The Nuclear Age?

Economics of Nuclear Power & Future Implications

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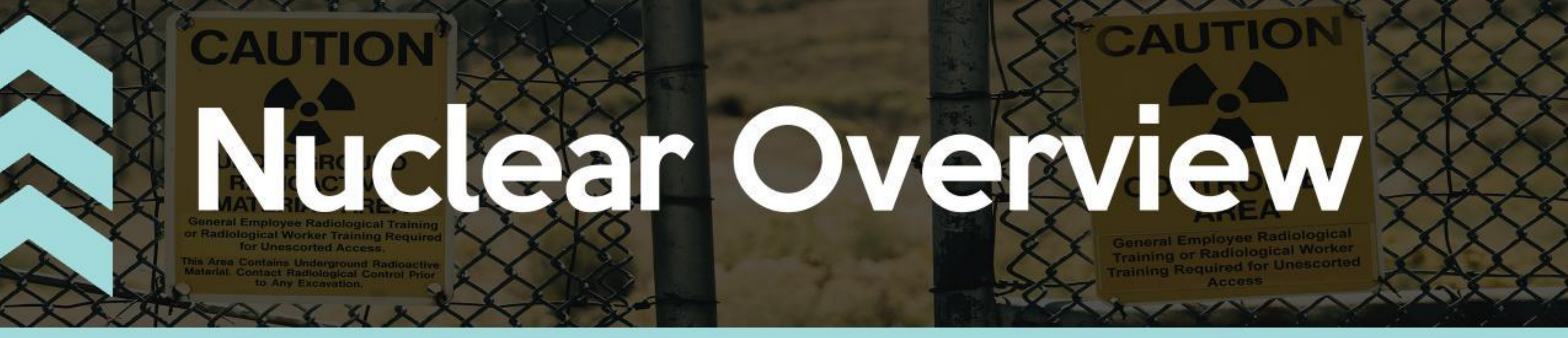


Nuclear Overview

- Nuclear energy has proven to provide stable and reliable energy
- Technologies required to build nuclear reactors are complicated and capital intensive
- The world currently has over 400 operational nuclear reactors - producing roughly 10% of the world's total energy supply
- Ukraine's nuclear power grid currently runs in island mode - experts worried about the long term safety of Nuclear reactors in the country
- Uranium prices are soaring in response to the Russia-Ukraine war as Europe already grapples with high energy prices
- A re-thinking is taking place across the world - some states are reviving ambitions to expand nuclear power capabilities, whilst other countries do not buy into the hype
- Germany reached a decision to not prolong the life of its reactors, meanwhile China is aiming to establish itself as a nuclear power leader by building over 150 reactors in the next 15 years.
- Given the existential threat of nuclear warfare, the existence of nuclear energy is inherently political and brings with it growing international tension.
- The commercialization of Fusion technology, and Advanced Nuclear technology towards Small Nuclear Reactors is still too far into the future to play a significant role in decarbonization to 2050.
- Nuclear energy, as an emissions-free source, will continue to play a significant role in the low-carbon transition. It is expected to make up 8% of primary baseload power in a net-zero 2050, and act as a stabilizing source against the intermittency of other renewable energy.

Nuclear Technology

Nuclear energy technology has now been widely adopted all over the world with more than 440 nuclear reactors operational in 32 countries in addition to 55 power reactors currently being constructed in 19 countries. Nuclear energy in 2020 produced 2,553TWh of energy, contributing to roughly 10% of the world's electricity, producing zero emissions in the process. Nuclear energy is undoubtedly one of the most consequential inventions of modern history. While the technology has developed significantly since the 1950's, we are still learning on ways to make the technology more efficient and less dangerous. This brief will be broken down as follows: firstly it will go over the functionalities of nuclear power plants and economics of nuclear plants, followed by the state of nuclear energy around the world, followed by the geopolitics surrounding nuclear energy and finally will conclude with the future outlook of nuclear energy.

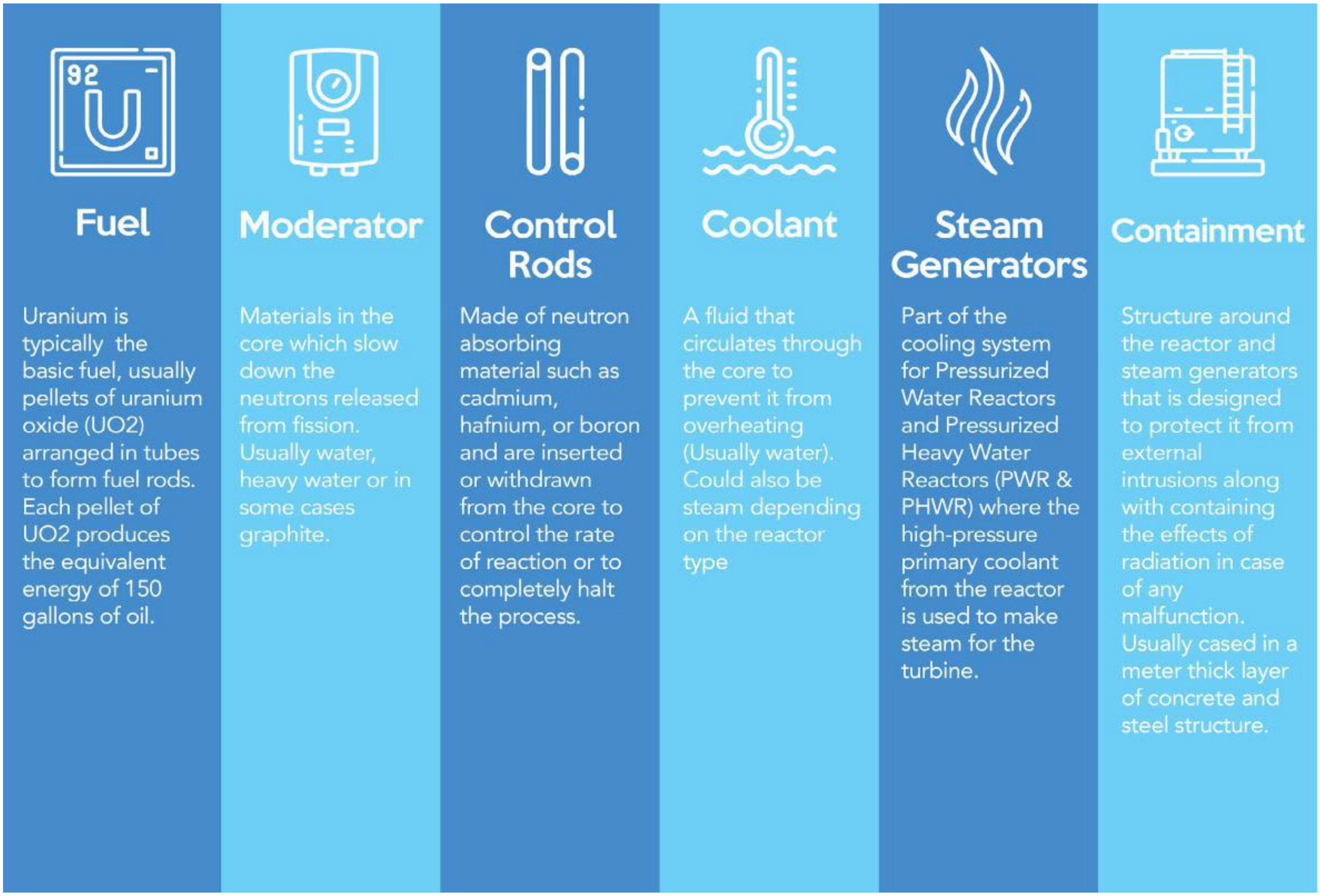
How Energy is Produced: Fission vs. Fusion

There are two main ways that nuclear energy is produced: fission and fusion. Fission is the most common and reliable way of producing energy while fusion energy production is still being explored. Fission is a process where heavy elements, namely uranium, spontaneously decays causing their nuclei to split. The atoms start to hit other nuclei and cause a chain reaction, with the resulting atoms having less mass than the original atomic core and the missing mass is converted into energy. In nuclear reactors, this chain reaction is carefully controlled and is an isolated process. Fission is controlled in nuclear reactors; however, when fission is allowed to happen in an uncontrolled manner it results in a positive feedback loop which releases a massive amount of energy, which is what makes nuclear weapons so devastating.

Fusion on the other hand is the reverse of fission where two nuclei of lighter elements such as hydrogen overcome their natural electromagnetic repulsion and merge into a heavier nucleus. The merging of the two nuclei creates a slightly less massive nuclei than the original two, and like fission, the missing mass is converted into energy. The problem with fusion, unlike fission, is that the conditions that allow the process to occur is hard to emulate as it only occurs naturally at the core of the sun. Despite the obstacles, there has been progress in recent years with research being conducted at the Large Hadron Collider or European Organization for Nuclear Research (CERN) along with the Chinese Fusion Engineering Test Reactor (CFETR) has made significant progress on making this technology viable for use in the near future.

Reactor Components & Different Nuclear Reactors

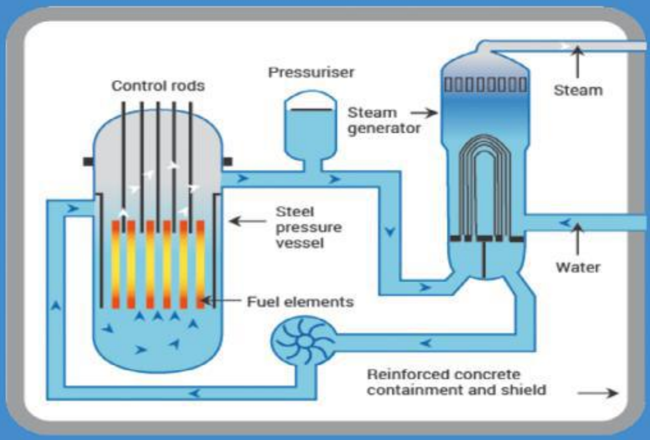
With over 400 operational nuclear reactors, there is a wide variety of reactors with different operational capacities. This section will explore the three most common reactors in use today. Before going into detail of the different types of reactors, it is important to go over the six different components that are nearly universal in all nuclear reactors.



Source: World Nuclear Association

Components will vary depending on the reactor; however, generally speaking the role of each component remains largely the same throughout most reactors

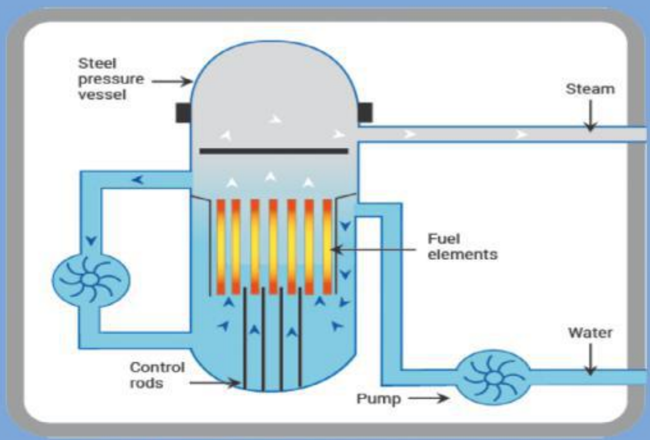
Pressurized Water Reactor (PWR)



Source: World Nuclear Association

The PWR is the most common reactor with more than 300 units being operational worldwide. PWRs are characterized by having two circuits, one primary cooling circuit which cools the core of the reactor under intense pressure, and a second circuit where the steam generated is used to spin the turbines. Water in the reactor core reaches temperatures up to 325 degrees and must be kept under 150 times the atmospheric pressure to prevent the water from boiling. The water in the secondary circuit is under less pressure allowing steam to be generated, which drives the turbines to produce electricity.

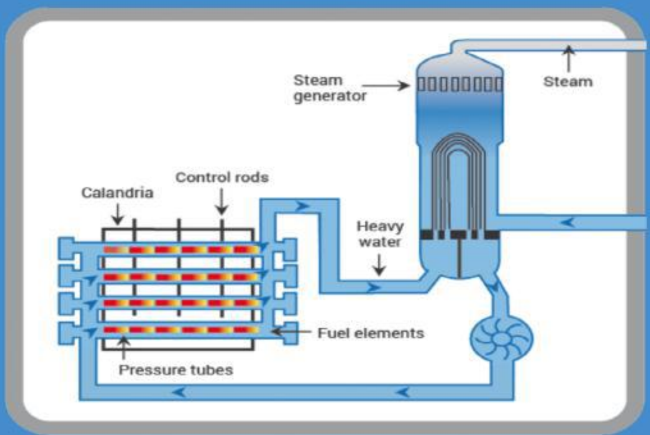
Boiling Water Reactor (BWR)



Source: World Nuclear Association

BWRs are similar to PWRs save forn the fact that there is only one circuit in which the water is circulated under less pressure (x75 atmospheric pressure) enabling the water to boil in the core at around 285 degrees. Steam generated from the core is then directly sent to the turbines which is also part of the circuit in BWRs. The simpler design allows BWRs to be cheaper to build compared to PWRs.

Pressurized Heavy Water Reactor (PHWR)



Source: World Nuclear Association

PHWRs unlike PWRs and BWRs use natural uranium oxide as fuel – requiring more efficient moderators and hence utilizing heavy water. The advantage of this is that PHWRs produce more energy per kg of mined uranium compared to other reactors but at the cost of producing more used fuel compared to other reactors. Additionally, PHWRs can utilize a variety of fuel sources, even some recycled or depleted uranium making them more versatile and flexible. PHWRs operate similarly to PWRs in the sense that the two-circuit system operates under the same principle; however, the individual pressure tubes that are isolated from the cooling circuit means the reactor can be refuelled progressively without shutting down.

Economics of Nuclear Energy

Unsurprisingly, the cost of building a nuclear reactor is extremely capital intensive, with a 1,100 MW plant costing anywhere between $5 billion - $9 billion on average. Additionally, the cost of constructing a nuclear plant varies widely depending on the country, which will be discussed later. The cost of nuclear power can be further broken down into four categories.

Capital

Cost of site preparation, construction, manufacture, commissioning and financing a nuclear power plant

Plant Operating Costs

Costs of fuel, operation, and maintenance (O&M), and a provision for funding the costs of decommissioning the plant and treating and disposing of used fuel and wastes

External Costs

Costs that will be put on society from the operation. Nuclear power plants generate no carbon emissions through operation, which is usually the main external cost; but these costs could include the costs of dealing with a serious accident that is beyond the insurance limit and requires government intervention. Additionally, while nuclear plants do not produce emissions while producing energy, emissions are produced during mining, construction and transportation.

Other Costs

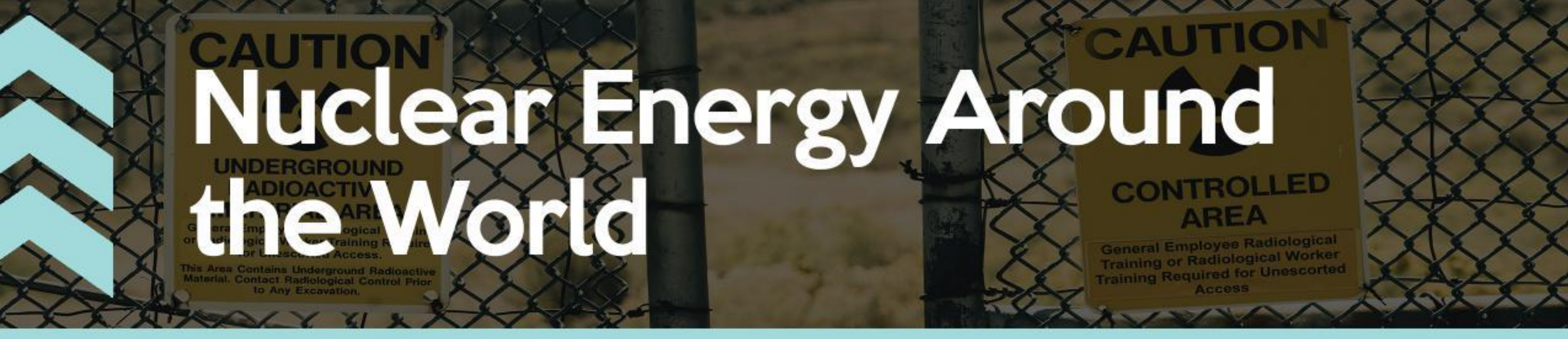
System costs and nuclear-specific taxes

The most capital-intensive aspect of a nuclear plant is the "overnight costs" which is the capital cost needed for engineering, procurement, and construction (EPC) costs, owners' costs (land, cooling infrastructure, associated buildings, site works, etc.) and various contingencies. The chart below breaks down the costs of labour, goods, and materials for an average nuclear plant.

While nuclear plants are the most expensive energy infrastructure to construct, once complete, the cost to operate the plant is relatively low and stable compared to other energy sources. Additionally, due to the stable and consistent output of energy, the cost of producing electricity is significantly lower and the energy is less volatile compared to other renewable sources.

The cost of constructing nuclear plants has increased over the years. There are various factors associated with the rise in costs such as costs of new technologies, inflation, labour, resources, etc. Another major problem is that nuclear reactors have failed to reach economies of scale unlike coal fire plants andgas plants. In 1990 the OECD average for constructing a nuclear power plant was $1,900/ KWe, this figure rose to $3,850/ KWe in 2009 and to $5,157/ KWe in 2019 (Worldwide average inflation adjusted). These figures, while useful for providing benchmarks, fail to show the drastic difference in cost for different countries; for example, overnight costs ranged from $2,157/ KWe in South Korea to $6,920/ KWe in Slovakia. The dramatic difference in costs could be associated with scale as South Korea has 24 nuclear reactors operational while Slovakia has four in comparison. China's overnight costs are currently at $2,500/ KWe, while being on the lower end, it is expected that prices will go down further as China is expected to build a staggering 150 nuclear reactors with over 40 currently under construction.

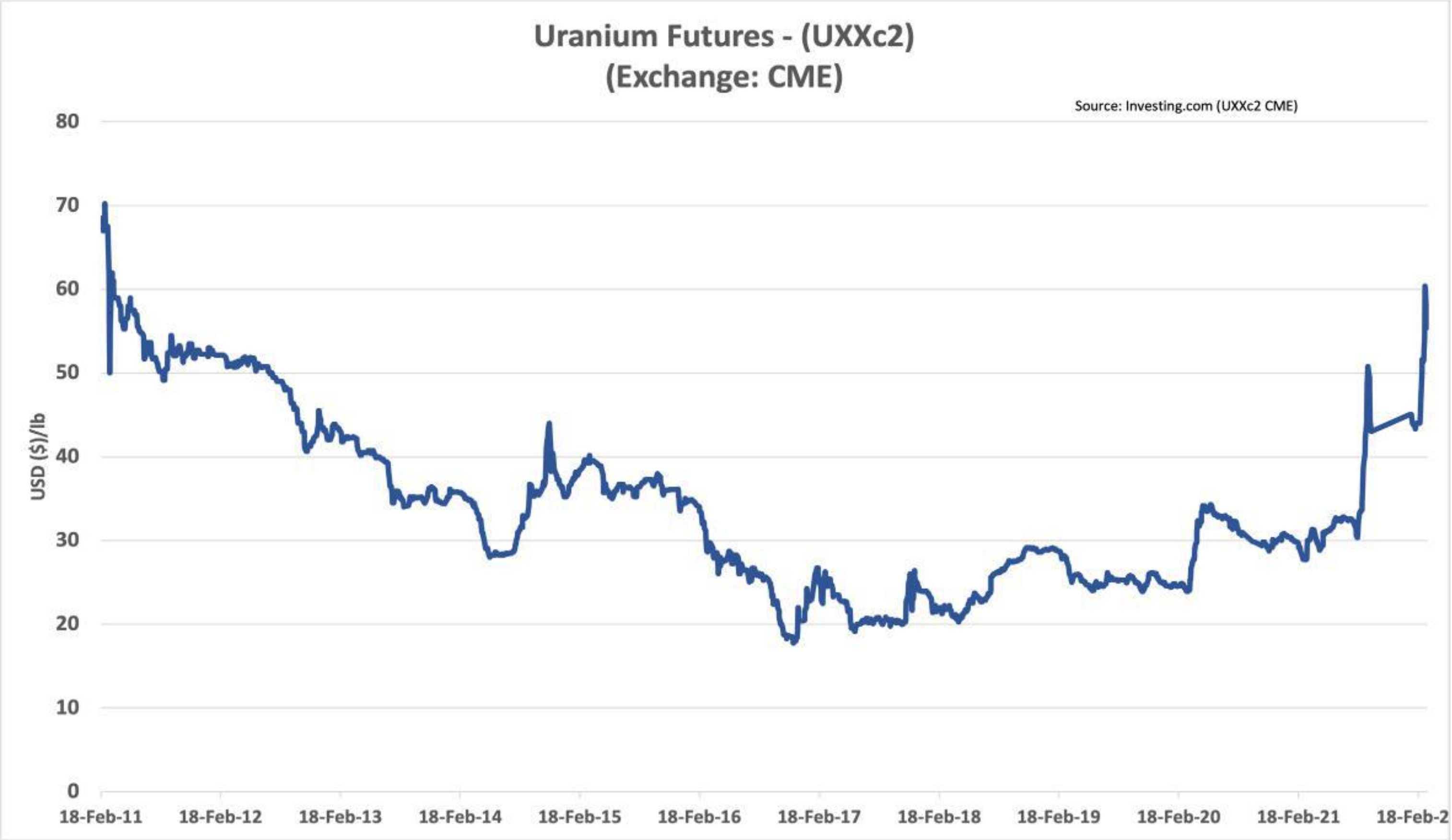
Nuclear Energy Around the World



On a global scale, nuclear power constitutes the second largest source of carbon neutral energy production after hydropower. As such, nuclear plants do not emit any direct CO2 and their carbon footprint is comparable to various renewable energy sources. Globally, 440 nuclear reactors that bear an [average age of 35 years continue to provide just over 10% of global electricity.] Following the 2011 Fukushima disaster, the past decade has been characterized by an increased push among states to replace nuclear power with renewable and 'safer' sources of energy. While this dynamic was particularly evident in Germany, other countries - including China, India, and Russia - had committed themselves to augmenting their commitment to nuclear energy. Historically, aside from the 2011 Fukushima and the 1986 Chernobyl disasters, nuclear power showcases a sound global safety record, as the majority of plants are operating in relatively safe and developed countries.

The recent Russian invasion of Ukraine has highlighted how war can quickly turn an otherwise safe source of energy production into a large-scale risk. Europe's largest nuclear power plant in Zaporizhzhia covers ~35% of Ukraine's domestic energy needs. However, after the Russian invasion and following the shelling of the Zaporizhzhia plant, the Ukrainian energy grid currently runs on an "island mode" (disconnected from any electrical grids outside of Ukraine), as the war threatens to cut vital connections between Ukraine's nuclear plants and the overall electric grid. Experts see this as a mounting risk as the war drags on. Ukraine's nuclear plants rely on a steady stream of outside electricity in order to keep critical safety systems running, and any possible long term interruption of the electric grid could provoke a core meltdown of a reactor. The chances for this remain slim for now, as a number of other backup systems would need to fail for such a worst case scenario to occur. Nonetheless, the war has re-ignited debates on nuclear power, especially in Europe and Asia. For one, the world has recently been reminded that a large-scale war does pose a risk for nuclear safety through the case example of Zaporizhzhia. Secondly, the Europeans have had a rude awakening to their dependency on Russian energy imports, putting new urgency behind Europe's nuclear energy debate.

As a consequence of the Russia-Ukraine war the world is witnessing a number of new dynamics that complement the already soaring energy price levels. These new dynamics include both a spike in the price of uranium on the spot and futures markets, as well as re-thinking on prolonging the life of nuclear power. The price for Uranium, reached USD $60.4/lb on March 10th, 2022, the highest price point since the Fukushima disaster in March 2011 (see figure X).



This price surge is mainly driven by fears of a uranium supply shortage as the U.S. weighs sanctions on Russia's Rosatom and its subsidiaries, which account for ~35% global uranium enrichment and 16.5% of uranium imports into the U.S. in 2020. Experts, however, have not stirred into panic, citing that Canadian uranium production by big players like CAMECO Corp. could likely boost output if prices improve in order to justify additional long-term production.

Another consequence of the sustained high energy prices and the Russia-Ukraine war is global re-thinking on giving nuclear power a second chance. Nuclear energy production is concentrated in a handful of countries, few of which have been growing their production over the past decade (see table on the next page).

Top 10	Exajoules	Global Share	10Y Annual Growth Rate
United States	7.6	30.5%	-0.6%
France	3.6	14.%	-1.2%
China	3.1	12.5%	15.0%
Russia	1.9	7.5%	1.7%
South Korea	1.3	5.2%	-1.8%
Canada	0.9	3.6%	-0.1%
Ukraine	0.7	3.0%	-1.2%
Germany	0.7	2.7%	-7.1%
Sweden	0.6	2.4%	0.1%
Japan	0.6	2.3%	-15.6%

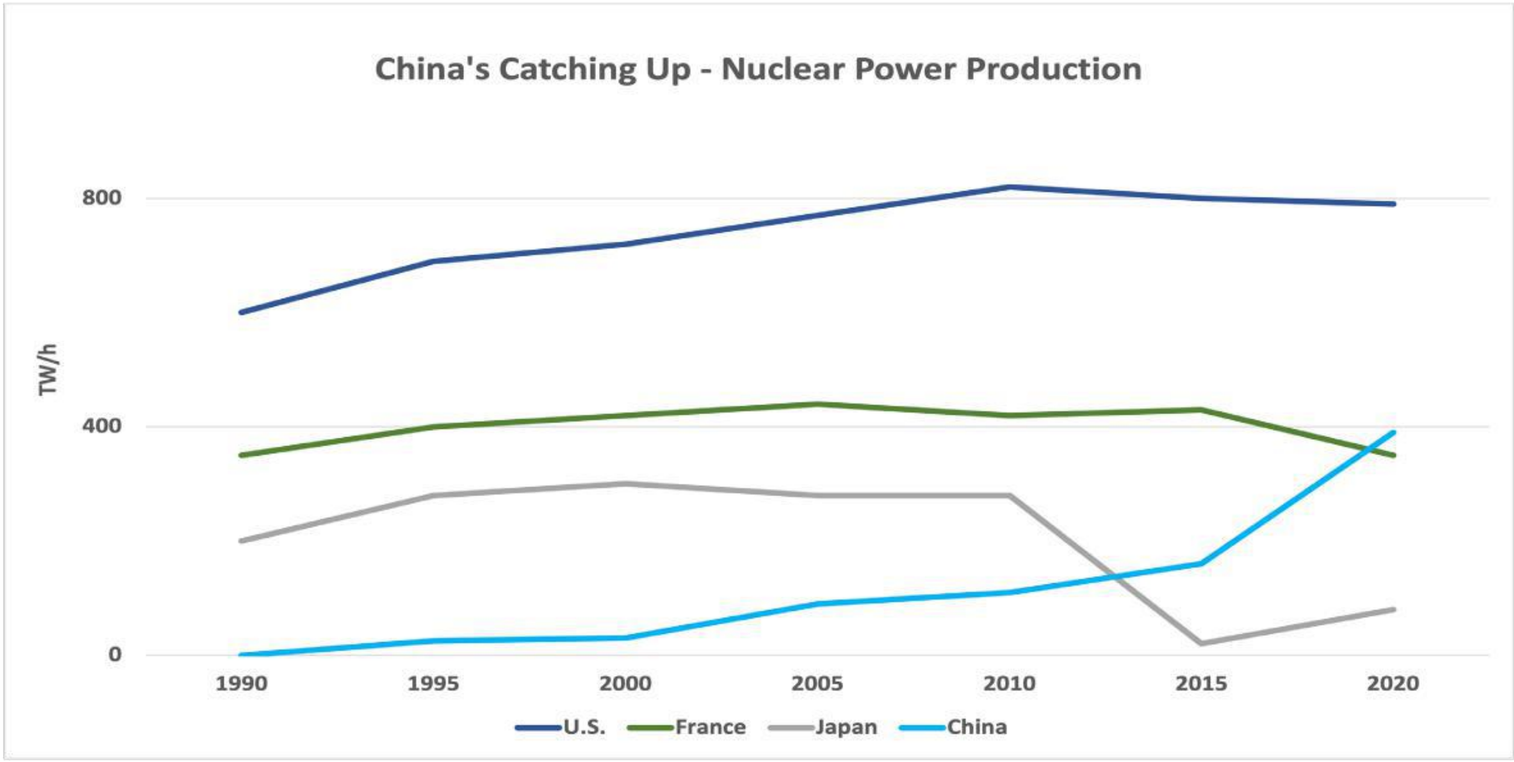
Table 1: Global Nuclear Energy Production and 10Y Growth

The European market now finds itself in an energy crunch due to both the consequences of the war and prior gas shortages. France, the largest producer of nuclear power in the European Union (EU), faces soaring prices as domestic reactor outages caused by prolonged repairs and maintenance issues are putting pressure on energy supplies. Europe's dependency on Russia has been laid bare, in turn rapidly igniting debates around either prolonging the life of existing power plants or revisiting a commitment to new construction investments. The investments would however come at a high price, with upfront costs for a single new power plant clocking in anywhere between USD $5-9 billion. In order to gain complete energy independence from Russia, experts estimate that the EU alone would need to invest ~170 billion Euros (~$188 USD) in infrastructure and maintenance of existing capital on an annual basis. Therefore, a number of EU countries are currently assessing their options on whether to commit to nuclear power or whether to hedge their bets on continued energy imports and renewables. Whilst Germany has made it clear it will stray away from nuclear power, Belgium is among those countries, next to France and the United Kingdom (UK), which is expected to extend the life of their nuclear reactors beyond 2025. President Macron has pledged to provide billions in funding for Electricite de France (EDF) in order to drive the construction of as many as 14 reactors by 2025. Similarly, Finland is committing itself to the expansion of its nuclear program, having just taken a new plant (Olkiluoto 3) online. Olkiluoto 3 is to meet 14% of Finland's electricity demand and decrease the country's import dependence on outside sources from Russia, Sweden, or Norway.

Meanwhile, in Asia, South Korea and China are driving the nuclear agenda. South Korea's President-elect Yoon plans to harness nuclear energy to attain the country's net zero emission targets, as well as to push total energy generation and turn South Korea into an exporter of nuclear expertise. In light of a global energy crunch, the Philippines are also seeking to adopt nuclear power once again by reactivating a 37-year old reactor. Meanwhile, China is taking the lead in planning the construction of over 150 new reactors within the next 15 years across the country - a total investment of USD $440 billion. China's rise in prominence will be elaborated on further below.

Case Example: China - A Nuclear Renaissance

China is immensely boosting its commitment to nuclear energy in order to curb pollution levels and to somewhat work towards the targets set by the COP26 Climate summit. The country's aim is to achieve a closed nuclear fuel cycle and become self sufficient in reactor design, as well as construction. For the past decade, China has made full use of western technology and know-how, in turn refining it and establishing a strong nuclear supply chain. Under the 14th Five-Year Plan (2021-2025), the CCP plans to achieve 70 GWe of gross nuclear production capacity by 2025, and this year, nuclear generation was raised by 18% over 2018 to 295 TWh. As part of its long run strategy, China seeks to export its nuclear expertise and technology abroad, which would arise within the framework of the Belt Road Initiative. Currently, China is well on track to surpass the United States (US) as the world's biggest producer of nuclear power by the middle of this decade (see graph below). One major advantage China has in this sense is the significantly lower costs of production. While the exact figure remains a secret, BloombergNEF and the World Nuclear Association estimate China can build plants for about $2,500-$3,000/kilowatt, which is about 30% of the cost of projects in the U.S. ($5945/ KW) and France. The country will undoubtedly establish itself as a nuclear leader in terms of production and know-how by 2030, yet it remains to be seen in which global context this will occur, given the ongoing Russia-Ukraine war and the soaring global energy prices.



Source: Bloomberg

Geopolitics of Nuclear Energy

While nuclear energy presents a unique opportunity for countries to move away from carbon intensive energy sources, it also presents an inherent security risk that can have catastrophic impacts around the world. The development of nuclear weapons, only deployed twice in Hiroshima and Nagasaki towards the tail-end of World War II, presents a constant threat to the safety of citizens worldwide, establishing the notion of "mutually assured destruction (MAD)". Five states have declared a nuclear arsenal under the Treaty on Non-Proliferation of Nuclear Weapons (NPT) (US, Russia, United Kingdom, France, and China), while three states who are not parties to the NPT have also conducted nuclear weapons tests (India, Pakistan, North Korea). Outside of the focus on the targeting of Zaporizhzhia during the ongoing war in Ukraine, countries are advancing nuclear interests on all fronts, causing geopolitical tensions that could be disastrous.

In 2021, the US was ramping up its nuclear testing research, generating more than 10 quadrillion watts of fusion power in under a second at the National Ignition Facility in California. While this record could generate over 700 times the generating capacity of the entire US electrical grid, this precision fusion could also help scientists understand and simulate how nuclear weapons can detonate, fueling controversy.

Elsewhere around the world, the US has spent the better part of the last year reviving the dormant Joint Comprehensive Plan of Action (JCPOA) with Iran, which would see Iran eliminate and cut down on its stockpiles of both medium and low enriched uranium respectively in exchange for lifted economic sanctions, curbing their path to a nuclear weapon. However, talks have broken down at the last minute, with Russia demanding guarantees that sanctions stemming from its invasion of Ukraine will not impact its relations with Iran, leaving the negotiations unresolved. Israel, widely considered to be an undeclared nuclear state, has been in stark opposition to the JCPOA, stating that the deal will further empower Iran and destabilize the Middle East and is ramping up its military capabilities in the meanwhile. Saudi Arabia, another staunch opponent of the Iranian regime, have also recently announced their intention to establish a national nuclear energy company, fueling speculation that they too have explored a nuclear arsenal in the wake of former US President Donald Trump by passing Congress to enable sales of nuclear technology to the Kingdom. As mentioned above , China is emerging as a leader in nuclear energy internationally and has been open in its willingness to share its nuclear technology to further develop nuclear energy. Recently, however, China has signaled its dismay for Japan's call to host US nuclear weapons amidst Japan's concerns over Chinese actions towards Taiwan.

Nuclear Energy Outlook

Nuclear energy, with essentially no direct operating emissions and the highest potential energy density of all contemporary energy sources (Nuclear Reaction of Uranium-235 has a potential density of 3,900,000 MJ/kg), has long been considered a viable renewable source for the low-carbon transition. The high energy density means that for long-term operation, the large plants are undercutting all other sources of electricity provision out there with levelized costs of US $35/ MWh.

Energy Source	Overnight Capital Cost per installed capacity ($/kW)	Variable O&M costs ($/MWh)
Advanced Nuclear	$5,945	$2.3
Natural Gas Combined Cycle[2]	$978	$3.5
Solar Photovoltaic (Fixed)	$2,671	$0
Onshore Wind	$1,877	$0
Conventional Hydroelectric	$3,123	$12.7

Table 2: Capital & Operating Costs in America for various utility-scale power sources

Those that are in opposition of nuclear energy taking up a larger role note the main downsides of high capital investment (US $5 - $9 billion per reactor, often costing up to three time the original planned amount), safety concerns, the risks of proliferation from a geopolitical perspective, and the nuclear waste that is generated from the process. The opposition will justly highlight that even though nuclear energy might appear the cheapest source from a levelized cost angle, this figure typically does not account for decommissioning costs, and also assumes the economies of scale that are achieved by massive plants (with over 1100 MWe capacity). Decommissioning costs are not insignificant for this type of technology - depending on location and type of reactor, these can range from US $400 million all the way up to $1 billion. Similarly applicable for both the construction and decommissioning of large-scale nuclear, it can prove difficult to finance costs of these magnitudes .

Because of this divide, states have either taken the route of decommissioning a lot of their existing nuclear power plants or doubling down to construct more capacity. As we mentioned previously in this report, the world's 440 reactors in 32 countries produced approximately 10% of the world's energy in 2020. That same year, we saw the plan to add another 55 reactors to the world total, notably in Russia, China, India, and the United Arab Emirates (UAE). On the other hand, countries like Belgium (planning to close their 7 reactors by 2025), the US (where total reactors have decreased from 110 to 93) and Germany (where a total of 26 reactors are currently undergoing decommissioning) have been on the opposite path of phasing out nuclear energy and replacing it with renewables. The diverging paths to nuclear nearly cancel out with the world still adding additional capacity every year, but at a much slower pace

On a longer arc, the Organization for Economic Co-operation and Development's (OECD) International Energy Agency (IEA) predicts that nuclear energy will continue growing but will not keep up with world energy demand and eventually decrease down to 8% of world's total energy production by 2050. They note that most of the decline in proportional production will come from the developed world as investment in extending reactor life dwindles, mainly in response to public opinion.This longer-term prediction takes the current dominant technology (large-scale utility fission) for granted as the path forward. It does not take into account the development of nuclear fusion technology (the joining of atomic nuclei, instead of splitting them), nor micro and modular reactors.

With regards to fusion technology, "commercial-deployment of fusion technology has been 40 years away since the 1970's." This quote is meant to highlight the fact that research into this technology is both immensely capital-intensive and still at an early phase. The main issue is that to this day, we have not figured out a way to create more energy from fusion nuclear reactions than the energy that is required for the process. The number of private fusion technology companies has been increasing though (30 to date), with the combined group achieving billions of dollars in funding (US $2.4 billion to 17 firms), and some claiming that they will be ready for commercial viability by 2030.

When it comes to small to medium reactors, defined as those reactors having electrical capacity of up to 300 MW for the small category, and up to 700 MW for the medium category, the speed of development has been faster. There are currently around 40 advanced nuclear reactor (ANR) startups in the US, using technologies like liquid metal cooled reactors to advance their small modular designs. They have received broad support from the US Department of Energy (DOE) since as early as 2012. The latest round of support came in the form of May 2020's Advanced Reactor Demonstration Program (ARDP) which seeks to provide around US $160 million in cost-sharing to two ANRs that can be operational within 7 years. The main roadblock for these designs is on the public perception around small modular reactors powering commercial and residential buildings.If the general public still associates nuclear energy with accidents such as Chernobyl and Fukushima, and the associated radioactivity that continues to plague these areas, there will be little hope for a small modular designs market closer to where more people live.

We don't believe the mass commercialization of these, or of fusion technologies, will occur fast enough for the low-carbon transition if the world is to maintain global warming below the 2°C mark. The likeliest scenario is as is estimated by the OECD - fission nuclear energy will continue to provide some much needed redundancy and stability as we transition to more renewable energy sources. However, due to the political challenges and continuous doubts from broad public perception, not at all alleviated by the threat of nuclear warfare, nuclear energy will only grow as much as broad energy demand does and will not necessarily be a large slice of the renewable energy pie in 2050.