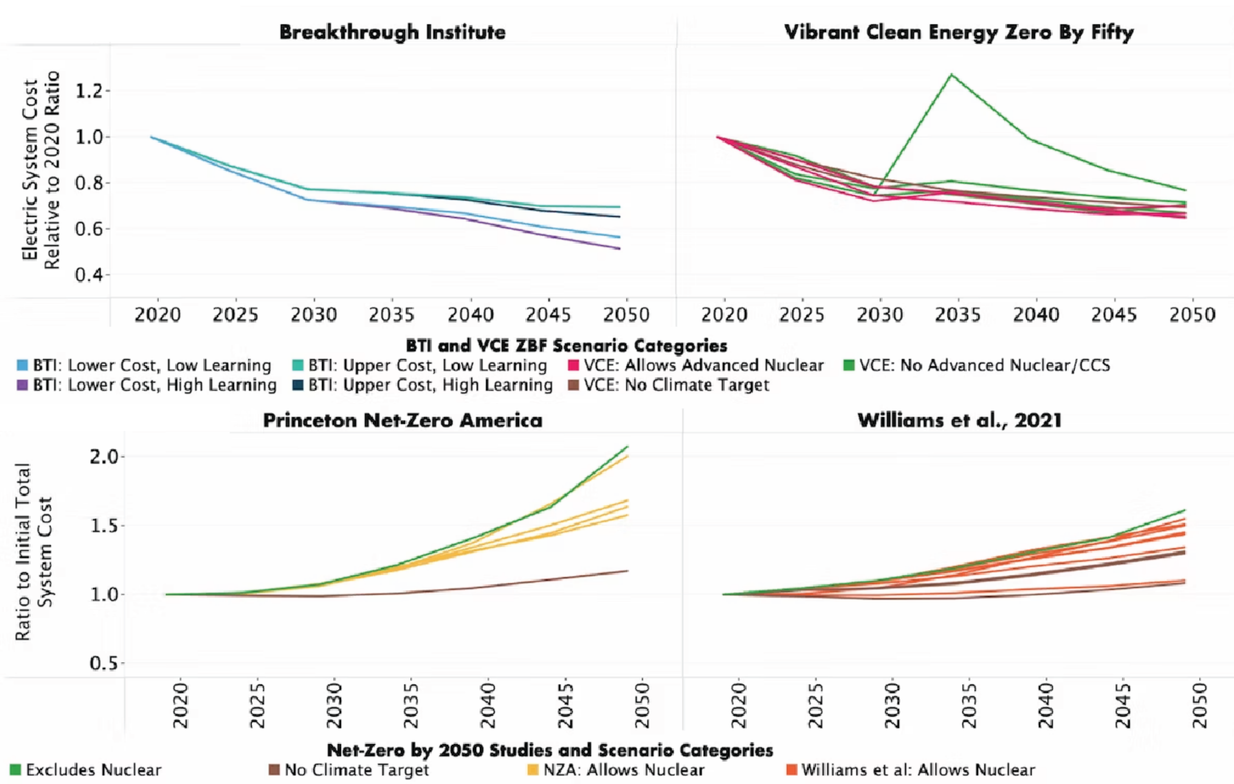

Figure 2. Trends in power system costs relative to the initial 2020 power system cost for the Breakthrough Institute and Vibrant Clean Energy studies (top) and trends in energy and industrial system costs relative to 2020 initial system costs for Princeton NZA and Williams et al. (2021) studies (bottom).

Therefore, the combination of assessment of U.S. energy and climate initiatives and comparison of future energy sector projections with net-zero emissions pathways reveals that the current low and decreasing adoption of nuclear energy does not stem from a lack of prioritization of low-carbon initiatives as a whole nor from the merits and capabilities of nuclear technology itself but rather from other factors unique to the nuclear industry and the social groups who shape its development.

While the primary force hindering nuclear development appears to have shifted from environmental opposition in the 1980s and 1990s to concerns over high capital costs in recent years, recognizing that nuclear energy forms only part of a larger socio-technical system through a SCOT analysis illuminates underlying factors which better explain its current positioning. The contribution of nuclear energy to reliable, cost-efficient decarbonization pathways relies upon its ability to compete in the energy marketplace and the development of advanced nuclear reactors, and, indeed, it has been costs which have most directly impeded these pursuits in the past decade. Vogtle 3 and 4, the two conventional reactors being added to Plant Vogtle in Waynesboro, Georgia, have more than twice exceeded their initial four-year construction time and overrun their budget by more than $4 billion (Lorenczik et al., 2020). These cost overruns are especially harmful for new nuclear plants as capital costs account for at least 60% of their levelized cost of energy (World Nuclear Association, 2017). The first NRC-approved small modular reactor (SMR) project has encountered similar challenges, announcing delays until 2030 and cost hikes from $4.2 billion to $6.1 billion. Eight of the 36 public utilities involved in the project have subsequently withdrawn, citing costs (Cho, 2020).

Several factors have established a reinforcing loop in which the perception of nuclear energy by a few social groups influences the interpretation of other groups and further entrenches their views, ultimately limiting the economic feasibility of new nuclear deployment in the U.S. The first factor is a lack of technical learning which stems from the more than 30-year moratorium on new nuclear reactor construction from 1978–2013. Researchers at MIT analyzed cost drivers for new nuclear plants and concluded that improved construction approaches and the development of a proven supply chain and skilled workforce are essential in reducing capital costs and shortening construction schedules. A lack of time-tested construction management practices and resources decreases site productivity and makes the need for rework more likely, introducing delays and costly accruals of interest (Buongiorno et al., 2019). Indeed, South Korea employed a strategy of building multiple reactor units per site using a standardized design so as to maximize learning for process improvement and saw overnight construction costs fall 50% as they added 28 new reactors between 1971 and 2008 (Lovering et al., 2016). Through the lens of the SCOT framework, nuclear industry professionals become a prominent social group responsible for shaping outcomes of nuclear projects and therefore the outlook of the technology in the U.S. Unsuccessful construction projects covered by the media in turn strengthen the arguments of anti-nuclear activists, further dividing voter bases and making it difficult for policymakers to advocate for nuclear adoption. The application of the SCOT methodology to the issue of nuclear energy is further elaborated in Figure 3.

Additionally, a lack of energy policies which fully remunerate nuclear energy for its low-carbon, load-balancing energy hinders its ability to compete in deregulated electricity markets and therefore attract investment. In deregulated energy markets, price alone wins, and the contribution of nuclear energy to cost-efficient decarbonization pathways is not recognized (Clifford, 2022). Subsidies from the IRA are not sufficient to change the economics of nuclear power and enable it to compete in energy markets (Kemp & Van Doren, 2022). Here, SCOT analysis emphasizes the direct contribution of policymakers to the outlook of U.S. nuclear energy adoption (Figure 3) which itself stems from divided views on nuclear energy (Leppert, 2022). The economic prospect of nuclear energy is therefore diminished as capital costs remain high from inexperienced construction management and investors are unable to profit from the full value nuclear supplies to the grid, which consequently discourages investment, reduces funding, and limits innovation and opportunities for technical learning.

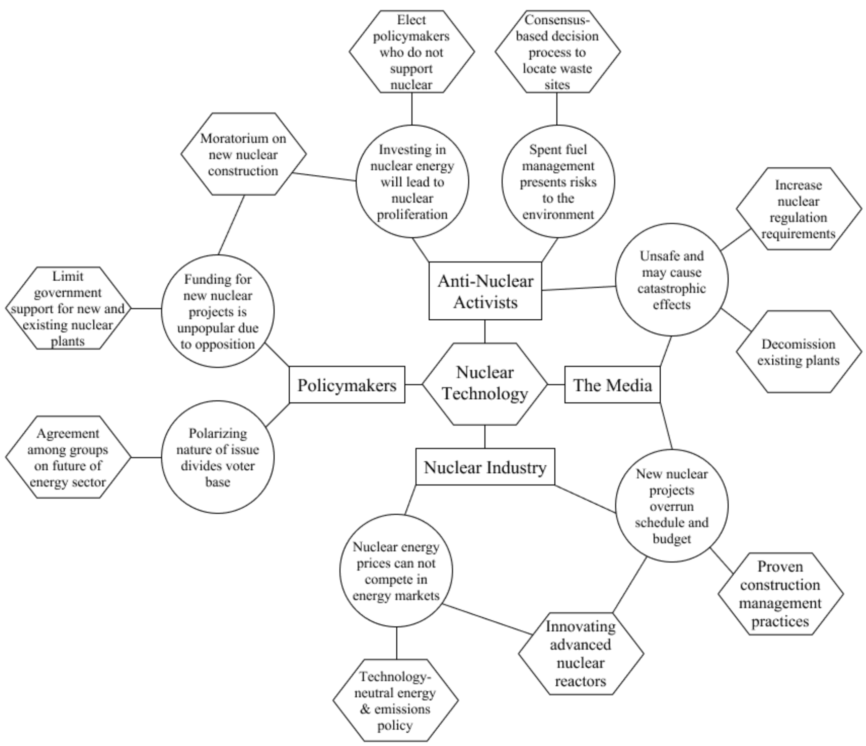

Figure 3. A spoke-and-wheel diagram detailing the relationship between a technological artifact (central hexagon), the relevant social groups (squares), the problems they perceive with the technology (circles), and possible solutions to the problems (exterior hexagons).

Discussion

This research and similar studies examining trends in historical adoption of nuclear and assessing its prospects in future energy pathways are part of a larger conversation on finding economical solutions to climate change and reaching carbon mitigation goals. While here I have focused on the role of nuclear energy in achieving net-zero emissions by 2050, other studies find similar efficacy in the expansion of carbon capture, utilization, and storage (CCUS), grid-scale battery storage in combination with renewables, or all of the above. In a report for the Institute for Energy and Environmental Research, Makhijani (2016) details a climate protection scenario incorporating solar and wind energy and battery storage in Maryland which decreases energy system costs relative to a business-as-usual case with fossil fuels. Akashi et al. (2013) find that the cost of achieving emissions reduction targets increases if carbon capture and storage is limited. De Sisternes et al. (2016) conclude that energy storage delivers value by increasing the cost-effective penetration of renewable energy. Sepulveda et al. (2018) indicate that availability of firm low-carbon technologies, including nuclear, natural gas with carbon capture and sequestration, and bioenergy, reduces electricity costs by 10%–62% across fully decarbonized cases.

This study does not address the influence of concerns over spent nuclear fuel or nuclear proliferation on the different interpretations of nuclear energy by the various social groups which shape its adoption. Both issues are universally considered barriers to the expansion of nuclear energy use. While there exist robust technical solutions for spent fuel management like interim storage in dry casks and permanent dispose in geological repositories, the political dimensions of siting such facilities are less easily resolved. Similar political resistance to further development of nuclear energy stems from the perception that it provides a path to gaining nuclear weapons materials or capability. As demonstrated in Figure 3, these two concerns are some of the primary problems perceived with nuclear energy by anti-nuclear activists. The SCOT framework explains the relationship between these problems and those identified by other relevant social groups—such as opposition which restrains legislative action by policymakers—which ultimately determines the multidirectional development of nuclear energy as a socio-technical system. Additionally, this study does not specifically examine factors related to funding or regulations which enable or hinder innovation in advanced nuclear reactor technology. Future studies should therefore assess the feasibility of implementing a well-managed, consensus-based decision process to locate nuclear waste sites in the U.S., quantify risks of nuclear proliferation posed by increased nuclear energy adoption, and characterize the relationship between funding and regulatory mechanisms and the rate of innovation in reactor designs.

As the SCOT framework outlines, technological development is not deterministic but rather constructed through ongoing negations and interactions between stakeholders. Relevant social groups such as nuclear industry professionals, policymakers, the media, and anti-nuclear activists have certainly altered the trajectory of nuclear energy adoption in the U.S. through their alternative interpretations of the technology. As each group defines different problems with nuclear energy according to their own unique values and interests and distinct sets of possible solutions arise, nuclear energy is pushed and pulled in different directions until the discord between each group's ideas is resolved. While consensus has not been reached on the best approach to decarbonization, whether it be via nuclear energy or another technology, the urgent need to transition the energy sector nevertheless remains and should inform the practice of engineers going forward. Engineers, as one of many social groups within larger socio-technical systems such as that which shapes the development of the energy sector, must recognize their potential to both directly and indirectly affect technological outcomes. In the case of the energy sector, engineers must realize their ability to effect change which brings the United States and the global community closer to decarbonization goals in pursuit of mitigating the escalating effects of climate change.

Conclusion

While the United States has announced a commitment to achieving net-zero emissions in the coming decades, the role of nuclear energy in facilitating the deep decarbonization of the energy sector has remained unrecognized. This SCOT analysis illuminates several underlying factors which harm the economic prospect of new nuclear construction and explain its expected decline in future years. However, investigation of the root causes of cost escalation and construction delays in recent nuclear projects reveals several recommendations needed to reverse this trend. First, nuclear industry professionals must adopt time-tested construction management practices, including the use of a proven supply chain and skilled workforce and a single primary contract manager with proven expertise, to increase the probability that projects are delivered on time and within budget. Next, taking after the South Korean model which maximizes technical learning, the industry should shift away from field construction of complex, site-dependent plants to serial manufacturing of standardized designs. Lastly, new legislation is necessary to allow nuclear energy to be fully compensated for its valuable contributions to cost-effective decarbonization pathways and therefore compete on the full extent of its merits in energy markets.

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