Nuclear Power: Is it Necessary? Is It Safe? What About the Waste?

A Report By the Ad Hoc Committee on Nuclear Power
Environment and Climate Caucus* of the Washington State Democratic Party

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Executive Summary

This paper reflects our findings in answer to the three questions below, after careful consideration of peer reviewed literature or governmental sources that are for the most part accessible to the general public:

1. In light of the cost and availability of renewable energy and various kinds of storage, is nuclear power really necessary to reach net zero?
2. Many fear radioactivity based on historical events. Is nuclear energy safe?
3. Nuclear power produces isotopes with half-lives of many thousands of years. What about nuclear waste disposal?

The answer to the first question is perhaps the most important part of this paper. We conclude that nuclear power must be included with renewable energy sources in order to address climate change and meet energy demand in a reliable, affordable, and equitable way. There is simply no other stable source of energy at anywhere near the same level of technological development and scale.

The second part of the paper concludes that nuclear power is highly regulated and safe, and explains that our cells contain robust protective systems that evolved to deal with radiation over more than a billion years.

The third part concludes that the disposal of nuclear waste generated by the nuclear energy is readily solved by reliable and widely agreed upon technology. Long-term disposal of nuclear waste is a current reality, not a hypothetical dream. Addressing waste disposal is a political problem, not a technical one.

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Part 1: Is Nuclear Power Necessary to Reach Net Zero?

This report involves several distinct and rather technical fields. A glossary is provided at the beginning of each of the three parts in an effort to make the document easier to read.

Glossary

$/MWh: cost of electricity in dollars per megawatt hour. In 2021 the average US cost of electricity to residential consumers was $14.11/MWh; in Washington state it was $10.38/MWh.[1]

Blackout: a complete loss of electrical supply, almost always out of the control of utilities or transmission operators.

Brownout: an under-voltage condition where the AC supply drops below the nominal value (120 V or 220 V) by 10-25%. Different kinds of electrical equipment will react in different ways to brownouts. Usually a condition controlled by the utilities or transmission operators as a way to avoid longer, more destructive, Blackouts.

CO_2(e): carbon dioxide equivalents, also called CO_2 eq., used to measure the climate effect of gasses other than carbon dioxide.

Clean energy: sources of electricity generation that produce low amounts of CO_2(e) per kWh on a lifecycle basis. A table showing emissions of various energy sources can be found in Appendix 1.A. Clean energy technologies include renewable energy sources (wind, solar, hydro, biomass) as well as nuclear power. A related term is **carbon intensity**, a description of the amount of CO_2(e) produced by a generating system.

Firm power: electricity that is available when it is needed, also called dispatchable power. Examples include nuclear, hydro, coal, natural/fossil gas.

Intermittent power: electricity that is generated under circumstances beyond the control of grid operators. Also called variable renewable energy (VRE). Includes solar and wind power.

Lifecycle carbon intensity: the total amount of CO_2(e) emitted by all phases of construction, mining, transportation, facility operation, and decommissioning/disposal of a power generating system.

Load-following: adjusting the power output as demand for electricity fluctuates.

NREL: National Renewable Energy Laboratory.

[1] https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

Net zero: when the amount of greenhouse gas released to the atmosphere equals or is less than the amount removed from the atmosphere. Also called carbon neutral.

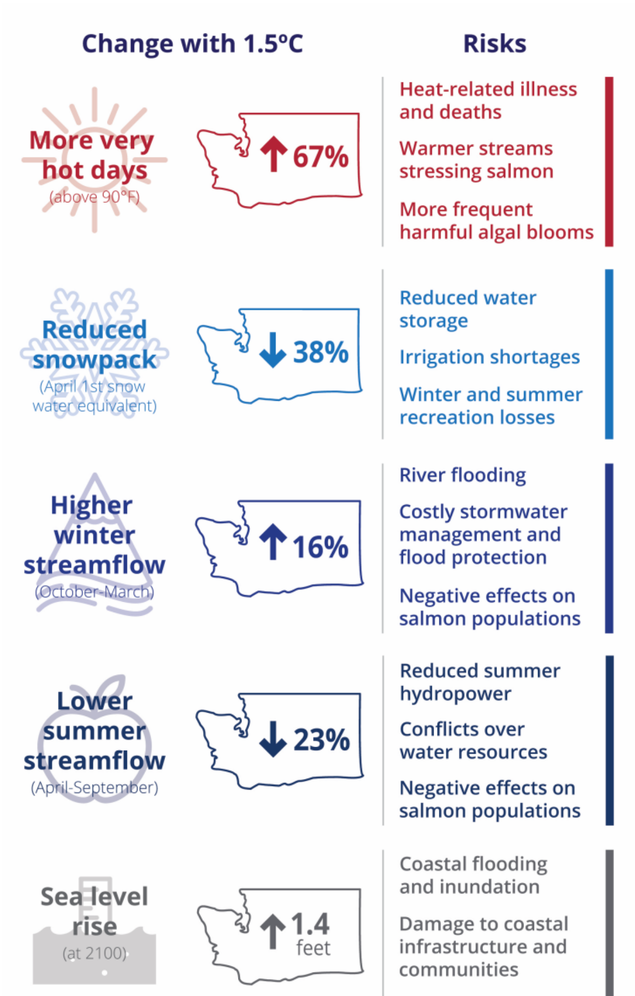
Renewable energy: technologies that generate electricity or heat using direct inputs that are naturally replenished, without considering the physical structure of the generating systems. Examples include solar-, wind-, and hydropower and biomass, and may or may not include storage in the form of batteries, pumped hydro, or other systems.

VRE: Variable renewable energy.

Is Nuclear Power Necessary to Reach Net Zero?

Introduction

As the climate situation becomes increasingly dire, it is important for us all to increase our understanding of relevant issues, some of which are complex and contentious. Nuclear power is both, and is especially contentious among Democrats. Better understanding of nuclear power could help address the climate crisis, and will build bridges between Democrats who currently hold differing opinions.



From UW Climate Impacts Group

Numerous governments, agencies, organizations, and individuals recognize that it is vital to reach net zero as rapidly as possible to avoid catastrophic global climate change; the 2016 Paris Agreement calls for the world to reach net zero by midcentury. Washington state passed the CETA act in 2019, committing the state to greenhouse gas emission-free electricity production by 2045. To do this, it will be necessary to convert as many fossil fuel-using industries as possible to the use of clean energy. We will reach a 1.5°C (2.7°F) increase by the mid 2030s; as shown in the figure at left, the increase will have significant implications for Washington state.

Obviously, in order to stop burning fossil fuels, we need to replace them with energy that is generated producing as little CO_2 as possible, and this must be done as quickly as possible. This means obtaining as much energy as possible from clean energy, and reducing the use of fossil fuel to an absolute minimum. (See Appendix 1.A regarding the carbon intensity of various energy sources.)

The idea that renewable energy alone can generate a sufficient amount of clean energy to make it possible to stop burning fossil fuels was initially popularized by Mark Jacobson and Mark Delucchi (2009)[2]. They were rebutted almost immediately in the scientific literature including by colleagues from their own institution, with twenty-one prominent scientists issuing a sharp critique.[3] In addition, recent results of modeling suggest that a renewables-only strategy carries significant risks and problems in terms of cost and grid stability. The goal of reducing the risks and costs of a renewables-only strategy will be called a "renewables-plus" approach for the purposes of this paper.

In this section of our report, our goal is to address whether nuclear power really is necessary to reach net zero, given the declining cost and increasing availability of renewable energy, from state, regional, and national perspectives. We have made our best effort to keep this report neutral and fact-based by limiting our sources, as much as possible, to recent peer-reviewed and federal government studies as appropriate. We have discussed this with James Hansen, the leading climate scientist who, along with other leading climate scientists including Kerry Emanuel on down, forcefully speak for nuclear, saying we cannot achieve our climate goals without it.[4] In addition, the European Union recently categorized nuclear as clean in order to meet their climate goals.

It is our hope that this report reaches as broad an audience as possible.

Energy Landscape and Resource Adequacy

Nuclear energy currently accounts for around 10% of the world's electricity production and for around one third of global low carbon electricity. The US Energy Information Agency (EIA) projects that there will be less nuclear electricity generation capacity in 2050, in the US, than in 2020 due to retiring plants.[5] Most of these retirements are either politically motivated or from lack of financial or legislative support as low-carbon energy sources -- the type of support that solar and wind enjoy.

At the end of 2020, there were 94 operating nuclear reactors in the US, down from 104 in 2012, producing about 20% of the total annual US electricity generation. In May 2020, the US

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[2] M.Z.Jacobson et al. (2015) Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind water and solar for all purposes. *PNAS* 49:15060-15065 (https://www.pnas.org/content/112/49/15060)
[3] Cembalist, M (2018) Renewable Rap Battle: A scathing critique of Mark Jacogson's 100% renewable grid proposal. J.P. Morgan Eye on the Market Annual Energy Paper (blog post, April 2018).
[4] Vaidyanathan, G (2015) Nuclear Power Must Make a Comeback for Climate's Sake. Scientific American, December 4, 2015.
https://www.scientificamerican.com/article/nuclear-power-must-make-a-comeback-for-climate-s-sake/
[5] https://www.eia.gov/energyexplained/nuclear/us-nuclear-industry.php

Department of Energy launched the Advanced Reactor Demonstration Program to support ten different advanced reactor designs which are expected to be fully functional within 7 years.[6]

Nuclear power accounts for about 8% of Washington's electricity generation. According to a Department of Commerce report on Washington State Energy Strategy, the electricity demand in Washington could grow by 13-20% over 2020 levels by 2030.[7] After 2030, electricity load growth is expected to accelerate, and by 2050 may reach 92% above the 2020 level. Sources of growth include electrification of the transportation sector, increased need for air conditioning/heating in the face of the increasing number of extreme weather events, additional server farms, population increase and so on.

Given these levels of projected growth, there is a legitimate concern about resource adequacy of our grid, with the planned Centralia coal plant shut-down, the potential removal of the Lower Snake River Dams, and continued construction of large wind power (i.e. VRE) projects. Another constraint on the grid is the fact that Washington state relies heavily on hydropower for its electricity supply, but climate change threatens our snowpack; we can expect up to 23% decline in hydropower production even in the best case scenario of a 1.5° C (2.7° F) warming.[8] Drought effects will increase demand for irrigation of farms as well.[8]

In addition, the retirements over the next ten years of nearly 15 GW of coal power in the surrounding states of Oregon, Idaho, Montana and Utah, all within the Pacific Northwest Power Grid, further stresses Washington State's ability to respond to extreme events, as we have always relied upon these sources when needed. The WA State Public Utility Districts (PUD) Commissioners have voiced grave concern at this situation and have determined that WA State will have a 26% chance of rolling blackouts in 2026 and going forward (personal communication Benton County PUD). Compared to a <5% chance over the past 40 years, they consider this a dangerous situation that is not being recognized in the State Legislature.

Before CETA[9] passed in 2019, the plan had been to replace these coal plants with natural gas plants, but now there is no reasonable plan of replacement. We do purchase hydro energy from British Columbia when needed but after 2025, we will be competing with Oregon, Idaho, Montana and Utah for the same energy as their coal plants close. Unfortunately, it takes about ten years to plan for replacing such a large production capacity and we do not have the time to do that before 2025.

Efficiency and Conservation

Energy efficiency and conservation are both important national goals in reaching emissions reduction targets while also addressing resource adequacy issues. According to DOE estimates, the US has the potential to reduce its nationwide electricity use by 16% by 2035 via energy efficiency.[10] This is welcome news, but in light of the growth expectations discussed above,

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6 https://www.energy.gov/ne/advanced-reactor-demonstration-program
7 https://www.commerce.wa.gov/growing-the-economy/energy/2021-state-energy-strategy/
8 UW Climate Impacts Group, "No Time To Waste", https://cig.uw.edu/projects/no-time-to-waste/
9 Washington state's Clean Energy Transformation Act, https://www.commerce.wa.gov/growing-the-economy/energy/ceta/
10 https://www.energy.gov/eere/slsc/energy-efficiency-savings-opportunities-and-benefit

efficiency alone won't be enough to meet our climate goals, because growth will outpace efficiency and conservation efforts

Possible Pathways for decarbonization

Renewables-only

There is an alarming trend of a growing reliance on natural/fossil gas for power generation, in Washington as well as nationwide, since the 1990s.[11] Despite falling costs of solar and wind, those sources have not been able to displace fossil fuels on the energy market to a greater extent due to the intermittent nature of the power they generate and the resulting mismatch between peak generation and peak demand. In the absence of scalable, affordable, long-term energy storage technology, grid operators must rely on firm power sources in order to balance the grid and avoid blackouts or brownouts. Additionally, in Washington, when most VREs are producing electricity, they are merely replacing another carbon-free source, hydropower.[11]

A renewables-only strategy depends on geography and is more expensive to implement in some places than others. There are two key techno-economic challenges in achieving a 100% renewable energy grid, setting aside other complex issues such as siting, land-use, transmission, environmental impact, material supply and manufacturing scale-up, not to mention considerations of equity and social justice:

(1) economically maintaining a balance of supply and demand in order to produce affordable power;
(2) designing and building technically reliable and stable grids.[12]

Strategies to address the daily mismatch of peak variable renewable energy -- especially solar -- production and peak demand include building excess VRE capacity, short-term storage, and flexible demand and shiftable load. It is unclear up to what level of market penetration of VRE this balance challenge can be met in practice, but an National Renewable Energy Laboratory (NREL) analysis found the Eastern Interconnection could operate stably at 68-73% solar and wind power.[13] In NREL's model, the source of the additional 27-32% of power needed to maintain the system was provided by a combination of fossil and nuclear power (the Eastern Interconnection is made up of Southeastern states). Obviously, it is desirable to eliminate the fossil fuel portion of this power.

Inverter-based resources such as photovoltaic cells also add to the uncertainty of maintaining grid stability with large scale deployment of VRE.[8] High VRE penetration into the grid is also

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[8] https://www.drought.gov/states/washington
[11] https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019
[12] Denholm, P., *et al.* (2021) The challenges of achieving a 100% renewable electricity system in the United States. Joule 5(6):1331-1352. (https://drive.google.com/file/d/1q4Z8FcDjr-eWgVlIWO7cPenfmOQbByY9/view?usp=sharing)
[13] Novacheck, Joshua, Greg Brinkman, and Gian Porro. 2018. Operational Analysis of the Eastern Interconnection at Very High Renewable Penetrations. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-71465. https://www.nrel.gov/docs/fy18osti/71465.pdf.
[11] https://transmission.bpa.gov/Business/Operations/Wind/

hampered by the fact that VREs, especially wind, do not produce much energy during extreme weather events, necessitating sufficient firm power sources, or extensive storage covering many days or weeks, to weather the event.

But the real stumbling block is actually the seasonal mismatch of supply and demand in any renewables-only scenario. The historically low average cost of natural/fossil gas power means that most VRE is backed up by natural/fossil gas generating capacity. But even then, there is usually insufficient gas pipeline capacity to back-up wind while dealing with the extreme event itself, as Texas learned last year.

Although it is very site-specific, pumped-hydro storage is the primary energy storage system in the world, accounting for 97% of all energy storage globally. Yet, whenever pumped hydro is proposed, it is usually shot down by the public and special interest groups, as is presently occurring in WA State with the Rye Development Project along the lower Columbia River.

As an indication of the costs involved in energy storage, the Gordon Butte pumped hydro project in Central Montana will be able to produce 400 MW for 8.5 hour at a capital cost of $1 billion (that is, $2.5 million per megawatt) and annual operating cost of around $173 million ($433,000/MW).[14] If it were built in Washington, it would satisfy only 0.5% of Washington's current average electricity demand -- for only 8.5 hours.

The idea that it is possible to reach net zero through the use of renewable sources of power alone is supported by a number of large environmental organizations, and is based almost solely on the work of Mark Z. Jacobson.[15] His model relies on large-scale thermal energy storage, offshore wind generation, the construction of high-voltage power lines to connect remote areas with good wind and solar resources to urban areas where power demand is located, a large increase in hydropower for backup, and other modifications to the electrical grid. It has been criticized for its methodology and lack of attention to the resulting costs for electricity.[16]

<u>Renewables-plus</u>

Estimates vary, but renewables-only costs rise sharply as the proportion of renewables approaches 100%. (see figure below) This is most clearly illustrated by Sepulveda *et al.,* who wrote in their 2018 paper:

> "We find that in the absence of firm low-carbon resources, affordable decarbonization of the power sector would simultaneously require further steep reductions in the cost of VRE and battery energy storage technologies, significantly oversizing installed capacity relative to peak demand, significantly

[14] Brown, M. (2019) Montana energy storage project lines up financial partner. AP News. https://apnews.com/article/8c3bd5aff52a400592ea141bf0061968

[15] M.Z.Jacobson et al. (2015) Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind water and solar for all purposes. *PNAS* 49:15060-15065 (https://www.pnas.org/content/112/49/15060)

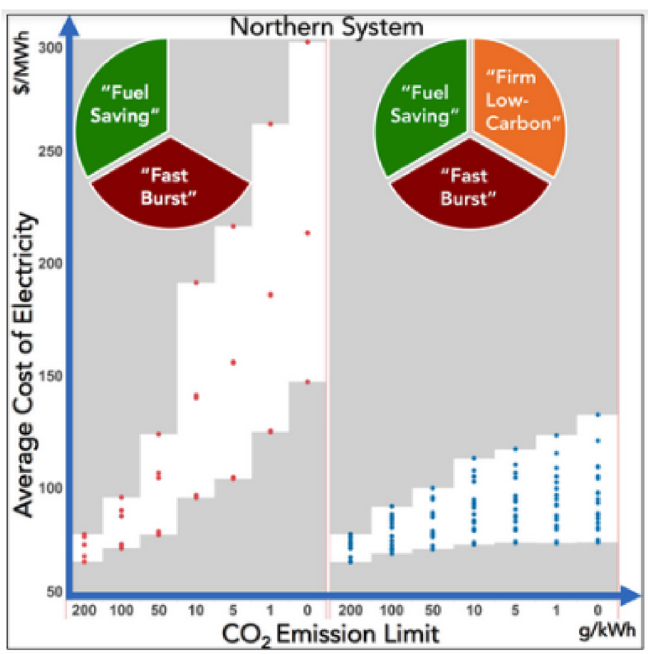
[16] Bistline, J.E. *et al.* (2016) More than one arrow in the quiver. PNAS 113(28): E3988. https://www.pnas.org/content/113/28/E3988

greater demand flexibility, and expansion of long-distance transmission capacity connecting wide geographic regions."[17]

In other words, a renewables-only approach would be expensive and complicated. The increased cost would have obvious effects on low-income communities.

On the global scale, the most recent IPCC Special Report on 1.5°C includes only renewables-plus approaches, with all four illustrative model pathways assuming increases in nuclear power by 2050 compared to 2010.[18] The International Atomic Energy Agency recently published a case study focused on 12 developing countries and concluded that nuclear power has a strong potential in their national climate change mitigation strategy.[19]

In the Pacific Northwest, a study of energy resource adequacy by Energy, Environmental Economics Inc., sponsored by utilities in both WA and OR, found that deep decarbonization of the Northwest grid is technically feasible but, without technological breakthroughs, prohibitively expensive using only wind, solar, hydro and energy storage. As they note: "Firm capacity – capacity that can be relied upon to produce energy when it is needed the most, even during the most adverse weather conditions – is an important component of a deeply-decarbonized grid."[20]



Full decarbonization of the electricity sector is critical to global climate mitigation. Across a wide range of sensitivities, firm low-carbon resources—including nuclear power, bioenergy, and natural gas plants that capture CO_2—consistently lower the cost of decarbonizing electricity generation. Without these resources, costs rise rapidly as CO_2 limits approach zero. Batteries and demand flexibility do not obviate the value of firm resources. Improving the capabilities and spurring adoption of firm low-carbon technolo

Sepulveda, et al., 2018 Visual Abstract

The bottom line is that the power cost of a 100% renewables grid would cause significant hardship in terms of both economics and equity/social justice. This can clearly be seen in the visual abstract from Sepulveda et al., 2018[14] at left.

In the figure, the left panel models the cost of electricity in the Northern US under a renewables-only scenario, and the right panel shows the modeled cost of electricity if firm low-carbon sources (nuclear, natural/fossil gas with carbon capture and sequestration, biomass, and biogas) are permitted -- a renewables-plus scenario.

The direct lowest-cost source of firm generation capacity today is natural/fossil gas, but without carbon capture and sequestration

qVcDMDmTHK9Hx9sB-0
er/spm/spm-c/spm3b/

[19] IAEA report 2021, https://www.iaea.org/newscenter/news/nuclear-energy-for-climate-change-mitigation-to-benefit-several-countries-new-studies-show

[20] https://www.ethree.com/wp-content/uploads/2019/03/E3_Resource_Adequacy_in_the_Pacific-Northwest_March_2019.pdf

(CCS), it is not a low carbon source of power. And even with CCS, natural/fossil gas generation costs do not include all life cycle environmental impacts, including fracking, pipeline leaks, and subsidies.[21] And, carbon capture technology is still in its infancy in terms of development and deployment. Olabi, *et al.,* (2022) provides an interesting review of carbon capture technologies in the context of sustainable development goals.[22]

Nuclear power is a source of firm capacity with decades of history. It has the lowest carbon footprint of all existing sources of energy (see Appendix 1.A). Nuclear power also provides the highest-paying jobs and it has the highest rate of unionization of any industry in the sector.[23]

Conclusion

Some source of low-carbon firm power is needed in order to support electrical grids that use high levels of renewable power. Without some source -- approximately 20-25% -- of low-carbon dispatchable power, electricity costs would be high, and reliable 24/7/365 delivery of electricity will not take place. The cost-effective options are nuclear or natural/fossil gas. Nuclear is the only carbon-free option.

The direct answer to the question posed in the title of this paper is that, yes, the science and data show that nuclear power is required to reach net zero within the time frame of meeting the 2° C (3.6° F) target limit of the IPCC. The IPCC stated as early as 2018 that all four scenarios to reach the goal involve some increase in nuclear energy. We can meet Clean Energy Transformation Act (CETA) goals in the state of Washington with nuclear, hydro, wind, and solar.[24]

What we need for the electric grid in WA:

- Pursue efficiency and conservation to the maximum extent possible.
- Replace the base load electricity and union jobs currently provided by coal power plants.
- Reverse grid fragility in the Western Electricity Coordinating Council region by adding firm power.
- Keep electric heat and air conditioning affordable for all homes and businesses.
- Meet the projected 25-50% increase in electricity demand for electric vehicles and transit.
- Maintain low electricity rates and the capacity needed to continue growing high tech union jobs in energy-intensive industries.

[21]https://www.imf.org/en/Publications/WP/Issues/2021/09/23/Still-Not-Getting-Energy-Prices-Right-A-Global-and-Country-Update-of-Fossil-Fuel-Subsidies-466004

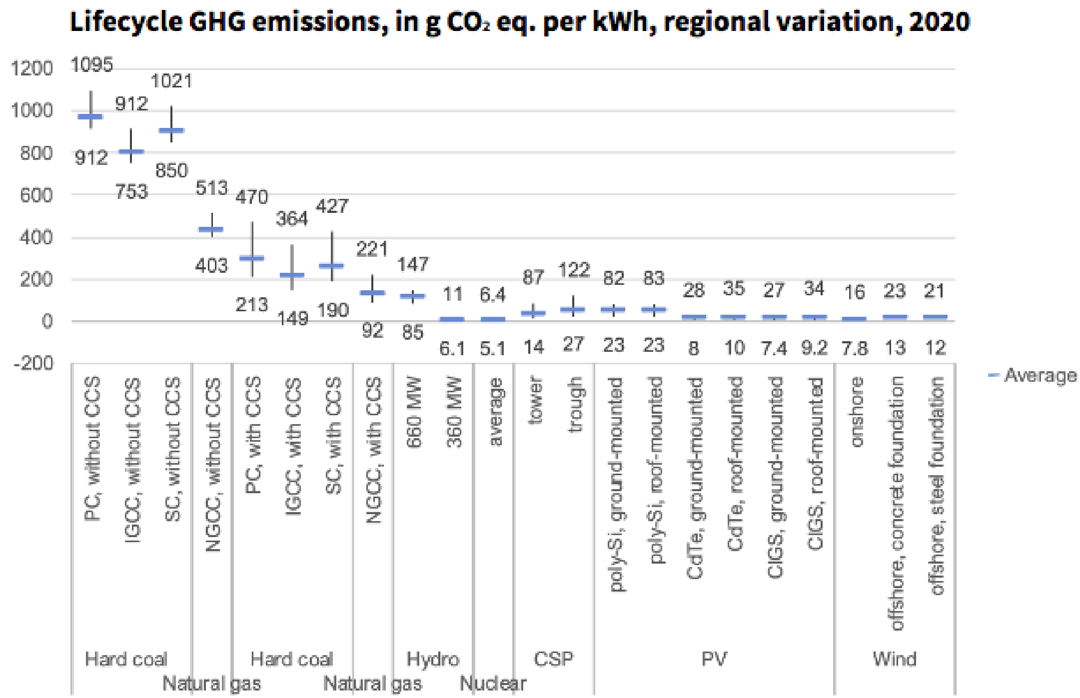
[22] Olabi, A.G. *et al.* (2022) Assessment of the pre-combustion carbon capture contribution into sustainable development goals SDGs using novel indicators. Renewable and Sustainable Energy Reviews, Volume 153, 11171. https://www.sciencedirect.com/science/article/pii/S1364032121009849

[23]US Energy & Employment Jobs Report, 2021. US Energy & Employment Jobs Report (USEER), Link to Key Findings

[24] https://www.commerce.wa.gov/growing-the-economy/energy/ceta/

Appendix 1.A -- Life cycle greenhouse gas emissions of generating technologies

Figure 1 Lifecycle greenhouse gas emission ranges for the assessed technologies



Source: UNECE (2021) Life Cycle Assessment of Energy Generation Options (Draft). United Nations Economic Commission for Europe.[25] Life Cycle Assessment of Electricity Generation Options

CSP: concentrated solar power
PV: photovoltaic solar panels

[25] 2022 Life Cycle Assessment of Electricity Generation Options. UN Economic Commission for Europe. https://unece.org/sites/default/files/2022-01/LCA_final-FD_0.pdf

Part 2: Nuclear Power: Is it Safe?

Glossary

About radiation terms and units: the US EPA maintains a useful site with the basics,[26] including an interesting personal radiation dose calculator.[27] Radiation units can seem complicated because both US and international units are used to measure three aspects of radiation: amount of radioactivity in a sample; amount of radiation absorbed by tissue; and the effective dose, which is the effect of the radiation absorbed by a specific tissue. For the purposes of this report, mrem is used for effective dose, and where necessary international units have been converted to mrem for simplicity and ease of comparison.

Background radiation: the naturally occurring dose of radiation received by humans as a result of cosmic rays, radioactive isotopes in food, radon, and other sources. Background radiation varies with location. The EPA's personal radiation dose calculator can be used to estimate one's own exposure to background radiation.[21]

Fission: the "splitting" of certain atoms under controlled conditions, which releases large amounts of energy.

Fusion: the opposite of fission, this approach to producing energy has been in the news lately but is not discussed in this report.

Gen I, Gen II, Gen III, Gen IV: successive generations of nuclear plant design. Gen III reactors are the current generation, and incorporate passive safety systems and other changes in response to the Fukushima- Daiichi accident. Gen IV, or next-gen reactors, include gas cooled, molten salt reactors (MSR's), and small modular reactors (SMR).

Health physics: the science and study of the biological effects of radioactivity.

Ionizing radiation: forms of radiation that can damage tissue by the formation of ions. Includes alpha- and beta particles, gamma rays, X-Rays, and cosmic rays. Visible light, for example, is non-ionizing radiation.

LNT: linear no-threshold model of radioactivity exposure, which (erroneously) assumes there is no safe dose of radioactivity.

mrem: the US unit of unit of effective dose, a mrem is 1/1000 of a rem. Radiation workers are not permitted to receive an annual dose of greater than 5000 mrem. The average effective dose for Americans is around 620 mrem.

MWe: megawatts of electric generating capacity, a common measure of nuclear power production. The Columbia Generating Station near Richland has a capacity of 1207 MWe.

NRC: US Nuclear Regulatory Commission.

Nuclear power plant: a facility that generates electricity by using nuclear fission to indirectly produce steam that is used to drive a turbine.

Passive safety systems: engineered safety that does not depend on human intervention and mitigates against human error.

Radiation: all forms of light are radiation, but in the context of nuclear power the word refers to emissions from radioactive isotopes.

Radon: one of several natural sources of human exposure to radioactive isotopes, radon gas is produced by the decay of elements naturally present in rock and soil. Local

[26] https://www.epa.gov/radiation/radiation-terms-and-units

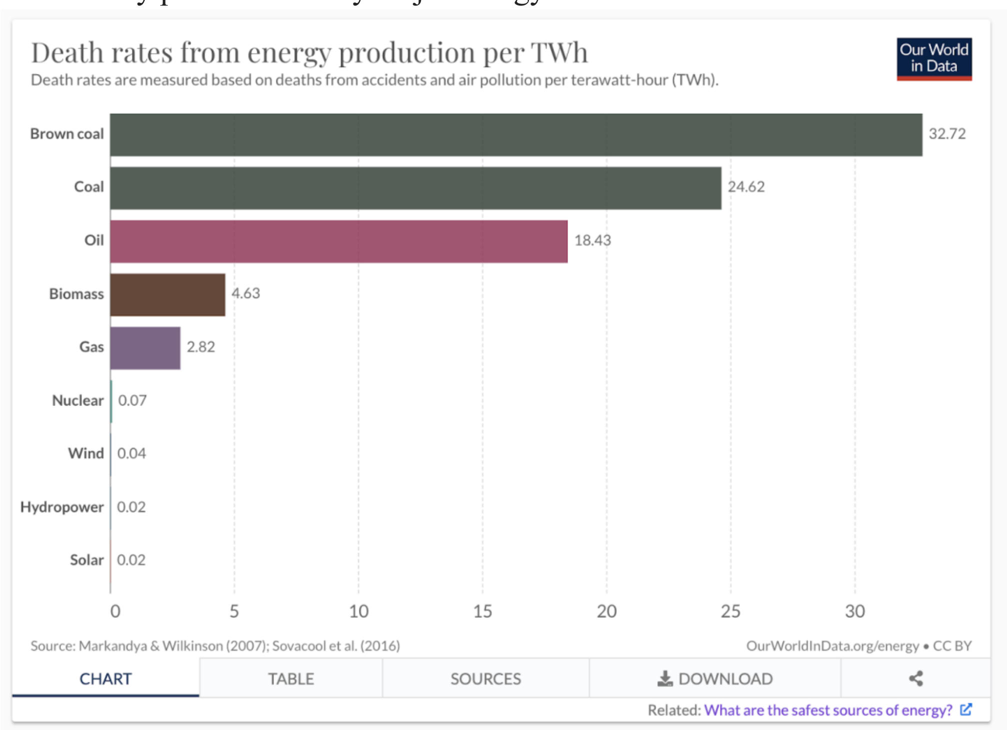
[27] https://www.epa.gov/radiation/calculate-your-radiation-dose

amounts of radon can vary considerably depending on the underlying geology of a region; the Northwest has relatively few radon hotspots.
SMR: small modular reactors.
Thoron: an isotope of radon which is produced naturally in the same way as radon.
UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation.

Introduction

Nuclear energy is the most regulated industry in the country. As with any source of large amounts of energy, there are risks associated with nuclear power plants, including fire, reactor core meltdown and accidental release of radioactive materials. There is, however, no possibility of a nuclear bomb-like explosion. The Nuclear Regulatory Commission (NRC) and commercial power plant designers and operators ensure that nuclear reactors are designed to be safe against natural disasters and against human error. Meanwhile, all next generation reactors are designed with passive safety systems that do not need human intervention to prevent a meltdown or are simply not capable of melting down.

As shown in the chart below, the nuclear power industry has one of the lowest rates of fatalities per unit of electricity produced of any major energy source.[28,29]



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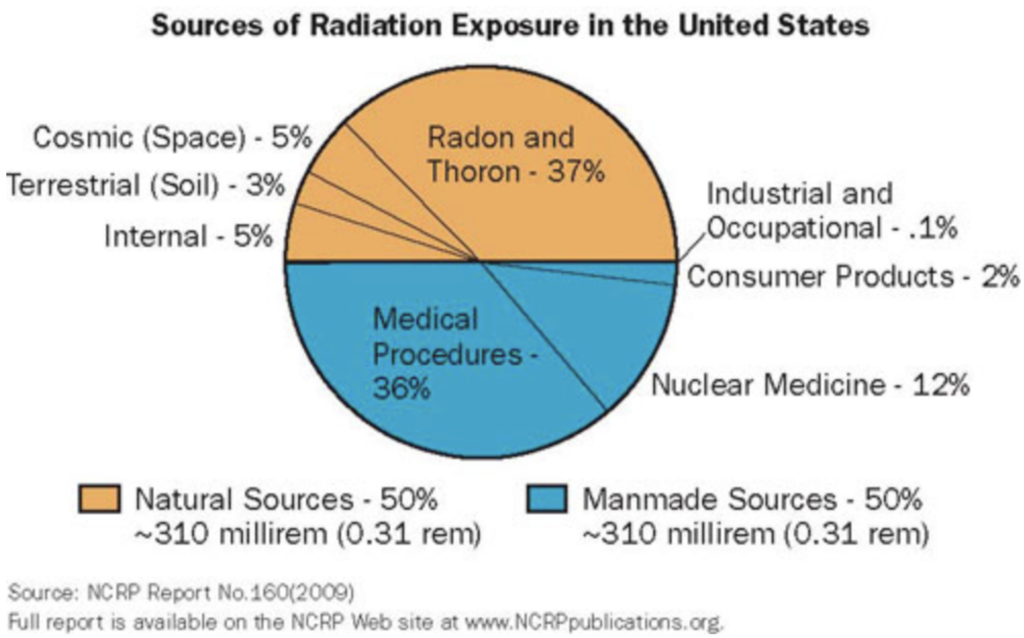
[28] Markandya, A, and Wilkinson, P (2007) Electricity generation and health. The Lancet 370:979-990. https://www.thelancet.com/pdfs/journals/lancet/PIIS0140673607612537.pdf
[29] https://ourworldindata.org/nuclear-energy

Recognizing the persistent fear of nuclear power, and with the expectation that better understanding is a benefit, we begin with an overview of the health impacts of radiation. We then review the history of nuclear accidents and some lessons learned. Last we address how safety is incorporated in the design of the existing nuclear fleet and the next generation reactors under construction.

Health Effects of Radiation

Radiation is all around -- and in -- us. The reader is invited to estimate their own exposure to background radiation using EPA's effective dose calculator.[30] US background radiation averages 620 mrem per year; living within 50 miles of a coal-fired power plant results in three times as much exposure to radioactivity as living near a nuclear power plant.

According to the Health Physics Society, the average annual workplace exposure to ionizing radiation for workers at a nuclear power plant is 100 mrem for the 64,761 workers screened.[31] Airline crews are exposed to as much as 500 mrem per year at work.[32] Nuclear power plants release extremely small levels of radiation and are responsible for less than 0.1% of the radiation exposure of the public.[33]



The interaction between radiation and the body is complicated and interesting. Long-term exposure to low doses of radiation is not harmful, according to multiple studies of cancer

30 https://www.epa.gov/radiation/calculate-your-radiation-dose
31 http://hps.org/documents/nuclearpower.pdf
32 https://www.cdc.gov/niosh/topics/aircrew/cosmicionizingradiation.html
33 https://www.nrc.gov/about-nrc/radiation/around-us/sources.html

occurrence.[34,35,36,37,38] Indeed, parts of the world have very high levels of background radiation with little negative -- or actually positive -- effect on human health. For example, some residents of Ramsar, Iran, receive annual effective doses of 26,000 mrem (26 rem), in comparison to the US average of 620 mrem/yr, from radon in their homes.[39,40] Yet lung cancer rates appear to be lowest in the areas of Ramsar that receive the highest doses of radon, a phenomenon called hormesis.[41,42] Research indicates that people exposed to higher background radiation for long periods of time show less DNA damage with age.[43,44]

Nuclear Accidents

The three nuclear accidents that have shaped the public's perception of nuclear plant safety are the events at Three Mile Island, Chernobyl, and Fukushima.[45] It is important to note that no reactor licensed by the NRC has ever failed while operating. Three Mile Island was built before the NRC came into existence.

<u>Three Mile Island, 1979</u>

The approximately 2 million people around TMI-2 were estimated to have received an average radiation dose of about 1 millirem above the usual background dose, less than the amount of additional radiation received from a one-way airplane flight from Seattle to Washington, D.C. There were no injuries or deaths as a result of the event. The containment vessel worked as designed, and the accident led to improved safety designs. The accident has been intensively studied, and no health effects have been detected.[46]

<u>Chernobyl, 1986</u>

The disaster at the Chernobyl nuclear power plant in Ukraine[47] is by far the worst nuclear accident to date, and released the greatest amount of radioactivity into the environment of any event. It is unlikely to be matched by a future accident because it was the product of a seriously flawed Soviet reactor design (the lack of a containment vessel around the reactor is just one example of bad design) coupled with unsanctioned experiments by plant operators. The reactors at Chernobyl were dual-purpose weapons reactors designed to produce a large amount of

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[34] https://atomicinsights.com/methods-used-to-create-the-no-safe-dose-myth-about-radiation-supports-immediate-transition-to-a-better-model/
[35] http://dos.sagepub.com/content/13/3/1559325815592391.full
[36] Dose–effect relationship and estimation of the carcinogenic effects of low doses of ionizing radiation: The joint report of the Académie des Sciences (Paris) and of the Académie Nationale de Médecine
[37] Health Impacts of Low-Dose Ionizing Radiation: Current Scientific Debates and Regulatory Issues
[38] UNSCEAR assessments of the Chernobyl accident
[39] Sources Of Radiation | NRC.gov
[40] https://www.academia.edu/download/3254106/Ramsar.pdf
[41] https://www.academia.edu/download/63262818/j.ics.2004.12.01220200510-27663-1a74ynu.pdf
[42] https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/hormesis
[43] Ghiassi-nejad, M; Mortazavi, SMJ; Cameron, JR; Niroomand-rad, A; Karam, PA; Very High Background Radiation Areas of Ramsar, Iran: Preliminary Biological Studies. Health Physics, 82(1): 87-93, 2002.
[44] http://dos.sagepub.com/content/13/3/1559325815592391.full
[45] Safety of Nuclear Power Reactors
[46] Backgrounder On The Three Mile Island Accident | NRC.gov
[47] https://www.world-nuclear.org/information-library/country-profiles/countries-t-z/ukraine.aspx

plutonium for nuclear weapons, as well as to produce power. This meant that graphite was used to moderate the speed of the neutrons, the most serious design flaw, as the graphite would increase the power of the core when the water coolant was lost, inevitably leading to the graphite catching fire and causing the steam explosion.

All US reactors use water to both cool and moderate, so no such failure can occur. US reactors also do not contain graphite.

The Soviet system lacked scientific collaboration and a safety culture at that time. The accident destroyed the Chernobyl 4 reactor, killing operators and firemen within three months and followed by several additional deaths later.[48]

As summarized by Dr. William Burchill, former President of the American Nuclear Society, the actual fatalities were:

- 2 immediate, non-radiation deaths
- 28 early fatalities from radiation within 4 months,
- 19 late adult fatalities presumably from radiation over the next 20 years, although this number is within the normal incidence of cancer mortality in this group, which is about 1% per year, and
- 9 late child fatalities from radiation resulting in thyroid cancer.

These last nine fatalities are an inexcusable tragedy since they were totally avoidable with warning and simple actions from the Soviet government, which intentionally failed to act in time. Children were the most affected by consuming milk containing radioactive iodine, which could have been easily avoided with a simple warning from the Soviets. Interestingly, there was no increase in thyroid cancer among the adult general population or the Chernobyl liquidators, the name given to the emergency workers.[49,50]

In addition, almost a thousand Chernobyl liquidators that fought the fire in the first days of the accident received high doses of radiation, and about 50 died from cancer and other health issues.

According to Mikhail Balonov, Secretary of Science at the International Atomic Energy Agency, the 600,000 recovery and operations workers that have worked at Chernobyl since the accident, and the 5 million residents of the contaminated areas in the Ukraine, Belarus and Russia, received minor doses comparable to natural background radiation.[51] There have been no

[48] http://www.world-nuclear.org/reactor/default.aspx/CHERNOBYL-4
[49] Wolfgang Weiss (2018) Chernobyl Thyroid Cancer: 30 Years of Follow-Up Overview, *Radiation Protection Dosimetry*, 182(1):58-61, https://doi.org/10.1093/rpd/ncy147
[50] Fiori, M., et al. (2019) Role of emerging environmental risk factors in thyroid cancer: a brief review. *International journal of environmental research and public health*, *16*(7), 1185. https://www.mdpi.com/1660-4601/16/7/1185/pdf
[51] UNSCEAR assessments of the Chernobyl accident

observable radiation-induced health effects in these people. And certainly none have occurred in areas outside these regions which received even lower doses.[52]

As concluded in the 2008 report of the United Nations Scientific Committee on the Effects of Atomic Radiation: “There is no scientific evidence of increases in overall cancer incidence or mortality rates or in rates of non-malignant disorders that could be related to radiation exposure.”

Immediately after the accident, the ultra-cautious regulatory-based Linear No-Threshold (LNT) dose hypothesis was used to predict that about 4,000 deaths would eventually occur by radiation from Chernobyl, but these still have not been observed. The United Nations has since warned that using the LNT model to calculate such deaths is an incorrect use of this model, and should be avoided.

The other three reactors at Chernobyl, Units 1, 2 and 3 of the same design, kept operating continuously, with personnel coming and going throughout the accident and for many years afterwards, with no observed health effects. All have since been decommissioned.

Ukraine continued to commission nuclear power stations after independence from Russia in 1991, and today about 50% of Ukraine’s electricity comes from nuclear power. See Appendix 2.A for a statement on the war in Ukraine and its effect on the nuclear power stations there.

Fukushima-Daiichi, 2011

In this case, the reactors shut down in response to, and survived, the magnitude 9.0-9.1 Tōhoku earthquake without damage, as they were designed to do, but backup generators were flooded by the ensuing tsunami, causing a partial meltdown in three reactors. There were no deaths due to acute radiation exposure but around 19,500 people were killed by the tsunami and about 1,600 people died as a result of the evacuation around the facility.

UNSCEAR evaluated the information regarding the radioactive material released by the accident through the terrestrial, freshwater, and marine environments. By 2012, a year after the accident, concentrations of cesium (^{137}Cs), even in the coastal waters off the Fukushima-Daiichi site, were little above the levels prevailing before the accident. UNSCEAR continues to consider that regional impacts on wildlife populations with a clear causal link to radiation exposure resulting from the Fukushima accident are unlikely, although some detrimental effects in some plants and animals have been observed in areas with the highest radiation levels. Radionuclide concentrations in most monitored food had declined rapidly following the accident.[53] Studies of fungi of the US western coastal states did not reveal contamination with ^{137}Cs above background levels.[54]

[52] The UNSCEAR has assessed the incidence of thyroid cancer that could be inferred from the estimated radiation exposure and concluded that this is not likely to be discernible, in any of the age groups considered, including to children and those exposed *in utero* to radiation.
[53] A decade after the Fukushima accident: Radiation-linked increases in cancer rates not expected to be seen
[54] Cesium radioisotope content of wild edible fungi, mineral soil, and surface litter in Western North America after the Fukushima nuclear accident

A note about DNA repair

Public opinion began to turn against nuclear power around the time of the Three Mile Island accident in 1979. In general, fear of nuclear power and radiation stems from the realization that radiation can damage DNA, and DNA damage can lead to cancer. There are, however, a myriad of DNA repair systems in cells of all types, and it has been known since the mid-1930s that cells can (and do) recover from radiation damage.[55] After all, we live in a sea of background radiation, anywhere from 3 to 10,000 mrem per year across the Earth and there is no correlation with health effects or cancers. In fact, the ten or so high background radiation areas in the US have lower incidences of cancer mortalities than the lower areas. The existence of background radiation is one reason organisms have evolved the ability to repair DNA, and is the reason exposure to radiation rarely causes any health effects.

Over the last decade or so, our understanding of molecular biology has increased to the point where we can see the cellular response to stimuli such as radiation, hazardous chemicals, or viruses like COVID in living people. Especially illuminating are changes in gene expression as a function of radiation dose. Radiation stimulates the Nrf2 antioxidant response system as a result of the formation of reactive oxygen species when ionizing radiation interacts with water in cells.[56]

Importantly, the health effects from radiation are not cumulative. It is easy for the public, and even scientists outside this field, to confuse global regulations developed during the Cold War, primarily to stop America's above ground nuclear tests, with actual science. We adopted LNT, ALARA and Cumulative Effects to be conservative, not to reflect scientific knowledge, even at that time. Those hypotheses assumed we did not have antioxidant response systems or DNA repair systems, partly because details of these systems were mostly unknown at the time. Our cells effectively repair all radiation damage up to acute doses of about 20 rem.[57] Recall that the annual background dose in the US is about 620 mrem.

Radiation primarily mimics oxidants in biological systems. Either as a gamma ray, a beta particle or an alpha particle, radiation acts by knocking an electron off a molecule, usually water. But oxygen is far more effective at oxidizing than radiation is; it is no surprise our cells can handle radiation easily because eukaryotic cells evolved about 2.3 billion years ago when oxygen first entered the atmosphere and background radiation levels were ten times what they are today.

The efficiency of antioxidant and DNA repair systems is why it takes an acute dose of over 20 rem -- more than 30 times the average US background dose -- to have any observable health effects.[58]

But the idea of cumulative effective dose is especially strange. Cumulative effective dose means that small doses spread out over a large number of people and time is the same as that total dose given over a short period. It has also been used in areas outside of radiation, such as in medicinal drugs. As examples, cumulative effective dose states that the risk of death from one person

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[55] Friedberg, E. A brief history of the DNA repair field. Cell Res 18, 3–7 (2008). https://doi.org/10.1038/cr.2007.113
[56] McDonald, JT, *et al.* (2010) Ionizing radiation activates the Nrf2 antioxidant response. *Cancer Res* (2010) 70 (21): 8886–8895. https://doi.org/10.1158/0008-5472.CAN-10-0171

[57] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4763322/
[58] https://www.cdc.gov/nceh/radiation/emergencies/arsphysicianfactsheet.htm#table1

taking 100 aspirins a day is the same as 100 persons taking one aspirin a day. Or that one person absorbing 60,000 mrem a year has the same risk of death as 100 people absorbing 600 mrem a year. Both of these scenarios are clearly absurd, but it is ingrained in our radiation regulatory institutions, along with the notion that we are totally defenseless against radiation. Far from being defenseless, we have multiple robust systems that protect us from radiation.

Nuclear Plant Safety

It is important to realize that, as in the airline industry, accidents are analyzed and designs and construction are updated in response, and this process has been going on for the full 65-year history of US nuclear power. This leads to continuous improvement in safety. In addition, in the US, every nuclear power plant in operation is assigned at least two full-time on-site NRC resident inspectors, who are free to observe anything at the plant at any time. Risk of accidental release of radioactive elements in the existing fleet of nuclear power plants is mitigated in part via double containment surrounding the reactor and reinforced concrete used for the reactor building. Any meltdown risk is mitigated, by backup generators above ground.

As a result of regulatory responses to Fukushima, the safety of all US nuclear reactors that began construction after 2011 significantly exceeds that of the previous nuclear fleet by the introduction of passive safety systems and other design modifications.

For example, the current generation (Gen III) AP1000 reactors for the Vogtle Plant (units 3 and 4), each with a capacity of 1250 MWe, being built by Westinghouse in Waynesboro, GA, were undergoing licensing in 2011, the year of the Fukushima Daiichi accident. As a result, the AP1000 reactors received extensive regulatory attention. Notably, Vogtle's original passive safety system, designed in 2007, would have prevented the Fukushima disaster from happening if it had been used in the Fukushima reactors. The AP1000's core makeup tanks are designed for 100% decay heat removal without depending on external power or backup generators.[59] The system maintains safe conditions for 72 hours following the initiation of a design basis shutdown.[60] The physical system has been validated using the APEX facility at Oregon State University.[61]

The physical risk of operating small reactors is exponentially lower than a large reactor. The related mathematical principle is the "square-cube law" described by Galileo, when an object undergoes a proportional increase or decrease in size, its new surface area is proportional to the square of the multiplier and its new volume is proportional to the cube of the multiplier.[62] Under the same principle a mouse survives a fall much more easily than an elephant. The next generation of nuclear power plants under construction, within the scope of DOE's Advanced Reactor Demonstration Program, are the Gen IV Small Modular Reactors (SMR). The surface area-to-volume ratios are so much larger that they can bleed off decay heat very rapidly. Other safety improvements include better pressure and temperature tolerances, as well as improved

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[59] AP1000 Passive Safety Systems.
[60] AP1000 The PWR Revisited
[61] https://web.archive.org/web/20071019060444/http://www.uic.com.au/nip16.htm
[62] https://en.wikipedia.org/wiki/Square%E2%80%93cube_law

burn-up efficiency, in addition to passive safety. The choice of new coolants allows higher temperature tolerance. See Appendix 2.A for an overview of SMR safety profiles.

Conclusion

In the US there are 93 commercial scale nuclear reactors, over 300 smaller research and training reactors, and over 80 reactors powering US Navy vessels. US commercial reactors have been operating for a combined total of nearly 3700 years. Worldwide there are at least 441 nuclear power plants operating in 30 countries. The human health effects of the three accidents have been, if anything, surprisingly limited. Even with the effects of those three accidents included, nuclear power is as safe as wind and solar power. Climate scientist James Hanson has noted that, by replacing power that otherwise would have been generated using fossil fuel, nuclear power has saved more than 1.8 million air pollution-related deaths and avoided emission of 64 gigatonnes of carbon dioxide.[63]

So why are so many people so afraid of nuclear energy? Because we told them to be. One of the purposes of the Cold War was to make people afraid of nuclear weapons. Unfortunately, nuclear power was conceptually connected with weapons even though they have almost nothing to do with each other except basic nuclear science. We cannot make a nuclear weapon from spent nuclear fuel from a commercial reactor because commercial reactors breed in too many neutron poisons that make any resulting weapon a dud. It's why we don't care that Iran recently powered-up their Bushehr Nuclear Power Plant, but are very concerned about their ability to enrich uranium-235 up to weapons-grade concentrations.[64]

But the main reason is the huge difference between the perception of a risk and the actual risk. Per megawatt-hour generated, nuclear is one of the safest forms of energy production, comparable in safety to renewables, while annually fossil fuel use kills 1 in 5 people worldwide -- and this situation has been accepted for decades.[65] Despite historic accidents that have tarnished its reputation, the existing nuclear reactor technology has the lowest number of direct fatalities of any major energy source per kWh of energy produced—over 100 times less than hydro and liquefied natural/fossil gas. The advanced, or "next-generation," technology has substantial improvements in design, taking advantage of downsizing the reactors, using coolants other than water and implementing passive safety principles. All of these improvements are intended to render the new reactors in construction "walk-away" safe.

Hopefully, this discussion has increased the reader's interest, or addressed some of the concerns with nuclear power. If there are any other questions, we have dedicated progressive democrats who are also nuclear scientists at the PhD level who are willing to answer any questions regarding nuclear power.

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[63] Pushker A. Kharecha and James E. Hansen (2013) Prevented Mortality and Greenhouse Gas Emissions from Historical and Projected Nuclear Power. *Environmental Science & Technology* 47(9):4889-4895 https://pubs.acs.org/doi/10.1021/es3051197

[64] https://world-nuclear.org/information-library/country-profiles/countries-g-n/iran.aspx

[65] https://www.nrdc.org/stories/fossil-fuel-air-pollution-kills-one-five-people

Appendix 2.A -- A Note on the War in Ukraine

Given the ongoing war in Ukraine, there has been a lot of concern expressed about the state of Ukraine's nuclear power plants. For updates on their status, check the websites below:

SNRIU (equivalent of NRC in Ukraine) website:

https://snriu.gov.ua/en

IAEA press releases:
https://www.iaea.org/news?year%5Bvalue%5D%5Byear%5D=2022&type=3243&topics=All&keywords=ukraine

Appendix 2.B -- Safety Discussion of Small Modular Reactor Projects Currently Underway

NuScale, Idaho Falls ID

Site: VOYGR-6, Idaho Falls, Idaho
Brownfield groundbreaking: 2020
Designer: NuScale (Corvallis, OR)
Projected completion: 2029 (2), 2030 (4)
Capacity: 6 x 77 MWe

In collaboration with the Nuclear Energy Institute and certified by the Nuclear Regulatory Commission, NuScale developed a "defense in depth" approach which minimizes the typical emergency planning zone requirement. The fundamentally smaller core size is supported by simplified safety systems which means fewer components that might experience failures. This simplification and proper maintenance leads to a mean-time-to-failure of one event every 3 billion years of operation.[66]

Finally, in case of a beyond design basis accident, the small size and relatively large safety barriers of the NuScale modules reduces accident risk. The very large heat rejection pool containing borated (reaction halting) water surrounds the reactor so that if an accident occurs it will progress slowly, providing time for corrective action. Individual modules are isolated from the cool heat rejection water using a vacuum chamber. If the vacuum seal is broken the heat from the reactor is dissipated into millions of gallons of water. Dissipating the heat preserves the other physical barriers which contain the reactor's radiation.

The NuScale SMR has potential for enhanced non-proliferation measures including refueling operations distant from the operating reactors. As each fuel load reaches the end of its generation campaign the entire reactor pressure vessel is cooled down and then moved into an isolated part of the heat rejection pool. This allows the plant to return to full capacity more quickly, and

[66] https://www.nuscalepower.com/benefits/safety-features/emergency-planning-zone

allows refueling operations to be scheduled. Refueling takes place separately from active reactor pressure vessels in a dedicated location under the supervision of verification personnel and equipment.[67]

Xe-100, Richland WA

Site: WNP-1/4, Columbia Generating Station, Richland, Washington
Brownfield groundbreaking: TBA
Designer: X-Energy (Rockville, MD)
Projected completion: 2027
Capacity: 4 x 80 MWe

The Xe-100 reactor greatly benefits from the "square-cube Law" which results in exponentially lower risk than gigawatt scale nuclear reactors. This new reactor design will also be the first Gen IV commercial reactor deployed in the US.

This high-temperature gas-cooled reactor uses the inert gas helium[68] at 60 atmospheres of pressure.[69] This is a relatively low pressure system compared to the typical light water reactor which operates at over 150 atmospheres. This reactor uses helium as the primary coolant, which provides a large range of stable temperature and pressure, unlike water which vaporizes at high temperatures, requiring very high pressure. The lower pressure permitted by the use of helium leads to a further simplification of safety systems.

The Xe-100 reactor system also achieves a fuel to energy conversion of 160 GWd/tHM (gigawatt-days per ton of heavy metal), which is nearly three times as efficient as a light water reactor (60 GWd/tHM)[70]. This means a 60% reduction in used fuel mass per unit of energy (i.e. less spent fuel waste). The physical packaging of the fuel is a billiard-ball sized composite of pyrocarbon and silicon carbide surrounding fissionable fuel which has been under development since 2015.

This solid fuel form extracted during online refueling must be accountable to the IAEA in order to verify the non-proliferation chain of accountability. Similar to other reactor designs which enable online refueling care must be taken to account for each ~1-kg fuel pellet.[71]

Natrium, Kemmerer WY

Site: Naughton Power Plant, Kemmerer, Wyoming
Brownfield groundbreaking: 2024
Designer: TerraPower (Bellevue, WA)
Projection completion: 2028
Capacity: 1 x 350 MWe

[67] https://www.nrc.gov/docs/ML0908/ML090850080.pdf
[68] All helium on Earth results from the radioactive decay of isotopes that produce alpha particles, which are helium nuclei.
[69] https://x-energy.com/reactors/xe-100
[70] https://aris.iaea.org/PDF/AP1000.pdf
[71] https://www.powermag.com/the-allure-of-triso-nuclear-fuel-explained/

The Natrium reactor is another type of GenIV commercial reactor called the sodium cooled fast reactor. It uses pellets of high-assay low enriched uranium (HALEU, meaning 5% to 20% enrichment).[72] While the first implementation will not provide a breeding capability, Natrium has a burn-up efficiency higher than the standard light water nuclear reactor. Future iterations of the fuel pellets will further improve the fuel efficiency and safety of this reactor.

Natrium has operational characteristics somewhat similar to the Xe-100 because of the large temperature range of its coolant: liquid metallic sodium. While the sodium coolant further reduces the pressure to very near normal atmospheric pressure, it is highly reactive with water vapor in the atmosphere. This requires a small number of new safety systems, including the separation of steam generation from the reactor core primary coolant and a sodium leak mitigation mechanism.

Natrium achieves sodium leak mitigation using a secondary low-pressure shell of inert gas surrounding the reactor and all metallic sodium coolant pipes.[73] Any metallic sodium leaks will rapidly cool and solidify while the leak slightly increases the pressure of the inert region, allowing instrumentation to detect the leak. Steam generation is separated from the metallic sodium coolant using an industry standard mix of molten salts used by concentrated solar generators such as the Ivanpah Solar Power Facility.

Another significant safety feature of the Natrium reactor is a negative reactivity coefficient. As demonstrated by the EBR-2 experimental reactor, as the Natrium fuel becomes more reactive it creates local hot-spots which force atoms apart. As the atoms move further apart, the reactivity between them decreases. This sets an upward temperature limit for the reactor core even with no steam generator connection. Because of the physical temperature limit the reactor core never exceeds the point where it fails and natural air circulation in the reactor building keeps components outside the reactor core safe.

The Natrium reactor has discrete fuel units loaded into “pins” which limit the reactivity. Exact specifications are not available, but in NRC documents they are compared to the Fast Flux Test Facility and the EBR-2. The precursor reactors’ fuel was somewhat similar in cross section to LWR fuel assemblies and varied in length from ⅓ to 1 meter. Conventional non-proliferation measures to account for used fuel will apply here.[74]

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[72]https://www.canarymedia.com/articles/nuclear/bill-gates-wants-to-build-advanced-nuclear-power-at-retired-wyoming-coal-plants
[73] https://www.youtube.com/watch?v=a2FbMFqwZYg
[74] https://www.nrc.gov/docs/ML2105/ML21057A008.pdf

Part 3: What About the Waste?

Glossary

HALEU: High Assay Low Enriched Uranium
HLW: High level waste
IAEA: International Atomic Energy Agency
LLW: Low level waste
ILW: Intermediate level waste
MOX: Mixed oxide fuel, usually consisting of plutonium and uranium from reprocessing of weapons and/or spent fuel.
NRC: Nuclear Regulatory Commission
SNF : Spent nuclear fuel
TRU: Transuranic waste
WIPP:Waste Isolation Pilot Program
Yellowcake: mined, processed uranium ore that is used to make new nuclear fuel. Reprocessing of spent fuel reduces the need for mining and production of yellowcake.

Introduction

Nuclear power is the only large-scale energy-producing technology that takes full responsibility for all its waste and fully costs this into the product. The volume of waste generated by nuclear power is surprisingly small, especially in comparison to the waste generated by fossil fuel plants. Spent nuclear fuel may be disposed of as waste, but it still contains usable fuel which can be extracted and recycled. Whether it is recycled through reprocessing or disposed of as waste, spent nuclear fuel is not hard to manage relative to other toxic industrial waste. Safe methods for its storage and final disposal are technically proven and the IAEA provides technical expertise and a platform for international exchange for member states. While on- or off-site dry cask storage is safe, the international consensus is that geological disposal is the best long term option.

A note about Hanford waste

In Washington state we are acutely aware of a particular kind of nuclear waste: the waste from the military production of plutonium for bombs at the Hanford Works near Richland in Central Washington. At one time there were nine reactors operating to produce plutonium, which was extracted by a messy process that produced hundreds of billions of gallons of liquid waste. At best, the waste was placed into scores of large, buried tanks. At worst, it was poured out onto the desert.[75] In comparison, the waste from nuclear power plants is almost entirely solid, not liquid, and modern reprocessing methods manage wastes in a far more responsible manner.

What is power plant nuclear waste and what are its hazards?

[75] https://www.hanford.gov/page.cfm/AboutHanfordCleanup

Radioactive waste is any waste that is either intrinsically radioactive or has been contaminated by radioactive elements. One kind of waste associated with nuclear power is from mining: uranium mill tailings are the residues remaining after the processing of natural ore to extract uranium, and they are not radioactive. Spent fuel rods are radioactive, and unless they are re-processed to be reused after being removed from the nuclear reactor, they are considered radioactive waste.

Unlike other kinds of toxic waste that remain toxic forever, nuclear waste becomes less hazardous with time. Eventually all radioactive isotopes decay into non-radioactive elements. The more radioactive an isotope is, the faster it decays. In doing so it releases energy. The "afterglow heat" refers to the energy released by the nuclear fuel after it has been removed from the reactor. This is what makes nuclear power plant waste hazardous.[76]

The level of radioactivity determines the type of waste, according to the classification adopted by IAEA: low level, intermediate level or high level.[77] Low level waste (LLW) is mostly tools, clothing, and filters contaminated by small amounts of short-lived radioisotopes. Intermediate level waste (ILW) is more radioactive than LLW but generates low amount of heat. ILW comprises not only contaminated materials but also ion exchange resins, chemical sludges, and metal fuel cladding. High level waste (HLW) is sufficiently radioactive for its heat to increase its temperature significantly and requires both cooling and radiation shielding while radioactive decay reduces heat generation. In addition to this international classification scheme, the US has its own classification that is based on the origin of the waste instead of its level of radioactivity. For example, non-defense related waste generated by industry and medical fields containing uranium and transuranic elements is categorized as transuranic (TRU) waste, while spent nuclear fuel (SNF) is a category of its own.[78]

Spent nuclear fuel (and waste generated from reprocessing of spent fuel) are both counted as high level waste in either classification.[79] They both initially contain short and long-lived radioisotopes. While LLW accounts for 90% of the volume of all radioactive waste produced, HLW accounts for 95% of the radioactivity of all nuclear waste produced and that is why HLW is the focus of attention in the context of nuclear power.[80]

How much waste does the nuclear power industry produce?

The US generates about 2,000 metric tons of used fuel each year. This number may sound like a lot, but it's actually quite small. In fact, the US has produced roughly 83,000 metrics tons of used fuel since the 1950s—and all of it could fit on a single football field at a depth of less than 10 yards[81]. If all the electricity in the US was produced by nuclear power, the amount of radioactive waste generated would be about 40 grams (1.4 ounce) per person per year. It is significantly less in volume than any other type of energy production. In comparison, billions of gallons of toxic

[76] https://whatisnuclear.com/waste.html
[77] https://www.iaea.org/publications/14739/status-and-trends-in-spent-fuel-and-radioactive-waste-management
[78] https://www.yumpu.com/en/document/read/63590033/atw-international-journal-for-nuclear-power-06-072020/25
[79] https://www.nrc.gov/waste/high-level-waste.html
[80] https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-waste-management.aspx
[81] **https://www.energy.gov/ne/articles/5-fast-facts-about-spent-nuclear-fuel**

fluids and billions of tons of solid toxic waste come from fracking for gas and from mining for oil and coal, every year. Interestingly, there is radioactivity in these fossil fuel waste streams but they are regulated entirely differently.[82] Recent non-peer reviewed papers claiming nuclear waste from advanced reactor designs is larger than traditional reactors have been refuted by the nuclear scientific and engineering community. Any change in the volume of waste resulting from new reactor design will not significantly change the total volume of waste in need of disposal.[83,84]

How is nuclear waste managed?

Under the Atomic Energy Act of 1954, a single agency, the Atomic Energy Commission, originally had responsibility for the development and production of nuclear weapons and for both the development and the safety regulation of the civilian uses of nuclear materials. The Energy Reorganization Act of 1974 split these functions, assigning to the Department of Energy (DOE) the responsibility for the development and production of nuclear weapons, promotion of nuclear power, and other energy-related work, and assigning to the NRC the regulatory work, which does not include regulation of defense nuclear facilities.

The Nuclear Waste Policy Act (NWPA) of 1982 governs the radioactive waste disposal and storage.[85] Under the NWPA, the DOE has the responsibility to site, build and operate a deep geological repository for the disposal of high level waste and spent nuclear fuel. The NRC is to serve as the independent regulator for the repository. The EPA develops standards for protection of the environment from offsite releases of radioactive material in repositories. The NRC also regulates the spent fuel pools and dry cask storage, as well as the decommissioning of nuclear facilities, with inspection, investigation and enforcement authority.

There are three steps in the timeline of spent nuclear fuel management:

Short Term Storage

Spent nuclear fuel (SNF) is never kept unshielded. It is kept underwater (water is an excellent shield) for 5–8 years in spent fuel pools, at the reactor site, until the radiation decays to levels that no longer require water for cooling. After this cooling, nuclear spent fuel is either recycled or moved into large concrete and steel canisters called dry casks. These casks each hold several spent fuel assemblies and shield the remnant radiation to the point where you can safely stand next to the casks. Dry casks are designed to resist earthquakes, projectiles, tornadoes, floods, temperature extremes and other scenarios. The heat generated by a loaded spent fuel cask is typically less than what is given off by a home-heating system. The heat and radioactivity decrease over time without the need for fans or pumps. The casks are under constant monitoring and surveillance. In fact, no accidental release of radiation, nor injuries or mortality have been reported from dry cask storage in US history. The US Nuclear Regulatory Commission states: "Since the first casks were loaded in 1986, dry storage has released no radiation that affected the public or contaminated the environment. There have been no known or suspected attempts to

[82] https://www.rollingstone.com/politics/politics-features/oil-gas-fracking-radioactive-investigation-937389/
[83] https://www.theregister.com/2022/06/02/nuclear_reactors_waste/
[84] https://s24.q4cdn.com/104943030/files/PNAS-Letter-Reyes-NuScale-5.31.22-(002).pdf
[85] https://www.epa.gov/laws-regulations/summary-nuclear-waste-policy-act#:~:text=(1982)

sabotage cask storage facilities. Tests on spent fuel and cask components after years in dry storage confirm that the systems are providing safe and secure storage." [86]

Interim Storage

There is one commercial interim storage facility in operation in the US, the Consolidated Interim Storage Facility near Andrews, Texas.[87] This is a dry cask storage facility at an away-from-reactor site for SNF awaiting disposal at a permanent disposal repository. Texas Interim Storage Partners were first licensed for this in 2021 for a 40 year period. This will be used to store SNF from plants where there is limited on-site storage space.[88]

Long-term storage

There is scientific consensus that putting nuclear waste in geologic formations that are expected to be stable for many millions of years is appropriate (e.g. Blue Ribbon Commission report[89] and the 2020 OECD report[90] on nuclear waste disposal). Yucca Mountain was ultimately abandoned due to political issues.[91] In the 1980s the US constructed a deep geological repository nearly half a mile below the surface at a site near Carlsbad, New Mexico: the Waste Isolation Pilot Project (WIPP). It is in a massive salt formation that is waterproof, stable and is self sealing.[92] WIPP was originally designed for all types of nuclear waste, but a political decision was made to restrict it to defense-related transuranic waste. Part of the thinking was that spent commercial fuel could be reprocessed at some time in the future, and so should be accessible for retrieval after being deposited in a facility; this is not possible at WIPP by design. WIPP is a huge facility and has plenty of room to store commercial waste as well.

Cost of waste management

The cost of waste management for nuclear energy is borne by the industry and is incorporated into the price of its electricity. The nuclear industry pays for its spent nuclear pools and dry cask storage and monitoring, as required by the NWPA. The monitoring of the pools and casks is being done by the NRC through its licensing process. In comparison, the cost of fossil fuel waste is borne by the taxpayers, through the Superfund sites, etc, and by all of humanity, as a result of global warming and premature death from lung disease and cancer.

In 1987, NWPA established a Nuclear Waste Fund (NWF) for the long term storage and the nuclear industry has been paying 0.1 cent/kWh for the nuclear waste program. The NWF balance is currently about $45 billion and the interest alone keeps increasing the fund by about $1.5 billion per year. After DOE pulled out of the Yucca Mountain project, the industry stopped contributing to the fund in 2014, following a lawsuit that concluded in its favor. Unable to meet its disposal commitment, the US government has paid reactor owners about $9 billion for

[86] https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/dry-cask-storage.html
[87] https://www.nrc.gov/waste/spent-fuel-storage/cis.html
[88] https://www.nrc.gov/waste/spent-fuel-storage/cis.html
[89] https://www.energy.gov/sites/prod/files/2013/04/f0/brc_finalreport_jan2012.pdf
[90] http://www.oecd-nea.org/rwm/pubs/2020/7532-dgr-geological-disposal-radioactive-waste.pdf
[91] https://www.yumpu.com/en/document/read/63590033/atw-international-journal-for-nuclear-power-06-072020/25
[92] https://wipp.energy.gov/

storage. The Government Accountability Office has made valuable policy recommendations to address the situation.[93]

Technological breakthroughs on the horizon

There are encouraging developments regarding the long-term disposal options for nuclear waste as well as renewed efforts in reducing the amount of waste produced.

Finland is the first European country to build a deep geological repository for commercial waste, the Onkalo Nuclear Waste Disposal Facility at Olkiluoto, which will commence operations in 2024.[94] The SNF will be transported in special casks to an encapsulation plant located above ground at the site, where it will be packed into copper and cast-iron canisters. The canisters will then be lowered 450 m below ground, deep inside the bedrock, isolated from groundwater, for final disposal. Sweden and France also aim to have their own deep geological repositories within this decade.

In the US, deep borehole technology is being considered as an alternative long term storage option. The waste emplacement zone will be significantly deeper than the WIPP or the Onkalo repositories. A start-up company called Deep Isolation proposes to use the directional drilling technology used in oil and gas industries to dig long narrow horizontal holes 1 to 4 km beneath the surface to store canisters of SNF. It has recently been awarded $3.6 million by the DOE.[95]

In an effort to reduce the amount of waste produced, the DOE is working on HALEU fuel (High Assay Low Enriched Uranium fuel) development. HALEU fuels are 2-3 times more efficient than standard nuclear fuels. Similar fuel is used in the US nuclear navy, which allows ships to stay at sea for prolonged periods of time. Some next generation commercial reactors will use HALEU (TerraPower, X-Energy). X-Energy’s first TRISO-X fuel fabrication facility is partly funded by the DOE under the Advanced Reactor Demonstration Program and is expected to start operations in 2025.[96]

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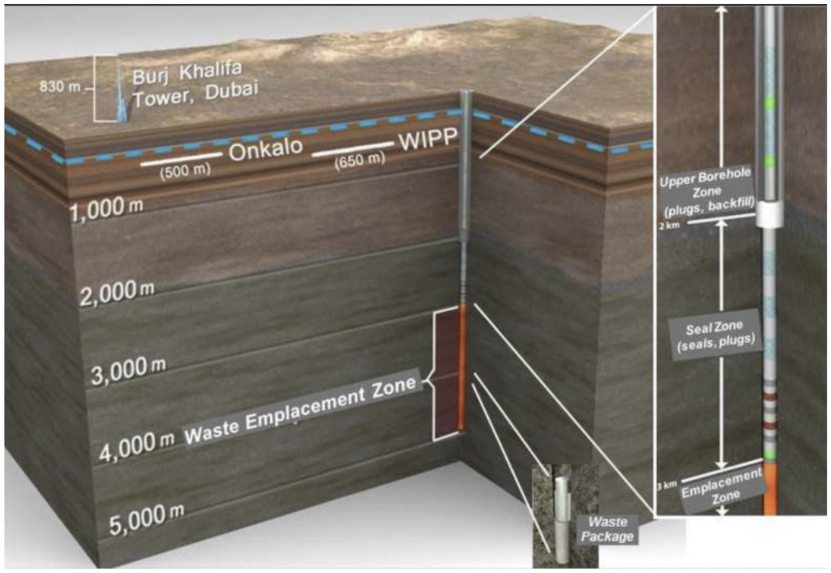
[93] https://www.gao.gov/products/gao-21-603
[94] https://www.world-nuclear-news.org/Articles/Posiva-applies-to-operate-used-fuel-disposal-repos
[95] https://www.cnbc.com/2022/04/04/deep-isolation-aims-to-bury-nuclear-waste-using-boreholes.html
[96] https://www.energy.gov/ne/articles/x-energys-triso-x-fuel-fabrication-facility-produce-fuel-advanced-nuclear-reactors



Reprocessing (recycling) of SNF is being considered again in the US, after a 40 year hiatus. Reusing SNF drastically reduces the amount of radioactivity in the waste and decreases the volume of waste approximately 10-fold.[97] A major obstacle to nuclear fuel recycling has been the perception that it is not cost-effective and that it could lead to nuclear proliferation. The Carter Administration decided not to reprocess in the 1980's to support the Non-Proliferation Treaty.[98] Meanwhile, France, Japan, Russia, UK and India have continuously reprocessed their waste. The longest-lived transuranic radioisotopes in the SNF are the ones that can be used as reprocessed fuel. Thus reprocessing significantly reduces the time involved in long-term storage, from millions down to thousands of years, eliminating the need for geological repository.[99]

Nuclear warheads can also be repurposed as nuclear fuel, reducing the demand for uranium mining. In 1993, an agreement between the US and Russia led to the Megatons to Megawatts Program, allowing surplus weapons-grade uranium from Russia to be re-processed into nuclear fuel that the US bought. Highly enriched uranium from weapons stockpiles replaced 8,850 tons of mined "yellowcake" (U_3O_8) per year and met about 13%-19% of fuel needs of nuclear reactors worldwide until 2013. Plutonium can also be repurposed as a "mixed oxide" (MOX) fuel. A MOX fuel fabrication plant has been in construction at the DOE Savannah River site since 2007 but it is still not completed.[100] By completing it, the US will be able to fulfill its disarmament obligations while producing clean electricity. Advanced nuclear reactors could be built to use MOX fuel.

[97] https://www.scientificamerican.com/article/smarter-use-of-nuclear-waste/
[98] https://www.forbes.com/sites/realspin/2014/10/01/why-doesnt-u-s-recycle-nuclear-fuel/?sh=38fcfe32390f
[99] https://world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-fuel.aspx
[100] https://world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/military-warheads-as-a-source-of-nuclear-fuel.aspx

Conclusion

Nuclear power is the only large-scale energy producing technology that takes full responsibility for the waste it produces and factors managing its waste into the cost of the energy produced. Contrary to public perception, nuclear waste is neither particularly hazardous nor hard to manage relative to other toxic industrial waste. The safety profile for waste management for nuclear spent fuel is well documented and exemplary. How to manage it is well understood. However, decisions about how to manage spent fuel have been politically influenced. The scientists know what to do with it.