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Atoms For Peace: Revisiting the Promise of Nuclear Power on the Cusp of Climate Catastrophe

Amelia Louise Tiemann
Bard College, at2470@bard.edu

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By
Amelia Tiemann

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Preface

When people think about nuclear power, they typically identify with one of two binary positions: either they believe nuclear power is an important part of the solution to climate change, and favor its expansion; or they believe its risks far outweigh any benefits it may provide. Those in the latter group might picture vast areas of uninhabitable land, massive evacuations of people from their homes, or the famous three-eyed fish from *The Simpsons*. Those in the former might view nuclear power as an often overlooked clean energy source with enormous potential to perform in the midst of uncertain climate conditions, and critical in addressing impending catastrophic consequences of greenhouse gas emissions. Most people who are informed about the issue of climate change can agree that action is needed — at nearly inconceivable scale and speed. Reaching a consensus about the scientifically demonstrated need to rapidly remove carbon emissions from our energy generation took world governments longer than environmental leaders hoped, but eventually happened; now the challenge is tackling the remaining obstacles causing stagnation at global climate negotiations. Our aversion to nuclear power is one of these obstacles; this paper aims to show that including it in energy discussions once again is crucial not only but in our strategies for survival.

Introduction: Climate Change and the Need for Energy Reform

Human reliance on fossil fuels to generate energy allowed modern civilization to flourish beyond previous experience. The Industrial Revolution saw the beginnings of exponential progress in technology that would continue throughout the 20th century. The transition from burning wood for fuel to burning coal, an extremely cheap and abundant source of fuel, allowed large-scale machinery to power factories and provide electricity for cities. Fossil fuels (coal, oil, and natural gas) facilitated substantial and speedy industrial and economic development. In the mid-20th century, however, scientists began to take notice that cheap and abundant energy from fossil fuels came at a price: higher atmospheric concentrations of greenhouse gases led to a warming climate. A few decades later, the scientific community agreed that climate change is likely the single largest existential threat to human beings in history (Rich, 2018). Currently, world governments are confronted with the task of identifying and implementing large-scale energy and technology reform to address carbon emissions. While the modern, industrial world needs scalable, reliable energy to meet the basic livelihood needs of a growing population, climate stability must be a central consideration to ensure the safety of future generations.

Humans have caused more than 1 degree Celsius of warming since the Industrial Revolution from the indiscriminate burning of fossil fuels (Rich, 2018). Current projections from the Intergovernmental Panel on Climate Change (IPCC) estimate that 1.5 degrees Celsius above pre-industrial levels is the upper margin for acceptable warming, before catastrophic effects are predicted to cause irreversible damage to global systems (IPCC Report 2018). If the world is only able to limit warming to 2 degrees Celsius above global average temperatures, climate scientists predict the extinction of the world’s coral reefs and sea level rise of several meters (Rich, 2018). Renowned climate scientist James Hansen describes 2 degrees of warming as “a prescription for long-term disaster” (Hansen, 2009). If emissions patterns remain unchanged and warming exceeds 2 degrees Celsius, dangerous ecological thresholds could be crossed, which would likely cause irreversible acceleration of environmental damage and warming.

These estimates are striking, but not surprising. Most industrialized nations have relied primarily on coal for most of their energy generation for at least a century, which includes electricity, heating, transportation, and other services. United States coal production steadily increased throughout most of the 20th century, peaking in 2006. In 2018, the U.S. relied on coal for 39% of its total energy supply (Energy Information Administration). The electric power sector accounted for over 90% of total coal consumption in 2017 (EIA.gov annual coal report). Natural gas has also supported energy generation in the U.S., and surpassed coal for the first time as the most prevalent fuel for electricity production during 2015 (EIA). Production of coal and natural gas soared in the U.S. in the 20th century because these fuel sources can generate vast amounts of energy at low costs, and can provide electricity at all hours of the day. This constant generation is referred to as base load generation. Base load is the “minimum amount of electric power delivered or required over a given period of time at a steady rate.” In order to generate electricity at the scale required to service the needs of millions of people, not to mention industry infrastructure, power must come from plants that are able to generate the required load on a constant basis. Million of tons of coal and natural gas are burned each day in the U.S. alone to produce baseload electricity that is necessary to power cities, homes, and factories.

Generating base load to power industrialized economies largely from sources that do not emit greenhouse gases would be an important component in combating climate change. In the 1950s, the United States deployed a dispatchable source of energy that could provide just that: nuclear energy, or energy derived from the splitting of the nuclei of atoms of uranium, could provide baseload electricity needs with negligible emissions. Nuclear power plants were particularly advantageous for energy production because they could provide the necessary base load capacity that fossil fuel plants provided, but without the combustion of a fuel source that created pollution. They did not rely on natural conditions to produce energy the way solar and wind generators do, so they could run at all hours of the day. The first nuclear reactor came online in the U.S. in 1957, and delivered as much electricity to the grid as a regular-sized coal plant. The initial deployment rate for U.S. nuclear power in its first two decades was relatively rapid; after this period, however, it stopped. Public fear of nuclear power, which had begun to spread during the environmental movement of the 1970s, accelerated after two major meltdowns occurred, one in the U.S. and one overseas. A wave of protest against nuclear power swept the country, and deployment rates virtually came to a halt.

The nuclear power story is one small part of an evolving climate discourse that has influenced the past several decades of governance. As new scientific findings strengthened the evidence for global warming and the need for emissions reduction, protests from environmental activists in the 1970s pressured politicians to add climate change to their political agendas. Nuclear power had a brief moment of favorability during this period as a symbol of hope for eliminating this new problem. Since then, effective climate policy appears to have reached a standstill. Almost no current climate resolutions are inclusive of nuclear power. The Conference of the Parties to the UNFCCC (COP) meetings have facilitated agreements among world governments for legally binding emissions reduction commitments. The recent Paris Agreement, the result of COP21 in 2015, resolved to pursue a limit of 1.5 degrees Celsius in average global temperatures increase. Most international treaties do not mention nuclear power as part of their proposed energy transition scenario. Meanwhile, climate scientists continue to debate the role nuclear power should play in mitigating the threat of climate change, as valuable time is lost.

This paper postulates that this failure is connected to slowed nuclear power deployment rates. This hypothesis guides the central research question of this thesis, which asks whether overall cost and benefit to human health and safety of nuclear energy relative to the same metrics of *not* deploying it. Scientists currently agree that negative effects are happening as a direct result of emissions from fossil fuel burning, but current fossil fuel replacement rates in the U.S. and the world are much too low to make a significant contribution to emissions reduction recommendations such as those outlined in the UN SDGs. Despite negotiations, the global energy mix has not become cleaner since 1990. In 2015, 65% of world electricity production came from coal, gas, or oil sources, having increased on average by 0.2% each year since 1995, the year of the first COP (WorldBank). Decreases in U.S. coal-fired generation after peak production in 2006 were met with increasing natural gas production, which caused emissions to drop slightly. Still, natural gas is remains a major source of carbon emissions in the U.S. Total consumption of hydrocarbon energy has grown significantly, and carbon emissions continue to climb every year.

This paper hypothesizes that the reversal in nuclear power learning curves is a crucial yet forgotten piece of this puzzle. Nuclear power was, once, a brand new technology that environmental organizations praised for its ability to mitigate carbon emissions; it is wise to revisit it given the slow pace of current energy reforms in the United States and the world. This question requires critically examining political decision-making not to expand nuclear energy, despite the current environmental reality. A review of the literature suggests that past nuclear accidents, coupled with socio-psychological factors, are responsible for creating entrenched fear and aversion to nuclear power. However, safe operation of nuclear power has proved an effective emissions reduction strategy, which could play a crucial role in climate change reversal if expanded. This paper presents a researched review to identify the origins and causes of continued nuclear fear. A rigorous evaluation of these concerns assesses their validity relative to historical data and projected data, and addresses their significance within the context of the capabilities of nuclear power as one of many climate change mitigation options. Yet unexplained through a purely scientific perspective, this investigation aims to shed light on the social and political reasons that public resistance to nuclear power does not soften, through a multidisciplinary evaluation of costs and benefits associated with nuclear technology.

This thesis does not argue that aversion to nuclear power or arguments against it are irrational. Rather, while nuclear fear results from risk aversion, it has historically played a dominant role in energy discussions, at peril to comprehensive decision-making. The analysis presented in this paper finds that this distinct division in attitudes about energy policy that includes nuclear power stems from an overwhelming sense of fear and disgust among the public, more entrenched and primal than simple disagreement over which is the best technology. Given the severity of the climate crisis, as well as the demonstrated ability of nuclear power to significantly boost carbon-free energy generation, this paper argues that it is crucial to understand and evaluate the technological, environmental, and economic factors involved with nuclear power in order to determine its cost-benefit tradeoff as a carbon-free energy source. Historical analysis helps to pinpoint the origin of nuclear fear, and social psychology sheds light on its propagation in mainstream culture and discourse. The theoretical framework underlying this analysis incorporates elements of political theory, discourse theory, and social psychology in order to impartially evaluate contemporary discourse surrounding nuclear power.

Chapter I: An Historical Timeline of Nuclear Power Use

1.1 Nuclear power in the world

Nuclear power is a source of energy generation that possesses unique qualities that could help unite development and protection of the environment. Within a large-scale vision of a clean energy transition, nuclear energy programs offer scalable and far-reaching prospects for economic growth and energy security. The emissions profile of nuclear power is extremely low, even relative to other non-hydrocarbon energy sources. The IPCC assessment of life cycle emissions for nuclear power shows that it is one of the cleanest energy sources currently in operation: nuclear power has median life cycle emissions of 12 grams of carbon dioxide per kilowatt-hour, approximately equal to wind and hydro power, whereas coal's carbon median balance is 820 gCO_2/kWh and large-scale solar power's median carbon balance is 48 gCO_2/kWh. This assessment includes uranium mining, enrichment, and fuel fabrication, as well as total emissions involved in long-term management of nuclear waste and in plant operation from building to decommissioning (IPCC Life Cycle Assessment).

Nuclear power possesses technical characteristics that make it a potential solution to catastrophic climate change. The extreme energy density of uranium fuel makes it the largest source of clean energy in the U.S. The U.S. avoided more than 14 billion metric tons of CO_2 emissions between 1995 and 2016 from using nuclear power, the equivalent of removing three billion cars from the road (NEI). Nuclear reactors provided 56% of domestic clean electricity and 19% of total electricity in 2017 (United States Department of Energy). By comparison, renewable energy sources (solar, wind, hydroelectric, geothermal, and biomass combined) provided 11% of total U.S. electricity consumption in 2017 (United States Energy Information Administration). Nuclear power provided 8.1% of world electricity production in 2015; at its peak in 1996, it provided 17.6% of world electricity production (WorldBank).

Nuclear power is particularly well-suited for large-scale energy generation because it is structurally ideal for providing base load electricity. A single 1 GW power plant could easily replace the capacity of a typical 600 MW coal plant, and provide constant energy without intermittent shortages. Nuclear reactors operated at full capacity more than 92% of the time in 2017, making them twice as reliable as coal and natural gas plants. Therefore, a nuclear reactor can reliably substitute for fossil fuel sources to provide the backup generation necessary in an electricity system that relies in large part on variable renewable sources like solar or wind power, which cannot generate constant power without backup (U.S. EIA).

The threat of climate change was not yet apparent in the public consciousness by the time nuclear technology was readily available to help facilitate the transition away from fossil fuels. In the U.S., interest in nuclear power was primarily based on growing awareness of the health effects of burning coal. Some European countries deployed nuclear power programs in order to lessen their reliance on foreign oil imports and improve their energy security. France and Sweden are examples of countries that capitalized on the opportunity to build expansive nuclear capacity. Both nations expanded their nuclear power production during the 1970s and

80s and experienced proportional decreases in total energy supplied from crude oil and fossil fuel sources. Within two decades of beginning its nuclear power program, Sweden had displaced over half of its fossil fuel use with new nuclear capacity (Qvist & Brook, 2015).

The invention of nuclear power illuminated new technological possibilities for 20th century America. Nuclear-powered generators allowed U.S. Navy submarines during World War II to travel long distances without needing to refuel. After the war, engineers adapted the nuclear generators from submarines for residential and commercial electricity generation on land. The first nuclear reactors came online in the 1950s, and these were able to generate vast amounts of electricity from relatively small quantities of fuel. In the 1960s, experts predicted that a large-scale transition from hydrocarbons to nuclear power would emulate other century-long energy transitions — much like the switch from burning dung to burning wood, and from wood to coal. Politicians and environmentalists spread hopeful messages that nuclear fission would one day power the entire country, eliminating the need to extract fossil fuels for energy and providing universal prosperity. Once a wartime technology, nuclear reactors had become the new way to generate vast amounts of dispatchable electricity (Jaczko, 2018).

Electricity from nuclear power plants is derived from the fission of atoms of uranium to create a chain reaction that releases vast amounts of energy. The process of fission is a nuclear, not a chemical reaction which causes atoms to split, changing the identity of the atoms and releasing immense heat. The heat boils a water coolant, which creates steam that turns a turbine and makes electricity. This nuclear reaction does not involve combustion of any kind and occurs without releasing a waste product into the atmosphere. In coal and gas reactors, the combustion of fuel produces toxic compounds, most notably carbon dioxide and methane. These chemicals remain in the atmosphere as waste products, preventing heat from the sun from exiting the atmosphere and causing global warming. Unlike unregulated greenhouse gas emissions, nuclear waste is stored and internalized into operating costs.

"Decarbonization" is the broad term for the overall global removal of the carbon content in the atmosphere through transitioning to lower-emission industrial methodologies, carbon capture and sequestration (CCS), and reformed agriculture. While some countries have begun to phase out hydrocarbons and make developments in renewable technologies and carbon capture, energy production is still the single largest contributor to carbon emissions globally and, hence, to climate change. In order to drastically lower emissions and slow climate change, large-scale decarbonization of the energy system before mid-century is a major first step. To achieve decarbonization (or near-zero emissions), it is necessary to identify the best possible mix of energy technologies that minimize carbon emissions, which are at the same time scalable to the world's growing energy needs, and reliable for constant electricity at all hours of the day.

Some parts of the global energy system are more difficult than others to decarbonize. These include long-distance transport and aviation, production of structural materials like cement and steel, and a reliable electricity supply. According to Davis et al. (2018), infrastructural transformations and carbon management must become married in order to reliably decarbonize these services, which produce 27% of total global emissions. Replacement of truck fleets with electrified vehicles, for example, is not only difficult and costly, but is insufficient on its own to reduce the overall emissions contribution of truck shipping. Long-distance truck shipping alone was responsible for 0.8% of global emissions in 2014. Even if all trucks did become electric, their batteries would still run on electricity from the grid, which still relies mostly on fossil fuels. Alternative fuels like biofuels, synthetic hydrocarbons, and hydrogen and ammonia fuels may become available to offset the carbon output of these services. As fuel markets are more flexible than electricity markets because of the storability of large amounts of chemical fuels, using emissions-free electricity to manufacture fuel could help to integrate electricity and transportation systems (Davis et al., 2018). The energy density and reliability of nuclear power could prove highly favorable in bridging the divide between stationary electricity production and production used for transportation and industrial services, facilitating the move toward an integrated decarbonization framework.

Today, nuclear power has demonstrated its capability to reliably provide low-emissions, dispatchable energy generation at a large scale. The average household in OECD countries consumes approximately 1,000-1,500 watts of electricity per hour every day (the amount of electricity required to sustain the average lifestyle in OECD countries). Several European countries receive a substantial fraction of their electricity from nuclear power, and have quickly and significantly decreased their overall emissions since adding nuclear power generation to their energy portfolios. France currently receives approximately 76% of its total energy from its 58 nuclear reactors, and generated twice as much clean energy as Germany in 2017. Economic and human development goals, trends in international trade and travel, expansion of variable renewables, and large-scale electrification of other sectors will mean increases in demand for energy processes and services, including those with difficult-to-eliminate emissions. Historical examples demonstrate that nuclear power is well-suited to perform favorably across sectors and services while contributing appreciably to decarbonization efforts.

1.2 Fear of radioactivity and weapons

Globally, deployment rates of new nuclear power plants were quickly accelerating before 1970, and nuclear power took up a large proportional share of new energy supply. By the 1970s, however, the image of nuclear power in the U.S. drastically shifted when nervousness about radioactive poisoning turned into widespread panic about the possibility of unknowable danger. Nuclear technology had never maintained an entirely pristine public image, as its origin as a wartime technology solidified its association with weapons. Even before the discovery of nuclear fission, the discovery of ionizing radiation — the transformation of an atom into a completely different element through the release of rapidly-moving matter and energy — evoked powerful imagery, at the same time hopeful and idealistic as terrifying and apocalyptic, that has lasted until today (Weart, 2012).

The discovery of radioactivity was culturally significant, as it symbolized the possibilities of the new millenium. Leading scientists of the early 20th century wrote extensively about the concept of atoms containing inexhaustible power, which humans could harness to create a utopian society free of ardor and labor, and which offered possibilities for universal peace and the end of human suffering. Limited facts about radioactivity became known at the turn of the twentieth century, and sparked fear. Decades later, it became increasingly associated with general unease about the role of science and technology in determining the evolution of society (Weart, 2012).

Beginning with the dropping of atomic bombs on Hiroshima and Nagasaki that preceded the Japanese surrender to the United States, cyclical surges of concern and fear about atomic energy were observable in the U.S. throughout the rest of the 20th century (Boyer, 2016, p. 76). Whereas relief and jubilation initially swept the nation after World War II ended, nervousness soon largely replaced these feelings as media began to report on the levels of destruction in Hiroshima and Nagasaki. Fears arose about humanity's capacity to handle its own technological power (Weart, 2012, p.19). Nuclear themes became ubiquitous in American popular culture, spanning science fiction stories, music, and political activism (Boyer, 2016). During the Cold

War of the 1960s, existential dread of atomic weapons plagued the American public and sparked renewed panic. The image of a "mushroom cloud" many miles in diameter eclipsed the coveted utopian vision of a future powered by nuclear fission (Graham & Montgomery, 2018).

The perceived nuclear weapons threat catalyzed anti-war protest. In the 1970s, the beginning of the environmental movement created a psychological bridge between nuclear weapons with nuclear fission used for energy. The new decade marked a final cycle of cultural awareness and nuclear activism, which promoted the message that nuclear power could lead to total destruction of large swaths of land and potentially the eradication of humanity. Persistent anxiety about the insidious and hidden threat of uncontained radioactivity infiltrated discussions about nuclear power as a tool to combat climate change, and modern discourse about nuclear power evolved. Safety issues, waste, accident risk, and ongoing exposure to dangerous radioactive contamination are among the biggest concerns associated with nuclear power on the global scale.

Visceral emotions, in this case fear and dread, are important as part of mental clusters that aid in our quick response to danger. When symbols become associated with clusters of other associations shared by many people, beliefs and images become part of the collective public imagination (Weart, 2012). Atomic energy encapsulated a narrative of the unknowable, a sense that unthinkable danger was imminent and omnipresent. This fear of the unknown became the psychological link between radioactive fallout from weapons testing and radiation from energy generation. A group of activists released publications warning that a proposed nuclear power plant would release "death dust" that would contaminate the local milk (Shellenberger, 2018). Once the subject of headlines praising the possibilities of scientific discovery, radiation became evocative of an invisible and insidious threat whose long-term effects were yet unknown (Graham & Montgomery, 2017).

Leading environmental organizations like the Sierra Club initially endorsed the benefits of nuclear power for facilitating a phase-out of polluting fossil fuels. During the 1970s, however, the Sierra Club flipped its position on nuclear power when an anti-nuclear faction formed within the organization and began to warn the public about the dangers of radioactive contamination. Ralph Nader, a political activist who joined the organization, famously said that "a nuclear accident could wipe out Cleveland, and the survivors would envy the dead." Some environmental activists even began to take a stance in favor of fossil fuels over nuclear power, arguing that long-term genetic damage from nuclear plants was a much more immediate threat than any health effects from the burning of coal. One Sierra Club leader claimed that nuclear power "risks long term genetic health damage" but "coal's impacts won't be felt generations from now" (Shellenberger, 2018). While no scientific study existed to substantiate long-term genetic damage, opposition to nuclear power by virtue of this potential risk had become extremely popular.

Over time, the public came to regard nuclear waste, weapons, fallout, and energy generation itself as a health danger. A 1961 article published in the journal *Science* made headlines around the world when it showed that levels of strontium-90, a radioactive isotope produced during nuclear weapons testing, were found at concentrations 50 times higher in the teeth of children during periods of weapons testing. While the study's findings were alarming, the strontium-90 levels were 200 times lower than levels known to cause cancer. *McCall's*, a leading women's magazine, printed on its 1957 cover the simple but jarring headline: "Radioactivity is Poisoning Your Children" (Shellenberger, 2018). At the same time, no discourse existed about a “safe amount of radiation” — radiation was simply a poison to be avoided at all costs (Graham & Montgomery, 2018, p.).

In the late 1970s, leaders of the anti-nuclear movement became particularly influential, and appealed to mothers through the association of nuclear power with danger and immorality. Helen Caldicott, an Australian pediatrician, appealed to mothers by advocating through a narrative of the engaged mother, fighting against health dangers that could affect children. Her speeches about children dying of leukemia as a result of radiation, and the injustice that nuclear power imposed upon innocent citizens, framed her as a concerned mother, pediatrician, and citizen rather than a scientist. The panic from Three Mile Island also served to push Caldicott into the mainstream. With an emotional appeal in place, conflating weapons and nuclear plants became increasingly popular. Campaigns like these created a perception of nuclear power that conjured images of weapons, toxic waste, and fallout; the alleged health danger of nuclear power replaced excitement about its ability to lower pollution in the public imagination. Critics of the nuclear industry frequently used unpleasant words like “sewage” to talk about nuclear waste, and the industry described waste as the “back end” of the nuclear fuel cycle, terms which were evocative of dirtiness and excrement. The campaign was highly successful, and 150% more nuclear power plants were cancelled than built by the 1980s (Shellenberger, 2018).

The narrative of imminent and unknowable danger from nuclear weapons, which was the origin point for fear of nuclear reactors that produce electricity, has produced concern since the Cold War about nuclear materials from civilian plants falling into the hands of nefarious actors. One of the primary existential concerns of the 1970s, in addition to growing concern about climate change, was the possibility of proliferation of nuclear materials. Nuclear proliferation means the diversion of fissile materials for use in nuclear weapons development.

Most countries are participants in international initiatives to safeguard against nuclear weapons proliferations. Since 1970, an international safeguards system, enshrined in the Nuclear Non-Proliferation Treaty has diverted the proliferation of fissile materials (WNA).

Proliferation resistance is a technical and institutional requirement for a nuclear power-inclusive energy future. Feiveson (2008) stated that “the obstacles to proliferation will be both intrinsic technical barriers and extrinsic institutional barriers.” For a terrorist group to potentially construct nuclear weapons, it would need to access required amounts of weapons-grade material, which is not possible to obtain from the civilian nuclear fuel supply chain, for the following reasons. First, the enrichment level of uranium determines its critical mass, meaning the amount of fissile material (the isotope U-235) required to maintain a nuclear reaction. At lower enrichment levels, such as those used in standard nuclear reactors (3 to 5%), critical mass is substantially higher because it is roughly equal to the inverse square of the enrichment level. At 20% U-235, for example, critical mass is about 140 kg, whereas critical mass for 90% enrichment is about 10 kg (Feiveson, 2008). While low enrichment levels already create a significant proliferation barrier, impurities in uranium create further complications in weapons design. Second, substantial effort, capital and virtually unknowable know-how would be required if a country were to develop and operate the technologies necessary to produce its own fissile weapons-grade uranium. If terrorists were able to surpass these barriers to acquisition of enriched uranium, they would run into other obstacles. Satellite detection of radioactive signatures can detect this type of activity, for example.

New nuclear reactor designs are also engineered to act as safeguards against proliferation. The Integral Fast Reactor (IRF) and Advanced Fast Reactor, in addition to generating electricity, are capable of providing safeguards against bomb production. Two fast reactors can generate electricity using the energy they obtain from consuming the plutonium and 99% of the actinides created from the burning of fuel in five pressurized water reactors. As basic fast reactors are able to recover nearly all of the energy remaining in spent nuclear fuel, fast reactors on site can uptake this energy without the hazards involved in transporting radioactive material (Cravens, 2008).

A more nuanced approach to the nuclear terrorism threat will extend beyond technical advances to include institutional. Opponents have blurred the distinction between peaceful use of nuclear fission for electricity generation, and the use of atomic energy to build weapons of mass destruction. Popular misunderstanding of the intersection between the two as a result of this type of messaging is therefore understandable.

1.3 The Three-Mile Island and Chernobyl meltdowns

The 1979 meltdown at Three Mile Island, a nuclear power plant in eastern Pennsylvania, was the world's first major civilian nuclear accident. A failed water pump cut off the exchange of heat to the reactor's steam generators, causing a pressure spike that led to a partial meltdown within the reactor core. Although the Three Mile Island meltdown caused no fatalities or injuries, it catalyzed widespread panic and created lasting public distrust of the nuclear power industry. Seven years later, the world's worst nuclear disaster occurred at the Chernobyl Nuclear Power Plant in northern Soviet Ukraine. These accidents attached emotional weight to a technology whose energy generation characteristics otherwise appeared favorable. They remain implanted in the public perception of nuclear power.

Examining the response of industry, environmental organizations, and the public to nuclear accidents illustrates how nuclear fear came to be seemingly so irreparable in the global imagination. The Three Mile Island nuclear meltdown in Pennsylvania was, to Americans old enough to remember, the defining event in U.S. nuclear history. Environmental groups like the Sierra Club demonized the nuclear industry after the Three Mile Island accident. *Time* magazine put the phrase "Nuclear Nightmare" across the cover, capturing nationwide chaos and confusion. The meltdown also occurred only 12 days after the release of "The China Syndrome," a film about a fictional nuclear meltdown. The accident triggered nationwide fear and panic over radioactive contamination, as if the film had predicted a real event. The building anti-nuclear movement gained momentum after the accident, and protests spread across the country. However, neither the accident depicted in the film or the real accident caused a single death. Industry influence over the regulatory bodies that bear the responsibility of ensuring safety is to blame for the inadequate response to the Three Mile Island accident (Jaczko, 2019).

The accident happened when a failed water pumped cut off the massive heat exchange in the reactor. The reactor engine immediately turned off, but the hot reactor fuel continued to produce "decay heat" that caused a significant pressure spike in the cooling pipes. A relief valve also stayed open once the pressure was relieved, which meant water drained out of the pressurizer and exposed nuclear fuel to the air without a cooling mechanism to keep them from melting. A combination of human error and lack of adequate training allowed the accident to prolong to the point of meltdown: plant operators failed to recognize and identify the type of accident that was occurring, and poorly designed indicator lights resulted in operators manually mismanaging the cooling system. The resulting damage was a release of radioactive material into the containment structure that caused a partial meltdown of the reactor, and release of radioactive gases and iodine into the environment. Epidemiological studies suggested no statistically significant increase in cancer rates in the area after the accident (Hatch et al., 1990; Levin et al., 2008).

After Three Mile Island, the U.S. Nuclear Regulatory Commission (NRC) demanded countless additions and modifications to existing regulations in order to address weaknesses (Jaczko, 2019). These modifications, which resulted in changes to equipment and operating procedures, improved plant safety considerably. Comparative analyses of the performance of U.S. nuclear reactors from 1994-1998 showed that probability of system malfunctions causing core damage had declined by a factor of about 100 since the decade preceding Three Mile Island (Sailor et al, year). In 2006, the NRC published an official disclaimer that explained that research from 1977 and 1991 about the safety of plants was outdated (Jackzo, 2019).

Evidence suggests that the 1986 Chernobyl accident may be the only instance of mortality from a civilian nuclear power plant accident. The reactor meltdown at Chernobyl was unique, in that it occurred during a routine operations test as a result of inherent design flaws and operators arranging the reactor core contrary to instructions. Uncontrolled reaction conditions led to an explosion of the reactor core and subsequent graphite moderator fire, which released fission products into the atmosphere that precipitated as far as Western Europe. There have been 15 confirmed deaths from thyroid cancer, and 28 emergency workers died of lethal radiation doses or acute burns. More than 500,000 recovery workers were exposed to 0.02 to 0.5 Gy from 1986 to 1990, but further studies have not confirmed evidence of increased risk among workers from this exposure (Sato and Lyamzina, 2018). An estimated 9,000 people will continue to experience health effects from Chernobyl (mostly thyroid cancer). However, an estimate from over one hundred of the world's leading radiation scientists representing eight international organizations and Ukraine, Belarus, and the Russian Federation suggests that the accident is unlikely to cause appreciable health effects (The Chernobyl Forum, 2003-2005).

Unfortunately, the Soviet government neglected to counteract some of the avoidable health effects from the accident. If the Soviet government had ordered swift evacuation during the accident, forbidden the use of contaminated foods, or provided iodine pills to the public, thousands of people would have been spared from radiation poisoning (Partanen & Korhonen, 2015, p.53). Greenpeace estimates that Chernobyl deaths are higher than 9,000, but these estimates account for health conditions unrelated to radiation poisoning. An increase in the prevalence of suicide, alcoholism, drug abuse, and other conditions tied to mental illness among people still living in the area suggests that psychological impacts are likely the biggest threat to public health and safety (health report from CG).

1.4 Stalled deployment rates

Until the late 1960s, nuclear power had seen rapidly increasing deployment rates in several countries, including the U.S. Some experts predicted that based on this growth, and on the trends of earlier energy transitions, nuclear power would supply 14-21% of global primary energy by 2000 (Lang, 2017). However, the current deployment rate of nuclear power is less than it was in 1972, marking nearly five decades of stalled deployment. The transition rate to nuclear power, which had climbed as high as 4% per year by 1969, stalled. The vision of a nuclear-powered future all but dissipated at the end of the 1960s because of public opposition. This was in response to growing safety concerns, high costs, and the misguided fear that nuclear energy was a pathway for nuclear weapons and nuclear war. Plans for construction of hundreds of new plants were cancelled in the USA alone. As of 2015, the current growth rate of U.S. nuclear power is far below 4% per year (Lang, 2017). In fact, it is in decline. Fossil fuels have continued to dominate the energy portfolio in the United States, despite pushes for increased renewable capacity.

The learning rate of a technology is the reduction in costs as experience is gained. Put another way, the fractional reduction in cost per doubling of cumulative capacity or production creates a cost-experience curve. Lang (2017) highlighted the reversal in learning rates beginning in the late 1960s, throughout the entire period of nuclear power generation to date. Before 1967, positive learning rates meant that Overnight Construction Costs (OCC) decreased as cumulative capacity increased. OCC learning rates in the U.S. were as high as 23%. Had these rates continued, nuclear power could have replaced up to 100% of total coal-generated capacity and 76% of gas capacity in the United States in the year 2015 alone. A single year like that would have avoided up to 540,000 pollution-related deaths and 11 Gigatonnes (Gt) of CO^2 emissions from entering the atmosphere (Lang, 2017). Lang identified evidence of disruption of the transition from fossil fuels to nuclear power, and demonstrated that substantial ecological benefits were lost as a result. Learning rates for 58% of the world's reactors in seven countries from 1954 to 2015 were studied. The pre-1967 rates were then extrapolated over the post-1967 period to calculate the benefits forgone as a result of learning rate reversal and subsequent stalled deployment.

Environmental organizations were initially favorable to nuclear energy as an extremely dense source of low-emissions energy capacity that could quickly replace fossil fuels in providing base load energy needs. By 1975, nuclear power plants were contributing 559 TWh to the total U.S. primary energy supply (roughly 2.6%).This power came from the 65 reactors that were in operation at the time (WNA). By 2000, nuclear power contributed 2,300 TWh, or roughly 8% of total primary energy consumption. During this 25-year period, total primary energy consumption in the U.S. grew by 7,900 TWh/year (37%) — new nuclear reactors took up 22.2% of this added capacity.

The conclusions of Lang (2017) highlight the missed opportunity of nuclear power to avoid nearly all current carbon dioxide emissions in highly polluting countries had construction improvements continued at pre-1967 rates. Had early learning rates continued, the price of electricity would have decreased, leading to higher demand and more people able to access the electricity grid. Additional nuclear power could have substituted for 69,000-186,000 Terawatt-hours of coal and gas generation. It would have spared 9.5 million lives and avoided 174 Gt of carbon dioxide emissions. For perspective, the world currently emits 36.2 Gt of CO_2 per year as of 2018. This suggests that based on historical rates, nuclear power could have prevented all global industrial emissions five times over. It is possible or even likely, in this scenario, that the threat of climate change would not exist today. The disruption of nuclear power learning rates and stalled transition to nuclear power prevented the realization of significant environmental and economic benefits from nuclear power capacity that was never built.

Although nuclear is now the world's second largest source of carbon-free power, most governments oppose nuclear power due to concerns about the technology's safety. Despite its ability to provide an enormous share of regional supply for high-capacity generation, due to its high level of power output per plant, nuclear power now provides electricity in only a select few regions around the world. Belgium, Spain, Switzerland, and Germany are currently planning a phase-out of their nuclear power plants. Current energy and climate policies in the U.S. are largely unfavorable to nuclear power, although they have improved in the past 24 to 36 months.

1.5 Fukushima to present day

The most recent nuclear accident in history occurred in Japan in 2011. The Tohoku earthquake — the third largest earthquake in recorded history — created a tsunami that hit the coast of Japan, causing three of the reactors at the Fukushima Daiichi nuclear power station to melt down. The disaster killed 16,000 people and forced many more to evacuate their homes. Worldwide panic immediately ensued over the safety of nuclear power plants; anti-nuclear politicians often reference the accident at Fukushima when they claim that nuclear power poses a threat to nearby populations. Before Fukushima, the world had been free of nuclear accidents since the 1986 meltdown at Chernobyl, the worst nuclear accident in history. Nearly a decade later, world governments still cite Fukushima as an example of the peril of nuclear power, and are still deciding on the role of nuclear energy in their future energy portfolios.

The shock of the Fukushima meltdown reverberated around the globe. The Japanese government halted operations of all 54 of its nuclear reactors, and the accident prompted other countries to begin phasing out their nuclear capacity because of public concerns over safety. Several countries with existing nuclear power programs are planning phase-outs of all or part of their nuclear fleets. For example, concerns about nuclear safety after Fukushima led to changes in Germany’s nuclear energy policy. Germany is planning to close down all of its nuclear facilities by 2022, which will mean the country will have to replace 12% of its electricity supply.

The Fukushima accident is the only nuclear accident that has caused a large external release of radioactivity. However, an examination of the series of events that caused the reactor meltdown and their specific consequences would suggest that public fear disproportionately influenced policy changes, and that misunderstanding of the cause of the thousands of deaths at Fukushima created this fear. The Tohoku earthquake and tsunami caused thousands of deaths, but the circumstances of the Fukushima Daiichi accident were vastly different than at Three Mile Island, and caused zero deaths or illnesses. IAEA estimated that at the time of the meltdown, 100-400 Petabecquerels (PBq) of iodine-131 and 7-20 PBq of caesium-137 were released into the atmosphere. Every fatality from the Fukushima Daiichi accident can be attributed either to disorganized evacuation proceedings during the tsunami (1,600 evacuees, mostly old and infirm, died during rushed evacuation) or to the tsunami itself, not to radiation or proximity to the nuclear power plant. The evacuees from Fukushima received a radiation dose similar to living in Finland for a year: higher than most other regions in the world, but still too negligible to affect health (Partanen & Korhonen, 2015, p.48). The World Health Organization (WHO) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimate that Fukushima will never cause negative health impacts anywhere in the world (UNSCEAR 2013 Report).

After Fukushima, media coverage of the disaster showed the 100,000 people being forced to leave their homes, the emergency response workers who received high levels of radiation, and the rising death toll as evacuees were unable to escape the devastation of the tsunami. Headlines attributed these fatalities to the meltdown without evidence. Whole-body evaluations of internal radiocaesium contamination among Fukushima residents revealed that the vast majority were not affected with detectable levels of radioactive contamination. Additionally, emergency response workers did not show higher levels of health problems. The response of world governments that made changes to their nuclear policy was therefore disproportionate to the actual effect of the meltdown itself.

Since the Fukushima meltdown, Japan’s government has devoted tremendous resources to recovery. Sato and Lyamzina (2018) found that public concerns have affected the ability of residents of Fukushima to return to normal life. Despite the decline in radiation to levels lower than natural background levels in other parts of Japan, residents are still reluctant to return to the area, even if their homes were unaffected by the tsunami. The team identified issues associated with radiation concerns interfering with the recovery process in the aftermath of the accident, and extensively explored the status of post-accident operations as well as public engagement efforts during recovery from other comparable events. As radiation levels in the area continue to decrease and the Japanese government reopens municipalities that were in the previous evacuation zone, various problems like lack of sufficient infrastructure including schools and hospitals, lack of employment, destroyed homes, and persistent anxiety about radiation keep evacuees from choosing to return to the area. Ex-residents fear that continuous low-level radiation exposure will cause cancer in their families and in later generations (Sato & Lyamzina, 2018).

Nuclear accidents evoke strong associations with malignancy, destruction, and invisible danger. Fear of future accidents remains so robust because a worst-case scenario has yet to happen; although extremely unlikely, the outcome could be potentially catastrophic. Although data assessments can provide data for malignancy cases among populations living close to the site of a nuclear accident, mortality from future accidents is unknown. If an accident occurs whose consequences are orders of magnitude greater than those of previous accidents, rates of cancer developments or other conditions related to radiation exposure could conceivably be far higher. With no way to predict *whether* an accident of this type will ever occur, analysis of the likelihood of accidents occurring across a spectrum of magnitudes provides useful insight into the cost-benefit tradeoff of building nuclear power plants. Probabilistic risk assessment helps predict the likelihood of different cost outcomes, but factors into an overall qualitative risk assessment.

Misrepresentation of the events that actually occurred inevitably equates the nuclear meltdown itself with the enormous loss of life and livelihoods that occurred in Fukushima prefecture, even when the entirety of these deaths were tsunami- or evacuation-related. This misrepresentation perpetuates a discourse of fear, which both misleads people to adopt a negative but uncorroborated view of nuclear power based on superficial knowledge, and causes persistent mental health issues in the region. It also delays restoration and reintegration efforts because it causes stagnation among the public. Social divisions and family separations caused higher levels of psychological trauma, and lifestyle-related illnesses became more prevalent. Recovery options are limited in Fukushima, and restoration and reintegration of livelihoods in Fukushima depends on understanding the issues that contribute to the perpetuation of this anxiety. Mental health problems as a result of continuing fear are higher in Fukushima prefecture than in other areas affected by the Great East-Japan Earthquake and tsunami, because of a gap between experts' opinions and public perceptions about continuing radiation problems (Sato & Lyamzina, 2018).

Although nuclear power has caused many orders of magnitude fewer deaths than both hydrocarbons and renewables, fears about potential future deaths are the most severe for nuclear power. Economic theory of risk aversion states that people rationally prefer a lower standard deviation for risk, meaning a lower risk of extreme outcomes. Since people are naturally risk averse, they prefer lower-risk events, even if the probability of these events is relatively higher. By contrast, a high-impact event that is extremely unlikely to occur seems less favorable, as its cost far outweighs the cost of many low-impact events. In terms of energy technologies, the perceived risk of nuclear power is much higher than that of fossil fuels, because a meltdown of the highly radioactive reactor core operating in a nuclear power plant is perceived to cause extremely widespread harm, conflating without basis in fact the destruction from nuclear weapons with the destruction caused by a nuclear reactor. Though sixty years of nuclear power operations have not seen a single accident of this kind, perception of risk is limited, in so far as past trends cannot serve to predict the magnitude or frequency of this type of low-probability, high-cost catastrophe. In the most technical terms, the most high-profile accidents to date did not inflict a fraction of the damage that could possibly (even if this possibility is near zero) occur in the worst case scenario. However, fear of extreme outcomes persists, while the public accepts deaths from air pollution and coal manufacturing as commonplace.

To expand upon the insights from Sato and Lyamzina, public aversion to low-probability, high-risk events sheds light on ways that surface-level knowledge of nuclear accidents translates in practical policy applications. Heightened fear of nuclear power after the accident was based on a superficial understanding of the actual series of events that created a nuclear meltdown and its aftermath. The location of the plant near to the coast was the reason its reactors were within range of the tsunami wave and melted down. Unlike Chernobyl and Three-Mile Island, the meltdown of the plant's nuclear reactors was not related to a malfunction that happened on its own within the plant's operating system; malfunction occurred when the tsunami compromised the protective wall and breakers of the plant (Jaczko, 2019), flooding the redundant systems, and causing the cooling systems to fail. Nonetheless, the fear and skepticism that Fukushima triggered reflect an understandable response to a shocking and traumatic incident. If misrepresentation of facts and risk profile are propagated, the negative consequences it brings for future policy will have a far worse effect, by deselecting the most appropriate set of tools with which to mitigate climate change.

With Chernobyl included, civilian nuclear power has the safest record of any industry. Zero deaths per year are reported in the civilian nuclear industry, every year since inception, with the solitary exception of 1986, to account for the less-than 100 deaths at Chernobyl.

Meanwhile, WHO estimates that air pollution from fossil fuel burning causes seven million deaths each year (WHO, 2016). For additional perspective, 200,000 deaths from medical procedures, drug use, 160,000 from tobacco, 110,000 from alcohol, 60,000 from auto accidents, and 20,000 from coal occur each year in the U.S. (Conca).

1.6 Conclusion

Medical and scientific data inform societal standards for safety as it relates to public health, but society is ultimately the arbiter of what behaviors and risks are acceptable for companies and individuals (Jaczko, 2019). In the case of nuclear power, the determination of safety as it pertains to the operation of plants, levels of radiation exposure, and other technical components is a public policy decision that balances competing interests. Norms, politics, and traditions are all involved in the determination of safety standards. Nuclear accidents ensured that fear of nuclear power became the accepted paradigm, and missteps by regulatory authorities during accident scenarios only reaffirmed these fears. The expectation of a 100% risk-free scenario is fallacious and unproductive; therefore, zero-risk is not a viable requirement for any energy system. Additionally, a balanced analysis of human health and safety impacts from energy generation must also inform uncertain outcomes. Safety concerns, which evolved into fear and revulsion, are the primary reason that nuclear power is often either entirely absent from climate conversations, or is grouped in with fossil fuels as unnecessary, harmful, and outdated. The following chapter illustrates the concerns, risks, and disadvantages of nuclear power as they compare across the current array of energy production technologies.

Key similarities and differences between these accidents are important to note. Accidents did not occur because of technological flaws inherent to nuclear power; rather, they occurred because of flawed safety protocols, miscommunication between regulatory bodies and governments, and poor design choices. All of these mistakes are avoidable with proper policy changes, regulation, and consultation between plant designers and scientists. However, all three of these accidents occurred for different reasons, and unique sequences of events determined their individual outcomes. The reasons for each of the three accidents are all avoidable.

Scholarship in the field of social psychology suggests that if an individual sees a piece of evidence as a threat to their own worldview, they are likely to immediately reject it (Cook et al., 2017). Worldview also has the complementary effect, wherein it leads people to openly accept misinformation that is consistent with the information or opinions that they already accept or believe. This type of automatic acceptance lacks scrutiny, meaning that groups of ideas become embedded in the overall ideology and discourse of a group, and identifiers tend to adopt these ideas indiscriminately. The conclusions outlined in Cook et al. illuminate the mechanisms by which nuclear fear is propagated. In the U.S., today's complaints about nuclear safety are virtually identical to the arguments that started in the 1970s. The accidents that occurred in more recent years, like Fukushima, gave anti-nuclear voices an avenue to protest the use of nuclear power as dangerous and immoral. Additionally, while mainstream concerns have remained virtually constant from their origin through to the current decade, a single event like Fukushima was liable to spur renewed fear and harden existing attitudes. The linking of the terrifying images in the public imagination to real feelings of despair, panic, and psychological distress ensured that nuclear fear became absolute (Montgomery, 2018).

Chapter II: Comparison of Nuclear Power's Ability to Make Safe, Reliable Electricity

2.1 Life cycle emissions

In several instances, environmental organizations that are opposed to nuclear power have neglected to credit it for facilitating successful emissions reduction schemes. In 2009, the World Wildlife Fund (WWF) published its WWF Climate Scorecard 2009, in which it ranked countries based on their successes at climate change mitigation. Reputable global statistics and reports found that the WWF report had falsely and arbitrarily quadrupled the electricity carbon footprint of France and Sweden, countries with high proportions of nuclear power generation, and which also had the lowest carbon balances of all industrialized countries. In the report, French electricity production had a carbon emissions of 362 gCO_2/kWh, while German electric production emitted 495 gCO_2/KWh. France's true carbon emissions is just 86 gCO_2/kWh due to its large share of low-carbon nuclear power. WWF noted that since it did not support the expansion of nuclear power, it chose to assign it carbon emissions similar to that of natural gas, an arbitrary decision uncorroborated by any mainstream climate science (Partanen and Korhonen, 2017, p.32).

Germanwatch and Climate Action Network Europe also published The Climate Change Performance Index in 2014, which claimed that nuclear power had similar carbon emissions to the dirtiest coal-fired generation (Partanen and Korhonen, 2017, p.33). Based on this arbitrary metric, a country that replaced essentially emission-free nuclear power with virtually any other energy source could actually improve its score. Mainstream scientific evidence would suggest that the organizations did not credit the countries that truly cut their emissions the fastest and the most, in order to further their own agendas. France's and Sweden's actual results were substantially better than Germany's, even though their energy use per capita increased.

2.2 Mortality

The human health and safety risks of energy generation are inextricably intertwined with considerations of the risks associated with climate change mitigation pathways. The perceived danger of nuclear power has led to opposition by advocates of its use as an emissions mitigation tool, even with acknowledgement of its potentially enormous benefit.

Leading climate scientist James Hansen and his research team published a 2013 paper that calculated the total prevented deaths from replacing fossil fuel generation with nuclear power. The paper, published in *Environmental Science and Technology*, used data for global electricity generation to calculate historic deaths and predict prevented mortality related to air pollution from projected nuclear power. The team examined the prevented greenhouse gas emissions from both historical and projected nuclear power. They were focused on providing a statistical analysis of deaths both directly and indirectly related to nuclear power, and comparing what happened to mortality rates when they substituted projected nuclear production for fossil fuels. They calculated historical effects from 1979-2009, and used recent nuclear trajectory estimates given by the UN International Atomic Energy Agency (IAEA) to make predictions for 2010-2050.

Alongside deaths per unit electricity generated, they calculated emissions for nuclear power and for fossil fuels. The team applied mortality data analysis to the world as a whole, OECD Europe, and the five most polluting countries (China, US, India, Russia, Japan, which together produced 56% of global emissions from 2009-2011). Total prevented mortality is based on historical data for deaths caused per unit of carbon emissions from pollution-related illnesses, and quantified as a measure of deaths avoided as a result of displaced emissions from global nuclear capacity. They concluded that nuclear power has been responsible for preventing 1.84 million premature human deaths worldwide.

Kharecha and Hansen estimated that nuclear power has caused fewer than 5,000 deaths globally — a number 370 times lower than deaths prevented. This includes 1,800 deaths in OECD Europe, and 1,500 in the U.S. Total deaths caused is then applied to prevented mortality to calculate the total net mortality of nuclear power. The study suggests that prevented mortality is several orders of magnitude higher than mortality caused, as a conservative estimate. This avoided mortality is directly related to the 64 gigatonnes of CO_2-equivalent emissions that have not entered the atmosphere from nuclear power generation. This estimate excludes indirect mortality, meaning deaths that have occurred from climate change-related incidents; the world's nuclear power has likely spared many more lives merely by slowing effects of warming such as extreme weather events that can kill thousands of people per year globally. The authors also noted that total deaths could be many times lower, but this was the absolute most conservative estimate that included routine occupational accidents present in any industry.

This study explores the specific role of nuclear power in relation to *mortality* from pollution. It directly compares the human health impacts from six decades of nuclear power operation with the overall performance and contribution of the technology in prevention of adverse effects from fossil fuels. It also provides projections of future prevented mortality from displacement of greenhouse gas emissions. Other studies have quantified the avoided greenhouse gas emissions from nuclear power, but total deaths directly related to greenhouse gas displacement were previously unexplored. The findings help place into perspective the need for balanced assessments of mortality related to energy generation. While future adverse effects to human health from nuclear power, such as from potential accidents, are impossible to predict, statistics from historical nuclear power accidents are heuristic. Namely, that exceedingly few deaths or injuries occurred indicates that the cost of historical nuclear power operation is close to nil. Projections of other mortality metrics like climate change and air pollution are additional tools. Past trends provide significant insight about the enormous human health risk of uncontrolled climate change and air pollution.

Several key takeaways from the Kharecha and Hansen study highlight ways that psychological distress influences attitudes on nuclear power. Their findings were published in 2013, as Japan was still freshly recovering from the Fukushima disaster. Panic about continuing radiation contamination led to fear and anger among former residents of Fukushima.

The team included all-coal and all-gas scenarios to yield the full range of prevented impacts of fossil fuels. They simplified assumptions of the future energy mix because of uncertainty about future changes in economic conditions and technological innovation. These limitations are unavoidable, as impending, unprecedented climate conditions are not linearly predictable in scope or magnitude. Other non-fossil sources could very well replace a significant portion of fossil fuel capacity in the future, but these have so far made too small a contribution to appreciably shift the data. Non-nuclear carbon-free energy sources, with the possible exception of hydroelectric power, have not made near as significant a contribution to prevented mortality from avoided emissions (Kharecha & Hansen, 2013).

Normal background radiation is present everywhere in the world, and is usually higher in denser metropolitan areas, or at higher elevations. Humans are unaffected by low levels of radiation found in the surrounding environment. Exposure to extremely high levels of radiation, however, can cause serious health problems in humans. Consensus holds that upon exposure to more than 100 millisieverts per year of ionizing radiation, humans are at increased risk for cancer. This is still 100 times the effective dose limit in many countries (CNSC). However, little or no scientific study has been undertaken with respect to high level radiation exposure because correlations are hard to trace. Virtually all known health effects are anecdotal and not codified with scientific experimentation. This makes it difficult or impossible to accurately develop safe exposure protocols. While conclusive evidence does not yet exist about the risk of harm from small doses of radiation, the evidence suggesting that this risk is too small to pose an imminent health danger is solid (Addison, 2015).

2.3 Energy generation

Further fueling the anti-nuclear movement was the increasingly popular notion that nuclear technology was not needed. Advocates claimed that solar and wind technologies were sufficient to entirely or mostly replace fossil fuels, and that scaling up these technologies if necessary was easy and economic (Partanen and Korhonen, 2017). Additionally, they argued that these technologies were already economically competitive with conventional fossil fuel sources, or were on their way to becoming competitive, while nuclear plants are getting ever more costly. A nuclear power plant produces as much power as 3.125 million solar photovoltaic panels,[1] 431 utility-scale wind turbines, or 100 million LED bulbs (United States Department of Energy).

Renewable sources like wind power, solar power, and hydro power are only able to perform as efficiently as natural constraints allow. Wind turbines rely on windy weather conditions in order to generate power, and solar panels cannot generate power without direct sunlight. Hydroelectric dams contribute a much greater proportion of clean energy than wind and solar power combined, but harm natural waterways and can only work in limited

[1] Based on the average silicon model panel size of 320 watts.

geographies. Hydropower does not experience the same intermittency as wind and solar power because water flow is relatively consistent.

The capacity factor of an energy source is important to its overall viability as a contributor to the energy mix, as well as its economic potential. The U.S. Energy Information Administration defines capacity factor as “the ratio of electrical energy generated by a generating unit for the period of time considered to the electrical energy that could have been produced at continuous full power operation during the same period” (EIA). A generator operating at 100% capacity produces 100% of the energy it is capable of producing at a given time. Nuclear power is advantageous in that it is the only energy source that routinely operates at greater than 90% capacity utilization. By comparison, utility-scale solar photovoltaic generators operate at an annual average of 27.7% capacity. Wind generators operate at annual average of 29.9% capacity. These renewables either require backup power storage, which is not currently available at grid scale, or backup baseload generation from nuclear power or fossil fuels. Accordingly, nuclear power is able to operate approximately three times more efficiently on average than renewables. Utility-scale geothermal has a capacity factor of about 78% (Partanen and Korhonen, 2015, p.).

According to the International Renewable Energy Agency (IRENA), the global energy-related “carbon budget” for meeting the Paris Accord target of less than 2 degrees Celsius of warming will only last 20 years under current emissions policies. IRENA predicts that by 2037, cumulative energy-related CO_2 emissions have a 66% chance of exceeding the budget of 790 Gt, which is supposed to last until 2100 (IRENA). IRENA proposes a global energy transition roadmap, REmap, which suggests that countries can increase their use of renewables to provide over 60% of their total final energy consumption (TFEC) by 2050.

2.4 Land Use

Renewable energy sources require more land space than nuclear power for their comparable fuel cycles. Although solar power is advantageous in that its fuel source is virtually inexhaustible, solar panels are only able to harness small amounts of sunlight at a time. As a result, solar fields must cover a large surface area in order to produce a relatively small amount of energy. Renewables manufacturing also spoils land. A typical 1,000 MW nuclear power plant requires approximately one square mile of land. Solar PV requires 75 times more land space to produce the same amount of electricity, because 3 million solar panels are needed to produce the amount of power generated at a typical nuclear plant, and even then, only 27% of the time. Wind farms require 360 times more space, and 430 wind turbines, and again, generating power only less than 30% of the time (United States Department of Energy).

Advocates for non-nuclear scenarios sometimes argue that biomass, plant matter which can be burned for energy, is a renewable energy alternative that ought to contribute significantly to decarbonization. All organic material contains stored solar energy in the form of carbohydrates, which can be burned or converted into fuels for energy — biomass refers to any type of use of organic matter for energy. Commonly used sources of biomass include wood and wood processing wastes, burned to generate heat or electricity; food and yard waste from garbage to be burned for electricity in power plants; agricultural crops used for fuel or converted into liquid biofuels; and animal manure, converted into biogas. Crops like corn and sugarcane can produce ethanol, which can be used as transport or heating fuel.

Biomass is a cornerstone of decarbonization scenarios because of its reputation as a “green” source of energy, but expanding it to the level required would severely impact biodiversity and agricultural production (Partanen and Korhonen, 2017, p.11). The supply of biomass on earth provides a renewable resource for energy generation; however, we must first grow the fuel to burn. Areas of fertile land are required for growing the monocultures that become fuel in biomass burning operations. Biomass fuels generated 5% of the total primary energy used in the U.S. in 2017.

2.5 Waste management and storage

The management of radioactive nuclear waste is one of the most significant concerns that must be addressed in discussions of nuclear power. Discussions of health risks from nuclear power typically emphasize concerns about risks involved in storing radioactive waste for several reasons. First, current storage methods are not designed to store spent fuel permanently, but waste from nuclear reactors remains radioactive for thousands of years after disposal. Second, environmental contamination that could pose a risk to humans during handling and transport of waste is a concern, as waste is present in the entire production and consumption sequence. Finally, fear and frustration among the public about living near to waste storage facilities can affect mental health.

All industries that generate electricity produce some form of waste. Management of this waste is critically important in order to safeguard human health and the environment. Waste from energy production is any byproduct of the reaction that occurred in order to release the energy stored inside a fuel source. For coal and gas generators, this waste is carbon dioxide and methane, NOx and SOx, and other particulate matter, which are released into the atmosphere during operation. No regulations exist that require coal- and gas-powered facilities to contain gaseous or particulate waste in order to prevent it from polluting the atmosphere. Waste from fossil generation is an externality, meaning that it is a quantifiable cost but does not appear in electric utilities' accounts. Society at large bears the cost of waste from fossil fuels, in the form of health care costs associated with pollution-related illness, or extreme weather damage associated with climate change. Nuclear waste, on the other hand, is a solid that never comes into contact with the atmosphere. The nuclear power industry is the only large-scale source of energy that is required to be fully accountable for all of its waste material everywhere in the world, and must contain it from the outside environment. Nuclear waste is therefore much more fully internalized into the overall economics of nuclear power.

The World Nuclear Association defines radioactive waste as: "any material that is intrinsically radioactive, or contaminated by radioactivity, and deemed to have no further use" (WNA). In countries with nuclear power, radioactive nuclear waste makes only a small contribution to overall industrial hazardous waste (<1% in the United States). Ordinary spent fuel is distinct from other radioactive waste, as it can undergo reprocessing and reuse.

Nuclear waste is made up of radionuclides. The half-life of any radionuclide, which is the amount of time it takes for half of its atoms to decay, determines its radioactivity. Particles with a long half-life are alpha and beta emitters, making them easier to handle as nuclear waste because they are not very radioactive and therefore require minimal protection to be handled by people. Alpha radiation can be blocked by the surface layer of skin. Beta radiation can generally be blocked by any thin material, such as paper, or cloth. A shorter half-life means the isotope emits more penetrating gamma rays, making the waste more radioactive, and hence requiring much more protection when being handled by people. The nuclear fuel cycle produces three types of radioactive waste: low-level waste (LLW), intermediate-level waste (ILW), and high-level waste (HLW). HLW has a shorter half-life, meaning it is more radioactive than lower-level waste. HLW comprises a small share (3%) of the total volume of radioactive waste from nuclear reactors, but this highly radioactive waste accounts for 95% of the total radioactivity in all nuclear waste. HLW contains fission products and transuranic elements produced in the reactor core from the transmutation of uranium. LLW and ILW, on the other hand, can include materials that have been exposed to low levels of radioactive contamination during reactor operation, such as gloves or tools. LLW makes up 90% of total volume of waste, but only 1% of the total radioactivity. It does not require shielding during transit and handling, and is often compacted or incinerated before disposal to reduce its overall volume (WNA).

When plants produce waste, it is submerged in water for three to five years to allow decay of short-lived radionuclides, then transported to on-site storage casks (Conca). All nuclear waste material in the U.S. is currently stored in more than 100 temporary storage sites around the country, which are designed to securely store the waste for up to 100 years (Conca, United States Department of Energy). All stages of the nuclear fuel cycle produce waste; including mining and milling of uranium ore, fuel processing and fabrication, the fuel's use in the reactor and subsequent reprocessing, and eventual disposal of waste. Careful monitoring and regulation of radioactive waste is a critical component of safety within nuclear power operation.

Nuclear waste is relatively easy to handle, as only small quantities are generated throughout the entire nuclear fuel cycle. Nuclear fuel is extremely dense. By volume, the nuclear industry produces the smallest volume of waste of any industry (Conca). The U.S. has about 80,000 tons of spent nuclear fuel, and the same amount of HLW. All spent fuel generated in the United States in the past six decades can fit into a regulation-size football field at a depth of less than ten yards (United States Department of Energy). Meanwhile, coal-fired plants produce 100 million tons of solid waste per year; two billion tons of unregulated CO_2 per year; 500 million tons of solid chemical and sanitary waste per year; and 2 quadrillion gallons of wastewater every year (Conca). Coal plants also produce 3,000 tons of uranium, thorium, and their daughter decay products each year. IAEA estimates that the nuclear industry has produced 370,000 tons of heavy metal (tHM) waste since its inception in 1956 (WNA).

Just as nuclear accidents have not caused a single death in the United States, no one has ever died or suffered a serious injury or illness from handling nuclear waste since civilian operation of nuclear power plants began in the U.S. (Markandya & Wilkinson, 2007). Standard operational injuries in nuclear power plants are the least frequent out of any industry. Existing methods of disposal of HLW are demonstrably safe.

Nuclear waste management is also safer than managing other types of waste. Solar panels create 200-300 times more toxic waste by volume each year than produced by nuclear reactors, none of which is regulated or safely contained. Lead, cadmium, and chromium are among the toxic elements embedded in solar panels. Unlike nuclear waste, none of these elements decay to become less toxic over time. Wind turbine blades also have similar levels of toxicity (Shellenberger). Coal-fired plants produce 100 million tons of solid waste per year; two billion tons of unregulated CO^2 per year, which comprise % of atmospheric CO^2 concentration; 500 million tons of solid chemical and sanitary waste per year; and 2 quadrillion gallons of wastewater every year (Conca, 16). Coal plants also produce 3,000 tons of uranium, thorium, and their daughter decay products each year. Meanwhile, IAEA estimates that the nuclear industry has produced 370,000 tons of heavy metal (tHM) since its beginning (WNA). All spent fuel generated in the United States in the past six decades can fit into a regulation-size football field at a depth of less than ten yards (United States Department of Energy).

Waste Reprocessing

Spent nuclear fuel (SNF) can undergo reprocessing to extract fissile materials for reuse. Fuel reprocessing can extract 25-30% more energy from the original uranium ore, and reduces the original volume of high-level waste by 85%. Several European countries, in addition to Russia, China, and Japan, use closed-cycle fuel reprocessing. Typically, uranium fuel takes 18 months to fully cycle through a nuclear reactor, after which fission product neutron absorbers cause the fuel to become too inefficient to use (Cravens, 2007). Some systems, however, are able to reprocess the bulk of the waste. France, Japan, and Russia practice closed-cycle fuel processing, whereby radioactive clutter is separated out and plutonium is sent back through the reactor again as fuel. This method reduces the ultimate volume of nuclear waste that the plant produces, although at marginally greater expense.

Geological Disposal

Interim storage allows for the separation of HLW from other waste. Specific requirements exist for geological repositories for nuclear waste: Simple hydrogeology and geologic history; tectonically interpretable area; assurance of isolation of all kinds of waste; minimal reliance on engineered barriers; sufficient socio-political and economic infrastructure to allow operation remote to any densely populated area. At present, natural examples have already shown that geological isolation is possible in argillaceous rocks and bedded salts (Conca, 2018). Massive salts satisfy the necessary characteristics more easily because salts have extremely low molecular diffusion and porosity. In geologic massive salt formations, globally, many salt formations meet the criteria to act as permanent nuclear waste repositories. One permanent repository, the Waste Isolation Pilot Plant (WIPP), has stored U.S. nuclear waste. Located 700 feet below ground level in the massive salt bed of the Salado Formation in New Mexico, WIPP is the only operating permanent geological repository for nuclear waste. The plant opened in 1999 and has so far disposed of over 80,000 m^3 of waste, including high level waste (HLW).

The Carlsbad Environmental Modeling and Research Center has conducted extensive environmental modeling of the area, beginning six years before the start of operations at WIPP to the present. Radiological analyses of monitoring samples from residents of the area, site workers, aerosols, water, and other sources have never shown evidence of increased radioactive contamination from the site (Conca, 2008). From a human safety standpoint, the geological soundness of massive salt deposits, as shown by the perfect safety record of WIPP, as well as the relative ease with which radioactivity can be measured, demonstrate that various other sites around the world may offer a ready solution to permanent nuclear waste disposal.

2.6 Materials Use and Acquisition

Nuclear power has the lowest material throughput of any carbon-free energy source. Nuclear generation requires 760 tonnes of concrete per terawatt-hour (TWh) and 160 tonnes of steel per TWh, while solar photovoltaic generation requires 16,447 tonnes per TWh (including cement, concrete, steel, glass, and others) and hydro power uses over 14,000 tonnes per TWh (United States Department of Energy).

Uranium mining operations have historically drawn the attention of environmental organizations concerned about the risk of nuclear power to humans and the environment (Heard, 2017). Like nuclear waste management, uranium mining is an area of historical concern with regard to environmental contamination from radioactive material. In Australia, which provides roughly 12% of the world’s uranium supply, environmental groups oppose uranium mining operations on the grounds that radioactive waste contaminates the surrounding areas and poses a danger to the livelihood of human populations living nearby. The Australian Conservation Foundation (ACF) is outspoken in its opposition to uranium mining. In one instance, the transport of nuclear waste across indigenous land created uproar within the ACF, which claimed that spillage of waste into pristine environment was an injustice to nearby Aboriginal communities (Sweeney, 2014). In December 2013, about a million liters of acid spilled at a mine site near Ranger uranium mine in Kakadu National Park. Energy Resources Australia released a statement claiming that the accident had “no impact to the environment.” In their respective reports on the event, the company’s explanations of the event were notably different. The Traditional Owners of the land spoke of feeling unsafe after the incident, which caused further outrage from ACF. However, the accident caused no injuries.

Australia’s uranium mining industry provides 35% of the country’s energy exports. mined from two deposits: Olympic Dam, and Ranger. (Ranger has depleted its economic orebody and is now only processing previously mined ore.) The 7,000 tons of uranium oxide that Australia ships each year can provide equivalent energy capacity to 140 million tons of thermal coal — capacity that is cleanly generated and displaces the need to ship vastly larger amounts of fossil fuels. Four hundred tons of uranium produces more than half the energy that 30 million tons of brown coal can produce, with virtually zero carbon emissions and no removal of topsoil. For perspective, Australia exports 100 million tonnes of coal per year, which require 3-4,000 bulk carrier voyages — many of which cut through vulnerable ecosystem environments like the Great Barrier Reef and sacred Aboriginal sites.

Uranium mining in Australia is already well-regulated. Stringent safety protocols are in place to ensure that mines always operate at radiation levels that are not hazardous to biological life or to the environment. Still, opposition to uranium mining is high on the agenda of Australian environmental organizations. Uranium mining in Australia has caused negative environmental impacts in the distant past, but stricter regulations worked to eliminate the problems that allowed for these impacts. Several case studies demonstrate that. For example, Rum Jungle was a poorly regulated uranium mine which had legacy environmental implications in the region that are difficult and expensive to remedy. Mining techniques and safety protocols have improved since the 1950s, and more stringent health and safety measures are in place for new operations.

The potential for environmental harm from unmanaged tailings is the biggest risk involved in uranium mining. Most of the nuclear waste in the United States exists in tailings from mining projects. In traditional uranium mining, these fine sandy tailings containing radioactive elements are naturally found in uranium ore. Short-term tailings are mixtures of crushed rock and processed fluids that remain in the mining site as by-products of extraction. The US Environmental Protection Agency (EPA) requires treatment of tailings by capping them with rock and clay, in order to prevent the escape of fine dust particles into the air which are a risk to human health. Globally, mining operations of all kinds produce 5-7 billion tonnes of tailings. Acid rock drainage (ARD) poses the most serious risk of long-term environmental damage related to mining tailings. ARD occurs when minerals in recently exposed rock chemically interact with water to form sulfuric acid, which extracts impurities from the tailings that pollute waterways when the acid seeps into the rock.

Fortunately, adequate planning and management of tailings virtually eliminate the risk of ARD. Disposal of tailings material into submarine and riverine systems also causes environmental harm, but only 0.6% of operations do so. Primary methods like ponds and dams to retain water, in addition to more active strategies like water balance management, have proven effective at tailings management. Management is necessary and continues to improve with increased oversight and safety standards, but stringent safety protocols ensure that radioactivity levels in uranium mining are unable to harm humans and the environment (Heard, 2017).

While environmental impacts are present in any extractive process, Heard (2017) asserts that the mineral itself is the least to blame for problems associated with mining operations. Environmental impacts from uranium mining are not entirely unique to the chemistry and radioactivity of uranium. Impacts in any extractive process can include removal of vegetation from land areas, disturbance of land from mineral removal, and possible discharge of hazardous contaminants into ecosystems. The environmental impact of uranium mining is not comparable to that of coal mining, as uranium mining does not require destruction of topsoil. Open cast mines, smelters, tailings ponds, and pollution are inherently involved in the mining of any element. The rare earth minerals involved in mining operations for the manufacture of renewable plants also create radioactive waste. The waste from these operations is comparable to uranium mining or more harmful. The potential for environmental impacts is therefore dependent on the quality of regulation of mining practices, and not influenced by the mineral involved.

2.7 Conclusion

Difficult choices are involved in dealing with climate change as quickly and seamlessly as possible. The nature of risk management means that cost-benefit tradeoffs are always present. These trade-offs are constant in everyday life. For example, people understand that balancing personal safety with other priorities, though uncomfortable and emotionally taxing, is a necessary part of the overall cost-benefit balance of our lives. Policy issues require the same level of diligent attention to all factors involved in trade-offs, whether financial, environmental, or health and safety-related. Current climate policy is responsive to public attitudes toward nuclear power, which are not reflective of the actual cost incurred from the use of nuclear power for energy provision. As this analysis has shown, nuclear power is capable of providing large amounts of carbon-free energy at the scale required for timely decarbonization. Further examination of cost relative to alternatives is necessary to aid decision-makers in rigorous consideration of nuclear power across geographies and political realities, before time runs out to fully consider all possible options.

Chapter III: Climate Change and Nuclear Power

3.1 What is needed to stop climate change, and the costs of inaction

An evaluation of the choice to use and expand nuclear power involves cost-benefit assessment of decarbonization pathways that are both inclusive and exclusionary of nuclear power. This paper explores nuclear power as a solution to climate change and qualitatively examines whether potential benefits to human health and safety of expanding nuclear power surpass the combined costs of climate change and disadvantages of the technology. In order to make an overall evaluation of total qualitative cost, this chapter examines costs and benefits of historical nuclear power expansion scenarios based on its ecological effects.

Climate change is currently the single largest threat to human health and safety. As early as 1957, scientific data had confirmed that human activity was to blame for changes to the earth's atmosphere and to the climate. Slowly, consensus formed that modern-day production and consumption of energy creates heat-trapping atmospheric emissions that lead to warming of the global atmosphere. In the latter quarter of the century, renewable energy sources and nuclear power began to take up some of the growing energy demand, but fossil fuel production continued to increase much faster. In 1979, world leaders attended the first of many international negotiations to create commitments to reduce their contributions to environmental pollution. Participation in international climate conferences increased as more world leaders began to stress the urgency of the problem of climate change in addition to pollution, but the global energy mix did not improve beyond 1990. Relative to projections for future warming, several decades of making commitments has not brought the world significantly closer to the necessary emissions reduction.

By the time experts began to direct their attention toward establishing basic axioms about climate change and predicting its consequences, two decades had already passed since the confirmation of human-caused warming. In February 1979, the first World Climate Conference was held in Geneva, Switzerland with the goal of establishing a comprehensive global emissions reduction treaty. While experts knew relatively little about the consequences of global warming, they predicted that dangerous weather conditions and air pollution would jeopardize human and non-human livelihoods. During the decade from 1979-1989, world leaders narrowly missed the opportunity to solve the environmental crisis and reverse global climate change. A few more signatures would have passed a binding commitment to emissions reduction (Rich, 2018).

The timeframe to make major changes was still relatively flexible, however. In the U.S., Democrats and Republicans largely agreed that the climate problem was a rare winner in American politics, as it was a non-partisan issue of extremely high stakes, with implications across all economic sectors. Prominent Republican leaders, including President George H.W. Bush understood the need for immediate action and called for urgent and far-reaching climate policy, as scientists of the 1980s believed that disaster would be unavoidable by the end of the decade (Rich, 2018).

The past several decades of climate governance have not achieved the meaningful reforms necessary to prevent warming. Despite a decades-long history of climate negotiations, fossil fuel energy sources currently make up only a slightly smaller share of the global energy supply than they did in 1990. Oil, coal, and gas produced 88.1% of the world's energy in 1990 and 86% in 2015. As overall energy consumption has increased substantially since the 1990s, emissions have increased accordingly. Meanwhile, zero-carbon energy sources including hydro power, biomass, wind, and solar have only increased from 6.4% of global energy production to 9.5% in 25 years. Globally, the contribution of fossil fuels to energy generation has remained virtually the same since 2005. Energy generation from fossil fuels continues to increase faster than carbon-free energy generation (BP Statistical Review, 2016).

The current environmental reality reflects these continued failures to adequately address the extent of the climate change crisis. Robert Watson, a former chairman of the UN IPCC, argued in 2016 that three degrees Celsius is the realistic minimum level of warming. Watson said that the world has a 50% chance of preventing warming greater than 3 degrees Celsius, stressing that realizing goals to reduce carbon emissions will still not rule out the possibility of an increase as high as 5 degrees if these goals are not paired with significant improvement in carbon capture and storage technologies (Kirby, 2013). A 3-degree increase would likely result in millions of people facing exposure to increased water stress and the death of the world's coral reefs (UNDP). In the absence of drastic cuts to global emissions, environmental impacts continue to worsen, in turn increasing requirements for stricter climate mitigation strategies.

The 2018 UN IPCC report projected a 20-30 year timetable for achieving large-scale global emissions reduction that keeps warming under 2 degrees.

Some regions are more susceptible than others to the effects of climate change, including small-island developing states, the world's least developed countries, arctic systems, and dryland habitats. Sea level rise poses a direct physical threat to the populations in low-lying areas like islands and coastal cities. Forty percent of the global population lives in coastal cities (Columbia University). As climate change advances, changes to the weather and geography of these places affect geological and ecological processes that are essential for habitat maintenance and, consequently, the ability of human populations to thrive. Changes to the global climate also create new and unexpected conditions that affect agricultural production and the availability of certain species that are key to the livelihoods of subsistence populations. A decrease in biodiversity as a result of species extinction will mean that resilience is lost in ecosystems, further threatening natural wilderness that is not already either destroyed or severely altered. Climate change also has adverse effects for oceans, including risks to aquaculture and fisheries as well as to the physiology and health of marine habitats (IPCC, 2018).

In addition to diminishing coastlines, extreme weather, and warming that will make some regions uninhabitable, additional environmental impacts associated with continued reliance on hydrocarbons, such as air pollution and extreme weather events, will have devastating effects on millions of people (Rich, 2018). Risks from effects like droughts and precipitation events are projected to become more extreme if warming reaches two degrees. Pollution-related health crises are also on the rise. Millions of people die prematurely each year from ambient air pollution from the burning of fossil fuels for energy. Coal-fired power generation alone is responsible for causing 3.3 million deaths each year (Conca, 2012). Climate-related human health effects are strongly linked to poverty, so non-OECD countries are highly vulnerable. Principal emissions from coal include carbon dioxide (CO_2), the primary greenhouse gas produced from burning any type of fossil fuel including coal, oil, and natural gas; sulfur dioxide (SOx), which contributes to respiratory diseases and acid rain; nitrogen oxides (NOx), which create smog; mercury and other heavy metals, which are linked to neurological damage and developmental issues in both humans and animals; and other particulates. Coal emissions also include uranium, thorium, and other radioactive isotopes, which emit far more radiation into the environment than nuclear power does on a per-unit-of-energy basis.

In developing countries, air pollution also speeds the onset of climate change-related weather events. In places like India, which experience a monsoon season and a dry season, air pollutants that build up during the dry season prevent sunlight from exiting the atmosphere, further decreasing evaporation. Without the moisture in the atmosphere that comes from evaporation, pollutants are no longer washed out in the normal water cycle. Reduced evaporative cooling also makes heat waves more frequent and severe, exacerbating drought conditions and wildfires. As pollutants become more concentrated in the atmosphere, managing the complex chemistry that produces the adverse effects of pollution will become increasingly difficult (Tibbetts, 2015). The continued use of natural gas in order to compensate for variable renewables, for example, will prolong the addition of these particulates into the atmosphere and make their effects more difficult to abate.

Assessments show that net CO_2 emissions from human activities must decrease to near-zero to stabilize global mean temperature (Davis et al., 2018). However, this decrease must account for projected population growth and intensifying global energy demands. Global electricity output is projected to increase from its current 10,000 Terawatt-hours per year (TWh/year) to 30,000 TWh/year by 2040 (Conca). To merely maintain current levels of fossil-fuel produced electricity, two-thirds of all electricity produced until 2030 must therefore come from other sources. If just half of this output came from non-nuclear and non-hydropower clean energy sources (i.e. wind and solar), these sources would require a 3,000% increase (Conca). The remaining half of the output would also need to further compensate for reliability issues. Integration of sectors that are difficult to decarbonize into a carbon-neutral energy system will also entail massive infrastructural and institutional transformations. Achieving a scale-up in carbon-neutral electricity generation that guarantees emissions stabilization requires extensive qualitative and economic modeling; current research provides some insight into which combinations of known carbon-neutral technologies are better suited for provision of essential energy services and processes (Davis et al., 2018).

Nuclear power is uniquely suited to contribute essential energy services without adding carbon dioxide to the atmosphere that will exacerbate these threats. However, it is often not considered in international negotiations about energy reform. As the risks associated with global dependence on fossil fuel energy technologies became more salient in the 1980s, public discourse began to focus on low-carbon alternatives. In 1995, the UN Climate Change Conference in Berlin (the first Conference of the Parties, or COP) brought world powers together to negotiate legally binding treaties. Governments began to devise strategies for generating the clean energy capacity that is required to phase out fossil fuels and meet rising demand for energy in the developing world. In more recent negotiations, world leaders have begun to make emissions reductions commitments in global climate negotiations like the UNFCCC COP series.

The UN Sustainable Development Goals (SDGs) outline broad targets for uniting human development with protection of the environment. Energy reform goals can be separated into three distinct strategies. The first strategy, which is to identify the “best” portfolio of alternative energy technologies to replace fossil fuels, is a primary aim of climate scientists and governments. Development of carbon capture technologies, which recover the CO_2 from sources of emissions and sequester it underground, is another strategy. Current carbon capture and storage technologies are in development, but none have been demonstrated to be economically viable to date. A final strategy is reduction in energy consumption through electricity storage, energy efficiency, and reducing demand.

Some positive developments have begun to impact overall emissions generation in the U.S. and elsewhere, but these represent a relatively gradual rate of change in comparison to the IPCC timeframe for required global decarbonization. On the whole, international negotiations have yielded largely ineffective strategies. Technological advances, decreasing costs, and stronger clean-energy policies have spurred investment in renewable energy sources. Energy generation from natural gas and renewable energy sources has experienced rapid growth since energy prices fell during the past decade. However, renewable sources like solar and wind power are non-dispatchable energy sources because they are only able to provide power intermittently. Renewable sources like wind power, solar power, and hydro are only able to perform as efficiently as natural constraints allow. Wind turbines rely on windy weather conditions in order to generate power, and solar panels cannot generate power without direct sunlight. They therefore require backup generation from an equivalent capacity in order to maintain uniform power generation most able to scale up. Hydroelectric dams contribute a much greater proportion of clean energy than wind and solar power combined, but harm natural waterways and can only work in limited geographies. Hydro power does not experience the same intermittency as wind and solar power because water flow is relatively consistent.

Overall coal-fired power also began declining in the U.S during the past decade, as natural gas has replaced the majority of retired coal power capacity. Natural gas generates roughly half the emissions of coal power, on a per-unit-of-energy basis. Energy sector emissions have declined 28% in the U.S. from 2005 levels as a result. This transition from coal to natural gas, while an overall improvement in U.S. energy production, is only a transitional step in achieving the emissions reduction necessary to limit warming to 1.5 degrees Celsius. Despite the lower emissions profile of natural-gas-fired power, total growth in renewable energy capacity has not offset the contribution of additional gas capacity. As of 2019, production and use of refined coal in the U.S. is also increasing. Refined coal has been processed to produce fewer emissions when burned, a small improvement from regular coal. Coal production in 2017 reached 33.9% of total U.S. electric capacity (US EIA).

3.2 Renewables

The intermittency of wind and solar generators make them unable to match supply to demand because increasing capacity yields marginally decreasing returns as the grid curtails more surplus capacity. The marginal value of wind and solar power therefore decreases as they become a larger part of the electricity mix because of diminishing returns of usable power. The value factor of wind power decreases by 40% by the time it reaches 30% market share, and solar power experiences a 50% value drop at 15% market share. By comparison, nuclear power never experiences a value drop because it provides steady capacity at all times, with the domestic U.S. fleet operating at over 90% capacity utilization in 2018. However, with the exception of a few small economies that rely principally on hydro and geothermal, such as New

Zealand, Costa Rica, and Iceland, no developed country currently operates a diverse renewable-powered grid.

The expansion of renewables in the U.S. came about as a result of advocacy from environmental organizations like Friends of the Earth, the Sierra Club, and Greenpeace, for a clean energy transition that relies 100% on renewables. These organizations routinely publish reports, studies, and scenarios that claim that renewables and conservation alone can solve the global energy problem. While these are both important tools, caveats and pitfalls exist in almost every one of these reports (Partanen & Korhonen, 2017, p.2) Heard et al. (2015) outlined feasibility criteria for 24 different 100% renewables pathways outlined by environmental organizations and research groups, as development of renewable energy capacity has proven disadvantageous for large-scale electricity production.

According to Heard et al. (2015), any scenario must contain a realistic projection of future energy demand. The current consensus in the social sciences community, including the United Nations, is that the world's population will grow to 9-10 billion by mid-century, so energy demand projections should adjust for this growth. Static or reduced demand is inconsistent with projections and existing trends, except for OECD member nations. Growth in per capita income and energy consumption per capita should also correspond with this population growth, though energy demand projections routinely ignore industrialization of smaller economies. Hence the underestimation of future energy demand. Fossil fuels comprise 80% of primary energy and two-thirds of final energy consumed. To date, fossil fuels have been the only energy source capable of the scale of growth required by such a growth in demand.

Second, the supply of energy must sufficiently match real-time energy demand year-round. This criterion also includes an additional margin for backup supply, a requirement to remain within regulatory limits, and considerations for climatic conditions. These additional requirements are in place to ensure that supplies meet expectations in realistic and not idealized conditions. Just as environmental groups expect arguments for nuclear power to be infallible, renewables-only proponents must present proposed scenarios with equally rigorous consideration to detail. The reliability of any power system depends on its ability to respond to disruptions in supply. The findings were that variable power was seldom generated at the times when it was demanded. Solar power generation was greatest during summer in Northern regions, while demand was greatest in the winter months. Wind power generation is often greatest during the night when demand is lowest. These examples are illustrative of the problems of matching supply with demand when variable systems are used. Another criterion required that the scenario show how critical ancillary services, such as back-up generation, or grid-scale storage, factor into the overall operation of the power system. The need for additional ancillary services increases at higher renewable penetration levels.

The team found that none of the 100% renewable energy studies that they examined convincingly demonstrated feasibility. Half (12 out of 24) relied on unrealistic energy-demand scenarios, by arbitrarily assuming either reductions in primary energy or increases in electrification. Heard et al. deemed these types of assumptions conceptually impractical. A minimum threshold of intensity is required for development of complex energy systems in places without existing power infrastructure. They demonstrated that all of the 100% renewables scenarios diverged significantly from mainstream projections for energy demand.

As subsidy-driven growth of solar power in Germany, Spain, and Japan has led to greater grid instability and enormously high feed-in tariff expenses, these countries have had to reign in solar growth (Partanen and Korhonen, 2017, p.17). Local opposition also poses a challenge to growth of large and highly visible infrastructure projects like wind and solar farms. Numerous renewable-only scenarios have called for unprecedented increases in energy efficiency, to offset the decreases in capacity.

A scenario that heavily relies on renewables for energy generation is achievable at the cost of significantly decreasing global energy use (especially the projected growth in demand in non-OECD countries) and allowing for suboptimal reductions in environmental impacts. Energy production will continue to operate in opposition to goals for sustainability and development, as it will fail to address key social, economic, and technical challenges that become much more severe without reliable baseload power. Interdependencies and paradoxes within the framework of an approach that calls for heavy reliance on renewables further weaken its practical foundation. Economic disadvantages highlight the impracticality of such a scale-up in variable generation. A 2014 report by Williams et al. concluded that an 80% decarbonization in the U.S. would cost approximately four times more if renewable sources facilitated most of this shift than if nuclear power was responsible.

Additionally, critical examination of possible renewables pathways is an important part of ensuring the success of these technologies. Studies that fail to acknowledge the limitations of renewables will only delay the development of strategies to mitigate these operational challenges, thereby inhibiting the successful use of renewables (Heard et al., 2015). Heard et al. contend that supply solutions must be scalable to realistic projections of future demand. The global scenarios that Heard et al. studied, published by WWF and Greenpeace, assumed that total global primary energy demand 2050 would be lower than it was during their baseline years. As human population will grow to nine billion by 2050, assumptions like these are implausible. When paired with highly dispatchable nuclear power, however, renewables are more equipped to contribute to scale-ups in clean energy generation that can realistically meet future demand.

Global climate conferences have called for developed countries to address their energy use and pursue “sustainable reform.” The 1992 United Nations Conference on Environment and Development in Rio de Janeiro secured growing recognition of the importance of energy in achieving sustainable development goals. First articulated in Agenda 21 from the Rio Conference and in the UN Millenium Development Goals for 2000-2015, the idea of affordable and clean energy for all became a staple of the overarching pursuit that world leaders termed “sustainable development.” Acknowledgement of the effects of climate change on the health and livelihoods of vulnerable populations became increasingly explicit. Energy poverty, pollution-related illness, and resource scarcity are projected to increase as consequences of climate change. Premature deaths from pollution-related health issues are also directly linked to availability of clean energy services.Therefore, affordable clean energy services are critical to realizing economic aspirations to elevate more people out of poverty while phasing out hydrocarbon power (IAEA).

Energy diversification is critical to ensure a low-carbon energy transition that minimizes the growing threat of energy security vulnerabilities, extreme costs, or further environmental degradation (Conca, 2018). Electricity is one form of energy, and comprises roughly one-third of total energy consumption. Other energy generation comprises that which is used in transport, building heating, and production of industrial materials. While increasing electrification of the transportation and industrial sectors is a positive development for emissions reduction, the generation and transmission of electricity from hydrocarbon-powered plants and transportation emits harmful carbon dioxide into the atmosphere, and still comprises well above 90% of these energy applications.

3.3 Carbon Capture and Storage

Carbon Capture and Storage (or Sequestration) is a collection of methods for collecting carbon from a large point source and storing it securely. CCS can potentially allow for the continued used of fossil fuel generation without contributing to atmospheric CO_2 concentrations. As base load power depends on energy stations responding to flexibility in demand, CCS is advantageous in that it allows for some margin of continued use of hydrocarbon power. Used in conjunction with other methods of emissions reduction, namely carbon-free electricity production, overall cost of electricity is minimized because fossil fuel sources can more readily vary their output in response to intermittencies from sources like solar and wind power (Boot-Handford et al., 2014). While all individual components of the chain have been demonstrated at or close to industrial scale, integration of these components into a single system remains an outstanding engineering challenge.

A review of the most recent developments in the field suggests that commercialization of some CCS technologies is potentially feasible within the next 10-20 years (Boot-Handford et al., 2014). Solvent scrubbing, oxyfuel combustion, chemical looping and calcium looping are the most developed CCS options. Current development of CCS technologies is largely focused on their application to coal-fired plants. Overcoming challenges to large-scale deployment of CCS technologies within the next few decades is crucial, as integration of climate mitigation strategies is highly time-sensitive. Capture of gaseous waste from energy generators requires energy, so CCS reduces the overall power output of the generating system. In typical coal-fired plants, for example, CO_2 capture by amine scrubbing would reduce energy output by 20-30%.

Secondary environmental impact is an additional consideration in deployment of CCS, as storing large amounts of carbon dioxide can potentially be dangerous. These factors have delayed the deployment of CCS technology anywhere on a commercial scale.

3.4 Case studies of nuclear power deployment and emissions reduction

Ongoing debate exists about the potential deployment rates of alternative energy plans that aim to meet greenhouse gas mitigation targets. Analysis of historical deployment rates of nuclear power programs suggests that it has been effective in reducing emissions on a national basis in numerous instances. The following are some practical case studies of construction and deployment of new nuclear capacity in different locations.

Sweden

From 1960-1990, Sweden's decision to rapidly deploy nuclear power generation reduced its emissions per capita despite doubling its inflation-adjusted GDP per capita. Before nuclear power came online in Sweden in 1972, the country's rising CO_2 emissions exceeded relative economic growth. As greenhouse gas reduction was not a central factor in political or environmental discourse at the time, the reduction in per capita carbon emissions was an inadvertent byproduct of the policy decision. Sweden's goals in implementing the nuclear power expansion included reducing its dependence on foreign oil imports and protecting four major rivers from hydropower installations. Emissions began to rapidly decline after the first power station, Oskarshamn-1, came online in 1972. By 1986, half of national electric capacity came from nuclear power plants, and total emissions per capita had decreased 75% from peak levels in 1970s (Qvist & Brook, 2019).

Sweden's nuclear expansion provides a historical benchmark for a rapid nuclear power scale-up scenario. Based on Swedish nuclear power deployment rates, replacing all current global fossil fuel electricity production would not take longer than two decades. Sweden built 12 new commercial reactors, which by 1986 were providing a significant proportion of its total electric output only 24 years after research on commercial boiling water reactors began in the country. From 1982 to 1986, Sweden added 740 Gigawatt hours per year (GWh/y) of nuclear powered electricity generation. Emissions declined because nuclear reactors replaced fossil-powered plants. Total energy supply from oil decreased 40%. Sweden's electricity prices after this expansion period were among the lowest in the world with all taxes and surcharges included.

France

Similarly to Sweden, France also rapidly deployed new civilian nuclear energy capacity in response to the 1970s oil shock. France is the world's largest exporter of electricity. France derives 75% of its electricity from nuclear power, due to its long-standing commitment to energy security. Given France's extensive experience with heavy engineering and few known indigenous energy sources, nuclear power seemed a practical choice that would minimize cost and imports, and maximize energy security in the country. The country rapidly expanded its nuclear capacity as part of its policy decision to favor low-cost dispatchable energy. By the 1980s, France had inadvertently contributed more to climate change mitigation than any other industrialized country. France's electricity costs are among the lowest in Europe and the country enjoys total energy independence (WNA).

In terms of speedy implementation of scalable clean energy capacity to meet economic goals, France is a success story. France implemented a successful transition to 80% nuclear power between 1980 and 1987, which rolled back its emissions to 1960s levels. While energy consumption increased by 46% during this time period, emissions dropped 28.4% from 134 million tons per year to 96 million tons per year. The French scenario is the only example of a major energy-producing country meeting Kyoto Protocol requirements. France's ambitious and sustained construction of new nuclear plants successfully reduced the number of anticipated fossil fuel plants over the next several decades.

United States

U.S. nuclear reactors generated 805 billion kilowatt-hours of energy in 2017, more than any other nation, and enough to power 73 million homes. America's 98 reactors supplied 20% of America's electricity that year. Civilian reactors have supplied more clean energy to the grid than any other source, more than all other clean energy sources combined, accounting for over 60% of the country's clean energy electric production every year since 1990. Total capacity of U.S. electricity generating plants was approximately 100 GWe in 2012 (WNA). Illinois has 11 reactors, the most of any state, which deliver 50% of its power (United States Department of Energy).

Canada

Nuclear power makes up 15% of Canada's electricity portfolio, with 19 reactors operating, mostly in the most populous province of Ontario. Canada is a leader in nuclear research and technology, and has exported its CANDU reactor systems around the globe. According to the Canadian Energy Research Institute, the country's reactors contribute C$6.6 billion to its GDP. Canada's nuclear program also creates billions of dollars in government revenue and exports, and directly employs 21,000 workers. Canada is also a world leader in nuclear research and technology, and provides a high proportion of the world's supply of radioisotopes used for medical purposes.

Ontario’s nuclear reactors account for 13.5 GWe of capacity, which is over 60% of the total electricity supply for the province of Ontario. Toronto, Canada’s largest city, with a population of over 9 million, located in southern Ontario, is world-renown for its clean electricity grid -- rated at less than 60 grams CO_2/kWh. Three large nuclear power plants in the region, consisting of a total of 18 nuclear reactors, are the principal contributors to its clean power, with hydropower capacity making up the majority of the balance. Bruce Nuclear Generating Station is currently the largest operating nuclear power plant in the world.

Developing World

Growing concern over climate change has led developing nations to consider nuclear power as a technically and economically viable carbon-free solution to growing issues of energy security. Affordable clean energy services are critical to realizing economic aspirations to elevate more people out of poverty. Nuclear power is used primarily in industrialized countries, and most reactors are in OECD countries or countries with transitioning economies. However, new nuclear construction has started to take on a different pattern: 30 out of 58 new reactors currently under construction are in developing countries. China and India have the largest nuclear programs among developing countries, with 22 reactors in operation in India and 45 in China (WNA). The IEA also projects that both total energy use and per capita energy use will grow disproportionately in developing countries, at about twice the rate of the world average, by 106% by 2030 (Environmental Progress).

South Africa is home to the only nuclear power station on the African continent, Koeberg Nuclear Power Station, located 30 kilometers north of Cape Town. The country is also one of the first in the developing world to introduce a democratically restructured power sector. So far, South Africa’s nuclear power program has lowered emissions and yielded significant economic growth in the country. Koeberg consists of two pressurized water reactors (PWRs), Koeberg I and Koeberg II, which have generated 5% of the country's electricity and 50% of electricity in the Western Cape since 1984. Each reactor is capable of generating 970 MWe in gross capacity and deliver 930 MWe to the grid. Koeberg's annual production is 13,668 GWh. Its turbine generators are also the largest in the Southern Hemisphere.

Before Koeberg Power Station began operation, South Africa relied on coal for over 98% of its electricity. Most of its main coal reserves are located in Mpumalanga in the northeast, where coal is shipped to refinement and distribution stations around the country. The South African government first considered nuclear power because transporting coal long distances to existing power stations was costly, and it was a more economical alternative to constructing more fossil fuel power stations, particularly in the Western Cape. These stations were also too small to provide adequate electricity to the province, especially as demand grew.

South Africa produced 253 TWh of electricity in 2014, of which 232 TWh (92%) came from coal and 14 TWh (6%) from nuclear. The remaining 4 TWh (2%) came from hydropower (WNA). Under the IEA "Current Policies Scenario," global coal demand is projected to be 7,500 MTCE (Megaton-coal-equivalent) in 2035. Growth of coal capacity will take place entirely in non-OECD nations, where the share of the global coal market is expected to rise from 66% to 82% during this period, and will offset coal plant closures in the OECD member nations. Globally, coal remains the dominant energy source, especially as industrializing nations significantly expand their energy generation. Electricity consumption in South Africa has grown rapidly since 1980, and the country remains heavily dependent on coal. Still, the two largest coal plants in the world are currently under construction in South Africa, and the country is the largest distributor of power to the Southern African Power Pool (SAPP). Total installed generating capacity in the thirteen member countries of the SAPP (which includes a cooperation of national electricity companies within Sub-Saharan Africa) is 55 GWe, 80% of which is South African power (IAEA).

South Africa closely mirrors the worldwide trend in income per capita during the last half-century, whereas none of its Sub-Saharan neighbors, which have no access to nuclear power, experienced comparable changes (Google public data). In 1974, one decade before Koeberg was commissioned and began operation, GDP per capita for South Africa was $1,469.85 USD. Ten years after the plant began operation, GDP per capita had increased to $3,445.70 USD. By comparison, cumulative GDP per capita for Sub-Saharan Africa was $387.26 USD in 1974, and increased to $510.67 USD by 1994, an increase of 31%, as compared to the increase for South Africa of 134.4% during the same period. Between 1980 and 1987, the real income per capita in Sub-Saharan Africa dropped by about a quarter. Meanwhile, malnutrition in the region rose sharply while food production declined relative to the population. South Africa's development indicators are therefore closer to the worldwide average than to its regional neighbors, as world GDP per capita increased from $1,326.05 USD to $4,931.83 USD during the same time period (CIA World Factbook).

In terms of immediate observable effects of CO_2 emissions, changes in mortality rates from ambient pollution require specific epidemiological studies. However, premature deaths and pollution-related health issues are directly linked to availability of clean energy services. South Africa's nuclear power program has directly contributed to increased air quality standards, as toxic emissions from burning coal decreased in the decades after Koeberg began. In 1984, CO_2 intensity was 315 grams CO_2/kWh, and this figured dropped to 287 grams CO_2/kWh by 2010.

In the developing world, expansion of electricity access has liberated portions of the developing world from relying on rudimentary fuel and hard labor for their livelihoods. However, billions of people still suffer from immediate risks to health and wellbeing as a result of environmental damage, without reaping the rewards of modernization. According to the International Energy Agency (IEA), 1.6 billion people in developing countries still lack basic access to electricity. Three billion people still rely on wood fuel for basic cooking and heating needs. An estimated 836 million people, or 11% of the world's population, live in informal settlements with almost no reliable electricity, sanitation, or robust dwellings. With no electricity access, women in developing countries spend hours of the day retrieving clean water, and are less likely to provide skillful contributions to the regional economy.The World Health Organization (WHO) estimated that approximately three billion people cook and heat their homes by burning animal dung, wood, charcoal, coal and other waste from crop yields. Indoor air pollution as a result is to blame for 4.3 million deaths each year, and outdoor ambient pollution for another 3.7 million.

Electricity is essential in modern, industrialized societies. Access to electricity is a primary driver of standard of living and quality of life, and permits extensive social benefits and conveniences. Electricity itself is relatively clean and safe for use in homes, industry, and elsewhere, but the process of generating energy that is converted into electricity is often harmful to the environment. While many societies operate without access to or use of electricity, rapid development and increasing urbanization in developing nations are linked to improved livelihoods, lower fertility rates, and increasing economic independence, especially for women. The world's urban population is expected to increase by more than 1 billion by 2030. Access to reliable and affordable energy will be a key component in this development (IAEA, 2017).

Climate leaders therefore advocate that non-fossil fuel energy generation replace current methods in order to continue to increase overall electricity production and encourage continued industrialization in developing regions.

3.5 Conclusion

Consideration of the highly complex relationships that are central to the issue of climate change is imperative in decision-making about solutions. Yet, nuanced understanding of these dynamics is not reflected in the prevailing belief system of policy makers and environmental NGOs. For example, although lowering carbon emissions is the principal objective of the Paris Agreement, consideration of nuclear power alongside renewables is absent from commitments that emerged from Paris. The former and the latter do not signify equivalence, and can have entirely different outcomes in the context of climate mitigation. It is also not well known that the UN IPCC rates the life cycle carbon emissions of nuclear power at approximately one-quarter that of solar power, and the life cycle costs at approximately equal. If this is true, and if lowering carbon emissions is the principal objective of the Paris Agreement, Solar power is disproportionately preferred as an ecologically viable energy solution over and above nuclear power. This evidence suggests conclusively that fundamental misunderstanding or bias have historically influenced, and continue to influence, prevailing notions of what is required to mitigate climate change.

Climate change poses risks to humans on multiple levels. As global climate change advances, these problems will only become more difficult to resolve, as reconciling these compounded ecological and economic consequences will become increasingly complex. The limited time frame for achieving large-scale energy reform means that investigation into the most historically effective strategies will be key. Policy-makers ought to consider the nuclear power cost-risk dilemma with broadened attention to the complex matrix of uncertainty about climate change and human health.

Chapter IV: Economic Feasibility

4.1 Economics of Nuclear Power

Economic barriers and opportunities for the management and limitation of carbon emissions are present across all energy services, all of which operate within the boundaries of current progress and policy. Feasibility concerns are also involved in the economics of nuclear power expansion to lower global carbon emissions. These factors include deployment rates, availability of nuclear fuel known to be in global uranium reserves, and concerns related to the nuclear supply chain. Energy services that are traditionally difficult to decarbonize require the consideration of a wide array of pathways toward carbon neutrality, and nuclear power can potentially be a substantial driver of a decarbonized energy system. As these key technical components will influence the net benefit afforded by expansion of nuclear power in climate change mitigation efforts, they belong within an overall cost-benefit examination of past and current expansion. This chapter will evaluate the costs incurred and benefits gained through nuclear power, and make predictions relative to the feasibility of other electricity options.

As of April 2018, 60 new reactors were under construction around the world, and 150-160 were planned. Nuclear power plants in the US support 475,000 jobs, add $60 billion to national GDP, and contribute an estimated $100 billion in exports. The economics of nuclear power involve capital costs, plant operating costs, external costs, and other costs. Nuclear power has a high up-front capital requirement for construction and licensing of power plants. Cost comparisons between nuclear power and other energy sources that appear in studies by the European Commission report that new nuclear power generation is economically competitive, and even favorable to other clean energy sources (UN IPCC, 2013, p.541). Low electricity prices are used politically to oppose long-term investment in new nuclear power, however (Shellenberger, 2018). Ignoring system-wide and external costs, as well as the quality of electricity produced, will create problems as costs of variability escalate the more that variable sources increase. Internalization of external costs involved in other types of energy generation would increase the relative favorability of nuclear power.

Plant lifetime is an additional factor. Nuclear power plants operating today have a lifespan of 60 years or longer, while the lifetime of wind and solar generators is typically 25-30 years. Investment in a nuclear power plant is therefore an investment in carbon-free energy generation for the next six decades or more, meaning the cost of solar or wind doubles in accounting for years of operation. With proper maintenance, these plants could even, in theory, last up to 80 or 100 years (Partanen & Korhonen, 2017, p.81).

Economic challenges to nuclear power include subsidies to renewables, prolonged low prices of natural gas, and deregulated electricity markets. Nuclear power receives a minute fraction of the subsidies that renewables do (Partanen & Korhonen, 2017, p.). In addition, rising natural gas prices will mean that operating nuclear plants will protect consumers and industries from future price shocks as nuclear power does not depend on global energy supplies.Long-term commitment by the state to nuclear power is also a primary driver of cost reduction because the cost structure of nuclear programs can be streamlined through construction standardization and low-interest financing. China provides an example of this. In China, nuclear power is a pillar of their Belt and Road policy (WNA).

The environmental organization Friends of the Earth campaigns for the closures of nuclear power plants as “practical, cost-effective solutions for communities and the climate.” (Judson, 2018). The organization cites concerns that decades-old coal and nuclear plants are becoming uncompetitive, and do not belong in the current energy transition toward fast-growing renewables and energy efficiency. It claims that the impact of reactor closures on emissions and electricity service reliability is easily offset by identifying cost-effective replacements. However, no reactor closure has ever been replaced entirely, or even mostly, by non-fossil power alternatives (Environmental Progress).

Nuclear plants closed in the 1990s in anticipation of economic stress from electrical industry restructuring, as well as competing power generation. While remaining reactors withstood competition from other sources of cheap power, additional closures resumed due to prolonged low prices of natural gas, rising regulatory costs, stagnant electricity demand, generous subsidies for solar and wind power, and deregulation of power markets, all placing an unfair burden on unsubsidized electricity producers. The San Onofre reactors in California were retired after steam-generator replacements were mismanaged and unnecessarily created a need for cost-prohibitive repair. Other plants, such as Vermont Yankee, Kewaunee, Diablo Canyon and others were retired because they had become unprofitable for the reasons above.

Opposition of financial support for nuclear power is based on arguments that it potentially compromises other important factors like safety, consumer protections, and investments in energy efficiency programs and renewable technologies. Approximately one-third of U.S. nuclear plants are unprofitable. It is important to note that there are ways to prevent the premature shutdown of nuclear plants, as well as to increase the profitability of suffering plants, while remaining mindful of these concerns. Power markets must be designed and operated to treat all power sources fairly, with no unfair advantages given to some clean sources while not awarding them to others. While production tax credits or renewable portfolio standards have improved the economic feasibility of renewable energy, asymmetric treatment of nuclear power plants have proven to lead to premature shutdowns, which offset any potential emissions reduction from renewables. Nuclear power plants are already zero carbon. The notion of replacing zero carbon energy sources with other zero carbon energy sources is unhelpful because of the unnecessary capital cost associated with new power sources. Furthermore, it is carbon-intensive. As above, the market reality is that premature nuclear power plant closures are never replaced 100% by zero carbon power sources, nor anything close to 100%. The power is typically replaced mostly by natural gas (Shellenberger, 2018).

4.2 Nuclear vs. Alternatives: Economic Feasibility

From an economic standpoint, all possible tools merit consideration in pursuit of the most cost-effective energy portfolio for permanent removal of nearly all CO_2 emissions from the atmosphere. World governments, NGOs, and private sector interests have presented a comprehensive suite of arguments about necessary global reforms in energy generation and distribution in order to address climate change. While parties differ on the specific composition of energy reforms necessary to halt dangerous climate change, most resolutions within the international community emphasize significant emissions reduction through a large-scale switch to non-emitting sources of energy. While a smooth economic transition is the ideal result of this transition, the world must still face the immense tasks of intermittent shortages, transition costs, and environmental degradation before economic growth can become compatible with energy reform. Additional methods of reducing atmospheric emissions that do not involve energy generation include the development of technologies to sequester carbon from the atmosphere.

Carbon capture and storage technology (CCS), geoengineering, and synthetic fuels are all possible additional options for deep decarbonization.

Nuclear power is cost-competitive with most other energy sources. However, it is difficult for nuclear power to compete in regions that have direct proximal access to low-cost fossil fuel resources. Total capital costs are 1.5 times greater than capital costs of coal and 6 times greater than capital costs of natural gas combined cycle (NGCC) (US EIA, 2016). Fuel costs contribute minimally to overall operating costs for nuclear power, but immensely to fossil fuel plants. The fuel costs of a natural gas power plant is nearly 90% of the operating costs, for example, whereas the fuel costs of a nuclear power plant is approximately 10% of the operating costs. Furthermore, the operating costs of a natural gas plant represent the majority of the life cycle costs, whereas the operating costs of a nuclear power plant, though they are expended over a period of 60 years or more, represent a small minority of the total life cycle costs — typically 25% or less. Hence, the price of natural gas poses great volatility risk for the cost of electricity, should a community or region be largely dependent on natural gas for its power. The cost of new nuclear power plants is complex, as it depends on a variety of economic factors. Location of the plant plays a part in determining costs (WNA). Market prices for fossil generation are artificially low because they are not reflective of the societal value of low-carbon energy generation, while they simultaneously externalize the immensely harmful effects of using these energy sources (UCS Report).

As different fuels are suited for different tasks, the potential of nuclear power must be compared against that of other non-fossil energy technologies that serve the same tasks, as well as carbon capture alternatives. A broad array of transition pathways have already proven effective to varying degrees. While low-carbon energy technologies display unique benefits, the specific combination of these technologies and their applicability to the region determine their true effectiveness. For example, a desert region with few riverine systems could not make use of hydro power to provide the bulk of its electricity without a substantial, potentially cost-prohibitive, investment in transmission infrastructure.

4.3 Grid-scale storage

Investment in energy storage systems would help provide additional dispatchable power during peak demand times by allowing stored power to accumulate during low-demand periods. Storage of energy is also potentially helpful in balancing the contribution of renewable sources. While oil, coal, and natural gas can be stored, the rate of electricity generation from renewable sources like wind and solar generation must match the rate of consumption. All types of generation facilities must ramp power station output up or down in order to maintain grid frequency, which incurs costs. Energy storage schemes help with this problem, as they consume power in surplus and return it in the future when needed. However, grid-scale applications of energy storage technologies based on battery technology currently do not have financial backing. In practice, over 99% of all grid-scale storage globally is provided by pumped storage hydroelectricity. That is water that is forced up from a lower elevation, using power to do so, and releasing that water down to the lower elevation when it is needed.

Battery technologies, such as lithium-ion, though often claimed by renewable energy proponents to have experienced sharp cost declines over the past two decades, and relied upon to provide load balancing of variable renewable energy, still constitute less than 1% of total global grid-scale storage capacity. The world’s largest existing lithium-ion installation is the Hornsdale Power Reserve in Australia, capable of discharging 129 MWe without a charge. However, this amount of power, though the largest installation of its kind in the world, is at least four orders of magnitude too small to supply power to the city of London for a seven-day period, which is approximately 1,250,000 MWe — a reasonable test of grid-scale storage capability. London is not a large city in the context of major Asian centers. As of 2018, there are 19 urban centers globally with populations in excess of 20 million. This number is projected to grow.

Nevertheless, the grid storage market has become increasingly competitive, as costs have indeed exhibited a trend of cost declines. Newer battery designs have improved upon the inefficiencies of conventional batteries. For example, flow batteries, such as vanadium redox batteries, while still experimental, are demonstrating the ability to supply energy for longer periods than conventional batteries can. However, energy storage capacities must match the entire rate of energy consumption at peak demand. An industrial society cannot function with interruptions of power supply. Critical power-consuming functions, such as airports, hospitals, manufacturing facilities, data centers and many others cannot bear even an instant of power interruption, without experiencing potentially disastrous results. This is a non-negotiable requirement of grid-scale storage, and at the present time, there is no remote suggestion of when this level of storage can be achieved. The Hornsdale example is illustrative of how immensely wide the gulf is between the state of the art, and the practical need. Reversible pumped hydroelectric storage schemes can function as viable storage sites, but are largely unpopular because of concerns about flooding, and are also geographically constrained. Seasonal heat storage could potentially provide dispatchable load to contribute to heat electrification (Energy for Humanity). Heat is relatively easy to store. However, this is also a geographically-dependent solution. Not all areas have underground heat sources within economic reach of the surface.

According to the UN, 68% of the world's population will be living in large urban areas by the year 2050 (United Nations, 2018). Grid-scale storage applications must meet the needs of urban power demands. Despite the broad variety of available energy storage technologies, the seasonal variation and intermittent shortages (lasting up to several days) that are characteristic of wind and solar power require that storage remain economic for longer time periods than demonstrated thus far.

4.4 Nuclear Power Applications: Economics of Energy Transition Scenarios

In 2014, Greenpeace published a report titled Energy Revolution: A Sustainable USA Energy Outlook. In the report, Greenpeace iterated its revised strategy for a nationwide transition away from fossil fuels, the Energy Revolution. The transition strategy heavily emphasized the rapid scale-up of renewable energy sources, in addition to development of carbon capture and storage technologies, to facilitate a phase-out of coal and nuclear power. It also supported the use of natural gas as a transitional replacement fossil fuel source. The Energy Revolution scenario demands a 46% reduction in primary energy demand by 2050, and projects that renewable generation will take over 87% of the remaining demand. Greenpeace plans to achieve this goal through a complete coal, oil, and nuclear power phase-out. These changes are supposed to facilitate a carbon reduction in the U.S. energy sector from 5,420 million tonnes in 2011 to 188 million tonnes in 2050, whereby annual per capita emissions will drop from 17.1 tonnes to 0.5 tonnes.

The Energy Revolution scenario requires a shift of 95% of the entire investment toward renewables and cogeneration. Meeting this goal for future investment in clean power generation would require US $6,750 billion to meet the 2050 requirements of the Energy Revolution scenario in the USA alone. This means that in order to meet Energy Revolution goals, the

United States will have to spend approximately $160 billion annually on renewables and cogeneration alone. For comparison, global clean energy investment totaled $332.1 billion in 2018 (Bloomberg New Energy Finance). The annual clean energy expenditure required for the U.S. to meet Energy Revolution growth requirements, which excludes nuclear power, would therefore be equivalent 48% of total annual world clean energy expenditure. These costs do not include grid-scale storage costs, which are currently inestimable.

From an economic perspective, these proposed scenarios present significant challenges. First, the required increase in spending is unprecedented. The United States is already the second-biggest global investor in renewable energy behind China, at $64.2 billion. In order to match average annual investment in the power sector required under the Energy Revolution scenario, current annual renewables financing would need to suddenly increase by approximately 250%. If global trends are any indicator of the ability of the U.S. to significantly increase its financing of installed renewable capacity, the International Energy Agency reported that global investment in renewables fell 7% in 2017. The IEA projected that this decline would threaten energy security and challenge climate change mitigation and pollution reduction goals. For the first time since 2014, the share of fossil fuels in total energy supply investment increased. Although investments in coal power dropped, increases in oil and natural gas spending easily offset this reduction (World Energy Report, 2017). According to world climate leaders, world investment in fossil fuel energy must decrease to 40% of total energy financing by 2030 in order to meet climate targets. Fossil fuel investment trends behaved in the contrary fashion in 2017, due to the uptick in oil and gas spending, increasing to 59%. Spending in gas-fired power stations increased by 40%. Second, the called-for increase in renewables capacity would also require unprecedented gains in conservation, energy efficiency, and rate of capacity construction, as well as the unprecedented increase in the scale of mining for the materials required for renewable power. Third, the scenario does not account for changes to renewable growth estimates when measuring actually generated energy rather than installed capacity.

One pathway that Greenpeace suggests will help make the drastic changes mandated in the Energy Revolution plan is to praise the value of natural gas generation as a transitional energy source. Natural gas generation produces roughly half the emissions of coal-fired generation on a per-unit-of-energy basis (480 grams CO2/kWh vs. 980 grams CO2/kWh) (IPCC, ibid), and has so far contributed to overall emissions reduction in the U.S. However, natural gas cannot remain part of a carbon-neutral portfolio without dramatic improvements in the economics of carbon capture and storage technology. Greenpeace states that a transitional phase is required as part of switching away from fossil fuels and nuclear power, and that natural gas used in "appropriately scaled cogeneration plants" will facilitate the eventual cost-effective decentralization of the entire energy sector that it argues is required to support an eventual renewables-only grid. Cogeneration, as outlined in the scenario, entails the combined use of heat and power generation (CHP) for electric power generation, as well as simultaneous industrial heat power production. CO_2 emissions from load following were 4000 Mt CO_2 in 2014, about 12% of global fossil fuel and industry emissions (based on the proportion of electricity demand in excess of minimum demand).

Decentralization of the energy distribution system is also requisite for the Energy Revolution scenario. Large-scale renewables require a decentralized system, meaning energy is generated near to the point of use rather than in a centralized location, which would require a complete transformation of the existing energy system. As the current grid is designed for large, centralized base load generators, optimized integration of renewables as the primary purveyor of energy supply will be disruptive to infrastructure which has been in use for many decades.

The IEA also projects that both total energy use and per capita energy use will grow disproportionately in developing countries at about twice the rate of the world average, by 106% by 2030. Over 2,400 GWe of new capacity will be needed in developing countries by then, which means developing countries are projected to produce more electricity than OECD countries. Still, the projected gap in per capita electricity use for 2030 is substantial: 2,300 kWh per capita in developing countries and 10,400 kWh per capita in industrialized countries. Scenarios that include the phasing out of nuclear power in favor of renewables and natural gas must take into account rising demand for energy, otherwise the increases they call for are infeasible.

To further break down global energy investment, a report from Bloomberg NEF that created preliminary estimates for annual new wind and solar PV capacity added worldwide shows the following. Solar PV capacity additions totaled 10 GWe from 2017 to 2018. Wind capacity increased by 47 GWe globally in 2017 (BP, 2018), even though wind saw $125 billion in new asset investment globally during that time period. The biggest wind projects were the 706 MW Enel Green Power South Africa portfolio, which cost approximately $1.4 billion, and the Xcel Rush Creek installation in the U.S., which cost an estimated $1 billion for 600 MW. Together, these projects add an estimated 1.1 GW to total world wind capacity, and cost world governments approximately $2.4 billion. A 1.1 GW increase is equivalent to about 1.4% of total wind power generated in the U.S. alone in 2016 (EIA), or a mere 0.1% of global wind power. Assuming costs remain the same, expanding global wind power to 40% of global energy capacity, as Greenpeace recommends, would require global wind power investments to sharply increase to approximately $4.3 Trillion. However, this is only for capacity of 40% of electricity. Because wind's average capacity utilization is less than 30%, this is not a complete estimation of costs to replace fossil fuel or nuclear or hydro generation, which all have capacity utilization of nearly 100%.

The capital cost of adding nuclear capacity ranges widely. In China and South Korea, recent cost data suggests that the capital costs are less than $4 USD/Watt. However, cost data in the USA and Europe are much higher, ranging in practice from $8 to $13 USD/Watt, or even higher. Again, nuclear capacity additions are fundamentally different from wind capacity additions for two reasons: 1) they operate at nearly 100% capacity utilization, substantially decreasing the need for grid-scale storage, or back-up power systems, and, 2) they can be built near the point of demand, substantially decreasing the need for capital development of transmission infrastructure.

A technology-neutral energy transition scenario, which would not entail the phase-out of current nuclear power generation, would be far less costly. If the international community invested the equivalent amount in nuclear energy that Greenpeace proposes the U.S. invest in renewables, current global nuclear capacity could increase ten-fold. On a per capita basis, nuclear power has added capacity at least twice as fast as any national renewable solar and wind addition. The Swedish example suggests that deployment of new nuclear capacity can rapidly increase even while GDP expands. Global trends in renewables investment are not reflective of commitments to expand these technologies. 2018 estimates of world clean energy spending show an 8% decrease from 2017, including a 24% decline in solar commitments partly due to sharply declining capital costs. Countries are beginning to phase out politically determined tariffs, which fed the early growth of renewable energy, because the new electricity from renewables becomes less valuable as their share of total energy production increases. The vision within the Energy Revolution scenario for decentralized electrical production will require dramatic alterations in the business operations of utilities, energy technology manufacturers, and other energy suppliers. Examining the economic feasibility of the type of change necessary requires analysis beyond the scope of the report. Policymakers must consider the magnitude and timing of carbon reduction schemes when making decisions about where to allocate financial support.

Modern economies demand highly reliable electricity, meaning demand must be met 99.9% of the time. A reliable electricity supply is inclusive of industrial applications, which require year-round, reliable heat energy. As the share of renewable energy has grown in the U.S., natural gas-fired generators have increasingly been used to provide flexibility because of their generally low fixed costs and ability to ramp up and down quickly. A combination of known technologies related to essential energy services and processes is required, but costs are still a barrier in every category. Large-scale electrification of other sectors means that demand for energy services and processes associated with these difficult-to-eliminate emissions will increase into the future. Davis et al. estimates that by 2100, emissions from these services in the U.S. will be comparable with the current level of total U.S. emissions. Investment in energy generation or storage assets that can be used a small percentage of the time, when demand is higher than base load or variable generation, is a requisite for decarbonization of these services. Therefore, the implementation of large-scale carbon-free energy portfolios with high levels of generation flexibility will necessarily bolster these services (Davis et al., 2018). Nuclear power is one such energy source whose value never decreases over time, because generation can adjust to lower relative demand. Policy makers ought to take into consideration these future costs in overall economic evaluations of energy quality.

Conclusion: The Cost of Opposing Nuclear Power

5.1 The Politics of Uncertainty

Anti-nuclear arguments about the nature of safety and the need for improvements are frequently self-contradictory. If nuclear power was truly safe, one might argue, there would not have been decades of disagreement between industry lobbyists, regulatory bodies, and the public about the need for improvements in safety. One might also argue that the accidents and near-accidents that occurred at U.S. plants would not have even been possible had safety been a non-issue. These arguments signify the broader expectation that nuclear power not pose a threat to public health and safety which, at face value, is reasonable. Safety standards are incorporated into every type of industrial production or service. However, the arguments themselves are contingent upon an all-or-nothing value judgment of safety rather than statistically supported evidence of *relative* safety.

Scientific research can necessarily distill the true overall net human health and safety effects of nuclear power and other energy sources into numerical data, thereby mitigating miscalculation of risk in policy-making. However, scientific evidence on its own has not assuaged public fear, nor has it been sufficient to eliminate black-and-white conceptualization of what constitutes safe operation. Socio-psychological analysis, which offers insight into ways the human mind manages and processes uncertainty, is needed alongside rigorous statistical analysis. Kharecha and Hansen's results show that nuclear meltdowns appear much more threatening as stand-alone events than when they are factored into historical statistics. Mortality from routine coal plant operation is several orders of magnitude higher than total nuclear-related deaths, including from accidents. Based on their evidence, nuclear power has contributed more to simultaneously reducing global mortality and carbon emissions than any other power source. Japan has since begun plans to diversify its energy portfolio, which has relied mostly on coal and natural gas from LNG imports, and has recommissioned eight of its nuclear reactors since the Fukushima accident. Fukushima prefecture is a safe place to live. Still, nuclear fear pervades the public imagination and the climate policy agenda in the U.S.

Uncertainty and human error are embedded within the process of innovation and the use of technology. None of today's technologies is risk-free, in any industry. Physical and mental health are both at stake when we decide to use technologies to enhance our lives, but we choose to continue the innovative process of improving their safety and effectiveness rather than discontinuing their use. Tens of thousands of people are killed yearly in the U.S. from automobile accidents, but automobile purchases continue to increase. People still drive even with the knowledge that accident likelihood is relatively high, and that they have no control over the behavior of other drivers on the road. Car manufacturers continue to market new and improved safety mechanisms to increase competitiveness of their product. Unlike driving a car, though, operating a nuclear power plant requires extensive professional training — which includes safety protocols designed to protect the public from all known possible accident scenarios, including terrorist attacks. Even when these protocols were not properly followed during the Three Mile Island accident, disaster did not ensue and no one was injured. With the exception of the reactor designs at Chernobyl, nuclear power has demonstrated technological soundness and high standards for safety. Over 30,000 people die from car fatalities in the U.S.

alone every year, and over 2 million suffer injuries (CDC); zero die per year from nuclear power.

5.2 Paradoxes in Attitude Development

When measured against all other energy sources, the total mortality and health damage from nuclear accidents is extremely small in comparison.While skeptics may acknowledge the carbon-reducing capabilities of nuclear power, they may continue to dismiss it as dangerous to public health. Several key instances illustrate the influence of these arguments, even in the absence of compelling data. In the mid-1970s, the then-head of the Sierra Club sent a memo to its board of directors about its recommendation to stress the hazards of nuclear power in order to promote the rationale for stricter regulations. At this time, no scientific study had been published showing that nuclear power was as hazardous as they claimed. It was a strategy directed at making nuclear power cost-prohibitive by causing sharp increases in regulatory costs (Shellenberger, 2019). The strategy was successful.

Energy provision must have regard for minimizing public health impacts in addition to environmental impacts, whether these effects are related to energy generation or to obtaining and disposing of fuels. However, arguments that focus entirely on the hazards of nuclear power ignore measures in place for risk management, as well as the historical safety metrics that quantify its relative performance. This in turn fosters a false narrative that the presence of risk and the occurrence of accidents mean that nuclear power is an irredeemably dangerous technology. The fear of nuclear danger becomes so resoundingly absolute (Montgomery, 2018), that people associate nuclear risk with worst-case outcomes and opposition to nuclear power on safety grounds becomes excessive and misplaced. Consideration for risk aversion must become paired with an inclusive array of cost-benefit trade-offs surrounding the central goal of climate change mitigation.

5.3 Implications for Policy

No renewable energy technology or energy efficiency strategy has ever been implemented at the scale necessary to achieve the CO2 emissions reduction appreciably close to strict requirements outlined in any climate change mitigation study (Qvist & Brook, 2015). Given the severity and magnitude of the challenge of climate change, any climate change mitigation scenario will be strictly based on extrapolation of existing data and conservative assumptions about future demand. Current policy still requires more stringent consideration of practicality and timescale, and removal of the impediments of nuclear power expansion and innovation is a first step toward more technology-inclusive and strictly evidence-based energy policy.

The nuclear industry is flawed in several important ways, and addressing these flaws in a serious and timely manner is crucial for the continuation of nuclear power plant operation. Opponents are wise to demand that nuclear power advocates address each concern separately and comprehensively. Active voicing of these concerns has in fact led to increased understanding of challenges involved in the safe operation of nuclear plants, as well as the behavior of core-damage accidents and the potential of accidents to cause harm (EPRI). Increased regulation, more intensive application processes for plant owners, and more stringent operator training protocol all came about in response to industry stress after major accidents, even when these accidents happened in other countries (Jackzo, 2019). Advocates are, however, misplaced to assert that nuclear power presents far too great a risk to human health and safety simply because of the existence of numerous concerns — or because they assume that more opportunities for error must mean even greater risk — in the absence of evidence overwhelmingly demonstrating that the combined areas of concern have indeed caused statistically significant harm. In order to identify where flawed argumentation techniques contribute to the misrepresentation of the true meaning and significance of risk, balanced analysis of factual evidence regarding risk in comparison to alternatives is required. Regular assessment of benefits and costs based on updated data is an appropriate policy goal for deployment of energy generation (WNA).

Consideration of statistical analysis of mortality from energy generation in the U.S., coupled with psycho-social elements of economic theory, points to a compelling puzzle about the persistence of nuclear fear. Superficial or incomplete understanding of historical human health effects of nuclear accidents, including the causes of these effects, has heightened public perception of nuclear danger. When compared against the same metrics for all other energy sources, however, mortality from nuclear power is negligible. Despite evidence of extremely low total mortality, risk aversion theory provides insight into the natural tendency of human beings to minimize uncertainty by favoring higher-probability, low-cost events. Additionally, cultural representation of nuclear power has allowed misconceptions to propagate within the public imagination, which maintained the image of disaster and dread associated with nuclear technology of any sort. This fear and dread has, over time, become divorced from the fear associated with climate change, leading to the exclusion of nuclear power from climate agendas, even though the extremely low emissions profile of nuclear energy generation has helped to avoid millions of climate-change related deaths. More expansive and rigorous research is needed to identify the optimal combination of strategies that can most speedily and costeffectively address the emissions from burning fossil fuels, and inform policy makers about energy reform pathways to combat climate change.

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