The Viability of Nuclear Power as an Alternative to Renewables for Clean Energy for Climate Change Mitigation

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Introduction

The need for sustainable, non-carbon power sources has never been greater. Climate change is an accelerating global crisis. It cannot be effectively addressed without cleaner energy sources that displace the use of fossil fuels. Energy from renewable sources, such as solar, wind, geothermal, hydro, and biomass provides communities and electric utilities with “green” energy, i.e.: zero-emissions energy coming from sustainable sources. Renewable energy capacity has been growing significantly in recent years, with an increase of 10% globally in 2020 alone, or approximately 107 Gigawatts (GW), bringing total global capacity to 1398 GW [1]. In the United States, renewable energy will account for almost 70% of new generating capacity in 2021, with installed capacity of 284.6 GW providing 23.4% of the electricity [2].

At the same time, renewables have several problems with their widespread deployment [3]. They are dependent on the right conditions for harvesting energy (e.g., the wind must be blowing, or the sun must be shining), which means that renewables are variable (i.e., intermittent) energy sources. Thus, they require either some storage capacity or else a baseload power source to cover energy demands when they are not available. Energy storage via batteries have environmental costs, as do renewable power technologies (e.g., wind turbines, photovoltaic panels, geothermal piping, etc.) themselves. Batteries require significant amounts of metals and non-metals, which often have to be mined in remote or constrained areas [4]. The lifecycle costs of solar power is actually slightly higher than the life cycle costs of nuclear power, while wind power is slightly less [5].

Renewable energy requires significant other resources, as well. For instance wind and solar farms take a significant amount of land [3]. A study led by Pimentel estimated that renewables could provide almost 50% of US energy needs, but this would require approximately 17% of the nation’s land area [6]. A more recent study showed that for solar energy to provide one-third of US energy needs, it would take approximately 10,000 square kilometers of real estate [7], approximately 2 times the size of Delaware or 83% the size of Connecticut [8]. Providing the same amount of energy from wind power would require the allocation of approximately 66,000 square kilometers of land [7], slightly more than the area of New Hampshire, Vermont, and Massachusetts combined [8]. With both of these sources providing this energy, they would still only provide 2/3 of the energy needs of the United States. There would remain another 1/3 of energy to produce. This real estate is not readily available. The best land for renewable power is not necessarily in remote “uninhabited” locations. Solar power, for instance, is best located in southern latitudes with plenty of direct sunlight. However, these parts of the US are also populated. Displacing people for renewable energy installations is likely to be unacceptable. In addition to disrupting human habitat and agricultural areas, significant renewable energy installations are likely to disrupt wildlife habitat, potentially leading to greater human vulnerability through disease.[1] As mentioned above, mining metals and non-metals have additional impacts on land [4].

The final concern with renewable energy is the cost [3]. Evidence suggests that renewables are increasing the price of electricity. For example, electricity prices in California rose by 28% between 2011 and 2018, seven times more than the national average of 5%. Electricity prices in Germany have risen by 50% since 2006, largely as a result of the adoption of renewable energy [10]. In some states in the US, such as Ohio, legislatures are looking to nuclear power as an alternative to renewables [10]. In many countries, the deployment of renewables has been aided by subsidies that have lowered costs to utilities and customers. Though the costs are decreasing, there are concerns that the deployment of renewable energy may stall as governments announce ends to subsidies. For instance, China has announced that renewables will have to openly compete with fossil fuels in the energy market [11]. In the US, subsidies are due to expire at the end of 2021, though renewal is possible [10].

Though not strictly a renewable energy, nuclear power is akin to renewables in its ability to provide energy without greenhouse gas emissions. It can provide emissions-free, clean baseload energy [12]. However, nuclear power has many issues that make it questionable as a sustainable energy source. Innovation has the potential to solve many of the problems with nuclear power. However, it is unclear whether these innovations can be developed and implemented within the next twenty years, when significant progress towards a zero-carbon energy grid is essential in order to escape the direst impacts of rapid climate change.

This chapter examines nuclear technology innovation and industry regulation in order to understand the difficulties of relying on nuclear power as a meaningful alternative to renewable power deployment. It considers the current status of nuclear energy innovations and the extent to which the progress and obstacles for nuclear power supports including it as a viable alternative, or supplement, to renewable energy. We extend this introduction by providing an overview of current challenges within the nuclear energy sector and briefly surveying nuclear reactor designs and innovations. Then, we discuss the process of nuclear design and development within the US, with an emphasis on the role of the NRC. The results of an empirical study on discussions by the NRC on Gen III and Gen IV reactors are presented. Finally, we discuss the implications for the urgent need to address climate

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[1] For example, the loss of wildlife habitat is one of the concerns around the creation and spread of new diseases, such as the novel Coronavirus (i.e., Covid-19) 9. Gosalvez, E. *How Habitat Destruction Enables the Spread of Diseases Like COVID-19, North Carolina State College of Natural Resource News, April 22, 2020*. 2020 March 9, 2021]; Available from: https://cnr.ncsu.edu/news/2020/04/habitat-destruction-covid19/..

change.

Nuclear Power

Nuclear power has been an important source of energy for the past 50 years. Nuclear power currently provides a significant portion of the electricity in many countries: 71% in France, 48% in Belgium, 34% in Sweden, 49% in Hungary, 26% in South Korea, 20% in the United States, 20% in Russia, 16% in the United Kingdom, and 15% in Canada [13]. Nuclear reactors in the US currently provide 50% of the carbon-free energy [14].

Nuclear reactors are generally classified into four types. The first is Generation I (Gen I), which were the prototypes and reactors originally developed in the 1950s and 1960s. Gen II reactors are the reactors currently deployed and operating around the world. They were designed and built in the 1960s through the 1990s [15]. Gen III reactors are enhanced Gen II reactors, with greater thermal efficiency, modularized construction, and improved safety systems (Goldberg and Rosner, 2011). They were developed in the 1990s to have standardized, simpler designs, passive safety features, greater fuel efficiency to reduce refueling and spent fuel, and a longer design life [16]. Gen III+ reactors are Gen III reactors with enhanced safety and smaller production capacity able to be sequenced and combined (called Small Modular Reactors). These are the most advanced reactors currently being deployed for large scale production [17].

Gen IV Reactors are the next iteration of advanced nuclear reactors[18].[2] Nuclear power capacity has been increasing, with approximately 50 reactors currently under construction [19]. Most of this expansion is occurring in Asia and Russia. Many of the existing reactors in the US and those in other developed countries such as the UK, Canada, and France, are reaching the limits of their operating lives and will need to be replaced with some form of energy production. Most of the retiring nuclear power plants in the US are typically replaced with energy produced by either coal or natural gas [20]. Significant capacity is being created by extending the life of nuclear plants and increasing their capacity through changes to the thermal cycle, called uprates. In the US, the Nuclear Regulatory Commission (NRC), the federal regulator, has approved 165 uprates since 1977, yielding in an increased capacity of 7500 MWe [19].

New nuclear reactor designs are proposed to be much safer, without the long-term legacy problems of radioactive waste [21-23]. However, most of these reactor designs are still in early phases of development. While the People's Republic of China and Russia are developing and constructing new nuclear reactors, other jurisdictions such as the US, Canada, and the EU struggle with their nuclear policies and developing new nuclear technologies.

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2 All the reactor designs discussed in this chapter are fission reactors. Deriving usable energy from controlled fusion processes (combining two atoms of Hydrogen to create one Helium atom) is still at an experimental stage, with any potential commercial deployment estimated to be at least several decades in the future.

Nuclear power remains a contentious source of energy. The problems of nuclear power are well-documented. Light water reactor technologies—by far the most common reactors operating today—have inherent problems that have proven difficult to solve, including safety, waste management, and cost overruns. They also face significant public backlash due to these problems. The nuclear industry itself is burdened with cost overruns, safety concerns, and waste management problems [24].

Meltdowns and accidents are a major public concern about the nuclear power industry. In 1990, the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) jointly developed the International Nuclear and Radiological Event Scale (INES), which was designed to consistently identify nuclear and radiological events [25]. The INES scale goes from Level 1 (for Anomalies) to Level 7 (Major Accidents). The global nuclear industry has experienced two Level 7 events since 1970: The meltdown and explosion at Chernobyl in the Ukraine in 1986 and the tsunami-induced meltdown at the Fukushima-Daiichi power plant in March 2011 [26]. The accident that occurred in 1979 at the Three Mile Island power plant resulting in the partial meltdown of one of its reactors was rated at a Level 5 [27]. This incident marked a major turning point in public perception of nuclear safety in the United States [28]. These accidents demonstrate that meltdowns, and the corresponding social, environmental, political, and economic impacts, are both possible and substantial [29]. However, nuclear power generation also has a strong safety record over its history of operations, with the lowest deaths from energy-related accidents per unit of energy produced of any source of energy, including wind power and solar energy [30].

Nuclear power plants are far more complex than conventional fossil fuel plants. Where a typical fossil fuel plant has roughly 4,000 valves and 5,000 pipe supports, a typical nuclear plant might have 10 times the number of valves, and 4 or 5 times the number of pipe supports [31]. This complexity is one of the things that makes nuclear power plants riskier and in greater need of inherent system-wide safety [32]. Complex systems are more likely to be brittle and susceptible to failures and problems [33].

Table 1: Costs of Electricity Generation by Source in the United States (in 2016$)[3]

Source	Average Size (MW)	Construction Cost	Baseline Construction Costs	Variable Operating Costs	Fixed Operating & Maintenance costs	Levelized[4] Electricity Cost per	Baseline Construction Costs for 2000 MW

[3] From 34. U.S. Energy Information Administration. *Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2017* 2017 December 30, 2017]; Available from: https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf. and 35. U.S. Energy Information Administration. *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2017*. 2016 December 30, 2017]; Available from: https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

[4] Levelized Cost of Electricity is the total costs over the lifetime of the power plant divided by the total electrical energy produced over that lifetime.

		(per kW)	(in $000)	(per MW hour)	(per kW/year)	MW hour	Plant (in $000)
Natural Gas	702	$969	$680,238	3.48	10.93	$140.00	$1,938,000
Wind	100	$1,686	$168,600	0	46.71	$57.50	$3,372,000
Solar Photovoltaic	100	$2,277	$227,700	0	21.66	$99.10	$4,554,000
Coal with 30% Carbon Sequestration	650	$5,030	$3,269,500	7.06	69.56	$52.20	$10,060,000
Advanced Nuclear	2,234	$5,880	$13,135,920	2.29	99.65	$66.80	$11,760,000
Hydropower	500	$2,442	$1,221,000	2.66	14.93	$66.20	$4,884,000
Geothermal	50	$2,715	$135,750	0	117.95	$43.30	$5,430,000
Biomass	50	$3,790	$189,500	5.49	110.34	$102.40	$7,580,000

The capital costs of reactor development, licensing, and construction make it unattractive economically and are major impediments to developing new nuclear power plants [18, 36]. Advanced Nuclear Power has approximately four times the estimated capital costs for coal, based on the current average size of the power plant (See Table 1).

Even for the same sized plant, construction costs for advanced nuclear are forecast to be more than every other type of energy. Though variable operating costs for advanced nuclear is relatively low, it is still higher than wind, solar photovoltaics, and geothermal power. Advanced nuclear also has relatively high fixed operating and maintenance costs. Its track record of consistent and volatile cost overruns and project delays make nuclear power a problematic investment. Thus, advanced nuclear has a significant market disadvantage.

Construction cost overruns and delays are major obstacles. Construction of nuclear power plants frequently takes many years. The average construction time for the 37 reactors started globally since 2004 is ten years, twice as long as is typically forecast at the start of the projects [37]. Of the 53 reactors currently under construction worldwide, 37 of them are behind schedule [38]. Cost overruns, ongoing delays, and numerous increasing budget forecasts create barriers for the adoption of nuclear reactors [39].

The events of the tsunami that ultimately led to nuclear meltdowns at the Fukushima Daiichi power plant in 2011 renewed fears of nuclear accidents and decreased public support for nuclear power [40]. Gen III reactors were supposed to be simpler and less expensive, but the financial challenges for both Westinghouse and Areva show that Gen III reactors are running into the same escalating costs and schedule delays [41]. This makes it hard for policymakers, utility companies, and the general public to trust nuclear construction forecasts, budgets, and technologies. The nuclear industry has consistently been overly optimistic about forecasts for construction times and budgets. Thus, it is entirely reasonable that the promises of advanced nuclear reactors are viewed with considerable skepticism.

Solutions for the problems with nuclear power are certainly needed if nuclear power is to contribute to a sustainable energy future. Gen III and III+ reactors aimed to increase safety by incorporating some design features developed after the deployment of Gen II reactors. One important enhancement is passive cooling. Gen II reactors required the active cooling of reactors from electricity-driven pumps. If power is lost, the pumps can fail and the coolant system can be lost.[5] Passive cooling requires no action from an operator for the plant to shut down in the event of an emergency[6] [43]. Thus, it is viewed as much safer for operations. Another important feature was standardization and modularization. Small modular reactors (SMR) are designed to be relatively small (typically 50 to 100 MWe), closed systems where multiple SMRs are used together (modularity), rather than relying on a single mega-unit. The advantage of SMRs is that the utilities can lower their capital costs and increase design certainty and safety [44]. In September 2020, a SMR from NuScale was approved by the US Nuclear Regulatory Commission, the first SMR approved by the NRC after a lengthy design and development process [45].

No country has yet solved the problem of spent fuel (i.e., nuclear waste) entirely.[7] Currently, spent fuel is stored onsite at each nuclear power plant since there is no domestic repository in the US [48]. Every country supporting the development of advanced nuclear reactors has a stated goal of a closed fuel cycle, which would eliminate the problem of spent fuel [see 13, 30, 49, 50-52]. However, this goal is still theoretical.

Progress on some of the other problems with nuclear power, such as the spent fuel

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[5] This is what happened with the Fukushima-Daichii power plant in March 2011 42. ANS, *Fukushima Daiichi: ANS Committee Report*. 2012, American Nuclear Society,: LaGrange Park, IL.

[6] Some cooling is still required when a reactor shuts down, but it is significantly less than when the reactor is operating and can normally be maintained with backup cooling systems.

[7] Spent fuel is the more appropriate term for nuclear waste. Spent fuel is the portion of uranium that is no longer suitable for use in the current nuclear reactor designs. France reprocesses and reuses spent fuel (Hecht, 1998), which significantly reduces its waste problem. However, the United States is restricted from reprocessing its spent fuel under restrictions put in place by President Jimmy Carter over security concerns about the proliferation of weapons-grade fissile material 46. Mahaffey, J., *Atomic Awakening: A New Look at the History and Future of Nuclear Power*. 2009, New York, NY: Pegasus Books LLC.

problem, will not come until more advanced reactors are designed and deployed. However, Gen IV reactor designs are incomplete and commercially unproven. New reactors are costly to design, particularly when it is uncertain how much of a market will exist for these new power sources. The returns for any investments are uncertain, which is one of the reasons that public sector investments in these technologies are critical for their development. As discussed in the next section, nuclear power innovations are proposed and under development in many countries around the world. We also discuss the viability of these designs.

Nuclear Power Innovation

Innovative nuclear reactor designs are touted as solutions to many of the problems that exist with the nuclear energy industry. The next generation nuclear reactors are forecast to be inherently safer, with passive safety systems [53].

One of the underlying characteristics of innovation is a willingness to experiment and take on risks in unproven design. The cost of development for advanced reactors is significant and companies cannot afford to undertake these development activities when the return on them is uncertain.

Nuclear reactor designs are extraordinarily expensive and cannot be easily modified. The design becomes "locked-in" 12-15 years before actual operation,[8] which can then last from 40-80 years. Thus, a lack of regulator engagement increases the uncertainty during research and development (R&D). Without regulatory approval, all design and R&D work could be for naught. There is no way to recoup investments until the design has been licensed and deployed. Long lead times mean that significant capital resources and managerial contingencies need to be factored into the design process. The regulatory and economic constraints mean that companies have little chance to test and improve their design on an iterative basis because of the costs associated with changes. Thus, innovation is too expensive. The technical and regulatory challenges substantially increase the risks and costs for nuclear reactor designs and power plant construction.

Four new nuclear power plants in the United States were announced in the 2000s [57] – two in South Carolina and two in Georgia – which were to use the AP1000 from Westinghouse.[9] However, in 2019, the South Carolina Electric and Gas Company announced that they were halting construction on the two new nuclear plants in the state. The two Gen III+ reactors had faced significant cost over-runs and increasing competition from cheap natural gas, making the estimated additional $15 billion required for completion uneconomical [58].

Companies based in developed nations, such as Westinghouse, Areva, Hitachi, and

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[8] The AP1000 design was approved in 2005 by the NRC (NRC, 2017b). The design for the AP1000 began in the 1980s along with the smaller AP600 reactor (Taylor et al., 1988).
[9] Units 3 and 4 at the Vogtle plant in Georgia, owned by Southern Company and Units 2 and 3 at the Virgil C. Summer plant in South Carolina, owned by the South Carolina Electric and Gas Company.

Mitsubishi Heavy Industries, have led in nuclear technologies in the past. However, both Westinghouse and Areva have struggled with recent construction projects. Areva began building a reactor in Finland in 2005 with a forecast cost of €3.2 billion and a target completion of 2009. Cost overruns and delays initially pushed back the target completion to 2018 at a cost of €8.5 billion [59]. It was then delayed again, currently targeted for completion in February 2022 [60]. Westinghouse had been responsible for the construction of the new nuclear power plants in the United States and had experienced problems, resulting in a $6.1 billion loss for the company. The company filed for bankruptcy in early 2017 [61]. Westinghouse sold off its nuclear division to Toshiba, which subsequently sold it to a private equity firm, Brookfield Business Partners, in 2018 [62].

In the US, nuclear power production has fundamentally used the same technology since the 1950s. Despite the fact that other reactor designs have been proposed (and some have even been tested), light water reactors (either boiling or pressurized) remain the dominant designs. They are the only designs in commercial operations in the US [63]. Advanced reactors (Gen IV reactors) are not forecast to be deployed until 2030-2050 [18]. Though there are proponents of these technologies, the cost of developing and regulating nuclear reactors makes it virtually impossible for any private entity or company to undertake this on their own [64]. Thus, the development of new nuclear reactor designs has generally been done by the public sector, either through the military as was done in the US, or through partnerships with private sector organizations [65]. Developing nuclear reactors are long-term projects that have hitherto been undertaken as strategic public investments.

Gen IV reactors are still being designed and developed. None have been commercially deployed. As yet, there is no consensus on the optimal technology for the mass deployment of Gen IV reactors. In 2000, nine countries formed the Generation IV International Forum (GIF) to identify and advance Gen IV reactor technologies [66]. They identified six potential designs: Very High Temperature Reactor (VHTR); Sodium Fast Reactor (SFR); Super-critical Water Cooled Reactor (SCWR); Gas Cooled Fast Reactor (GFR); Lead Cooled Fast Reactor (LFR); and Molten Salt Reactor (MSR) [67].

A *Very High Temperature Reactor* (VHTR), or *High Temperature Gas-Cooled Reactor* (HTGR), is a thermal reactor cooled by flowing gas [68]. The high temperature of the coolant (up to 1000 °C) enables high thermal efficiency of the reactor, which is desirable for high-thermal energy applications and industrial co-generation [69]. The designs are either pebble bed reactors (PBR) or prismatic block reactors (PMR). The VHTR typically uses a graphite moderator with a helium coolant [70]. The VHTR can be designed with passive safety features [69], enabling the reactor to automatically shut down and reduce nuclear reactions if there is a problem.

A *Sodium-Cooled Fast Reactor* (SFR) is a fast neutron reactor that uses liquid sodium metal as the reactor coolant in a closed coolant system [69]. A Fast Neutron Reactor uses a fast neutron spectrum, which means that the neutrons can react in a fission process without having to be slowed down with a moderator, as is done in other reactors designs [68]. This process is less efficient when uranium is used as the fuel and, therefore, fast reactors normally use plutonium as the fuel [71]. Using molten (or liquid) metal as the coolant with a solid core has the advantage of creating substantial thermal inertia against overheating should coolant flow be restricted or lost [72]. The reactor can also be used as a breeder reactor, to regenerate the fuel, reducing the need for new fuel and the problems associated with spent fuel [73]. These reactors are safer than current designs for two reasons. First, the reactor can be operated close to atmospheric pressures because the boiling point of sodium is higher than the operating temperature of the reactor. Second, molten salts cannot produce hydrogen, which is combustible [74]. The major drawback to the SFR is that sodium is highly reactive with air and water and any contact between them risks both the creation of toxic sodium-oxide, along with possible explosions or sodium fires [69].

A *Super-Critical Water Cooled Reactor* (SCWR) is a high temperature, high-pressure, fast reactor, cooled with supercritical water [75]. A supercritical fluid exists when the fluid is at a pressure and temperature above the critical point, so that there is no longer any distinctive liquid and gas phases, but the pressure is too low to force the substance into solid state. Operating above the critical pressure means that the coolant does not go through a phase change between liquid and gas; therefore, there is no need for many of the components needed to deal with the phase change, such as recirculation and jet pumps, steam generators, steam separators, and pressurizers [76]. Thus, SCWR plants are also considerably simpler mechanically. They also require a relatively smaller containment than current Boiling Water or Light Water Reactors. SCWR's have much higher thermal efficiency at approximately 45% over current Light Water Reactors, which have about 33% thermal efficiency. This makes them suitable for applications such as the production of hydrogen [76].

A *Gas Cooled Fast Reactor (GFR)* is a variant on a sodium-cooled reactor [21]. It is a Fast Spectrum reactor that uses Helium as a gaseous coolant, though CO_2 and steam have also been proposed [77]. GFR is viewed as an intermediary to the deployment of other gas-cooled thermal reactors, which makes the design work easier as it draws upon existing research and designs [78]. Like other fast reactors, the GFR is designed to use only spent fuel, relying on depleted or natural uranium to seed the reactions, which will then be regenerative reducing both the fuel used and the waste produced [79]. One of the advantages of Helium is that it is not corrosive, making the system more sustainable [21]. However, the Helium must be maintained at a high pressure and an appropriate pressure system has yet to be designed [74].

A *Lead Cooled Fast Reactor* (LFR) uses molten lead (Pb) or lead-bismuth eutectic (LBE) as the coolant. Molten lead has a low melting point and high boiling point. Thus, it quickly solidifies in the event of a leak, supporting passive safety [80]. Lead and LBE do not react with water and air, which eliminates the need for an intermediary coolant system [81]. One of the drawbacks of using lead is that it is highly corrosive and requires highly corrosion-resistant components [21]. Several countries have worked on developing lead-cooled and LBE reactors, including the Soviet Union, Japan, the United States, and China [80].

Molten Salt Reactors (MSR) use molten salt (either fluoride or chloride) as both the base for the fuel mixture and the coolant [21]. The MSR is the most radical departure from Gen III designs. MSR's require the development of specialized materials and additional servicing of the graphite core during the reactor's operating life [21]. As with some of the other Gen IV designs, MSR's are designed to use spent fuel from other reactors as a source of fuel, reducing the need for new fuel and nuclear waste [68].

These designs are in various stages of research and development. To bring them to commercial energy production, significant investments are still needed. Some advancements have been made towards developing Gen IV reactors, particularly VHTR and SFR [50]. Other potential reactor designs are under development or investigation [82]. The next section discusses some of the investments that are being made in Gen IV reactors around the world.

Investments in the Development of Advanced Nuclear Reactors

Nuclear power has been used globally since the 1960s in both civilian and military applications. The US and Russia both have long-standing nuclear power programs. Both are making public investments in the development of Gen III and Gen IV reactors, as is China. China has the stated goal of being a major exporter of nuclear reactors and technologies [83]. Organizations that develop technologies that dominate a market are often difficult to displace [84] If either China or Russia come to dominate the market for advanced nuclear reactors, it will have serious implications for the current balance of power around the world. If either country is able to create a standardized advanced nuclear reactor with relatively certain costs for construction and operation, it would revolutionize the global market for nuclear energy. Countries with relatively low energy costs will be able to offer their goods and services much less expensively, giving them significant competitive advantages.

The United States

The US has been making investments in advanced nuclear reactor research and development through the the Department of Energy's Office of Nuclear Energy (US DOE ONE). The US DOE ONE is responsible for nuclear energy innovations, including developing new technologies and supporting the improvement of reactors. They are also charged with developing sustainable fuel cycles [85].[10]

For the fiscal year 2017, the US DOE ONE was allocated $994 million for its activities, including: $90 million for Small Modular Reactor (SMR) development project with NuScale; $109 million for new Reactor concepts; $250 million for Fuel cycle research and development; $90 million for Nuclear Energy Enabling Technologies; $365 million for the

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[10] Spent fuel and current nuclear waste management are handled by the Office of Environmental Management in the Department of Energy.

Idaho National Laboratory; and $5 million for the International Nuclear Energy Coordination program. The budget eliminated $5 million for the integrated university program and the STEP R&D, but significantly increased funding for SMR Licensing technical support [86].

By 2020, the budget for the US DOE ONE had risen to $1.5 billion, including $230 million for the Advanced Reactor Demonstration Program [87]. The DOE has announced that it intends to build prototypes for two advanced nuclear reactors in the next seven years using public-private partnerships [88]. In addition to domestic investments, the US has partnered with Canada, France, Japan and the UK to jointly fund R&D on Gen IV reactors, agreeing to share any technical information gained from the project [50].

Russia

Russia has continued to be actively involved in the development and construction of nuclear reactors. Russia plans to replace all its current nuclear power plants with new ones. This requires commissioning a new nuclear power plant approximately every year until 2035 [89]. Russia also has an active export program. Rosatom, the state-owned company responsible for civilian nuclear energy, is currently constructing or operating reactors around the world, including Ukraine, China, Iran, India, Belarus, and Bangladesh, with additional reactors ordered by Turkey, Finland, Armenia, Egypt, Vietnam, Hungary, Slovenia, and Jordan [30].

Rosatom is now a major global nuclear manufacturer. It is building 28 of the 68 nuclear reactors currently under construction globally [90]. Part of Russia's success is in providing flexible financial arrangements for its customers [91]. Russia supports a model of Build-Own-Operate (BOO), which allows customers to avoid the risks of nuclear power construction costs and overruns [92]. This is possible because the Russian government is actively involved in supporting nuclear exports [93]. The Ministry of Foreign Affairs promotes Russian nuclear technologies and President Vladimir Putin has directly engaged in some of the negotiations. Profits from Russia's fossil fuel industry have been used to support the nuclear industry, in an attempt to diversify Russia's energy industry and provide future economic stability [92].

The safety of Russian technology remains open to questions, given its history. However, Russia is vocal about being conscious of its safety record and in working to demonstrate the safety of its reactors [94]. They assert that Chernobyl made them conscious of safety in a way that was not possible before the accident and, thus, their reactors are safe because of Chernobyl, with more safety features built into their newer reactors [90].

The World Nuclear Association (WNA) reports on the nuclear industry and development in each country with a civilian nuclear program. The WNA reports that Russia is now working on developing advanced nuclear reactors [89]. They have been developing several research and commercial reactors with various designs. Their BN-600 fast neutron reactor has been operating since 1980. Russia has developed the BREST reactor, a Lead-Cooled Fast Reactor [50]. In 2010, the Russian government approved a program designed to develop commercial fast reactors. Russia began construction on a multi-loop research reactor in 2015. The BN-800 fast reactor has been operating since 2016 [83]. Rosatom plans to have fast reactors with a closed fuel cycle by the mid-2030s. The CEO of Rosatom stated that their goal is to make themselves the global leader in nuclear power construction and operation [30].

China

In the 1980s, China relied on technology transfer and foreign direct investments (FDI) to support their industries [95]. In the late 1990s and early 2000s, Chinese firms transitioned to a focus on indigenous innovation [96]. China is currently committed to developing its domestic reliance on nuclear power and in becoming a nuclear exporter. China has developed the domestic capacity to design and construct nuclear reactors, so that it is now largely self-sufficient in nuclear engineering [51].

The Chinese have been making significant investments in nuclear technologies. The Chinese government intend to become global exporters of nuclear reactors [51]. The WNA reports that China is investing billions of dollars into the development of their nuclear industry, including aggressively designing and building new reactors, with 17 currently completed, 30 under construction, and another 45-50 proposed and under review [51].

The Chinese are expected to surpass the US in installed generating capacity by 2030. They have committed hundreds of millions of dollars to developing new reactors, including $350 million to a molten salt reactor and $476 million to a high-temperature-gas-cooled reactor [51]. The Chinese have invested political capital into developing their nuclear technologies. For instance, the Molten Salt Reactor project was originally led by Jiang Mianheng, son of Jiang Zemin, the former President of the People's Republic of China and Secretary General of the Communist Party, which indicates significant political commitment to this project [97].

Sustained competitive economic advantage comes from leading in technological innovation and development, rather than simply following others. Though the Chinese obtained the original design for Molten Salt Reactors from the experimental reactor that the US built and operated at the Oakridge National Laboratories in the late 1960s and early 1970s, they are now investing heavily in building a working prototype, with the goal of producing a commercial reactor in the next 10-15 years [98, 99]. China is constructing a prototype solid-fuel Thorium Molten Salt Reactor (TMSR) at the TMSR Research Center at the Shanghai Institute of Nuclear Applied Physics [50]. They have now invested $3.3 billion in the development of a Molten Salt Reactor [100], and they are continuing to invest around $300 million per year [83]. They are the only country that is actually constructing a MSR [97].

China has developed a High-Temperature Gas Reactor (HTGR), the HTR-10, completing cold functional tests in late 2020 [101]. They began operating a 10 Megawatt (MW) Helium High Temperature, Gas-Cooled (pebble fuel) test reactor in 2003. They recently completed a 200 MW prototype [102]. They started a 65 MW Sodium-Cooled Fast Reactor (SFR) in 2010, with a 600 MW commercial reactor expected to begin operations in 2023. China plans to build a 1000 MW Supercritical Water-Cooled Reactor by 2022-2025 [103].

China has several stated goals in the development of their nuclear fleet [51]. The first is that Pressurized Light Water Reactors will be the main type of reactor, but they will diversify beyond this technology. The second is that nuclear fuel assemblies and equipment will be primarily designed and manufactured domestically. That is, their aim is to have an indigenous nuclear industry. Beyond this, China has ambitions to become an exporter of nuclear technologies and to leapfrog others in this area. The government of China listed nuclear power as one of its 16 science and technology priorities [104]. The first Chinese Hualong One reactor went into production in early 2021 with 90% domestically produced components. It is a domestically-designed Gen III pressurized light water reactor [105]. China has stated that it is aiming to be a global exporter of nuclear reactors [83].

China is aggressively pursuing its nuclear strategy. China's construction of nuclear reactors represents about one-third of all global nuclear construction [106]. Thus, China is helping to offset the decline in global nuclear power [107].

Other Public Investments in Advanced Nuclear Reactors

Other countries are also investing in new reactors. In 2010, the European Commission announced the European Sustainable Nuclear Industrial Initiative (ESNII) [70]. The initiative was designed to support the development and prototyping of three Generation IV reactors: €5 billion ($5.7 billion USD) for a 500 MW Sodium-Cooled Fast Reactor (SFR) to be built in France starting in 2020; €1.96 billion ($2.2 billion USD) for a 75 MW Lead-Cooled Reactor Fast Reactor (LFR) to be built in Eastern Europe starting in 2020; and €1.2 billion ($1.4 billion USD) for a 300 MW Gas-Cooled Fast Reactor (LFR) to be built in Romania beginning in 2020 [70].

For the past few years, India has been actively working on developing a reactor to use its reserves of thorium as fuel. It currently has a small fast breeder reactor, and it is constructing a larger one. India is also working on the development of a Molten Salt Breeder Reactor [108]. The Indian government plans to build six more fast reactors, with the goal of creating thorium-based fast reactors in approximately 20 years [108].

These projects indicate that investments are being made in nuclear reactor innovations by governments around the world. Since developing Gen IV reactors are long-term undertakings, investments must be made decades in advance of actual deployment. As the next section shows, private investors want to develop these technologies, but generally they only pursue these investments in conjunction with government or philanthropic support.

Private Sector Investments in the Development of Advanced Nuclear Reactors

Private sector companies are also working on the development of advanced nuclear reactors. For example, TerraPower was founded by a consortium of investors led by Microsoft founder Bill Gates to develop new nuclear technologies. They are working with the Chinese National Nuclear Corporation to develop of a Traveling Wave Reactor. They have also been working on developing a Molten Salt Reactor. In 2016, they were awarded $40 million from the US Department of Energy to research, design, and test a Molten Chloride Fast Reactor and another $80 million in 2019 to demonstrate their reactor and integrated energy system [109]. Transatomic Power was founded in 2011 by two graduates from the Massachusetts Institute of Technology (MIT) to develop a Molten Salt Reactor [110]. UPower Technologies was founded by three MIT engineers in 2013 to develop an Experimental Breeder Reactor [111]. Terrestrial Energy, founded in 2013 in Canada, is working on an Integral Molten Salt Reactor [112]. The Canadian Nuclear Safety Commission (CNSC) has agreed to a pre-licensing review of their technology [113]. Elysium Industries was founded in 2015 in Canada with the goal of developing a Molten Chloride Salt Fast Reactor (MCSFR) [114]. Moltex, based in Britain, is working on a Stable Salt Molten Salt Reactor [115]. Flibe Energy was founded in 2011 to develop a Liquid Fluoride Thorium Reactor (LFTR) [116]. These private sector efforts show that there are many companies that are investing in advanced nuclear reactors as part of the future of energy production.

These investments indicate that many countries expect that nuclear energy production is going to continue. However, the design and development of an advanced nuclear reactor is only part of the process for commercializing and deploying the reactor. The energy market, financing options, and governance structure are also important factors in creating a healthy nuclear power industry.

It is unclear whether the environment needed for wide-spread deployment of advanced nuclear power in the United States is there. The commercial nuclear industry in the United States has struggled for decades. There are now 96 reactors, down from 113 in the early 1990s [88]. Of the 53 nuclear reactors currently under construction globally, only two located in the US [117]. Thus, the development of the technology is not necessarily going to lead to its adoption domestically. It remains to be determined whether US manufacturers will be leaders in these advanced nuclear technologies or whether other countries' reactor designs will dominate the global market. There are also questions about whether the current regulatory process in the US is hindering nuclear reactor commercial development and deployment, putting US-based designs at a competitive disadvantage.

Regulations

In the US, the Nuclear Regulatory Commission (NRC) has been charged with ensuring the safe development and use of civilian nuclear power in the country. With the ongoing wave of international advancements and global sales, the Chinese and Russian nuclear regulations and safety standards are of interest and concern. While the NRC once claimed to be the global standard for nuclear energy regulation and safety, this position is now in doubt, as more Russian and Chinese reactors are sold and deployed globally.

Originally, the US Congress established the Atomic Energy Commission (AEC) to regulate and advocate for nuclear power. However, this led to questions about regulatory capture and conflict of interests associated with regulating and advocating for a technology. Thus, the AEC was broken up in 1974, with the NRC taking on regulatory responsibilities and the research division being segregated and later absorbed into the Department of Energy [118]. The NRC is expressly forbidden from advocating for any specific technology or design. In fulfilling an explicit mandate of safety and effective oversight, the NRC has avoided the regulatory capture that can occur in other industries. The NRC has regulated the nuclear industry to ensure that safe use of nuclear power technologies is the primary objective [119].

The NRC has three major activities that it regulates [120]:

1. Nuclear Reactor and Facility construction, operation, and decommissioning.

2. Nuclear materials possession, use, processing, exporting, importing, and transportation.

3. Spent Fuel or Waste Disposal siting, designing, constructing, operating, and decommissioning.

A license is required from the NRC for any company that wants to build or operate a nuclear power plant in the US. To get a license, an applicant (either an individual or organization) first submits an application to the NRC. The application is evaluated on both the technical merits (including safety) and environmental impacts. This licensing process is governed by US Code of Regulations 10 CFR[11] Part 50 [121].

The NRC is a fee-based regulator. That is, applicants and/or regulatees are responsible for paying the full cost of licensing. This cost is substantial. An applicant must pay for both the preparation of the application and the processing fee once the application is submitted [122]. The average 2021 cost per professional staff-hour was $288 [123]. Since the amount

[11] U.S. Code of Federal Regulation.

of time for the review by the NRC is not known in advance, the cost of licensing is uncertain ex-ante. That is, the total cost is only known once the obligation to pay for it has been undertaken.

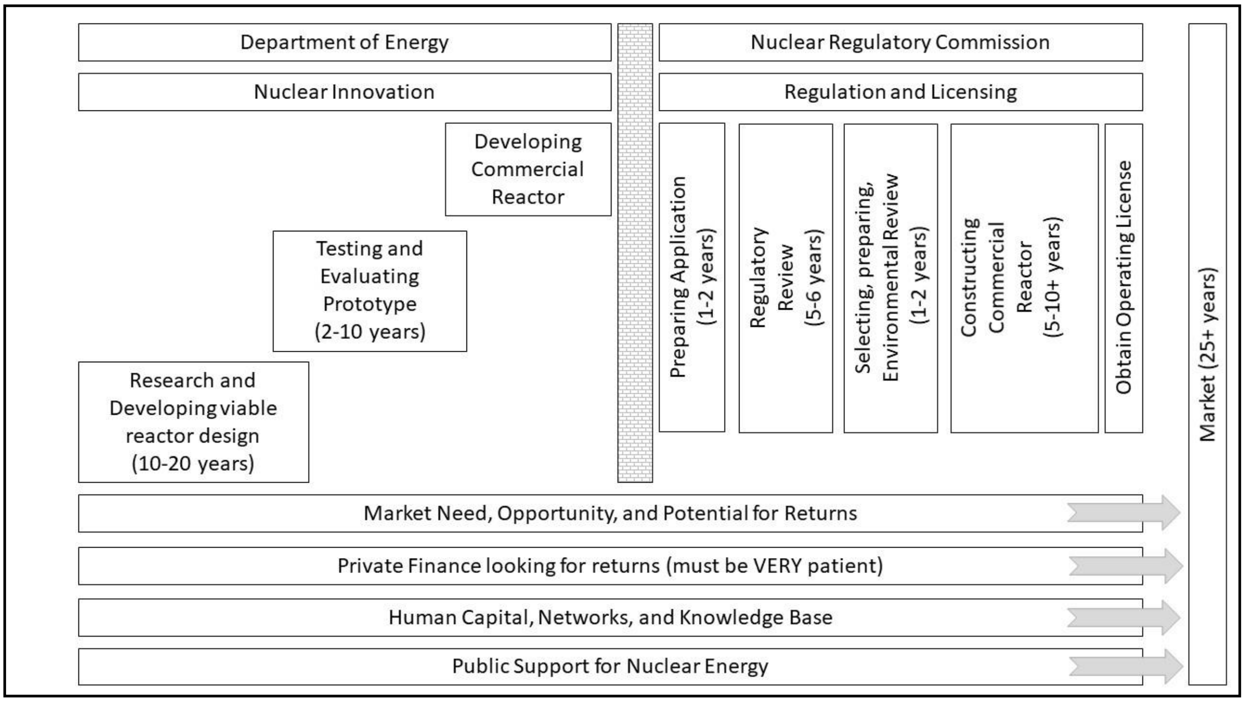
There is also an annual regulatory fee charged by the NRC on each operating reactor [124]. In 2021, this fee was $ 5,050,000. This includes the annual fee for the reactor, a spent fuel storage and decommissioning fee, and additional associated charges. There are different fees for reactors being decommissioned or non-operating with spent fuel. Research reactors are charged an annual fee of $78,800 [125].

The process of designing, building, and licensing a nuclear reactor has numerous steps, governed by 10 CFR Part 52. In general, the process requires:

1. Developing a viable reactor design
2. Testing and evaluating the design with a prototype or research reactor
3. Developing a commercial design
4. Preparing the application (1-2 years)
5. Going through a regulatory review of the commercial design that certifies the design (5-6 years)
6. Selecting, preparing, and getting approval for a specific site (1-2 years)
7. Constructing the commercial reactor, including an environmental and site review (5-6 years)
8. Obtaining an operating license for the reactor

Steps 4 through 8 can take approximately 12-15 years: 2 years to prepare the application [126]; 5 to 6 years to approve a new reactor design, including time for public review, once the NRC has the complete application [127]; 4 years for the regulatory review itself [126]; and another 5-6 years to construct the power plant, assuming that there are no undue delays [128]. This is when the commercial reactor design is complete. Developing a new reactor design can add many years to the process, particularly when there is no previous experience with an actual (similar) reactor.

Figure 1: New Nuclear Reactor Development, Deployment, and Licensing Process



The first stages of design research and development, prototype testing and evaluation, and commercial design are under the purview of the US Department of Energy. That process is more organic, allowing for some overlapping and feedback. The stages of Regulatory Review and Licensing are under the Nuclear Regulatory Commission. This is a prescriptive process. It takes a minimum of 25 years for a new design to get to market. Throughout the duration of the process, the market opportunity and need, as well as the supporting private sector investments, human capital, the knowledge base, and public support for nuclear energy, all need to remain in place. A wall exists between the Department and Energy and the Nuclear Regulatory Commission. The DOE and the NRC have distinct mandates; therefore, systemic coordination and consistent goals are non-existent. The NRC is not viewed as a partner in innovation. Instead, it considers itself an independent agency without technical bias or interest [129].

Whether these lengths of time are problematic for innovation is debatable. One of the primary functions of a regulatory body is to develop the rules and regulations for the activities that it is overseeing. Regulators and policymakers have to balance public protection and safety with commercial and economic considerations. Nuclear regulations have to protect public interests and enable investments when they are in the public interest [122]. Unlike many industries that have many new entrants and new venture failures, the nuclear industry cannot risk these failures. Companies have to spend millions of dollars and many years developing technologies. To ensure ongoing public support, the regulatory process in the nuclear industry must be open and transparent, which necessarily makes it a slower, more deliberate process [130]. Many of the features of advanced nuclear reactors are theoretical. Their designs are unproven. Therefore, regulators need to carefully review and assess these new designs [122]. This necessarily makes the approval process slow, but it does not necessarily mean that the process is cumbersome. On the other hand, private sector organizations and finance must consider the expected returns versus the investment time and challenges. Investing in the development of new nuclear reactor designs and construction requires significant human capital and patience from investors.

In a normal innovation process, the different phases of development, testing and evaluation, and deployment are not entirely sequential nor easily delineated. Often, there is significant overlap and feedback between these phases. However, within the nuclear industry, the process tends to be more linear than in other industries. No company can build a nuclear reactor in the United States until it has been licensed by the NRC licensing. Companies are naturally reluctant to go through the expense of developing and completing a design for a commercial reactor unless they can be assured that their design has a reasonable expectation of regulatory approval. In addition, potential licensees must bear all of the regulatory and licensing costs. Thus, even beginning to have any preliminary discussions about reactor designs can be prohibitively expensive.

To determine whether regulations are hindering innovation, important questions need answers. The first is whether the NRC is engaging in discussions of advanced reactor development or just awaiting applications. If it is the latter, then the follow-up question is whether the regulatory structure prevents the NRC from engaging in these discussions. To answer these questions, we analyze the way that advanced reactors are discussed by the NRC.

NRC Discussions of Gen IV Reactors

One of the ways to assess the progress of new nuclear designs towards commercialization and the role of the NRC in the innovation process is to investigate the conversations between the NRC and its stakeholders. Presumably, as advanced technologies get closer to commercial licensing and operation, the volume of communications and discussions about these technologies should increase. In addition, the communications around safety and operations should increase, while the communications around design and development should correspondingly decrease (since the closer the reactors get to commercial operation, the more fixed the design should be, and the less development of the design should be going on).

In order to analyze discussion within the NRC, it is necessary to use an appropriate methodology. This chapter employs text data analytics, grounded in corpus and computational linguistics. At the start of this process, documents are gathered and then transformed into an analyzable corpus that can be investigated using linguistic tools and techniques [131]. The first step in analyzing the corpus is to develop linguistic markers around the concept under investigation [132]. The set of search terms defining the concept under investigation is called a marker set. Marker sets are developed through an iterative process of investigating the results within the corpus to ensure that the returns are genuinely related to the concept under investigation.

Text has three forms of complexity [133]. The first is the technical complexity of the corpus (i.e., the difficulties of gathering and managing the data). The second is the complexity of language itself. The third type of complexity is in the concept under examination.

Marker sets were developed to investigate how each of the stages of innovation for Gen IV reactors are discussed by communications to and from the NRC.

The search terms used for Gen IV reactors are:

> brayton cycle turbine*; generation iv; generation four; gen iv /3 reactor*; gen four /3 reactor*; gas cooled /3 reactor*; gas turbine modular helium; helium /3 reactor*; lead cooled /3 reactor*; liquid metal /3 reactor*; molten salt /3 reactor*; next generation /3 nuclear; next generation /3 reactor*; fluoride salt cooled; pebble bed /3 reactor*; sodium /3 reactor*; supercritical water cooled; super critical water cooled; high temp* /3 reactor; and vhtr.

The data for this study comes from the Nuclear Regulatory Commission's AMPS data. That is, the publicly available documents for the NRC. The available documents between 2001 and 2015 were gathered and converted into an analyzable corpus. The distribution of these documents is shown in Table 2.

Table 2: NRC Corpus Descriptive Statistics and Gen IV occurrences

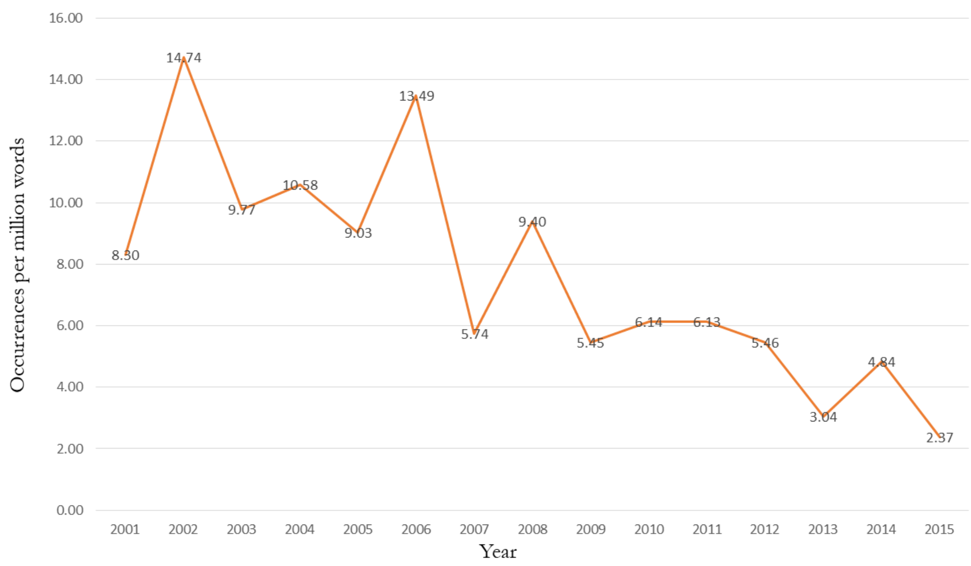
Year	Number of Files	Number of Words	Gen IV Occurrences per million tokens
2001	42,605	245,248,744	8.30
2002	43,480	259,849,377	14.74
2003	54,129	323,706,196	9.77
2004	46,527	279,383,980	10.58
2005	48,358	256,265,543	9.03
2006	47,307	273,857,113	13.49
2007	58,650	329,250,439	5.74
2008	65,395	372,865,261	9.40
2009	63,866	438,590,196	5.45
2010	65,799	432,058,385	6.14
2011	84,810	441,133,690	6.13
2012	65,490	550,954,815	5.46
2013	99,500	503,442,812	3.04
2014	51,314	375,924,344	4.84

2015	63,900	328,896,631	2.37
Average	60,075	360,761,835	7.63
Standard Deviation	15,730	95,060,151	3.56
Total	901,130	5,411,427,526	114.48

There are a total of 901,103 documents used in the analysis, with an average of 60,075 documents each year. In the corpus, there is a total of 5.411 billion words, with an average of 360.8 million each year.

For the searches, an occurrence of the search terms in the marker set is recorded each time the word appears. The total number of occurrences indicates the number of times that the words occurred in the whole corpus. This can be difficult to interpret, since the number of occurrences is also dependent on the size of the corpus. To account for this variation, the number of occurrences is concerted to a standardized number by dividing the total by the number of million words in the corpus. This yields the occurrences per million words, which makes it possible to compare the occurrences per year or even between corpora. Table 4 shows the occurrences per million words for Gen IV reactors. Figure 2 shows the occurrences per million words visually.

Figure 2: Gen IV Occurrences in the NRC Corpus



Gen IV reactors are currently conceptual and beyond the mandate of the NRC. Therefore, it is expected that there will not be a significant number of occurrences. What is surprising is the trend line. If there had been some progression in the development of Gen IV reactors, it would be expected that the discussions would increase as potential applicants engage more with the NRC on their reactor designs and future licensing requirements. Instead of the expected upward trend, there is a downward one.

The results of the analysis show that there was little progress towards Gen IV licensing between 2001 and 2015. In fact, there was actually less communication and correspondence at the end of the period then the beginning.

Conclusions

Our analysis strongly suggests that the Nuclear Regulatory Commission is not actively engaging in discussions on advanced nuclear reactors. Though there are innovative activities and private sector engagements in the nuclear industry in the United States, – with funding from the Department of Energy for private sector companies working on nuclear science and advanced reactor designs, – these are not yet filtering into discussions involving the NRC in any substantive way. It is not that the NRC does not engage with the DOE on other issues, they do. It is just that with respect to new reactor designs, the NRC remains silent.

The NRC is also keenly aware of these concerns and its place in the nuclear industry and the innovation process. In December 2016, the NRC issued the "NRC Vision and Strategy: Safely Achieving Effective and Efficient Non-Light Water Reactor Mission Readiness, Document ML16356A670" [129]. The document states:

> The NRC is fully capable of reviewing and reaching a safety, security, or environmental finding on a non-LWR design if an application were to be submitted today. However, the agency has also acknowledged the potential inefficiencies for non-LWR applications … that are reviewed against existing LWR criteria, using LWR-based processes, and licensed through the use of regulatory exemptions and imposition of new requirements where design-specific review, analysis, and additional engineering judgement may be required. (p. 8)

The report goes on to acknowledge that the NRC has a significant amount of work to do in order to be prepared for non-LWR applications. They will need to establish "processes, procedures, and internal guidance…for non-LWRs" [129, p. 8]. Their near-term strategy (0-5 years) is to acquire non-LWR knowledge, technical skills, technical capacity, computer technologies and tools to perform these reviews [129p. 16]. This clearly indicates that they do not currently have these resources. They are also looking to develop regulatory guidance for non-LWR reviews, which requires the NRC to establish the "criteria necessary to reach a safety, security, or environmental finding for non-LWR applicant submissions" [129p. 16], "identify and resolve current regulatory framework gaps for non-LWRs" (p. 17).

The document continues to outline the timelines for non-LWR:

> The NRC has aligned its readiness activities to support the DOE's identified goal of having at least two non-LWR designs reviewed by the NRC and ready for construction by the early 2030s. As such, the NRC plans to achieve its strategic goal of readiness to effectively and efficiently review and regulate non-LWRs by not later than 2025. The timeframe from 2016 until 2025 will be used to execute the agency's non-LWR vision and strategy to achieve readiness…[A] non-LWR vendor could present an application to the NRC for review at any time. The NRC will be able to review [a non-LWR] application, but early applications will not benefit from the efficiencies gained as the non-LWR vision and strategies are implemented. [129, p. 20]

In other words, the NRC is willing to review applications before 2025, but does not yet have the capability or capacity to do so. This means that any applicant would face substantial delays as the NRC tried to catch up to the technology in the application and simultaneously develop the framework and procedures for evaluating the application. At this point, however, there is no expectation that Gen IV reactors will be developed and deployed before the 2030s.

This contrasts with the timelines for Gen IV reactors in Russia and China. Russia is looking to have commercialized Gen IV reactors by 2020-2030 [30], while China is targeting to have a commercial design in operation by the early 2020s [51].

The need for sustainable energy will continue, as fossil fuels become less desirable and available. A nuclear technology that is truly sustainable, safe, and able to address the spent fuel issue, would be a disruption to energy markets if the technology also proves to be economically competitive. Significant disruptions to a market require multiple technologies coming together to interact and combine [134]. Thus, for the kind of disruptive change to energy markets that would be needed for genuine sustainability, there need to be multiple innovations and innovators.

As the empirical study suggests, the regulatory/financial bottle-neck that prevails in the US, due to the current operational procedures of the NRC, is a significant obstacle to ground-breaking nuclear innovation coming from the developed world. Currently, it appears most likely that innovative nuclear reactor designs are going to be deployed and made commercially available first in China and possibly Russia. Both the nations of the developing world, and well as the developed economies of the "Western" or "Global North" will then become dependent on them for their designs and technical expertise in advanced nuclear power generation. This raises questions regarding the different safety cultures of different nations, as well as having broader geo-political implications. A more robust response to these issues, as well as reducing the impacts of rapid climate change, would be for both the US, along with other advanced nations, to work towards alleviating the political, economic, and societal barriers to nuclear innovation. This would contribute to a robust global marketplace where various technologies can compete—rather than allowing the situation to emerge where a single authoritarian regime controls the technology, deployment, safety protocols, and profits from widely deploying advanced nuclear power plants.

A major element to supporting a more broadly-based drive towards deployment of innovative nuclear power plants must be persuading the citizens of the developed nations that nuclear energy should be viewed as a beneficial component to building societies powered by clean energy. Some of the strongest proponents for clean energy are environmental activists, specifically climate activists. But many of these stakeholders are either skeptical or antagonistic towards nuclear energy. From almost the beginning of its use, environmentalists and opponents criticized nuclear power [cf. e.g., 135, 136]. Others criticized the nuclear industry, including its costs, and the politics surrounding it [cf. e.g., 137, 138, 139]. Some still argue that nuclear power is more environmentally harmful than fossil fuels [cf. e.g., 140]. Schellenberger asserts that the underlying reason for the animosity of the environmental left is that nuclear does not offer the same potential for fundamentally remaking society as a switch to purely renewable community-based grids. Many climate activists seem to have a blind spot for the potential ecological impact of massive deployments of solar and wind energy [141]. However, that position is debatable, and scientists and environmentalists are starting to question this position. NASA scientists pointed out that fossil fuels are far more harmful than nuclear power [142]. Other activists and environmentalists are reluctantly accepting the necessity of nuclear energy [143].

Those advocating for decisive action against Climate Change ought to strongly support the rapid expansion of innovative nuclear energy technologies, but, as of this writing, most are not. Many problems need to be addressed and advanced reactors are still in the future. Advocates for nuclear power are going to need to find more effective ways of arguing for the technology. For several decades, nuclear industry advocates and their political allies have been ineffective in arguing on behalf of the technology. One problem is that the industry needs to be forthright and transparent about problems, letting other concerned stakeholders openly voice their anxieties. Another problem is that technical arguments are not necessarily persuasive, because emotions are often much more powerful in human decision-making processes. So nuclear energy advocates will need to effectively marry positive emotional persuasion with technical arguments. This turn-around needs to come very quickly.

In his recent book, Bill Gates advocates for using both renewable energy AND nuclear power. He sees that the climate disaster facing us is too significant to leave any clean energy source unused [144]. No single energy source or technological solution is going to eliminate the use of fossil fuels and still provide sufficient energy to maintain our lifestyles [145]. Supplementing renewable energy with fossil fuels is not a viable solution. Neither is continuing to promote nuclear energy without a sustainable and reasonable solution to the spent fuel problem. Renewable energy and nuclear power are not alternative paths to climate change mitigation. They are both key components to decarbonizing the global energy supply chain, while still meeting energy demands. However, unless advanced nuclear reactors are embraced as a serious alternative, the regulatory barriers to the design, development, and deployment of these reactors will make it difficult for nuclear power to be a viable complement for renewable energy or an alternative to fossil fuels.

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