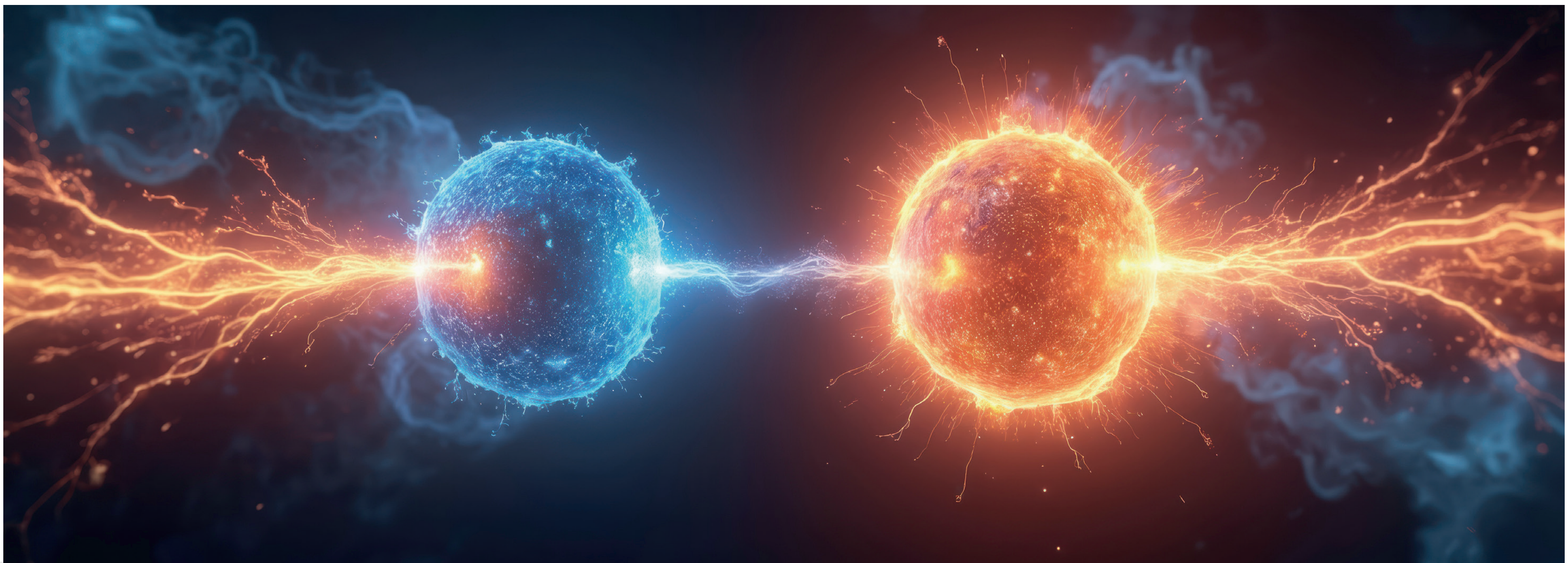


NUCLEAR FISSION ADVANCEMENTS AND DEVELOPMENTS

Nuclear Energy is a rising energy production industry across the world. It is a reliable carbon-free energy source many countries are turning towards as an alternative for oil and gas fueled energy production plants. Every nuclear energy reactor in use today utilizes the nuclear fission reaction where heat and radiation are created when an atom's nucleus is split. Through different companies and organizations like the Generation IV Internation Forum (GIF), Rolls Royce, General Atomics, and many more, the standard designs for reactors (Pressurized Water Reactors and Boiling Water Reactors) are being improved to address current issues. The focus is on developing fuel recyclability to reduce uranium mining and dependency, reduction of land dependency to improve cost efficiency, and waste storage solutions to prevent humans from being harmed from long-term radioactive waste. These developments promote commercialization which encourages governments to switch to more environmentally friendly methods of producing energy.

Introduction

Nuclear energy accounts for 9% of the world's electricity generation and 20% of the world's carbon-free electricity. It is a dependable alternative energy source to fossil fuels and was heavily relied upon during the 1970s oil crisis when Arab producers set an oil embargos causing governments to turn to other sources to produce energy [1],[2]. Over the last decade, nuclear energy has become more popular with the need for alternative forms to fossil fuel and nuclear energy is carbon-free as it does not directly produce carbon dioxide or other greenhouse gases that promote climate change [3]. As of January 2025, there were 63 nuclear reactors being constructed around the world with most new reactors being built in China and Russia.

Countries with advanced economies like the United States have older nuclear reactors that are much harder to restart after they have been unused for years. There were more than 410 reactors in operation across 30 countries, providing the world's nuclear energy supply strengthening energy security by reducing the need to import fossil fuels [4]. Currently, there are 54 operational nuclear power plants in the United States [5]. In 2019, the Finnish government announced a new policy aimed to phase out coal resulting in a switch to nuclear energy. Finland has five operating nuclear reactors which now provide the country with a third of its electricity. This helps reduce the carbon dioxide being produced as a byproduct to energy production [6]. Nuclear power has many benefits; however, the challenges arise around nuclear waste disposal, upfront costs on reactors which discourage governments to invest in it, fuel accessibility, and materials needed to keep the reactor sustainable.

Nuclear energy harnesses the power of an atom, creating a large amount of energy from the heat of reaction. There are different forms of nuclear energy, currently, all the power coming from nuclear energy is through nuclear fission, where an atom's nucleus splits, overcoming the binding energy of the nucleus and breaking into smaller nuclei and subatomic particles, as seen in Figure 1 [7]. Fission can occur spontaneously when radioactive materials decay into lighter elements to create large amounts of radiation and heat. However, the reaction can be initiated when a nucleus is bombarded by particles. Nuclear fusion, a less commonly used form of nuclear energy, produces energy through the combination of two nuclei to form a single nucleus which releases massive amounts of heat [1].

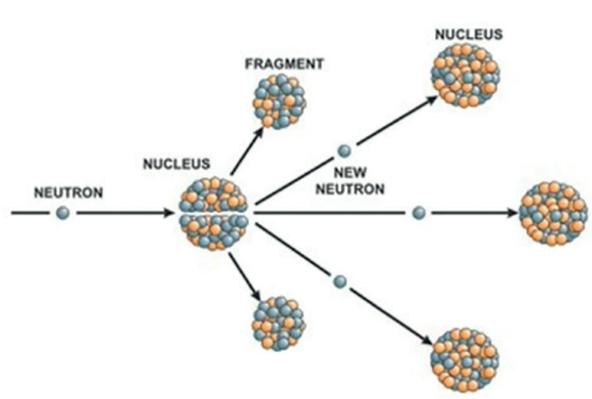


Figure 1: Process of Nuclear Fission where an atom is split breaking into smaller nuclei [7]

All commercially used nuclear power plants today work on fission technology and most of the plants are fueled by uranium. Uranium is an extremely dense fuel, 33,000 more energy densethan oil by volume and occurs naturally as U-235 or U-238. Fission happens every time a U-235 nucleus splits, releasing two or three neutrons creating a chain reaction. U-235 is fissile so it can capture a slow neutron and split it apart. U-238 on the other hand, is fertile and can capture a neutron through radioactive decay to become fissile [7]. However, U-235 cannot absorb high-energy neutrons, a moderator must be utilized to slow the neutrons down to capture the fuel. There are three types of moderators: ordinary or light water used to control the reactor core, deuterated or heavy water, and high purity graphite which both slow neutrons down without absorbing them [8]. This basic design for fission reactors has been developed to make processes more efficient and easier to commercialize at larger scales.

Traditional Nuclear Technology

The most common type of nuclear fission reactor is the Pressurized Water Reactor (PWR) followed by the Boiling Water Reactor (BWR), as shown in Figure 2. Both reactors use light water as a source for steam, a coolant, and a neutron moderator [9]. PWRs have a primary cooling circuit flowing through the core of the reactor at high pressures and secondary circuit, at lower pressure, generating steam to drive towards the turbine. The BWR only has one circuit with water, leading to a less moderating effect, the secondary control system involves restricting water flow through the core [10]. The main difference between the two processes is the steam generation process. In a BWR, steam is created in the Reactor Pressure Vessel (RPV) and then goes directly to the steam turbine generator (STG). However, in a PWR, hot water from the RPV creates steam in a steam generator (S/G) before going to the STG. In both reactors, the steam is cooled in the condenser and recycled to start the process again, in the case of the PWR the water goes to the steam generator, for the BWR, the steam goes to the RPV [9].

There were challenges with these systems however, including the materials going through stress and corrosion due to high pressure and radiation in the system. To prevent this, the materials chosen for the processor are less likely to corrode or succumb to stress. The components used for pressure boundaries are made from low carbon or stainless steel while the springs, fasteners, and generator tubes are made from a nickel-based alloy. These metals have low corrosion rates in dry environments, and a high-density protective surface layer that grows slowly at operating temperatures to help prevent excessive disintegration of the structure [11].

Furthermore, the need for more efficient and carbon-free sources of energy is increasing with the threat of climate change motivating innovations in fission technology. Another challenge with fission technology is waste management and its

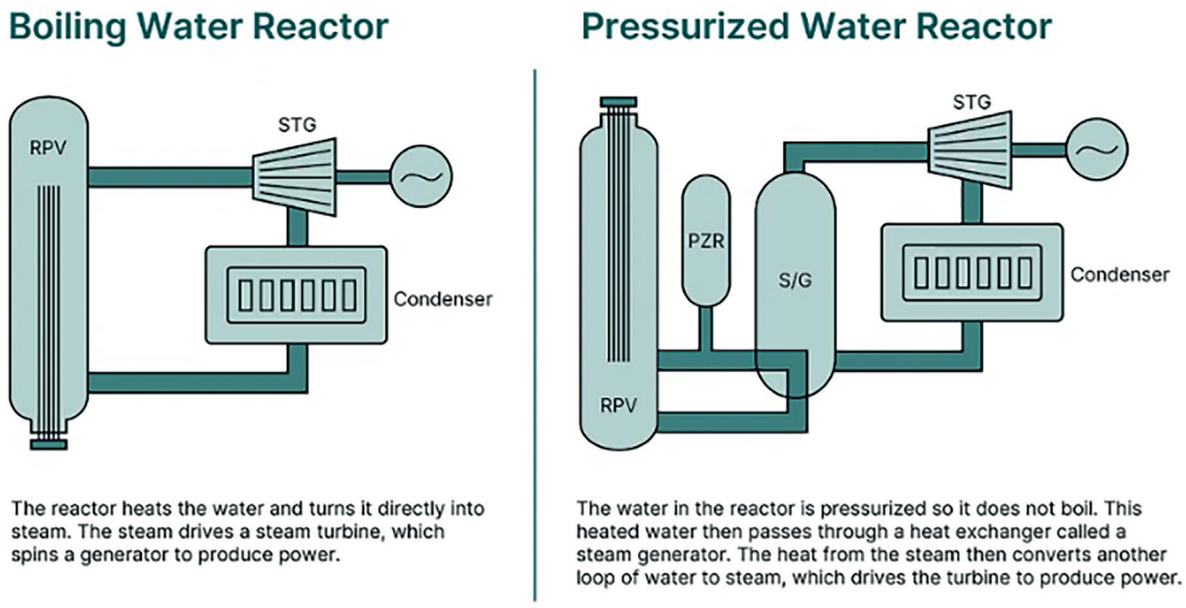


Figure 2: Schematic of Boiling Water Reactor and Pressurized Water reactor [9]

environmental impacts. Nuclear technology may not directly release pollution into the air, but the radioactive waste created during this process can last a long time contaminating the environment and more importantly, local water supplies [1].

Key Developments in Fission Technology

There have been many developments on standard nuclear fission reactors to increase efficiency and address waste management challenges. Small Modular Reactors (SMRs) are nuclear reactors that have about one-third the power capacity (300 MWe) of traditional nuclear reactors (1 GW). SMRs are modular, which means that the components of the system can be assembled and transported as a unit for installation. SMRs are more affordable and flexible compared to nuclear reactors as they do not require as much land or construction as large traditional reactors. They can also be incrementally increased to meet the energy demand as to not use excessive fuel or produce unnecessary amounts of energy. Additionally, SMRs are safer and require less fuel; they are refueled every 3-7 years instead of the 1-2 years that a regular plant is refueled [12]. Nuclear fission reactors are fueled with uranium fuel pellets or rods, created by mining uranium which can be both difficult and dangerous. Less frequent refueling means a reduction in the amount of uranium needed [3]. There are also microreactors, which are a subset of SMRs that have an even smaller footprint and heat capacity than SMRs. These are more appropriate for areas that don't have access to clean or reliable energy. The comparison between conventionally large reactors, small modular reactors, and microreactors can be seen in Figure 3 [12].

SMRs have further encouraged government support to help promote a path to nuclear energy, especially with the demand for clean power from the private sector [4]. Governments are more willing to invest money into nuclear technology and pass policies promoting nuclear technology research. Rolls-Royce, a Britishengineering company, is working on SMR development to help ensure the UK continues towards tackling the global threat of climate change [13]. SMRs offer energy security for countries around the world. Rolls- Royce's SMR is set to generate 470 MW which is enough to power 1 million homes for about 60 years [13]. Finland is also currently studying SMRs to use for district heating and electricity generation. They are working on validating the passive safety system ahead of commercial deployment [6].

The Generation IV Internation Forum (GIF) was formally established in 2001 with a purpose to develop the research necessary to test the feasibility and performance fourth generation nuclear systems. The goal is to make them available for industrial deployment by 2030. Gen IV focuses on six reactors: Gas-cooled fast reactor (GFR), Lead-cooled fast reactor (LFR), Molten salt reactor (MSR), Sodium-cooled fast reactor, Supercritical-water-cooled reactor, and very high-temperature reactor. GIF's criteria for developing these reactors focuses on sustainability, economics, safety and reliability, as well as proliferation resistance and physical protection [12].
Since the establishment of the forum, many countries have been involved with this research but recently, there have been some major developments

General Atomics is working on developing a modular version of the GFR, a gas-cooled modular reactor, to make the manufacturing process easier and more cost efficient [14]. With their design, the reactor could be made in factories and assembled on-site with the ability to deliver 44 MW with less than 0.2 acres of land needed for the reactor. The design also pairs with a cooling system that is helpful for rural, remote, or arid locations. It runs on silicon carbine-wrapped high assay low-enriched uranium which can handle temperatures twice the outer layers of fuel rods used in light water reactions. The current design of the rods is undergoing irradiation testing at Idaho National Laboratory to verify integrity as of November 25, 2025 [13].

Westinghouse, a nuclear energy company, is working on a design of LFRs that can compete with the challenging global energy market [15]. Their design is medium sized and a passively safe modular reactor. They opted for a lead coolant which has a boiling point greater than 1700 ℃ allowing the rector to run at high temperatures and atmospheric pressure without risk of boiling the coolant [15]. The increased thermodynamic efficiency (42-48%) reduces capital cost upfront and improves safety with decreased pressure requirements. Furthermore, lead does not react with air or power conversion fluids in an exothermic fashion, eliminating the need for extra safety components. Therefore, 50% of systems can be reduced or eliminated.
This design, seen in Figure 4, creates a safer reactor with a simplified compact plant which decreases construction time and reduces costs [16].

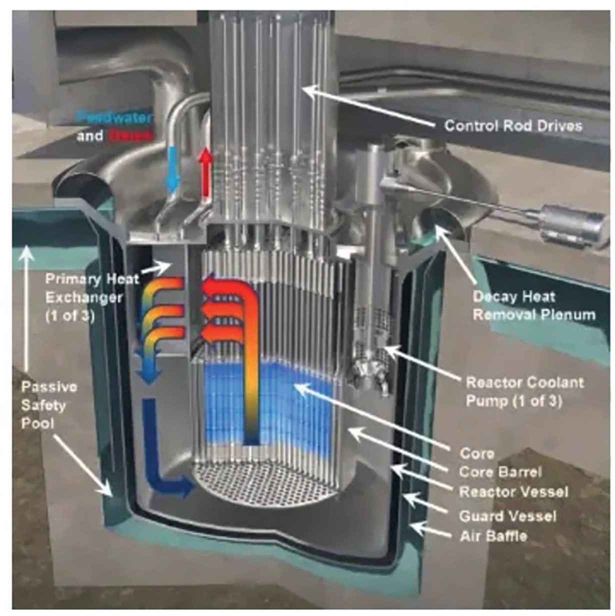


Figure 4: LFR with distinguished features labeled. [15]

The United Kingdom National Nuclear Laboratory has been working on MSR fuel longevity and recyclability. Many plants use aqueous reprocessing to separate out the reusable parts of the fuel to prevent excessive waste and recycle the unreacted fuel that can be reused. The United Kingdom National Nuclear Laboratory has been working on pyrochemical processing techniques to separate elements of the fuel to be recycled to create more energy. This process removes the fission products from the potential fuel so that the unused fuel can be put through the reactor again. The salt is first melted down into a liquid molten salt and used as an electrolyte in an electrochemical cell. The useful materials are the ions that are drawn to the cathode where they are processed and used as fuel again.
This allows nuclear energy to be more consistent and less reliant on uranium mining [14].

Another aspect of nuclear energy that poses issues is waste management due to radioactivity. High-level waste must be kept away from humans and is often stored in cooling pools or underground, however, there is no long-term storage solution that exists [1]. Nuclear waste or spent nuclear fuel are the parts of the used fuel that must be disposed of and are often put in deep geological repositories, which have retention barriers to prevent environmental contamination. The outer layer of the Spent Nuclear Fuel (SNF) rod forms a layer of Zirconia (ZrO_2). Finkeldei et al. investigated the incorporation of Eu^{3+} and Cm^{3+} through co-precipitation and crystallization. This resulted in hydrothermal aging for 460 days in alkaline media which indicates stability with these incorporated species [17].

Commercializing Nuclear Technology

Nuclear technology has developed into a reliable, clean, and carbon-free energy alternative to traditional fossil fuels. With recent research and discoveries, the challenges with longevity and waste management are being addressed. More countries like Finland, Slovakia, and the UK have been switching to nuclear

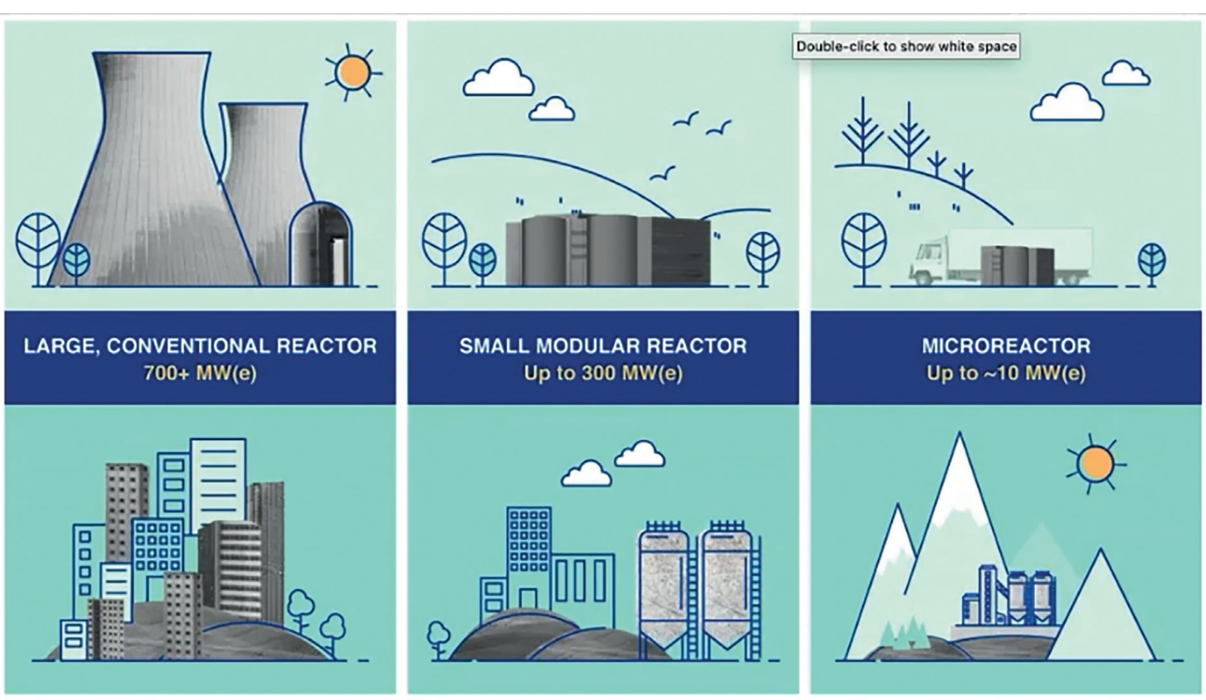


Figure 3: infographic to compare large conventional reactor, small modular reactor, and microreactor. [12]

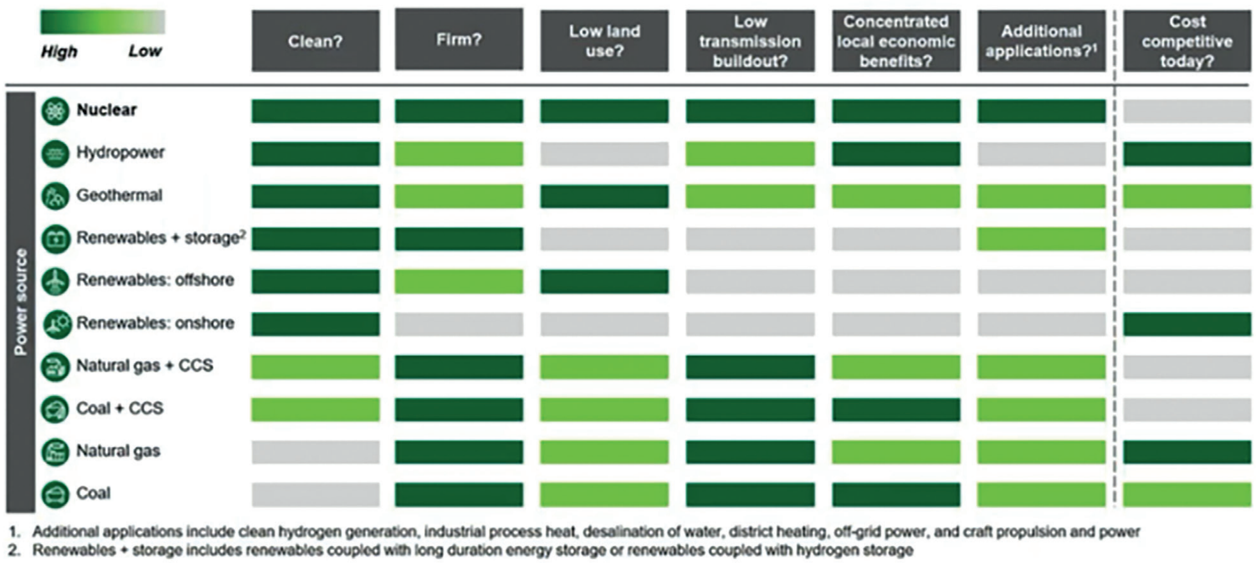


Figure 5: Chart comparing different properties of various forms of energy production [18].

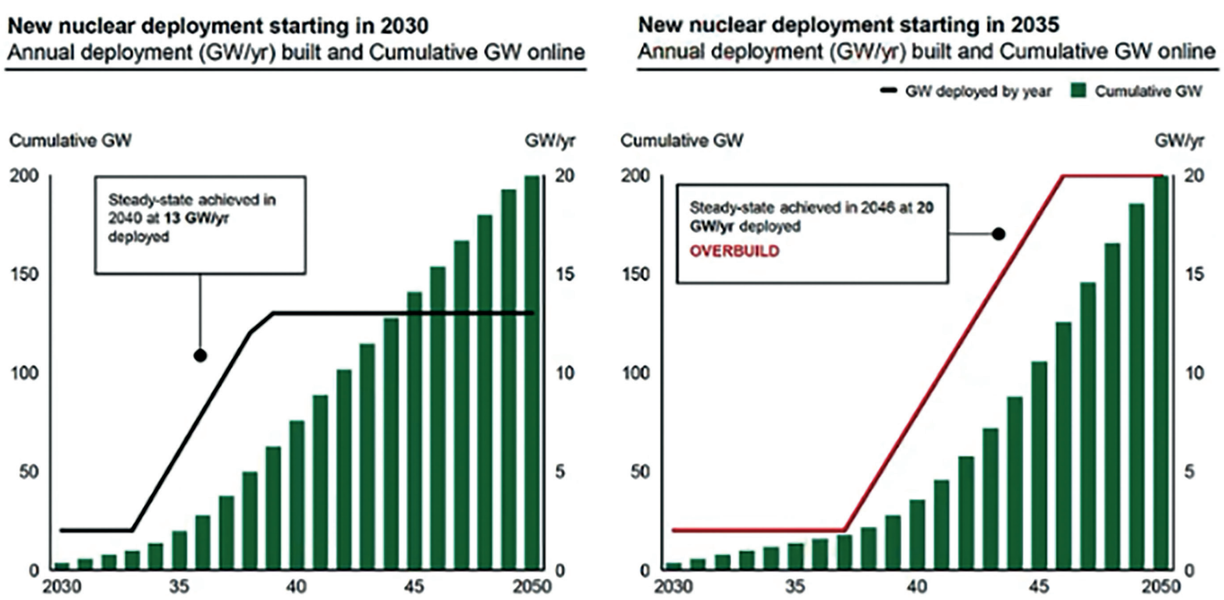


Figure 6: Graphs depicting steady state in 2030 compared to 2035. [18]

reactors to meet their energy needs. As seen in Figure 5, nuclear energy matches every other form of energy production but not the cost competitiveness which can be improved with the further commercialization of nuclear fission reactors [15]. There are concerns of jobs being lost with the transition from coal power plants to nuclear power, however with every new small modularreactor, there is projected to be 240 permanent jobs per gigawatt while traditional reactors employ around 500 per gigawatt [18]. Those who work at existing coal power plants would be suitable to be employed at nuclear facilities in the future. As artificial intelligence expands, The USA data centers are projected to drive nearly half of the USAelectricity demand growth. To meet these needs, TerraPower and Sabey Data Centers announced a memorandum of understanding on January 21, 2025.

Terrapower's Natrium Technology is the first advanced nuclear technology to be used in the nation with 245 MW sodium-cooled fast reactor coupled with molten-salt-based energy storage increasing the system's output to up to 500 MW. This reactor is projected to be online by 2030 and will be the first commercial, utility-scale advanced nuclear power plant in the United States [17]. Currently, most reactors are projected to be deployed in the 2030s, however, the delay in deployment could threaten the decarbonization goals of the United States leading to an overbuild of the supply chain [18]. TerraPower and the Generation IV Internation Forum plan to deploy their projects in 2030 with many others following them. [19],[16]. Along with negative climate impacts of the delay, there is also expected to be a 50% increase in capital required to achieve the same amount of capacity due to the scaling due to the 5-year delay as seen in Figure 6 [18]. Delaying the deployment of new nuclear reactors not only harms the environment but also increases costs to create these power plants.

Slovakia uses nuclear reactors to meet their energy needs by importing their nuclear fuel causing radioactive waste management and storage problems. Nucleo, a French-based nuclear energy company, developed lead-cooled fast reactors with fuel that can be reused after going through the reactor. Javys, a Slovakian company, formed a joint venture with Nucleo to develop four lead-cooled fast reactors. They operate with uranium-plutonium oxide fuel, a derivation of Slovakia's spent fuel. The fuel will be reprocessed in France and created into new fuel rods which will then be used to power the reactors in Slovakia. Together, Javys and Nucleo closed the nuclear fuel cycle lowering Slovakia's reliance on imported fuel and reducing the amount of radioactive waste [20].

Conclusion

Over the last several years, nuclear fission has been reinvented and developed with the assistance of organizations like the GIF advancing research and innovation further [18]. With the world relying more on nuclear energy, there will be a reduction of carbon dioxide released into the environment from other forms of energy production. Challenges that conventionally large-scale reactors have faced when producing energy for decades are finally being addressed. Recent research is advancing nuclear technology by addressing consistency, waste management, and capital cost reduction. Designs like the SMR focus on accessibility and easy manufacturing to provide the same amount of energy.

Thus far, nuclear energy has exclusively been produced for use through nuclear fission, which is known to produce nuclear waste, as seen in Slovakia, with no current solutions for sustainable long-term waste management solutions [20]. Fusion on the other hand, has the potential to produce energy at a lower -cost without the byproduct of nuclear waste [21]. The new roadmap to fusion commercialization has taken input from hundreds of scientists, engineers, and industry stakeholders and aims to find key research materials and technology gaps that should be addressed to produce a successful fusion pilot plant [22].

References:

[1] Understand Nuclear Fission. (2025). Understand Energy Learning Hub; Stanford University. https://understand-energy.stanford.edu/news/understand-nuclear-fission

[2] Corbett, M. (2013, November 22). Oil Shock of 1973–74. Federal Reserve History. https://www.federalreservehistory.org/essays/oil-shock-of-1973-74

[3] White, A., & Krol, A. (2024, July 24). Nuclear Energy. MIT Climate Portal. https://climate.mit.edu/explainers/nuclear-energy

[4] IEA. (2025, January 16). The Path to a New Era for Nuclear Energy – Analysis - IEA. IEA. https://www.iea.org/reports/the-path-to-a-new-era-for-nuclear-energy

[5] US Energy Information Administration. (2023, August 24). U.S. Nuclear Industry. Eia.gov; U.S. Energy Information Administration. https://www.eia.gov/energyexplained/nuclear/us-nuclear-industry.php

[6] World Nuclear Association. (2024, December 6). Nuclear Power in Finland - World Nuclear Association. World-Nuclear.org. https://world-nuclear.org/information-library/country-profiles/countries-a-f/finland

[7] Department of Energy. (2023). DOE Explains...Nuclear Fission. Energy.gov. https://www.energy.gov/science/doe-explainsnuclear-fission

[8] Massachusetts Institute of Technology. (2023). The Fission Process – MIT Nuclear Reactor Laboratory. Mit.edu. https://nrl.mit.edu/reactor/fission-process/

[9] Large Boiling Water Reactors | GE Hitachi Nuclear Energy. (n.d.). Gevernova-Nuclear. https://www.gevernova.com/nuclear/carbon-free-power/large-reactors

[10] Nuclear Power Reactors - World Nuclear Association. (2025). World-Nuclear.org. https://world-nuclear.org/information-library/nuclear-power-reactors/overview/nuclear-power-reactors

[11] Zinkle, S. J., & Was, G. S. (2013). Materials challenges in nuclear energy. Acta Materialia, 61(3), 735–758. https://doi.org/10.1016/j.actamat.2012.11.004

[12] Liou, J. (2023, September 13). What Are Small Modular Reactors (SMRs)? International Atomic Energy Agency; IAEA Office of Public Information and Communication. https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs

[13] Rolls Royce. (2025). To Deliver Clean, Affordable Energy for All - Rolls Royce SMR. Www.rolls-Royce-Smr.com. https://www.rolls-royce-smr.com/

[14] General Atomics Finalizes Concept for New Fast Reactor Design. (2025, November 25). Energy.gov. https://www.energy.gov/ne/articles/general-atomics-finalizes-concept-new-fast-reactor-design

[15] Lead-cooled Fast Reactor | Westinghouse Nuclear. (2026). Westinghousenuclear.com. https://westinghousenuclear.com/innovation/lead-cooled-fast-reactor/

[16] Welcome to the Generation IV International Forum | GIF Portal. (2024). Gen-4.org. https://www.gen-4.org/

[17] Opitz, L., Hübner, R., Shams Aldin Azzam, S., Gilson, S. E., Finkeldei, S. C., & Huittinen, N. (2023). Investigations towards incorporation of Eu3+ and Cm3+ during ZrO2 crystallization in aqueous solution. Scientific Reports, 13(1), 12276. https://doi.org/10.1038/s41598-023-39143-0

[18] Commercializing Advanced Nuclear Reactors Explained in Five Charts. (n.d.). Energy.gov. https://www.energy.gov/ne/articles/commercializing-advanced-nuclear-reactors-explained-five-charts

[19] TerraPower. (2025). TerraPower and Sabey Data Centers Developing Strategic Collaboration Agreement for Wide-Scale Deployment of Natrium® Plants. Terrapower.com. https://www.terrapower.com/terrapower-and-sabey-data-centers-agreement-for-natrium-wide-scale-deployment

[20] N, S. A. (2025, October 28). Five Landmark Commercial Agreements in Nuclear Fission. Net Zero Insights. https://netzeroinsights.com/resources/commercial-agreements-nuclear-fission/

[21] Funding the fusion revolution. (2025, December 8). Main. https://energy.mit.edu/news/funding-the-fusion-revolution/

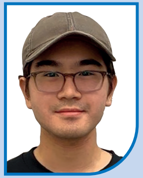
[22] https://www.facebook.com/WorldNuclearNews. (2025, October 20). USA sets out roadmap for fusion commercialisation. World Nuclear News. https://world-nuclear-news.org/articles/usa-sets-out-roadmap-for-fusion-commercialisation

Biographies

Dr. Raj Shah, is a Director at Koehler Instrument Company in New York, where he has worked for the last 25 plus years. He is an elected Fellow by his peers at IChemE, ASTM (https://tinyurl.com/mbz22vjv/) , AOCS, CMI, STLE, AIC, NLGI, INSTMC, Institute of Physics, The Energy Institute and The Royal Society of Chemistry. An ASTM Eagle award recipient, Dr. Shah recently coedited the bestseller, "Fuels and Lubricants handbook", details of which are available at ASTM's Long-awaited Fuels and Lubricants Handbook https://bit.ly/3u2e6GY. He earned his doctorate in Chemical Engineering from The Pennsylvania State University and is a Fellow from The Chartered Management Institute, London. Dr. Shah is also a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute and a Chartered Engineer with the Engineering council, UK. Dr. Shah was recently granted the honorific of "Eminent engineer" with Tau beta Pi, the largest engineering society in the USA. He is on the Advisory board of directors at Farmingdale university (Mechanical Technology), Auburn Univ (Tribology), SUNY, Farmingdale, (Engineering Management) and State university of NY, Stony Brook (Chemical engineering/ Material Science and engineering). An Adjunct Professor at the State University of New York, Stony Brook, in the Department of Material Science and Chemical Engineering, Raj also has over 775 publications and has been active in the energy industry for over 3 decades.(https://tinyurl.com/22arr3tj/)

Kate Marussich

Ms. Prinika Kondoju and **Ms. Kate Marussich** are interns at Koehler Instrument Company, Holtsville, NY under Dr. Raj Shah.



William Chen

Mr. William Chen has earned his undergraduate degree in Chemical Engineering from the State University of New York, Stony Brook, NY and is a member of the senior internship program at Koehler Instrument company in Holtsville.

Gavin Thomas

Mr. Gavin Thomas is part of a thriving internship program at Koehler Instrument Company in Holtsville, NY and is a recent graduate of the Chemical and Molecular Engineering program at Stony Brook University. He also works as a process engineer at Mill-Max in Oyster Bay, NY where he becomes hands-on with various production processes to ultimately improve safety, efficiency, and cost-effectiveness.

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