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NUCLEAR POWER AND CLIMATE ACTION

An Assessment for the Future

By Tim Judson

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The Rosa Luxemburg Foundation is an internationally operating, progressive non-profit institution for civic education. In cooperation with many organizations around the globe, it works on democratic and social participation, empowerment of disadvantaged groups, alternatives for economic and social development, and peaceful conflict resolution. The New York Office serves two major tasks: to work around issues concerning the United Nations and to engage in dialogue with North American progressives in universities, unions, social movements, and politics.

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Presentation

When nuclear power started to develop into an ever more important source of electric energy during the second half of the twentieth century, there grew widespread optimism regarding the potential of this seemingly unlimited, clean and, in the long run, economic resource. The unresolved problem of how to dispose of nuclear waste—which degrades very slowly, with a half-life of up to 15.7 million years—existed from the beginning but was widely ignored. Instead, much hope was placed in finding a solution to this problem—a solution that, up to this date, still does not exist.

Those who were skeptical of nuclear power were proven right by the accidents of Three Mile Island in 1979, Chernobyl in 1986, and Fukushima in 2011. The latter two incidents in particular encouraged demands for a nuclear power phase-out and led to the establishment of phase-out plans in several countries, including Germany. When the urgency of climate change, along with the necessity of rapid decarbonization, became more evident, many scientists and activists alike pleaded for the use of nuclear power as a transitional technology. They argued that the use of nuclear power could help to avoid shortages in energy supplies caused by the relative unreliability of renewables like wind and solar energy.

In this important new study, Tim Judson, Executive Director of the Nuclear Information and Resource Service (NIRS) and renowned nuclear power expert, does away with persistent myths about the importance of nuclear power. Starting not from an abstract position but by considering real-world events, the author demonstrates the very concrete challenges that the production of nuclear power poses for the environment as well as for our economy.

In addition to the long-lasting environmental impacts of nuclear power production, Judson pays attention to how it affects communities—and in particular poor communities of color—through the mining and processing of uranium as well as the disposal of nuclear waste. While mainly focusing on the production and use of nuclear power in the US, as well as possible phase-out scenarios, this study can easily be applied to other contexts around the world. Informed by global trends in climate change, this study is of utmost urgency in showing us a path toward a nuclear-free, sustainable future.

Rosa Luxemburg Stiftung—New York Office introduces this study as an opportunity to carefully investigate the possible potential as well as the dangers of nuclear power, and the question of its suitability as a transitional technology. It is a pleasure for me to present you this text today.

Andreas Günther
Executive Director of the New York Office, November 2018

Nuclear Power and Climate Action

An Assessment for the Future

By Tim Judson

There is a growing consensus on the urgency of ambitious action to mitigate the scale and scope of global warming. This imperative has been elevated by a report issued in October 2018 by the Intergovernmental Panel on Climate Change (IPCC). In short, the global panel of climate scientists has found that the continued addition of greenhouse gases (GHG) must be dramatically reversed by 2030, or else severe climatic changes will "significantly worsen the risks of drought, floods, extreme heat and poverty for hundreds of millions of people."[1] These trends are expected to increase economic, political, and security risks to even the wealthiest and most powerful nations.[2]

The IPCC report finds that, in order to limit average temperature increases to 1.5°C, global greenhouse gas emissions must be reduced by 45% by 2030, and reach net zero by 2050.[3] The report also shows that achieving those targets is still feasible and affordable, but ambitious, sustained action is needed. Fossil fuels constitute about 85% of total energy use, both worldwide and in the U.S. Decarbonization, then, requires replacing the vast majority of our current energy sources within 30 years or so. As one news report aptly summarized: "The details in the report are worth understanding, but there's one simple critical takeaway point: we need to cut carbon pollution as much as possible, as fast as possible."[4] In that light, one of the essential questions is what actions we need to take in order to phase out the use of fossil fuels that quickly as well as what it will take to make that happen.

It is not enough to say that we have to pursue every low-carbon technology. The resources to achieve decarbonization are available—including time and money—but they are not unlimited. Time is short and solutions need to be as cost-effective as possible to ensure there is enough finance/capital. At the same time, because of the advance of climate change, ecosystems and vital resources, such as drinking water, biodiversity, arable land, fisheries, etc., are increasingly under stress and must be protected. Strategies to reduce emissions have to be rapid, affordable, dependable, compatible, and sustainable. In short, we cannot afford to waste time, money, resources, and political will on technologies and policies that impede the pace of decarbonization, involve significant uncertainties, or further compromise the natural environment.

This short report presents an overview of the very real and practical reasons why nuclear power is not going to be a viable tool in the climate solutions toolbox, and why states and nations should plan on nuclear-free paths to decarbonization. Rather than looking at the question through the abstract lenses of emissions and energy resource mix modeling, it is important to understand the real-world trends and conditions of this technology in particular. Nuclear power is a mature industry, and its prospects can be assessed with an understanding of its track record, trends, and economic and technological challenges. The report presents examples and recommendations for how nuclear can be phased out in concert with decarbonization.

It also provides models for how to minimize the negative impacts of the energy transition while maximizing the benefits and avoiding negative political feedback loops that could impede or derail the multi-decade project. The report is informed by the global picture, but focuses on the U.S. as a useful microcosm, because it has the largest nuclear industry in the world, is the largest emitter of greenhouse gases historically, and remains the second-largest GHG emitter today.

It is essential to keep in mind that there are countervailing reasons to avoid reliance on nuclear power as much as possible, which are as significant and real to affected communities and regions as the risks of climate change. Many of the problems with nuclear power intersect with impacts of climate change and a number of them compound the risks of global warming. For those and related reasons, a number of countries have decided to phase out nuclear power concurrent with decarbonization. Germany, Italy, Scotland, Taiwan, and South Korea have all have set such goals, and France has established a goal to reduce its reliance on nuclear. Among U.S. states, California, Iowa, Oregon, and Vermont have all made or implemented plans to phase out nuclear and are dramatically reducing fossil fuel consumption as well as increasing renewable energy production. These jurisdictions demonstrate that pursuing nuclear-free paths to decarbonization is not only possible and preferable; they are discovering that it is likely beneficial and even necessary to do so.

Not Clean, Not Safe

Unlike renewable energy sources, such as wind and solar, nuclear power generation entails major, long-lasting environmental impacts and damage to natural resources. The mining, processing, and enrichment of uranium for reactor fuel produces immense amounts of radioactive waste, and has an extensive track record of contaminating land, air, and drinking water. This disproportionately affects indigenous peoples and developing nations.

The cooling systems of nuclear reactors also place stress on drinking water sources and ecosystems, typically withdrawing more than a billion gallons of water per day, and discharging hot water and radioactive effluents. Reactors produce numerous streams of radioactive waste, including irradiated ("spent") nuclear fuel, which is lethally radioactive for hundreds of years and environmentally hazardous for up to a million years. Indigenous nations and communities of color are most often targeted for radioactive waste dumps.

The consequences of nuclear disasters such as Chernobyl and Fukushima are as overwhelming and long-lasting as the impacts of climate change. Due to rising sea levels, increasing frequency and severity of extreme weather events, and rising water temperatures, the potential for nuclear disasters is increasing along with other risks of climate change. Reducing the chances of compounding catastrophic events should be viewed as a climate adaptation measure.

Nuclear Power: An Industrial Analysis

Some argue that nuclear power is necessary to reduce GHG emissions on the premise that decarbonization will require using every low-carbon resource available. The implicit assumption is that nuclear power is a viable tool in the climate toolbox because it already exists. That is wishful thinking, at best. Uninformed assumptions about nuclear energy are a weak foundation for a decarbonization strategy. More specifically, they routinely fail to recognize the following practical realities about nuclear energy and trends in the industry:

- ⇒ Relative to fossil fuels, nuclear power represents a small amount of global, regional, and national energy supplies. Focusing on nuclear tends to distract from the big picture.
- ⇒ Building new reactors has proved to be too expensive and technically challenging to do with the speed, scale, and dependability needed to meet GHG reduction targets, or even to replace currently operating reactors.
- ⇒ Nuclear reactors throughout the world are aging and becoming increasingly expensive to operate. The vast majority will retire before 2050.
- ⇒ Renewable energy sources have proven technically and economically capable of the type of dramatic expansion necessary to decarbonize (and denuclearize) energy supplies.
- ⇒ Nuclear reactors are the most inflexible generation sources and do not integrate well with renewables, which require flexible and responsive energy systems.

Decarbonization strategies must anticipate a significant decrease in nuclear power within the 2030 and 2050 timeframes, if not a total phase-out. As the fossil fuel and nuclear industries decline and lose the economies of scale that they have enjoyed for decades, they will face rising costs of production and increasing economic pressures. Recognizing these realities, phasing out nuclear can spur development of renewable energy and efficiency, and help to accelerate decarbonization.

History, Recent Trends, and Modern Competitors

Civilian nuclear power is a mature industry. Founded in the 1950s, it emerged from military technologies and government-sponsored research and development programs undertaken by some of the largest and most advanced technology and engineering firms in the world: In the U.S., these included Westinghouse, General Electric, Babcock & Wilcox, Stone & Webster, and Bechtel. Westinghouse and General Electric designed most of the first generation of reactors in use today worldwide, usually under partnerships and licensing agreements with corporations in France (Framatome), Japan (Toshiba, Hitachi), and other countries.

The industry has benefited from heavy government sponsorship and favorable policies from its inception. From 1950-1993, nuclear power accounted for 62% of total energy R&D in the U.S.[5] The Price-Anderson Act, extended repeatedly from 1957 to 2025, currently caps the industry's limit for primary and secondary liabilities for nuclear disasters at a total of $13.06 billion, and it indemnifies private insurance carriers from covering any such damages. The Nuclear Waste Policy Act adopted in 1982 establishes federal government responsibility for the permanent management of commercial nuclear waste. These and numerous other direct and indirect subsidies for nuclear "have often exceeded the value of the power produced."[6]

Despite such support, after nearly 60 years, nuclear power only represents a small contribution to energy supplies globally and nationally. In the U.S., nuclear is only 8.6% of total primary energy use, ten times less than fossil fuels; globally, it is only 4.4% of the total energy supply, nearly 20 times less than fossil fuels.[7] Since 1996, nuclear's share of global electricity has declined from 17.5% to 10.5%.[8] While nuclear power is a significant source of energy in a few places—it constitutes 38% of primary energy in France and 48% of electricity in Illinois, for example—they are the exception.

That trend will continue through 2030 and 2050, as reactor construction has no prospect of keeping pace with retirement of reactors, the majority of which were built in the 1970s and 1980s. If all reactors in the world that are currently operating and under construction serve out their current operating licenses, the number of operating reactors will decline nearly 40% by 2030 and nearly 80% by 2050.[9] In the U.S., the number of reactors would decline by 24% in 2030 and 97% in 2050.

In contrast to nuclear power, wind and solar have demonstrated dramatic decreases in costs as the technologies have matured and the industries have expanded. Nuclear generation as a whole has increased due to improved operating performance, but total nuclear capacity has effectively been flat since 1990. Due to the slow rate of nuclear construction (averaging 10.1 years for reactors that started up in the last ten years), small increases in capacity have barely offset retirements. The last decade has seen the first appreciable increase in reactor construction since the 1980s, but the levelized (unsubsidized) cost estimates have increased by 20%.[10] In the U.S., actual construction costs have grown even more dramatically from original cost estimates, with reactors in Georgia and South Carolina nearly tripling in cost by the time they are 50% built: from $4.3 million/MW in 2009 (pre-construction) to $11.4 million in 2017 and $12.5 million in 2018. Renewable energies, particularly wind and solar, have exhibited precisely the opposite performance. Costs have declined dramatically over the last decade, with unsubsidized wind costs falling 67% and utility-scale solar costs falling 86%. Both are now the lowest cost sources of energy generation. Wind and solar have also sustained high and even increasing growth rates over the last 18 years. From 2007-2017, total nuclear generation declined by 200 million MWh worldwide while renewables increased by more than 3 billion MWh.[11]

The same trends are evident in the U.S. where nuclear declined slightly from 2007-2017 (-1 million MWh) whereas wind and solar increased by 313 million MWh.[12] In some regions of the U.S. renewables are now growing at scales faster than nuclear power ever has. Texas has more nuclear generation than all except six states, but in 2017 it generated 50% more electricity from wind than it does from nuclear power.[13] In fact, Texas generated more electricity with wind than all other states (except two) do with nuclear. In just three years (2014-2017), the state expanded electricity from wind by 27 million MWh—as much as three new nuclear reactors could generate. Texas is not an isolated example. Over the same three-year period, four other states also increased renewable energy in amounts equivalent to, or greater than, nuclear reactors generate: California (14.5 million MWh of solar); Iowa (5.2 million MWh of wind); Kansas (8 million MWh of wind); and Oklahoma (12 million MWh of wind).

The Science is In: Nuclear is Out

A thorough assessment of the conditions facing the nuclear industry has recently concluded that nuclear power will not play a meaningful role in addressing climate change. In July 2018, a panel of the U.S. National Academy of Sciences—the country's highest scientific body—published the findings of its multi-year investigation. The panel found[14] that nuclear power will be incapable of playing a role in reducing GHG emissions in the critical mid-century timeframe for several reasons:

1. The current fleet of reactors is shrinking: Advanced age and lower-cost renewables and other alternatives have "turned nuclear reactors into mid-merit generators." Extending their operations through subsidies will only slow the pace of retirements, and license extensions "will require expensive refurbishment and careful regulatory consideration," increasing their costs further.
2. Contemporary reactor designs have proved not to be commercializable: "Recent efforts to kickstart nuclear construction in the United States have failed. … These reactors have proven unaffordable and economically uncompetitive. In the few markets with the will to build them, they have proven to be unconstructible." Twenty-eight out of thirty proposed reactors have been cancelled, and the prospects for completing the final two remain uncertain.
3. New "advanced" reactor designs are decades away from commercialization: The Department of Energy "has spent $2 billion on this effort since the late 1990s, with very little to show for it." The increased spending and multiple reforms necessary to commercialize advanced reactor designs are "all very heavy lifts."
4. Small modular reactors (SMRs) are likely to be even less economical than contemporary reactors: SMRs are being promoted as the next great "solution" to making nuclear power commercially viable, but the panel found "the vision of the dramatic cost reduction that SMR proponents describe is unlikely to materialize. … Because light water SMRs incur both this economic premium and the considerable regulatory burden associated with any nuclear reactor, we do not see a clear path forward for the United States to deploy sufficient numbers of SMRs in the electric power sector to make a significant contribution to greenhouse gas mitigation by the middle of this century." Also, "several hundred billion dollars of direct and indirect subsidies would be needed to support their development and deployment over the next several decades."
5. The policy rationales for government intervention to develop SMRs are infeasible or inadvisable: There are few to no viable options to "hybridize" the use of SMRs for electricity and other industrial purposes (e.g., desalination) to improve their economic value. Direct government procurement of SMRs—for instance, to power military bases—would be impractical and would violate non-proliferation norms separating military and civilian nuclear programs.

The panel acknowledged that it favors nuclear as a climate solution, which lends greater weight to its conclusions about the obstacles to and viability of nuclear. The scale of unprecedented, sustained government preferences and interventions that would be necessary to advance nuclear far exceed those necessary to advance renewable energy-based paths to decarbonization.

Old Reactors, Existential Challenges

The NAS report was published against the backdrop of an emerging trend of reactor closures in the U.S. Seven of 105 operating reactors have retired since 2013, including Kewaunee (Wisconsin), Unit 3 at Crystal River (Florida), Units 2 and 3 at San Onofre (California) in 2013, Vermont Yankee in 2014, Fort Calhoun (Nebraska) in 2016, and Oyster Creek (New Jersey) in 2018. Another twelve plant closures are planned over the next seven years, including Pilgrim (Massachusetts) and Unit 1 at Three Mile Island (Pennsylvania) in 2019; Unit 2 at Indian Point (New York), Davis-Besse (Ohio), and Duane Arnold (Iowa) in 2020; Unit 3 of Indian Point, Perry (Ohio), Unit 1 and Unit 2 at Beaver Valley (Pennsylvania) in 2021; Palisades (Michigan) in 2022; Unit 1 at Diablo Canyon (California) in 2024; and Unit 2 at Diablo Canyon in 2025. Some assessments have predicted that as many as half of the nuclear power plants in the U.S. will be uncompetitive by 2020.[15]

The factors driving this trend are evident: The costs of operating nuclear reactors are rising significantly as they age, while electricity prices have become much lower (see textbox). As a result, several reactors have become unprofitable in the near-term. In the long-term, lower electricity prices and strong growth of renewables and efficiency will make more reactors less competitive as they age, operating costs increase, and the role for inflexible "baseload" generation sources like nuclear and coal decrease.

Competitive Headwinds

Rising operating costs: Reactors in the U.S. are nearing the ends of their mechanical lives, and their operating costs increased over 50% from 2002-2012 to $44.17/MWh.[16] 2016 estimates suggest average costs might have come down to $33.12/MWh, but were still nearly 28% higher than in 2002.[17]

Lower electricity prices: Market prices for electricity have declined by about 60% nationwide from 2008-2016 to around $30/MWh.[18] This trend was initiated by the advent of low-cost natural gas from horizontal hydraulic fracturing made possible by major environmental exemptions enacted in 2005. Energy efficiency and renewables have become major contributors to low market prices since 2010, making nuclear less competitive going forward.

Lower electricity demand: Instead of the 3% per year growth rates the utility industry has historically planned for, electricity demand has been stagnant and decreasing, even as the overall economy recovered since the 2008 recession.

Surplus generation capacity: Lower demand has contributed to a large surplus of generation capacity in many parts of the country, leading to stiff competition among power plant owners.

Increasing energy efficiency: Efficiency and other cost-effective forms of consumer demand management have become mainstream resources, helping to keep market prices for electricity lower.

Wind and solar: The costs of wind and solar have declined dramatically since 2010. Growth rates have been strong despite inconsistent policies. Given that they have near-zero operating and fuel costs, wind and solar also help keep wholesale electricity prices lower.

Operating Cost Structure

The contribution of energy market trends has gotten most of the attention, but many analysts misunderstand key factors that most affect the industry's prospects going forward: the unique cost structure of nuclear reactors, the key role of reactor characteristics in their unit cost of operation, and the significant effect of aging on their operating and maintenance costs.

Operating costs for nuclear reactors are driven by fixed labor and capital expenses. The complexity of reactor systems and the particular safety and security regulations require much larger workforces than fossil fuel plants. Reactor components and maintenance are also very expensive, because of their robustness and quality standards. There are also distinct "life-cycle" stages to reactor operating costs, which are very high in the years after a reactor first comes online due to the initial construction costs and any retrofits; less expensive in "mid-life" years after construction has been paid off; and increasingly expensive again in later "wear-out phase" years as maintenance and refurbishment needs increase.

This highly fixed-cost structure makes economies of scale extremely significant in reactors' unit cost of operation and, ultimately, their competitiveness and profitability. Capital costs and workforce size are similar no matter the size of a reactor—though co-located units can share some expenses. The average generating capacity of reactors currently operating in the U.S. is 1,022 MW—by far the largest single generating units in the electricity industry. However, reactor capacity varies widely, from the recently closed 476 MW Fort Calhoun reactor in Nebraska to the massive 1,478 MW Grand Gulf reactor in Mississippi. Other factors being equal, Fort Calhoun's cost of operations ($/MWh) could be three times higher than Grand Gulf's. The unit cost of plants with multiple reactors is also lower than single-unit plants. Average operating costs for the latter were $50.54/MWh in 2012, whereas average costs for multi-reactor plants were $39.44/MWh—more than 20% less.[19] As a result of these and other factors (such as age, property tax rates, etc.), there is a wide range of operating costs within the industry. A breakdown of 2012 operating costs showed the 15 highest-cost plants average $62.36/MWh, with the 15 lowest-cost plants averaging just $28.22/MWh. It is not hard to see that some reactors in the country are very likely uncompetitive and/or unprofitable, but that others are still operating quite profitably.

The Bathtub Curve

As a general principle, the mechanical lifespan of a reactor is represented by what is called the "bathtub curve": Mechanical failures and maintenance retrofits are most frequent in the initial years after a reactor starts operation, as well as toward the end of its mechanical life in the "wear-out" or "breakdown" phase.[20] Reactors are, by necessity, extremely complex machines, requiring multiple, separate backup cooling, power, and other safety systems, all of which must be maintained and operational to minimize the chances of a nuclear disaster, or at least of failures that could be extremely costly.

Nuclear components are very expensive because they must be extremely robust and of high material quality to maximize safety margins and reliability. Intense radiation bombardment causes material defects to develop in reactor components over time, increasing their embrittlement. Reactor components are also exposed to incredible material stresses, from heat and pressure. These issues are exacerbated by corrosion mechanisms related to water impurities and chemicals added to cooling water. The degradation mechanisms are not well-understood, particularly in combination, making the timing and frequency of major expenses difficult to predict with accuracy. Rates of aging-related degradation in critical components have frequently exceeded initial projections.

Rising Costs

The U.S. has the oldest "fleet" of reactors in the world. The average age of the 98 operating reactors in the U.S. is 38 years. Of these, 43 have already surpassed their original 40-year licenses while another 42 have operated more than 30 years.[21] 88 reactors have received 20-year license extensions, authorizing them to run for up to 60 years. However, it is speculative to assume they will operate that long. In the last 30 years, no U.S. reactor has closed due to its license expiring; all have closed several years before then. Additionally, no reactor in the world has yet operated up to 50 years, and more than half of the 173 reactors that have closed around the world did so between 20 and 40 years of operation.

Consistent with the bathtub curve model, operating costs industry-wide have increased substantially over the last 15 years. According to data reported by the Nuclear Energy Institute, the average cost of operating reactors in the U.S. increased by 58% from 2002 to 2012—that is, from $27.91 to $44.17/MWh.[22] It was during that period that reactors began surpassing 30 years in large numbers and owners began seeking license extensions. Attempting to prolong the operations of reactors as they age entails significant investments that make them even less competitive and more expensive.

There is disagreement about how quickly and in what order nuclear plants might be retired, but there is virtual consensus—even at the highest levels of the industry establishment—that the conditions for nuclear will continue to worsen. For instance, Department of Energy officials recently indicated that nuclear energy only has about a decade left before it starts to become irrelevant in the energy supply.[23]

Planning Considerations

Everyone with a direct stake in decarbonization and the energy transition needs to take the above realities of nuclear power into account. Knowing that the nuclear "tool" is not going to be in the climate action toolbox does not mean we cannot meet the challenge of decarbonization—nuclear is a small slice of the pie and there are so many other proven, cost-effective, and promising resources. It is better to recognize up front that we should focus on those and plan accordingly rather than waste vital time and money trying to preserve a role for nuclear. The fact that nuclear will not play a meaningful role in phasing out GHG emissions in 2030 and 2050, does not mean all reactors will retire at once and lead to sustained increases in fossil fuel generation. In the near term, older, smaller nuclear plants tend to be the most uneconomical and are the easiest and most cost-effective to replace with renewables and efficiency. Larger, newer, multi-unit plants will tend to be more competitive in the coming years, and more time is available to plan their phase-out.

Decarbonization will require realistic, comprehensive planning, and the closure of nuclear reactors can and should be factored in. Phasing out fossil fuels will require not only converting electricity supplies to renewable energy sources, but converting most transportation and heating to electricity-powered systems, such as geothermal heat pumps and battery-electric vehicles. "Merging" transportation, heating, and industrial energy use into the electricity sector will most likely increase total electricity demand from current levels, but increased energy efficiency will reduce the extent of that. For instance, heat pumps and electric vehicles are inherently more energy-efficient than the fossil fuel-combustion systems we need to phase out; energy efficiency standards will also reduce the amount of electricity demand for "traditional" uses (appliances, computers, lighting, etc.).

As more and more renewable energy is installed, the "carbon footprint" of all energy uses relying on electricity will decrease. At the same time, because the primary renewable electricity sources—wind, solar, and hydro power—are variable in their output, integrating them into a reliable and resilient system requires engineering electricity transmission and distribution systems differently. Not only do we need to incorporate energy storage, but, just as importantly, we have to manage electricity demand dynamically and responsively. For instance, two-way communication systems can enable people to automatically shift the usage of dishwashers and car chargers to times of day when wind or solar electricity is abundant.

Managing this transition may actually benefit from phasing out nuclear in many locations. Electricity is typically a very "local" energy source. That is, it must be generated fairly close to where it is used. Transmitting it over long distances is feasible, but the farther it is transmitted, the more electricity is lost in the process. Within the constraints of local and regional transmission and distribution systems, nuclear is unlikely to integrate well with renewables, because it is such an inflexible and unresponsive generation source. For instance, when wind is generating at maximum capacity during late night and early morning hours, or solar in the afternoon, large nuclear generators can cause congestion problems with two much electricity being fed into the utility's network. This is already happening to a limited degree where wind and nuclear are abundant, like Illinois. When these events occur, renewable sources generally have to be "curtailed" by reducing their output, because the nuclear generator cannot respond, nor recover, quickly enough.

Uneven Distribution of Nuclear

Most electricity system planning occurs at the state level in the U.S., and the electricity generation mix varies widely in different states and regions. Fossil fuels make up 63% of electricity generation nationwide, but on the state level it ranges from 0% in Vermont to 98% in Delaware. The same is true with nuclear. 20 states and the District of Columbia have no nuclear generation at all, but in South Carolina it constitutes 58% of the electricity produced. Of the 30 states with nuclear power, twelve have less than the national average of 20%. The 18 states that exceed the national average rely significantly less on fossil fuel sources, averaging 51% while those with no nuclear generation average 64% fossil fuels. States with nuclear power also tend to have lower shares of renewables: The states with more than 20% nuclear generated only 5% from renewables (non-hydro) in 2017, those with 20% or less nuclear averaged 9% renewables, and states with no nuclear averaged 13% renewables.

Changes in nuclear generation primarily affect local energy supplies and can be addressed effectively through state and regional planning. The same is true internationally, with only 31 out of 195 countries having any nuclear generation in 2017, ranging from France generating 71% of its electricity with nuclear to just 2% in Brazil and Iran. Since nearly all nuclear generation will phase out before 2050, decarbonization will not be substantially more demanding for localities with significant amounts of nuclear than for the vast majority of the world where nuclear is minor or non-existent.

Phase-Out Planning Factors

Policymakers and utilities should anticipate reactor closures based on driving factors and develop transition plans accordingly. Reactor size, age, major refurbishments, and license expirations can be used in decarbonization plans to optimize changes in the energy supply mix. Smaller reactors can be replaced with renewables and efficiency most easily; they are also likely to be the most uneconomical to operate, so doing so would free up resources to invest in more renewables and grid modernization. Multi-reactor plants can be phased out one reactor at a time rather than all at once. Instead of refurbishing reactors to extend their licenses, those expensive investments could be directed to efficiency and heat pump conversions instead.

There are also climate factors that will impact reactor operations and environmental impacts, including warming water temperatures, sea-level rise, and severe weather events. These should also be considered in energy planning and climate adaptation.

Warming water temperatures could have significant impacts on electricity output by mid-century. Reactors were designed and licensed based on historical water temperatures in the bodies of water they use to supply cooling water (usually, a river, lake, reservoir, or ocean). When water temperatures exceed the rated limit, the reactor must reduce its power output or shut down because the cooling system cannot remove the amount of heat necessary to prevent the reactor from overheating. Numerous reactors in the U.S. and around the world have had to reduce power for periods of time, due to higher water temperatures, and that is expected to become more common as average temperatures continue to rise.[24] Reactors that might be affected in this way could become even more uneconomical to operate.

Nuclear Risks and Climate Adaptation

Planning should also consider the risks that the increasing frequency and severity of extreme weather events entail for operational, economic, and nuclear safety risks to reactors. Flooding, tornadoes, hurricane-force winds, and other events could damage power supplies and cooling to reactors, and precipitate a nuclear disaster, much as the tsunami following the 2011 Tohoku earthquake in Japan led to the meltdowns of three reactors at the Fukushima Dai-Ichi plant.[25] Sea-level rise could increase the risk of flooding at reactor sites further, with implications for operations and radioactive waste storage as well as nuclear safety. There are long-term concerns about encroachment of sea water on reactor facilities, including nuclear waste storage. In the first move of its kind, Entergy recently announced that it will relocate the dry-cask storage facility at the Pilgrim reactor in Massachusetts to higher ground.[26]

A nuclear disaster would compound the impacts of a hurricane and complicate both emergency response and the recovery of affected populations. The Fukushima disaster is estimated to cost between $200 and $600 billion, as great or greater than the direct damages from the earthquake and tsunami.[27] Because nuclear disaster impacts are not covered by private insurance, recovery and compensation could well create even greater hardships. Radioactive contamination could require permanent evacuation of communities, expanding the scale of social and economic impact.

Resilient Decarbonization Planning

A nuclear disaster could also disrupt energy policies and decarbonization plans. Japan, with its role in facilitating the Kyoto Protocol in 1997, was once viewed by some as a climate leader on the global stage. Because nuclear power was (and remains) a core element focus of Japan's energy policy and climate strategy, both have been derailed by the Fukushima catastrophe. Safety concerns and revelations of negligence by the regulatory agencies and utilities required the shutdown of all reactors for inspections and quickly led to widespread public opposition to nuclear power. The country's powerful utility corporations have sought to protect their financial interests in refurbishing and restarting as many nuclear reactors as possible. The conservative LDP government that resumed power in the wake of the Tohoku/Fukushima disaster has largely supported the utilities' agenda—for instance, by affirming their right to refuse grid access to renewable energy sources, particularly wind.[28]

Nevertheless, it is extremely uncertain that nuclear power will ever provide a major share of Japan's electricity again. Going on eight years after the disaster, only nine of Japan's 54 reactors have been restarted, providing just 3.6% of total electricity in 2017. 19 reactors have been permanently shut down. The remaining 26 are in the indefinite limbo of restart applications that are under review and subject to legal as well as local political opposition. The government and utilities' impractical and unrealistic commitment to preserving nuclear is actually preventing the country from developing new energy policy that would enable Japan to decarbonize. For instance, though Japan has substantial wind energy potential and 7 GW of projects have been proposed (onshore and offshore), there has been virtually no growth in wind capacity in recent years.

By contrast, Germany had already been advancing renewables and efficiency aggressively prior to Fukushima Dai-Ichi. As a result, the government's recommitment to phase out nuclear has been achieved with relative success. GHG emissions and fossil fuel generation have continued to decline in the electricity sector, despite resistance by the major utility companies, which have increased their burning of lignite, the dirtiest form of coal. The government is now developing a schedule to phase out coal, similar to the country's nuclear policy, to be decided by an appointed commission.[29] The decision is controversial, with environmentalists arguing for dates in the 2030 timeframe and the major utilities and trade unions arguing to extend coal plant and mining operations into the 2040s.

There some important conclusions to be made about nuclear power and decarbonization strategies:

⇒ "Refuse-to-choose" is not a reliable climate policy for meeting the Paris targets. Insisting that all low-carbon technologies need to be pursued invites failure. Some sources, like nuclear, have a track record of failure and create risks that need to be avoided.

⇒ Renewables and efficiency have proven to be the most rapid, cost-effective, scalable, and dependable resources for decarbonization.

⇒ Prioritizing renewables and energy efficiency provides a resilient foundation for decarbonization, against contingencies like the closures or phase-out of nuclear reactors.

⇒ The greatest obstacles to advancing ambitious decarbonization strategies are now political rather than technological. They include politically powerful corporate interests, including utilities, that are reluctant to change their business strategies; and the resistance of impacted workers and communities, who are justifiably concerned about their futures.

Policy and technological solutions to advance the transition to net-zero or negative emissions by mid-century are now at hand. What is missing is the political consensus necessary to pursue them with the necessary ambition. The political obstacles must be addressed in order to do so quickly and sustainably enough to limit the scale and scope of global warming.

Economic Transition Policies

Politically powerful business interests have been able to exploit alliances with affected civil society constituencies to obstruct climate action. The interests of these stakeholders are narrowly inter-connected but different. They must be addressed in different ways, and the groundwork for sustained, broad-based support must be built first. The impacts of decarbonization on workers and local communities must, therefore, be factored into the energy transition. If they are not, it is impossible to see how the broad-based support necessary to undertake an ambitious, decades-long transition can get off the ground, let alone be sustained.[30]

The risks and uncertainties that workers and communities face are significant. The impacts of macroeconomic changes in the U.S. since the 1970s have heightened concerns about major industrial transitions. Programs to mitigate the impacts of, for instance, relocation of production through free trade agreements, have not proven successful enough at helping workers find good careers. Too many communities that experienced deindustrialization still face high unemployment and anemic property tax bases, leading to underfunding of schools and other basic services and infrastructure.

Programs that provide meaningful protection and assistance to communities and workers that will be directly affected by the energy transition—“just transition” programs—must be a core part of decarbonization strategy. They must also apply to reactor closures and phase-out plans. A report[31] commissioned by the Labor Network for Sustainability eloquently describes the principles that should undergird just transition programs:

> *The workers displaced from fossil fuel industries are not cardboard cutouts. They have done hard, dirty and dangerous jobs that kept our lights on and our cars moving for all the years before we recognized the need for a different energy future. In addition to our thanks, they deserve a just transition, with assistance in training and placement in new jobs, or retirement with dignity.*
>
> *But the transition to new ways of producing energy is not primarily a story of loss. Rather, it offers new pathways into vital roles producing and using the resources of the twenty-first century. It can rejuvenate and expand the blue-collar American work force for those who have been displaced, for their children, and for hundreds of thousands of others who have been excluded from the constricted prosperity of the recent past.*

Energy sector workers deserve to be treated with dignity and guaranteed that their families’ economic security will not be sacrificed. They did not create the climate crisis, but have done dangerous work to make sure that society has the energy and infrastructure we need on a daily basis. This is true of nuclear workers as much as any others. They are exposed to hazardous conditions due to radiation, heat, steam, electricity, and industrial machinery. They are responsible for operating and maintaining reactors to prevent a nuclear disaster, guard reactor sites against attack, and manage the storage of lethally radioactive materials as safely as possible.

The goal should be that no community or worker is left behind through climate action. Saving the planet and making a better world should not leave whole communities and workforces behind. Programs should directly address the impacts of power plant closures, fuel extraction and production, and related industries. Also, it is important to recognize that the impacts of decarbonization will not be primarily negative. There are many more jobs and economic opportunities to be created from decarbonization, not only through renewables and efficiency, but infrastructure and manufacturing.

It is, however, key to plan proactively for economic and workforce transitions; to align the economic benefits of decarbonization equitably, and ensure that communities and workers facing plant closures are able to access them; and to provide additional support and economic backstops to ensure that workers and communities are not stranded. These programs need to have guaranteed sources of funding, be mission-driven, not impose onerous barriers to accessing services and assistance, and remain adaptable to the circumstances of different communities and populations. Such Community and Worker Protection Funds could be financed through a small tax on energy corporations or a small fee on energy sales (e.g., 0.1 cents/kWh for electricity).

Specific Considerations for Nuclear Industry

Reactor closures entail unique challenges as well as opportunities for economic transition. Nuclear plants employ much larger workforces than coal and natural gas plants: A single-reactor site typically employs 600-800 full-time workers and over 1,000 more for maintenance and refueling projects while multi-reactor plants employ at least 800 to 1,000 full-time workers, and even more contract workers. Reactors also tend to be among the largest sources of property tax revenue in the rural communities in which they primarily operate.

However, nuclear reactors must also undergo a lengthy and complex process of decommissioning and environmental cleanup. Federal regulations require that reactor owners set aside hundreds of millions of dollars to assure funding for decommissioning. Although the required amounts have rarely proven adequate to completely fund cleanup of reactor sites, decommissioning trust funds provide a starting point. The skills and institutional memory of the existing workforce are vital resources for the hazardous work of radiological decommissioning and cleanup. It is possible to keep a substantial portion of the nuclear workforce (up to half) employed through the ten to 20 year decommissioning process.

Programs should provide workers not employed in decommissioning with a range of options, such as rehiring or transfer to another power plant or utility division, with retraining and relocation assistance, as needed; guaranteed job opportunities in energy industries that are growing through decarbonization, such as renewables or manufacturing, for instance, by setting aside 10-20% of jobs in new energy and manufacturing facilities for transitioning energy workers. Education/training and job placement assistance for workers who need to change career tracks is also crucial; as is the option of a dignified early retirement for workers within ten years of retirement when equivalent career options are not available. Financial support and medical care should be available to workers through all points of the transition to make sure no one falls through the cracks.

For communities, there need to be programs in place to provide revenue support and economic development. As much as possible, economic planning must happen proactively as soon as it is known that facilities will be closing. Advance planning will minimize the amount and duration of revenue support communities need after power plants shut down. It would also ensure local residents and reactor workers are trained and qualified for new jobs and careers when they become available. A full suite of community transition programs would encompass the following:

- ⇒ Property tax assistance, that is, supplemental revenues to compensate for lost property taxes when energy facilities shut down.
- ⇒ Economic planning and development, which means providing professional assistance to local governments to identify sustainable economic or expansion opportunities and incentives for emerging energy industries to locate in transitioning communities.
- ⇒ Training and job placement, so that education and training opportunities, connected to new employment opportunities created by the energy transition, are provided to local residents.
- ⇒ Environmental cleanup funds that ensure sufficient funding for cleanup of reactor sites and fossil fuel plants, either from the facility owners or through a public fund.

Such a comprehensive program is virtually unprecedented in the U.S., but it would very likely still be productive and cost-effective. NIRS and Alliance for a Green Economy published a white paper in 2015, mapping out such a proposal for the pending closure of the FitzPatrick reactor in New York. The paper estimated that a program incorporating reactor decommissioning, renewable energy development, and worker and community protection could cost around $40 million/year, over five to ten years.[32] The cost turned out to be minor compared to the upwards of $1.9 billion in subsidies the state is now providing to prevent the same reactor from closing over a 12-year period.[33] Furthermore, because FitzPatrick is likely to close in 2029 when the subsidies are scheduled to end, the local community and workers will still face the same need for transition planning and support. The profits that the reactor operator will have accrued through the subsidy will not have been invested in the long-term welfare of the community.

Nuclear Power and Climate Opportunity Costs: Case Studies

There are enormous climate opportunity costs to pursuing nuclear power. This is equally true of decisions to build new reactors and to extend their operations later on. The time and money spent on reactors could have a much greater impact in reducing GHG emissions if dedicated to renewables, efficiency, and other decarbonization strategies.

In addition, phasing out reactors creates opportunities to accelerate deployment of renewables, efficiency, and related investments that can facilitate decarbonization. What is more, giving the utility industry clear guidance that the energy system must be transformed will help overcome the institutional inertia of trying to preserve the value of aging infrastructure.

Three recent developments in the U.S. provide good examples of the opportunity costs and benefits of nuclear power. The case of the V.C. Summer 2 and 3 reactors in South Carolina as well as that of nuclear subsidies under New York's Clean Energy Standard involve decisions by utilities and/or policymakers to promote nuclear energy. A third example, that of the Diablo Canyon 1 and 2 reactors in California, shows how the phase-out of nuclear can accelerate renewable energy development, support decarbonization, and optimize outcomes for workers and local communities.

V. C. Summer 2 and 3 Reactors

In 2008, South Carolina Electric & Gas (SCE&G) announced plans to build two new reactors at the Virgil C. Summer Nuclear Power Plant, a single-reactor plant in operation since 1984. The V. C. Summer expansion was one of more than a dozen new reactor projects proposed between 2007-2010, comprising 31 reactors, under the aegis of a "Nuclear Renaissance." Heavily promoted by the industry for years, federal and state governments enacted policies to subsidize and incentivize nuclear power development. The Energy Policy Act of 2005 provided a number of incentives and subsidies for new reactor construction, including project financing through $18 billion in taxpayer-guaranteed loans; $6 billion in production tax credits for new nuclear generation; and a 20-year extension of the Price-Anderson Act. South Carolina passed the Baseload Review Act in 2007, which permitted utilities to recover financing costs from ratepayers while the reactors were under construction. Such policies, also referred to as Construction Work in Progress (CWIP) or Advanced Cost Recovery, were widely used by utilities in building the first generation of reactors in the 1970s and 1980s, and contributed to their tolerance of massive cost overruns.

Santee Cooper, a public authority in South Carolina that co-owns Summer Unit 1, agreed to partner with SCE&G on Units 2 and 3 as well. In 2008, the utilities contracted Westinghouse to design and build the reactors with its AP1000 design at an estimated cost of $9.8 billion.[34] Cost overruns eventually ballooned to $25 billion in 2017 before Westinghouse declared bankruptcy and the utilities canceled the project. The 1,100 MW reactors were only 40% built—nine years after the project was announced. The utilities had already spent $9 billion, and, under the Baseload Review Act, nuclear finance charges on that balance have raised consumers' bills by 20%. Originally projected to begin operation in 2018 and 2019, the reactors' construction schedules were delayed to 2022 and 2024.

It was good the utilities got out when they did. An identical project in Georgia (Vogtle Units 3 and 4) continued construction in 2017 despite the same cost increase and similar delays. Just one year later, Georgia Power announced a further $2.5 billion cost increase in 2018, raising total project costs to $27.5 billion and casting doubt on whether that project will ultimately be completed.

Canceling Summer 2 and 3 avoided an even worse outcome, but the opportunity costs of the project are still enormous. If the utilities had invested in energy efficiency and renewables instead, both energy costs and GHG emissions would be substantially lower today. The costs of energy efficiency programs in South Carolina were 4.1 cents/kWh ($41/MWh) in 2012, the same year that the Nuclear Regulatory Commission issued the construction and operation licenses for Summer 2 and 3. At that rate, the $9 billion South Carolina utilities spent on the reactors could have paid for 219 million MWh in electricity savings—as much electricity as the reactors would have generated in twelve years of operation.[35] Over time, such reductions in electricity use would avoid 89 million metric tons of GHG emissions (MMT CO2e) from natural gas plants in South Carolina.[36] Those GHG reductions would have come at a net savings to consumers, avoiding the 20% share of nuclear costs in today's electricity rates and reducing rates even further through lower consumption of electricity.

With the same capital investment, SCE&G and Santee Cooper could also have invested in renewable energy sources instead of nuclear. For instance, the installed cost of wind generation in 2013 was $1,895 per watt[37] (compared to $12,500/watt now projected for nuclear). If the utilities had entered into $9 billion in contracts to develop wind generation in 2013 instead of breaking ground on Summer 2 and 3, they could have built 4,750 MW of wind capacity within a few years. At modest performance levels, that much wind capacity could generate 10.4 million MWh/year of electricity—more than half the electricity that Summer 2 and 3 could have generated at three times the price. Most or all of that wind capacity could be producing today, years ahead of the reactors' potential completion. By avoiding 10.4 million MWh of natural gas generation in South Carolina, the utilities could have reduced GHG emissions by 4.2 MMT CO2e/year with wind. SCE&G and Santee Cooper could likely have invested in both efficiency and renewables, compounding GHG reductions while still reducing consumers' electricity costs.

Nuclear Subsidies in New York

In 2016, the State of New York created a program to subsidize the operation of four aging reactors. The owners of the reactors had scheduled two of them (Ginna and FitzPatrick) to retire in early 2017, and they claimed the other two (Nine Mile Point Units 1 and 2) were not profitable enough to continue operating. The governor of New York, Andrew Cuomo, directed the utility regulator to initiate a Clean Energy Standard, setting a goal of 50% renewable electricity and, separately, creating a subsidy to prevent reactor closures. The renewable energy standard (RES) would increase renewable generation by over 33 million MWh/year in 2030 and support the state's emissions target of 40% reductions by 2030.

The rationale provided for the nuclear subsidy was also to reduce GHG emissions as well as to provide a "carbon-free bridge" to renewable energy. However, the state never conducted an analysis of how the nuclear subsidy would achieve those goals. For instance, two of the reactors would not be available in 2030 to assist in meeting the emissions target. The operating licenses for Nine Mile Point 1 and Ginna, which are among the oldest reactors in the world, have already been extended to 60 years and they expire in 2029. Similarly, FitzPatrick was already known to be an uneconomical reactor and its owner was not interested in continuing to operate it, with or without subsidies. The proposed policy did not include a provision to ramp up renewables and/or efficiency if reactors shut down before 2030, nor a phase-out plan to do so at the end of the subsidy program.

The PSC initially proposed subsidizing the reactors at a limited level, based on the difference between their operating costs and the market prices for electricity. The PSC later revised the entire proposal, establishing a uniform subsidy price for the nuclear Zero Emissions Credits (ZECs) through a program that would run for 12 years (from 2017-2029). Instead of being based on the operating cost margins of the reactors, ZEC prices are based on the Social Cost of Carbon (SCC)—the value established by federal government agencies to estimate the global impact of CO2 emissions. Subsidy prices would increase every two years according to escalations in the SCC, with adjustments possible if electricity market prices increase.

The nuclear subsidy program has proved thoroughly uneconomical. Over the course of twelve years, total nuclear subsidy costs could amount to $7.6 billion—more than three times the total projected cost of RECs ($2.4 billion) needed to meet the 50% renewables goal.[38] The RES will increase renewable electricity generation by 33.7 million MWh in 2030—about 25% more electricity than the subsidized reactors produce (27.6 million MWh)—making the RES four times more cost-effective than nuclear subsidies in supporting low-carbon generation. However, because the nuclear subsidy ends in 2029, not all of the subsidized reactors would even be operating in 2030. Assuming Nine Mile Point 1 and Ginna shut down when their licenses expire, there would be only 17.7 million MWh of nuclear online in 2030. New renewable generation would provide about twice that amount at one-third the cost, making investments in renewables six times as cost-effective in meeting the 2030 emissions target. Purely on an emissions accounting basis, new renewables brought online through the RES from 2017-2030 would generate about two-thirds as much total electricity as subsidized reactors in New York. At one-third the total cost, renewables will be at least twice as cost-effective as nuclear subsidies in abating GHG emissions in New York.

The NY PSC also chose not to consider energy efficiency investments as an alternative in the CES. A detailed study provided to the PSC in support of a proposal to incorporate an energy efficiency standard showed that electricity savings could provide an equivalent resource to nuclear generation at a much lower cost. The study evaluated the impact of a 3% annual efficiency standard through 2030. It found that New York could reduce electricity demand by about 25.4 million MWh/year in 2030—approximately the same as the four subsidized reactors could normally generate each year, and at least 7.7 million MWh more than nuclear will in 2030 after scheduled retirements in 2029.[39] The efficiency standard would generate a net cost savings to electricity consumers of $3 billion—$10.6 billion less than the nuclear subsidy and $600 million less than the RES. The PSC ruled that energy efficiency was not within the scope of the Clean Energy Standard proceeding and such a program could be considered at a later date. Going on three years later, the agency still has not done so, but consumers have paid over $700 million in subsidies to aging reactors that may not be operational in 2030. Had the PSC opted to create a Clean Energy Standard with renewables and efficiency instead of nuclear, the program would have generated $600 million in net savings to consumers instead of $10 billion in increased costs with over 7 million MWh less fossil fuel generation in 2030.

Diablo Canyon Phase-Out Plan

In June 2016, California utility Pacific Gas & Electric reached an agreement with environmentalists and labor unions to phase out the state's last nuclear power plant and replace it with renewable generation and energy efficiency over a nine-year period.[40] PG&E found that continuing to operate the Diablo Canyon 1 and 2 reactors (total 2,200 MW) would be impractical and uneconomical in light of the state's 50% renewable energy goal. The combination of solar and nuclear generation would frequently exceed electricity demand, creating congestion on the transmission system and economic inefficiencies. The reactors' initial operating licenses expire in 2024 and 2025. PG&E submitted an application to extend the licenses for 20 years in 2009, but the review was ongoing as a result of legal challenges.

PG&E decided to withdraw the license extension and phase out the reactors when the licenses expire. Under the plan, PG&E found that it would be more cost-effective to voluntarily exceed California's 50% renewable energy standard, ramping up energy efficiency goals and increasing its renewable energy target to 55% by 2031. In total, PG&E will add over 30 million MWh of renewables by 2030 (compared to Diablo Canyon's 18 million MWh/year of generation), and it will reduce carbon emissions by 35%-60% below 2014 levels. The plan also calls for PG&E to increase energy efficiency by 4 million MWh per year over previous targets: 2 million MWh before 2025 and 2 million MWh more before 2030. One of the most significant aspects of the agreement is PG&E's conclusion that 24/7 baseload generation—long held up as the backbone of reliable electricity service—is outdated, unnecessary for reliability, and presents obstacles to renewable energy and decarbonization.

Agreements with environmentalists, labor, and local governments also provides a model of a comprehensive approach to decarbonization, including protections for nuclear workers, the local community, environmental restoration, and grid modernization. In addition to increasing renewables and efficiency, the agreement provided incentives for workers to continue at Diablo Canyon through 2025; severance packages to workers when the reactors close; retraining for workers for the decommissioning project; and $50 million in additional property tax payments through 2025. PG&E later reached an agreement with local communities and the school district to increase the latter payments to $85 million: $75 million for property taxes and $10 million for economic development.

The community and worker transition package is not comprehensive, but it represents an important precedent for a reactor closure to address environmental impacts, the future employment of the workforce, and the security of the local community. The negotiations with all parties—the utility, labor unions, environmental groups, and local officials—ensured that key stakeholders were able to represent their interests in achieving broader societal objectives: cost-effectiveness, GHG reductions, and environmental sustainability.

The case also illustrates the need for policymaking to provide the necessary authorities and financing for just transitions. The California Public Utilities Commission initially rejected most of the community and worker protections in the proposed settlement—not because the parties did not make a convincing case for them, but because the PUC did not have the statutory authority to force PG&E consumers to pay for them: "It is uncontested that the retirement of Diablo Canyon would result in reduced local tax revenues and a loss of well-paying jobs, with a corresponding potential for significant adverse economic impacts on the local area," Allen wrote in his decision. "The question before this commission is not whether there will be economic impacts, or even the potential size and scope of those impacts, but rather whether PG&E ratepayers should pay to mitigate these impacts."[41]

The plan was rescued by the state legislature in September 2018, when legislation was enacted that directs the PUC to approve funding for the community and worker transition terms: $85 million for community assistance and $350 million for employee retention and retraining.[42] The law is an important precedent, but it only applies to the Diablo Canyon settlement and does not broaden the PUC's authority to fund just transition plans generally.

Nuclear is Dirty, Dangerous, and Unjust

Nuclear power has major environmental and social impacts, completely aside from those associated with climate change. At every stage of its production, nuclear power pollutes the environment with some of the most dangerous, long-lived poisons in the world. The nuclear fuel chain describes the long series of extractive and polluting processes that are necessary to generate electricity with nuclear fission as well as the large amount of wastes that flow from it. With the immense threats of climate change, it is tempting to overlook other environmental hazards in the effort to address it. That is a mistake with nuclear power especially, because its environmental impacts are so severe and long-lasting and so many of them intersect with and compound impacts of global warming as well as issues of climate justice.

Carbon Footprint

Nuclear power generates electricity by the same mechanism as most fossil fuel power plants: by boiling water to spin a turbine, which generates electric current. It is, in effect, the most complicated and dangerous way to boil water ever invented, but it is considered a low-carbon technology, primarily because reactors do not directly emit large amounts of GHG. Nuclear does have a notable carbon footprint, estimated to be 66 g/kWh on a lifecycle basis, about twice that of solar PV (32 g/kWh) and six to seven times that of wind (9-10 g/kWh).[43] Until heavy industry and transportation are substantially decarbonized, this should be considered.

Mining and processing of uranium is very energy-intensive, involving heavy equipment and energy-intensive processes. A glut of uranium on the market has generally made nuclear fuel inexpensive, but the quality of uranium ore varies widely, and greatly affects the carbon footprint of the nuclear fuel chain. As high-grade ores are depleted, the overall carbon footprint of nuclear increases.

In addition, the construction of reactors involves massive amounts of steel and concrete. Both materials are energy-intensive to produce, and the concrete entails significant GHG emissions, due to the production of CO2 as it cures. Decommissioning reactors and transporting heavy components and radioactive waste to dump sites, often hundreds of miles, is inherently energy-intensive. Construction and decommissioning must be considered when deciding whether to construct reactors, because the decision to build a reactor entails a "carbon debt" on both ends that must be paid. For instance, the now-abandoned Summer 2 and 3 reactors already consumed large amounts of concrete and steel—enough to build a professional football stadium[44]—in laying the foundations and producing the major components and structural materials.

Uranium Mining, Milling, and Enrichment

Uranium is a radioactive heavy metal that, when ingested even in small amounts, is chemically as toxic as a heavy metal and it is also a radioactively dangerous alpha particle emitter. Its radioactive decay produces other dangerous radioisotopes, including radium and radon. All are known to be risk factors for various cancers and immunodeficiency disorders. Of the four primary isotopes of uranium, U-235 is the fissile isotope preferred for nuclear power and atomic weapons. It occurs in only trace amounts (ca. 0.7%) and must therefore be "enriched" to increase the concentration to levels needed for reactor fuel (typically 4%-5%). This results in the production of massive amounts of radioactive and toxic waste.[45]

Uranium mining and milling are extremely polluting, typically generating over 5,000 pounds of uranium waste rock and mill tailings for every pound of nuclear fuel. After mining, ore is sent to a mill for refining, which generates an acidic, radioactive sludge of mill tailings. These massive piles of waste rock and mill tailings are generally left out in the open, where they can seep into the ground, blow downwind, and emit radon gas to be inhaled. Once the uranium ore is refined, the enrichment process generates seven to eight pounds of depleted uranium by-product for every pound of enriched uranium reactor fuel. Depleted uranium is hazardous for millions of years.

Antiquated laws covering conventional uranium mines do not require environmental remediation and cleanup, which has resulted in over 15,000 abandoned uranium mines in the U.S., disproportionately on indigenous lands. The worst radiological disaster in U.S. history was, in fact, the collapse of a mill tailings dam on Navajo Nation territory, in Church Rock, New Mexico, which released over 1,000 tons and 93 million gallons of mill tailings sludge into the Rio Puerco, which flowed 80 miles downstream.

Radioactive Waste

Reactors produce a wide array of radioactive wastes, emissions, and effluents through their routine operations, including 20 tons of lethally radioactive nuclear waste per reactor annually, in the form of irradiated/spent nuclear fuel. In addition, reactors routinely release highly radioactive gases and contaminated water, and they emit radioactive gases and tritium vapor during refueling outages. Reactors also leave behind contaminated parts and equipment for disposal, radiologically activated corrosion and wear products ("CRUD"), which are intensely radioactive and must be removed from the cooling system, and contaminated uniforms and radiation gear, which have to be sent to specialized industrial laundries that generate contaminated water, filters, lint, etc. Finally, reactors also frequently have accidental leaks of tritium and other radioisotopes, and the tritiated cooling water has to be packaged and shipped to offsite management/disposal facilities.

Several of these wastes and effluents contaminate the reactor community and areas downstream/downwind; others are shipped to facilities elsewhere. After a reactor closes, the decommissioning process involves stripping the reactor and major structures apart and disposing of immense amounts of radioactive and chemical wastes. The irradiated (spent) fuel is lethally radioactive for hundreds of years, and remains radiologically hazardous for a million years or more.

Environmental Justice and Human Rights

The targeting of indigenous peoples and communities of color for uranium mining and radioactive waste is such a pervasive practice within the nuclear industry—in the U.S. and around the world—that it presents inherent environmental justice and human rights concerns. The promotion of nuclear power as a GHG-reduction strategy violates principles of climate justice in the Paris Agreement.

In addition, nuclear power has disproportionate and discriminatory impacts on women, children, and future generations. Longitudinal studies of radiation exposure show that women and girls are affected by radiation exposure at rates two to ten times greater than boys and men.[46] Radioactive waste and contamination place indiscriminate burdens on future generation and inflict intergenerational harm.

Water Consumption

Nuclear reactors require large amounts of water for their cooling systems, and tend to be the most water-intensive of thermal generation sources.[47] Most reactors in the U.S. do not utilize the iconic cooling towers associated with nuclear power. They use once-through cooling systems, which draw immense amounts of water in from a nearby river, ocean, lake, or reservoir, and then discharge hot water back into the same body of water. Nuclear power plants can withdraw billions of gallons per day, as much as a major city, destroying wildlife in the process.[48] The thermal pollution ejected back into the water also harms aquatic wildlife, reducing oxygen levels and causing thermal shock. Though reactors with cooling towers draw in substantially less water, they effectively consume far more by evaporating millions of gallons per day. In regions prone to drought, the strain on drinking water supplies can be significant.[49]

Disaster Impacts

The impacts of nuclear disasters can be immense and wide-ranging. A worst-case event, like Chernobyl and Fukushima, can involve the rupture of containment structures and the wide dispersal of large amounts of radioactive material. Emergency response can be complicated, both by untimely notifications of officials and the public, incomplete and inaccurate information, changing weather conditions, and other factors. Acute radiation exposures can cause serious injuries and death, but long-term health impacts and cancers can affect even greater numbers, years down the road. Updated estimates of the impacts of the Chernobyl disaster anticipate over 40,000 fatalities over the next fifty years.[50] Large populations can be permanently dislocated. Damages, recovery, and cleanup costs are effectively uninsurable, stretching into the hundreds of billions. The economic and political fallout can be destabilizing.[51]

Security and Proliferation Risks

Nuclear reactors also present security risks. They are vulnerable to sabotage and attack, and can be attractive targets for those intent on inflicting serious harm and damage. As Gordon Thompson[52] of the Institute for Resource and Security Studies put it,

> *It is clear that U.S. civilian nuclear facilities are candidates for attack under conditions of asymmetric warfare. They are large, fixed targets that are, at present, lightly defended. In the eyes of an enemy, they can be regarded as pre-deployed radiological weapons. They can be attacked using comparatively low levels of technology. Given the United States' overt reliance on nuclear weapons as offensive instruments, civilian nuclear facilities offer highly symbolic targets.*

These considerations could be heightened with the advance of global warming. The potential for increased international conflict is recognized as a possible consequence of resource conflicts and dislocated populations.[53] Mitigating the potential for such events by phasing out nuclear power and hardening nuclear waste storage facilities could be an important adaptation measure.

In addition, although it is less of a risk in the U.S. because of well-established, strict controls on enrichment capabilities and commercial nuclear waste, there are inherent weapons proliferation risks with efforts to export civilian nuclear power. These connections are evident in controversies over Iran's nuclear program: Enrichment facilities and other technologies needed to produce reactor fuel utilize the same technology needed to produce high-enriched uranium for atomic weapons.[54] Commercial reactors generate fissile isotopes of plutonium within the irradiated fuel, which can be extracted through reprocessing.[55] The production of plutonium for weapons was the original purpose of nuclear reactors, electricity generation being added as a secondary "co-benefit" later on.

Recommendations

The imperatives of climate action laid out in the 2018 IPCC report demand a reframing of ambition in the implementation of the Paris Agreement. If we are to limit global warming to 1.5°C, then we must decarbonize the energy sector by 2050, with sharp reductions in GHG emissions by 2030. The IPCC report rightly points out that these goals are still achievable, if concerted action is taken now.

Given the enormity of the task, it is tempting to think that we must use every tool at our disposal. But accomplishing this task requires us to be smart and deliberate as well as ambitious and visionary. We cannot afford to waste precious time and resources pursuing technologies and strategies that we have good reason to believe will be ineffective—or could have significant risks and impacts that would impede or derail efforts to decarbonize.

Nuclear power is one such technology. Due to its prohibitive costs and unique characteristics, it has proven to be impractical at best and failure-prone at worst. Nuclear power also entails severe environmental impacts and safety risks that must be avoided in a warming world, where resource constraints, severe weather events, social distress, and conflict are likely to worsen.

In reality, nuclear power may not be available in any meaningful capacity by 2050. Existing reactor fleets in most of the world are already reaching the end of their mechanical lives and will mostly phase out within the critical climate timeframe. Decarbonization strategies must take this into account. Because fossil fuels make up 86% of global energy, decarbonization will require a total transformation of energy systems in most parts of the world. Renewable energies have proven to be the most promising option—complemented by heavy investments in energy efficiency, development of complementary technologies, and integrated reliably and resiliently. Nuclear power does not integrate well with renewables and phasing it out is likely to create greater opportunities to accelerate the transformation and decarbonization of the energy system. This approach is being proven in places like Germany and California, where nuclear is being phased out in concert with emissions reductions.

The primary obstacles to ambitious decarbonization are political at this point rather than technological. It is essential to create and fund programs that will protect energy sector workers and their communities through the transition and ensure that no one is left behind. Providing a meaningful safety net and a realistic roadmap to new, sustainable energy economies will help develop the broad-based support necessary to drive, implement, and sustain the decades-long mission of decarbonizing—and denuclearizing—our energy system.

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