Anthropocene Institute

World Nuclear Investment Factbook

Data curated until

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MESSAGE FROM OUR LEADERS

The United States is preparing to announce a pledge to triple the world's production of nuclear energy by 2050, with more than 10 countries on four continents already signed on to the first major international agreement in modern history to ramp up the use of atomic power.

There is a significant shift in global interest towards nuclear energy, with the United States leading a major initiative to triple global nuclear power capacity by 2050. This initiative, representing a notable change in attitude towards this historically controversial technology, has garnered international support. Key countries like the UK, France, Sweden, Finland, and South Korea are expected to join the US in this commitment. The plan includes a call for major financial institutions to incorporate nuclear energy in their lending policies, highlighting the growing recognition of nuclear power's role in achieving net-zero greenhouse gas emissions by mid-century. Furthermore, this move is complemented by the nuclear industry's own commitment to significantly increase generation resources. This global pivot towards nuclear energy, including new technologies like small modular reactors, is increasingly seen as essential for supplementing renewable energy sources and enhancing energy security. The COP28 summit, set to start on November 28, will be a key moment for solidifying this global commitment to nuclear power as a vital component in the fight against climate change.

"Nuclear is 100% part of the solution, it's clean energy."

- John Kerry *United States Special Presidential Envoy for Climate*

Table of Contents

CONTENTS

Table of Contents

INTRODUCTION

This comprehensive report offers a strategic overview of the global landscape for nuclear investments, delineating both government and private sector engagement across a range of technologies. The Anthropocene Institute has diligently compiled and analyzed data on nuclear startups and the distribution of funds across more than twenty key nations, employing sophisticated statistical visualizations to forecast future market positions. This analysis takes into account a myriad of critical factors—from prevailing market trends and national policies to the broader geopolitical climate—that shape the prospects for nuclear energy deployment.

Amid a global push for ambitious climate targets, we recognize that nuclear energy presents a compelling investment opportunity. It stands as a clean, reliable, and low-carbon energy source, perfectly poised to complement the renewables sector and meet burgeoning energy demand. Importantly, the advent of cutting-edge technologies such as small modular reactors and microreactors signals a transformative shift towards more economically viable and adaptable nuclear plant installations.

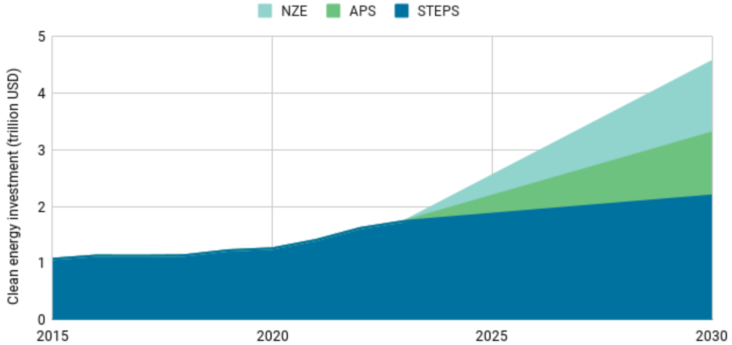
Investing in nuclear energy is not just about embracing a sustainable future—it's a strategic economic move to be invested in the most energy dense resource we have on the planet. This report not only underscores the vitality of nuclear energy in the global energy matrix but also showcases the profound investment potential inherent in the sector, making a compelling case for why nuclear energy demands our focused attention now.

Current Climate Investment Landscape

Currently, investment in clean energy outpaces the growth of fossil fuel investment, but this growth is still not on track to meet net-zero requirements (McKinsey, 2022). Between 2017 and 2022, the ratio of clean energy investment to fossil fuel investment increased from 1:1 to almost 1.7:1 (IEA, 2023b). Across all sectors, clean energy investment grew to a total of $1.617 trillion in 2022, with the highest levels of growth in electrified transport and renewables (IEA, 2023; BloombergNEF, 2022). Particularly, recovery from the pandemic and the recent energy crisis has accelerated growth in renewables investment since 2021 (IEA, 2023b). In 2022, China accounted for almost half of the world's $1.1 trillion of energy transition investment (funding spent to deploy clean energy technologies, excluding investment in power grids, supply chain, and climate-tech corporate financing) followed by the EU, then the US as indicated in Figure 1 (BloombergNEF, 2023). In 2022, demand-side investment (i.e., electrification) outweighed supply-side investment (i.e., energy production, storage) for the first time, receiving $561 billion and $550 billion respectively (BloombergNEF, 2023).

Reaching net zero by 2050 will require a tripling in spending on clean energy and infrastructure by 2030, with a shift towards higher investment in developing economies (IEA, 2022e; BloombergNEF, 2023). Total clean energy investment is predicted to increase to about $2.19 trillion to in the Stated Policies ("STEPS") scenario, $3.30 trillion in the Announced Pledges (APS) scenario, and must increase to $4.56 trillion for net zero ("NZE"), three times the current annual spending as shown in Figure 1 (IEA, 2023b).

Figure 1: Total Annual Clean Energy Investment to 2030



In the past five years, clean energy investments in the power sector have grown at a rate fast enough to put the world on track to surpass its announced pledges by 2030, but it is unlikely that this rate will be maintained without supportive policies in developing markets (IEA, 2022e). Based on the net zero scenario, the total investment opportunity in clean energy is about $3.2 trillion between 2023 and 2030, and 72% of this will be in electrified transport ($1.47 trillion per year), renewable energy ($1.18 trillion), and grids ($630 billion - $830 billion) (BloombergNEF, 2023; IEA, 2021). The International Energy Agency ("IEA") predicts that by 2050, annual clean energy investment will fall back to $4.5 trillion as the cost of renewables continues to decline (IEA, 2021d). Clean electrification will play an important part in reducing emissions, as it decreases demand for emissions-intensive energy sources, shown in Figure 2 & Figure 3 (IEA, 2021d).

Figure 2: Share of electricity in final energy consumption 2020-2050

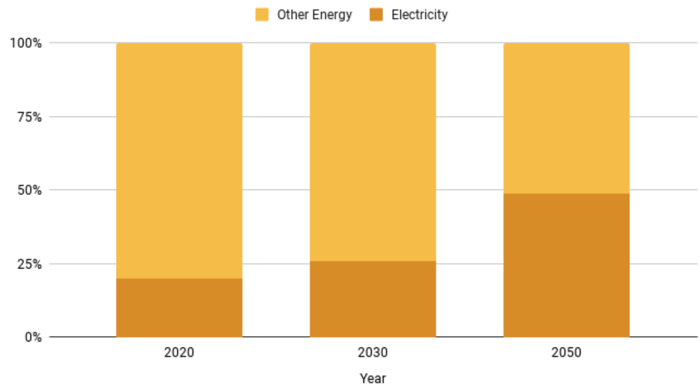
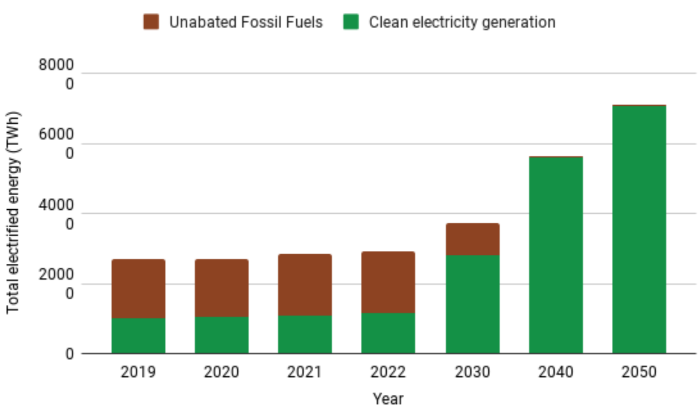


Figure 3: Electricity generation needed for Net Zero



Achieving net zero emissions by simply increasing the share of renewables may seem promising considering the levelized cost of energy ("LCOE"), but this approach fails to account for the grid-level costs necessary to compensate for variable renewable energy's ("VRE") variability and intermittency (NEA, 2022). The 2022 energy crisis, triggered by Russia's reduction in natural gas deliveries to the European Union after the invasion of Ukraine, highlighted nations' reliance on natural gas as a stable baseload power source and the need to scale up alternatives to fossil fuels (IEA, 2023b). Nuclear energy can be a highly competitive solution to fulfill the role of a low-carbon baseload, with grid-level analyses showing that significantly less built capacity is required for decarbonization with dispatchable, baseload nuclear power compared to renewables and energy storage alone (Sepulveda, 2016).

While the current strategy of retiring coal and deploying new VREs alongside natural gas may seem like progress toward 2030 emissions targets, investing in more nuclear now would prevent the difficulty of phasing out baseload natural gas when it becomes necessary (NEA, 2022). Heavier government involvement will be valuable in promoting further nuclear development making nuclear energy more attractive to private investors (IEA, 2022c). Nuclear capacity needed by 2050 in a cost-effective net zero scenario is estimated at 1,160 GWe of electricity, compared to the 479 GWe projected based on current policy trends (NEA, 2023a). Nuclear energy investment will need to rise to 125 billion per year by 2030 to be on track for this scenario.

Figure 4: Total Nuclear Energy Generation (1965-2022)

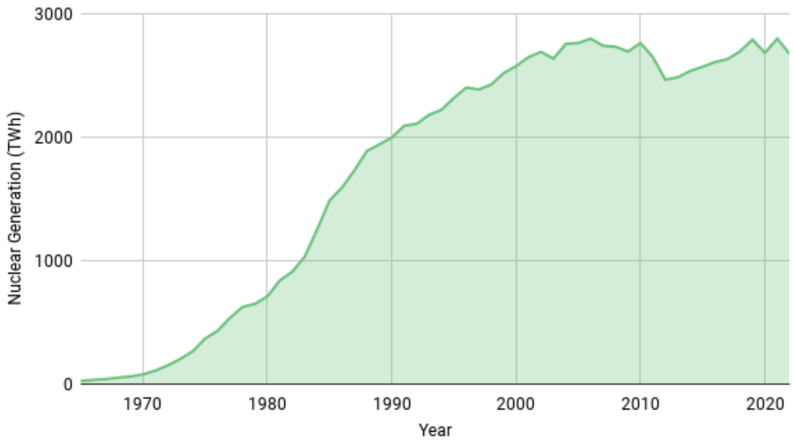


Figure 5: Nuclear Power Capacity Additions and Retirements in the Net Zero Scenario

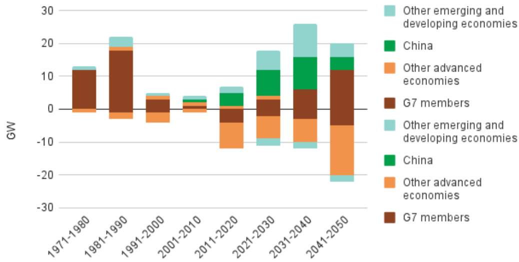
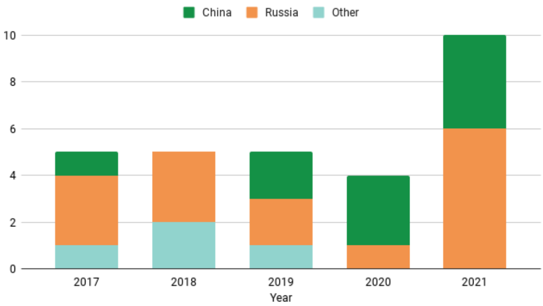


Figure 6: Nuclear energy construction stats by country, 2017-2021



The nuclear power capacity additions and retirements according to IEA's Net Zero Scenario in China, G7 countries - Canada, US, UK, France, Germany, Italy, Japan and the EU, other advanced economies and developing and emerging economies is shown in Figure 5. While other clean energy technologies have seen record levels of investment in recent years, global investment in nuclear has remained flat (BloombergNEF, 2023; Energy Institute, 2023). Nuclear energy generation has stagnated in the US, compared to countries like China, Japan, and France, where there has been interest in lifetime extensions of existing reactors and constructing small modular reactors (IEA, 2022e)

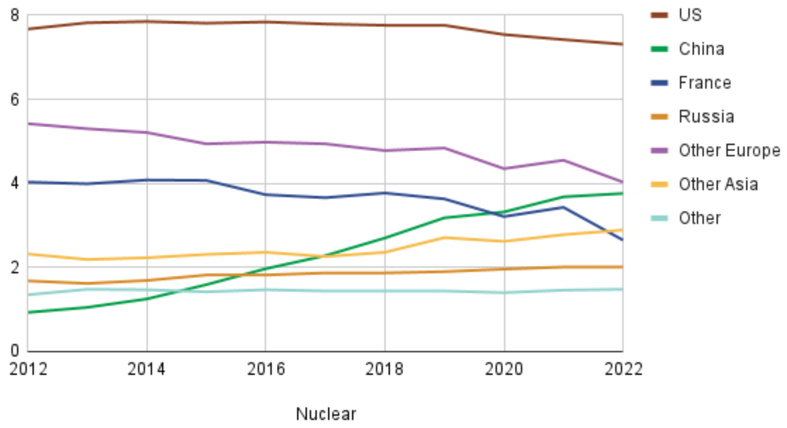
Since 2017, the majority of new commercial nuclear construction has taken place in just China and Russia (Figure 6) (IEA, 2022c). In 2022, the growth rate of nuclear energy consumption was -1.0% in the US, as opposed to +2.5% in China (Energy Institute, 2023).

The major challenges facing nuclear power and stymieing its growth are its high capital costs and long development timeline (McKinsey, 2023; Eash-Gates et al., 2020). Building a traditional nuclear plant, with about 1 GW capacity (Harman, 2021), takes a median of 88 months as of 2021 (WNA, 2023ll) with capital costs of about Levelized cost of energy of $8,475 – $13,925 per kWe, or $8 billion to $14 billion total (Lazard, 2023). In comparison, a gas plant's capital costs can be as low as $700/kWe for gas, with a development timeline of just 42 - 60 months(Lazard, 2023). In the US, safety regulations, decreased labor productivity, and low resilience to construction conditions have contributed to a steep increase in the cost of nuclear power (Eash-Gates et al., 2020). As gas prices have decreased, nuclear energy faces lower profitability, discouraging investment into nuclear energy and thereby threatening the success of emissions reductions targets (Hsain et al., 2021). Despite these challenges, emerging next-generation reactor designs are predicted to reduce costs and make it possible to more fully realize the potential of nuclear energy (Eash-Gates et al., 2020).

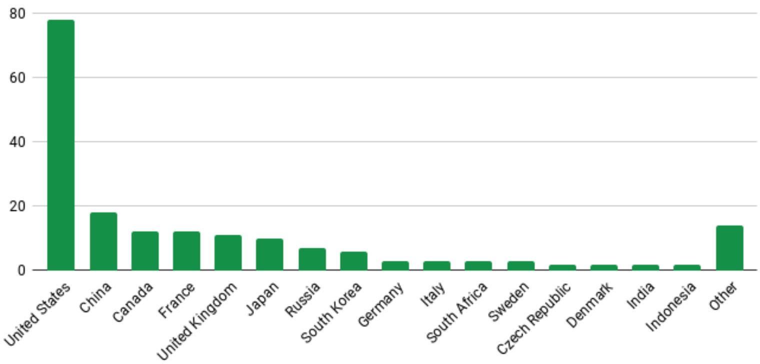
Small modular reactors ("SMRs") could reduce upfront costs and construction time, due to their simple, more modular design (McKinsey, 2023). SMRs typically generate under 300 MW, as opposed to 1GW for standard reactors, and may be able to modulate their power outputs, making them both cheaper and more flexible (Hsain et al., 2021). SMR companies are developing reactors that can be entirely fabricated in a factory and installed on-site, reducing development costs (Hsain et al., 2021). SMRs will use serial construction; as more units are built, the unitized costs will decrease through additional learnings from previous units, the standardization of designs, and the amortization of non-recurrent costs(NEA, 2023a). SMRs are also advantageous in that they target applications of nuclear energy in sectors which are difficult to abate and have limited renewables potential, such as industry and district heating (NEA, 2023a).

The first SMR units are already in operation in China and Russia, and over 80 designs are under development in 19 countries (Perera, 2023). In an ambitious case, the NEA estimates that 375 GW of SMR capacity could be installed by 2050, over 50% of the nuclear capacity gap to NZE (NEA, 2023a). However, these technologies may require over a decade to be deployed at scale (Hsain et al., 2021), and greater investment is crucial to further improve the cost, timeline, and complexities of SMRs (McKinsey, 2023). In the IEA's Net Zero scenario, half of global emissions reductions by 2050 are from such advanced technologies that are not yet commercially viable (IEA, 2022c).

Figure 7: Nuclear Energy Consumption (EJ)



Country Profiles



CHINA

China plays a crucial role in the global energy transition, being responsible for a third of all CO2 emissions, mainly from coal. As of 2021, China's energy production was dominated by fossil fuels (82%) but also included renewables (16%) and nuclear energy (2%). The country has been increasing its clean energy share and advancing rapidly in nuclear electricity generation. China, which aims to achieve carbon neutrality before 2060, has a significant nuclear program with 55 active reactors and more under construction, aiming to increase nuclear capacity significantly.

China's nuclear developments include a focus on advanced reactors like modular small-scale reactors, commercial high-temperature gas-cooled reactors (HTGRs), and offshore nuclear platforms. Notable projects include a thorium-fueled molten salt reactor and a low-temperature reactor for decarbonizing the heating sector. Internationally, China collaborates on nuclear technologies, including the construction of the Linglong-1, the world's first commercial land-based small modular reactor (SMR) plant.

The country's energy strategy includes increasing non-fossil fuel energy use to 25% by 2030, with nuclear power playing a significant role. By 2035, China's nuclear capacity is expected to reach 180MW, contributing 5% to total capacity and 10% to electricity production. The country has been actively expanding its nuclear capacity and investing heavily in nuclear technology, also exporting this technology globally. This expansion is part of China's broader commitment to significantly increasing nuclear power's contribution to its energy mix by 2060.

Figure 8: Total Energy Supply of China by Year

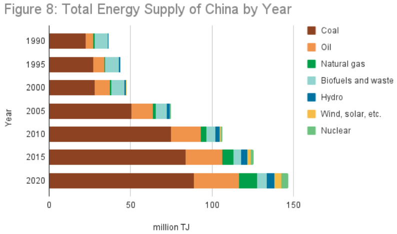


Figure 9: Nuclear Electricity Generation: China

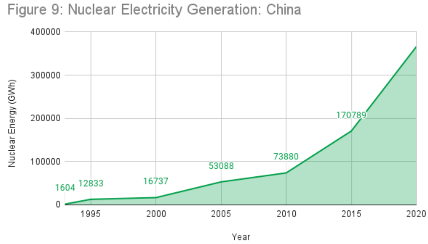


Figure 10: Installed Nuclear Capacity Targets in China

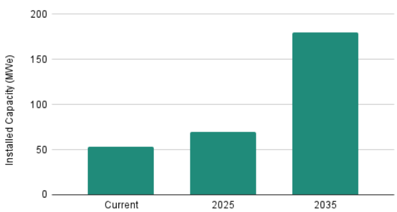
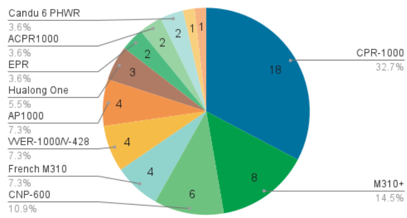


Figure 11: Operational Reactors: China



JAPAN

In 2022, Japan's energy mix comprised 85% fossil fuels, 3% nuclear, and 12% renewables. There's been an increase in renewables and nuclear energy in the past 5-7 years, as seen in a yearly total energy supply chart. Despite leading in energy efficiency and reducing emissions, Japan faces limitations in expanding renewable capacity due to geographical constraints. Consequently, nuclear energy is significant in Japan’s energy strategy. The country operates 10 pressurized water reactors and is constructing 2 boiling water reactors, but post-Fukushima, 27 reactors were shut down, and 23 suspended.

Japan, which aims for carbon neutrality by 2050, has seen a revival in nuclear energy use, from almost none in 2014 to about 6-7% by 2023. The government plans to restart many suspended reactors and extend the lifespan of existing ones, despite the high costs and public concerns. Nuclear energy is expected to make up 20-22% of Japan's energy mix by 2030, alongside 36-38% renewables. However, achieving this goal faces challenges, including financial costs and feasibility within the given timeframe.

Public opinion on nuclear energy is shifting, with a majority now supporting reactor restarts, influenced by the 2022 energy crisis. Japan is also exploring advanced nuclear technologies, including small modular reactors (SMRs) in collaboration with the U.S. Over a dozen Japanese companies are investing in the UK's Core Power floating molten salt reactor project, and there are partnerships for developing commercial fusion energy. Japan is also working on a demonstration high-temperature gas-cooled reactor and a fast breeder reactor. These advancements indicate Japan's commitment to diversifying and modernizing its nuclear energy sector.

Figure 12: Nuclear Electricity Generation: Japan

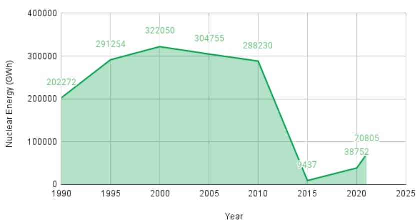
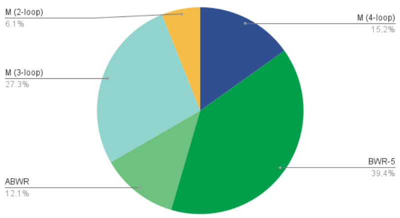


Figure 13: Types of Operable Reactors: Japan



INDIA

India's primary energy mix is currently dominated by fossil fuels (88%), with renewables (10%) and nuclear energy (1%) playing smaller roles. The country's energy demand is expected to grow rapidly, driven by population growth, industrialization, and urbanization, with an estimated annual increase of 3% from 2021 to 2030. Despite low per capita emissions, India's large population and reliance on coal make it the third-largest CO2 emitter globally.

Although there has been growth in nuclear and renewable energy, the increase in coal, oil, and biofuel production has been much more significant. India has become the world's second-largest producer of energy from coal and is expected to continue increasing its coal usage in absolute terms until 2030, challenging its net zero goal by 2070.

To achieve net zero, India needs to scale up renewable and nuclear energy significantly. The country is experiencing rapid growth in renewables, aiming for a capacity of 500 GW by 2030. Solar power, supported by technology and policy, has become cheaper than coal plants. However, the deployment of renewables faces challenges due to land constraints, as India is densely populated and heavily reliant on agriculture.

Nuclear energy is seen as a key component in transitioning away from coal, due to its stability and low land use compared to renewables. India currently operates 22 nuclear reactors with a total capacity of 6,795 MWe, contributing 3% of its energy. There are plans to triple this capacity to 22,480 MWe by 2031 and generate 9% of electricity from nuclear by 2047. The country is building new reactors and has approved plans for more efficient construction methods. The Bhabha Atomic Research Centre is focusing on developing indigenous nuclear technologies, including thorium-fueled breeder reactors, aiming for self-sufficiency in nuclear energy.

Figure 14: Total Energy Supply of India by Year

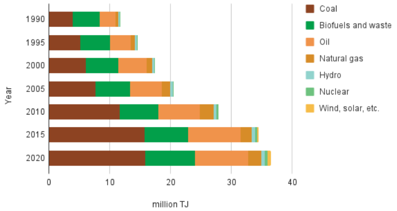
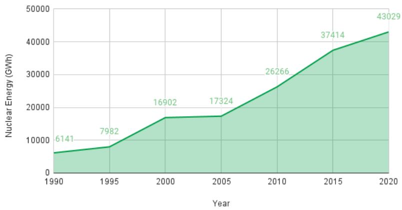


Figure 15: Nuclear Electricity Generation of India



INDONESIA

Indonesia heavily depends on coal and natural gas for its electricity generation, with each contributing 62% and 18% respectively to the country's generation mix (WNA, 2023j). Indonesia has targeted to reduce its emissions by 29% (WNA, 2023j). The country has also made plans to achieve net-zero by 2060 (2022a). Though in recent years Indonesia has made efforts to harness its renewable energy potentials, (see Figure 16) it currently has no operable nuclear reactors. In 2014, the government issued the National Energy Policy ("NEP"), which promotes the growth and use of New Renewable Energy ("NRE") that includes nuclear energy (WNA, 2023j). In December 2022, Indonesia's Nuclear Energy Control Agency (Bapeten) announced that the Indonesian government plans to build a new nuclear power plant by 2039 (Enerdata, 2022). In March 2023, the US and Indonesia announced a strategic partnership to help Indonesia develop its nuclear energy program, supporting Indonesia's interest in deploying SMR technology to meet its energy security and climate goals (WNA, 2023y).

Figure 16: Total Energy Supply of Indonesia by Year

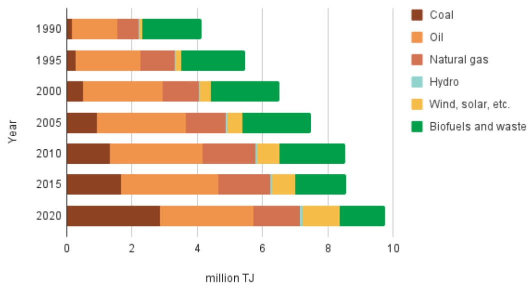
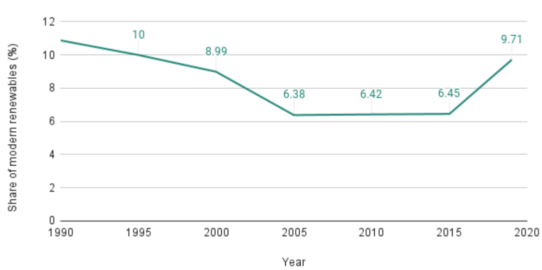


Figure 17: Share of Modern Renewables (%) vs Year: Indonesia



SOUTH KOREA

Fossil fuels like coal, oil, and natural gas dominate South Korea's energy supply (see Figure 25) and account for 85% of the country's primary energy consumption (WNA, 2023m). Nuclear power accounts for about 30% of the country's electricity generation (IAEA, 2023). The yearly nuclear electricity generation of the country is shown in Figure 21. The country has 25 operable reactors (22 PWRs and 3 PHWRs) with a capacity of 24,489 MWe, and 3 PWR type reactors are under construction with an estimated capacity of 4020 MWe (IAEA, 2023). The technology types of the operable reactors are shown in Figure 20.

In 2017, the president of South Korea introduced the phasing out of nuclear energy (WNA, 2023m). However, in 2022, the newly elected president of South Korea rejected this policy. South Korea has also made a target for nuclear energy to provide a minimum of 30% of electricity by 2030 (WNA, 2023m). The 10th Electric Plan (2022-2036) proposed that nuclear energy should account for up to 34.6% of generated electricity (WNA, 2023hh). In 2021, South Korea was the fifth largest CO2 emitter in Asia, emitting 627 Mt total and 12.13 t per capita (Crippa et al., 2022). Under the Paris Agreement, Korea is committed to limit its emissions to 536 million tons of carbon dioxide equivalent ("Mt CO2-eq") in 2030 (IEA, 2020a). It has also set a target to reach carbon neutrality by 2050 (Government of the Republic of Korea, 2020). Nuclear is considered a source of baseload power in South Korea and its affordability and reliability can be further utilized to reach the country's climate goals (Government of Korea, 2020). Globally, South Korea is a leader in nuclear energy, having signed a $20 billion contract to build the UAE's first nuclear power plant (WNA, 2023hh). It has also made plans to export 10 nuclear power plants abroad (WNA, 2023hh). Recently, South Korea has focused on developing SMRs through public-private partnerships (WNA, 2023hh). An agreement has been signed between South Korea and the US for cooperation regarding SMRs (WNA, 2023aa).

Figure 18: Total Energy Supply of South Korea by Year

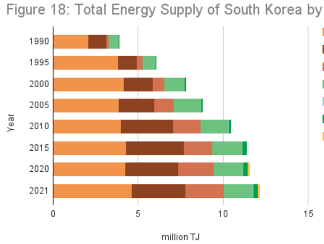


Figure 19: Nuclear Electricity Generation: South Korea

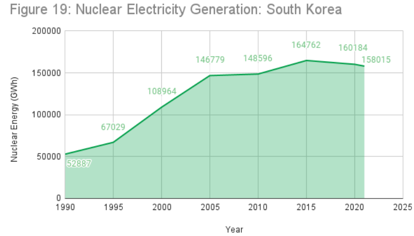
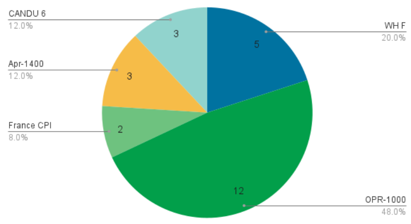


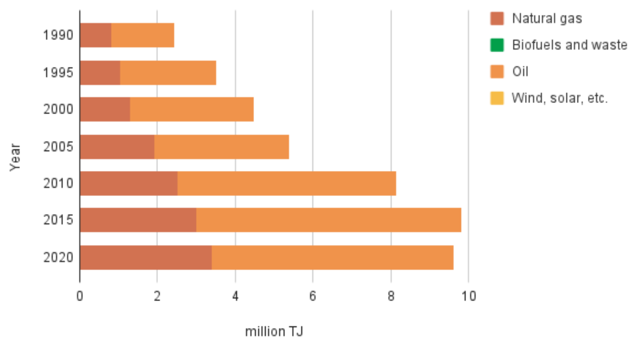
Figure 20: Operable Reactors: South Korea



SAUDI ARABIA

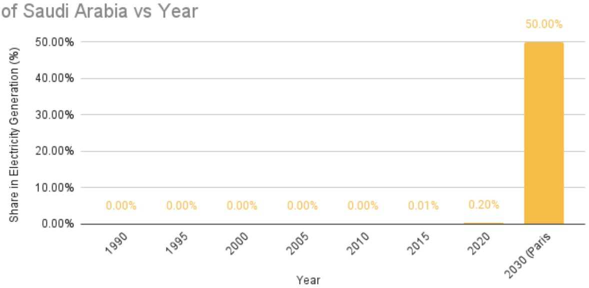
Natural gas accounts for 56% and oil accounts for 44% of the generation mix in Saudi Arabia (WNA, 2022c). The energy mix of the country is shown in Figure 22. With some of the largest natural gas reserves in the world and around 17% of the world's proven petroleum reserves (OPEC, 2022), Saudi Arabia relies heavily on fossil fuels, which hinders the growth of clean energy in the country. As part of the Paris Agreement, the country committed to generate 50% of its electricity from renewable energy and 50% from natural gas by 2030 (Climate Action Tracker, 2021).

Figure 21: Total Energy Supply of Saudi Arabia by Year



Solar energy is Saudi Arabia's only clean energy source, making up a share of just 0.03% of generated energy in 2019 and 779 GWh (0.20%) out of a total 395,118 GWh of electricity in 2020 (IEA, 2020b). Figure 23 shows the great disparity between the country's current energy mix and its targeted goals. In 2013, the country set a goal to achieve 17 GWe of nuclear energy by 2032. However, this target was canceled in 2015 and the country still has no nuclear reactors (WNA, 2022c). Thus, Saudi Arabia is far behind its climate goals and sustainability ambitions. It must focus on expanding its solar energy and building nuclear energy to meet its targets. In February 2022, Saudi Arabia confirmed the establishment of the Nuclear Holding Company, which will be responsible for the country's nuclear development (WNA, 2022c).

Figure 22: Share of Renewables (Solar) in Electricity Generation (%) of Saudi Arabia vs Year



PAKISTAN

Pakistan's generation mix is primarily made of natural gas (33%) followed by hydro (26%) and coal (19%) (WNA, 2023k). With a 9% contribution to the generation mix, Pakistan has 6 operable nuclear reactors and a capacity of 3,262 MWe. All 6 of its operable nuclear reactors are PWRs built by China (WNA, 2023k) and Pakistan also relies on China for enriched fuel for its reactors (WNA, 2023k). Even though Pakistan is not a signatory of the Nuclear Non-Proliferation Treaty (an agreement to prevent the spread of nuclear weapons), China has played a major role in nuclear cooperation with Pakistan (WNA, 2023k). In 2021, Pakistan set a target to reduce its projected emissions by 50% by 2030 (UN, 2023). The total energy generated by source per year shows the growth of hydro, nuclear, solar and wind energy (Fig 24). In July 2023, the Prime Minister of Pakistan launched a $3.5 billion Chinese-designed nuclear energy project - the Chashma-V nuclear power plant - a PWR with a 1,200 megawatt capacity (Ahmed, 2023).

Figure 23: Total energy Supply of Pakistan by Year

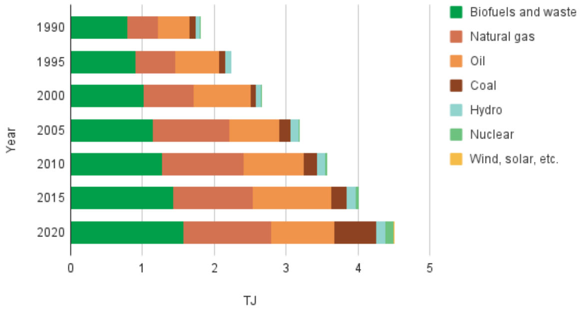
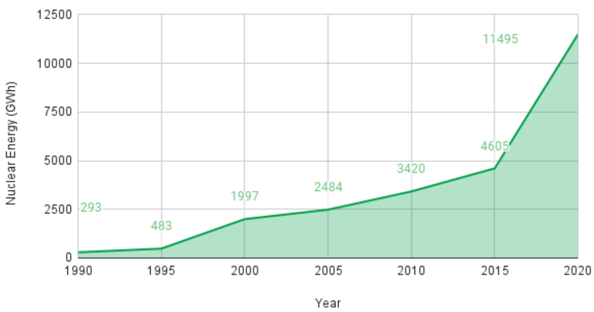


Figure 24: Nuclear Electricity Generation: Pakistan



TURKEY

Turkey is primarily dependent on coal for its energy supply (WNA, 2023q) (see Figure 26). Hydro comes second, followed by natural gas (WNA, 2023q). Due to rapid population and economic growth (see Figure 27), energy demand has also sharply escalated in the past two decades (IEA, 2021e). This has resulted in a rapid rise in energy imports since the 1990s. (Dierks, 2023). Construction of the first nuclear power plant at Akkuyu is currently underway (WNA, 2023q). It started in April 2018 and is expected to be commissioned in 2023. The nuclear power plant will have a capacity of 4,800 MWe. The $20 billion project is a product of the agreement between Turkey and Russia and will be built by Russia's state nuclear energy company Rosatam. It is expected to generate 10% of the country's electricity needs. A nuclear cooperation agreement with South Korea was signed in June 2010 and two more with China in April 2012. In January 2023, Korea Electric Power Corporation ("KEPCO") submitted a preliminary proposal to Turkey for the construction of four APR-1400 reactors at an undisclosed site in the northern part of the country (WNA, 2023q).

Figure 25: Total Energy Supply of Turkey by Year

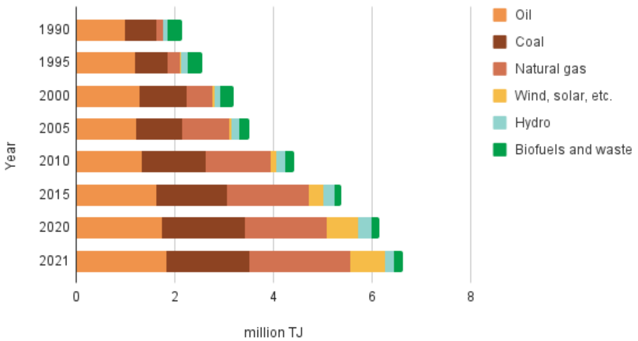
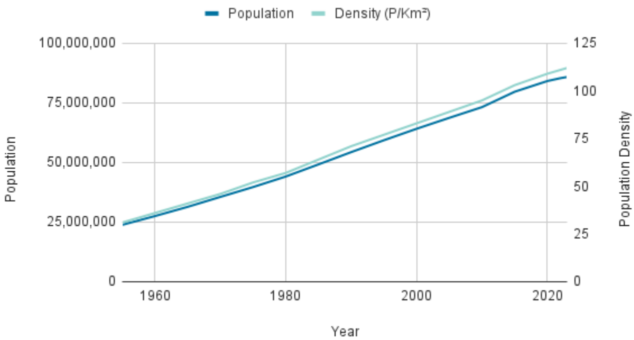


Figure 26: Population and Density (P/Km²): Turkey



UNITED KINGDOM ("UK")

In recent years, particularly following the threat to energy security during Russia's invasion of Ukraine, the UK has been working to reverse these trends and incentivise investment in domestic nuclear power (UK Government, 2022). The 2022 Nuclear Energy (Financing) Act will reduce the costs consumers pay for energy from new nuclear plants by providing regulated financial support during nuclear energy construction, commissioning, and operation (IEA, 2022c). Also in 2022, the UK Parliament committed to investing in over £2 billion in new nuclear energy, including £100 million for the planned Sizewell C power station and £210 million to develop SMRs (UK Government, 2022). The UK startup Core Power is developing a molten salt reactor for maritime applications and has raised about USD 100 million, largely supported by Japan (WNA, 2023cc). By 2030, the UK plans to build 8 more nuclear reactors, delivering the equivalent of one reactor a year (UK Government, 2022). By 2050, the UK aims to increase the share of nuclear power in electricity from 15% to 25%. The Hinkley Point C site is currently being constructed, with the first new reactors in over 30 years (WNA, 2023x). However, its completion was first delayed to June 2026 (WNA, 2022f), and then to June 2027, after originally being planned for 2025 in 2016 (WNA, 2023x). These delays increased the projected cost from under £22 billion to £25-26 billion (about $30-31 billion) (WNA, 2022f; WNA, 2023x).

Figure 27: Total Energy Supply of UK by Year

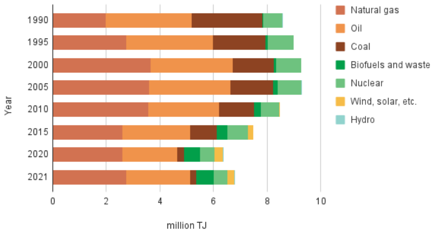


Figure 28: Nuclear Electricity Generation: UK

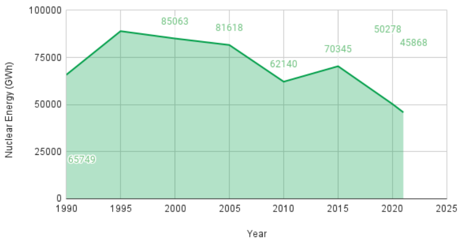
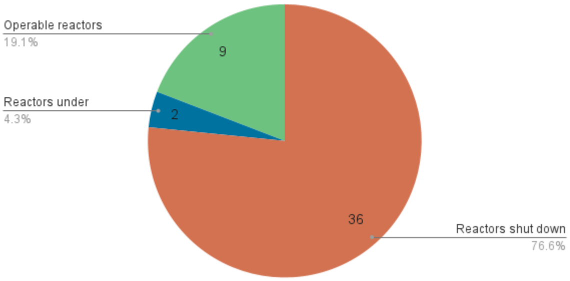


Figure 29: Nuclear Reactors: Shut Down, Operable and Under Construction: UK



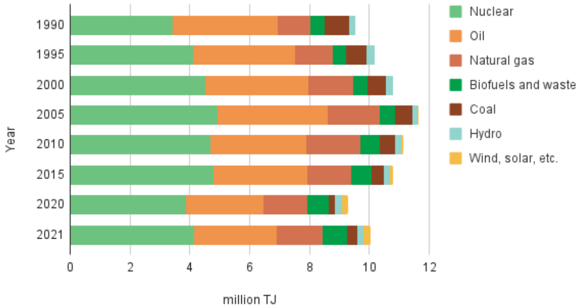
FRANCE

In 2022, France's primary energy consumption was mainly composed of fossil fuels (61%), nuclear energy (36%), and renewables (17%). Nuclear power is significant in France, accounting for 79% of domestic energy production and 63% of electricity production, with the country operating 56 nuclear reactors. However, France's nuclear sector faces challenges due to aging reactors, with the average age over 35 years and a decrease in output due to maintenance issues. Additionally, increased temperatures have affected energy demand and the cooling capacity for nuclear reactors.

The French government initially planned to reduce nuclear electricity's share to 50% by 2025, but this target was first delayed to 2035 and later repealed in 2023. Now, France considers building at least six new reactors and investing in advanced nuclear technologies, including small modular reactors, to address current challenges. The government has allocated significant funding for nuclear energy research and development, focusing on areas like nuclear fusion.

To achieve carbon-free electricity by 2050, an analysis suggests that the most cost-effective approach for France is to accelerate renewable energy investment while extending the life of existing nuclear reactors. The International Energy Agency (IEA) recommends that France implement more focused policies to boost investor confidence in clean energy and coordinate energy and climate policies more stringently across sectors and regions. This strategy aims to maintain nuclear energy's role in France's energy mix while transitioning to a low-carbon future.

Figure 30: Total Energy Supply of France by Year



RUSSIA

In 2022, Russia's energy mix was dominated by fossil fuels (86%), with nuclear and renewables each contributing 7%. The country operates 37 nuclear reactors with a total capacity of 27,727 MWe, making it an influential player in the global nuclear sector through Rosatom, its state nuclear company. Despite this, Russia's CO2 emissions were high in 2021, totaling 1,942 Mt, and its per capita emissions stood at 13.52 t.

Russia has set a goal to reach carbon neutrality by 2060, but this ambition has been met with skepticism, particularly regarding the reliance on its forests to neutralize emissions. The country has a history of setting weak climate targets and failing to meet them, as seen in 2020 when it missed its energy efficiency target significantly.

Russia's economy is heavily reliant on the export of fossil fuels, and decarbonization is not a major priority in its energy strategy. Despite international sanctions, Russia has continued to profit from exporting fossil fuels to Asian countries. Its National Energy Strategy up to 2035 suggests an increase in the production and export of carbon-intensive energy, casting further doubts on achieving its climate goals.

While Rosatom is expanding Russia's nuclear capacities, this seems more aligned with freeing up fossil fuels for export rather than reducing domestic fossil fuel consumption. Russia's engagement in nuclear research and construction is growing, but its dependence on fossil fuel exports and lackluster efforts towards meeting emissions targets pose challenges to the global energy transition.

Figure 31: Total Energy Supply of Russia by Year

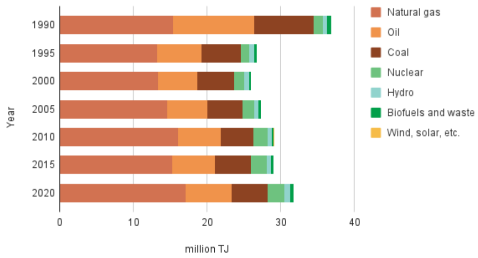
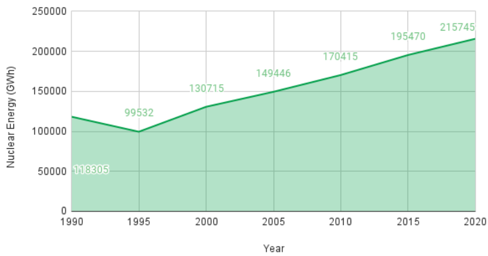


Figure 32: Nuclear Electricity Generation: Russia

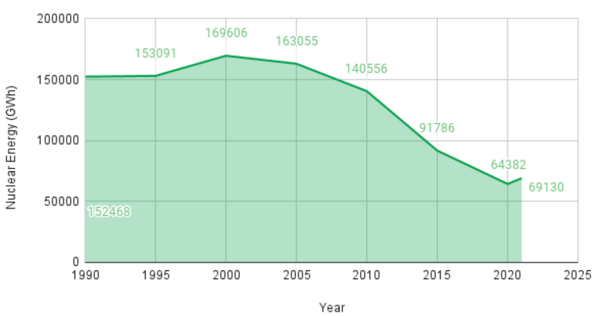


GERMANY

From obtaining a quarter of the electricity from nuclear power plants until 2011 to phasing out all of them by 2023, Germany has witnessed a steep fall in its utilization of nuclear energy (IAEA, 2023). Fossil fuels dominate the energy supply (see Figure 41) and generation mix of Germany (IEA, 2023c). Wind is its primary source among renewables. Germany began operating commercial nuclear power plants in 1969, but a coalition government formed after the 1998 federal elections adopted nuclear phase-out policies, influenced by anti-nuclear sentiments following the Chernobyl disaster in 1986 (WNA, 2023h). Though the policy was canceled in 2009, it was reintroduced in 2011 after the Fukushima accident, when the government decided to phase out all nuclear power plants by 2022 (WNA, 2023h). The phasing out of the last three reactors was postponed to mid-April 2023 in light of the Russia-Ukraine war (WNA, 2023h). To date, 36 reactors, with a capacity of 26,375 MWe, have been shut down (IAEA, 2023). Nuclear electricity generation has been declining since the 2000s (see Figure 33) and the country has expanded its reliance on fossil fuels, a move which has been globally criticized (WNA, 2023h).

While Germany has not seen any further development in traditional fission reactors, the country made announcements in early 2023 about new programs to support fusion commercialization (Fusion Industry Association, 2023). Germany is home to three nuclear fusion startups, Gauss Fusion, Marvel Fusion, and Proxima Fusion, and has partnered with the US on another startup, Focused Energy. Germany's fusion industry is seeing increases in investment, including funding from the German Federal Agency for Disruptive Innovation (Fusion Industry Association, 2023).

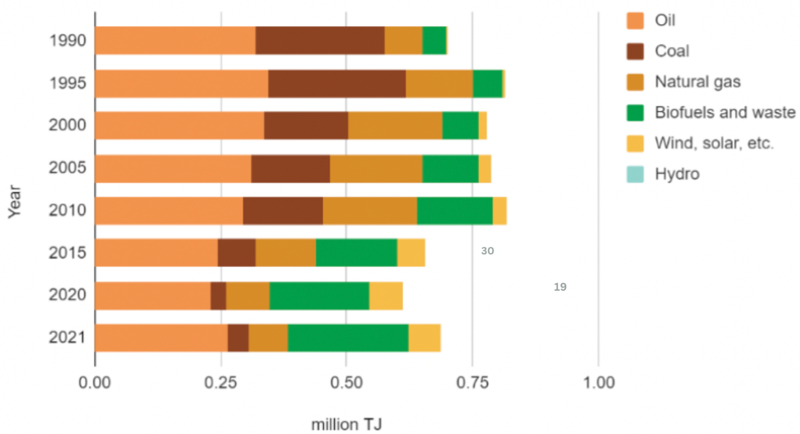
Figure 33: Nuclear Electricity Generation: Germany



DENMARK

Wind energy contributes nearly 57% to the electricity mix of Denmark, much of which is exported (WNA, 2022a). However, there are no commercial nuclear power plants; a 1985 resolution stated that no nuclear power plants would be built, and it has never been reversed (WNA, 2022a). However, for the first time in 2022, 39% of survey respondents against nuclear power plants were outnumbered by 46% who were in favor (Brixen, 2022). There are currently two domestic nuclear start-ups in Denmark, Seaborg Technology and Copenhagen Atomics, which are independently developing molten salt reactors, though not intended for the domestic market. Denmark faces limitations in research, as no government funding is allocated to nuclear power research (Brixen, 2022).

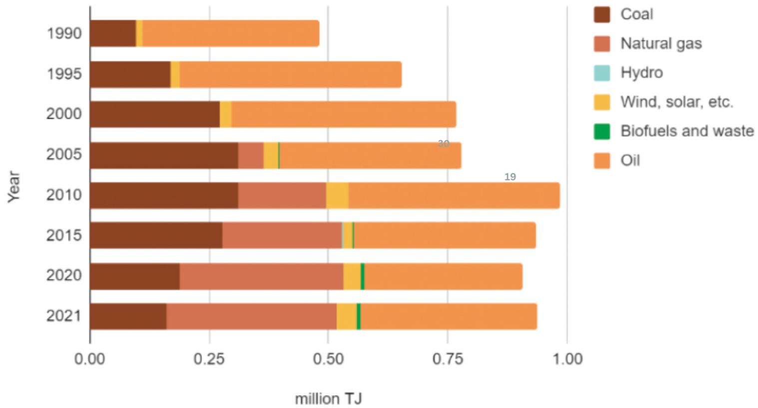
Figure 34: Total Energy Supply of Denmark by Year



ISRAEL

Israel is largely dependent on fossil fuels for its power production (WNA, 2023a). Though the country operates nuclear research reactors, it does not have any nuclear power plants (WNA, 2023a). This is primarily because Israel is not a part of the Nuclear Non-Proliferation Treaty which prevents the country from engaging with international suppliers of nuclear technology (WNA, 2023a). Over the years, Israel has maintained opacity regarding its nuclear military arsenal (NTI, 2022), which makes it difficult for it to acquire nuclear equipment or fuel from outside the country (WNA, 2023a). Also, large deposits of natural gas make it more cost-effective to produce electricity from gas rather than through nuclear energy (ANI, 2023). As of November 2015, Israel targeted a reduction in greenhouse gas emissions of 25% by 2030 (Cohen, 2015). As of 2020, Israel has targeted generating 10% of the country's electricity from renewable sources (IEA, 2021c). However, solar thermal, photovoltaic power, wind energy, and biomass are considered to be at the forefront of their de-carbonization path (IEA, 2021c).

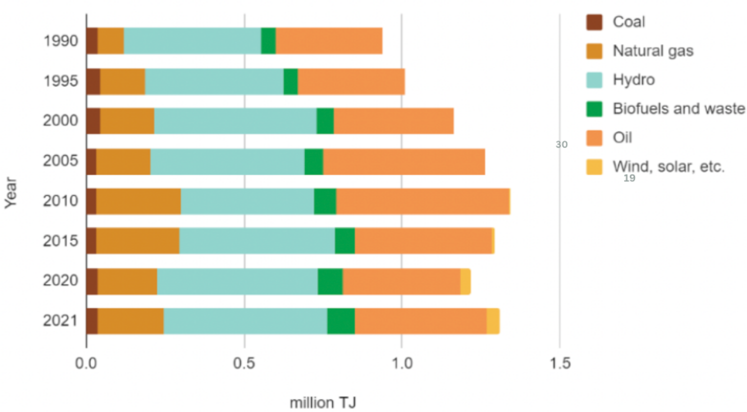
Figure 35: Total Energy Supply of Israel by Year



NORWAY

Norway's energy sector is dominated by hydropower, with no commercial nuclear power plants. It had four research reactors, one at Halden and three at Kjeller, all of which were eventually shut down by the end of 2019 (Nikel, 2021). The Norwegian Radiation Protection Agency has licensed an underground repository inside a mountain for radioactive waste from the country's oil and gas industry. It will hold 6,000 tons of naturally occurring radioactive material ("NORM") waste, and 400 tons have already been placed there (WNA, 2023a). Norway has 12 tons of used fuel from its Halden research reactor, and in 2010 a commissioned report recommended that this be sent to Mayak in Russia for reprocessing. If reprocessed, the uranium would be used in RBMK reactor fuel and the plutonium recycled in Russia as mixed oxide ("MOX") (WNA, 2023a). In June 2023, Norwegian firm Norsk Kjernekraft signed a letter of intent with TVO Nuclear Services, a Finnish consulting company to jointly investigate the deployment of SMRs in Norway (WNA, 2023ee). The country has huge deposits of thorium, a potentially more environment-friendly alternative to uranium (Nikel, 2021).

Figure 36: Total Energy Supply of Norway by Year



SWITZERLAND

Oil is a major source of the country's energy supply, followed by nuclear (see Figure 37). However, 57% of the country's electricity is generated from hydro. Nuclear comes second with a 40% contribution to the generation mix and is generated by 3 nuclear power plants with 4 nuclear reactors (WNA, 2023n). The four reactors (3 PWRs and 1 BWR) have a capacity of about 2,973 MWe. Currently, nuclear electricity generation has been declining since the 2011 Fukushima disaster, in 2017 a referendum was passed confirming the phasing out of all nuclear reactors; one plant has already been shut down (WNA, 2023n).

Figure 37: Total Energy Supply of Switzerland by Year

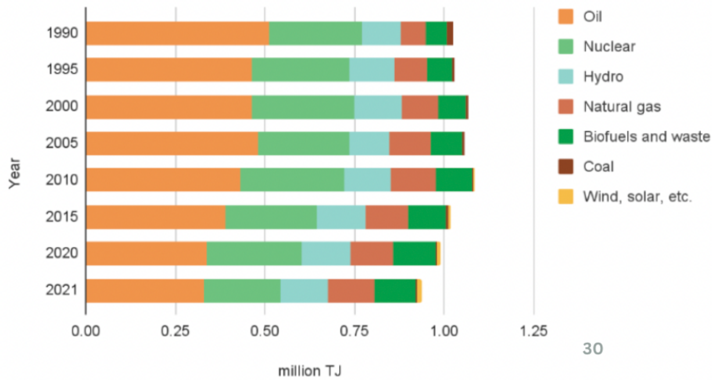
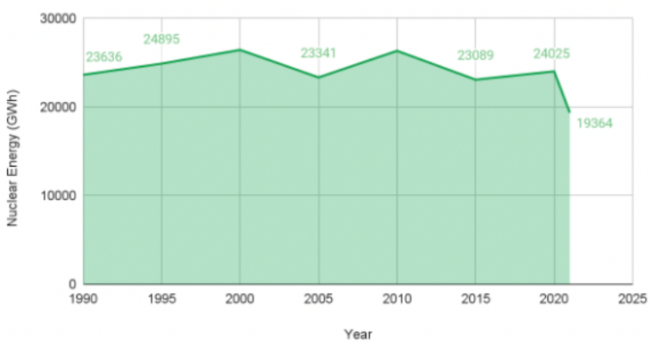


Figure 38: Nuclear Electricity Generation



NETHERLANDS

Natural gas is a major energy source (see Figure 39) and is a primary contributor (47%) to the generation mix of the Netherlands. Wind (15%) comes second, followed by biofuels and waste (10%). The country has one nuclear reactor, the Borssele Nuclear Power Plant. This PWR produces only 482 MWe, contributing just 3% to the country's electricity (WNA, 2023p). The yearly nuclear electricity generation (see Figure 40) of the Netherlands has remained relatively flat. A previous decision to phase out nuclear power was reversed, and in 2021 the government announced plans to build two new nuclear units (WNA, 2023p). In December 2021, the Dutch government committed $5 billion for the construction of two new nuclear power plants in its efforts to meet climate goals (van Halm, 2022).

Figure 39: Total Energy Supply of Netherland by Year

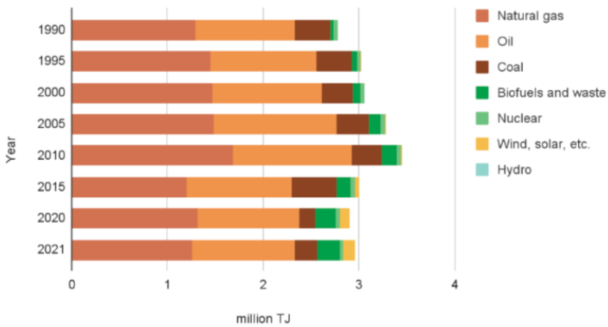
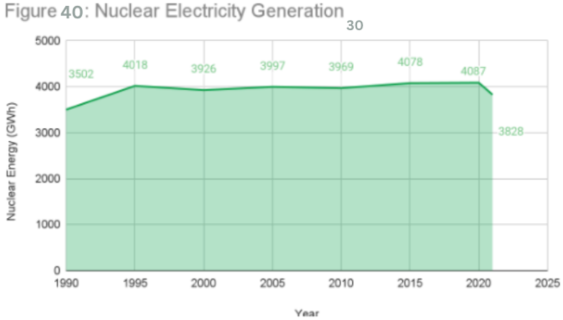


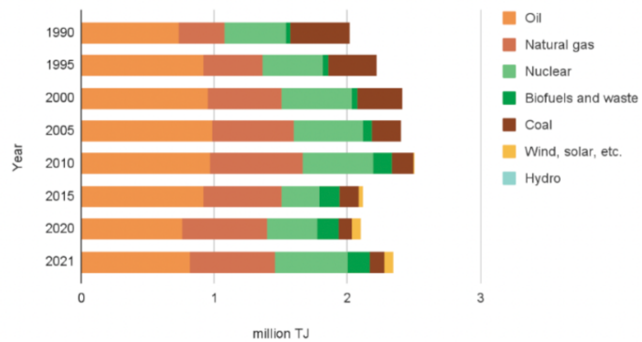
Figure 40: Nuclear Electricity Generation



BELGIUM

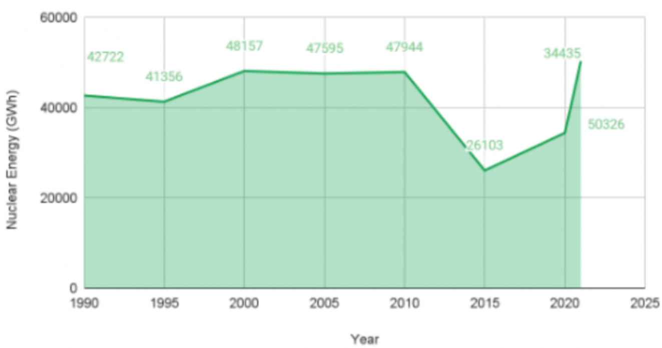
Belgium is primarily dependent on nuclear energy for its electricity generation. It is the second largest energy source in the country (see Figure 41). With five operable PWRs, nuclear energy covers 50% of the country's generated electricity (WNA, 2023d). Combined, the nuclear power plants have a capacity of about 3,928 MWe (WNA, 2023d). The nuclear electricity generation of Belgium every year is shown in Figure 42.

Figure 41: Total Energy Supply of Belgium by Year



Though the country decided to completely phase out nuclear energy by 2025, in March 2022, the phase-out date was postponed by 10 more years (WNA, 2023d). In September 2022 and January 2023, two reactors were shut down (ENS, 2022). Again in 2023, Belgium signed an agreement with Engie to extend the use of the country's nuclear reactors by 10 years (Strauss, 2023). This was in response to the Russia-Ukraine war and rising fossil fuel prices (Strauss, 2023).

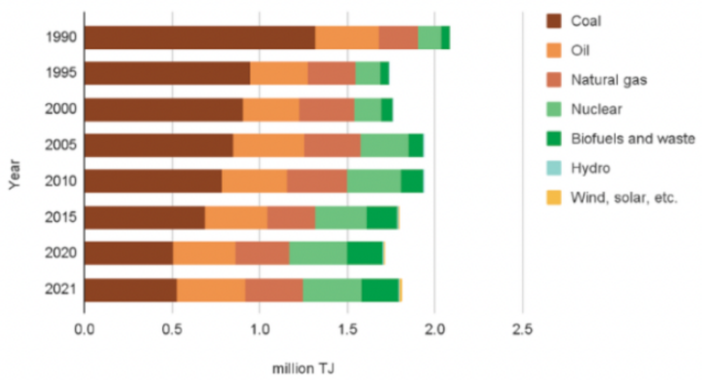
Figure 42 : Nuclear Electricity Generation



CZECH REPUBLIC

The country's energy supply (see Figure 43) and its generation mix is dominated by coal (41%). Nuclear comes second with 36% contribution to the country's generated electricity (WNA, 2023o). The Czech Republic has 6 functional pressurized water reactors with a capacity of 4,212 MWe (IAEA, 2023). One third of the country's electricity needs are met by nuclear energy (WNA, 2023o). The nuclear electricity generation of the country steadily increased from 2000 to 2005. After a dip in 2015, it has steadily risen. In May 2023, a tender was launched to add two generators to the Temelin Nuclear Power Station, a 2,056-MW facility with two VVER-1000 units designed by Russia's Gidropress (WNA, 2023o). Investments are estimated to be around $160 million, and will take place between 2028 and 2030.

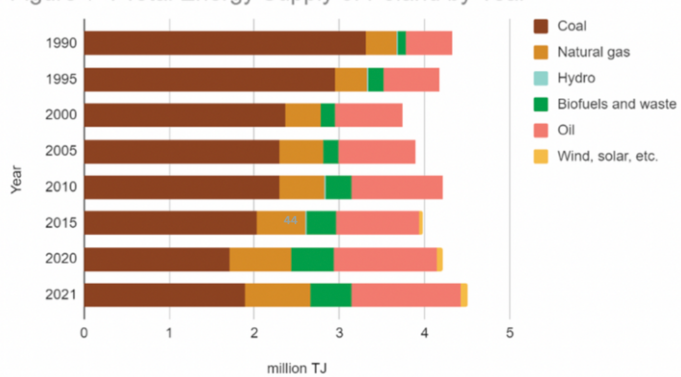
Figure 43: Total Energy Supply of Czech Republic by Year



POLAND

Fossil fuels, particularly coal, dominate Poland's energy mix (IEA, 2022d). In the year 2014, Poland started off its nuclear power program to ensure energy security and to address the rising issues of climate, environmental and economic challenges (NEA, 2023b). In September 2021, the setting up of six large pressurized water reactors with a combined capacity of 6-9 GWe by 2040 was announced. The government estimates that by 2040, nuclear energy will contribute 16% to the country's energy mix (IEA, 2022d). The first plant was announced in November, 2022. It will be built in Pomerania with a capacity of 3750 MWe using AP1000 technology (WNA, 2023gg). A strategic partnership has been established with US nuclear power technology provider Westinghouse who will build the reactor by 2033, with a cost of around $20 billion (Kość, 2022). In April 2023, an agreement has been signed between Polish energy company Orlen and two U.S. government financial institutions - U.S. Export-Import Bank and U.S. International Development Finance Corporation to develop small nuclear power reactors.

Figure 44: Total Energy Supply of Poland by Year

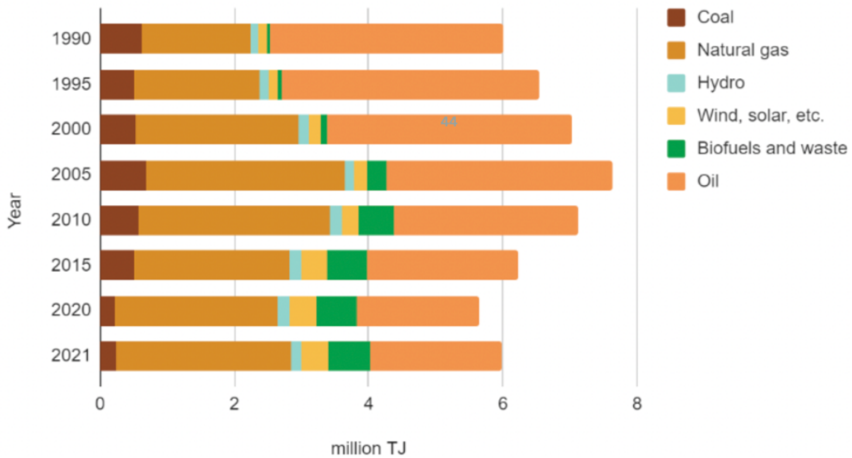


The two institutions are ready to lend up to $3 billion and up to $1 billion respectively. The aim is to develop around 20 small BWRX-300 modular reactors designed by GE Hitachi Nuclear Energy (Scislowska, 2023). ZE PAK, Polska Grupa Energetyczna and Korea Hydro & Nuclear Power have signed a letter of intent to cooperate on a nuclear power plant project in Patnow, central Poland, assessing the viability of building South Korean APR1400 reactors on the site (WNA, 2023gg). In April, copper and silver producer KGHM Polska Miedź SA submitted an application for a decision-in-principle on the construction of a NuScale VOYGR SMR power plant in Poland. Orlen Synthos Green Energy applied for a decision-in-principle on the construction of power plants based on GE Hitachi Nuclear Energy's BWRX-300 at six locations (WNA, 2023gg). Energy-intensive companies in Poland are also working to upgrade their plants by inducing SMRs. At present, the country has only one operating research reactor - the Maria research reactor (IEA, 2022d).

ITALY

Natural gas (49%) contributes primarily to the generation mix of Italy followed by hydro (17%) and solar (9%). It has no operable nuclear reactors (WNA, 2022b). Following the 1987 referendum (Chernobyl accident), the nuclear reactors in Italy were shut down and to date, Italy is the only G8 country without its own nuclear power plant (WNA, 2022b). The country however relies on imported nuclear energy, which contributes nearly 6% to its consumed electricity (WNA, 2022b). Italy is the world's second largest net importer of electricity (WNA, 2022b). Such high reliance on imports also affects Italy's economy, putting electricity prices well above other European countries (WNA, 2022b). In 2009, the government made a policy to generate 25% of the country's electricity from nuclear energy by 2030, however it was canceled in 2011 (WNA, 2022b). On 9th May 2023, the Chamber of Deputies of the Italian government approved a motion to incorporate nuclear energy in the country's energy mix.

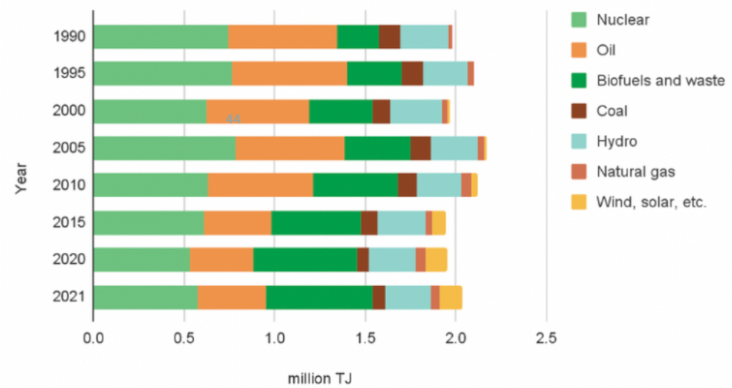
Figure 45 : Total Energy Supply of Italy by Year



SWEDEN

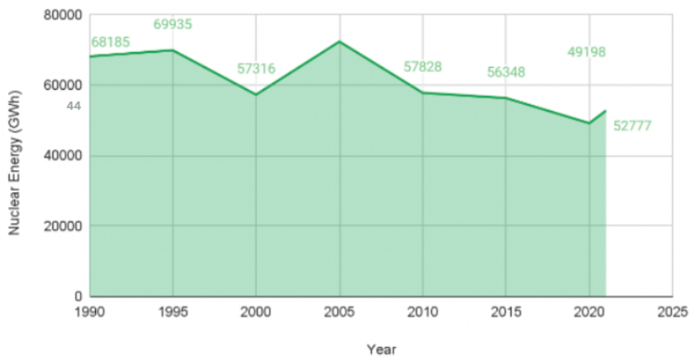
In Sweden, nuclear power plants dominate the energy supply (see Figure 46) and provide approximately 40% of the country's electricity (WNA, 2023b). It is second only to hydro(44%) in the generation mix of the country. It currently has 3 nuclear power plants with 6 operating reactors with a capacity of 6937 MWe (WNA, 2023b). The primary reactor type used is BWR (Boiling Water Reactor) along with PWR (Pressurized Water Reactor) (WNA, 2023b). The nuclear electricity generation per year is shown in Figure 47.

Figure 46: Total Energy Supply of Sweden by Year



It is expected that electricity demands will double in Sweden by 2040 (Johnson & Humphries, 2023). In order to meet such rising demands, the government has shifted its target from "100% renewable" to "100% fossil-free" electricity by 2040 and to reach net zero emissions by 2045. These targets have paved Sweden's way towards nuclear energy and the new parliament has promised generous loan guarantees (Johnson & Humphries, 2023).

Figure 47: Nuclear Electricity Generation



UNITED STATES

As of 2022, the US energy mix is approximately 80% fossil fuels, primarily natural gas and petroleum, 13% renewables, and 7% nuclear. The US is the world's largest producer of nuclear energy, contributing 18% to its electricity generation and 29.9% to global nuclear electricity generation. There are 93 operable nuclear reactors across 28 states, with a total capacity of 95.55 million KWe and an annual electricity generation of 778,188 million KWh. However, recent years have seen a decline in nuclear electricity generation due to market pressures, leading to the premature closure of thirteen reactors, resulting in the loss of 85.1 million MWh of clean energy.

This decline is attributed to low natural gas prices and the rise of renewables, combined with the failure of the market to value nuclear energy's stability and clean attributes. States like New York, Illinois, New Jersey, and Connecticut have implemented policies to recognize and compensate nuclear plants for their social and environmental contributions.

The US energy transition pace is set to increase due to recent policies like the Infrastructure Investment and Jobs Act of 2021 and the Inflation Reduction Act of 2022, which provide significant funding for clean energy, including advanced nuclear research. The Inflation Reduction Act, in particular, aims to lower electricity sector emissions by 50% by 2030 and boost electrified transportation.

Despite these efforts, current policies fall short of the US Federal Sustainability Plan's goal of 100% carbon-free electricity by 2030. With the existing policies, the US is on track to reduce emissions by 40% relative to 2005 levels by 2030. The US remains a significant contributor to global emissions, with the second-highest total CO2 emissions in 2021.

The future of US nuclear energy is uncertain, primarily due to high construction costs, with projects like the Vogtle 3&4 reactors facing significant overruns. The Nuclear Energy Institute suggests integrating nuclear technology in clean energy policies, incentivizing electric vehicle and appliance purchases, accurately reflecting the value of nuclear energy in economic models, supporting advanced nuclear development, and educating state authorities on the benefits of nuclear technologies.

Figure 48 : Total Energy Supply of US by Year

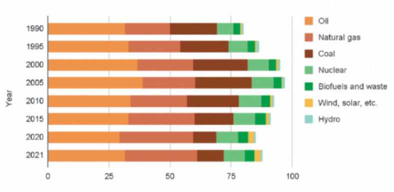
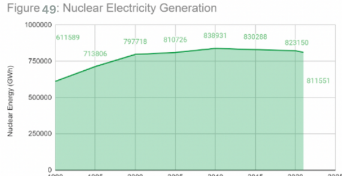


Figure 49: Nuclear Electricity Generation



CANADA

Canada, as a Tier 1 nuclear nation, ranks nuclear energy as its second-largest electricity source, just behind hydro. Nuclear power, primarily generated by Pressurized Heavy Water Reactors (PHWRs) located in Ontario, contributes 15% to Canada's total electricity, with these reactors producing 13,624 MWe. Ontario and New Brunswick rely significantly on nuclear power, with 60% and 36% of their electricity, respectively, coming from nuclear energy.

In 2023, Alberta joined Ontario, New Brunswick, and Saskatchewan in a memorandum of understanding to explore the development and deployment of Small Modular Reactors (SMRs). The federal government has recognized nuclear energy as a key component in its climate and hydrogen plans, aiming to phase out coal-fired electricity by 2030, exceed the 2030 Paris Agreement emissions target, and achieve net-zero emissions by 2050.

Canada is investing $26 billion in refurbishing the Darlington and Bruce Nuclear Power Plants, marking this as the second-largest energy investment in Canada and one of the largest in North America. The country also takes a leading position in the international development of SMRs. In 2018, Natural Resources Canada issued an SMR Roadmap, and in 2019, New Brunswick and Saskatchewan agreed to collaborate with Ontario on SMR development for climate change mitigation, energy demand, economic development, and innovation.

Canadian Nuclear Laboratories (CNL) received nearly 20 proposals for siting an SMR at a CNL-managed site, aiming to have a new SMR operational at Chalk River by 2026. In February 2023, the Canadian government launched the 'Enabling Small Modular Reactors Program' with $22 million in funding, supporting projects with up to 75% of their costs, or up to 100% for indigenous-led projects.

Canada is also the world's second-largest uranium producer and the fourth-largest exporter of uranium. The country's unique CANDU reactor model, used in all 19 of its reactors, has been sold globally to countries including India, Pakistan, Argentina, South Korea, Romania, and China.

Figure 50: Total Energy Supply of Canada by Year

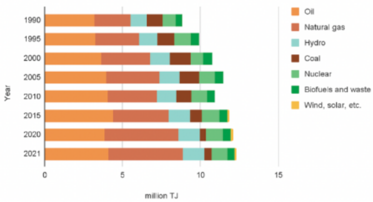
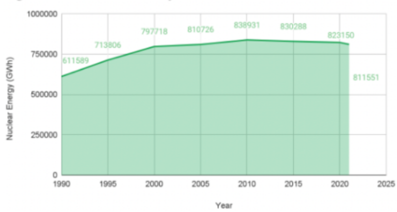


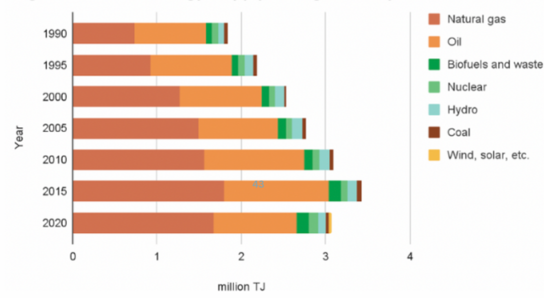
Figure 51: Nuclear Electricity Generation



ARGENTINA

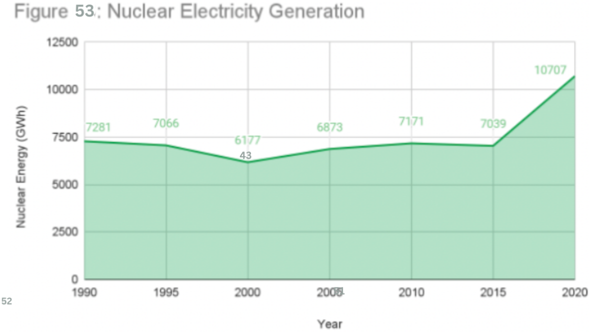
Argentina has the second largest shale gas reserve and the fourth largest shale oil reserve in the world (2023a). Therefore, natural gas and oil dominate the energy supply of Argentina (see Figure 52) with a combined 74% contribution to the generation mix in 2020 (WNA, 2023c). Hydro comes second in the generation mix (WNA, 2023c), followed by nuclear that accounted for 5.4% of electricity generation in 2022 (IAEA, 2023). The yearly electricity generation from nuclear energy is shown in Figure 53 which shows a steady rise from 2015 to 2020. With 3 nuclear reactors and a capacity of 1641 MWe (IAEA, 2023), Argentina is the first South American country to use nuclear energy (NTI, 2015). All the 3 reactors are Pressurized Heavy Water Reactors of which one is a CANDU reactor (WNA, 2023c).

Figure 52: Total Energy Supply of Argentina by Year



A PWR type reactor is under construction with an estimated capacity of 25 MWe expected to produce power by 2027 (IAEA, 2023). In 2014, a cooperation agreement with China was signed to construct a second CANDU reactor (Atucha III) but in 2019 the plan was changed to a 1150 MWe Hualong One unit (WNA, 2023c). However in 2022, it was reported that the progress has slowed down due to Argentina's eagerness to fabricate the fuel assemblies within the country (WNA, 2023c).

Figure 53: Nuclear Electricity Generation



BRAZIL

Fossil fuels such as oil and biofuels are the primary sources of Brazil's supply of energy (see Figure 55). The generation mix in 2022 was dominated by hydro (63%) (Energy Institute, 2023) while nuclear had only a 2.5% contribution (IAEA, 2023). Brazil has 2 nuclear reactors with a capacity of 1884 MWe, both Pressurized Water Reactors at Angra (IAEA, 2023). The nuclear electricity generation per year is shown in Fig 54. A third PWR reactor at Angra is under construction and is expected to have a gross capacity of 1405 MWe (IAEA, 2023). However, construction of this third reactor Angra 3 has faced continued disruptions (WNA, 2023e).

Figure 54: Nuclear Electricity Generation

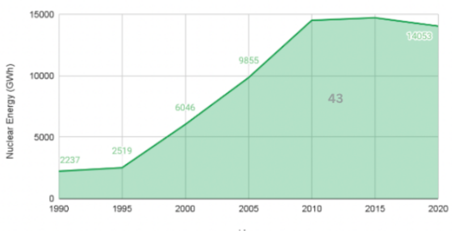
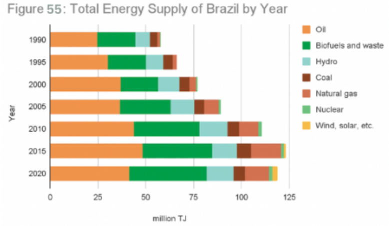


Figure 55: Total Energy Supply of Brazil by Year

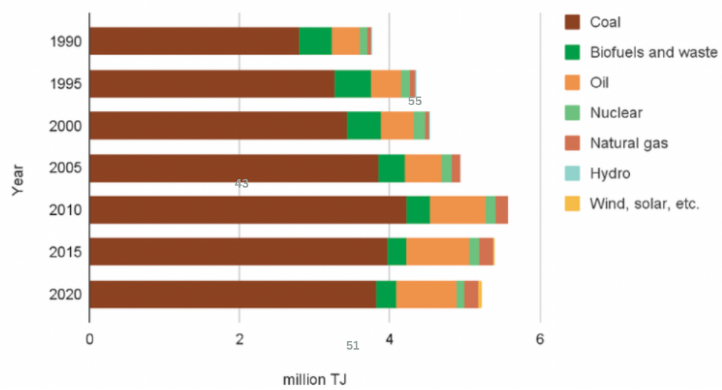


The construction was started in 1984 but was suspended in 1985. It resumed in 2010 but, contracts were suspended in 2015 following a corruption probe (WNA, 2023e). Again in it was stopped in April 2023 by the municipal government (WNA, 2023e). In February 2023, the Joint Parliamentary Front for Nuclear Technology and Activities was launched in which goal was set to complete the Angra 3 construction soon and plans were made for a fourth reactor (WNA, 2023u). The development of SMRs was also discussed in the light of new job opportunities and decarbonizing targets (WNA, 2023u). The country is largely dependent on hydro for electricity generation which has proved itself as unreliable and has made the country vulnerable at times of drought (WNA, 2023e). In 2018, electricity generation from hydro reduced from 80% to 65% due to rainfall patterns (WNA, 2023u). As a result the country is progressing towards shifting to other reliable sources. Brazil's National Energy Plan to 2050 is aimed to add 10 GW of nuclear capacity in the next 30 years (WNA, 2023u). In 2022, the process of locating suitable sites for nuclear power plants for this purpose was started (WNA, 2022d).

SOUTH AFRICA

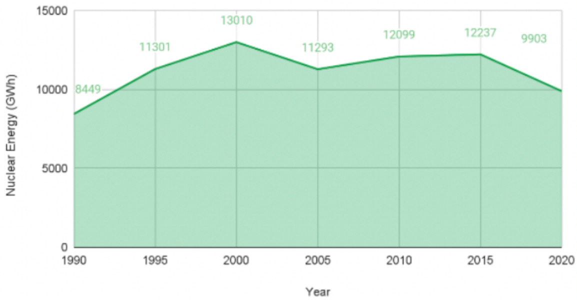
With a dominant energy supply (see Figure 56) , the generation mix of South Africa is heavily dependent on coal at 88%, while nuclear comes second with a contribution of 4% (WNA, 2023l). The yearly nuclear electricity generation of South Africa is shown in Figure 57. South Africa is the only country in the African continent with commercially operable nuclear reactors (Deo, 2020). Two pressurized water reactors are at the Koeberg Nuclear Power Station with a capacity of 1854 MW (WNA, 2023l). The station is connected to the national grid and the excess production from it is used to redistribute at times of need. Koeberg Nuclear Power Station is one of the first power stations that is designed to be earthquake-resistant (WNA, 2023l).

Figure 56: Total Energy Supply of South Africa by Year



According to the NDP (National Development Plan), by 2030 more than 90% of South Africa's population should get access to electricity. To achieve this the energy capacity of the country has to be expanded. New installed capacity will primarily be composed of renewables and nuclear in order to promote energy transition. South Africa's research reactor which is scheduled to retire in 2030, will be replaced by Multi-Purpose Reactor for nuclear technology research purposes by the same year.

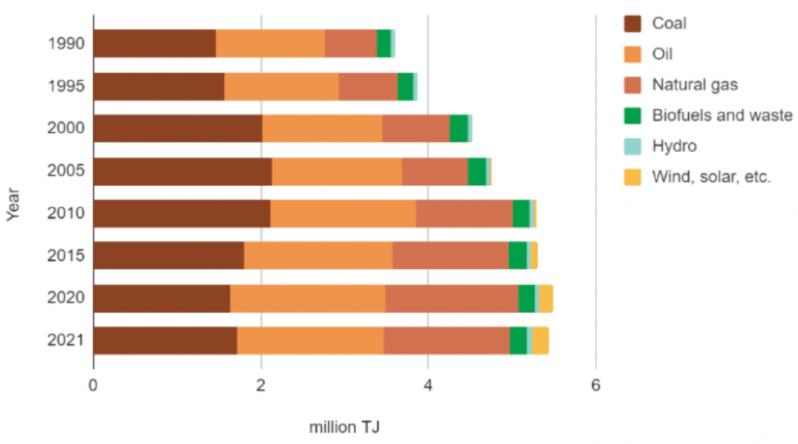
Figure 57: Nuclear Electricity Generation



AUSTRALIA

Australia is heavily dependent on coal, oil and natural gas, with fossil fuels accounting for 71% of total electricity generation in 2021 (Australian Government, n.d.). The share of renewables has increased from 8% in 2001 to 29.1% in 2021, driven mainly by rapid expansion of wind and solar (Australian Government, n.d.). Nuclear power is banned by federal law and not a part of the energy mix but holds potential to serve as a cheaper alternative to coal abatement (Australian Nuclear Association "ANA," 2018; WNA, 2019). Australia has vast uranium reserves and was the third largest exporter of uranium in 2016 (ANA, 2018). Despite this, Australia has much more abundant and cheaper coal resources, making nuclear a less economically attractive option domestically (AFR, 2023). Additionally, many still oppose nuclear energy and have concerns about the timeframe and costs required for a nuclear power plant (Murphy, 2019). Australia currently has one research reactor the Open Pool Australian Lightwater (OPAL) reactor (CSIRO, 2023). It is believed that SMRs would be best suited for Australia's transmission grid to replace coal plants (ANA, 2018).

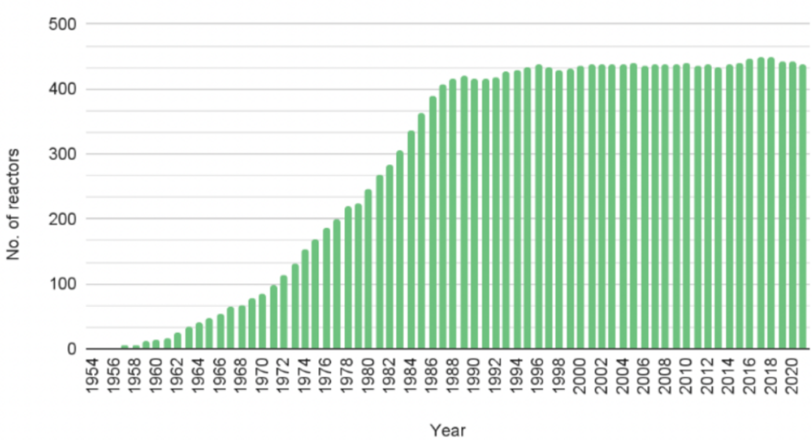
Figure 58: Total Energy Supply of Australia by Year



NUCLEAR TECHNOLOGY TYPES

Nuclear reactors work by using the heat energy released from splitting atoms of certain elements to generate electricity (WNA, 2023r). The first successful nuclear reactor nicknamed 'Chicago Pile-1' came into existence on December 2, 1942 in a squash court under the stands of Stagg Field at the University of Chicago (Lerner, 2020). On December 20, 1951, EBR-1 in the US became the first power plant to produce electricity using atomic fission (US DOE, 2019). On June 27, 1954 the world's first nuclear power station to generate electricity for a power grid, the Obninsk Nuclear Power Plant, came into the picture (Kaiser & Masden, 2013). Today, nuclear energy accounts for 10% of the world's electricity (WNA, 2023r). The number of operable reactors every year across the globe is shown in Figure 59. The technology behind nuclear power production has evolved over all these years.

Figure 59: Number of operable reactors worldwide 1954-2021

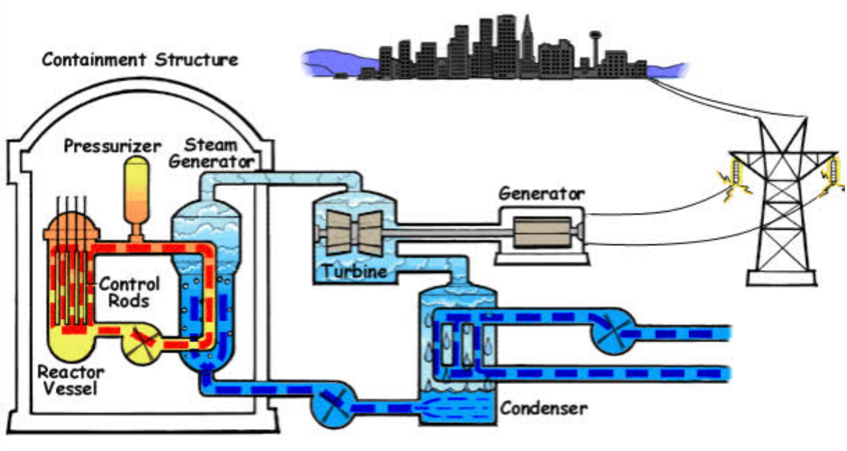


A nuclear power plant comprises of a number of components and technological advancements have taken place in all these sectors (WNA, 2023r).

1. Fuel
2. Moderator
3. Control rods or blades
4. Coolant
5. Pressure vessel or pressure tubes
6. Steam generator
7. Containment

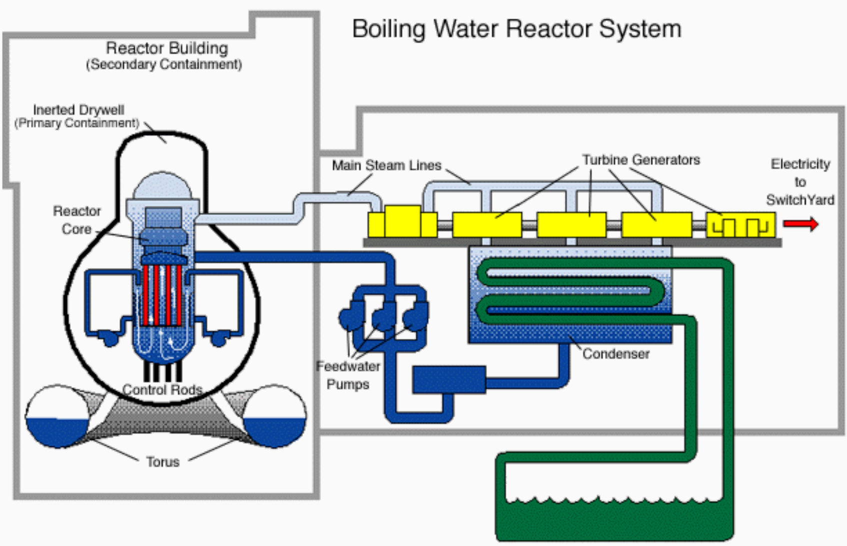
Nuclear reactors are mainly of the following types :

Pressurized Water Reactor (PWR) - This is the most common type of reactor (WNA, 2023r). The design is distinguished by having a primary cooling circuit which flows through the core of the reactor under very high pressure, and a secondary circuit in which steam is generated to drive the turbine (WNA, 2023r). Water in the reactor core reaches a temperature of about 325°C which is maintained under about 150 times atmospheric pressure by steam in a pressurizer to prevent boiling. In the primary cooling circuit the water is also the moderator, and if any of it turned to steam the fission reaction would slow down. This negative feedback effect is one of the safety features of the type. The secondary shutdown system involves adding boron to the primary circuit. The secondary circuit is under less pressure and the water here boils in the heat exchangers which are thus steam generators. The steam drives the turbine to produce electricity, and is then condensed and returned to the heat exchangers in contact with the primary circuit. This is a type of light water reactor which uses water as both moderator and coolant. Countries like USA, France, Japan, Russia, China, and South Korea extensively use these reactors. Currently, there are 307 operational PWRs in the country (WNA, 2023r).



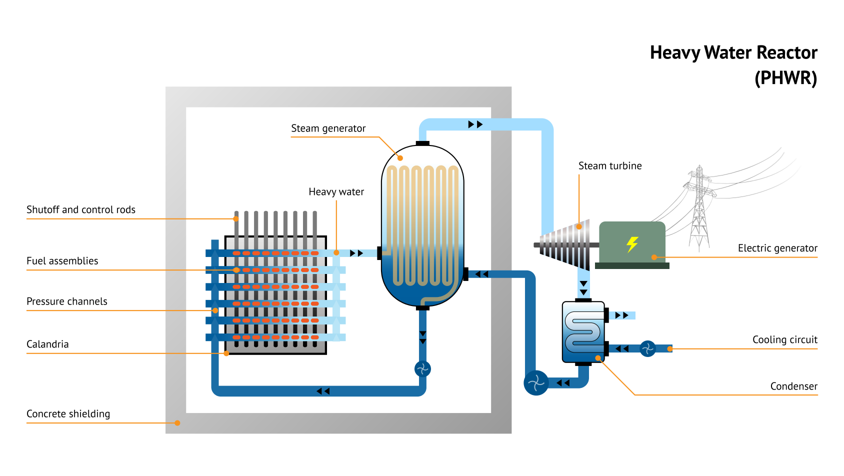
Source: NRC

Boiling Water Reactor (BWR) - It is the second most popular type of reactor and very similar to PWR. It also uses water both as coolant and moderator except that it has only a single circuit in which the water is at lower pressure (about 75 times atmospheric pressure) allowing it to boil in the core at about 285°C. The reactor operates with 12-15% of the water in the top part of the core as steam. The steam passes through drier plates (steam separators) above the core and then directly to the turbines. The water around the core of a reactor is always contaminated with traces of radionuclides, therefore the turbine has to be shielded and radiological protection provided during maintenance. The cost due to this nearly balances the savings due to the simpler design. A BWR reactor core has up to 750 assemblies and they comprise of 90-100 fuel rods and holds 140 tons of uranium. The secondary control system restricts water flow through the core to reduce moderation. BWR units can operate in load-following mode more readily than PWRs. As of now, there are 60 BWRs in the world, mainly in USA, Japan and Sweden.



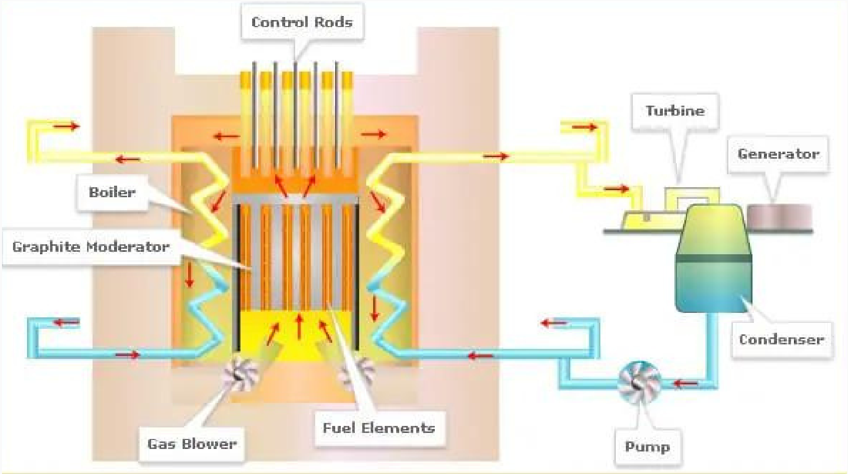
Source: NRC

Pressurized Heavy Water Rector (PHWR) - They are primarily used in Canada and is known as CANDU. In this type, natural uranium oxide is used as fuel and a heavy water is used as the moderator. The moderator is in a large tube called calandria which consists of several hundred pressure tubes placed horizontally through which the fuel flows. The temperature reaches 290°C. This design allows refueling of pressure tubes by isolating them individually from the cooling circuit without having to shut down completely. It is also less expensive however the tubes are not durable. Apart from Canada, they are found mostly in India. 47 PHWRs are functional across the globe.



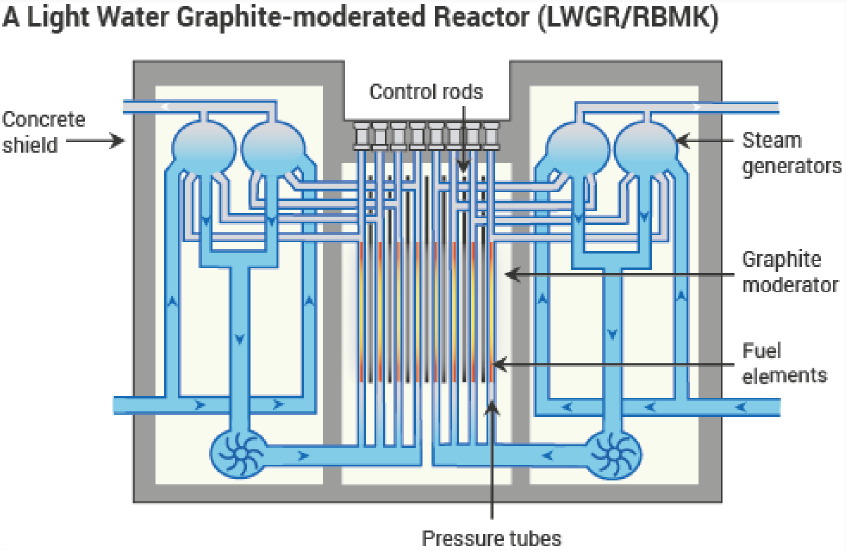
Source: Energy Encyclopedia

Advanced Gas-Cooled Reactor (AGR) - In these type of reactors, graphite is used as moderator and carbon dioxide as primary coolant. Uranium oxide pellets are used as fuel in stainless steel tubes. The carbon dioxide circulating through the core reaches 650°C. It also flows outside the steam generator tube. Control rods penetrate the moderator and a secondary shutdown system involves injecting nitrogen to the coolant. It has a high thermal efficiency of about 41%. They are in use in UK.



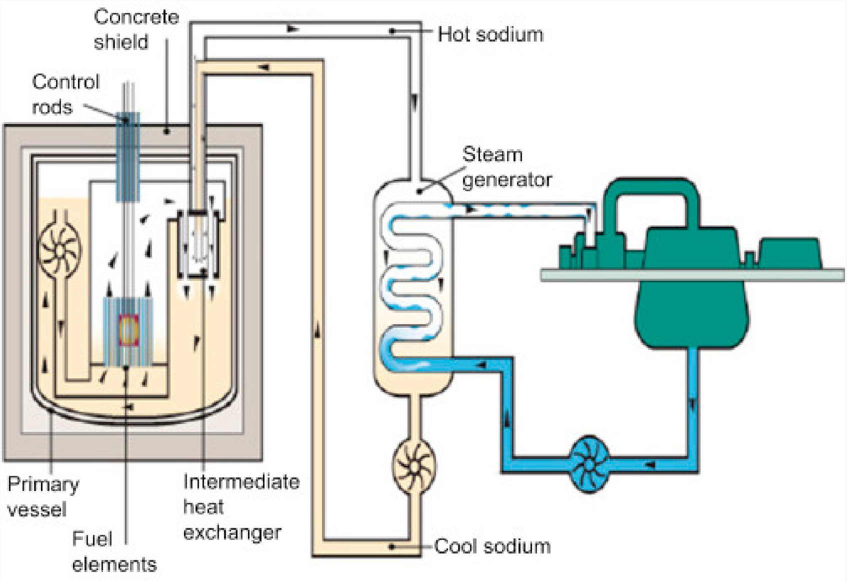
Source: www.hknuclear.com

Light Water Graphite-moderated Reactor (LWGR) - The LWGR design is primarily used in Russia. Low enriched uranium oxide acts as the fuel. It uses graphite moderator and water as coolant. It comprises of long vertical pressure tubes that penetrates through the moderator. The water boils in the core and reaches a temperature of 290°C.



Source: world-nuclear.org

Fast Neutron Reactor (FNR) - They utilize fast neutrons to generate power from plutonium which acts as the fuel. No moderator is used in this design and liquid sodium is used as coolant. It produces 60 times more energy than ordinary uranium. This is also much more expensive. FNRs are used in Russia and are currently 2 in number (WNA, 2023r).

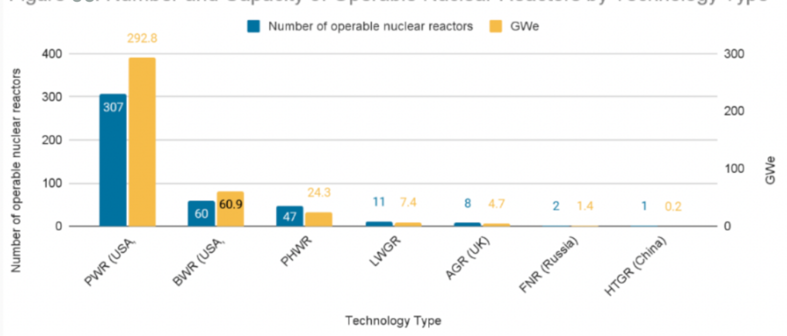


Source: sciencedirect

Molten Salt Reactor - In this design the fuel, uranium, plutonium or thorium is dissolved in the coolant as a fuel salt. Molten fluoride salt (lithium-beryllium fluoride or lithium fluoride) at low pressure is used as the primary coolant. The temperature is maintained at about 500°C up to about 1400°C. Graphite is generally used as a moderator. Global research in MSRs is led by China (WNA, 2021a).

Figure 60 below shows a graphical comparison between the number and capacity of reactors of each technology type and the countries in which they are majorly functional.

Figure 60: Number and Capacity of Operable Nuclear Reactors by Technology Type



Based on the location of the nuclear reactor, they can be broadly classified into -

Inland Nuclear Reactors - They use water from nearby lakes, rivers, etc. (other than coastal water) as coolants.

Floating Nuclear Reactors - The nuclear power plant is generally mounted on floating platforms such as ships or barges. They can provide electricity in remote and off grid areas.

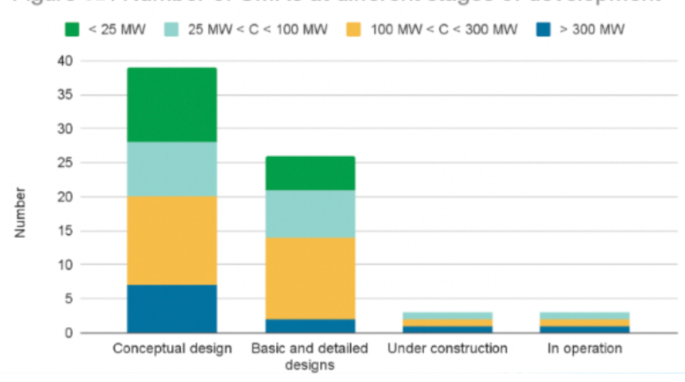
Transportable Nuclear Reactors - They are advanced nuclear reactors which are factory fabricated and are transported to the site. The advantage that it has over traditional reactors is that they can be operated in remote locations. Small modular reactors and micro reactors fall under this category.

Based on power capacity, reactors can be classified as:

Large Conventional Reactors - They have a capacity of 700+ MWe with a thermal output of more than 1,000 MWt (GAIN, 2023). All traditional reactors like PWR, BWR, PHWR, etc. fall under this category.

Small Modular Reactors (SMR) - They are advanced nuclear reactors with a capacity of up to 300 MWe per unit, which is nearly one-third in contrast to large, conventional reactors. They produce a thermal output of 30-1000 MWt (GAIN, 2023). The small and modular design of this reactor provides a number of advantages over traditional reactors and is therefore a prime domain of research and development in recent years globally. Units of SMRs can be manufactured remotely and then shipped on-site. This largely reduces construction costs and saves time compared to large power reactors. Another major advantage of SMRs is that they can be built in areas lacking vast areas of land needed for nuclear reactors. SMRs can be easily connected to an existing grid or remotely off-grid. SMRs also have reduced fuel requirements. Furthermore, SMRs rely on passive systems i.e. at times of any technical faults, the reactor will be shut down automatically due to physical phenomena without the need for human intervention. This provides greater safety in cases of radioactive accidents (Liou, 2021). As of 2022, there are 3 operational SMRs in the world, Russia, China and India (Perera, 2023). The number of SMRs across the globe at different stages of their development and their estimated capacity is shown in Figure 66.

Figure 61 : Number of SMRs at different stages of development



Micro Reactors - They have a power capacity of up to 10 MWe and are 100 to 1,000 times smaller than conventional nuclear reactors (Idaho National Laboratory “INL,” 2023). They have a thermal output of less than 30 MWt (GAIN, 2023). Microreactors can be operated as part of the grid, or part of a micro grid or even independently (INL, 2023). The are built in factory and can be installed directly at site (INL, 2023). They can be installed in desired sizes at remote locations for emission free power generation without transportation issues (INL, 2023). In addition, they can operate for up to 10 years without refueling featuring longer core life (US DOE, 2021).

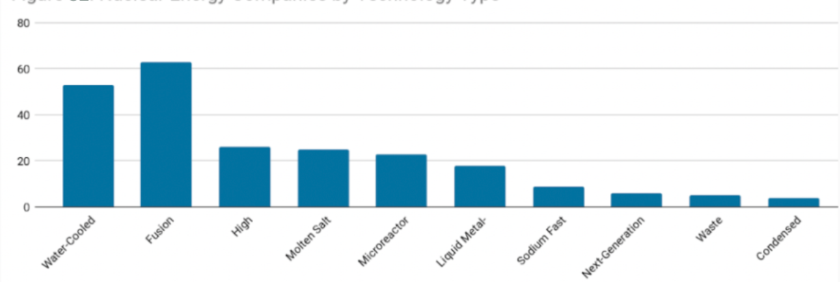
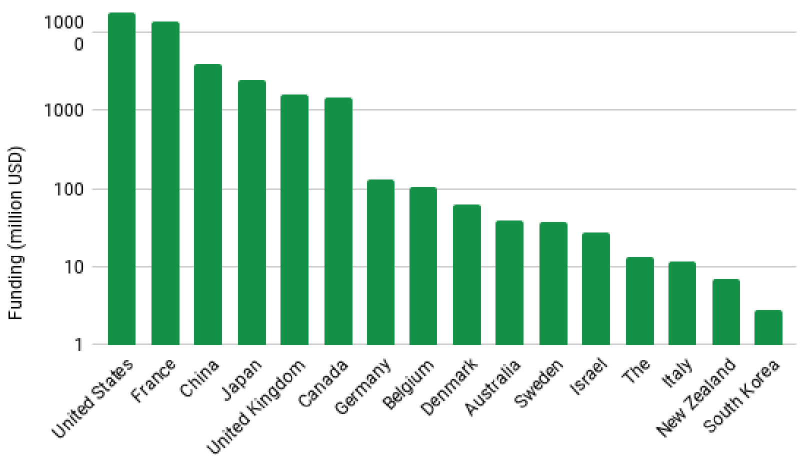


Figure 62: Nuclear Energy Companies by Technology Type

Analysis of the Findings

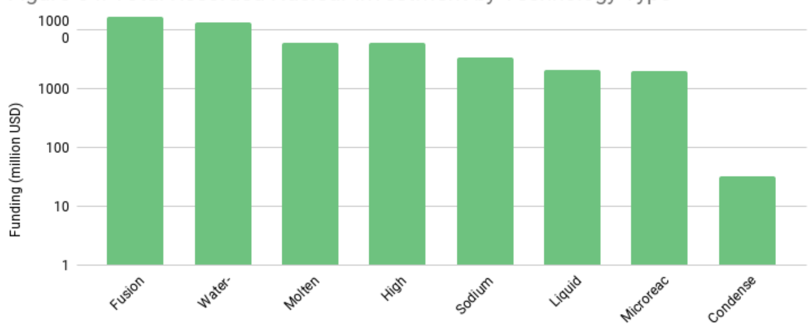
Demand for energy has been steadily increasing as the population grows and economic development gives more people access to energy. Energy demand is expected to continue increasing, as well as demand for clean energy and electrification, particularly for baseload nuclear power. Since much of the potential of nuclear energy depends on development and deployment of advanced reactor concepts, both small and large scale, it will be very important to track investment in nuclear energy.

Figure 63: Total Known Nuclear Investment by Country



The Nuclear energy technology development industry has received over $43 billion in funding globally with recent investments in both the public and private sectors, with about $27 billion in fission and $16 billion in fusion. Based on publicly available data, the United States has the highest levels of known nuclear funding at almost $20 billion, followed by France, China, Japan, and the UK. However China is estimated to have the highest nuclear spending, particularly in recent years, investing about $7 billion and $11.6 billion in 2022 and 2023 respectively, more than any other country. Based on this current trend, China should continue to have the most highly funded nuclear program, spending $440 billion for over 150 new reactors in the next 15 years to reach its climate goals. India has also significantly increased its nuclear spending in recent years, with its IAEA budget increasing from $720 million in 2015 to $10 billion in 2022. Russia plays an important role in nuclear development, deployment, export and investment. It has an extensive deployment portfolio around the world and it also produces the fuel that is being sold to other countries. It will have invested at least $6.35 billion of public funding in improving fast reactor technology and fusion by 2025.

Figure 64: Total Recorded Nuclear Investment by Technology Type



Out of all technology types, hot fusion energy has received the most total funding, at $16 billion, closely followed by water-cooled reactors at $13 billion. Funding in fusion energy and advanced water-cooled reactors has been dominated by US and French companies. In particular, the fusion industry is quickly expanding, with 13 new startups and 18 new private-public partnerships between 2022 and 2023, with important growth in Japan, China, Australia, New Zealand, Germany, and Israel (FIA, 2023) Investment in development of HTGRs is led by the US and Japan, and molten salt reactors are led by US and China.

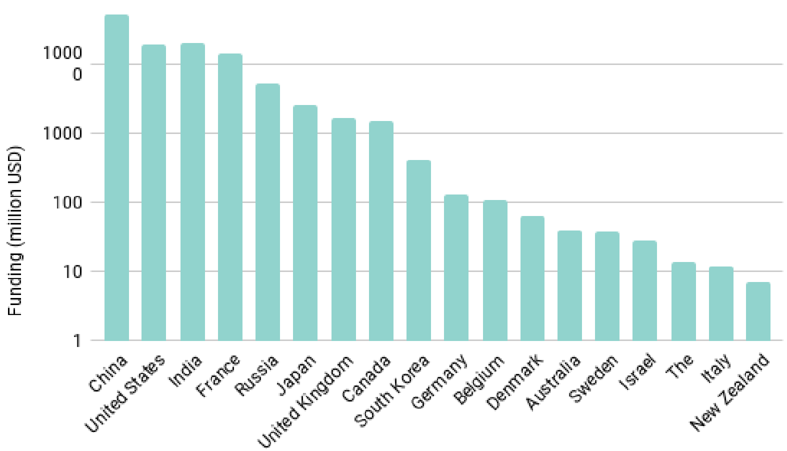


Figure 65: Estimated Nuclear Investment by Country

Microreactors are mainly developed in the US and UK, with about 50% of companies and 75% of funding for microreactors in the US. Most funding for liquid metal-cooled fast reactors is for US companies, but many countries are participating in their development, including China, Russia, India, South Korea, Canada, and EU countries. Development of sodium fast reactors is led by the US and Japan, with similar levels of known investment in both countries. Investment in condensed matter/low-energy reactors is lowest, as it is still in very early development stages, and it is mainly being developed privately in the US and Japan. There have been high levels of investment in SMRs across all cooling technology types, due to their broad range of potential applications and convenient, cost-effective design.

Figure **66**: Projected contributions of nuclear energy to cumulative emissions reductions (2020-2050)

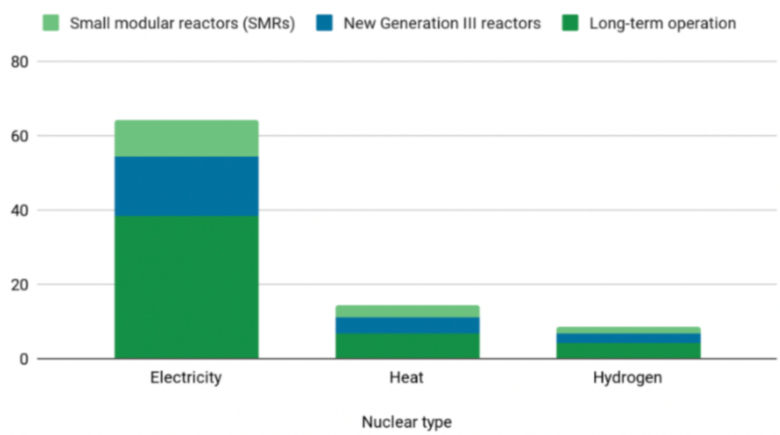


Figure 67 : Nuclear energy construction starts by country, 2017-2021

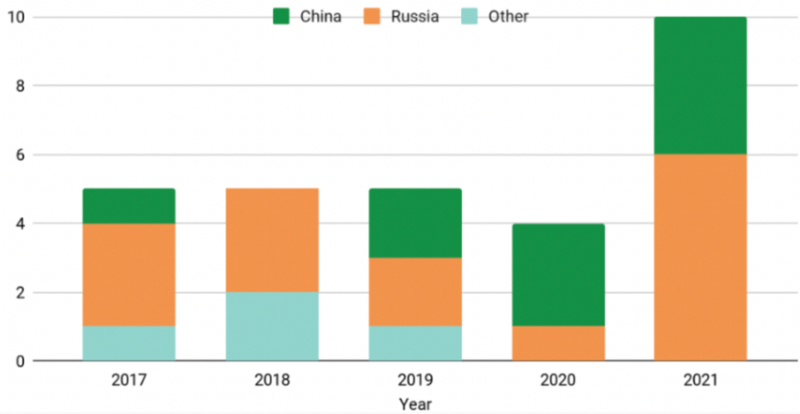


Figure 68 : Energy Transition Investment (2022)

Excludes investment in power grids, supply chain, and climate-tech corporate financing

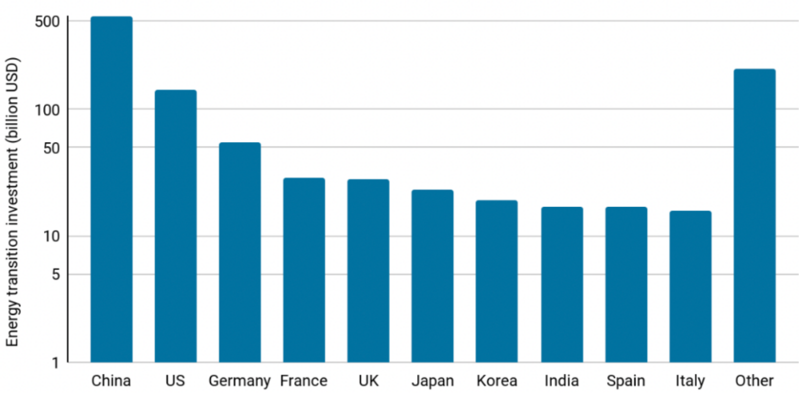


Figure 69 : Nuclear energy investment through 2023 and increase in investment need to reach net zero

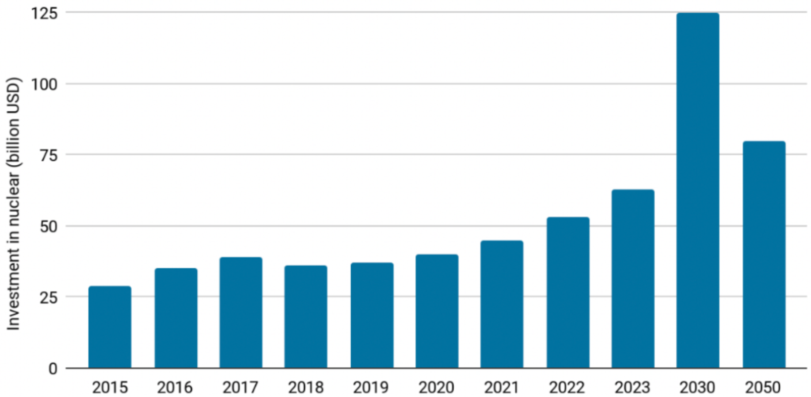
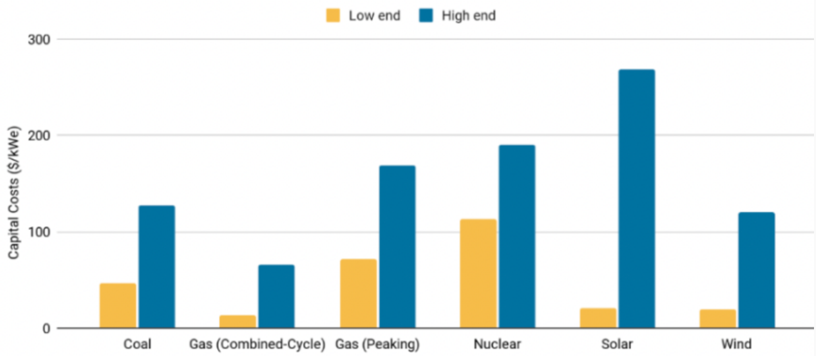


Figure 70: Capital Costs of Different Generating Technologies

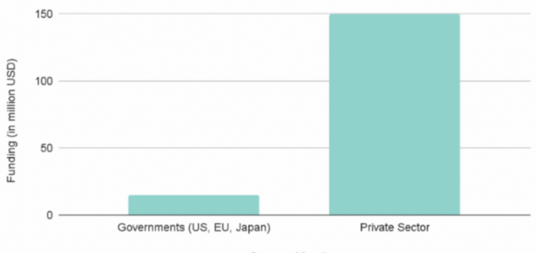


About Anthropocene

The Anthropocene Institute brings together entrepreneurs, investors, institutions, and decision makers to decarbonize our energy systems and accelerate humanity's transition to a future where the climate is restored to health conditions. The organization believes that nuclear energy, including both fission and fusion, are an essential component of a clean and reliable energy mix. The Anthropocene has been focusing its efforts on driving funding to both scientific research groups as well as innovative new companies in this space.

The institute takes a portfolio approach to nuclear technology and includes Solid-State Fusion (SSF) as a potential source of clean, efficient and reliable energy. In contrast to the popular know types of nuclear technology, SSF requires neither high temperature-pressures nor radioactive elements. In 2015, a team of 30 researchers from reputed educational institutions of North America were funded $10 million by Google to conduct extensive research on SSF. Consequently, in 2022, a $10 million funding opportunity was announced by the US Department of Energy's Advanced Research Projects Agency - Energy (ARPA-E) program to assist researchers from eight university groups in conducting fundamental research on SSF. An estimated $15 million is funded by the US, EU and Japan government along with a $150 million funding from the private sector for advancing research on SSF. Japan's Clean Planet Inc established in 2012 has developed the Quantum Hydrogen Energy (QHe) and is the leading country in the world in terms of cold fusion patents. USA based Brillouin Energy Corp. has claimed net positive power from its first transportable Hydrogen Hot Tube (HHT).

Figure 71 : Estimated Funding for SSF by Governments and the Private Sector



Conclusion

Today, nuclear energy provides 10% of the global electricity and is the second largest source of low-carbon power (WNA, 2023r). With the rising challenges of limited fossil fuels and fast-approaching climate goals, the necessity and significance of nuclear energy among other clean energy sources are more important now than ever. In the last 50 years, nuclear energy has avoided around 70 Gt of CO2 emissions globally. This is led not only by developed countries such as USA and European countries, but also by emerging and developing countries like China and India.

The US has the most nuclear energy consumption with the largest known nuclear funding of 19,852 million USD in the world. Among the 78 nuclear companies in the country, 35 companies work on fusion technology. With 13 companies dedicated to developing microreactors, the US is also leading the development of advanced reactors globally. France has the second largest known nuclear funding of 14,109.7 million USD followed by China with a known nuclear funding of 4,021 million USD. China's increase in nuclear energy consumption rate is globally the highest from 0.93 EJ in 2012 to 3.76 EJ in 2022. The country has 18 nuclear companies, of which 10 companies work on water-cooled reactors. Both France and Canada have 12 nuclear companies each and a vast majority of them are dedicated to water-cooled reactors. Across the globe, the total recorded investment for fusion reactors stands at 16,164 million USD while the corresponding investment for water-cooled reactors is 13,346 million USD. These are followed by Molten Salt Reactors. The estimated nuclear investment per country shows China at the top with funding of 51,509 million USD. This is followed by the US, with an estimated nuclear investment of 19,853 USD. India is very close, with funding of 19,758 million USD.

USA, with 93 operable reactors, is currently the largest producer of nuclear energy in the world. However, it is worrying that a capacity of 5506 MWe has been retired in the last 5 years alone. In addition, there have been no nuclear additions. At such a rate, the position of US as a nuclear leader remains in question in the upcoming years. Low natural gas prices, penetration of renewables, and a lack of recognition for nuclear energy as a clean source of energy have resulted in premature closings of nuclear reactors. Additions of 1114 MWe nuclear capacity have been planned consecutively for two years in 2023 and 2024. A big hurdle in building new nuclear power plants in US is their high cost, which often exceeds the projected budget accompanied by construction delays. However, funding should not be a problem, as US is the world's largest economy. High investments have already been made for the clean energy transition. A $65 billion is invested in clean energy including research into advanced nuclear by the Infrastructure Investment and Jobs Act of 2021. An important feature that sets the US apart from other countries is its large number of nuclear energy companies, 70 at present. They mostly work on fusion, molten salt reactors, and high-temperature gas-cooled reactors. Many of them are also focusing on advanced SMR designs. The US currently has 19 SMR designs. Greater government support and recognition of nuclear energy as a clean energy source will ensure a swift energy transition movement for the US.

Other countries such as Russia, India, Germany, France, Spain, Italy, and Japan have also targeted long-term climate goals to reach carbon neutrality. Russia has set a target of generating 20% of the country's electricity from nuclear energy by 2035. The economy of Russia is primarily dependent on export of fossil fuels. This can be linked to the energy transition goals of the country, where Russia reduces its reliance on fossil fuel for domestic electricity generation, and exports it for profits, a part of which can be utilized as investments for building new nuclear power plants and advanced nuclear research. A majority of the nuclear energy companies of Russia is focused on Liquid Metal-Cooled Fast Reactor. The country is also looking forward to advanced SMRs. It currently has 16 SMR designs, second only to US. Among them 6 are Water Cooled, 5 are Marine Water Cooled, 3 are High Temperature and 2 are Fast Neutron Spectrum.

In India, energy demand is growing at a rate faster than any other country. This creates a platform for the country to expand its already existing nuclear power plants and build new ones. However, the country increasingly relies on fossil fuels and therefore is running up against domestic coal shortages. Such high dependence on fossil fuels further leads to rising CO_2 emissions. This is in sharp contrast to India's goal of reaching net zero by 2070. India in recent years has expanded its renewable energy sources, particularly solar, but the country is an agricultural one with the largest population in the world. Availability of land is a major issue in recent years for deployment of renewables. Nuclear energy, with its low-land-use footprint, provides a solution to both CO_2 emissions and land usage problems. On an interesting note, India is one of the three countries in the world with its own operational SMR. Though India has long drawn climate goals, the policies currently undertaken are not sufficient to reach these goals.

Countries like Germany and Japan have seen a steep fall in nuclear energy following nuclear disasters - the Chernobyl disaster of 1986 and Fukushima disaster of 2011. Germany shut down all its reactors after 2011. For Japan, 27 reactors have been shut down following 2011. In these countries, there are strong anti-nuclear sentiments among the general population. However, Japan is slowly increasing its nuclear share again and is showing a steady rise from 2015. But, Japan is still far behind its earlier nuclear capacities. Nuclear energy has a significant role in Japan in helping it achieve net zero by 2050 because of the country's limited land resources. Thus, nuclear has become more preferable compared to other renewables. The general public opinion has shifted in favor of nuclear energy by a very low margin. The country is also looking forward to advanced and safer nuclear technologies. Over a dozen Japanese companies have invested $80 million in UK's core Power floating molten salt reactor project, a safer alternative because meltdowns are impossible.

The rising energy crisis in the world is causing upscaling of fossil-fuel-based projects by many governments, but there is a better alternative. Nuclear energy technology has huge scope of research and development in the upcoming decades. Exploration of this green source of energy requires large-scale investments in nuclear projects. This will ensure a rapid decarbonization in the energy industry. Apart from the evident energy and climate benefits, the nuclear energy industry will also provide a number of social benefits — greater job opportunities at various levels and poverty alleviation, contributing to widespread economic growth.

What we're looking for

Do you have an innovation in nuclear, Solid-State Fusion (LENR), climate restoration, grid electrification, or oceans that you are looking to get off the ground? Are you an investor looking for investment opportunities? If you fit these qualifications, we might be able to use our network to help.

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