Rethinking Nuclear Waste: Recycling Spent Fuel in the Era of Renewable Energy

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Abstract

Many utilities in the U.S. are incorporating renewable sources of energy such as wind power and solar into their energy mix to reduce their carbon emissions. For example, the Omaha Public Power District, has committed to decarbonizing its operations by 2050. While the use of renewables will certainly play an important role, spent nuclear fuel, commonly referred to as nuclear waste, is an untapped resource that can be recycled into nuclear fuel for use in small modular reactors. Nuclear waste retains over 95 percent of its energy potential and can be safely recycled using the pyroprocessing technique. The amount of recycled spent fuel needed to start-up General Electric-Hitachi's Power Reactor Small Innovative Module fast reactor was calculated, and its generation capacity was used to assess emissions offset and health co-benefits of replacing Omaha Public Power District's coal-fired power plants with nuclear. The quantities of spent nuclear fuel recycled from the national inventory were also scaled to estimate power potential as well as how fast nuclear energy could replace coal as a primary source of local, state, and national baseload power. Using these estimates the Omaha Public Power District can reach its goal of decarbonizing its operations within 10 years of starting construction on a recycling and modular fast reactor power plant facility. Doing so would eliminate 98 percent of its electricity generation-related greenhouse gas emissions, consume all of Nebraska's and neighboring states inventory of spent fuel, and generate enough electricity to meets the region's needs into the future. Recycling nuclear waste could be scaled to the state and national level, progressively eliminating the country's spent fuel stocks, significantly reducing energy-related greenhouse gas emissions, and providing upwards of 40GW of electricity by 2050.

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Chapter 1: Introduction

At the dawn of the nuclear age, a world of unlimited energy was envisioned as the way of the future. In 1954, Lewis L. Strauss, Chairman of the Atomic Energy Commission, on contemplating the outlook of nuclear energy stated in a speech given to the National Association of Science Writers that:

> "it is not too much to expect that our children will enjoy in their homes electricity too cheap to meter,— will know of great periodic famines in the world only as matters of history,—will travel effortlessly over the seas and under them and through the air with a minimum of danger and at great speeds…"[1]

In the 1950's, this was not hyperbole.

As a source of electricity, nuclear power is the single largest source of emissions-free energy available to the world. In terms of energy density—the amount of embodied energy per unit mass of a fuel source— one enriched Uranium (U_{235}) fuel pellet (approximately 3/8th inch in diameter by 5/8-inch in length) contains the same energy as one ton of coal, 149 gallons of oil, and 17,000 cubic feet of natural gas.[2] The tremendous release of energy from a single atom has been hotly debated since the first atom was split in 1945. Its close association with the development of the atomic bomb, concerns over the technology's safety, and especially the disposition of nuclear waste, often stir passionate debate that has limited the growth of nuclear energy.[3]

Noted Harvard physicist, Harvey Brooks, then head of the National Academy of Sciences committee on nuclear power, addressed the issue of nuclear waste directly, stating in 1977 that "No single aspect of nuclear power has excited so persistent a public concern as has radioactive waste management…I would predict that should nuclear energy ultimately prove to be socially unacceptable, it will be primarily because of the public perception of the waste disposal problem."[4] Indeed, public opinion polls in the mid-1970s reflected the public's anxiety over nuclear waste. Surveys taken in 1975 and 1976 identified waste as the most concerning aspect of nuclear power, more so than nuclear accidents, or the environmental release of radioactive

[1] (Strauss, 1954; Terzic, 2018)
[2] (Nuclear Energy Institute, n.d.)
[3] (Hore-Lacy, 2018; Hubbard, 2014; Reinhart, 2019)
[4] (Carter, 1977; Walker, 2009)

material.[5] The need to safely store and manage the country's spent nuclear fuel (SNF), for hundreds of thousands of years has been a political, and environmental albatross for decades. The back-end product of the nuclear fuel cycle, SNF was considered to be a minor problem with a manageable solution until the practice of reprocessing SNF was banned in the U.S. in 1977. Now, the United States is the only major economy that does not recycle its nuclear waste.[6]

NUCLEAR 101

Nuclear power begins with uranium (U). Ninety-nine percent of natural uranium is made up of U_{238} isotope, and .7 percent U_{235} isotopes—the type favored for nuclear reactors. Once, mined and milled, uranium must then be "enriched" to increase U_{235} to about 3-5%. Following enrichment, it is formed into pellets which are assembled into fuel rods, hundreds of which make up a reactor core. Inside the core, power is generated by the fissioning (splitting) of a U_{235} atom by striking it with a neutron. As the atom splits it releases energy in the form of heat, and nuclear radiation. It also releases its neutrons that, when slowed down through the use of a moderator such as water in conventional thermal reactors, go on to strike more atoms, releasing even more energy, radiation, and neutrons forming a chain reaction. As the chain reaction grows, U_{235} is "burned," giving off a great amount of heat that is used to boil water, generate steam, and drive a steam turbine generator.[7] The majority of nuclear fuel, however, is still composed of U_{238}. When U_{238} is struck by a neutron, the neutron is absorbed and the uranium is converted into neptunium (N_{239}) and eventually into plutonium (P_{239}).

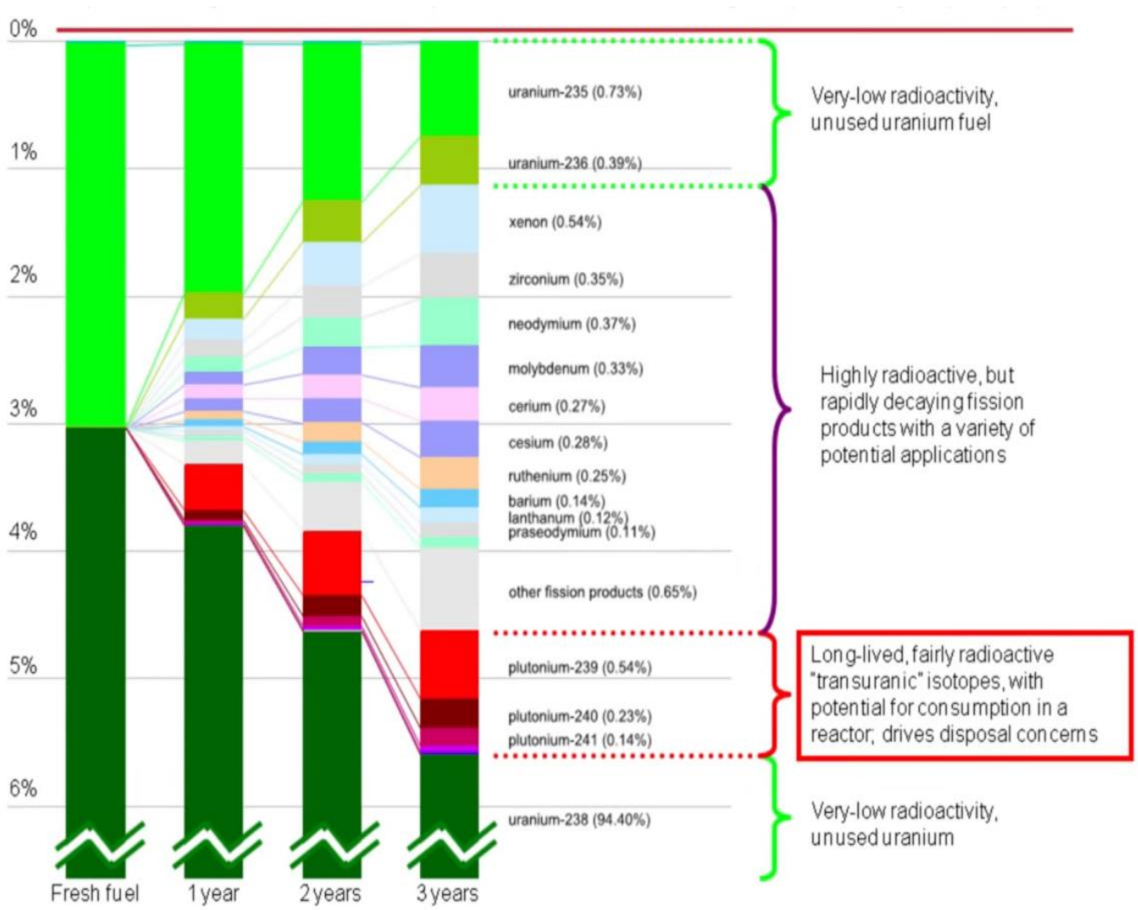
The fissioning of plutonium in the core contributes about 40 percent of a reactor's energy. P_{239} along with other plutonium isotopes are long-lived transuranic (TRU) elements which form inside the core over time. Within three or four years, a reactor core must be replaced because elements like xenon form inside the core and act as neutron absorbers inhibiting the nuclear chain reaction. Additionally, damage to the core's fuel cladding occurs with continued exposure to neutrons, and without replacement, the cladding may fail. Typically 25-30 percent of the core must then be replaced with fresh fuel every year.[8] If the "spent" fuel is to be recycled, then it is cooled before being shipped for reprocessing. The fuel's U_{235} and P_{239}, is typically recycled into fresh Mixed Oxide (MOX) fuel using the plutonium-uranium reduction

[5] (Walker, 2009)
[6] (Blees, 2008; Walker, 2009)
[7] (Hore-Lacy, 2018)
[8] (Till & Chang, 2011)

(PUREX) process. This procedure chemically separates plutonium and uranium from other "waste" products which are then collected for long-term storage. Nuclear waste retains over 90 percent of its energy potential and is comprised of about 95 percent uranium, with plutonium and other fission products and transuranic elements making up around 4 and 1 percent, as illustrated in Figure 1.[9] Because Uranium was once thought to be rare, nuclear power was originally conceived to employ a closed fuel cycle, as described above.[10] As it happens, recovered U235

Figure 1.

Composition of Conventional Nuclear Fuel



Note: (17x17 Westinghouse, 3% enr., 1100 day irrad, 33000 MWD/MTU, discharge composition, Origen Arp analysis)
Source: Thorium Remix, 2017

9 (Hore-Lacy, 2018; Nuclear Regulatory Commission, 2019; Thorium Remix, 2017; U.S. Department of Energy, 2020; U.S. Energy Information Administration, 2020f; whatisnuclear.com, 2020)

10 (Rossin & Frontline; Public Broadcasting Service, 2014; U.S. Energy Information Administration, 2020f; World Nuclear Association, 2018)

and P239, collected separately during PUREX are also ideal for manufacturing nuclear weapons. As nuclear technology matured and was shared throughout the world, a dangerous development occurred in 1974 that changed the course of nuclear energy policy in the U.S.[11]

The Smiling Buddha And U.S. Nuclear Waste Policy

Following WWII, geo-political competition had turned into a Cold War as the U.S. and the Soviet Union developed and fielded an increasingly worrisome number of nuclear weapons. President Eisenhower, who understood the strategic value of such weapons, sought to steer the world towards a managed approach of nuclear technology. His "Atoms for Peace" initiative was a means of achieving foreign policy goals through the sharing and development of nuclear know-how and material in exchange for promises not to develop nuclear weapons. Despite a pledge to the contrary, India developed and detonated an atomic bomb using nuclear material and knowledge from "Atoms for Peace."[12]

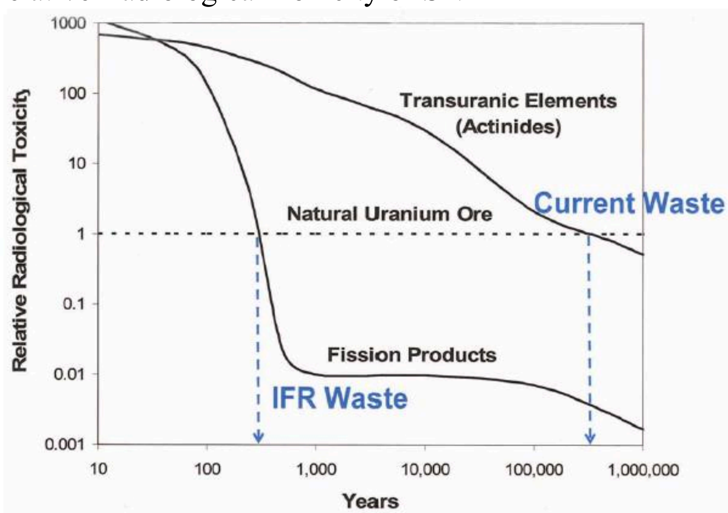
On May 18 1974, the Indian government tested its first nuclear weapon codenamed "Smiling Buddha." Using plutonium derived from a Canadian-Indian research reactor and other American supplied nuclear material and knowledge, India's test inadvertently ended "Atoms for Peace," and spurred a U.S. led effort of global nuclear counterproliferation. The timing was unfortunate, as Poneman writes: "India's test generated a backlash against peaceful nuclear cooperation that ran against the grain of the mid-1970's push to increase nuclear power generation around the world in response to the 1973 oil crisis, which intensified desires to replace oil dependence with nuclear independence on energy and national security grounds."[13] First under the Ford Administration, and codified by executive order under Carter, U.S. policy focused on safeguarding and preventing further nuclear material from being diverted into weapons programs. As the world's nuclear technology leader, Carter wanted the U.S. to set the example to other nations by indefinitely halting the reprocessing of SNF while an alternative was sought. Even though the Reagan Administration subsequently reversed the reprocessing ban in 1981, U.S. private investment in nuclear recycling and energy was left in limbo, and signaled the end of U.S. nuclear leadership as the rest of the world continued reprocessing and recycling SNF.[14] Without reprocessing SNF, the U.S. is left with thousands of metric tons of TRU high-

11 (Poneman, 2019)
12 (Eisenhower Presidential Library, n.d.; Hicks, 2014)
13 (Poneman, 2019)
14 (Andrews, 2008; Poneman, 2019; Rossin & Frontline; Public Broadcasting Service, 2014)

level waste (HLW) that is highly radioactive for hundreds of thousands of years requiring long-term disposal before reaching the safe levels of naturally occurring uranium. Figure 2 illustrates the problem.

Figure 2

Relative Radiological Toxicity of SNF



Source: Archambeau et al., 2011

Today, the country's 95 thermal reactors produce around 2000 metric tons heavy metal (MTHM)/yr in a once-through nuclear fuel cycle that has to be stored on-site until it can safely be transferred to the Department of Energy (DOE) for permanent disposal at a geologic repository.[15] Unfortunately, the implementation of the Yucca Mountain, Nevada site—chosen as a permanent geologic repository—has been bogged down in litigation, design and licensing challenges since 1987.[16] For a complete timeline of events related to Yucca Mountain, see Appendix A. Many plants have been driven into early retirement, confronted by the absence of realistic future waste management solutions, and confronted with an increasingly competitive market of renewable energy resources, low-cost natural gas supplies (driven by new extraction technologies,)[17] lower demand, and higher operating costs, many plants have been driven into early retirement.[18] The U.S. Energy Information Administration (EIA) now projects nuclear

[15] (U.S. Department of Energy, 2020; U.S. Government Accountability Office, 2020; World Nuclear Association, 2018)
[16] (U.S. Government Accountability Office, 2020)
[17] (U.S. Energy Information Administration, 2019a, 2019b)
[18] (Clemmer, Richardson, Sattler, & Lochbaum, 2018)

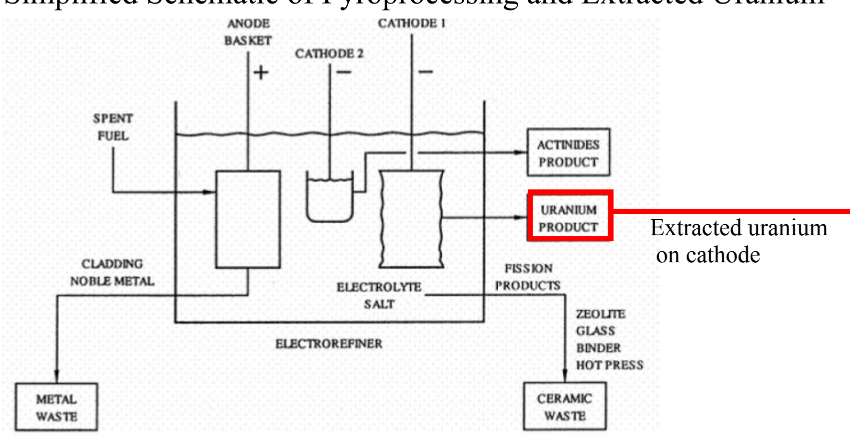
power's contribution to the nation's energy mix to decrease from 19 percent today, to 12 percent by 2050.[19] This trend undermines efforts to reduce carbon emissions which are necessary to combat the effects of climate change. Perhaps, as Dr. Brooks foresaw, the key to reversing this trend rests on solving the nuclear waste issue.

PYROPROCESSING

Pyroprocessing is an electrorefining technique developed in the mid-1960's by Argonne National Lab (ANL), similar to electroplating, that is used to reprocess SNF. Till and Chang explain, "Electrorefining is commonly utilized in the minerals industry to purify metals, such as aluminum and zinc. In spent fuel processing, electrorefining allows the valuable fuel constituents, uranium and the actinides, to be recovered and the fission products to be removed."[20] SNF is placed in a basket that serves as the "positive" anode and submerged in molten salt. A low voltage electric current then dissolves the used fuel and deposits uranium and TRU actinides on a "negative" cathode. Once collected they are extracted from any remaining sodium and cast into new fuel rods. The remaining fission waste products are separated and processed for vitrification and permanent storage. Because the long-lived actinides (P239, and others) are recycled back into the fuel cycle, the waste collected via pyroprocessing (~5% of the original fuel in an IFR) only requires storage for about 300 years (ref. Figure 2), reducing the "mass and toxicity life-time of the waste produced, by factors of 10 and 1000 (respectively)."[21]

Figure 3

Simplified Schematic of Pyroprocessing and Extracted Uranium



Source: Argonne National Laboratory, 2018; Till & Chang, 2011

[19] (U.S. Energy Information Administration; Office of Energy Analysis, 2020)
[20] (Till & Chang, 2011)
[21] (Archambeau et al., 2011)

The process and product are illustrated in Figure 3. One key advantage to pyroprocessing is that the uranium and plutonium resources are not separated, unlike the PUREX process, but rather collected and refined together with qualities unfavorable to diversion for nuclear weapons. Pyroprocessing was primarily used for experimentation, but took on a new life in the 1980's and 1990's as a complement to a new type of reactor called the Integral Fast Reactor (IFR), designed specifically to address the major issues surrounding nuclear technology at the time, namely proliferation, safety and waste. The IFR, also known as a "breeder" type reactor is a fast reactor that take advantage of neutron capture to produce more nuclear fuel than it burns. Dr. P. Andrew Karam explains,

> …a fast reactor uses a coolant that is not an efficient moderator, such as liquid sodium, so its neutrons remain high-energy. Although these fast neutrons are not as good at causing fission, they are readily captured by an isotope of uranium (U238), which then becomes plutonium (P239). This plutonium isotope can be reprocessed and used as more reactor fuel or in the production of nuclear weapons. Reactors can be designed to maximize plutonium production, and in some cases they actually produce more fuel than they consume.[22]

Recycling uranium and "breeding" more plutonium through neutron transmutation in a fast reactor is considered a means of maximizing uranium resources in a closed fuel cycle. In this sense, once a reactor is self-sufficient it could arguably be considered a renewable resource. But recycling SNF for fast reactors is not the only consideration. The IFR was designed to process SNF on-site and remotely in shielded chambers to protect against high levels of radiotoxicity, thereby limiting access to valuable uranium and plutonium resources. Furthermore, fast reactors have inherent passive safety features designed to handle the most hazardous reactor failures without operator interaction.[23] For a detailed description of fast reactor passive safety features and demonstrated performance see Appendix B.

At face value, pyroprocessing combined with a fast reactor's inherently passive safety features and proliferation safeguards would appear to satisfy nuclear energy's critics. However, many still rally against fast reactors, recycling nuclear fuel and/or pyroprocessing, with arguments centered around costs, others around the availability of abundant cheap uranium, or

[22] (Karam, 2006)
[23] (Till & Chang, 2011)

the mismanagement of pyroprocessing waste. The Rocky Mountain Institute, a prominent opponent of nuclear power, cites nuclear energy's high capital costs as reason alone to abandon the technology, claiming that "informed capitalists" have forsaken nuclear in favor of cheaper, safer and readily available alternatives so, they argue, we should too.[24] Harvard's own Belfer Center For Science And International Affairs at the Kennedy School of Government cite their economic models indicating storage in geologic repository is more economical than reprocessing for use in thermal and fast reactors, and only advantageous when uranium prices reach $340-$360/KgU. In a best case scenario where fast reactors achieve capital costs similar to those of thermal reactors, it would still require uranium to reach $140/KgU before reprocessing became economically viable.[25] With uranium's spot price hovering at around $70/KgU[26] it is unlikely the economics of energy production alone will drive the adoption of fast reactors. Others disagree, despite the higher lifetime levelized cost of electricity (LCOE), around $70/MWh, as compared to approximately $35 for wind and utility-scale solar, nuclear power's average capacity factor is much higher (90% vs. 35%, and 25% percent for wind and solar respectively).[27] Taking capacity factors into consideration, nuclear power is less expensive per MWh than renewable energy over the lifetime of the plant for current and future projections. This outlook is supported by previous studies by the United Nations' Intergovernmental Panel on Climate Change (IPCC) of nuclear power's LCOE at 10% weighted cost of capital per Megawatt hour (MWh) that place nuclear technology as comparable in cost to that of wind energy and lower than that of solar.[28] Even when high capital costs are factored for first-of-kind technology, there is no reason to suspect modular fast reactors cannot achieve economic viability if widely employed.[29]

Even if reprocessing could become viable, pyroprocessing, a key element to a recycling strategy has come under attack. The Union of Concerned Scientists goes so far as to claim that pyroprocessing was only further developed as a "consolation prize"[30] for ANL after the Clinton administration terminated the IFR program in 1994, and that in reality the technology is mostly

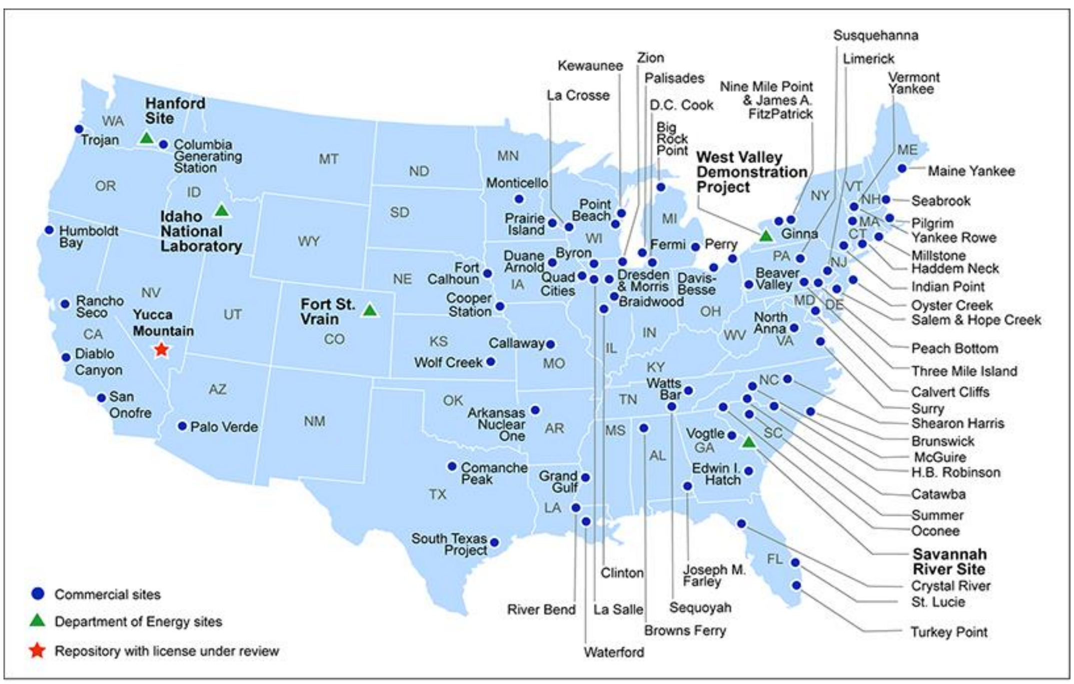
24 (Lovins, Sheikh, & Markevich, 2009)
25 (Bunn, Holdren, Fetter, & Van Der Zwaan, 2005)
26 (UxC, 2020)
27 (National Renewable Energy Laboratory, 2019; U.S. Department of Energy; Office of Nuclear Energy & Mueller, 2020; U.S. Energy Information Administration, 2020a)
28 (Intergovernmental Panel On Climate Change, 2014)
29 (Archambeau et al., 2011)
30 (Lyman & Union of Concerned Scientists, 2017)

unproven, and has served to only aggravated the problem it intended to solve. While these arguments may have merit on their own, none address the lingering issue of what to do with the 90,000 metric tons of SNF, not to mention the 750,000 metric tons of depleted uranium (DU) currently awaiting disposition at commercial and government sites throughout the country. Long-term storage of SNF is even more pressing today as the Yucca Mountain geologic repository, if ever operational, is limited to holding less than 70,000 MTHM.[31] Figure 4 identifies U.S. nuclear storage sites.[32]

With increasing awareness and debate over coal's contribution to carbon emissions and global warming, many utilities are incorporating a growing portfolio of renewable energy resources and laying out strategies to reach net-zero emissions in the decades to come. Notwithstanding the integration of renewables, the extent to which recycling SNF and fast reactors can contribute to a utility's green energy mix merits a closer look.

Figure 4

U.S. Nuclear Storage Sites



Source: U.S. Government Accountability Office, 2020

[31] (Nuclear Regulatory Commission, 2017; Vinson & Carter, 2019)
[32] (U.S. Government Accountability Office, 2020)

Chapter 2: Methodology

An SNF reduction-to-energy potential model was created to approximate SNF and reactor quantities sufficient to replace all coal plants in the Omaha area, and scaled to include the State of Nebraska. A broad-stroke coal plant replacement assessment based on MW capacity was also made for the U.S. To calculate how much energy could be mined from SNF, the quantity of SNF in MTHM was calculated using the DOE's 2019 Spent Nuclear Fuel and High-Level Radioactive Waste Inventory Report, Government Accountability Office (GAO), and U.S. Nuclear Waste Technical Review Board data. The total amount of SNF now in the U.S. is around 90,000 MTHM. Depleted uranium can also be recycled, as described by Archambeau et al.[33] The quantity of DU in usable form and composition in the U.S. is assessed to be 300,000 tons, according to the World Nuclear Association's 2019 Nuclear Fuel Report.[34] A General Electric-Hitachi (GEH) Power Reactor Innovative Small Module (PRISM) reactor was chosen as the sodium-cooled reactor of choice because it is was developed in close collaboration with ANL and is the most mature, U.S.-made fast reactor available for licensing and deployment. GEH envisions an Advanced Recycling Center (ARC) that includes a Nuclear Fuel Recycling Center (NFRC) and three PRISM power-blocks, each consisting of two, 311 MW modular fast reactors for a total of 1866 MW. The operational lifetime of a PRISM reactor is 60 years.[35]

Because construction of a first-of-kind pyroprocessing facility is estimated by GEH and ANL[36] to take around 10 years, the amount of SNF available in 2030 was estimated at 110,000 MTHM assuming the current rate of around 2000 MTHM/yr. Considering efficiencies expected to be gained from a small modular design, and assuming a strong national commitment to deploy these reactors, in a best-case scenario, construction timelines for every subsequent ARC was estimated to be 36 months, down from the median construction time for a nuclear power plant of 66 months[37] with two new modular PRISM power-blocks added each year, and a doubling of construction every ten years (low deployment scenario; max 8/yr), and five years (high deployment scenario; max 8/yr).

33 (Archambeau et al., 2011)
34 (World Nuclear Association, 2019)
35 (Triplett, Loewen, & Dooies, 2012)
36 (Yoon Il Chang et al., 2019; GE Hitachi, 2020)
37 (Blees, 2008; Sonnichsen, 2019)

The acknowledged baseline composition of SNF (~95% uranium, 1% transuranics, and 4% fission products), as detailed by GEH,[38] was used, and the amount of SNF needed for startup and two fuel reloads was calculated for each PRISM reactor according to calculations by Dr. Eric Loewen of GEH, and Dr. Yoon IL Chang of ANL.[39] These amounts include an initial ~500 MTHM/PRISM core; ~3000 MTHM/ARC with a yearly consumption per ARC of ~0.5 MT TRU/yr. Quantities of SNF available in the Omaha area at the decommissioned Fort Calhoun Station (FCS) were provided by the Omaha Public Power District (OPPD).[40] Further quantities of SNF and contributions to the national Nuclear Waste Fund were taken from state inventories as listed by the Nuclear Energy Institute (see Appendix D) and the DOE.[41] SNF consumption is calculated until SNF inventory is mostly consumed, at which point all reactors are then assumed switching their core configuration to "breeding" to produce more fuel for other reactors, or "breakeven" mode, and be self-sufficient with modest contributions from excess uranium from its initial load throughout their lifetime.[42] The waste fuel product is assumed at ~3 percent of the original fuel mass as detailed by Dubberley et al. in their description of the S-PRISM fast-reactor fuel cycle.[43] The time required in geologic depository is detailed in "Relative Radiological Toxicity," Figure 2.

Because the emission of Sulfur Dioxide (SO_2) and Nitrogen Oxide (NO_x) and other environmental pollutants are emitted from all of Nebraska's coal plants, the health benefits and impacts to air quality from eliminating coal emissions on the Omaha metro area and Nebraska were calculated and monetized using the EPA's CO-Benefits Risk Assessment (COBRA) Health Impacts Screening and Mapping Tool and complemented by publicly available yearly OPPD data on emissions. Target decarbonization date of 2050 was set by OPPD resource planning, OPPD future decarbonization strategy, and publicly stated policy intentions.[44] Further detail of Greenhouse Gas (GHG) emissions by facility in CO_2 equivalents and facility mapping were taken from the EPA's Facility Level Information on GreenHouse gases Tool (FLIGHT). Emission quantities of particulate matter (PM2.5; filterable and condensable), volatile organic

[38] (Cocked, Wu, & Lipps, 1993; Fletcher, 2006; E. P. Loewen, 2009; Price, 2009)
[39] (Yoon I Chang, 2020; E. Loewen, 2020)
[40] (Weaver, 2020)
[41] (Nuclear Energy Institute, 2020; Vinson & Carter, 2019)
[42] (Archambeau et al., 2011; Triplett et al., 2012)
[43] (Dubberley, Boardman, Carroll, Ehrman, & Walter, 2003)
[44] (Bowers, 2020; Omaha Public Power District, 2017)

compounds, (VOC), ammonia (NH_3), NO_x, and SO_2 were drawn from the April 2020 National Emissions Inventory (NEI)—2017 emissions dataset. 2018 OPPD emissions data were compared to COBRA and FLIGHT emissions data to assess their validity and gave strong confidence in the quality of both datasets. Two thousand and twenty eight baseline emissions reference data was used for COBRA scenarios to project ~10 years into the future to account for ARC construction and licensing. COBRA works by taking manual inputs of avoided emissions (by the ton or percentage), and subtracting them from a baseline set by pre-determined analysis years, 2016, 2023, and 2028. One hundred percent of avoided emissions were assumed when subtracted plant emission quantities were greater than the baseline. Prevented emissions and healthcare costs were calculated at a 3 percent, and 7 percent discount rate. 2018 nameplate and summer generation capacity data (whichever was greater) from FLIGHT was used to determine capacity per plant in MW. Power equivalencies and avoided emissions from wind turbines were taken from the EPA's Greenhouse Gas Equivalencies Calculator with area requirements estimated at 1.5 acres/2MW turbine.[45] Area equivalencies for solar energy are derived from the EPA's Green Power Equivalency Calculator-Calculations and References website and measured as a football field of solar panels equivalent.[46] An ARC's footprint is estimated to be 45 acres. The Walter Scott Jr Energy Center in Iowa, located 3 miles to the east of the Omaha suburb of Bellevue (Sarpy County), is a 1,600MW coal power plant that contributes to the Omaha metro region's air pollution. Because of its proximity, the plant was taken into account when considering reductions in particulate matter, emissions, and avoided healthcare costs. Co-benefits to Sarpy county in Nebraska were also assessed, but its emissions were omitted since no coal generation is present there. All land area measurements were plotted geographically using Google Earth Pro version 7.3.3.7721.

[45] (U.S. Environmental Protection Agency, 2020a)
[46] (U.S. Environmental Protection Agency, 2018)

Chapter 3: Results

At the local utility level, one complete 1866 MW (1.8 GW) ARC could replace OPPD's North Omaha Station, and Nebraska City coal plants within 10 years, while generating enough baseload electricity to meet OPPD's forecasted mean demand of 10,702 GWh in 2030, and for the next decade after that. In the context of 2019 emissions, this would represent a 98 percent reduction of coal-related NO_x, SO_2, HG (mercury), and CO_2 emissions, largely placing OPPD two decades ahead of its 2050 decarbonization goal.[47] The total amounts of eliminated pollutants are summarized in Table 1. However, a complete ARC would require recycling all of the state's current inventory of SNF (~1000 MTHM, including 348 MTHM held by OPPD), and all of the fuel from neighboring states, 887 MTHM from Missouri, 849 MTHM from Kansas, and 619 MTHM from Iowa, for example. This would also create about 150 tons of waste requiring long-term storage in the order of a few hundred years, as previously discussed.

Table 1

2019 Equivalent Avoided Emissions from OPPD Plants

CO2	9,739,048 t.
NOx	7,717 t.
SO2	16,184 t.
Mercury	48 lbs.

Note: Does Not Include Walter Scott Jr. Energy Center, Iowa

While switching to nuclear power offers a modest 0.19 µg/m3 reduction in PM2.5, the total avoided emissions are far more impactful, as seen above. These amounts would be the emissions equivalent of 2,327,618 passenger vehicles driven for one year or the carbon sequestered by 14,070,127 acres of U.S. forests in one year,[48] and monetized between \$9M-\$20M and \$8M-\$18M in avoided healthcare costs over 20 years (at 3% and 7% discount rate, respectively). Avoided early deaths over twenty years were between .79 and 1.79.

Omaha could replace its coal generating capacity with wind turbines instead. However, the footprint equivalent in terms of KWh/yr. of wind power, considering capacity factors for both sources, would require 2,333 turbines spread across 3,500 acres, an area just larger than Boston's Logan Airport. If solar panels were used, it would require the equivalent of 13,037 football fields, or 17, 246 acres. For a graphical representation of the required surface area, see Appendix C.

[47] (Bowers, 2020; Omaha Public Power District, 2017, 2020)
[48] (U.S. Environmental Protection Agency, 2020a)

At the State level, Nebraska could phase out coal baseload generation in less than four years with one ARC and an additional PRISM reactor. Because of the generating capacity of each PRISM reactor, a one-for-one replacement at the state level is not necessary, but in some cases could be employed if geographic proximity to customers, need for resiliency, or proximity to transmission lines limits centralization. This would require an additional 3,000 MTHM from another state with large amounts of SNF, like Illinois (10, 641 MTHM). For Nebraska, this would mean replacing just over half of its in-state electricity generation, now done by coal, with nuclear power in fourteen years.[49]

Statewide, co-benefit analysis reveals a .93 µg/m3 decrease in statewide PM2.5 emissions in counties with coal plants. However, if the state's coal plants were replaced with fast reactors, Nebraska would avoid 32, 365,120 MT of CO_{2e} which would be the equivalent of GHG emissions from 6,992,276 passenger vehicles driven for one year, or the carbon sequestered by 42,267,344 acres of U.S. forests in one year, according to the EPA.[50] Monetized, reductions in statewide emissions would result in \$62M-\$140M, and \$55-\$125M in total avoided healthcare costs over 20 years (at 3% and 7% discount rate, respectively). Avoided early deaths over twenty years were between 5.4 and 12.2.

Recycling nuclear waste as fuel for fast reactors could deplete the nation's inventory of spent fuel in about 25 years. Assuming a conservative "low" deployment scenario of one ARC (six PRISM reactors and NFRC) every 36 months beginning in 2030, with a doubling of plant construction capacity every 10 years for 30 years with an increase to 12 reactors per year after 60 years to make up for plant retirements. At that rate, by 2055 there would be 108 fast reactors generating a nameplate capacity of 33,588 GW of emissions-free baseload power. If DU were included in a low scenario, there would be an additional 22 years (2077) of nuclear fuel powering 284 fast reactors with a nameplate capacity of 88,324 GW. However, the same could be achieved by 2050 with a more ambitious "high" deployment scenario of doubling reactor construction every five years for 20 years, with maximum reactor production of eight per year reached in 2045. In this scenario, SNF inventory would be more or less depleted by 2050, with 116 PRISM reactors producing 36,076 GW of nameplate capacity. Under a high scenario, DU stockpiles would last until about 2071 having helped fuel 284 PRISM reactors with a nameplate

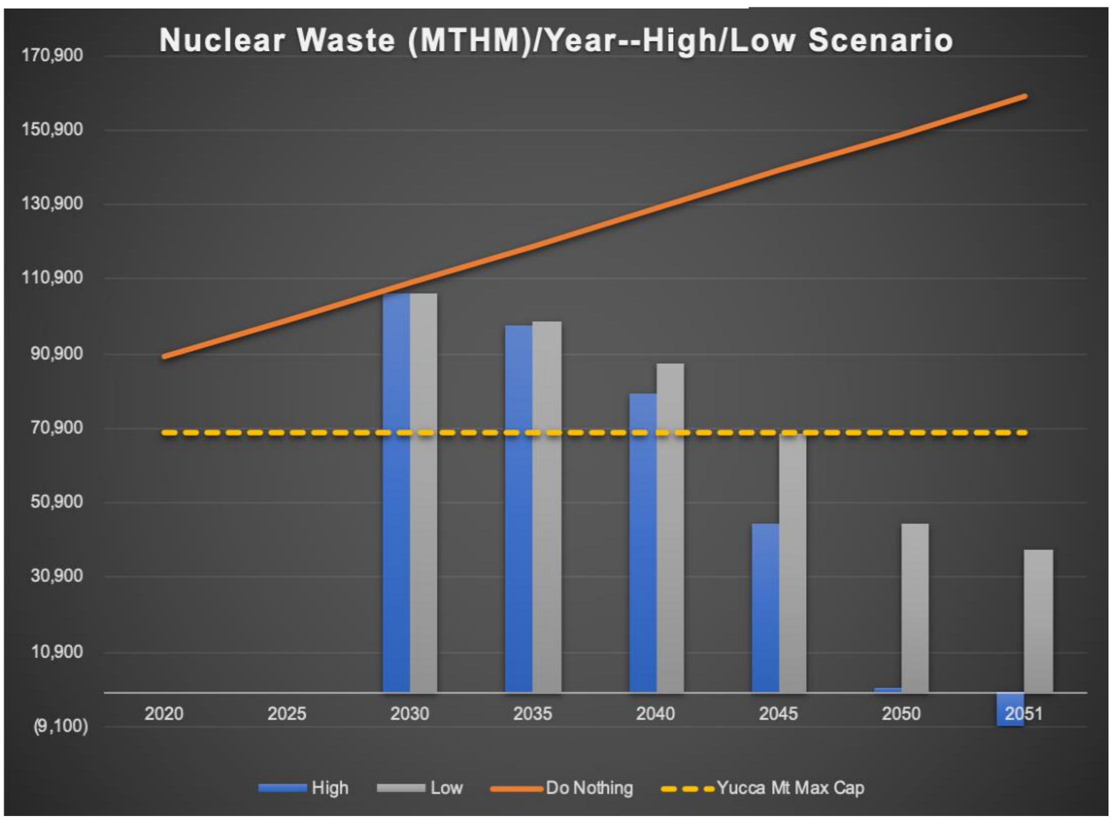
49 (U.S. Energy Information Administration, 2020e)
50 (U.S. Environmental Protection Agency, 2020a)

capacity of 88,324 GW. Under these scenarios, fast reactors would need to be reconfigured to "breed" their own fuel somewhere around 2040 by increasing plutonium conversion through nuclear transmutation, and making fast reactors self-sufficient and arguably renewable

In 2019, coal generated 966 BKWh of electricity.[51] To replace this generating capacity with fast reactors, the U.S. would have to build nearly 354 PRISM reactors which would be possible under a high scenario by 2080 and would require an additional 160,000MTHM which could be produced by existing reactors operating in "breed" mode over several decades.[52] If nuclear absorbed coal's share of electricity generation in today's energy mix, it would encompass around 40 percent of the nation's electricity resource.[53] Figure 5 illustrates results. For detailed data tables and charts see Appendix E.

Figure 5

SNF Inventories in High and Low Scenarios



[51] (U.S. Energy Information Administration, 2020c)
[52] (Blees, 2008)
[53] (U.S. Energy Information Administration, 2020d)

Chapter 4: Discussion & Recommendations

There are clear benefits to recycling spent nuclear fuel in terms of reducing long-term storage demands by time and volume in ways that are achievable with today's technology. Given current inventories of SNF, and no workable solution in sight for long-term storage, pyroprocessing nuclear fuel for clean energy reduces SNF stockpiles by 99 percent while meeting 40 percent of 2020's electricity demand equivalent for at least the next 50 years. Even though the evidence indicates avoided costs of air pollution are modest, there is a significant impact in terms of greenhouse gas emissions and SNF inventories. For Nebraska, recycling its nuclear fuel and that of neighboring states would mean GHG emissions reductions of close to 70 percent in a timeline that could be well ahead the IPCC's plea to reach net-zero carbon emissions by 2050.[54]

Nuclear power, especially the widespread deployment of new technology yet licensed to operate in the U.S. is risky and expensive—by some estimates upwards of $20-$30 billion for the first full-scale ARC.[55] But large scale nuclear is not unprecedented. France, for example, supplies 75 percent of its energy needs with nuclear power and is a net exporter of electricity throughout Europe. Also, France recycles nuclear fuel in a manner almost exactly like the one the U.S. banned in the late 1970s,[56] with none of the fears of nuclear doomsayers realized. On the other hand, Germany's experiment with rapid de-nuclearization in the wake of the Fukushima disaster has yielded a $70 billion increase in costs per year mostly related to "increased mortality risk associated with exposure to the local air pollution emitted when burning fossil fuels. Even the largest estimates of the reduction in the costs associated with nuclear accident risk and waste disposal due to the phase-out are far smaller than 12 billion dollars."[57] Similarly, the financial burden alone from coal-derived air pollution on the U.S. economy is estimated to be around $150 billion.[58]

When compared to the environmental, human, and costs of an as-of-yet inoperable geologic repository estimated at $90 billion in 2009 to $400 billion today,[59] the price for clean nuclear energy becomes reasonable. Regardless of costs, the IPCC urges "rapid, far-reaching

54 (Intergovernmental Panel on Climate Change, 2018)
55 (Archambeau et al., 2011)
56 (World Nuclear Association, 2018)
57 (Jarvis, Deschenes, & Jha, 2019)
58 (Clemmer et al., 2018; Tschofen, Azevedo, & Muller, 2019; U.S. Energy Information Administration, 2020b)
59 (Conca, 2019; U.S. Government Accountability Office, 2009)

and unprecedented changes in all aspects of society"[60] if we are to avert significant challenges to worldwide sustainable development. Even those who do not outright support nuclear as it exists today, lament the decline of such a huge source of clean power as a threat to sustainability.[61] In truth, nuclear power is not an environmental silver bullet. It is best used for reliable baseload power which may be called upon for demand peaking, but not preferably, leaving gas-turbine and possibly battery storage as better resources. Renewables and battery storage have an important role in any future energy discussion, but their limitations must be acknowledged and balanced with the clear benefits of recycling nuclear fuel.

In the U.S., renewable energy technologies, particularly wind and solar, are expected to be the fastest growing source of electricity for the next 30 years, according to the EIA.[62] Despite the growing popularity and market penetration of renewable energy, its inherent intermittency, regional and unit output variability, and footprint requirements stress utilities and compete with land use resources which limit their overall feasibility. For example, the Southwest Power Pool (SPP), the energy grid and wholesale power manager for the central U.S., (including Nebraska) indicates that,

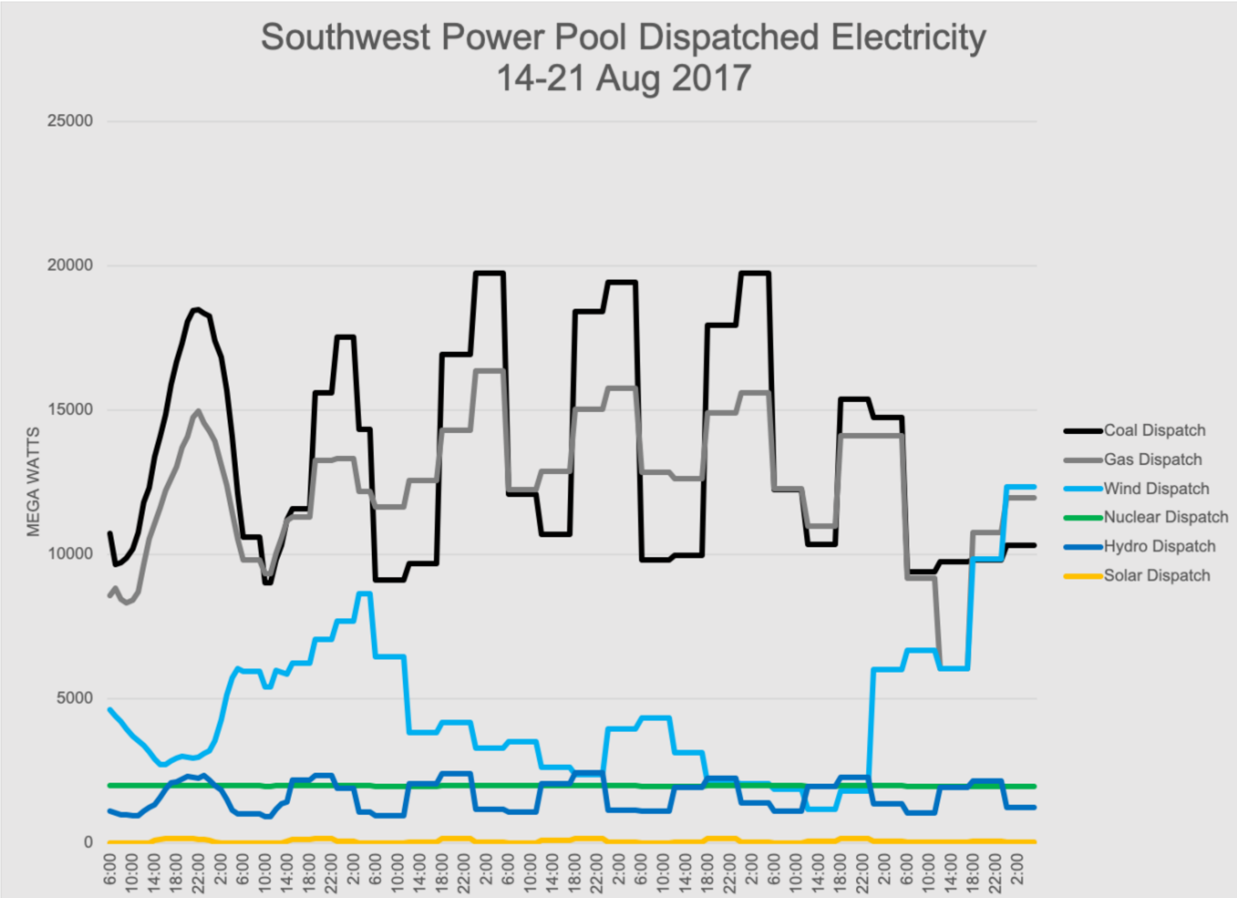
> Wind integration brings low-cost generation to the SPP region but does not count for much accredited capacity. The increasing magnitude of wind capacity additions since 2007, along with the concentration, volatility, and timeliness of wind, can create challenges for grid operators with regard to managing transmission congestion and resolution of ramping constraints (which began being reflected in scarcity pricing in May 2017) as well as challenges for short- and long-run reliability.[63]

Wind power's volatility is best appreciated in Figure 6. This graph shows the SPP's dispatched electricity over a week in August 2017.[64] As SPP's data demonstrates, wind peaked at providing 8600MW of electricity during the first two days of the week, then dropped to just over 2,400 MW only to peak again later that week by generating over 12,000 MW of electricity. Meanwhile, nuclear operated steadily along at its maximum capacity over that same period. Also, the limit of solar energy is clear as its dispatched electricity climbed and fell with the rise and setting of the sun.

60 (Intergovernmental Panel on Climate Change, 2018)
61 (Clemmer et al., 2018)
62 (U.S. Energy Information Administration; Office of Energy Analysis, 2020)
63 (Southwest Power Pool, 2019)
64 (Southwest Power Pool, 2017)

Figure 6

Southwest Power Pool's Dispatched Electricity, Aug. 2017

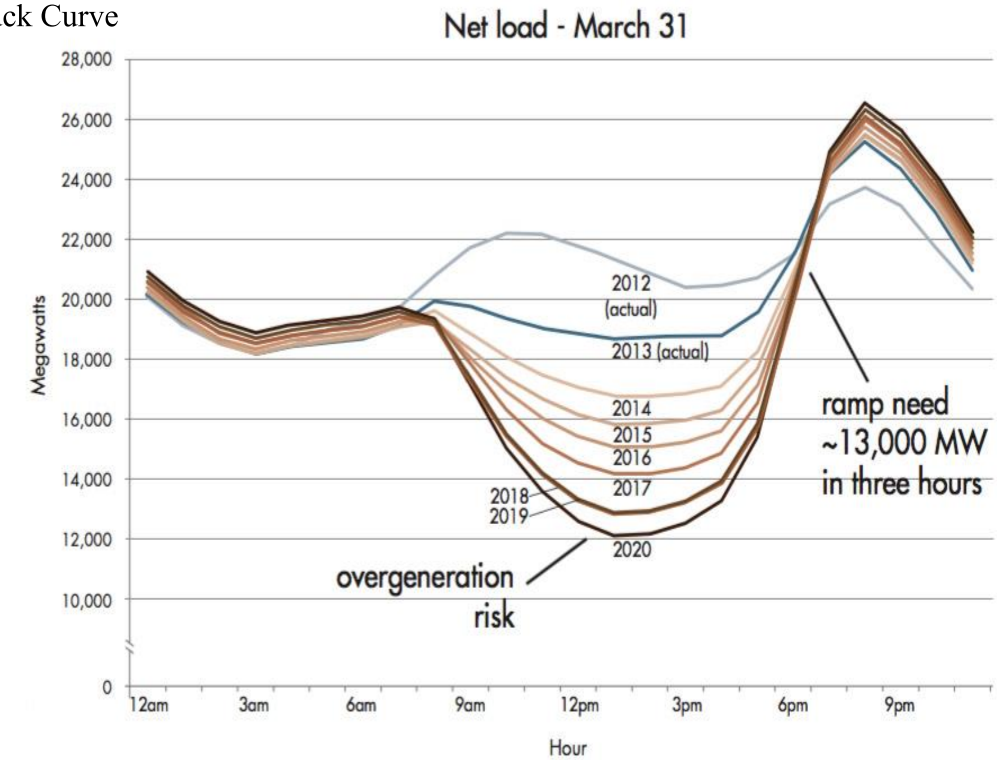


Source: Southwest Power Pool, 2017

Solar variability can often lead to times of over-generation at the height of the day, and the need to compensate grid supply when the sun sets. The daily and seasonal variability of supply is evident when analyzing grid load charts reflecting the "duck curve" of demand and over-supply, as in Figure 7. This chart illustrates demand decreasing at around eight in the morning corresponding with the start of the workday, and a steady increase beginning roughly at three in the afternoon and increasing into the evening hours reflecting demand as most people return home. For solar power, daylight hours are when its generation would be expected to peak—just as demand decreases, risking overgeneration.

Figure 7

Duck Curve



Source: Department of Energy, 2017

Utility-scale renewable projects have an additional drawback in terms of their required land-area footprint, and have given rise to concerns over what is termed "energy sprawl." [65] Renewable's footprint is evident from a comparison of land-area requirements seen in Appendix C, Figure 8. In this case, the generation capacity of one 45 acre ARC (90 percent capacity factor) would be the equivalent of 2,333wind turbines (36 percent capacity factor) on 3,500 acres, and about 13 thousand football fields worth of solar panels. With capacity factors in mind,

[65] (The Nature Conservancy, 2020)

nuclear energy's density per square foot is advantageous over renewables, particularly in areas of high urban density, or where competing demands for agriculture, wildlife, and recreation must be considered. Taking this into account allows us to approach atomic energy from a different perspective that is not strictly financial or biased strictly towards renewables.

Notwithstanding the uncertainties of costs, advances in green energy, and fears of nuclear power, it is evident that thousands of tons of spent nuclear fuel cannot continue to accrue indefinitely without a sustainable solution. Because nuclear power is inextricably tied with national energy policy, and federal and state regulations, the first step that must be made is to send a strong demand signal at the local and state level to the federal government on the urgent need to commercialize advanced reactors, and nuclear fuel recycling technology. The Advanced Nuclear Technology Development Act of 2017 is a step in the right direction. The bill requires the DOE and the Nuclear Regulatory Commission (NRC) to support private industry's commercialization of advanced reactor technology by developing a regulatory and licensing framework to "expedite and streamline the licensing process for advanced reactors" and ensure DOE has "sufficient technical expertise to support the civilian nuclear industry's timely development and commercial deployment of safe, innovative advanced reactor technology."[66]

The State of Nebraska could be proactive and assist local utilities with infrastructure and regulatory pathways towards being the first to introduce advanced reactor technology. Furthermore, Nebraska should leverage key advantages to the deployment of fast reactors and nuclear recycling. The state's large rural areas provide ample acreage in which to build an ARC-type facility with fewer regulatory hurdles. It also has an ample pool of renewable energy, namely wind, that could be integrated into a larger state-wide "green energy grid," and has manageable mid-sized cities with modest power demands that could serve as testbeds for small modular reactors. Omaha, in particular, is an excellent candidate to field such reactors because it already has a sizable cadre of naval nuclear engineers resident at U.S. Strategic Command. These Navy professionals, along with Air Force nuclear safety and technology experts, could form the core of a capable workforce familiar with nuclear energy operations and policy. There is also a body of corporate knowledge resident in former employees of Fort Calhoun Station whose experience and skills should not be ignored. Because Nebraska would be the first to dispose of its nuclear fuel, and that of its neighbors, it should be able to access a fair portion of

[66] (Latta, 2017)

state contributions available in the $20 billion Nuclear Waste Fund to invest through state universities in advanced Science, Technology, Engineering, and Math (STEM) education and vocational training and certification. In doing so, Nebraska could establish itself as a leader in nuclear engineering and recycling technology with a sustainable workforce to support what could likely be the first of many regional centers for clean energy generation. Omaha's local utility, OPPD, is progressively-minded and seeking out new technologies to reach net-neutral operations by 2050. Additionally, they would provide a local venue for job growth and innovation.

Furthermore, corporate tech-giants such as Google, Facebook, and PayPal, which have large, power-hungry data storage facilities in the Omaha area, should demand at the federal level, a greater source of reliable clean energy that is consistent with their corporate sustainability goals. In doing so, Nebraska and particularly OPPD would encourage other states and utilities to take a bold approach at reaching net-zero by 2050, if not before. Finally, imposing a carbon tax and extending financial incentives and credits to all clean energy providers at the federal and state level would go a long way towards making nuclear fuel recycling and advanced nuclear less risky. A carbon tax would penalize carbon emitters' outsized role in the external health and environmental costs of polluting technologies and promote all forms of carbon-free energy on a "level playing field."[67]

[67] (Poneman, 2019)

Chapter 5: Conclusion

The data presented above indicate a discernable benefit to recycling nuclear fuel. At the local level, utilities can take advantage of innovations in nuclear energy and lean forward in providing customers clean and reliable electricity by replacing aging and polluting coal plants with fast reactors. The added benefit, of course to states and the nation are cleaner air, a likely lower financial burden from healthcare costs, and a manageable path to dealing with the nation's growing spent nuclear fuel inventory. The scale of nationwide deployment is certainly daunting, but it would appear that local utilities and states can do much at their level to promote and demand access to nuclear technology. For its part, the federal government should do even more to accelerate advanced reactor technology and enable SNF recycling with the appropriate safeguards. Fast reactors and pyroprocessing are backed with decades of U.S. funded research into safety, counterproliferation, and waste management that should not be cast aside, but embraced as we head into an uncertain future.

Even admitted skeptics and environmentalists are now rethinking nuclear. The Ecomodernists Manifesto, a declaration of environmental values penned in 2015 by 18 academics, scientists, and citizen-activists, declares, "Nuclear fission today represents the only present-day zero-carbon technology with the demonstrated ability to meet most, if not all, of the energy demands of a modern economy."[68] Spent nuclear fuel is a carbon-free resource that is energy-dense and should be thought of as a national resource. Considerable investment has been made over the decades to secure this resource and is readily available to extract its potential for generating cleaner electricity. However, perhaps the most important aspect is that recycling nuclear fuel removes the uncertainty of storing hazardous radioactive material in geologic repository while maintaining its integrity for hundreds of thousands of years. As a means to reestablish American nuclear leadership, pyroprocessing provides the way to channel those resources into fuel for advanced fast reactors while turning large inventories of spent nuclear fuel from a generational liability to a source of sustainable energy perhaps for centuries to come.

[68] (Asafu-Adjaye et al., n.d.)

Appendix A: History Of Yucca Mountain[69]

Two federal agencies—the Nuclear Regulatory Commission (NRC) and department of energy (DOE)—are primarily responsible for the regulation and disposal of the nation's spent nuclear fuel and high-level radioactive waste. The Nuclear Waste Policy Act of 1982 directed DOE to investigate candidate sites for disposing of spent nuclear fuel and high-level radioactive waste. It also directed the President to consider whether a separate disposal facility would be required for the defense-related nuclear waste. Since then, several decisions have affected U.S. disposal plans.

- In 1985, President Reagan found that there was no basis to conclude that a separate defense—only waste repository was required. A DOE evaluation concluded that cost efficiency favored a commingled repository.
- In 1987, Congress amended the Nuclear Waste Policy Act of 1982, directing DOE to investigate only Yucca Mountain for a national repository.
- In 2008, DOE submitted a license application to NRC for authorization to construct a permanent geological repository at Yucca Mountain.
- In 2010, DOE terminated its licensing efforts at Yucca Mountain, stating that a geologic repository at Yucca Mountain is not a workable option.
- In 2013, DOE announced a new strategy for disposing of spent nuclear fuel and high-level radioactive waste. This included temporarily storing waste at centralized locations and then commingling commercial and defense waste in a single repository—to be operational by 2048—at a site other than Yucca Mountain. DOE recommended creating a separate waste management organization to use a phased, adaptive, consent-based approach to siting and developing the new repository.
- Also in 2013, in response to a lawsuit brought against NRC for suspending its license review in 2011, a federal appeals court ordered NRC to resume the Yucca Mountain licensing process.
- In 2015, having used available funding, NRC reported that DOE's license application for Yucca Mountain generally satisfied nearly all of NRC's regulations. NRC must still review and rule on challenges submitted by parties admitted to the licensing process, but this effort could take several years and cost NRC an additional $330 million, according to NRC.
- In 2015, President Obama found that a separate repository for defense-related radioactive waste was required. DOE reported that defense waste is smaller in volume, less radioactive, and thermally cooler than commercial spent nuclear fuel, stating that a defense repository may be easier to develop. After the finding, DOE announced plans to build two repositories, one for most of the nation's defense-related radioactive waste and another for commercial spent nuclear fuel and residual defense waste.
- In 2016, the National Defense Authorization Act for Fiscal Year 2017 denied funds for a defense-only repository.
- In 2017, President Trump's fiscal year 2018 budget request included $120 million for the resumption of the license review for the repository at Yucca Mountain and for interim storage of nuclear waste, which reflected a change in policy and effectively terminated

[69] (U.S. Government Accountability Office, 2020)

DOE's plans to build a separate defense waste repository. According to DOE, Congress did not provide this funding.

- In 2018, President Trump's fiscal year 2019 budget request included $120 million for the resumption of the license review for the repository at Yucca Mountain and for interim storage of nuclear waste. As of February 2019, Congress has not directed funding for the license application to resume.

Since DOE terminated its licensing efforts at Yucca Mountain in 2010, there has been no consensus between the Administration and the Congress on a path forward for managing commercial or defense nuclear waste. However, two independent entities have recently submitted license applications to the NRC for the consolidated interim storage of spent nuclear fuel—one located in Texas and one in New Mexico—a process which may take several years

Appendix B: EBR-II Passive Safety Test And Fast Reactor Safety

On April 3rd, 1986, a 20Mw sodium-cooled fast nuclear reactor in Idaho operating at 100% capacity suffered a catastrophic power system failure known as a loss-of-flow event.[70] The primary and secondary pumps which force coolant through the reactor core shutdown, all automatic emergency backup systems failed to respond, and a manual "scram" shutdown—the last line of defense against a core meltdown—was not initiated. Within 40 seconds the core's temperature rose from around 900°F to just under 1300°F, and then the core's temperature began to creep lower and lower as the reactor powered itself down to its normal operating temperature. Hours later, the reactor's intermediate pump, which circulates the hot liquid sodium coolant away from the core, stopped working in what is known as a loss-of- heat-sink. The same malfunction had occurred at Three Mile Island in 1979 leading to a core meltdown. As coolant and core temperature increased, the reactor's automatic and manual emergency systems again failed to engage in an effort to stop the runaway event. However, within minutes the core's temperature rose to the point where the reactor ramped itself back down to normal operating temperatures and power.[71] What would have been a nuclear disaster was averted.

These seemingly calamitous events were not a result of operator negligence or faulty safety systems. Rather, they were part of a controlled safety demonstration carried out by Argonne National Laboratory on the Experimental Breeder Reactor-II (EBR-II) located at the then Argonne-West facility in Idaho. These tests were intended to showcase the passive safety characteristics of an advanced Sodium-Cooled Fast Reactor (SFR) design, and exercised two of the worst kinds of incidents that can befall any nuclear facility: loss-of-flow due to a station power blackout, and loss-of-heat-sink. If these events had occurred in thermal reactors of the time they would have resulted in power and temperature increases leading to cooling water evaporation and a reactor core meltdown.[72] Just three weeks later, on April 26th, a Soviet RBMK reactor underwent a real-world loss-of-flow event. The resulting explosion and fire at the Chernobyl nuclear power plant in Ukraine resulted in the loss of 30 lives and released high doses of radiation throughout Europe.[73] A sodium-cooled fast reactor has several key design features

[70] (Argonne National Laboratory, 2002)
[71] (Bishop, 1986; Sackett, 1997; Till & Chang, 2011)
[72] (Hore-Lacy, 2018; Till & Chang, 2011)
[73] (World Nuclear Association, 2020)

that enable this passive safety, namely “the liquid sodium coolant, pool-type coolant system, and its metal alloy fuel.”[74] Walt Deitrich, from ANL details:

> The sodium coolant is a highly efficient heat-transfer material and has the additional advantage of operating at normal atmospheric pressure. In the typical commercial reactor, the water coolant must be pressurized at 100-150 times normal to keep it from boiling away. But sodium can cool the core at normal pressure, because its boiling point is 300-400 degrees Celsius (575-750 degrees Fahrenheit) higher than the core's operating temperature.
>
> …"the sodium pool eliminates the possibility of the coolant boiling away during an accident and leaving the core uncovered, which is one of the more serious potential trouble spots in a light-water reactor. By submerging the core in thousands of gallons of liquid sodium, you provide the reactor with an immense heat sink that adds greatly to its safety. If the reactor starts to overheat, the pool can absorb vast amounts of heat and never approach its boiling point."
>
> …the pool design…passively removes decay heat if the normal heat-removal systems fail. "When a reactor shuts down," he explains, "it continues to produce heat, because the core contains a large inventory of radioactive material that releases energy as it decays. …natural convection in the sodium pool can transport the decay heat to downstream systems. All of this can be done passively, without need for active systems or components."
>
> Sodium also increases the reliability and long life of components, partly because it does not corrode common structural materials, such as stainless steel. "Our experience in decommissioning EBR-II," says John Sackett, Argonne's deputy associate laboratory director for Argonne-West, "shows that materials and components in the core can operate in liquid sodium without significant damage or corrosion. We removed components from the sodium pool after 30 years and found them just as shiny as the day they went in. We saw original marks that welders and other craftsmen had made 30 years earlier when they created the component."
>
> Other sodium properties also enhance reactor safety and reliability. For example, sodium is chemically compatible with the metal fuel. This makes small failures in the cladding, the stainless-steel tubes that encase the fuel, far less likely to grow. In addition, sodium tends to bind chemically with several important radioactive fission products, which reduces radioactive releases if fuel fails. Although sodium can be dangerous if allowed direct contact with air or water, with appropriate care, it makes a nearly ideal coolant. "Properly handled, as we did for 30 years at EBR-II, sodium offers significant advantages over water as a coolant…"
>
> The third leg of AFR safety is its metallic fuel — an alloy of uranium and other metals. Metal fuel provides inherent, "reactivity feedback" mechanisms that alter a reactor's power when its core temperature changes. The primary feedback in a metal-fuel reactor

[74] (Argonne National Laboratory, 2002)

comes from thermal expansion of fuel, sodium and steel around the core. Simply put, when the core temperature increases, the fuel, sodium and the stainless steel components in the core expand, and that tends to shut down the reactor.

"When the fuel expands…the distances between the fissile nuclei increase. This slows the chain reaction, because the neutrons necessary to drive it strike fewer fissile nuclei." Radial expansion of the core also limits reactor power. "Normally…the sodium and steel around the core reflect neutrons back into the core to help maintain the chain reaction. But when sodium and steel expand, more neutrons escape from the core and are unavailable to drive the reaction."

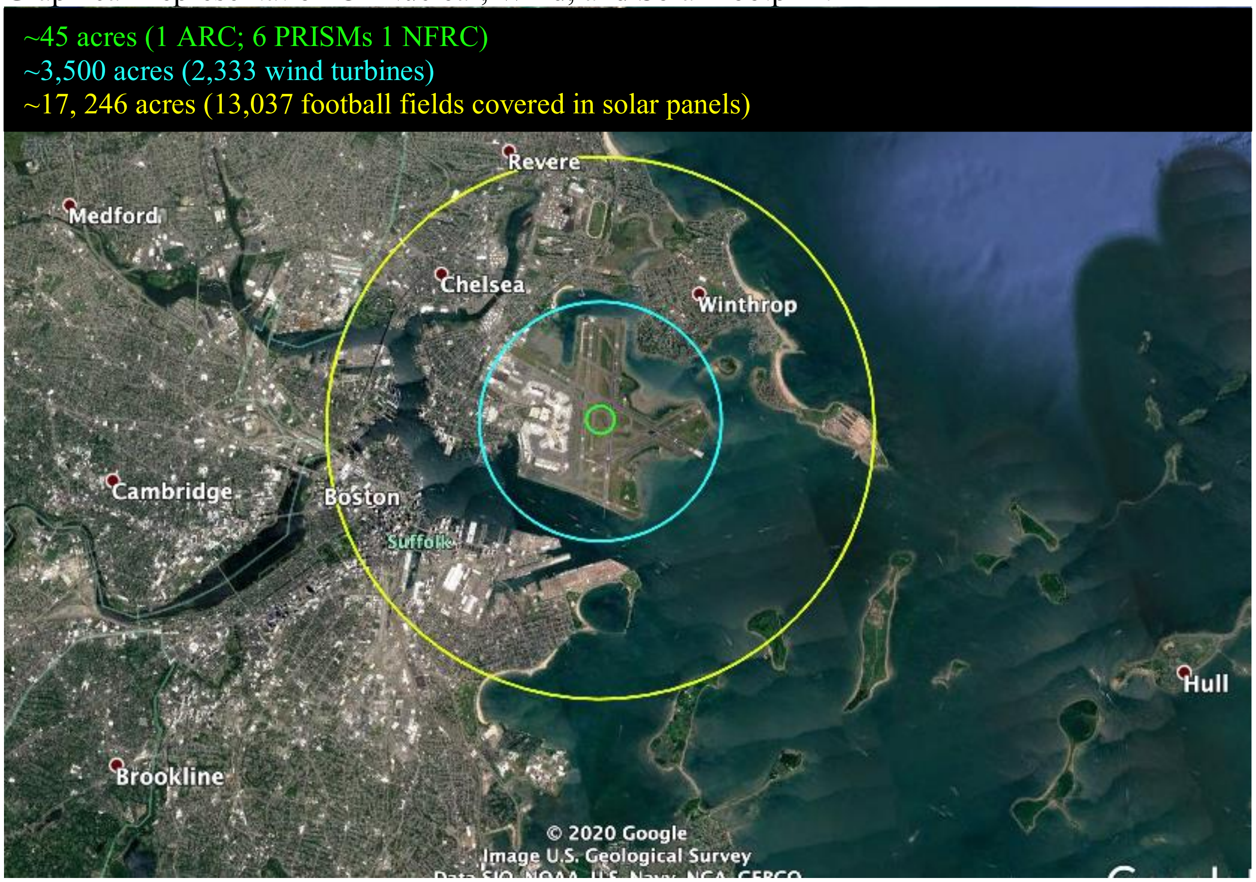
The safety bottom line for the AFR is that all these natural feedback mechanisms tend to maintain coolant temperature near its normal 500 degrees C (930 degrees F) operating value — well below sodium's 900 C (1,650 F) boiling point — even when the reactor loses its engineered cooling systems. If an AFR started to overheat, the natural properties inherent in its materials and design would step in to shut it down without the intervention of human operators or specially engineered safety systems.[75]

[75] (Argonne National Laboratory, 2002)

Appendix C: Graphical Representation Of Nuclear, Wind, and Solar Footprint

Figure 8

Graphical Representation Of Nuclear, Wind, and Solar Footprint



Note: ARC Capacity factor 90%, 1,679.4MW/45 acres; Wind Turbines capacity factor 36%, ~2MW/1.5 acres; 1,287,336 kWh annual electricity generated by one football field covered with solar PV.

Appendix D: Table 2; State SNF Inventories and NWF Contributions

Table 2

State SNF Inventories and NWF Contributions

State	MT Uranium (as of 12/31/2019)	Nuclear Waste Fund Contributions in millions of Dollars (as of 9/30/2016)
Alabama	4,039	962
Arizona	2,650	697
Arkansas	1,623	375
California	3,383	977
Colorado	25	0
Connecticut	2,349	468
Florida	3,528	904
Georgia	3,304	862
Idaho	153	0
Illinois	10,641	2,307
Iowa	619	141
Kansas	849	229
Louisiana	1,661	412
Maine	541	69
Maryland	1,534	433
Massachusetts	860	191
Michigan	3,234	844
Minnesota	1,486	457
Mississippi	1,046	254
Missouri	887	248
Nebraska	1,020	305
New Hampshire	703	202
New Jersey	3,232	783
New York	4,381	1,028
North Carolina	4,346	1,051
Ohio	1,481	386
Oregon	359	80
Pennsylvania	7,734	1,977
South Carolina	4,948	1,524
Tennessee	2,275	605
Texas	2,957	815
Vermont	698	121
Virginia	3,073	853
Washington	816	202
Wisconsin	1,543	424

Source: (Nuclear Energy Institute, 2020)

Appendix E: Data Tables and Charts

Table 3

Low PRISM Deployment Scenario

	Year Spacing	MTHM/PRISM (Year 1 only)	MTHM/PRISM (annual)	MTHM Inventory	DU		*.05 waste fission product		
	10	500	50	110000	300000				
	Year (in Service)	New PRISM/Out of Service	No PRISM	MTHM Consumed/yr	Total MTHM Consumed	MTHM Remaining	Waste Fission Products MTHM	Mwe	
2030	0	6	6	3000	3000	107000	150	1866	1866
	1	2	8	1300	4300	105700	65	622	2488
	2	2	10	1400	5700	104300	70	622	3110
	3	2	12	1500	7200	102800	75	622	3732
	4	2	14	1600	8800	101200	80	622	4354
2035	5	2	16	1700	10500	99500		622	4976
	6	2	18	1800	12300	97700		622	5598
	7	2	20	1900	14200	95800		622	6220
	8	2	22	2000	16200	93800	100	622	6842
	9	2	24	2100	18300	91700		622	7464
2040	10	2	26	2200	20500	89500		622	8086
	11	4	30	3300	23800	86200		1244	9330
	12	4	34	3500	27300	82700	175	1244	10574
	13	4	38	3700	31000	79000		1244	11818
	14	4	42	3900	34900	75100		1244	13062
2045	15	4	46	4100	39000	71000		1244	14306
	16	4	50	4300	43300	66700	215	1244	15550
	17	4	54	4500	47800	62200		1244	16794
	18	4	58	4700	52500	57500		1244	18038
	19	4	62	4900	57400	52600		1244	19282
2050	20	4	66	5100	62500	47500	255	1244	20526

Table 4

High PRISM Deployment Scenario

	Year Spacing	MTHM/PRISM (Year 1 only)	MTHM/PRISM (annual)	MTHM Inventory	DU		*.05 waste fission products		
	5	500	50	110000	300000				
	Year (in Service)	New PRISM/Out of Service	No PRISM	MTHM Consumed/yr	Total MTHM Consumed	MTHM Remaining	Waste Fission Products MTHM	Mwe	
2030	0	6	6	3000	3000	107000	150	1866	1866
	1	2	8	1300	4300	105700	65	622	2488
	2	2	10	1400	5700	104300	70	622	3110
	3	2	12	1500	7200	102800	75	622	3732
	4	2	14	1600	8800	101200	80	622	4354
2035	5	2	16	1700	10500	99500		622	4976
	6	4	20	2800	13300	96700		1244	6220
	7	4	24	3000	16300	93700		1244	7464
	8	4	28	3200	19500	90500	160	1244	8708
	9	4	32	3400	22900	87100		1244	9952
2040	10	4	36	3600	26500	83500		1244	11196
	11	8	44	5800	32300	77700		2488	13684
	12	8	52	6200	38500	71500	310	2488	16172
	13	8	60	6600	45100	64900		2488	18660
	14	8	68	7000	52100	57900		2488	21148
2045	15	8	76	7400	59500	50500		2488	23636
	16	8	84	7800	67300	42700	390	2488	26124
	17	8	92	8200	75500	34500		2488	28612
	18	8	100	8600	84100	25900		2488	31100
	19	8	108	9000	93100	16900		2488	33588
2050	20	8	116	9400	102500	7500	470	2488	36076

Table 5

Co-benefit Assessment to OPPD Service Area assessed at 3% Discount Rate

FIPS	State	County	Base PM 2.5	Control PM 2.5	Delta PM 2.5	$ Total Health Benefits (low estimate)	$ Total Health Benefits (high estimate)	Mortality (low estimate)	$ Mortality (low estimate)	Mortality (high estimate)
19155	Iowa	Pottawattamie	6.29	6.27	0.02	$1,051,846.10	$2,363,931.58	0.09	$1,035,208.90	0.21
31055	Nebraska	Douglas	6.26	6.24	0.02	$4,107,239.33	$9,234,472.46	0.36	$4,023,858.72	0.81
31131	Nebraska	Otoe	6.11	5.97	0.13	$1,785,425.56	$4,017,199.71	0.16	$1,768,832.48	0.35
31153	Nebraska	Sarpy	6.29	6.26	0.02	$2,144,794.69	$4,812,288.57	0.19	$2,101,633.58	0.42

$ Mortality (high estimate)	Infant Mortality	$ Infant Mortality	Nonfatal Heart Attacks (low estimate)	$ Nonfatal Heart Attacks (low estimate)	Nonfatal Heart Attacks (high estimate)	$ Nonfatal Heart Attacks (high estimate)	Hospital Admits, All Respiratory
$2,338,144.41	0.00	7175.77	0.01	1103.70	0.06	10253.66	0.02
$9,107,632.18	0.00	32389.55	0.03	5242.12	0.30	48701.78	0.07
$3,984,583.00	0.00	4207.56	0.01	1935.52	0.12	17959.16	0.03
$4,744,177.62	0.00	15308.38	0.02	3009.69	0.17	27959.53	0.04

Hospital Admits All Respiratory Direct	Hospital Admits, Asthma	Hospital Admits, Chronic Lung Disease	$ Hospital Admits, All Respiratory	Hospital Admits, Cardiovascular (except heart attacks)	$ Hospital Admits, Cardiovascular (except heart attacks)	Acute Bronchitis	$ Acute Bronchitis
0.01	0.00	0.00	703.73	0.02	841.25	0.13	82.03
0.05	0.01	0.01	2415.25	0.06	2993.76	0.74	461.76
0.03	0.00	0.00	1252.84	0.02	1167.92	0.15	92.78
0.03	0.00	0.01	1373.31	0.03	1704.51	0.40	251.87

Upper Respiratory Symptoms	$ Upper Respiratory Symptoms	Lower Respiratory Symptoms	$ Lower Respiratory Symptoms	Emergency Room Visits, Asthma	$ Emergency Room Visits, Asthma	Minor Restricted Activity Days	$ Minor Restricted Activity Days	Work Loss Days	$ Work Loss Days	Asthma Exacerbation	$ Asthma Exacerbation
2.38	102.86	1.67	45.67	0.03	18.70	52.11	4623.72	8.82	1765.12	2.33	174.65
13.36	577.80	9.40	256.86	0.09	48.53	309.07	27421.94	52.83	10576.72	13.27	996.34
2.70	116.90	1.89	51.73	0.02	10.21	62.04	5504.33	10.26	2054.29	2.65	198.99
7.29	315.36	5.13	140.14	0.05	26.13	166.86	14804.67	28.41	5687.99	7.18	539.06

Note: Includes Walter Scott Jr. Energy Center, Pottawattamie County, Iowa

Table 6

Co-benefit Assessment to OPPD Service Area assessed at 7% Discount Rate

FIPS	State	County	Base PM 2.5	Control PM 2.5	Delta PM 2.5	$ Total Health Benefits (low estimate)	$ Total Health Benefits (high estimate)	Mortality (low estimate)	$ Mortality (low estimate)	Mortality (high estimate)
19155	Iowa	Pottawattamie	6.29	6.27	0.02	$938,652.38	$2,108,066.48	0.09	922044.10	0.21
31055	Nebraska	Douglas	6.26	6.24	0.02	$3,667,219.87	$8,237,491.24	0.36	3583986.94	0.81
31131	Nebraska	Otoe	6.11	5.97	0.13	$1,592,015.14	$3,581,167.79	0.16	1575470.95	0.35
31153	Nebraska	Sarpy	6.29	6.26	0.02	$1,914,966.98	$4,292,878.14	0.19	1871891.60	0.42

$ Mortality (high estimate)	Infant Mortality	$ Infant Mortality	Nonfatal Heart Attacks (low estimate)	$ Nonfatal Heart Attacks (low estimate)	Nonfatal Heart Attacks (high estimate)	$ Nonfatal Heart Attacks (high estimate)	Hospital Admits, All Respiratory
2082548.03	0.00	7175.77	0.01	1074.78	0.06	9984.95	0.02
8112023.09	0.00	32389.55	0.03	5094.42	0.30	47329.65	0.07
3549004.68	0.00	4207.56	0.01	1886.63	0.12	17505.55	0.03
4225563.53	0.00	15308.38	0.02	2923.97	0.17	27163.20	0.04

Hospital Admits All Respiratory Direct	Hospital Admits, Asthma	Hospital Admits, Chronic Lung Disease	$ Hospital Admits, All Respiratory	Hospital Admits, Cardiovascular (except heart attacks)	$ Hospital Admits, Cardiovascular (except heart attacks)	Acute Bronchitis
0.01	0.00	0.00	703.73	0.02	841.25	0.13
0.05	0.01	0.01	2415.25	0.06	2993.76	0.74
0.03	0.00	0.00	1252.84	0.02	1167.92	0.15
0.03	0.00	0.01	1373.31	0.03	1704.51	0.40

$ Acute Bronchitis	Upper Respiratory Symptoms	$ Upper Respiratory Symptoms	Lower Respiratory Symptoms	$ Lower Respiratory Symptoms	Emergency Room Visits, Asthma	$ Emergency Room Visits, Asthma	Minor Restricted Activity Days	$ Minor Restricted Activity Days	Work Loss Days	$ Work Loss Days	Asthma Exacerbation	$ Asthma Exacerbation
82.03	2.38	102.86	1.67	45.67	0.03	18.70	52.11	4623.72	8.82	1765.12	2.33	174.65
461.76	13.36	577.80	9.40	256.86	0.09	48.53	309.07	27421.94	52.83	10576.72	13.27	996.34
92.78	2.70	116.90	1.89	51.73	0.02	10.21	62.04	5504.33	10.26	2054.29	2.65	198.99
251.87	7.29	315.36	5.13	140.14	0.05	26.13	166.86	14804.67	28.41	5687.99	7.18	539.06

Note: Includes Walter Scott Jr. Energy Center, Pottawattamie County, Iowa

Table 7 and 8[76]

[76] Data Table 7 and 8 can be found at the following link: https://drive.google.com/file/d/1d1n64UFPU7fxKdlhzqUUWwodvC3qBbDK/view?usp=sharing

Table 9

2017 National Emissions Inventory for Coal-Generating Powerplants in Nebraska (April 2020 Release)

state	county	company name	site name	naics description	pollutant code	total emissions	emissions
IA	Pottawattamie	MIDAMERICAN ENERGY COMPANY	WALTER SCOTT JR ENERGY CTR	Fossil Fuel Electric Power Generation	NH3	7.292134	TON
IA	Pottawattamie	MIDAMERICAN ENERGY COMPANY	WALTER SCOTT JR ENERGY CTR	Fossil Fuel Electric Power Generation	NOX	6468.05573	TON
IA	Pottawattamie	MIDAMERICAN ENERGY COMPANY	WALTER SCOTT JR ENERGY CTR	Fossil Fuel Electric Power Generation	PM25-PRI	268.255239	TON
IA	Pottawattamie	MIDAMERICAN ENERGY COMPANY	WALTER SCOTT JR ENERGY CTR	Fossil Fuel Electric Power Generation	SO2	9753.02466	TON
IA	Pottawattamie	MIDAMERICAN ENERGY COMPANY	WALTER SCOTT JR ENERGY CTR	Fossil Fuel Electric Power Generation	VOC	94.3826041	TON
NE	Otoe	Na	Nebraska City Power Plant No 1	Fossil Fuel Electric Power Generation	NOX	6.09	TON
NE	Otoe	Na	Nebraska City Power Plant No 1	Fossil Fuel Electric Power Generation	PM25-PRI	0.67401216	TON
NE	Otoe	Na	Nebraska City Power Plant No 1	Fossil Fuel Electric Power Generation	SO2	0.2400001	TON
NE	Otoe	Na	Nebraska City Power Plant No 1	Fossil Fuel Electric Power Generation	VOC	0.48	TON
NE	Otoe	Na	Nebraska City Power Plant No 2	Fossil Fuel Electric Power Generation	NOX	0.5271	TON
NE	Otoe	Na	Nebraska City Power Plant No 2	Fossil Fuel Electric Power Generation	PM25-PRI	0.0477621	TON
NE	Otoe	Na	Nebraska City Power Plant No 2	Fossil Fuel Electric Power Generation	SO2	0.0000001	TON
NE	Otoe	Na	Nebraska City Power Plant No 2	Fossil Fuel Electric Power Generation	VOC	0.03	TON
NE	Lancaster	Nebraska Public Power District	NPPD Sheldon Station	Fossil Fuel Electric Power Generation	NH3	0.4917831	TON
NE	Lancaster	Nebraska Public Power District	NPPD Sheldon Station	Fossil Fuel Electric Power Generation	NOX	1399.2	TON
NE	Lancaster	Nebraska Public Power District	NPPD Sheldon Station	Fossil Fuel Electric Power Generation	PM25-PRI	2.5368449	TON
NE	Lancaster	Nebraska Public Power District	NPPD Sheldon Station	Fossil Fuel Electric Power Generation	SO2	1960.9	TON
NE	Lancaster	Nebraska Public Power District	NPPD Sheldon Station	Fossil Fuel Electric Power Generation	VOC	26.29481	TON
NE	Lancaster	Lincoln Electric System	LES Rokeby Generating Station	Fossil Fuel Electric Power Generation	NH3	2.47142555	TON
NE	Lancaster	Lincoln Electric System	LES Rokeby Generating Station	Fossil Fuel Electric Power Generation	NOX	30.096	TON
NE	Lancaster	Lincoln Electric System	LES Rokeby Generating Station	Fossil Fuel Electric Power Generation	PM25-PRI	0.0335	TON
NE	Lancaster	Lincoln Electric System	LES Rokeby Generating Station	Fossil Fuel Electric Power Generation	SO2	0.351	TON
NE	Lancaster	Lincoln Electric System	LES Rokeby Generating Station	Fossil Fuel Electric Power Generation	VOC	0.327	TON
NE	Hall	Grand Island Utilities Dept	C W Burdick Generating Station	Fossil Fuel Electric Power Generation	NH3	0.0000003	TON
NE	Hall	Grand Island Utilities Dept	C W Burdick Generating Station	Fossil Fuel Electric Power Generation	NOX	2.4100006	TON
NE	Hall	Grand Island Utilities Dept	C W Burdick Generating Station	Fossil Fuel Electric Power Generation	PM25-PRI	0.14560164	TON
NE	Hall	Grand Island Utilities Dept	C W Burdick Generating Station	Fossil Fuel Electric Power Generation	SO2	0.0500009	TON
NE	Hall	Grand Island Utilities Dept	C W Burdick Generating Station	Fossil Fuel Electric Power Generation	VOC	0.0900008	TON

Note: Includes Walter Scott Jr. Energy Center, Pottawattamie County, Iowa

Table 9 cont.

2017 National Emissions Inventory for Coal-Generating Powerplants in Nebraska (April 2020 Release)

NE	Lancaster	Nebraska Public Power District	NPPD Sheldon Station	Fossil Fuel Electric Power Generation	NH3	0.4917831	TON
NE	Lancaster	Nebraska Public Power District	NPPD Sheldon Station	Fossil Fuel Electric Power Generation	NOX	1399.2	TON
NE	Lancaster	Nebraska Public Power District	NPPD Sheldon Station	Fossil Fuel Electric Power Generation	PM25-PRI	2.5368449	TON
NE	Lancaster	Nebraska Public Power District	NPPD Sheldon Station	Fossil Fuel Electric Power Generation	SO2	1960.9	TON
NE	Lancaster	Nebraska Public Power District	NPPD Sheldon Station	Fossil Fuel Electric Power Generation	VOC	26.29481	TON
NE	Hall	Grand Island Utilities Dept	C W Burdick Generating Station	Fossil Fuel Electric Power Generation	NH3	0.0000003	TON
NE	Hall	Grand Island Utilities Dept	C W Burdick Generating Station	Fossil Fuel Electric Power Generation	NOX	2.4100006	TON
NE	Hall	Grand Island Utilities Dept	C W Burdick Generating Station	Fossil Fuel Electric Power Generation	PM25-PRI	0.14560164	TON
NE	Hall	Grand Island Utilities Dept	C W Burdick Generating Station	Fossil Fuel Electric Power Generation	SO2	0.0500009	TON
NE	Hall	Grand Island Utilities Dept	C W Burdick Generating Station	Fossil Fuel Electric Power Generation	VOC	0.0900008	TON
NE	Douglas	Omaha Public Power District	Omaha Public Power District - North Omaha Power Station	Fossil Fuel Electric Power Generation	NH3	1.1	TON
NE	Douglas	Omaha Public Power District	Omaha Public Power District - North Omaha Power Station	Fossil Fuel Electric Power Generation	NOX	3639.09	TON
NE	Douglas	Omaha Public Power District	Omaha Public Power District - North Omaha Power Station	Fossil Fuel Electric Power Generation	PM25-PRI	74.5059539	TON
NE	Douglas	Omaha Public Power District	Omaha Public Power District - North Omaha Power Station	Fossil Fuel Electric Power Generation	SO2	7896.85	TON
NE	Douglas	Omaha Public Power District	Omaha Public Power District - North Omaha Power Station	Fossil Fuel Electric Power Generation	VOC	36.1	TON
NE	Dodge	City Of Fremont	Lon D Wright Power Plant	Fossil Fuel Electric Power Generation	NH3	0.31	TON
NE	Dodge	City Of Fremont	Lon D Wright Power Plant	Fossil Fuel Electric Power Generation	NOX	879.00229	TON
NE	Dodge	City Of Fremont	Lon D Wright Power Plant	Fossil Fuel Electric Power Generation	PM25-PRI	77.5142151	TON
NE	Dodge	City Of Fremont	Lon D Wright Power Plant	Fossil Fuel Electric Power Generation	SO2	926.23	TON
NE	Dodge	City Of Fremont	Lon D Wright Power Plant	Fossil Fuel Electric Power Generation	VOC	9.5813375	TON
NE	Lincoln	Nebraska Public Power District	NPPD Gerald Gentleman Station	Fossil Fuel Electric Power Generation	NH3	1.74	TON
NE	Lincoln	Nebraska Public Power District	NPPD Gerald Gentleman Station	Fossil Fuel Electric Power Generation	NOX	6892.92	TON
NE	Lincoln	Nebraska Public Power District	NPPD Gerald Gentleman Station	Fossil Fuel Electric Power Generation	PM25-PRI	82.0927693	TON
NE	Lincoln	Nebraska Public Power District	NPPD Gerald Gentleman Station	Fossil Fuel Electric Power Generation	SO2	21254.58	TON
NE	Lincoln	Nebraska Public Power District	NPPD Gerald Gentleman Station	Fossil Fuel Electric Power Generation	VOC	149.38	TON
NE	Adams	City Of Hastings	Whelan Energy Center	Fossil Fuel Electric Power Generation	NH3	0.76	TON
NE	Adams	City Of Hastings	Whelan Energy Center	Fossil Fuel Electric Power Generation	NOX	677.11	TON
NE	Adams	City Of Hastings	Whelan Energy Center	Fossil Fuel Electric Power Generation	PM25-PRI	56.4313827	TON
NE	Adams	City Of Hastings	Whelan Energy Center	Fossil Fuel Electric Power Generation	SO2	2274.11	TON
NE	Adams	City Of Hastings	Whelan Energy Center	Fossil Fuel Electric Power Generation	VOC	27.7893152	TON
NE	Lancaster	Lincoln Electric System	LES Terry Bundy Generating Station	Fossil Fuel Electric Power Generation	NH3	1.47	TON
NE	Lancaster	Lincoln Electric System	LES Terry Bundy Generating Station	Fossil Fuel Electric Power Generation	NOX	39.173	TON
NE	Lancaster	Lincoln Electric System	LES Terry Bundy Generating Station	Fossil Fuel Electric Power Generation	SO2	0.415	TON

Source: (U.S. Environmental Protection Agency, 2020b)

Table 10

Generator Data (Operable Coal Units Only)

Utility Name	Plant Name	State	County	Generator ID	Nameplate Capacity (MW)	Summer Capacity (MW)	Winter Capacity (MW)	Status	Energy Source 1	Energy Source 2	Operating Month	Operating Year
City of Grand Island - (NE)	Platte	NE	Hall	1	109.8	100.0	100.0	OP	SUB		12	1982
City of Hastings - (NE)	Whelan Energy Center	NE	Adams	1	76.3	77.0	77.0	OP	RC		7	1981
City of Hastings - (NE)	Whelan Energy Center	NE	Adams	2	248.0	232.0	232.0	OP	SUB	RC	6	2011
City of Fremont - (NE)	Lon Wright	NE	Dodge	6	16.5	15.5	15.5	OP	SUB	NG	8	1957
City of Fremont - (NE)	Lon Wright	NE	Dodge	7	22.0	21.0	21.0	OP	SUB	NG	8	1963
City of Fremont - (NE)	Lon Wright	NE	Dodge	8	91.5	82.0	82.0	OP	SUB	NG	1	1976
Nebraska Public Power District	Sheldon	NE	Lancaster	1	108.8	104.0	104.0	OP	SUB		1	1961
Nebraska Public Power District	Sheldon	NE	Lancaster	2	119.9	115.0	115.0	OP	SUB		1	1965
Omaha Public Power District	North Omaha	NE	Douglas	4	136.0	120.1	111.8	OP	SUB	NG	3	1963
Omaha Public Power District	North Omaha	NE	Douglas	5	217.6	216.2	174.8	OP	SUB	NG	5	1968
Nebraska Public Power District	Gerald Gentleman	NE	Lincoln	1	681.3	665.0	665.0	OP	SUB		4	1979
Nebraska Public Power District	Gerald Gentleman	NE	Lincoln	2	681.3	700.0	700.0	OP	SUB		1	1982
Omaha Public Power District	Nebraska City	NE	Otoe	1	651.6	654.3	654.3	OP	SUB		4	1979
Omaha Public Power District	Nebraska City	NE	Otoe	2	738.0	691.0	691.0	OP	SUB		5	2009
Archer Daniels Midland Co	Archer Daniels Midland Lincoln	NE	Lancaster	GEN1	7.9	7.9	7.9	OP	SUB		7	1988
Archer Daniels Midland Co	Archer Daniels Midland Columbus	NE	Platte	GEN1	71.4	61.0	61.0	OP	SUB	BIT	5	2010
Western Sugar Cooperative	Western Sugar Coop - Scottsbluff	NE	Scotts Bluff	SCBF	5.0	5.0	5.0	OP	SUB		9	1987

Source: (U.S. Energy Information Administration, 2020g)

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