The Moral Imperative of Green Nuclear Energy Production

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The Crisis

A climate crisis is upon us. Human-caused global warming is already changing our planet's climate in dramatic ways and the effects are forecast to become far worse by the end of the century without rapid and radical changes to the global energy economy and the other forms of human activity that generate CO_2 and other greenhouse gases, such as methane. The ten hottest years on record have all occurred since 1998, with the past five years topping the list.[1] We are already seeing the disappearance of the arctic ice pack, massive glacial melting in Greenland, sea level rise, massive wildfires in northern Canada. the Amazonian rainforest, the western United States, Spain, France, and Siberia, ever more violent storms, and rapidly warming ocean temperatures. If we are to avoid potentially catastrophic climate change by 2100 by limiting the rise of global mean surface air temperature to 2.0 °C, compared to the twentieth-century average, then we must aim for the complete decarbonization of the energy economy, which will then also include a more or less totally electrified, global transportation system, by no later than 2065 (Goldstein and Qvist 2019, 16; Peters et al. 2017). The question is, "How do we do that?"

Are Solar, Wind, Hydro, and Geothermal the Answer?

There is, of course, widespread agreement that we must replace coal, oil, and natural gas with green energy sources, and that solar, wind, hydro, and geothermal power will be a vital part of that effort. But will those largely carbon-neutral energy sources suffice? Almost surely not. There are several problems with reliance on solar, wind, hydro, and geothermal energy.

The first and less serious problem is that, for the most part, steady strong winds, abundant, year-round sunlight, and high-volume, dammable water sources are not found near the major population and industrial centers where electricity is most needed, and most regions of the world do not have the infrastructure for high-capacity, continent-wide, long-distance electricity transmission. Of course, we can build such infrastructure, but it would be expensive, a 2014 study carried out for Western Electricity Coordinating Council, estimating a cost of nearly $3M per mile for a typical high tension line,[2] hence $3B for a 1000M line, and transmission efficiency goes down linearly with distance and as the square of the current, losses for a typical high-tension line being between 5% and 10% per 1000 miles.[3]

A second, and much more serious problem, is that the sun does not shine and the wind does not blow all day long, every day of the year, whereas what is referred to as "base load," the average minimum demand for electricity by all users remains more or less constant. With coal or gas fired generating stations or nuclear power plants, output can be raised or lowered as needed, within limits. That cannot be done with solar or wind. Hydro power does run 24/7 and flow rates can be adjusted to meet need, except in extreme low- or high-water conditions, but, again, abundant hydro is not usually found in areas where need is greatest. Solar and wind could meet the base load problem if we achieved a near-term breakthrough in high-capacity storage battery technology. But while research on new battery technologies is proceeding, there is little reason to expect a replacement for lithium-ion batteries any time soon.[4] Moreover, current generation lithium ion batteries are expensive, approximately $175 per KWh,[5] meaning that the cost of batteries that could store one day's power output from a typical 2,500 MW power plant would be an astonishing $10.5B, hence many times more expensive than the cost to build the plant in the first place. On top of that, even the best batteries have a limited life-span, units like Tesla's Powerwall system being expected to last only between seven and ten years (Smith et al. 2018). An additional problem with lithium-ion batteries is that lithium is a toxic substance, as is the cobalt widely used in the manufacture of lithium-ion batteries, combined with lithium as lithium cobalt oxide, $LiCoO_2$, in the battery's cathode (Archuleta 1995).[6] But there is no global infrastructure for the safe disposal or recycling of lithium and cobalt on the massive scale that would be required were battery storage to become a major part of our energy future (Jacoby 2019, Church and Wunnenberg 2019). Finally, while lithium supplies are forecast to suffice if we scale up lithium-ion battery production, global supplies of cobalt could run out by mid-century (Azevedo 2018).

A third major obstacle to a massive expansion of solar and wind is that both require large areas of land. A 2013 study by the National Renewable Energy Laboratory (NREL) reported that, depending on the specific design, photovoltaic solar farms require between 7.5 to 9.1 acres per MW, which means that to replace a 2,500 MW power plant with solar would require roughly 20,000 acres or 31.5 square miles (Ong et al. 2013). Wind is even more land hungry. A 2009 study by NREL estimated land use requirements of 64 acres per MW for typical wind farms (Denholm 2009). Replacing a 2,500 MW generating plant with wind would, therefore, require a whopping 160,000 acres, which is equal to 250 square miles. By comparison, a typical 2,500 MW coal fired or nuclear power plant takes up less than one square mile.

In more densely populated parts of the world, land is simply not available on the scale required for solar and wind farms equal in capacity to typical power plants. Germany, for example, which has aggressively developed both its wind and solar power generating capacity, had a wind power capacity of 56.3 GW by the end of 2017 and a solar capacity of 43 GW. Wind represented 18.8% of total power production in Germany in 2017 and solar contributed 7% (Burger 2018). Further expansion of both is planned, but as giant wind turbines dominate more and more of the German landscape, opposition grows among people who do not want giant turbines, averaging more than 800 ft in height near their homes.[7] That, combined with high costs and declining public subsidies, has dramatically slowed the growth of wind power in Germany in the last year or so.[8] In less densely populated areas such as the western United States and Canada, much of Africa, Siberia, western China, Australia, and parts of South America, there is abundant land for large wind and solar farms, but one again encounters the lack and expense of and the inefficiencies in continent-wide transmission.

Put the land use needed for solar and wind in perspective. How much land would be required to replace all current fossil fuels generating capacity in the United States with solar and wind. Our total fossil fuel generating capacity in 2017 was 842,529B MW.[9] If we replaced that with solar and wind in the same ratio that now obtains between the two, 22% solar and 78% wind, then we would need just over 68,000 square miles of land, which is roughly equivalent to the area of Missouri, Oklahoma, or North Dakota. That is a lot of land.

What would it cost to replace fossil fuels with wind and solar. In 2018, a total of 2,651B KWh of electricity was generated in the United States by fossil fuels.[10] Assuming the same 22%/78% mix of solar and wind used above, and costs of $0,05 per KWh for solar and $0.125 per KWh for wind,[11] the total annual cost to replace fossil fuels by solar and wind would be $289B.

But remember that the total decarbonization of our energy economy means also the total electrification of transportation as well as all residential, commercial, industrial, and agricultural energy use. A 2018 study by the National Renewable Energy Laboratory estimates that this will lead to an increase in the demand for electricity of between 17% and 38% (Mai et al. 2018). So add that much more to the estimates given here for land use and cost.

In summary, there are many, serious obstacles to the decarbonization of our energy system by means of solar and wind, the biggest of them being the seeming impossibility of solving the base load problem without a miraculous and unlikely, near-term breakthrough in storage battery technology. A combination of solar, wind, hydro, and geothermal simply cannot decarbonize our energy production by 2065.

The Nuclear Alternative

There is only one, currently available technology that can get us to the goal of a totally carbon free energy economy by 2065, and that is nuclear power. Let me repeat that. Nuclear power is the only option for preventing a climate catastrophe. But public misunderstanding of the risks associated with nuclear power and regulatory impediments partly driven by public fears make it almost impossible, at present, for utilities in the United States to invest in expanding our nuclear power capacity, even while most of the rest of the world is doing just that. So let us briefly examine the propects for expanded nuclear power, the risks, and the costs.

Nuclear Reactor Technologies

We having been generating electricity with nuclear reactors for nearly seventy years, beginning in 1951 with the Experimental Breeder Reactor operated by Argonne National Laboratory at the site near Idaho Falls that later became the Idaho National Laboratory (Mahaffey 2009, 206).[12] The first reactor expressly outfitted for electricity production was the Soviet AM-1 graphite moderated breeder reactor at Obninsk, which began generating electricity in 1954 (Josephson 2005, 2). Great Britain connected its CO_2 cooled, graphite moderated reactor at Calder Hall to the grid in 1956 (Brown 2003). The first large scale nuclear power plant in the United States, located at Shippingport, PA and operated by the United States Atomic Energy Commission, began producing power in 1957. Its pressurized light water reactor (PWR) design was a descendent of the Mark 1 reactor designed and built originally for the Navy's nuclear propulsion program, which launched the first nuclear powered vessel, the submarine USS Nautilus, SSN-571, in 1954. The reactor core of the Shippingport plant had been intended for use on a nuclear powered aircraft carrier, but was repurposed when the carrier project was canceled (Buttery 2012, Mahaffey 2009, 228-230).

All commercial power reactors work by the fissioning of a fissile element, such as uranium or plutonium, which releases tremendous amounts of energy and neutrons that propagate through the fuel triggering additional fissioning in a chain reaction. Shippingport's pressurized light water reactor was the progenitor of most of the commercial nuclear power plants built in the United States in the succeeding decades and is still the most common type of reactor in use today, sixty-four of the ninety-eight, currently operational, commercial reactors employing this design. Many such reactors have been built in other countries as well.[13] Enriched uranium fuel rods are cooled in the core by ordinary water, H_20 cycled through the core under high pressure. The extreme heat generated in the pressurized water turns unpressurized water in a secondary loop into steam that drives a turbine, making electricity The design makes possible high thermodynamic efficiency and comparative stability of operation (Glasstone and Sesonski 1994, 21-23).

The second most common design for power reactors is the boiling water reactor (BWR). In these, unpressurized water serving as the primary coolant in the core is boiled directly, driving the turbines. Boiling water reactors are less efficient thermodynamically, but engineering and maintenance are, in several ways, easier than with a pressurized reactor (Glasstone and Sesonski 1994, 21-23).

There are other reactor designs for electricity generation. Light water graphite moderated (LWGR or RBMK in Russian) were popular in the Soviet Union in the 1970s and early 1980s. As with boiling water reactors, steam generated in the core drives the turbines, but graphite, rather than water is used as the moderator for controlling neutron flux. Although the Chernobyl accident in 1986 exposed the problems inherent in this design, a number of such reactors still operate in Russia and some former Soviet client states.[14] All of the currently operational reactors in Canada and most in India are pressurized heavy water reactors (PHWR).[15] They use deuterium oxide, D_20, as the coolant and moderator, deuterium being an isotope of hydrogen with one neutron in addition to a single proton. Heavy water is considerably more expensive than ordinary light water, but it is preferable from the point of view of its ability to control neutron flux in the reactor.[16]

The first prototype nuclear power reactors at Calder Hall and Shippingport are now commonly referred to as “Gen I” reactors, with their design descendants being known as “Gen II” reactors. Gen III reactors, which began to appear in the 1990s, are versions of Gen II reactor designs incorporating safety, performance, and manufacturing modifications but without radical departures from existing PWR, BWR, and PHWR designs. Prominent among the modifications is a switch from active to passive control systems that can automatically shut down the reactor in the event of an emergency without the need for direct operator intervention and a downscaling of designs to below 100MW capacity so as to make possible easily transportable, pre-manufactured, self-contained reactors for use in areas with low power needs or for such purposes as emergency electricity production after a natural disaster. As of 2011, twenty-five advanced Gen III reactors were online in the United States and many more are online with more in plan or under construction in various places around the world (Goldberg and Rosner 2011).

In the past twenty years or so a number of dramatically different reactor design concepts have been proposed. These Gen IV reactors promise to be safer, cheaper, cleaner, and more scalable than existing designs. Safety is, again, a main goal, with some of these designs working in such a way that, for reasons of simple physics, a core meltdown is impossible. Reducing high-intensity radioactive waste is another important goal, with some Gen IV reactor designs producing little to no waste while consuming waste from older reactors.[17]

Many observers find most promising the fast-neutron molten salt reactor (MSFR). In a radical departure from conventional reactor designs, MSFR reactors dispense with fuel rods, instead dissolving the fissile material, in the form of uranium, plutonium, or thorium fluoride salts, in molten lithium fluoride. That fluid mixture serves both as the locus of the fission reaction and as the primary coolant. Because of the physics of the process, no moderator or control rods are needed and no cooling water is needed, the reactors being wholly self-contained (Siemer 2015). The technology was first tested in an experimental molten salt reactor built at the Oak Ridge National Laboratory in 1965.[18] Today concept evaluation and testing of MSFR reactors is proceeding in many countries. In the United States, with funding from the Department of Energy, the Southern Company, in partnership with TerraPower, backed by Bill Gates, has plans to begin physical tests on a molten chloride reactor (MCFR) in a test loop in the very near future.[19]

In the United States in 2018, nuclear represented 19.3% of electricity generation.[20] Globally, 10% of electricity generation is nuclear.[21] Electricity generated from Gen II and Gen III nuclear facilities in the United States costs between \$0.097/KWh and \$0.136/KWh in 2016, which is generally cheaper than that produced by coal fired plants but somewhat more expensive than onshore wind, utility scale solar, and natural gas, the costs of which range from \$0.32/KWh to \$0.078/KWh.[22] Gen IV reactor designs are expected to bring down the cost of nuclear considerably. For example, the Canadian company, Terrestrial Energy, expects the MSFR reactor that it is designing to produce electricity at a cost of \$0.05/KWh, which would be, on average, equal to the cost of solar and onshore wind, and cheaper than natural gas.[23]

In summary, nuclear power is an old, well-proven, easily affordable, shovel-ready, and more or less totally green technology. It solves the base load problem and Gen III nuclear power plants can be built anywhere as long as there is sufficient water for cooling, while Gen IV designs such as MSFR reactors eliminate even that need. The question, then, is why, knowing the devastating environmental consequences of burning fossil fuels, have we not already a decade ago launched a crash campaign to replace fossil fuel electricity generation by nuclear? Sweden and France long ago decarbonized their electricity production, and other nations, like Canada, China, and Russia are committed to rapidly expanding nuclear power (Goldstein and Qvist 2019, 20-29, 174-190, 207-208). Tragically, Germany and Japan are deliberately scaling back their once significant nuclear capacity (Goldstein and Qvist 2019, 29-40, 90, 93), and the expansion of nuclear power in the United States has been stalled for decades. With a clear path to decarbonizing electricity production, why have not all of the nations of the world committed themselves to following that path?

Health and Environmental Risks of Nuclear Energy

Why are we not greening our energy economy with a rapid shift to nuclear power? The answer is irrational fear. That fear focuses on two issues: the risk of major nuclear reactor accidents and the risk associated with the storage or disposal of nuclear waste. Consider, first, the danger of reactor accidents.

In the sixty-six years since we began to generate electricity in nuclear power plants, and with 631 nuclear power reactors having been or currently in operation globally,[24] there have been only three significant accidents, the Three Mile Island accident in Pennsylvania in 1979, the Chernobyl accident in Ukraine in 1986, and the Fukushima Daiichi accident in Japan in 2011. As serious as were those three accidents, that is actually a very good safety record. Only Chernobyl involved the release of significant amounts of radiation and human deaths and injuries, and the design of the light water, graphite moderated (LWGR) reactors at Chernobyl had long been recognized as problematic, by comparison with the PWR and BWR designs mainly employed in other countries, both because of inherent instabilities in reactor response in the event of a rapid shutdown and because those Soviet style reactors lacked containment structures. All three accidents involved partial or, in the case of Chernobyl, a near total core meltdown. But at Three Mile Island and at one of the three affected reactors at Fukushima, the containment structures worked as designed, preventing significant radiation releases and no serious injuries, illnesses, or fatalities (Rogovin and Frampton 1980; Mahaffey 2014, 325-375).

Three Mile Island

The Three Mile Island accident occurred on March 28, 1979. The initial cause was a failure of the pumps providing cooling water to the core. Backup pumps also failed owing to operator error. Temperature and water pressure in the core increased, a pressure relief valve opened automatically but then failed to close, as it was supposed to, allowing coolant to escape the core, which led to a partial core meltdown. A very small amount of low-level radiation escaped with the coolant, the extra exposure to nearby populations being no more than that consequent on living in a high-altitude city such as Denver, CO. Radioactively contaminated coolant also leaked from the core into the containment building but was held there. Understandably, in the confused, early hours after the accident, there was concern among authorities and the public about whether the accident would get worse and some voluntary evacuations were recommended by state officials at the suggestion of the Nuclear Regulatory Commission (NRC). But, aside from the small, temporary release of radiation through the pressure relief valve, no radiation escaped the containment facility, and there were no health or environmental consequences (Rogovin and Frampton 1980; Mahaffey 2014, 341-357).

Even though the containment at Three Mile Island worked and there were no health or environmental impacts, the accident stoked intense public fears about the risks of nuclear power. Why? One reason was surely that public concern about the health and environmental impacts of new technologies in general were acute in the late 1970s in the wake of major environmental and health disasters such as the Love Canal scandal, in which scores of people who lived and went to school on the site of a former industrial chemical dump in New York were sickened and died (Beck 1979; Newman 2016). Of more immediate relevance, however, is the fact that just twelve days before the Three Mile Island accident Columbia Pictures released the hit film, “The China Syndrome,” starring

Jane Fonda, Jack Lemmon, and Michael Douglas, which featured a potentially serious accident involving a potential core meltdown triggered by an earthquake at a nuclear power plant in California (Canby 1979; Goldstein and Quist 2019, 91). For many people at the time, it seemed as if fiction had become reality. Public opinion quickly turned against nuclear power and the expansion of nuclear power in the United States ground to a halt.[25] But while one understands the anxieties aroused by the accident, the fact remains that no one died, no one got sick, the containment structure worked as it was supposed to, and the damaged reactor was soon brought under control. It was a bad accident costing the owners, Metropolitan Edison, Jersey Central Power & Light, and Pennsylvania Electric, a lot of money.[26] Still, no one died, no one got sick, there were no environmental impacts, and the containment structure worked as planned, but for the inconsequential release of radiation because of the stuck pressure relief valve.

Chernobyl

The Chernobyl accident occurred on April 26, 1986. Ironically, a safety test was being run on the fairly new light water graphite moderated (LWGR) reactor number 4 to study the response of back-up electrical generators for providing power to the pumps in the primary cooling in the event of a power outage. Because of numerous, serious operator errors and the inherently unstable LWGR design, the reactor went into an uncontrolled chain reaction that produced, first, a steam explosion that breached the reactor core and, then a fire in the core that burned for nine days. Since there was no containment structure, the explosion and fire produced significant amounts of radioactive steam, smoke, and ash that spread quickly over a wide region, reaching parts of central Europe and Scandinavia within two days. Heroic first responders fought desperately and at great personal risk to control the fire, mainly with thousands of helicopter flights to drop a mixture of sand, lead, clay, and boron. To prevent material from the molten core from reaching the water table, which would have spread additional contamination over a wide area, there was, first, the injection of tons of liquid nitrogen under the reactor floor to cool the core. Then miners excavated a large chamber under the core to house a more permanent water cooling sysem. A concrete "sarcophagus" enclosing the site was completed by December of 1986, and a new, more durable containment structure was added in 2017. The nearby city of Pripyat was evacuated the day after the accident and eventually 2,800 sq km (1,084 sq mi) exclusion zone was established (Mahaffey 2014, 357-375; Plokhy 2018).

It was a horrible accident, the impact of which will be felt for decades more. The economic cost is hard to measure, but a widely cited recent literature review arrives at an estimate of $700B between 1986 and 2016, which would make it one of the costliest disasters in history. But, to put it into perspective, that is roughly equal to Canada's annual budget in 2017,[27] and it represents about 20% of the global cost of electricity in 2017, which, if amortized over the thirty years between 1986 and 2016, represents less than 1% of the global cost of electricity per year.[28]

The health and environmental impact of the Chernobyl accident is also hard to measure. Estimates of deaths and disease vary widely. The most widely accepted numbers come from reports prepared by the Chernobyl Foum, which is a consortium of eight major international agencies, including the World Health Organization (WHO) and the International Atomic Energy Agency (IAEA), along with the governments of Belarus, the Russian Federation, and Ukraine (Chernobyl Forum 2006) and United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2008). There were thirty confirmed deaths in the immediate wake of the accident, including two plant workers who died at the time of the accident from physical injuries and twenty-eight emergency workers who died of acute radiation sickness (ACS). An additional 106 individuals were diagnosed with ACS but survived (UNSCEAR 2008, 58). By 2008, approximately 6,000 cases of thyroid cancer were observed among people exposed to the radiation, chiefly from Iodine-131, with a significant number of those cases probably being attributable to Chernobyl exposure. Fifteen of those thyroid cancer cases proved fatal by 2002 (Chernobyl Forum 2006, 16). Otherwise, no statistically significant increases in cancer or other serious diseases have been observed. There has been a small increase in morbidity and mortality related to cardiovascular disease among emergency and cleanup workers, but experts are reluctant to attribute that directly to the accident because so many other factors can contribute to such illnesses (Chernobyl Forum 2006, 19).

The low number of deaths from radiation exposure is due to the fact that, except for emergency and cleanup workers, the average additional radiation exposure among the roughly five million people living in the affected area was about 1 mSv (Chernobyl Forum 2006, 13), which is roughly equivalent to normal, annual background radiation, less than a typical chest CT scan, and about half of the additional annual radiation exposure for an airline pilot.

The environmental impact has been comparably low. There were severe, short-term impacts in some areas near the reactor that received heavy radiation doses, including dead vegetation and birth defects in animals. But today forests and wildlife thrive in the exclusion zone, which has become, in effect, a protected nature reserve, and many have observed that the result is an unintended experiment in how rapidly traditional ecosystems can reestablish themselves when a human presence is removed (Barras 2016).

One does not want to portray the Chernobyl accident as anything other than a terrible disaster. Moreover, had it not been for the fast response by Soviet authorities and the bravery and sacrifice of the tens of thousands of people who fought the fire in the reactor core and secured the site over succeeding months, it could have become an even more calamitous event. The Soviet government was rightly condemned both for policies and practices that contributed to the accident in the first place, for their delay in alerting neighboring countries, and for their years-long coverup and denial of the extent and severity of the accident. But the actual consequences of the accident are far less dramatic than suggested in some popular media and by many opponents of nuclear power.

As bad as it was, Chernobyl is far from being the worst industrial accident in history. The Bhopal disaster at a Union Carbide chemical plant in India in 1984 killed at least 2,200 people and injured perhaps as many as 500,000 (Broughton 2005, Eckerman 2005, Mandavilli 2018). We do not, as a consequence, hear strident calls to close down all chemical plants. For another perspective, consider the fact that generating electricity by burning coal kills between 600,000 and 1,000,000 people every year, and sickens many more, mainly due to the health effects of the air pollution from coal fired power plants (Goldstein and Qvist 2019, 94-95). But those deaths take place one at a time and out of the public view, so they become invisible and, thus, largely ignored in debates about energy policy.

Fukushima Daiichi

The Fukushima Daiichi power station was a complex of six boiling water nuclear reactors near the town of Ōkuma in the Fukushima Prefecture of Japan. The station was built in the late 1960s and 1970s and was, at the time of the accident, one of the world's largest nuclear power plants. The accident began with the Tōhoku earthquake and tsunami at 14:46 JST on March 11, 2011. By design, the reactors shut down automatically as soon as the earthquake was detected, but the electrical supply to the plant failed, at which point backup diesel generators started automatically, supplying electricity to operate the pumps circulating cooling water to reactor cores. Direct damage from the earthquake was minimal and, were it not for the tsunami, the reactors would have been brought to a safe state without further incident. But approximately fifty minutes after the earthquake the roughly 14 m tsunami overtopped the 5.7 m seawall protecting the plant, flooding the basement where the diesel generators were located. Backup batteries then kicked in, but they could power the pumps for no more than about eight hours. Additional batteries and portable generators did not reach the site until shortly before midnight, but the generators could not be connected to the plant's power system due to the flooding in the basement. The uncooled fuel rods in reactors 1, 2, and 3 began to overheat, which led first to hydrogen explosions that breached the containment in units 1 and 3 and then core meltdowns in all three reactors. Because of the radiation escaping from the damaged reactors, on the following two days, approximately 170,000 people were evacuated from the area around the plant (Lochbaum et al. 2014, Mahaffey 2014, 376-403). In the eight years since the accident, many evacuees have been allowed back, but large areas, especially to the northwest of the plant, remain closed with thousands of people still blocked from returning to their homes.[29]

There has been only one fatality attributed to radiation exposure at Fukushima, this a plant worker who had been monitoring radiation levels, receiving, himself, a dose of 195 mSv and died of lung cancer (Meixler 2018). But some have disputed the attribution, because lung cancer is not a common consequence of radiation exposure and certainly not at that exposure level. It has been suggested that the Japanese government wanted to avoid a public fuss by allowing the man and his family to claim compensation (Conca 2018). There have been no additional deaths and no reported cases of cancer or other diseases attributable to radiation exposure, mainly because average exposure among the evacuees was very low, on the order of 2 mSv, which is barely above annual background radiation levels, and exposure levels for plant workers and others participating in the cleanup, though high enough so that some cancers might appear, were still not expected to have serious health impacts (UNSCEAR 2013, Hasagawa et al. 2015). However, something on the order of fifty deaths are attributed to the evacuation, chiefly among hospital patients and elderly nursing home patients as a result of hypothermia, dehydration, and existing medical conditions that were not well treated during the hasty evacuation (Hasagawa et al. 2015, Harding 2018). Was the evacuation, therefore, a mistake? Lives would have been saved had the order to evacuate not been given and what was known about radiation levels at the time would not, by itself, have warranted such a step. But, given uncertainty about the possibility of additional radiation releases and the horrible and confusing conditions in the larger region in the wake of the tsunami, it is hard to fault the decision.

So, at most one person died as a direct result of the Fukushima Daiichi accident and there have been no other cases of cancer or other diseases attributed to radiation exposure. But, curiously, the Fukushima accident had a far greater impact on public perceptions of the risks of nuclear power than even Chernobyl. Japan shut down all of its nuclear power reactors after the accident, making up for the lost power production mainly by burning more coal, though thirty-seven of their reactors are now back online.[30] Most dramatically, as a consequence of the Fukushima accident Germany decided to begin an immediate phase out of its nuclear power industry, replacing the lost capacity mainly by, like Japan, burning more coal.[31] Of course, there had long been widespread skepticism in Germany about nuclear power, opposition to nuclear power being a major part of the rise of the German Green Party.[32] But the Fukushima accident triggered the decision by the Merkel government to shutter all German nuclear power plants by 2020. In many other countries, such as South Korea, which was once determined to become a global leader in nuclear power, the Fukushima accident had a major impact on public opinion and, at the very least, slowed the further growth of nuclear power, giving rise to the term, “the Fukushima effect,” to describe the accident’s impact (Hindmarsh and Priestly 2015).

Nuclear Waste Disposal and Storage

Taken together, the three worst nuclear accidents killed fewer than 100 people, whereas hundreds of thousands die every year from burning coal to produce electricity. And, yet, the public fears nuclear power far more than fossil fuels. Why? There is one other concern about nuclear power that many cite as a reason for not going further down the nuclear path, namely, the risks associated with nuclear waste.

The IAEA reports that, as of the end of 2013, nuclear power plants around the world had generated approximately 370,000 metric tons of radioactive waste (IAEA 2018, 35). That seems a big number. But, in addition to CO_2 emissions, burning coal to make electricity produces in the United States alone some 120 million tons of highly toxic fly ash every year (Freese et al. 2008, 7). About 90% of the radioactive waste is in the form of what is termed “low-level waste” (LLW), which consists of easily disposed of ordinary refuse like paper, rags, tools, etc. that are contaminated with mostly short-lived, low intensity radioactive material. It can be safely buried in landfills or incinerated. 7% of the waste is “intermediate-level” (ILW) such as cladding from fuel rods. Some shielding is required, but such waste can be encased in concrete and buried. Only 3% of the waste is “high-level” (HLW). It consists mainly of the spent reactor fuel and is sufficiently radioactive that it generates enough heat so that both shielding and some form of cooling, at least in the near term, is needed, and it poses the greatest challenge.[33] According to the IAEA, at the end of 2013 22,000 m^3 of high-level waste was in storage.

Finland, Sweden, and France have taken the lead in developing long-term storage and disposal facilities for high-level waste. Finland and Sweden have collaborated on developing a new, permanent disposal technology, KBS-3, which involves encapsulating high-level waste in corrosion resistant copper containers that are buried deep underground, embedded in swelling bentonite clay. Finland is now building the first deep storage facility using this technology at Onkalo, near the northern tip of the Gulf of Bothnia, where the containers will be placed in tunnels cut in geologically stable rock at a depth of more than 400 m. The waste is expected to remain safely buried for at least 100,000 years. Plans currently call for waste to begin being deposited at Onkalo in 2024. Progress on Sweden's own first facility based on this technology at Forsmark has been slowed by legal challenges, but the Swedish Nuclear Fuel and Waste Management Company is now awaiting final license approval (Mikhailova 2019).

France, which makes 72% of its electricity from nuclear power, is the world leader in reprocessing spent nuclear fuel, turning spent plutonium and uranium into recycled fuel. Not only does this reduce the need for new fuel, it also eliminates roughly 96% of the high-level waste (Krikorian 2019). But France is also moving ahead with its own long-term storage facility, CIGÉO (Centre industriel de stockage géologique) near the village of Bure in the department of Meuse in northeastern France. Sealed containers will be buried in a geologically stable argillite clay formation at a depth of 500 m. There has been opposition to the CIGÉO facility.[34] Still, the operator, ANDRA (Agence nationale pour la gestion des déchets radioactifs) is awaiting final government approval, with the last phase of construction expected to begin in just a few years.[35]

The experience of Finland, Sweden, and France prove the feasibility of deep underground disposal as a safe, more or less permanent disposal method. Ironically, the United States could have been the world leader in this approach to handling high-level nuclear waste years ago had it not been for President Obama's ill-advised and politically-motivated decision in early 2009 to shut down the project to build our own such deep storage facility at Yucca Mountain in Nevada. A $12B investment in research, site preparation, and licensing preparation was written off and the United States was left with no safe, long-term storage option for high-level nuclear waste (Northey 2011). There had been a long history of local opposition and debate about whether the site would be as secure as promised over a time scale of 100,000 to 1,000,000 years, particular attention being paid to the site's vulnerability to seismic activity and ground water infiltration. But in early 2008 the Environmental Protection Agency declared that the site met all requirements, after which the Department of Energy filed an application for a construction license with the Nuclear Regulatory Commission (Schecker 2008),

The United States has had one, long-term, underground nuclear waste storage facility in operation since 1999, the WIPP (Waste Isolation Pilot Plant) near Carlsbad, New Mexico, where packaged waste is stored 2,000 feet underground in a massive salt formation. But WIPP is designed only to receive waste from nuclear weapons research and production, not waste from civilian nuclear power plants, and it is certified for only 10,000 years (Feder 1999, Iaconangelo 2017). In 2014, there was an accidental release of radiation when a waste canister ruptured. There was no significant harm to workers. It was eventually determined that the rupture occurred because the wrong kind of absorbate was used when the canister was packed at the Los Alamos National Laboratory for shipment to WIPP (DOE-OEM 2015). The facility reopened only in 2017 (Conca 2017). Prior to the accident, a number of people asked whether WIPP could replace Yucca Mountain as a disposal site for civilian nuclear waste (Wiener-Bronner 2014, Cravens 2007, 339-340),[36] but the accident seems to have killed interest in that proposal.

At the end of 2018, there were 81,518 metric tons of spent uranium fuel in storage in the United States.[37] With no long-term disposal facility and no reprocessing, this waste sits as it has for decades in insecure storage units at the reactors that generated the waste. Usually spent fuel rods are allowed to cool for about ten years in pools of water after which they are packed in sealed concrete casks that are stored above ground, typically outdoors (USNRC 2016). While this is a reasonably safe system for temporary storage, there is reason for concern about the obvious risks that it poses, risks that are significantly greater than those associated with deep geological storage. For example, were a large jet aircraft to crash into a group of storage casks, there could be a major release of radiation in the immediate area. Thus even if the United States does not expand its nuclear power capacity, it is a matter of great urgency that the long-term storage problem be addressed. There has been interest in congress and from the White House and the Nuclear Regulatory Commission in restarting the Yucca Mountain project, and President Trump's 2020 budget proposal includes funding for it.[38] But there is still strong opposition in Nevada, and the fate of the project remains unclear (Sadler 2019).

Much of the opposition to long-term nuclear waste storage sites seems to be of the "not in my backyard" variety. This is especially true in the case of Yucca Mountain, even though the site is ten miles from the nearby small towns of Beatty, Ashton, and Amargosa Valley, and roughly one-hundred miles from Las Vegas, the nearest large city, and the EPA has certified the safety and minimal environmental impacts of the project.[39] More serious and deserving of more respect is the long-standing opposition from Native American groups, especially the Western Shoshone, who regard the region as sacred land (Solis 2019).

Clearly the greatest source of justifiable concern is, precisely, the long-term stability and security of the site. Never in history have humans had the audacity to build something that could still be hazardous 100,000 years from now, more than twenty times longer than civilization has so far existed on the Earth. One wants to be sure that all possible failures of such storage sites have been addressed. That, is precisely the point of the site and engineering studies that are required for licensing. 100,000 years is a long time, but what does that mean from the point of view of the risks?

High level nuclear reactor waste contains a wide array of radioactive isotopes. The key questions concern the intensity of the heat and radiation produced by those isotopes and their half-lives, which is the time it takes for half of a radioactive substance to decay. For typical spent fuel from light water reactors, most of the heat and radiation is produced by light weight fission products, such as the isotopes cesium-137 and strontium-90. But these tend to have shorter half-lives, about thirty years for cesium-137 and strontium-90, which means that the high intensity isotopes will mostly be gone within one-hundred years and so not pose a problem on a longer time scale. A much smaller fraction of the spent fuel consists of heavy isotopes, such as plutonium-239, which has a half-life of 24,000 years and so would still pose a risk, albeit a steadily declining one, with one-sixteenth of the original amount still radioactive after one hundred years.

How significant is the risk? Posiva Oy, the nuclear waste management firm that is building the Onkalo disposal facility in Finland has conducted many studies to estimate the consequences of a buried waste cannister's rupturing and leaking radiation. Considering all possible pathways for the radioactive material to reach the surface and contaminate soil and water, mainly by leaching out via ground water, and extending the analysis out 10,000 years, they concluded that the most seriously exposed individuals would receive an annual dose of approximately 1.8×10^{-4} mSv, which is roughly equivalent to the dose one gets from eating two bananas (Hjerpe, Ikonen, and Broed 2010, 137).

The Moral Perspective

We must totally decarbonize our energy economy within at most a few decades if we are to avert a climate catastrophe that will kill billions of people and render large parts of our planet uninhabitable. We have seen that this cannot be done with solar and wind power alone. Nuclear power is the only technologically feasible solution. It is comparatively safe and shovel ready. Putting irrational fears aside, what could be the objection to a crash program to replace fossil fuels in electricity generation by nuclear power?

Critics of nuclear power have raised a number of ethical objections to nuclear power. But before we review them, let us recall that the decision to be made is not about nuclear power alone. Instead, the decision is a comparative one. The ethical issues concern a program of rapidly expanding nuclear power in comparison with other courses of action of which there are really only two:

> (1) Do nothing, which dooms the planet.
> (2) Continue on the path called for in the Paris Agreement by expanding renewables as rapidly as possible, reducing energy consumption, and developing new approaches to CO_2 capture and sequestration, all the while hoping for some miraculous technological breakthrough. This approach will mitigate the impacts of climate change, but will still leave our children and grandchildren with a planet dramatically different from the world we know, a planet far less hospitable, where those who survive will lead seriously diminished lives.

There are no other alternatives.

The more serious ethical objections to expanded nuclear power fall into two categories, social and environmental justice and obligations to future generations. Many of those who criticize nuclear power on grounds of social and environment justice base their arguments on serious but commonplace errors about the health and environmental risks and the comparative safety of nuclear power, errors that have already been addressed in this paper, as well as misunderstandings of the science and engineering of nuclear power. As an example, consider the Unitarian Universalist Association's 1976 Social Justice Statement on nuclear power, which starts from three premises:

> 1. The high probability that many people would be exposed to low-level radiation, an eventuality which is known to cause birth defects and to result in deaths from cancer, usually after time delays of years.
> 2, The highly probable exposure of future generations to the lethal effects of the long-lived radioactive waste products inevitably produced by nuclear power plants.
> 3. Uncertainty in regard to the likelihood of catastrophic release of radioactive materials into the environment, because estimates of "nuclear safety" published by the nuclear power industry and its government sponsors neglect the dangers resulting from defects in construction and the lack of an adequate program for training nuclear power plant inspectors and operators.[40]

Where do those probability estimates come from? Whence the uncertainty in those estimates of the likelihood of catastrophic releases of radioactive materials? No documentation is given and none could be given, because there are no such high probabilities, and the suggestion that risk analyses ignore possible construction defects and deficient training is hard to credit.

Or consider a recent paper on "Emerging Environmental Justice Issues in Nuclear Power and Radioactive Contamination" from the *International Journal of Environmental Research and Public Health*, where the authors, one a sociologist from the University of Texas Rio Grande Valley, the other a sociologist from Arizona State, write:

> Commercial nuclear power has also proved repeatedly to lack the "absolute safety" guaranteed by industry proponents (see [3]). As a series of catastrophic reactor accidents has

> shown, the commercial uses of nuclear fission materials to generate electricity are not without potentially severe multiscale risks. . . . This potential has been variously displayed at Chernobyl in Russia (1986), Three Mile Island (TMI) in U.S. (1979), and most recently at Fukushima in Japan (2011). Indeed, on the 30th anniversary of the Chernobyl disaster (2016), no technology yet exists to handle the melted highly radioactive 2000-ton core of the failed reactor, a core that will be lethal to humans for thousands of years [5]. (Kyne and Bolin 2016, 701)

When one follows the footnotes, the first leads to an article in the *Bulletin of the Atomic Scientists* that discusses the myth of "absolute safety" only in the context of the Fukushima accident, the point being about the practice in Japan of overselling the safety of nuclear power to allay concerns deriving from Japan's experience with nuclear weapons in World War II, a practice that, the authors argue, contributed to a lack of preparedness. The paper did not generalize beyond the unique situation in Japan, because there is no global myth of "absolute safety" (Funabashi and Kitazawa 2012).The second footnote leads to an article at *McClatchy* on the thirtieth anniversary of the Chernobyl accident that includes claims such as that the "death toll estimates run from hundreds to millions," when the actual death toll as determined by the United Nations Scientific Committee on the Effects of Atomic Radiation is, as was mentioned earlier, fifty-eight (Schofield 2016). And what is this supposed series of catastrophic reactor accidents? Chernobyl is the only accident that qualifies as a "catastrophe," and there only fifty-eight people died. At Three Mile Island there was no significant radiation release, and no one died or even got sick as a result of the Fukushima accident, aside from those who died because of the hasty and questionable evacuation.

Still, there are legitimate and serious questions of social and environmental justice concerning nuclear power. A good place to turn for more sober and well-grounded scholarship on the topic is the 2015 collection, *The Ethics of Nuclear Energy* (Taebi and Roeser 2015). Foremost among the significant social and environmental justice concerns about nuclear power are issues such as siting decisions, exemplified by government and industry's callous disregard of the interests of local communities in deciding to locate the Yucca Mountain storage facility on land sacred to the Shoshone and Paiute peoples or by regulatory agencies neither seeking nor respecting public input, an all-too-common occurrence (see Gardiner 2015, Krütli et al. 2015, and Pannikar and Sandler 2015). It goes without saying that the interests and opinions of all who are potentially affected by a decision on the location of a nuclear power plant or nuclear waste depository must be respected.

But there is nothing unique to the nuclear power industry in this regard. Exactly the same kind of insensitivity and indifference is encountered in every industry, as evidenced by disasters like the 2008 coal ash spill at the Tennessee Valley Authority's Kingston Steam Plant that unleashed more than a billion gallons of highly toxic fly ash slurry, destroying homes, farms, and the lives of some thirty clean-up workers (Bourne 2019). Any form of large-scale power generation will raise the same questions. If anything, the problem could be much worse with solar and wind, for, as we saw above, the land use needs for dramatically expanded solar and wind power are immense. While they do not produce waste on the scale of a coal fired power plant, there are toxic materials in those solar panels and significant toxic waste is generated in their manufacture. Currently we do not reprocess and recyle that waste, instead mostly just shipping it to less developed parts of the world and hoping, against the evidence, that it will be dealt with safely (Shellenberger 2018). A big problem with wind farms, aside from the huge amount on land they require, is their aesthetic impact on the environment. Owners of the land where towers are sited are compensated usually with annual payments, either a fixed rent, or a fixed rate based on the power produced. Neighbors are not compensated. There are also growing expressions of concern about impacts on wildlife.[41]

While nuclear and other forms of power production are on a par regarding social and environmental justice issues such as siting and waste disposal, one might argue that nuclear poses unique challenges of intergenerational justice, for the obvious reason that nuclear waste can remain a hazard for 100,000 years or more. When we start burying nuclear waste at the Onkalo facility in Finland, we will be imposing risks and obligations on generations to come. Can we even imagine the task of securing and monitoring these sites for, say, 5,000 years? It seems at first glance as if it were the height of arrogance and callous disregard of the interests of unborn generations to do this.

But, consider again that we cannot pose the question of intergenerational justice about nuclear power alone. These are also comparative questions. Viewed through that lens, nuclear power might appear more respectful of the rights and interests of future generations. Nuclear waste, for all of the risks it poses, decays over time. The toxic stew in the oceans of fly ash slurry adjacent to coal fired power plants all around the world will remain toxic forever. This is a crucial difference between many forms of chemical toxicity and radiological toxicity. The same is true of the chemical toxins associated with the production and disposal of solar panels. One recent study claims to show that photovoltaic solar panels produce three hundred times more waste (measured by volume), per unit energy generated, than does nuclear.[42] While some chemical toxins are eventually broken down naturally, by sunlight, water, bacteria, and other processes, many of the worst, including heavy metals, are not. Lead today is lead 1,000,000 years from now. They remain toxic forever. And, yet, we virtually never hear of this toxic burden being represented as a problem of intergenerational justice. Why not?

Of course, the single biggest problem of intergenerational justice is that of climate change, itself. If we do not take drastic action within the next few decades, we will bequeath to our descendants a planet far less hospitable to human life and civilization than it is today. If rapid decarbonization of the energy economy through expanded use of nuclear power is the only guaranteed route to a carbon-free energy economy by 2065 and we forego that option then our generation will have committed a crime of intergenerational injustice far larger than any that can otherwise be imagined.

The Consequentialist Argument for Nuclear Power

The two most helpful theoretical frameworks for an ethical evaluation of nuclear power are consequentialism and virtue ethics. Knowingly or not, almost everyone defaults to the consequentialist framework, so let us begin a summary evaluation there.

The key idea in the consequentialist framework is that one judges the comparative morality of various possible alternative courses of action by determining which maximizes human happiness and minimizes human suffering. It is a seemingly simple and straightforward mode of assessment employed in everyday moral judgments of relatively minor consequence and, in a more formalized way, in all cost-benefit analyses. There are famous challenges to consequentialism, such as whether it is possible to measure all forms of happiness and suffering with a single metric, as when, in many cost-benefit analyses, one assigns a dollar value to lives lost or saved. Two of the classic challenges loom especially large in the case of climate change. The philosopher, Stephen Gardiner dubs them the "spatial" and the "temporal" problems (Gardiner 2011). The spatial problem is whether the happiness or suffering of all people everywhere count equally, or do we rightly attach more weight to the happiness and suffering of those nearer and dearer to us. The temporal problem is this: How far out in time do we extend the calculation? Do we consider only those living today? What about the happiness and suffering of unborn generations or generations that might not be born because of decisions we make today? This is a very serious problem, because, if we extend the calculation far enough into the future, then the sheer number of people who will likely come after us will so overwhelm the population of the Earth today as to render our happiness and suffering relatively meaningless in the calculation. That cannot be right. Is there a reasonable and objective way to discount future harms and goods based on time elapsed from the present?

In spite of these problems, most of us think in consequentialist terms, so, again, let us start there. The argument to this point has been that the only guaranteed way to decarbonize our energy economy by 2065 and so preserve for future generations a modestly habitable planet is through the rapid expansion of nuclear power. Solar and wind cannot do it. CO_2 capture and sequestration is little more than a technological dream at present. Increased energy efficiency and reduced consumption cannot free up the green energy necessary both to replace fossil fuels and provide the energy needed to give the billions of people in the developing world the standard of living that is their due. The consquentialist calculation seems, then, obvious. Only the most rapid possible expansion of nuclear power can guarantee a world in which future generations can flourish rather than languish or die. Yes, it is really that simple. Go the nuclear route now or condemn future generations to death or a miserable existence.

The Argument from Virtue

Still, as noted, the consequentialist framework has its limits. How else might we assay the argument for nuclear power. An ever more important alternative to consequentialism is virtue ethics. As old as Aristotle, virtue ethics enjoyed a rebirth in the late twentieth century following the publication in 1981 of Alasdair MacIntyre's seminal book, *After Virtue* (MacIntyre 1981). It is, today, ever more widely employed in technology ethics (see, for example, Vallor 2016).

Virtue ethics departs radically from consequentialism by asking, first, not about the moral character of the act, but, instead about the moral character of the actor. It defines character as a set of virtues, each virtue being understood as a settled habit of action oriented toward a good. Many different virtues are found in the character of a genuinely virtuous individual, among them justice, temperance, mutual respect, charity, benevolence, fortitude, forbearance, prudence, and wisdom. Several of these might incline one to consider seriously the promotion of nuclear energy as the optimal route to a happy climate future. But, given the complicated and highly contested argument space in which these issues are being thrashed out, perhaps the most relevant is that form of individual and collective, intellectual and moral courage that is required to venture reasonable risk in the face of sometimes intense opposition to a still not widely popular plan of action.

To each virtue there correspond two vices, one the excess of the virtue, the other the defect of the virtue. In the case of courage, the vices are rashness and timidity. The rash individual rushes ahead, heedless of risk. The timid individual so exaggerates risk as to paralyze action. One might say of the critics of green nuclear energy that they err on the side of timidity. They would respond by saying that they exhibit the virtue of prudence, or warranted caution, which is, of course, a virtue. The vice of rashness and the vice of timidity both court disaster. The moral challenge, from the virtue ethics point of view, is to find the appropriate median between rashness and timidity. The argument of this essay suggests that the aggressive expansion of nuclear power, mindful always of risk and due precaution, is the properly courageous response to the challenge of anthropogenic climate change.

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