Nuclear

An Overview of Critical Factors for Energy Resources

Introduction

America generates energy from a number of sources. At its most basic level, each source turns a turbine to generate electricity. That power is then fed into the electrical grid to be distributed to homes and businesses. America consumes 4 trillion kilowatt hours (kWh) of electricity per year. The energy mix to generate this electricity is a blend of public policy and private action. Nuclear power is used to generate 19.7 percent of America's electricity as of 2020.

This policy brief will outline eight key factors that shape the current and future utilization of nuclear power for American energy needs. To help build a comprehensive picture of nuclear's energy outlook, this brief will examine its energy density, costs to generate energy, availability and reserves, land needed, overall safety record, climate impact, long-term impact, and potential limitations of the energy source.

Basics of Nuclear

Nuclear power is derived from the process of nuclear fission, where atoms are split apart into smaller atoms, releasing energy. Nuclear fission utilizes uranium as a fuel source. The uranium is packaged into small pellets inside metal fuel rods. The process of fission produces high amounts of heat, which is applied to water to generate steam, which turns turbines to generate electricity. Commercial energy production using nuclear power began in the United States in 1958 and today accounts for around 20 percent of U.S. electricity generation annually.[1]

Producing electricity from a nuclear power plant requires mining the necessary uranium, milling, converting, and enriching it, transporting it to nuclear power plants, and safely containing, storing, or recycling the spent nuclear fuel. Uranium mining can entail open pit or underground mining, followed by processing and compression of the uranium powder into small fuel pellets, and insertion into fuel rods inside a nuclear power plant.[2] Due to the radioactive nature of the spent fuel, high security and well-defined procedures dictate that the spent fuel and materials in contact with it be disposed of carefully.

Currently, nuclear waste is stored in wet pools and dry cask storage methods.[3] Pools are used on site to cool and allow radioactive decay for a period of time up to five years. The waste material is then packed into concrete and steel containers, which are filled with inert gas and built to withstand natural disasters.[4] These dry casks are secured on site until a permanent, national waste storage location is designated. One such site – Yucca Mountain, Nevada – has been planned for decades, but land-use, environmental, and political controversy has prevented its use.

1. Density

Nuclear fuel is massively energy dense. Depending on the grade of uranium, nuclear fuel contains heat potential of over 34 billion btus/pound (equivalent to over 10 million kWh/pound).[5,6,7] This high energy density means that a minuscule amount of nuclear fuel is capable of producing large amounts of energy. In fact, a single thimble-sized uranium pellet weighing only about 10 grams has the energy density equivalent to nearly 20 million btus (approximately 5,000 kWh).[8,9] Fuel rods full of around 400 uranium pellets are placed in assemblies able to stay in a reactor for up to six years, while fission chain reactions occur and the concentration of Uranium 235 decreases. Plants generally shut down to replace one third of the reactor's nearly 50,000 fuel rods every two years.[10,11]

Due to this high energy density, long fuel lifespan, and low short-term maintenance, nuclear power plants have the highest capacity factor of any other energy source, producing maximum amounts of power 93 percent of the time.[12] While uranium fuel contains enormous amounts of energy, real world conditions must account for burnup rate (or actual energy extracted) and the plant's thermal efficiency.[13,14,15,16] In practice, accounting for inefficiencies, one pound of uranium generates approximately 154,353.27 kWh of electricity.[17,18]

To picture the energy density of nuclear power, consider how much uranium it would take to power a modern house. The average U.S. household consumes 10,649 kWh of electricity per year. To run the average household on nuclear power for one year, it would take only 0.069 pounds of uranium, or about three individual fuel pellets.

2. Cost

Given the high energy density of uranium, electricity generated by nuclear reactors is relatively inexpensive. However, because of the extensive safety, regulatory, and up-front capital costs associated with constructing a nuclear plant, the total cost increases.[19] The average operating costs for nuclear power generation can be as low as 2.40 cents/kWh.[20] Factoring in capital costs, fixed operations and maintenance (O&M) costs, variable costs that include O&M and fuel costs, financing costs, an assumed utilization rate for each plant type, and waste management and storage, the total cost comes in higher. Accordingly, the leveled cost of electricity and storage outlook for advanced nuclear is projected to be 6.94 cents per kWh.[21,22]

To power a single U.S. household for one year, it would cost $739.04 per year.

3. Availability and Reserves

Nuclear material deposits are determined in part by economics, making price an implicit factor in the available reserves.[23] Nuclear power in the United States is produced from uranium, a nonrenewable mineral resource. The United States has deposits of uranium and phosphates accounting for an estimated one percent of the world's uranium supply. Only around 10 percent of U.S. nuclear material is source domestically each year.[24] As of 2018, uranium mines are largely concentrated on federal land in Arizona, Colorado, Utah, New Mexico, and Wyoming, with over two-thirds of the estimated uranium reserve found in Wyoming and New Mexico.[25]

U.S. domestic reserves contain an estimated economically retrievable 1.7 billion pounds.[26] This represents approximately a 33-year supply in domestic reserves. However, the global amount of economically-recoverable uranium currently is estimated to last over 230 years at the current rate of consumption, with improved technology projected to double the reserves recoverable.[27] Most of the world's uranium supply comes from six countries: Kazakhstan, Canada, Australia, Namibia, Niger, and Russia.[28,29]

Uranium exists plentifully within the earth, occurring at the same rate as tin and at higher rates than gold, silver, or mercury.[30] Open pit mines have largely been how uranium is extracted, although a process known as in-situ leaching can pull uranium out of the ore underground by injecting water mixed with an oxidizing solution into a deposit.[31] Natural uranium, however, is not ready for use at nuclear power plants. It must be mined, milled, converted, and enriched – a multistep process including a number of facilities and chemical processes – before it can be used as fuel.[32,33] The U.S. has one conversion facility, but it has remained idle for years, while most material is imported.

4. Land Required

Nuclear plants require relatively little land to generate power. On average, an active U.S. nuclear power plant is estimated to require 832 acres (1.3 square mile) per 1 million kW capacity.[34,35] In 2019, there were 58 nuclear power plants in the United States.[36] Combining the land for nuclear mining operations, transportation, power plants, and waste storage, nuclear power has a total footprint of around 363,000 acres.[37,38] Nuclear generated 790 billion kWh in 2020. This leads to an estimated 2,176,308 kWh per acre.

To power a single average household in the U.S. for one year using nuclear power would require 0.0049 acres of land (or 19.83 square meters).

5. Safety

Despite widespread fear of nuclear disasters or accidents at nuclear power plants, nuclear energy is the safest form of energy production. In over 18,500 cumulative reactor-years of commercial nuclear power generation in 36 countries, only 32 total fatalities have been caused by nuclear accidents.[39] The three main nuclear accidents – Chernobyl, Three Mile Island, and Fukushima – had total fatalities of thirty-one, zero, and one, respectively.[40]

Energy fatality rates are calculated from the first stage of development to the impact of end use. For nuclear, this includes mining all the way through the conversion and enrichment and potential pollution or environmental externalities from generation. Uniquely, it also includes radiation-related deaths from operations, waste disposal, or failures. Due to such a small record of reactor failures and no direct CO_2 emissions, the global fatality rate globally is low. The U.S. rate is lower still. Worldwide, the fatality rate per 1 billion kWh of nuclear energy stands at 0.07 deaths.[41]

In terms of the safety history of U.S. commercial nuclear power plants, no radiation-related health problems have been linked to any of the facilities.[42] Nuclear power plants are built to withstand extreme weather and earthquakes, in addition to being heavily guarded.[43] Additionally, uranium mines in the U.S. are largely located on federal land, due to the safety regulations surrounding uranium. Given higher safety and environmental standards in the U.S., the global fatality statistics are skewed by other nations.

Environmentally, potential radiation leaks can render both surface and groundwater unusable, but the rarity of nuclear accidents means that there is not significant data on environmental incidents. Irradiated environments are not suitable for human habitation although animal habitation may adapt to high radiation levels. Safe storage or recycling of radioactive waste presents an opportunity for leakage, but nuclear waste disposal sites are subject to intense regulation, scrutiny, and monitoring.

Overall, nuclear energy entails an extremely low fatality rate. The death rate for a nuclear powered U.S. household for one year would be 0.000000745. At this rate, over 1.3 million homes would be powered before there was a global death from nuclear power.

6. Climate Impact

Nuclear power plants do not produce air pollution or carbon dioxide emissions from their operation.[44,45] However, generating the amount of concrete and other building materials for a nuclear power plant's construction, mining uranium ore from the earth, and refining the uranium into reactor fuel all require large amounts of energy, much of which is derived from fossil fuels that do emit.[46]

Including its entire infrastructure footprint, nuclear power still generates very few emissions. Estimates place the life-cycle emission rate at a median rate of 12g CO_2/kWh, while the mean is estimated to be as high as 34g to 65g of CO_2/kWh.[47,48,49] Overall, the emissions for nuclear energy mirror its start up costs with up-front emissions from the mining of uranium, refinement of it into reactor fuel, and the construction of the nuclear plant, but emit no harmful pollutants or carbon dioxide during its operation.

The total carbon emissions from a median lifecycle basis to power an average U.S. household with only nuclear energy would be 127,788 grams (or 281 pounds) of indirect emissions per year.

7. Long-Term Impact

The two primary issues for nuclear power longterm are decommissioning sites and handling spent fuel and waste products. When dealing with radioactive material with a half-life in the thousands of years, the entire focus must be longterm.

The decommissioning process is commenced when a nuclear reactor has reached the end of its projected life and must be broken down for safety and efficiency. The plant owner must ensure radioactivity levels in the area are reduced to safe levels for humans.[50] The full decommissioning process involves removing the nuclear fuel from the reactor, cooling it in wet pools, and moving it into storage containers.[51] Items or parts of the reactor that have been contaminated with excess levels of radiation can also be stored on site or shipped to a storage facility. Nuclear waste can also be recycled back into the energy production process, so much of the nuclear waste generated by nuclear plants is low (LLW) or intermediate level (ILW) waste.[52]

Transportation of this waste to disposal sites has a high safety record, with no spills or leaks having been reported.[53] Most nuclear waste is safe to store in above-ground facilities, and waste disposal processes make up just 10 percent of the overall costs of nuclear power.[54] Underground disposal of high-level radioactive waste (HLW) and aboveground storage are constructed to withstand temperature changes and seismic activity, with additional layers built into storage containers in case one layer is ruptured.[55]

Overall, while radioactive waste is the clearest long-term concern, the technology and storage options already available, the regulatory apparatus governing decommissioning, and the ability of reactor fuel to be recycled back into nuclear power generation, means that the waste is not prohibitive for long-term reliance on nuclear power.

8. Limitations

The main limitations of nuclear energy include its water intensity, upfront costs, and safe waste disposal.[56] While water is primarily an environmental consideration, costs and waste overlap considerably with the political realm.

A nuclear power plant requires around 500,000 gallons minimum per kilowatt hour.[57] [58] Water is essential for generating electricity, as steam is what spins the turbine, but also for cooling pools for short-term waste management. This could pose both production and operational costs in areas that lack a reliable supply of water.

The high up-front costs of constructing a nuclear power plant can include indirect construction support costs including, field supervision, temporary construction facilities, home office services, payroll insurance and taxes, and quality assurance among others.[59] The plant's total cost in 2008 ranged between $6 billion to $9 billion, with estimates only rising since.[60] Outside of the U.S., costs have actually fallen, and a combination of design, project management, and supply chain considerations may help make nuclear more cost competitive domestically.[61,62]

Finally, due to a combination of environmental opposition, geologic concerns, misinformation, and popular fear of nuclear meltdowns alongside political challenges, the U.S. does not have a central depository for spent nuclear fuel.[63] A proposed permanent storage site at Yucca Mountain in Nevada has been planned since 1987.[64] Currently, all nuclear waste is stored securely on-site in containers either below or above ground.[65] This on-site storage is not ideal but is perfectly feasible for the intermediate term. Additionally, technology is currently in development to create smaller-scale nuclear reactors and alternative heat generation processes that are safer, cheaper, and have the potential to dramatically increase nuclear power's longevity in America.[66]

Conclusion

Nuclear power has been a staple in the U.S. for decades, quietly providing large quantities of zero-emission energy and supporting base load. Overall, nuclear energy is massively energy dense, relatively low cost, widely available, and with a virtually nonexistent carbon footprint and fatality record. This versatility, efficiency, and environmental potential makes nuclear energy a critical piece of the American energy mix going forward.

Despite clear advantages, several hurdles must still be overcome for nuclear power to retain its footing and grow as a share of the nation's energy mix. Widespread fear of nuclear meltdowns, coming from non-contextualized information about Chernobyl and Fukushima, have led to reluctance for nuclear energy. High costs to build nuclear power plants also hinder new constructions, while funds tend to flow to other clean energy alternatives viewed as less risky investments. The technology for more efficient nuclear power advances every day, and new research and development into waste management and storage continually improve nuclear's outlook. Further innovation will only reduce costs and concerns while solidifying the benefits of nuclear power.

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[38] This excludes the 4.8 million total acres of easements for the nation's power lines. This infrastructure is used to transmit all electricity from the nation's energy mix. While nuclear power is a share of the electricity going into the grid, we do not calculate the share in this brief. Nuclear power can be used to generate power close to urban centers and consumers of electricity. Calculating power lines as a share of nuclear's energy mix would further over count its footprint.

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