Evaluation of Nuclear Power as a Proposed Solution to Air Pollution, Global Warming, and Energy Insecurity

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8.10. Why Not Nuclear Power?

In evaluating solutions to global warming, air pollution, and energy security, two important questions that arise are (1) should new nuclear electricity-producing plants be built to help solve these problems, and (2) should existing, aged nuclear plants be kept open as long as possible to help solve the problems? This section discusses these issues after nuclear power is explained.

All nuclear electricity today is generated by nuclear fission. **Nuclear fission** is the process by which tiny neutrons bombard and split certain fissile heavy elements, such as uranium-235 or plutonium-239 in a **nuclear reactor**. The 235 and 239 refer to the isotope, that is the number of protons plus neutrons in the nucleus of a uranium or plutonium atom, respectively. A **fissile** element is one that can be split during fission upon neutron bombardment and whose neutrons released during splitting can split other fissile atoms in a chain reaction. Fissile elements do not spontaneously release neutrons, creating a chain reaction. Instead, they require outside neutrons to bombard them, thereby initiating the chain reaction. In most nuclear reactors, such neutrons are obtained from the decay of californium-252 and plutonium-238.

Uranium-235 is the only fissile element found in nature. Plutonium-239 is also a fissile element, but it is produced artificially in a nuclear reactor. It is the product of uranium-238 and a free neutron. This produces uranium-239, which decays to plutonium-239.

In a nuclear reactor, a moving neutron may either pass through or be absorbed by uranium-235. Slow-moving neutrons have a higher probability than fast-moving neutrons of being absorbed. If a neutron is absorbed, the resulting uranium atom's total energy is spread among all its 236 protons and neutrons now in its nucleus. The nucleus is now unstable, and some uranium atoms fragment into two smaller elements, whereas the remaining atoms form uranium-236. A variety of element pairs arise from fragmentation. Two of the most common are krypton-92 and barium-141. The fragmentation, with this product pair, also produces gamma rays and three free neutrons. The new neutrons may then collide with other uranium-235 atoms or with plutonium-239 atoms, splitting them in a chain reaction. When the fragments and the gamma rays collide with water, the collision converts kinetic energy and electromagnetic energy, respectively, to massive amounts of heat.

In a **boiling water reactor nuclear power plant**, the heat boils water directly. The high-pressure steam turns a turbine connected to a generator to produces electricity. The steam is then re-condensed to liquid water in a condenser, and the liquid water is returned back to the reactor core. In the condenser, heat from the steam (but not the radioactive water vapor itself) is transferred to a separate (in an enclosed pipe) stream of cooling water that originates from a lake, a river, or the coastal ocean. The heated water is then returned to where it originated from, warming the outdoor water body, creating thermal pollution. Other thermal power plants, such as those running on coal, oil, or gas, similarly heat water bodies.

In a **pressurized water reactor** plant, the air pressure in the reactor is increased substantially, up to 155 bar. For comparison, air pressure at the Earth's surface is one bar. Because the boiling point of water increases with increasing pressure, water in the reactor doesn't boil, even when the reactor temperature reaches 282 degrees Celsius (at sea level, water usually boils at 100 degrees Celsius). The hot water in the reactor, which is radioactive, passes through a pipe and exchanges its heat with a different batch of water maintained at normal air pressure, causing the latter water to boil. The boiling water creates steam that is pushed through a steam turbine to generate electricity. The water batches are kept separate to ensure radioactive material in the high-pressure reactor does not pass through to the water vapor running through the steam turbine. Boiling water reactors and pressurized water reactors are both called **light-water reactors**, which are reactors that use normal water.

Uranium in a nuclear reactor is stored in small ceramic pellets within a metal fuel rod, often 3.7-meters long. A conventional light-water reactor goes through one rod during about six years, and the rod and remaining material in it become radioactive waste. Reactors that use rods once are referred to as **once-through** reactors. The radioactive waste in the fuel rod must be stored for hundreds of thousands of years. In a typical once-through reactor, about 4 percent of uranium is uranium-235 and 96 percent is uranium-238 (3 percent of which gets converted to plutonium in the reactor). About one-third of the energy in a once-through reactor comes from the production and decay of plutonium. About two-thirds of the plutonium decays to fission products and one-third is left as waste. Overall, fuel-rod waste contains about 5 percent fission products, 1 percent plutonium, 1 percent uranium-235, and 93 percent uranium-238.

Thus, a fuel rod that has gone through a fission reactor once still has about 94 percent of its uranium left over, including a higher percent of uranium-235 than in natural uranium. Plutonium-239 can be extracted from a fuel rod after two to three years to provide reactor-grade plutonium. Alternatively, all remaining uranium-238, uranium-235, and plutonium can be extracted and reprocessed for use in a **breeder reactor**, extending the life of a given mass of uranium and reducing waste significantly. However, the reprocessing increases the cost of energy. It also increases the production of plutonium-239 by the collision of uranium-238 with fast-moving neutrons. Breeder reactors can thus be optimized to produce plutonium-239 for use in nuclear weapons[223]. As such, they are a concern with respect to nuclear weapons proliferation. Only two reactors today are breeder reactors.

Nuclear fission became a source of electricity starting in the 1950s. The first nuclear reactor to produce electricity was an experimental reactor in Arco, Idaho. On December 20, 1951, it powered four light bulbs. On June 26, 1954, a five-megawatt nuclear reactor was connected to the electric power grid for industrial use in Obninsk, Russia. Subsequently, on August 27, 1956, a 50-megawatt reactor was connected to the grid for commercial use in Windscale, England.

As of 2024, about 440 active nuclear reactors provided electricity in 33 countries for a combined nameplate capacity of 377 gigawatts. In 2023, their total energy output was 2,552 GWh of electricity. This was less than the world nuclear output of 2,616 gigawatt-hours per year in 2004[224]. Thus, world nuclear output has not grown in 20 years.

For all active reactors, uranium mines worldwide produced about 49,400 tonnes of uranium in 2022, Most uranium was mined in Kazakhstan (43 percent), Canada (15 percent), and Namibia (11 percent)[225]. Uranium reserves (aside from hard-to-extract uranium in seawater), as of 2019, were about 8.1 million tonnes[226]. This suggests that about 159 years of uranium are available for the number of once-through fuel cycle reactors operating in 2024. As such, even if the issues discussed below were not issues, uranium is a limited resource, and growing nuclear power will deplete uranium reserves faster.

An alternative fuel to uranium in nuclear reactors is thorium. **Thorium**, like uranium, can be used to produce nuclear fuel in a breeder reactor. The advantage of thorium is that it produces less long-lasting radioactive waste than does uranium. Its products are also more difficult to convert into nuclear weapons material. However, thorium still produces ^{233}U, which was used in one nuclear bomb core produced during the **Operation Teapot** bomb tests in 1955. Thus, thorium is not free of nuclear weapons-proliferation risk. In addition, thorium reactors require the same lengthy time lag between planning and operation as do uranium reactors and likely longer because hardly any contractors or scientists have experience building or running thorium reactors. Thus, thorium reactors will produce greater emissions from the background electric grid than WWS technologies, which have a shorter time lag. Finally, lifecycle emissions of carbon from a thorium reactor are similar to those from a uranium reactor.

A proposed alternative to the large once-through reactor and the breeder reactor is the **small modular reactor**. Small modular reactors are nuclear fission reactors that are on the order of one-third the size of traditional reactor. They have some parts that could be prefabricated in a factory, which could help to reduce construction time, costs, and mistakes during construction. However, as of early 2025, no small modular reactor has been commercialized worldwide, so it is difficult to determine whether any design will take advantage of prefabrication.

Many types of small modular reactors have been proposed, including miniature versions of current reactors. One type of new design is a **fast reactor**, in which the fuel is reformulated to allow fast-moving neutrons, rather than slow-moving neutrons, to split an atom. One way to do this is to increase the quantity of plutonium-239, which absorbs more fast-moving neutrons than does uranium-235. This is done by surrounding the core with uranium-238, which absorbs a fast-moving neutron to become uranium-239, which then decays to plutonium-239. By this mechanism, though, fast reactors become breeder reactors, increasing weapons proliferation risk.

In sum, whereas slow reactors produce significant radioactive waste, fast reactors would produce less waste but would increase nuclear weapons proliferation risk by producing more plutonium-239. Because all small modular reactors are small and many are proposed to be transportable, countries that don't currently have nuclear energy facilities will have an incentive to purchase them, increasing weapons proliferation risk. Most, but not all, small modular reactors also have meltdown risk. In addition, they require uranium, which must be mined. Small reactors have the same uranium mining resource limitation, underground mining lung cancer risk, and land despoilment risk as do large reactors.

Many start-up companies around the world are designing small modular reactors. However, no small modular reactor being designed in 2025 is expected to have a prototype available until past the year 2030 or a commercial product available until years after that. This is relevant, since the world needs to eliminate 80 percent of climate-affecting emissions by 2030 and the rest by 2035 to 2050 to avoid the harshest consequences of global warming. In addition, the world needs to eliminate 100 percent of its air pollution emissions today to avoid the over seven million air pollution deaths that occur yearly. As such, small modular reactors will not be able to help address global warning or air pollution in a rapid or meaningful way. Instead, money spent on them will prevent faster and less expensive solutions from being implemented, exacerbating the climate and air pollution problems the world faces.

Historically, small nuclear reactors were planned and developed before large ones were conceived. However, nuclear plant developers abandoned small reactors in favor of large reactors because building one large reactor was much less expensive than building three small ones. Even today, the cost per unit energy of a new small modular reactor is estimated to be higher per unit energy than that of a large reactor. Further, the cost per unit energy of a large reactor, in 2024, is five times that of new onshore wind or utility PV[191]. As such, it is expected that small modular reactors will be much more expensive than new WWS electricity generators.

Transition highlight. In late 2024, several companies proposed using small modular reactors in isolated microgrids to provide baseload electricity for computer datacenters, which consume a lot of relatively constant electricity. However, the same can be accomplished with either a combination of PV, wind and batteries or an enhanced geothermal system. Whereas small modular nuclear reactors are not expected to be commercial until the 2030s and at uncertain cost, planning-to-operation time, and security risk, the other two options exist and are being built today.

The sun and all stars in the universe are powered by a different type of nuclear power, nuclear fusion. **Nuclear fusion** involves the fusing together of light atomic nuclei (protium, deuterium, or tritium) into heavier elements. In theory, nuclear fusion could supply all power on Earth indefinitely. It could also do so without long-lived radioactive waste because its products are isotopes of helium, which are not harmful. Nuclear fusion has been explored for decades. However, its commercialization has always been about 30 to 100 years away. Recently, technical advances have been made in the development of nuclear fusion. But even the International Atomic Energy Agency acknowledges that a demonstration fusion reactor won't be available until at least 2040 and commercial electricity generation from fusion may or may not occur by the second half of the twenty-first century[227]. Given that we need to eliminate 80 percent of world emissions by 2030, that proposed date is too far away for fusion to be useful. As such, nuclear fusion will unlikely address global warning, air pollution, or energy insecurity in any meaningful way.

8.10.1. Risks Affecting Nuclear's Ability to Address Global Warming and Air Pollution

The risks associated with nuclear power can be broken down into two categories: (1) risks affecting nuclear power's ability to reduce global warming and air pollution and (2) risks affecting its ability to provide environmental security.

Risks under Category one include the following: delays between planning and operation of a nuclear power plant, emissions contributing to global warming and air pollution, and cost. Risks under Category two include weapons proliferation risk, reactor meltdown risk, radioactive waste risk, underground mining lung cancer risk, and land despoilment risk. These risks are discussed herein.

8.10.1.1. Delays Between Planning and Operation and due to Refurbishing Reactors

The longer the time lag between the planning and operation of an energy facility, the more the emissions of air pollutants and climate-damaging chemicals from the background electric grid. Similarly, the longer the time required to refurbish a nuclear plant for continued use at the end of its life, the greater the emissions from the background grid when the nuclear plant is down.

The time lag between planning and operation of a nuclear plant includes the times to secure a construction site, a construction permit, an operating permit, financing, and insurance; the time between construction permit approval and issue; and the time to build the plant, which includes the time between the end of construction and grid connection.

In March 2007, the United States Nuclear Regulatory Commission approved the first request for a site permit in 30 years. This process took 3.5 years. The time to review and approve a construction permit is another two years and the time between the construction permit approval and issue is about half a year. Thus, the minimum time for preconstruction approvals (and financing) in the United States is six years. An estimated maximum time 10 years. The time to construct a nuclear reactor depends significantly on regulatory requirements and costs. Although nuclear reactor construction times worldwide are often shorter than the nine-year median construction times in the United States since 1970[228], they averaged 7.4 years worldwide in 2015[229]. As such, a reasonable estimated range for construction time prior to 2016 was four to nine years, bringing the overall time between planning and operation of historical nuclear power plants worldwide to 10 to 19 years. However, since 2016, the range worldwide has expanded to 12 to 23 years and in North America and Europe, to 17 to 23 years. Below are specific examples.

The **Olkiluoto 3** reactor in Finland was proposed to the Finnish cabinet in December 2000 as an addition to an existing nuclear plant. Its construction started in 2005, and it first generated electricity in 2022, but it only began commercial operation on May 1, 2023, giving it a construction time of 18 years and a **planning-to-operation** time of 23 years. The total capital cost in 2024 was about $7.7 per watt-nameplate-capacity, about 3.7 times the original projected cost.

The **Hinkley Point C** nuclear power station in the United Kingdom was planned, starting in 2008. Construction began only on December 11, 2018. It has an estimated completion year of 2029 to 2031, giving it an estimate construction time of 11 to 13 years and a planning-to-operation time of 21 to 23 years. The projected capital cost in 2024 was about $19 per watt-nameplate-capacity, or about six times the original projected cost.

The **Vogtle 3 and 4** reactors in the U.S. state of Georgia were first proposed in August 2006 to be added to an existing nuclear power station site. Construction started for both in 2013. Unit 3 began operating commercially on July 21, 2023, and unit 4 began operation on April 29, 2024, giving them construction times of 10 and 11 years, respectively, and planning-to-operation times of 17 and 18 years, respectively. The final capital cost in 2024 was about $15.7 per watt-nameplate-capacity, about 2.5 times the original estimated cost.

The **Flamanville**, France, Unit 3 reactor was planned on an existing nuclear power station site starting in 2004. A contract was awarded in 2005. Construction started in 2007. The reactor is expected to be operating commercially in 2024, for an estimated construction time of 17 years and planning-to-operation time of 20 years. The final capital cost in 2024 was about $15.8 per watt-nameplate-capacity, about 5.8 times the original estimated cost.

The **Haiyang 1 and 2** reactors in China were planned in 2005. Construction started in 2009 and 2010, respectively. Haiyang 1 began commercial operation on October 22, 2018. Haiyang 2 began operation on January 9, 2019, giving them construction times of nine years and planning-to-operation times of 13 and 14 years, respectively.

The **Taishan 1 and 2** reactors in China were planned, starting in 2006. Construction began in 2008. Taishan 1 began commercial operation on December 13, 2018. Taishan 2 began operation on September 9, 2019, giving them construction times of 10 and 11 years and planning-to-operation times of 12 and 13 years, respectively.

The **Shidao Bay** nuclear power plant in China includes the development of a 200-megawatt high-temperature gas-cooled (as opposed to water-cooled) reactor. Planning started in 2005. Construction began in December 2012. Grid connection occurred in early 2022. Thus, the construction time was 10 years and the planning-to-operation time was 17 years.

The **Barakah 1-4** nuclear plant in the United Arab Emirates contains four reactors, all planned, starting in 2009. Construction of the four reactors began during July, 2012; April, 2013; September, 2014; and July, 2015, respectively. Commercial operation began during April, 2021; March, 2022; February, 2023, and in late 2024, respectively, giving construction times for all reactors of 9 years and planning-to-operation times of 12, 13, 14, and 15 years, respectively.

Planning of and procurement for four reactors in **Ringhals**, Sweden started in 1965. One took 10 years, the second took 11 years, the third took 16 years, and the fourth took 18 years to complete.

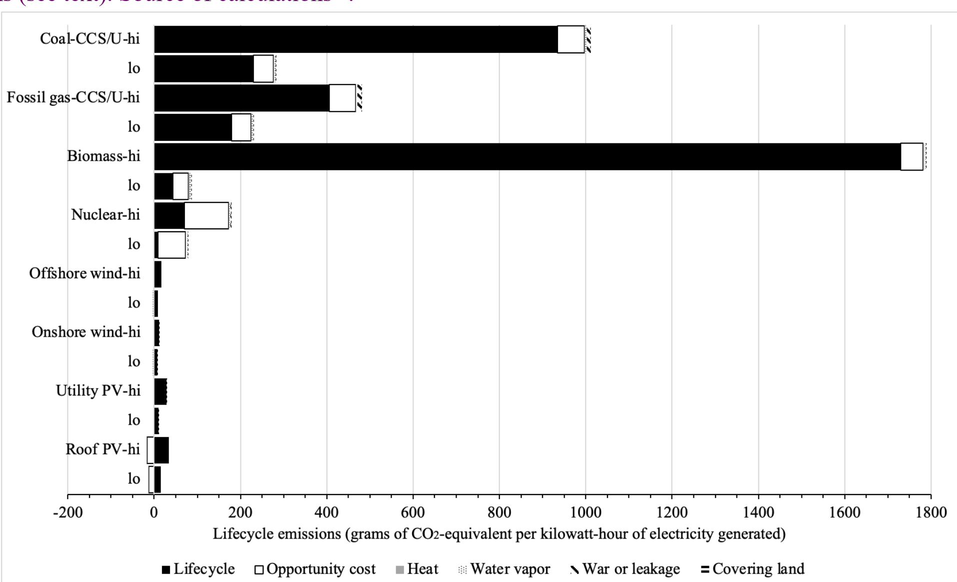
Some contend that France's 1974 Messmer Plan resulted in the building of its 58 reactors in 15 years. The **Messmer Plan** was a proposal, enacted without public or parliamentary debate, by the Prime Minister of France, Pierre Messmer, to build 80 nuclear reactors by 1985 and 170 by 2000. In fact, the plan had been in the works for years prior and was only proposed publicly following the international oil crisis of 1973[230]. For example, the Fessenheim nuclear reactor obtained its construction permit in 1967 and was planned before that. In addition, 10 of the reactors were completed only between 1991 and 2000. As such, the whole planning-to-operation time for the 58 reactors was at least 33 years, not 15. That of any individual reactor was 10 to 19 years.

In sum, planning-to-operation times for all reactors in history have been in the range of 10 to 23 years. For reactors operating prior to 2016, the range was 10 to 19 years. For reactors after 2016, the range is 12 to 23 years, with those in North America and Europe, between 17 and 23 years.

Planning-to-operation delays are also caused by downtime during reactor refurbishment. Nuclear reactors have a lifetime on the order of 40 years. To run longer, they need to be refurbished. The time to refurbish can be three to four years. Refurbishment of the Darlington 2, Ontario nuclear reactor, for example, began in October 2016 and was completed in June 2020, taking just less than four years.

The background grid, which consists primarily of fossil fuels in most places worldwide, emits pollution when a nuclear plant is being constructed or down for refurbishing. The total opportunity-cost emissions of nuclear due to both factors average out to be about 64 to 102 grams of CO_2-equivalent per kilowatt-hour of electricity generated (Figure 8.1). These emissions are higher than the lifecycle emissions of nuclear.

Figure 8.1. Low and high estimates of total 100-year-averaged CO_2-equivalent emissions from several electricity-producing technologies. The total for each bar is the sum of lifecycle emissions ("Lifecycle"), opportunity cost emissions ("Opportunity cost"), anthropogenic-heat emissions, ("Heat"), anthropogenic-water-vapor emissions ("Water vapor"), emissions from nuclear weapons proliferation or carbon capture leakage ("War or leakage"), and emissions from loss of carbon storage by covering land and vegetation with building materials ("covering land"). CCS/U is carbon capture and storage or use. Opportunity-cost emissions are relative to onshore wind, so negative opportunity cost emissions (for rooftop PV) are due to the shorter time-lag between planning and operation of roof PV versus onshore wind. All wind and solar have negative heat emissions; wind has negative water vapor emissions (see text). Source of calculations[10].



Transition highlight. China's decision prior to 2012 to investment in nuclear, which has a long planning-to-operation time, instead of wind or solar, may have resulted in China's carbon dioxide emissions rising 1.3 percent from 2016 to 2017 rather than declining by an estimated 3 percent during that period[10]. It may also have resulted in 82,000 more people dying from air pollution in China in 2016. The reason is that the nuclear plants planned prior to 2012 were not close to operating in 2016. Had China invested that same money in wind and solar, wind and solar farms would already have been operating by 2016, eliminating substantial CO_2 and air pollution emissions from coal.

8.10.1.2. Air Pollution and Global Warming Relevant Emissions from Nuclear

Nuclear power contributes to global warming and air pollution in several ways: through (1) emissions of health- and climate-damaging pollutants from the background grid due to nuclear power's long planning-to-operation and refurbishment times; (2) emissions of health- and climate-damaging air pollutants during construction, operation, and decommissioning of a nuclear plant; (3) heat and water vapor emissions during the operation of a nuclear plant; (4) carbon dioxide emissions due to the covering of soil or clearing of vegetation during the construction of a nuclear plant, uranium mine, and nuclear waste site; and (5) the risk of emissions arising from nuclear weapons proliferation.

Each of these categories represents an actual emission or emission risk, yet all of these emissions, except for lifecycle emissions, are incorrectly ignored in virtually all studies of nuclear power impacts on climate. Studies that ignore these real emissions distort the impacts of nuclear power on climate and air pollution health.

The estimated range of nuclear lifecycle emissions (9 to 70 grams of CO_2-equivalent per kilowatt-hour of electricity) in Figure 8.1 is well within the range (4 to 110) from studies cited by the Intergovernmental Panel on Climate Change[231]. On top of those emissions are opportunity-cost emissions (64 to 102); heat and water-vapor emissions (4.4); emissions due to covering and clearing soil (0.17 to 0.28); and emissions due to the risk of nuclear weapons use arising from the spread of nuclear energy (0 to 1.4). The total is 78 to 178 grams of CO_2-equivalent per kilowatt-hour of electricity. These emissions are 9 to 37 times the estimated emissions from onshore wind (Figure 8.1).

Although the emissions from nuclear are lower than those from coal or fossil gas with carbon capture, nuclear power's high CO_2-equivalent emissions coupled with its long planning-to-operation time render it an opportunity cost relative to the faster-to-operate and lower-emitting WWS technologies.

8.10.1.3. Nuclear Costs

The third risk of nuclear power that affects its ability to reduce global warming and air pollution is its high cost. In addition, the cost of running existing nuclear reactors has increased so much that many existing reactors are shutting down early. Owners of others have requested large subsidies to stay open. This section discusses nuclear costs.

The 2024 mean levelized cost of energy for a new nuclear plant in the United States is 18.2 cents per kilowatt-hour[191]. This compares with about 5 and 6 cents per kilowatt-hour for onshore wind and utility-scale solar PV, respectively. Thus, new nuclear electricity is 3 to 4 times the cost per unit electricity of new wind and solar. A good portion of the high cost of nuclear is due to its long planning-to-operation time, which in turn is partly due to construction delays.

This levelized cost of nuclear does not account for the future cost of storing radioactive waste. For example, in the U.S. alone, about $500 million is spent yearly to safeguard nuclear waste from about 100 civilian nuclear energy plants[232]. Such waste must be stored for hundreds of thousands of years. The cost also does not account for the damage due to nuclear reactor meltdowns. For example, the estimated cost to clean the damage from three Fukushima Dai-ichi nuclear reactor core meltdowns in 2011 was $460 to $640 billion[233]. This is equivalent to about 9 to 13 percent of the current-day capital cost of every nuclear reactor that exists worldwide.

The spiraling cost of new nuclear plants in recent years has resulted in the cancelling of several reactors under construction. For example, two reactors in South Carolina were canceled during July 2017. The high cost of nuclear has also resulted in threats by reactor owners to shut plants unless they received a subsidy. The risk of shutting a functioning nuclear plant is that its electricity will be replaced by electricity from a fossil-fuel plant. However, the problem with subsidizing nuclear is that the funds could otherwise be used to replace the nuclear electricity with lower-cost and lower-emitting WWS electricity. Because the nuclear plant usually needs to be replaced within a decade of a subsidy request in any case, incurring the cost of new WWS immediately will almost always cost less than paying nuclear a subsidy each year for ten years plus incurring the cost of new WWS in ten years.

Transition highlight. In 2016, three upstate New York nuclear plants requested and received subsidies to stay open until 2028 using the argument that the plants were needed to keep emissions low. However, subsidizing such plants may have increased carbon dioxide emissions and costs versus replacing the nuclear quickly with wind or solar**Error! Reference source not found.**.

In sum, before accounting for waste storage or meltdown damage costs, a new nuclear lant costs about 3 to 4 times that of a new onshore wind farm, takes 7 to 21 years longer between planning and operation than a wind farm, and produces nine to 37 times the emissions per unit electricity generated as a wind farm. Thus, funds spent on new nuclear means much less electricity, a much longer wait, and a much more emissions than the same funds spent on WWS. The Intergovernmental Panel on Climate Change similarly concludes that the economic, social, and technical feasibility of nuclear power have not improved over time[235],

> "*The political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies has improved dramatically over the past few years, while that of nuclear energy and Carbon Dioxide Capture and Storage (CCS) in the electricity sector has not shown similar improvements.*"

8.10.2. Risks Affecting Nuclear's Ability to Address Environmental Security

The second category of risk related to nuclear power is the risk of a nuclear plant not being able to provide environmental security. One reason is the risk of weapons proliferation. Others are the risks of meltdown, radioactive waste leakage, and cancer and land degradation due to uranium mining. WWS technologies do not create such risks.

8.10.2.1. Weapons Proliferation Risk

The first risk of nuclear related to environmental security is weapons proliferation risk. The growth of nuclear has historically increased the ability of nations to harvest plutonium or enrich uranium to manufacture nuclear weapons[236]:

> "*Peaceful nuclear cooperation and nuclear weapons are related in two key respects. First, all technology and materials related to a nuclear weapons program have legitimate civilian applications. For example, uranium enrichment and plutonium reprocessing facilities are dual-use in nature because they can be used to produce fuel for power reactors or fissile material for nuclear weapons. Second, civilian nuclear cooperation builds-up a knowledge-base in nuclear matters*."

The Intergovernmental Panel on Climate Change recognizes this fact. They conclude, with "*robust evidence and high agreement*" that nuclear weapons proliferation concern is a risk to the increasing development of nuclear energy[212]:

> "*Barriers to and risks associated with an increasing use of nuclear energy include* ***operational risks*** *and the associated safety concerns,* ***uranium mining risks****, financial and regulatory risks,* ***unresolved waste management issues, nuclear weapons proliferation concerns****, and adverse public opinion.*"

The building of a nuclear reactor in a country with no reactor increases the risk of the country developing nuclear weapons. It allows the country to import uranium for use in the reactor. If the country so chooses, it can secretly enrich the uranium to create weapons-grade uranium and harvest plutonium from uranium fuel rods used in the reactor for nuclear weapons. This does not mean any or every country will do this, but historically some have.

Nuclear weapons can be produced from nuclear energy infrastructure as follows. Uranium ore is mined in an open pit or underground and contains 0.1 to one percent uranium by mass. The ore is milled to concentrate the uranium in the form of a yellow power called **yellowcake**, which contains about 80 percent uranium oxide. Uranium is then processed further into uranium dioxide or uranium hexafluoride for use in nuclear reactors. However, before the uranium can be used in a reactor, it must be enriched.

Of all uranium on Earth, 99.2745 percent is uranium-238, 0.72 percent is uranium-235, and 0.0055 percent is uranium-234. Uranium-238 has a half-life of 4.5 billion years. Most commercial light water nuclear reactors use uranium consisting of three to five percent uranium-235. As such, the concentration of uranium-235 in a fuel rod must be increased to four to seven times its ore concentration. This is done by enrichment. **Uranium enrichment** is the process of separating the isotopes of uranium to increase the percent of uranium-235 in a batch. Enriched uranium is useful for both nuclear energy and nuclear weapons.

Enrichment is done either by gas diffusion, centrifugal diffusion, or mass separation by magnetic field. Only gas diffusion and centrifugal diffusion are commercial processes, and most enrichment today is by **centrifugal diffusion** because it consumes only 2 to 2.5 percent the energy as gas diffusion. Nevertheless, centrifugal diffusion still requires many centrifuges running for long periods, thus lots of energy. Centrifugal diffusion works by spinning a cylinder containing uranium. The heavier uranium-238 atoms collect toward the outside edge of the cylinder and the lighter uranium-235 atoms collect toward the inside.

Uranium with less than 20 percent uranium-235 is called **low enriched uranium**. **Highly enriched uranium** contains 20 to 90 percent uranium-235. A nuclear weapon can be made with highly enriched uranium. However, nuclear weapons increase their destructiveness with even more enrichment. Thus, ninety percent or more uranium-235 is considered **weapons grade uranium** and is generally used together with enriched plutonium in a nuclear bomb. An estimated 9,000 centrifuges can produce enough weapons grade uranium-235 for one nuclear weapon from natural uranium in about seven months. With 5,000 centrifuges, the process takes about one year[237]. Because uranium in a fuel rod used for nuclear energy has only three to five percent uranium-235 and even less once it goes through a nuclear reactor, spent fuel rods are not considered a useful source of weapons grade uranium.

Plutonium is also used in nuclear weapons. Ten kilograms of plutonium-239 were used in the bomb dropped on Nagasaki. Plutonium can be obtained from a once-through nuclear reactor running on a uranium fuel rod. When uranium-235 decays and releases neutrons in a nuclear reactor, one of the neutrons can bind with a uranium-238 atom to produce uranium-239, which decays to plutonium-239. Plutonium that contains 93 percent or more plutonium-239 is considered weapons-grade plutonium. Plutonium with less than 80 percent plutonium-239 is reactor grade. Because plutonium can be used to make a bomb and is easier to obtain than is enriching uranium (since plutonium can be harvested from a fuel rod running once through a nuclear reactor), plutonium is considered the element of even greater concern than uranium with respect to nuclear weapons proliferation.

A large-scale worldwide increase in nuclear energy facilities would exacerbate the risk of nuclear weapons proliferation. In fact, producing material for a weapon requires merely operating a civilian nuclear power plant together with a sophisticated plutonium separation facility. The historic link between nuclear energy facilities and nuclear weapons is evidenced by the development or attempted development of weapons capabilities secretly under the guise of peaceful civilian nuclear energy or nuclear energy research programs in Pakistan, India, Iraq (prior to 1981), Syria (prior to 2007), Iran, and North Korea, among other countries.

If the world's all-purpose energy were converted to electricity and electrolytic hydrogen by 2050, the nine trillion watts (TW) in resulting annual average end-use electric power demand would require about 12,500 850-megawatt nuclear reactors (28 times the number of active reactors today), or 1.4 installed every day for 25 years. Not only is this construction timeline impossible given the long planning-to-operation times of nuclear, but it would also result in all known reserves of uranium worldwide for once-through reactors running out in about three years. As such, there is no possibility the world will run solely on once-through nuclear energy by 2050.

Even if only 6.4 percent of the world's energy came from nuclear, the number of active nuclear reactors worldwide would nearly double to around 800. Many more countries would possess reactors, increasing the risk that some countries would use the facilities to mask the development of nuclear weapons, as has occurred historically.

If a country were to develop a weapon as a result of its acquisition of one or more nuclear energy facilities, the risk that it would use the weapons is not zero. Here, the emissions associated with a limited nuclear exchange are estimated.

The explosion of one-hundred 15-kilotonne nuclear bombs (a total of 1.5 megatonnes, or 0.1 percent of the yield of a full-scale nuclear war) during a limited nuclear exchange in a megacity could kill 2.6 to 16.7 million people from the explosion and burn 63 to 313 million tonnes of city infrastructure, adding one to five million tonnes of warming and cooling aerosol particles to the atmosphere, including much of it to the stratosphere[178]. The particle emissions would cause significant short- and medium-term regional temperature changes. The carbon dioxide emissions, estimated at 92 to 690 million tonnes, would enhance long-term global warming. The warming impact of one such nuclear exchange over 100 years is equivalent to 1.4 grams of CO_2-equivalent emissions per kilowatt-hour of electricity produced by nuclear during that period. It arises from nuclear weapons development facilitated by the spread of nuclear energy. That is the high-end risk of carbon dioxide emissions from nuclear weapons proliferation due to nuclear energy in Figure 8.1. The low-end estimate is zero emissions because no exchange occurs.

8.10.2.2. Meltdown Risk

The second risk of nuclear power related to environmental security is reactor core meltdown risk. The Intergovernmental Panel on Climate Change points to operational risks (meltdown) as a barrier and risk associated with nuclear power.

About 1.5 percent of all nuclear reactors operating in history have had a partial or significant core meltdown. Meltdowns have been either catastrophic (Chernobyl, Russia in 1986; three reactors at Fukushima Dai-ichi, Japan in 2011) or damaging (Three-Mile Island, Pennsylvania in 1979; Saint-Laurent France in 1980). The nuclear industry has suggested that new reactor designs are safer. However, these designs are generally untested, and there is no guarantee that the reactors will be designed, built and operated correctly or that a natural disaster or act of terrorism, such as an airplane flown into a reactor, will not cause the reactor to fail, resulting in a major disaster.

On March 11, 2011, an earthquake measuring 9.0 on the Richter scale, and a subsequent tsunami knocked out backup power to a cooling system, causing six nuclear reactors at the **Fukushima 1 Dai-ichi plant** in northeastern Japan to shut down. Three reactors experienced a significant meltdown of nuclear fuel rods and multiple explosions of hydrogen gas that formed during efforts to cool the rods with seawater. Uranium fuel rods in a fourth reactor also lost their cooling. As a result, cesium-137, iodine-131, and other radioactive particles and gases were released into the air. Locally, tens of thousands of people were exposed to the radiation, and 170,000 to 200,000 people were evacuated from their homes. 1,600 to 3,700 people perished during the evacuation alone[233,238]. At least one nuclear plant worker died from lung cancer from direct radiation exposure[239].

The radiation release created a dead zone around the reactors that may not be safe to inhabit for decades to centuries. The radiation also poisoned the water and food supplies in and around Tokyo. The radiation plume from the plant spread worldwide within a week[240]. Although radioactivity levels in Japan within 100 kilometers of the plant were extremely high, those in the rest of Japan and eastern China were lower, and those in North America and Europe were even lower. It is estimated that 130 (15 to 1,100) radiation-related deaths and 180 (24 to 1,800) radiation-related illnesses will occur worldwide, primarily in eastern Asia, during the decades after the meltdown[240]. The cost of the cleanup of the Fukushima reactors and the surrounding area is estimated at $460 to $640 billion[233].

The 1.5 percent risk of a nuclear reactor meltdown is a high risk. Catastrophic risks with all WWS technologies aside from the risk of a large hydropower dam collapsing, are zero. WWS roadmaps do not call for an increase in the number of large hydropower dams worldwide, only the more effective use of existing ones.

8.10.2.3. Radioactive Waste Risks

Another risk associated with nuclear power is the risk of human and animal exposure to radioactivity from fuel rods consumed by once-through reactors. Used fuel rods are considered **radioactive waste**. Currently, most used fuel rods are stored at the reactor site. This has given rise to hundreds of radioactive-waste sites in many countries that must be maintained for hundreds of thousands of years, far beyond the lifetime of any nuclear power plant. The United States houses about one quarter of all nuclear reactors worldwide. Plans to store the waste of all U.S. reactors inside of Yucca Mountain, Nevada, never passed into law, so waste will continue to accumulate at reactor sites. The more that waste accumulates, the greater the risk that a radioactive leak will damage water supply, crops, animals, and humans.

8.10.2.4. Uranium Mining Health Risks and Land Degradation

Nuclear power increases the risk that underground miners contract lung cancer and that open-pit uranium mines degrade land. Such risks continue so long as nuclear power plants operate because the plants need uranium to produce electricity. WWS technologies, on the other hand, do not require the continuous mining of any material, only one-time mining to produce the WWS equipment.

In 2022, 14 countries mined uranium. Of these, Kazakhstan, Canada, Namibia, Australia, Uzbekistan, Russia, and Niger produced the most uranium[225]. Mines can be open pit or underground. Open pit mines cause the most land degradation. Underground mines cause the greatest lung cancer risk.

Underground uranium mining causes lung cancer in large numbers because uranium mines contain natural radon gas, some of whose decay products are carcinogenic. Several studies have found a link between high radon levels and cancer[241,242]. One year-2000 study by the U.S. Center for Disease Control and Prevention of 4,000 underground uranium miners between 1950 and 2000 found that about 10 percent died of lung cancer, a rate six times that expected based on smoking rates alone[10]. Another 1.5 percent died of mining related lung diseases, supporting the hypothesis that uranium mining is unhealthy. In fact, the combination of radon and cigarette smoking increases lung cancer risks above the normal risk associated with smoking[243].

Clean, renewable energy does not have this risk because (a) it does not require the continuous mining of any material, only one-time mining to produce energy generators and storage; and (b) the mining for materials related to WWS does not carry the same lung cancer risk as does uranium mining.

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