NUCLEAR POWER: WHAT NEXT?

State of play and opportunities for philanthropic engagement

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INTRODUCTION

Purpose of this brief

As a growing number of philanthropic foundations increase focus on combating climate change and its impacts, several questions about nuclear power are emerging. How credible are claims about the safety and affordability of new-generation nuclear power? When will they become a reality? How relevant will they be for developing countries where most of the future growth in population and energy infrastructure will occur? What role can philanthropic foundations and impact investors play? This brief attempts to answer these questions, along with high-level discussions on the evolution of nuclear power over the decades, the major accidents of years-past and what caused them, if/how new-generation systems are designed to avoid similar risks, the regulatory landscape, and the market outlook.

Executive summary

The nuclear age has seen the horrors of Hiroshima and Nagasaki, and the failed expectations of electricity "too cheap to meter." Since then, much of the world has become skeptical of nuclear power. The Three-Mile Island scare (1979) and the Chernobyl disaster (1986) hardened public opinion to the point where global nuclear power capacity plateaued by the late 1980s. In the years since, the accident in Fukushima (2011) and the declining cost of alternative energy sources—natural gas, solar, and wind—appeared to have sealed the case against nuclear power.

Now, nuclear power is making a remarkable comeback with billions of dollars of investment from both public and private sectors. The apparent about-face is being driven by three forces: (i) the urgent need to transition away from carbon-intensive energy sources, combined with the as-yet unsolved challenge of large-scale energy storage for intermittent renewable power; (ii) the vulnerability of supply chains for conventional energy sources like natural gas to geopolitical shocks such as Russia's invasion of Ukraine; and (iii) innovations in nuclear reactor design which offer significant improvements over early-generation systems.

There are more than 130 active projects on fourth-generation nuclear reactors being led by private companies (including dozens of startups), national labs, and public-private partnerships. Most of these projects involve some combination of the following three innovations: (a) small modular reactors (SMRs) that are downscaled, productized and prefabricated; (b) reactor chemistries that are inherently safe and in theory immune to meltdown; (c) increased efficiency of nuclear fuel use leading to more sustainable resource use and less radioactive waste. Within these parameters, there is a wide diversity of specific designs, the majority of which appear sound. The main difference between the various projects is with respect to item (b) above, with several reactor designs: gas-cooled fast reactors, lead-cooled fast reactors, molten salt reactors, supercritical water reactors, sodium-cooled fast reactors, and very-high-temperature reactors. Some of the reactor designs use nuclear fuel in forms that are different from conventional rods, and involve additional costs and complications. However, the performance differences between different Gen 4 reactor chemistries—and between individual companies working on the same reactor chemistry—will likely be relatively minor compared to how much of a step-change they collectively represent over previous-generation reactors. Another potential benefit of nuclear power in general is "hybrid use" that makes other products (e.g., hydrogen, desalinated water) when demand for electricity is low.

Still, the debate rages on. A large portion of the global population as well as many influential institutions remain opposed to nuclear power. Innovators, risk-embracing investors and other technophiles remain bullish as ever. The perspective of many other institutions—including ours—lies somewhere in the middle. There are several new-generation nuclear reactor designs that can address critical safety challenges faced by early-generation systems, but they cannot entirely eliminate the risk of contamination triggered by unforeseen events or terrorism. They hold the promise of eventually becoming a mainstream commercial reality and offering a long-term option for reliable carbon-free energy. However, most of them are in very early stages and their eventual success will only be determined over time; while a small number of them are within a few years of demonstrating functioning systems, none are yet operational.

As such they will require rigorous testing and development before being commercialized. Even in wealthy countries, they will likely need 10-15 years before beginning to scale, which means that their contribution to the urgent climate mitigation efforts over the next 20 years will likely be limited. Design improvements leading to system modularity and downscaling will reduce costs considerably. However, nuclear reactors will remain more expensive than other sources of power, including renewables like solar and wind. While likely being an earlier option for wealthier countries, nuclear power will continue to be too expensive for the majority of developing countries for at least the next 15-20 years—until "productized" modular systems can be manufactured at a scale large enough to reduce unit costs. Until then, the economics of the industry will remain tricky, since many companies will face the risk of being too subscale to survive for the long haul. Another key determinant in the global scaleup of nuclear power will likely be the future availability of affordable grid-scale energy storage for intermittent renewables. The risk of proliferation for weaponization will remain, or potentially even get worse as the sheer amount of fissile material being transported and stored around the world increases, although some of this risk can be offset by particular reactor types that consume more of the fissile material.

With the above context, there are three opportunities for philanthropic funders to engage in nuclear power:

1. Co-create a large "pooled" fund for stage-gated investment in a gradually shrinking pool of companies. The typical project is raising (or targeting) upwards of US$100 million of funding, through a mix of grants and investments; across the ecosystem, that amounts to more than $10 billion. The companies and projects that are remotely close to market-readiness already have considerable funding. This means that an individual funder with $25-50 million with an interest in accelerating Gen 4 nuclear power can make meaningful investments in only a very small number of early-stage companies—in a very crowded field in which differences in technology are limited. A more effective approach would be to form a "challenge" pool with like-minded funders (with stage-gated evaluation across competing projects to support the ones most likely to succeed over time). There will also likely be opportunities to support technologies and companies that aim to produce new types of nuclear fuel as an alternative to conventional fuel rods, and those developing innovative approaches to tracking fuel to reduce the risk of proliferation.

2. Support civil society engagement in the development of a new global regulatory framework. The current global institutional and regulatory infrastructure was built around the safety/security considerations of a particular reactor type (pressurized light water), a particular fuel type (low-enriched uranium fuel rods), and use of nuclear power limited to a relatively small number of countries under strict government oversight. As the diversity of reactor and fuel types increases along with the number and geographic distribution of reactors and the sheer amount of nuclear material, the regulatory regimen needs to significantly evolve. As that happens, it will be important to ensure the voice and input of civil society is adequately incorporated.

3. Creative public engagement to earn the trust of communities around the world. Given the widespread negative perception of nuclear power, a long-term multifaceted effort will be required to thoughtfully engage the public, policymakers, civil society, and other influential voices on the various considerations. Lessons may be learned from countries with more favorable popular support for nuclear power, such as France.

THE CURRENT LANDSCAPE OF NUCLEAR POWER PLANTS

As of April 2023, there are 420 nuclear reactors producing electricity globally, with 56 additional reactors under construction.[1] The aggregate capacity of all operational reactors is 380 gigawatts (GW), generating 2,650 terawatt hours (TWh) of electricity each year—about 10% of global electricity production. The average reactor has a capacity of about 870 megawatts (MW) and generates 6 TWh of electricity annually—enough to power an American city of some 1 million people. Often, several reactors are sited together at a single power plant to leverage economies-of-scale for security, administration and logistics. **Exhibit 1** shows the number of nuclear reactors constructed over the years. Most of the reactors operating today were built in the 1970s and 1980s. The number of operational reactors has remained relatively stable since the late 1980s, as reactors removed from service (primarily in Western countries) have been balanced by new reactors coming online (mainly in China and Russia).

Few new nuclear plants have been built in the last 20 years in OECD countries (see **Table 1**). In contrast, China is building increasing numbers of nuclear reactors as part of a major electricity buildout that includes coal and renewable power plants. The majority of recently built plants have been conventional pressurized light water reactors, with any improvements being evolutionary not revolutionary.

The US is currently home to the largest number of reactors (96), followed by France (56), China (50), Russia (38), Japan (33), South Korea (25), India (22), Canada (19), the UK (18), and Ukraine (15). Twenty-five other countries have a single-digit number of reactors across Europe (53), Asia (13), Latin America (7), and Africa (2). France is the most nuclear-reliant country, obtaining 70% of its electricity from nuclear power. Ukraine, Slovakia, and Belgium also get half or more of their power production from nuclear plants. Globally, about 10% of all electricity is currently generated by nuclear power plants (compared to 37% from coal, 24% from natural gas, and 16% from hydro).[2] **Exhibit 2** shows a map (from a few years back) with all the nuclear power plants around the world—operational, decommissioned, temporarily offline, and under construction.

EXHIBIT 1

Timeline of nuclear power reactors constructed over the years. (Source: IAEA[3])

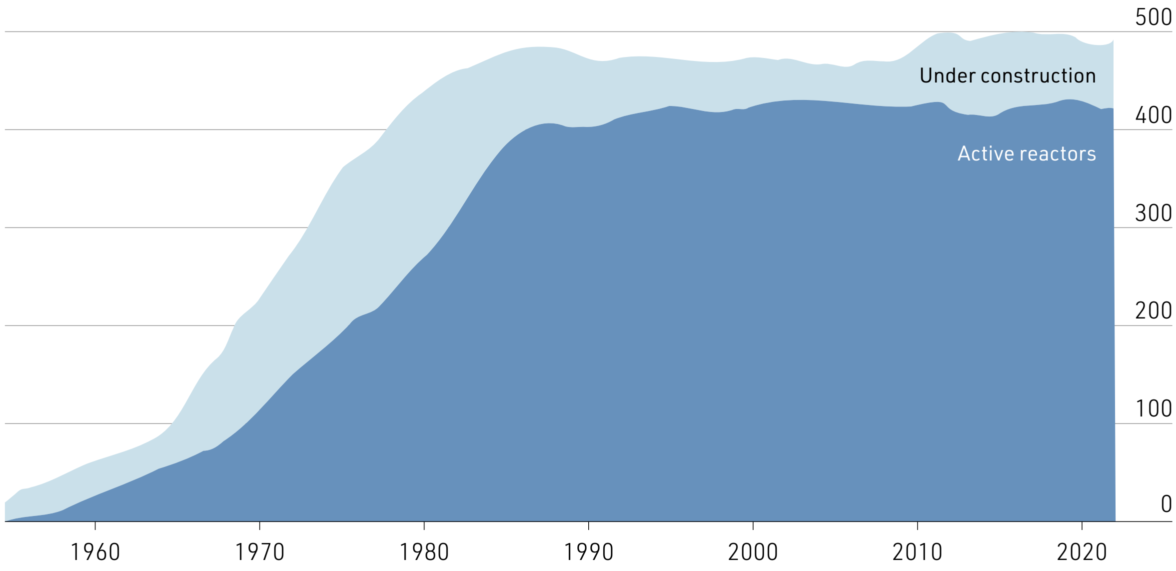


TABLE 1

Number of new nuclear reactors connecting to the grid since 1986, showing a major slowdown in OECD countries but a ramp-up in China, Russia and India. (Source: IAEA[3])

	1986-90	1991-95	1996-00	2001-05	2006-10	2011-15	2016-21
Germany	6						
UK	4	1					
Canada	5	2					
France	15	3	4				
Ukraine	6	1		2			
USA	22	1	1				1
Japan	8	10	3	4	1		
South Korea	4	2	5	4	1	3	2
India	1	3	4	1	4	2	1
Russia	4	1		2	1	3	7
China		3		6	4	18	19
All other	10	2	6	1	1	3	4
Worldwide	**85**	**29**	**23**	**20**	**12**	**29**	**34**

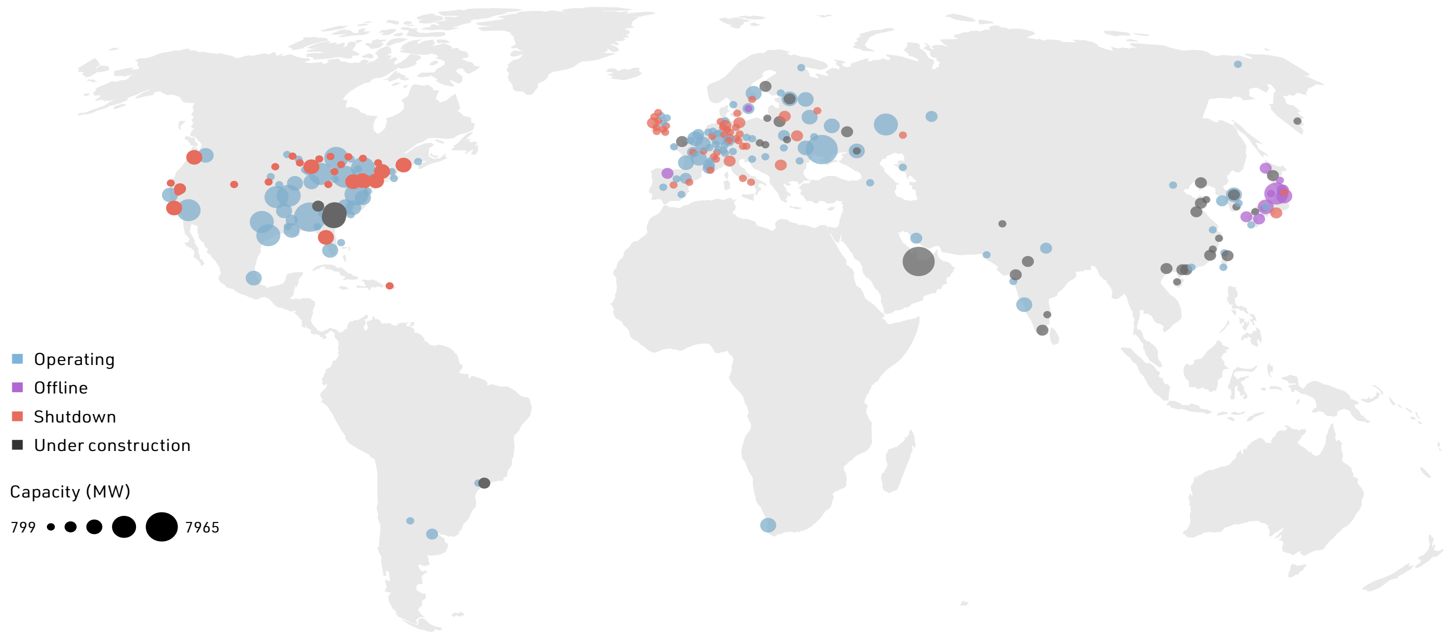


EXHIBIT 2

Map of nuclear power plants around the world. (Source: CarbonBrief[4])

Conventional nuclear power technology from first prototype to today

The majority (83%) of current operational reactors use a design known as Pressurized Water Reactor (PWR), essentially a 4-part process illustrated below in **Exhibit 3**. Note that most PWRs use light water (i.e., "normal" water) for cooling. However, about 13% of existing PWRs uses "heavy water" in the primary loop, which has an isotope of hydrogen known as deuterium with an extra neutron.[6] Heavy water does not absorb neutrons emitted by the fission reaction, thus heavy water reactors have better "neutron economy" and can work with natural uranium that is not enriched. Light water, in contrast, absorbs some of the emitted neutrons; therefore, light water reactors must use enriched fuel. However, the high cost of producing heavy water has limited the use of heavy water reactors.

The above description of PWRs applies to most currently operating reactors. Another reactor design, the Boiling Water Reactor (BWR), is used in about 12% of existing reactors.[7] In this design, light water is heated to a boil in the reactor core, and the steam is used directly to power turbines without going through a heat exchanger. While a simpler design with potentially lower capital cost because they avoid the use of a heat exchanger, operation and maintenance of BWRs are more challenging because the radioactive water is less isolated.

Nuclear reactors from the early prototypes to today: Generations 1-3

The first human-made self-sustaining nuclear chain reaction occurred in December 1942 at the University of Chicago as part of the Manhattan Project, towards creation of nuclear weapons. This was followed by additional reactors at Oak Ridge (Tennessee, USA), Los Alamos (New Mexico, USA), Chalk River (Ontario, Canada), and Richland (Washington, USA), all contributing materials or knowledge needed to produce the nuclear bombs dropped on Hiroshima and Nagasaki in 1945.[8]

While these first reactors focused exclusively on producing nuclear weapons, post-war efforts shifted to other uses including the generation of electricity. The first instance of nuclear-powered electricity occurred in 1951 in an experimental reactor located in Arco (Idaho, USA). The first grid-connected nuclear power plant came online in 1954 in Obninsk, Russia (then USSR), with a relatively modest generating capacity of 5 megawatts (MW). In concurrent efforts towards applications of nuclear power, the first nuclear-powered submarine, the Nautilus, was commissioned by the US Navy in 1954, followed in 1958 by the Soviet submarine Leninskiy Komsomol. Since these initial experimental and military reactors, nuclear technology for generating electricity has gone through three generations of evolution, with Generation 4 constituting a new range of yet-to-be-fully-realized reactor technologies.[9]

GENERATION 1

Generation 1 reactors were prototype systems built in the 1950s and 1960s. Examples include Calder Hall-1 (1956–2003) in the UK, and Shippingport (1957–1982) and Dresden-1 (1960–1978) in the USA. The earliest of these reactors typically

EXHIBIT 3

Schematic of a pressurized water reactor (PWR) nuclear power plant

Step 1

The fission process takes place in the reactor core, which contains fuel rods containing fissile nuclear fuel (typically Uranium-235 enriched to about 5% purity) which are bombarded with neutrons.[5] When one of these neutrons collides with the nucleus of the fissile atom, it destabilizes the nucleus and splits it into two or more smaller pieces. This releases a large amount of energy in the form of heat, as well as additional neutrons. The energy level of these neutrons is moderated by the surrounding water, enabling them to collide with other nuclei, causing them to fission as well. This creates a chain reaction that releases enormous amounts of heat. The reactor core is contained within a steel pressure vessel, which is itself within a large heavily-reinforced concrete structure designed to fully contain the radioactive material from escaping into the external environment.

Step 2

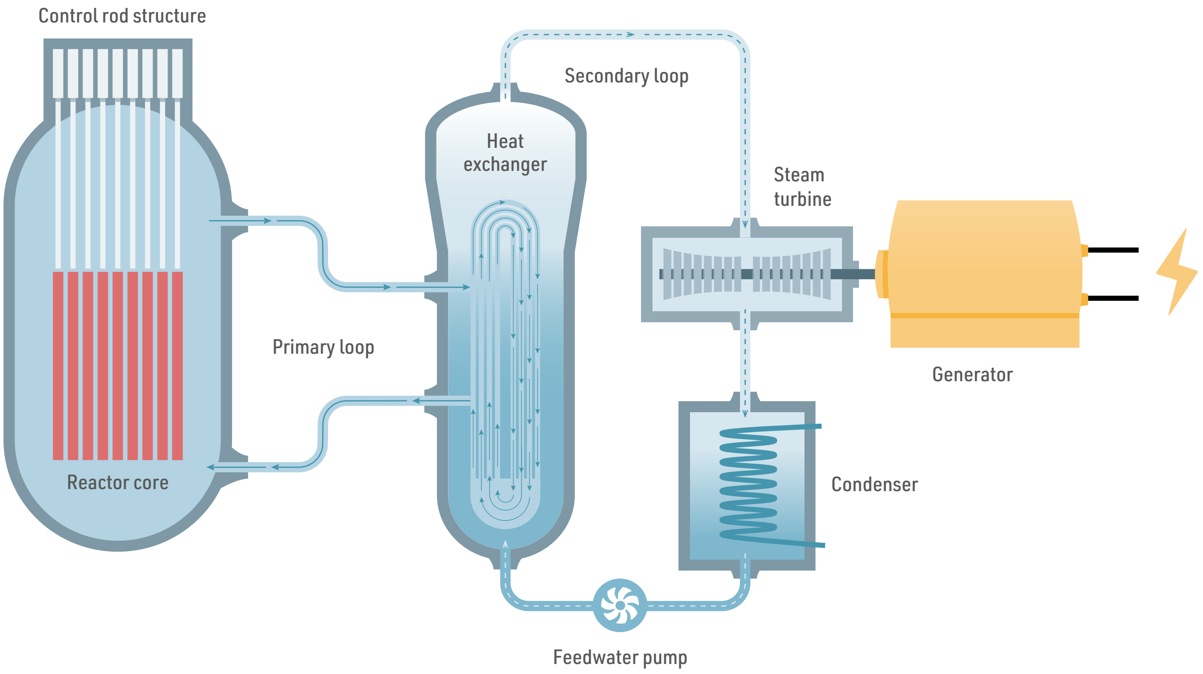
The rate of the fission reaction is controlled to enable appropriate level of heat production, and to initiate and stop fission as needed. This is done via control rods (made of materials that absorb neutrons, such as boron or cadmium) which are inserted into or withdrawn from the core to adjust the amount of fissile activity in the core (and hence the reaction rate).

Step 3

The reactor is cooled by water kept at very high pressure to prevent it from boiling. The coolant water is circulated through the reactor core using electrically powered pumps. The pressurized water is sent to a heat exchanger via what is known as the primary loop. Heat is transferred from the pressurized water in the primary loop, which boils water to create steam in a secondary loop.

Step 4

The steam is then used to drive turbines, which generate electricity much in the same way that other thermal power plants (e.g., coal-powered) do. The steam is then condensed back into liquid water and recirculated in the secondary loop back to the heat exchanger.



ran at "proof-of-concept" power levels (tens of megawatts), with some later ones reaching a few hundred megawatts. With nuclear submarine propulsion as the initial use case, most used light water as both the coolant and the moderator. The fuel was typically low-enriched uranium (~5% purity) in the form of solid fuel rods though some reactors used more highly enriched fuels. The reactors were relatively simple, typically with a single large pressure vessel containing the reactor core, coolant, and control rods. Control of the reaction was done through mechanical or hydraulic systems to adjust the position of the control rods, manually or with the help of automation. Gen 1 systems also experimented with a diversity of other reactor types; for example, the Wylfa plant in Wales used graphite for moderation, was cooled by carbon dioxide gas, and was fueled by natural (unenriched) uranium. This final Gen 1 plant began construction in Wales in 1963 and was decommissioned in 2015.

GENERATION 2

Generation 2 reactors, developed in the 1970s, 1980s and into the 1990s, represented the first at-scale realization of nuclear power for electricity generation, and constitute a majority of the 400+ reactors currently operational. A majority of Gen 2 reactors are still operational although some have been decommissioned due either to age or to anti-nuclear policy shifts. Gen 2 reactors incorporate significant improvements in control and safety based on electronics systems unavailable in Gen 1. With increased size and heat-to-electricity conversion efficiencies, the power output of Gen 2 reactors reaches 1 GW. Most Gen 2 reactors use light water for cooling and moderation, with pressurized water reactors (PWR) the most common, plus a number of boiling water reactors (BWR). Examples include the BWR series of reactors built in the US by GE, the CPR-1000 and CPN reactors in China, the KSNP reactors in South Korea, and the Vodo-Vodyanoi Energetichesky Reactors (VVER) built in the Soviet Union. Other designs are also used in Gen 2 reactors, such as the CANada Deuterium Uranium reactors (CANDU) that use heavy water and unenriched uranium fuel. Another Gen 2 design was the Reactor Bolshoy Moshchnosty Kanalny (RMBK) built in the Soviet Union. Advanced gas-cooled reactors (AGR) are a further Gen 2 design used in the UK and are improved versions of the Wylfa plant design using graphite for moderation and carbon dioxide for cooling. The power plants involved in all three accidents described later in this report (Three Mile Island, Chernobyl, and Fukushima Daiichi) used Gen 2 reactors.

GENERATION 3

Generation 3/3+ nuclear reactors, built in the 21st century, are the most sophisticated among the currently operational fleet. Third-generation reactors are advanced light water reactors that use water as the coolant and moderator, and have a number of safety features to prevent accidents. Gen 3 reactors are typically designed for an operational life of 60 years or longer. The fuel used in these reactors is typically low-enriched uranium that is used once and then disposed of as waste. More complex than Gen 2 reactors, they use improved materials and advanced safety features such as electronic systems to monitor and control the reaction rate, automated systems that do not require active intervention, and stronger containment structures. Some have passive cooling systems (a common feature in Gen 4 reactors described later). Thermal efficiency is also somewhat higher, with typical electrical power output still in the 1 GW range. Examples of Gen 3 reactor designs include the AP-600, ABWR, Areva EPR, and CANDU 6. Gen 3+ is a somewhat arbitrary category of reactors, which include evolutionary advancements over Gen 3 designs. Gen 3/3+ systems have been built since the turn of the century; they are operational and are expected to remain so until well into the 21st century although the Fukushima accident has prompted some delays or pauses in commissioning.

Challenges faced by conventional nuclear power

Nuclear reactors from Gen 1 through Gen 3+ (i.e., 100% of reactors currently operational around the world) face three major challenges which have collectively led to some high-profile accidents and significant public backlash against nuclear power—so much so that it has teetered on the edge of becoming politically untenable as a mainstream energy supply solution.

Challenge 1: Risk of reactor core meltdown leading to catastrophic radiation contamination

A meltdown of the reactor core can occur due to a failure of the coolant system or the control system that regulates the nuclear reaction. The three most significant accidents are Three Mile Island (USA; 1979), Chernobyl (Ukraine, formerly USSR; 1986), and Fukushima Daiichi (Japan; 2011). The specific causes have included equipment failure (pumps, valves, or sensors) leading to loss of the coolant flow to the reactor core, suboptimal control processes (e.g., inadequate safety protocols), human operator error (improper shutdown of the reactor, inadequate compliance with safety protocols, or improper crisis response), or a natural disaster. The nature of each of these accidents was quite different from the others.

THREE MILE ISLAND (1979)

TMI-2 was a pressurized water reactor in Pennsylvania (USA) that suffered a partial meltdown in March 1979.[10] It had been in operation only a few months when the incident occurred. The primary cause was a pressure-relief valve in the primary loop that stuck in the open position, leading to a loss of coolant. Additional contributing factors include inadequate instrumentation in the control room such that operators did not have a clear understanding of the malfunction, and insufficient training and preparation of the plant operators. The release of radioactive cooling water beyond the containment boundary caused exposure to plant workers and residents of the surrounding area. It is important to note that the issue with the pressure-relief valve was a known problem since the same type of malfunction had occurred several times previously in the TMI plant as well as in another plant of similar design. However, the faulty valve had neither been improved nor replaced. In other words, in a seemingly well-functioning, well-regulated system with lots of checks-and-balances around nuclear power, a component critical to safe operation of the reactor continued being used, up to a point where a meltdown was made possible. While this accident caused little human or economic damage, it nonetheless led to major public outcry and subsequent regulatory reforms.

CHERNOBYL (1986)

Chernobyl Unit 4 was a RBMK reactor in Ukraine (then USSR), which used graphite for moderation and boiling light water for cooling. It began operation in 1983 then suffered a meltdown and explosion in April 1986.[11] The incident happened during a test of the emergency cooling system, as operators ramped down power production of the reactor. Due to a series of reactor and plant design flaws and operator errors, the reactor overheated and caused a steam explosion. This further damaged the reactor cooling system and containment vessel, igniting the graphite moderators leading to widespread dispersal of radioactive smoke.

Large areas of Ukraine and Belarus became severely contaminated, and elevated radiation was detected throughout much of Europe. That such a reactor design could cause a meltdown would not have been surprising to most competent nuclear engineers. The problem was that the Soviet state was not conducive to the kind of rigorous scientific debate needed to improve approved technologies; this was exacerbated by the secretive nature of nuclear research, which prevented an exchange of ideas with scientists from other countries. The Chernobyl disaster, therefore, can be considered as much a failure of the Soviet system, than as a risk inherent to nuclear power production.

Chernobyl is considered the worst accident in nuclear power history, leading to the death of dozens of workers who were exposed to high-level radiation during cleanup immediately after the accident, the evacuation of hundreds of thousands of people (many of whom had to be permanently resettled elsewhere), long-term closure of thousands of square kilometers of land, and possibly thousands of deaths from cancer linked to low-level radiation exposure (although the specific number of deaths attributable to the accident remains a topic of debate).

FUKUSHIMA (2011)

The Fukushima Daiichi Nuclear Power Plant comprised 6 boiling water reactors that began operation in 1971 in Japan. Meltdowns in 3 of the reactors occurred in March 2011, following a severe earthquake and tsunami off the Japanese coast.[12] The reactors were designed to withstand strong earthquakes, and immediately upon sensing the earthquake control rods were automatically inserted into the reactors to stop the fission reactions. However, even after halting a fission reaction, the decay of unstable isotopes continues for several days, producing heat amounting to about 6% that of the initial fission. That was the case at the Fukushima plant as well, and diesel backup generators were automatically switched on to power cooling pumps to remove this decay heat. A large tsunami reached the shore fifty minutes after the earthquake, overcame the seawall intended to protect the power plant, and flooded the backup generators which were installed in a basement room. This loss of cooling led to meltdowns in three reactors, causing the generation of hydrogen gas from the breakdown of zirconium fuel cladding, leading to hydrogen explosions and the widespread dispersal of radioactive fallout.

Arguably, the Fukushima reactors and the power plant writ large were soundly designed and not at fault unto themselves. Rather, the meltdowns were the result of a once-in-generations natural disaster that wreaked devastation well beyond the power plant. As a result of this accident, over 150,000 people needed to be evacuated from exclusion zones. While there were no documented deaths associated with direct radiation exposure, [13] disruption due to the evacuation is thought to have caused some 2,500 deaths.[14] Even though the majority of those evacuated have been able to return, the accident caused significant economic damage.

As the above suggests, the accidents were caused by a combination of (a) inadequate checks and balances, and (b) assumptions about the likelihood of specific failure modes being triggered, even in the presence of reasonable checks and balances.

Challenge 2: Risk of weapons proliferation

Uranium needed for nuclear weapons is significantly more enriched than that used for power plants. Uranium ore found in nature typically contains less than 1% U-235.[15] The rest is mostly U-238, which constitutes >99% of naturally occurring uranium on the planet; it is not fissile and hence cannot be used to create a nuclear reaction. To be used in a nuclear weapon, it needs to be enriched to over 90% U-235.

The processes for uranium enrichment are complicated (gas diffusion, gas centrifugation, laser isotope separation) and require highly specific equipment that is difficult and expensive to manufacture. As a result, it is not easily available, and both manufacture and trade of such equipment is regulated and monitored by the IAEA. Likewise, extraction and trade of raw uranium ore (which occurs naturally in more than 10 countries, on most continents) is also regulated and monitored by the IAEA. Proliferation-resistant fuel designs can include the use of low-enriched uranium (LEU) instead of highly-enriched uranium (HEU) in fuel assemblies. Once-through nuclear fuel cycles are relatively resistant to material diversion, to the extent that permanent disposal of spent fuel can be ensured (which is not yet the case, as discussed below). Breeding and reprocessing of nuclear fuel, while enabling more efficient use of the available resources, provides many more opportunities for misuse of nuclear materials as weapons.

Even in cases where highly enriched uranium or plutonium is safely contained, the diversion of lower-level nuclear waste can result in low-tech “dirty bombs” dispersed using conventional explosives. Unfortunately, history shows that any country determined to circumvent the IAEA’s oversight has been able to do so (India, Pakistan, North Korea, Israel, Iran, Iraq, Syria). As the amount of uranium extracted and traded increases to accommodate a significant scaleup in nuclear power, so will the risk of proliferation of clandestine weapons programs by bad actors—state and nonstate.

Challenge 3: Risk of improper storage or misuse of radioactive waste

There currently isn’t a single operational permanent storage facility for spent fuel rods although two have been approved for construction in Europe, one of which, the Posiva site in Finland, is expected to be operational within the next 2-3 years.[16] As a result, hundreds of thousands of spent fuel rods (about 263,000 metric tons in 2022 and growing each year) are in temporary storage awaiting reprocessing or permanent disposal.[17] While there have been no major storage disasters to date, public concerns about the storage risks remain. In addition to accidents, there are legitimate fears about bad actors misusing spent fuel to build and deploy dirty bombs. Currently, in the absence of centralized storage and disposal, nuclear waste is dispersed across hundreds of different temporary storage sites with varying levels of safeguards. Under this status quo, it appears likely that some mishap will eventually occur—whether accidental or intentional—that spreads radiation and causes damaging health impacts.

THE REGULATORY LANDSCAPE FOR NUCLEAR POWER

Regulation of nuclear power involves a combination of many international and national institutions, agreements and measures. The key global umbrella organization is the International Atomic Energy Agency (IAEA) created in 1957[18] with the following mandate:

- Set international safety and security standards, establish operating guidelines for facilities, and work with member states on safety, research, etc.
- Facilitate international agreements, chief among which are the Convention on the Physical Protection of Nuclear Material (which establishes legal obligations for signatories regarding international transport of nuclear material) and the Convention on Nuclear Safety (which establishes safety standards for nuclear power plants).
- Provide technical assistance to member states.
- Implement agreements with individual member states to verify that nuclear materials and facilities are being used exclusively for peaceful purposes rather than weapons including, inspection of facilities and monitoring of nuclear material.
- Share knowledge with the global ecosystem.
- Provide a forum for advancement of nuclear power, notably as of 2001, serving as the home for the Generation IV International Forum (GIF), an international co-operative for supporting development and deployment of Gen 4 nuclear power by 2030.

While the IAEA plays an essential role in global cooperation towards safe and secure use of nuclear energy worldwide, it faces two critical limitations: it lacks the power of enforcement, and it does not have the resources to consistently carry out its difficult mandate or to mobilize sufficient responses to accidents like Fukushima.

In addition to the IAEA, sub-groups of countries have formed multilateral initiatives to address various aspects of the nuclear power space: the Nuclear Exporters Committee (NEC or the Zangger Committee in honor of its first chairperson) which was created to interpret and implement the Nuclear Non-Proliferation Treaty (NPT), and the Nuclear Suppliers Group (NSG) which was created in the aftermath of India's first nuclear test in 1974 to develop and enforce guidelines for nuclear-related exports.

There are also a number of regional agreements and agencies with variations of the IAEA's mandate: The European Union has a legal framework (binding on all member states) under the 1957 Euratom Treaty which dictates safety requirements for facility design, construction, operation, emergency preparedness, and emergency response, as well as for licensing and safety assessments. The Asia-Pacific region uses the Asia-Pacific Economic Cooperation (APEC) Nuclear Energy Cooperation Sub-Fund to support cooperation and information sharing with a decidedly weaker mandate than the EU agreement. Cooperation between OECD countries is also strong, with the Nuclear Energy Agency (NEA) serving as the public-facing, information-sharing agency for member states and their constituencies, and the International Nuclear Regulators Association (INRA) serving as the forum for their respective regulatory agencies. As interest in nuclear power is becoming more globalized, the International Framework for Nuclear Energy Cooperation (IFNEC) has emerged as a platform for inter-governmental engagement including from non-nuclear countries in Asia, Africa, and Latin America.

Naturally, all individual countries with nuclear facilities have their own national regulatory authorities with mandates based on national priorities. In the US, for example, the overarching agency is the Nuclear Regulatory Commission (NRC), an independent agency of the federal government responsible for all aspects of nuclear power in the country: licensing, design, construction, operation, safety, security, and emergency preparedness.[19] This includes setting guidelines as well as conducting inspections. (It is worth noting that many proponents of nuclear power have criticized NRC regulations as being excessive, and a significant obstacle to the promise of nuclear power.) The other major agency in US nuclear power is the Department of Energy (DOE) which has a mandate across all energy-related matters; in the nuclear context, it is responsible for managing nuclear waste and ensuring the safe transport and storage of nuclear materials. The Environmental Protection Agency (EPA), with a smaller role, sets regulations related to radioactive materials in the environment. Presumably, defense and intelligence agencies also play a role, the parameters of which are not public. Likewise in the EU, each member state has its own national regulatory authority responsible for implementing the EU-wide safety framework (including licensing, monitoring and enforcement) and overseeing facilities within its borders. The Western European Nuclear Regulators' Association (WENRA) provides technical support and guidance to member states.

Beyond regulatory agencies, there are also a number of private coalitions to advocate support for nuclear power, prominent among which is the World Nuclear Association (WNA), a trade association that advocates for nuclear power with policymakers and the media. The World Association of Nuclear Operators (WANO) provides support to operators of nuclear power plants around the world. With increased interest from the private sector in developing countries, the Nuclear Business Platform (NBP) has emerged with growing membership of businesses in Africa, Asia, and Latin America.

The evolution of the global ecosystem of institutions and regulatory regimens for nuclear power reflects a combination of several factors: The first wave represented the creation of agencies like the IAEA in the aftermath of World War II and the Manhattan Project (mid-1940s through the early 1960s) when nuclear power for civilian use was still in the formative Gen 1 years. The second wave (including the NRC) represented regulations to serve the needs of a civilian nuclear power industry becoming an on-the-ground reality in Gen 1. The Three Mile Island accident set off the third wave of regulations focused on significant improvements to operational safety. Finally, the terrorist attack of 9/11 and subsequent geopolitical shifts set off a wave of regulatory changes focused on preventing proliferation. Through this evolution, all technical matters related to civilian use focused exclusively on water-cooled reactor technology, institutional cooperation on facilitation between the "friendly club" of nuclear powers, and monitoring/oversight mechanisms on the small number of "pariahs."

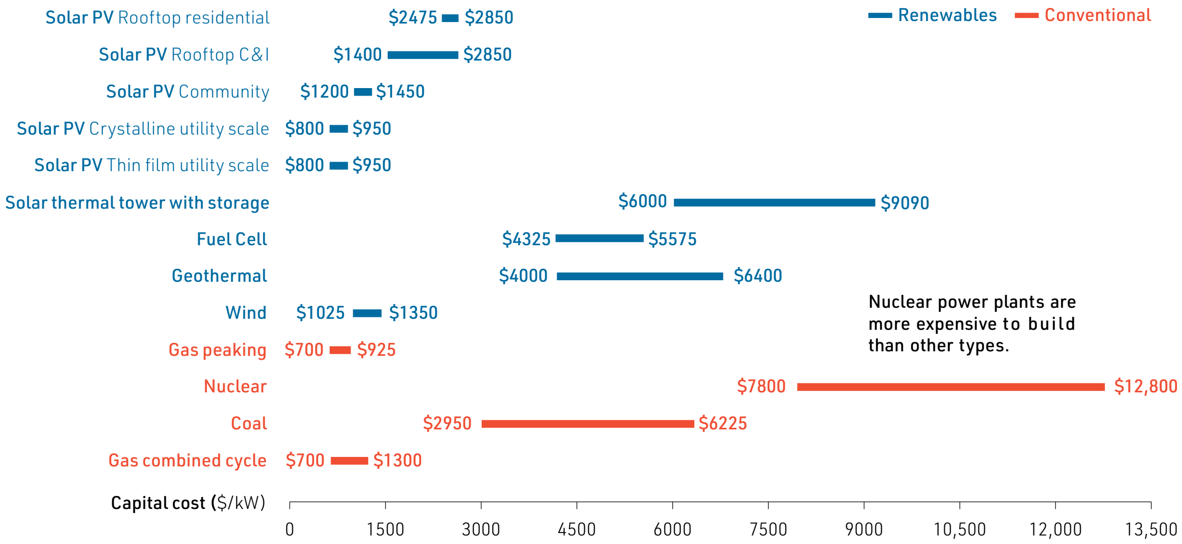
ECONOMICS OF NUCLEAR POWER TO DATE

Construction and operation of nuclear power plants is very expensive. A 1GW plant can cost US$5-10 billion to build, and upwards of US$250 million per year to maintain and operate.[20] The cost is driven by the sheer amount of high-quality, heavily regulated material required to contain the reactions, and the extreme need for safety and fault tolerance—which leads to an extraordinary level of system complexity. As a result, the per-unit cost of nuclear power is considerably higher than other commonly-used sources of power including renewables as shown in **Exhibits 4a & 4b** (capital and levelized costs, respectively).[21] Nuclear power has not been the most economically viable option and has remained wildly out of reach for the majority of developing countries. That notwithstanding, a small number of developing countries struggling with high levels of poverty (e.g., India, Pakistan, South Africa) have built homegrown nuclear power plants. These investments were seemingly motivated by a combination of national pride and clandestine weapons programs, rather than for cost-effective electricity.

The cost range for nuclear power is also very high; that is to say, the cost of building and operating two different power plants with the same type of reactor with similar production capacities can vary significantly. That is because each bespoke project has its individual complexities such as the site, how well the project is managed, and changes over the course of project implementation, given that it can take 10 years to build a nuclear power plant. Most industries go through an "experience curve" as they mature and develop personnel expertise, supply chains, and economies of scale, leading to lower per-unit costs over time.[22] **Exhibit 5** shows the basic capital cost (called "overnight cost") of building nuclear power plants over time in various countries around the world. Unlike the norm in other industries, the

EXHIBIT 4a

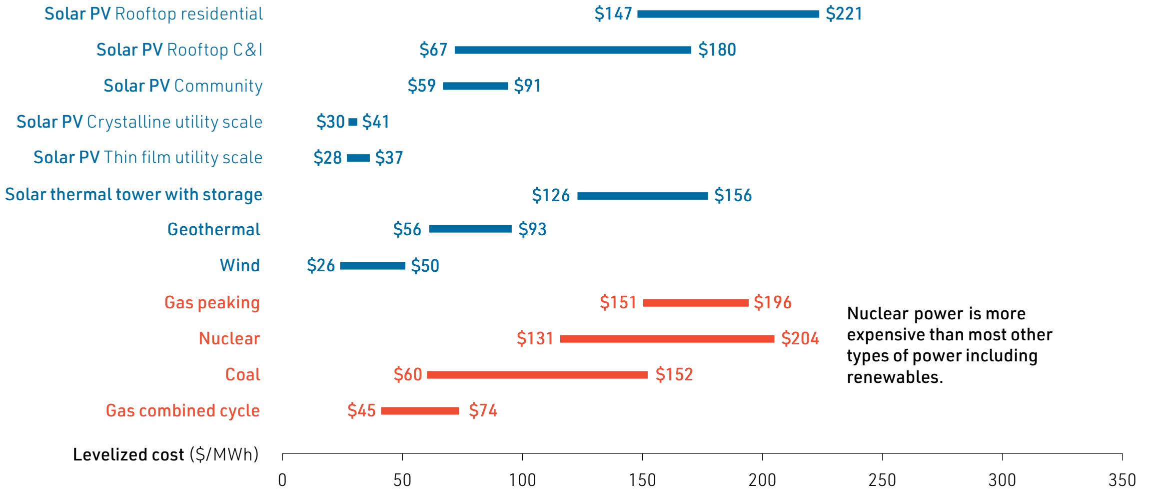
Capital cost (US dollars per kW of generating capacity) of constructing power plants with different energy sources. (Source: Lazard[21])



Nuclear power plants are more expensive to build than other types.

EXHIBIT 4b

Levelized cost of electricity (US dollars per MWh of produced electricity) from plants with different energy sources. (Source: Lazard[21])

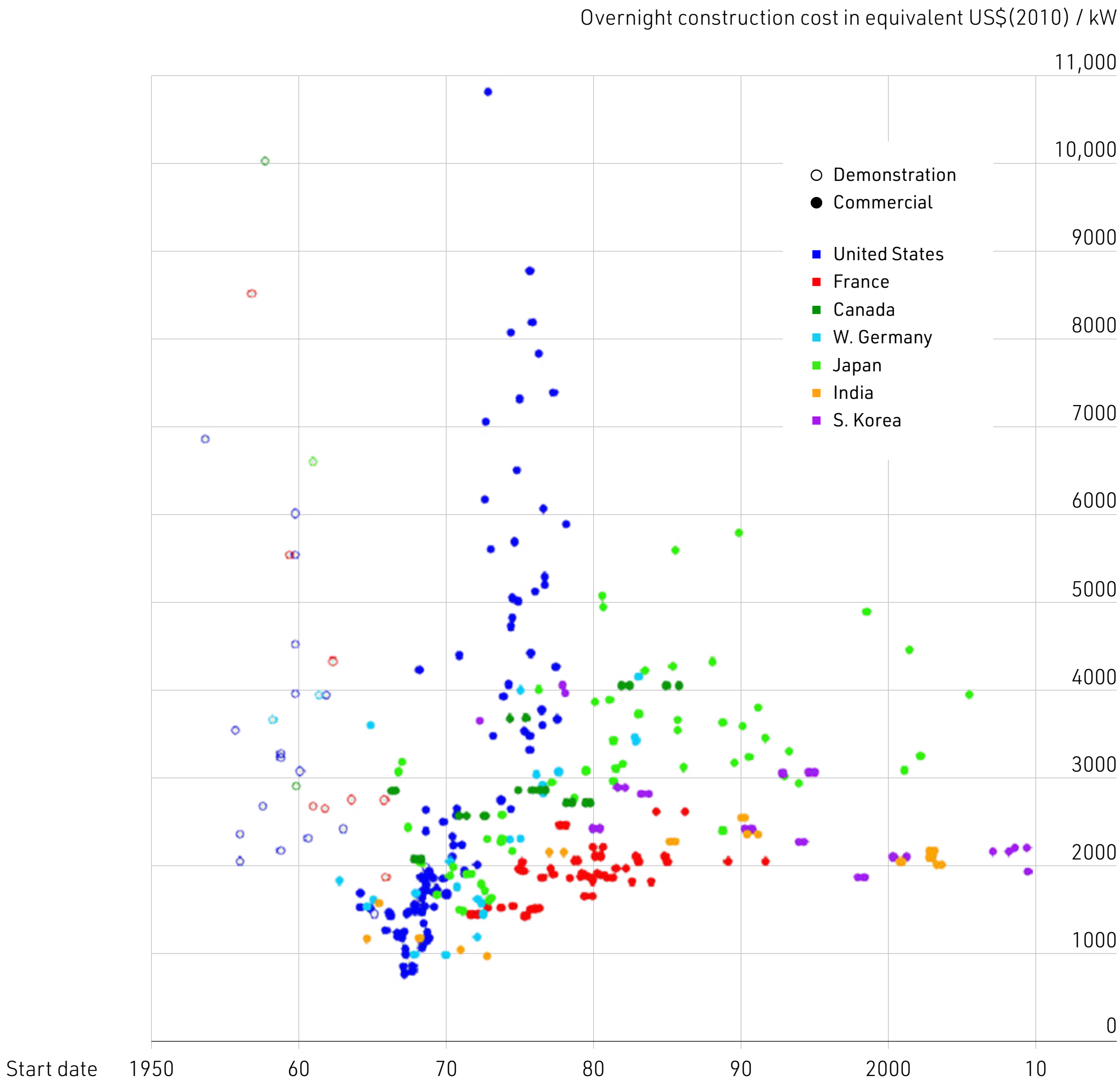


Nuclear power is more expensive than most other types of power including renewables.

nuclear power industry shows no experience curve. If anything, the only major apparent pattern is that the cost of building plants in the US dramatically increased for plants that began construction in the 1970s compared to those that began construction earlier. This is due in large part to the Three Mile Island accident which drove a significant increase in safety measures and equipment.[23] As a consequence, the economics of nuclear power combined with public concerns about safety have rendered it so untenable that few new nuclear plants have been built in the last 20 years in western countries.

EXHIBIT 5

Overnight construction costs of reactors in various countries. If the industry had benefited from an experience curve, the costs would be lower over time. Instead, there is no perceivable pattern. (Source: Lovering et al.[24])



ALTERNATIVES TO NUCLEAR POWER

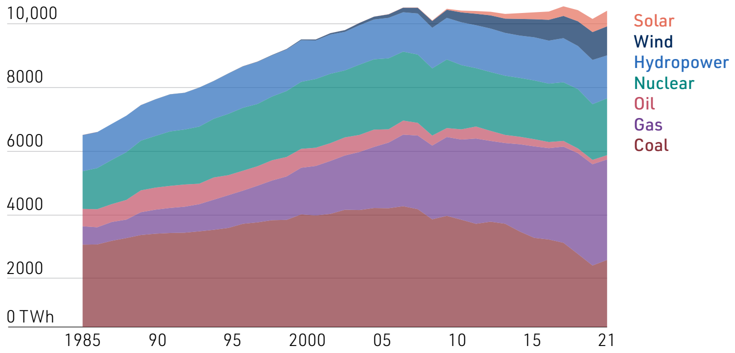
Before the pause in building global nuclear power infrastructure, it was unsurprisingly largely limited to wealthy countries which also constituted the bulk of global electricity consumption. In the intervening years, the existential threat posed by climate change has become increasingly acknowledged with coal-powered electricity being recognized as one of the worst offenders. This led to the growth of gas-powered electricity (as a slightly greener alternative to coal) and renewables (primarily wind and solar) in these countries (**Exhibit 6**). At the same time, there has been substantial economic growth in upper-middle and lower-middle income countries accompanied by a proportional increase in electricity consumption powered largely by coal, gas, and hydro. Low-income countries, however, have not seen similar growth in either electricity consumption or the relative mix of sources of power.

The question, therefore, is how future economic activity and growth can be powered while replacing coal and gas with cleaner sources. Hydropower, large as well as micro, is geographically limited and vulnerable to effects of climate change (i.e., increasing volatility of rain and snowfall). As such, recent bets have been on solar and wind, which have scaled well and are proving increasingly economical.

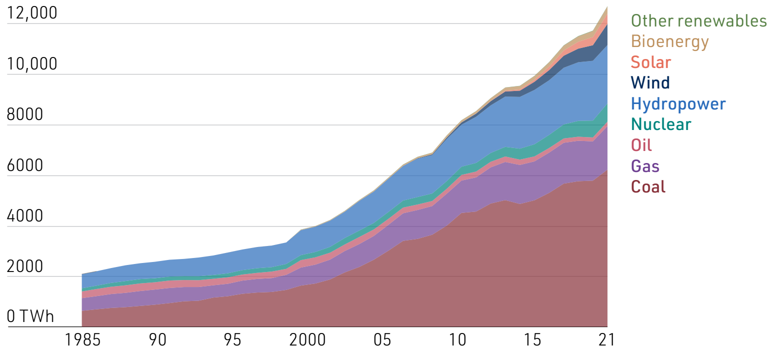
EXHIBIT 6

Growth in electricity consumption in different groups of countries based on wealth, along with changes in the mix of sources of power. (Source: Our World in Data[25])

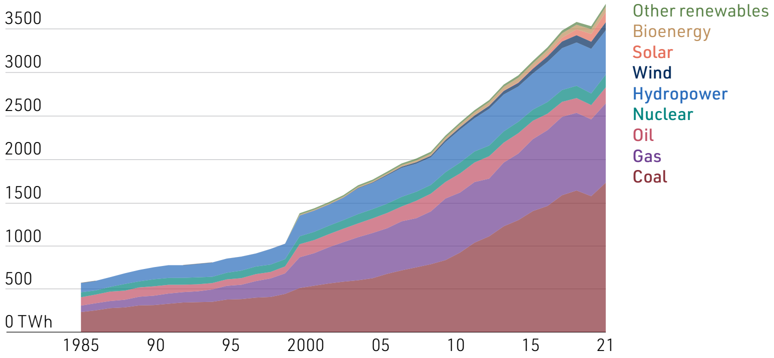
OECD countries



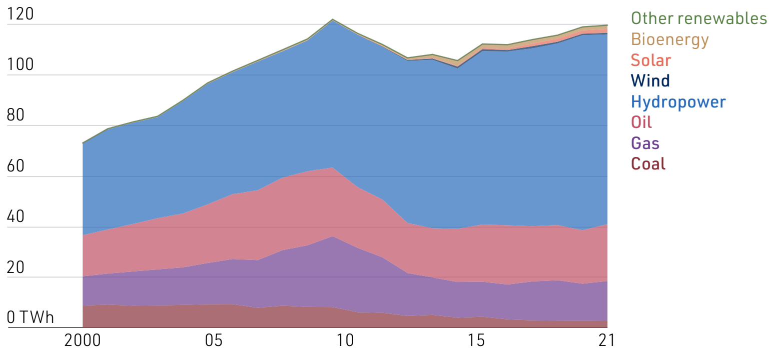
Upper-middle income countries



Low-middle income countries



Low income countries



In contrast to nuclear power which can be produced continuously, solar and wind are intermittent sources that require energy storage to ensure reliable dispatchable supply. Unfortunately, the challenge of grid-scale energy storage still remains unsolved. Lithium-ion batteries have continued to become more affordable as a part of the electric vehicle revolution, but the supply of key raw materials (lithium, cobalt, nickel) may become a significant limiting factor in the coming decades.[26]

Environmental impacts from mining exist for both nuclear and renewable energy though the global impacts from relatively limited uranium mining would likely be less than those from much larger scale mining of minerals needed for renewable energy production and storage. A small number of other storage technologies (flow, sodium-ion) are emerging but are still too nascent. (It is worth noting that another challenge faced by current solar and wind technologies, although not necessarily a deal-breaker, is that they are not space-efficient, and solar/wind farms are consuming an increasing amount of real estate.) In summary, the single biggest constraint to universal expansion of wind and solar is the availability of affordable, reliable energy storage. Until this problem is solved, the door remains open for nuclear power to make a comeback.

By virtue of its continuous operation a full power, nuclear power can offer considerable advantages over other energy sources:

1. Critical energy-intensive applications during periods of low electricity demand: When demand for electricity is low (e.g., at night), electricity from nuclear power plants can be used for desalination of seawater to address the growing problem of freshwater shortages, or for producing clean hydrogen which can be used a wide range of applications such as fuel cells for automobiles, and industrial processes such as cement, steel and fertilizer production. (It is worth noting that as global demand for electric vehicles grows, the environmental and societal impact of extracting minerals to produce lithium-ion batteries will grow with it; to that end, clean hydrogen offers a proven alternative to power automobiles.) Such opportunities would not be feasible for wind and solar because they are intrinsically intermittent.

2. Combined heat and power (CHP) production: Another advantage of nuclear power over renewables is the potential for combined heat and power production in which steam produced in the reactor is first used to generate electricity, with the residual heat then used for industry, residences, or greenhouses. This concept is currently used in some fossil fuel-fired power plants, and extracts more usable energy from the fuel resources.

GENERATION 4 OF NUCLEAR POWER

Even before the slowdown in construction of nuclear power plants, Gen 3/3+ systems had made significant improvements in safety and the reduction of meltdown risk. Unfortunately, in most countries the innovations were unable to overcome public perception of risk or the resultant political calculus of policymakers. Furthermore, the safety improvements came at a tremendous increase in system cost and complexity. The emerging fourth generation innovations are promising to address safety and cost as well as the issue of accumulating nuclear waste. Gen 4 designs have great technical diversity including gas-cooled fast reactors, lead-cooled fast reactors, molten salt reactors, supercritical water reactors, sodium-cooled fast reactors, and very-high-temperature reactors.[27] (Note that Gen 4 fission reactors are not to be confused with nuclear fusion, which involves joining, not splitting, atoms. Practical energy supply via fusion remains many decades away notwithstanding the 2022 advance made at Lawrence Livermore National Laboratory. Nuclear fusion is beyond the scope of this brief.)

Gen 4 innovations

There are three main Gen 4 innovations: small modular reactors, safe designs, and efficient fuel cycles.

1. Small modular reactors (SMRs) that are downscaled, productized and prefabricated. Reactors as small as 10MW and as large as 300MW capacity could be prefabricated on an assembly line rather than constructed onsite. These prefabricated systems are expected to be less expensive and more consistent in quality than systems constructed onsite.[28] Automated assembly methods such as robotic welders can ensure uniform build. Smaller systems naturally have lower total capital costs compared to large systems, but the per-megawatt capital cost can be higher than larger systems.

Notwithstanding the claims of manufacturers, it is too early to tell how much these reactors will cost. The economics of SMRs are discussed further below. The small modular concept also applies to traditional pressurized light water reactors that are being downsized and productized.

2. Reactor chemistries and concepts, including forms of fuel, coolant, and moderator, that are inherently safe and immune to meltdown. Gen 4 reactors will employ inherently safe methods that avoid loss of control.[29] One avenue to inherent safety is to exploit negative feedback to maintain stability. The different components of a reactor, such as fuel, moderator, and coolant, can interact to encourage or dampen the fission reaction. Negative temperature coefficient of reactivity implies that reactivity is reduced (producing less power) as the temperature of the reactor components increases. In addition to temperature coefficients, there are reactivity coefficients for pressure, voids, and other operational factors. (One of the critical design flaws of the RMBK reactor in Chernobyl was that it had a positive coefficient of reactivity due to interactions between its coolant and moderator which allowed unrestrained reaction.)

Another avenue to inherent safety is passive decay heat removal. Even after a reactor is fully shut down, heat continues to be generated for days by the decay of the radioactive isotopes. Passive decay heat removal systems seek to ensure that the reactor cools down safely in the event of a loss of power independent of pumps or electricity supply. They can work by using natural convection to circulate coolant through the reactor or by having ample cooling water that can boil away. (The meltdown in Fukushima was caused when the loss of power led to inadequate removal of decay heat.) There are other best-practice design approaches for safety such as having high heat capacity in the reactor environment which gives slower temperature increase for a given amount of heat production. Safe designs will use passive or self-actuated shutdown systems, and the reactor transient behavior will be smooth and predictable. There will likely be high levels of digitization, automation, monitoring, and control, with considerably less need for human intervention.

3. Increased efficiency of nuclear fuel use leading to more sustainable resource use and less radioactive waste. Gen 4 reactors will employ more complex fuel cycles compared to Gen 3 designs. Existing reactors are part of a one-way flow of uranium from the mine, to the processing plant, to the reactor, and then to permanent waste storage facilities. New designs will reuse spent fuel directly within the reactors or after reprocessing to separate the valuable radioactive isotopes from the waste (**Exhibit 7**). There will be higher fuel burnup (also known as fuel utilization) which measures how much energy is extracted from nuclear fuel. Efficiencies will be improved, both within the reactor (converting prepared fuel to electricity) and across the system (long-term energy production from available geological resources).

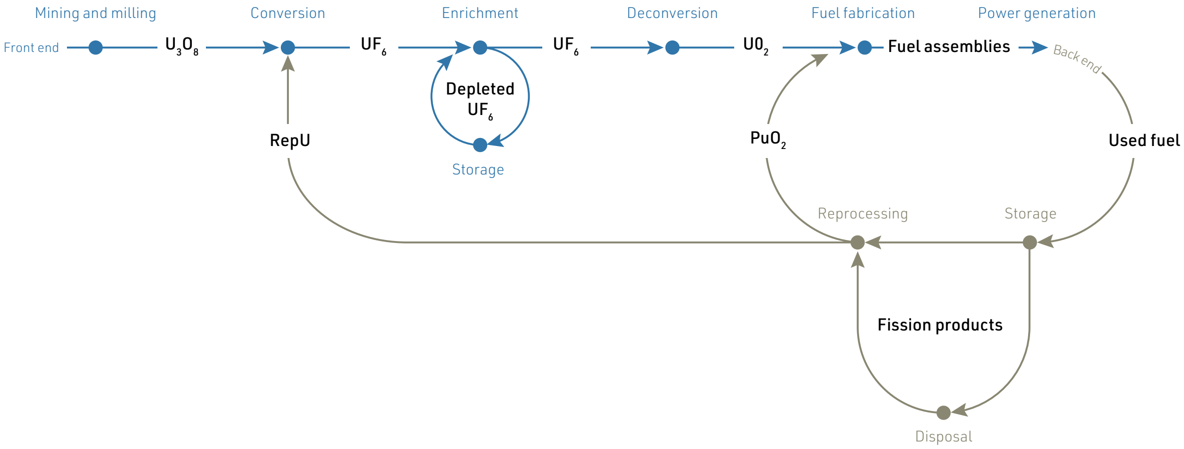
The Gen 3 reactors have a “once-through” nuclear fuel cycle from mine to reactor to disposal site. This requires extracting and processing raw uranium ore, enriching the U-235 to 5% purity, and fabricating the fuel rods. After typically 12-24 months in the reactor as the fuel rods become too depleted to produce sufficient fission energy, they are replaced with fresh rods. The spent fuel rods remain too radioactive for human exposure for thousands of years and need to be stored safely on-site for a period of time (several years in deep pools of circulating water and 20-40 years in air-cooled concrete-and-steel containers called dry casks) until a long-term disposal solution is available. Long-term storage requires geological containment (e.g., very deep underground facilities in stable rock formations) and highly specialized containers. Currently, there are no operational long-term storage facilities anywhere in the world due to political sensitivities as well as the technical complexity of the problem. Geological repositories have been approved for construction in a few countries (Sweden, France) but are several years from being operational. Another site in Finland is expected to be operational sooner.

Most Gen 4 reactor designs based on gas-cooled, liquid metal, or molten salt, will need high-assay low enriched uranium (HALEU) which has U-235 enriched to between 5% and 20%.[31] Advantages include smaller fuel assemblies and reactors, greater fuel utilization, and less frequent refueling of reactors. Current nuclear fuel supply chains enrich to only 5%, thus new production capacity will be needed using more complex enrichment technology. Currently, only Russia and China have the infrastructure to produce HALEU. However, Centrus Energy in Piketon, Ohio (USA) is constructing a demonstration HALEU plant with a cascade of advanced uranium enrichment centrifuges with the support of the US Department of Energy (DOE). The DOE could also, in principle, down-blend its highly-enriched uranium to produce HALEU.

In terms of proliferation risk of weapons-grade uranium, HALEU is far from the 90% enrichment needed for nuclear bombs. Twenty percent enrichment is still not nearly enough for nuclear weapons, and enrichment from 20% to 90% is only marginally easier than from 5% to 90%. (As discussed below, the bigger risk is the increase in the sheer amount of nuclear fuels being procesbbettersed, transported, and stored globally, that

EXHIBIT 7

The nuclear fuel cycle from extraction in the form of uranium ore to eventual disposal or reprocessing. (Source: World Nuclear Association[30])



will be needed to fuel a significant nuclear power scaleup. The question of LEU vs. HALEU, by itself, does not substantially change the proliferation risk.)

Another Gen 4 fuel innovation is tristructural isotropic (TRISO) fuel. TRISO particles have a HALEU fuel kernel encapsulated by layers of carbon- and ceramic-based materials.[32] About the size of a poppy seed, they can be agglomerated into pellets or billiard ball-sized spheres. Compared to traditional reactor fuel assemblies, they are more resistant to the harsh conditions within the reactor including neutron irradiation, corrosion, oxidation, and high temperatures. They will not burn even under meltdown conditions, thus containing the fission products from dispersal. TRISO fuels have advantages in high temperature gas and molten salt-cooled reactors. There are at least three US companies making TRISO fuel at pilot scale (BWXT, X-energy, and USNC) though the industry will need significant expansion for a full nuclear scaleup.

The thorium fuel cycle is often discussed as a breakthrough for next generation nuclear power.[33] Several thorium reactors have operated experimentally and semi-commercially since the 1960s. India is particularly interested in thorium reactors because it has large thorium reserves and limited uranium reserves. In the thorium fuel cycle, thorium-232 (which is not fissile) is placed in a reactor core together with a fissile material such as uranium-235 or plutonium-239. The thorium absorbs neutrons from the fission of the other materials and transmutes into uranium-233 which then fissions and provides additional power. Advantages of the thorium cycle include the relative abundance of thorium, lower proliferation risk, and less dangerous waste production.

Gen 4 companies and products

The aforementioned innovations are not mutually exclusive; indeed, most of the 100+ companies that have publicly announced their Gen 4 designs include a combination of at least two of the three innovations. A number of nuclear companies are at the stage of building demonstration infrastructure while seeking further regulatory approvals. They are developing products (not projects) that they expect to commercialize within the next decade. Here we mention several high-profile companies, describe their promised products, then discuss their progress to date.

TerraPower

TerraPower, based in Bellevue, Washington (USA) with significant support from Bill Gates, is developing the Natrium sodium fast reactor using HALEU fuel. It is planned to produce 345 MW electricity steadily or up to 500 MW peak power by using an integrated molten salt energy storage system. TerraPower is preparing for construction of a pilot facility in Kemmerer, WY. They anticipate submitting the construction permit application in 2023 and submitting the operating license application in 2026 for potential commissioning in 2030. Another TerraPower innovation at a less mature stage is the traveling wave reactor (TWR) that would employ a small core of enriched fuel in the center of a larger mass of non-fissile uranium and would breed then burn new fissile material in the surrounding mass.

eVinci

The eVinci microreactor is being developed by Westinghouse Electric Company, in Cranberry Township, Pennsylvania (USA). It is expected to be factory-made and transportable with on-site installation time less than 30 days. Each reactor is planned to produce 5 MW of electricity or 15 MW of thermal power. The eVinci reactors would use TRISO fuel and operate for 8 years without refueling. A novelty of this microreactor is the use of heat pipes instead of liquid coolant for heat transfer. Westinghouse has begun the regulatory approval process and builds on long experience in the nuclear industry.

Kairos Power

Kairos Power of Alameda, California (USA) is developing a low-pressure fluoride salt coolant high-temperature reactor called the KP-FHR. It is planned to produce 140 MW of electricity using TRISO fuel in pebble form. Kairos currently has a non-nuclear test facility operating in Albuquerque, New Mexico (USA) and is seeking approvals for a demonstration reactor in Oak Ridge, Tennessee (USA).

BWX Technologies

BWX Technologies in Lynchburg, Virginia (USA) is developing the BWXT Advanced Nuclear Reactor (BANR). The planned product is a high-temperature gas-cooled reactor using TRISO fuel that can deliver 50 MW of heat. The modular, factory-built microreactor components are compatible with standard shipping containers and transportable via rail, ship, or truck, with quick commissioning onsite. Stage of development of the product remains unclear though BWXT is an industry leader with strong capability. BWXT also manufactures TRISO fuel particles at its Lynchburg facility.

Seaborg

Seaborg of Copenhagen, Denmark is planning the Compact Molten Salt Reactor (CMSR) that would generate 200 MW of electricity. The uranium fuel is mixed in a molten fluoride salt coolant. Up to 4 reactors are planned to fit on each floating Power Barge producing from 200 to 800 MW of electricity. The Power Barges are designed to have an operational lifetime of 24 years with refueling after 12 years. Seaborg claims they will deliver the first Power Barge in 2028 though current activity remains in the lab.

X-energy

X-energy of Rockville, Maryland (USA) is developing the XE-100 reactor which will be a very-high-temperature helium-cooled pebble-bed nuclear reactor using TRISO fuel. Each unit is planned to make 80 MW of electricity. The system components will be prefabricated, shipped to the site by truck or rail, and assembled on site. A nimbler XE-Mobile plant is planned to be sized for standard shipping containers and produce 2 to 7 MW of portable electrical power. X-energy is also involved in fuel production and began construction in 2022 on a commercial scale facility in Oak Ridge, Tennessee (USA) to make TRISO particles using HALEU.

Core Power

Core Power with headquarters in London and Washington, DC (USA) is planning the MSR fast molten salt reactor. It will use HALEU uranium oxide fuel mixed in with molten NaCl salt. The technology will be ship-based, powering floating industrial production, and ocean-going ships.

Other Gen 4 companies

In addition to these innovative Generation 4 designs, there are also companies working on small modular versions of conventional pressurized light water reactors. These have the advantage of familiar and well-understood reactor fundamentals plus innovations in productization and prefabrication. These small-scale versions of conventional reactor designs may produce more waste compared to the larger versions, due to lower efficiency.[34]

NuScale Power

NuScale Power of Tigard, Oregon (USA) is developing the VOYGR series of small modular reactors. Each reactor unit would produce 77 MW of electricity and would require refueling every two years. They are small-scale versions of conventional light pressurized water reactors powered by low enriched uranium fuel. Investors include Flour Corporation and Rolls-Royce. In 2020 the US NRC approved a design for a NuScale small modular reactor, making the company relatively advanced in the process.

Holtec International

Holtec International of Camden, New Jersey (USA) is planning the SMR-160 small modular reactor which would be a conventional pressurized light water reactor using low enriched fuel. Electrical output is planned to be 160 MW per unit. The design incorporates passive safety features including decay heat cooling. Holtec is collaborating with GE Hitachi Nuclear Energy for implementation.

THE EMERGING STATE OF PLAY

The new ecosystem of innovators in nuclear power is well positioned to do what Elon Musk's Space X, and Jeff Bezos' Blue Origin, have done to NASA and exclusively government-led space flight programs. For nuclear power, Gen 4 innovations aim to address five challenges that need to be overcome before nuclear power can become a global reality in a timeframe so as to make a meaningful contribution to climate mitigation targets. The following summarizes the state-of-play on each.

Safety

Nuclear power will be significantly safer than before. Any damage will likely be closer to the scale of Three Mile Island than to Fukushima or Chernobyl.

However, it will take a while to establish the safety of novel reactor types; and even then, absolute safety will be virtually impossible to ensure. In theory, Gen 4 reactors through a combination of passive cooling, negative reactivity coefficients and system-wide safety features already developed in Gen 3/3+ represent a fundamental improvement over current installations. However, the only reactor types about which there is sufficient practical knowledge is PWR/LWR. As such, the only Gen 4 reactor types likely to be fast-tracked on safety grounds are LWR SMRs which do not incorporate the inherent safety features of novel Gen 4 designs.

The safety of all novel designs based on different coolants and fuel forms will take considerable time and effort to demonstrate. Indeed, rushing such reactors to market can increase the possibility of accidents. Assuming appropriate testing and regulations, there is every reason to believe accidents like those in the past will be avoided: Chernobyl can be written off as an artifact of the Soviet system; likewise, it can be argued that Three Mile Island precipitated a massive set of safety measures so that similar events should not reoccur. Fukushima, however, was a seemingly well-designed system with adequate safeguards in which the accident was caused by an unforeseen "perfect storm" of events. The tautology remains that unpredictable events are exactly that, which makes it difficult to imagine a fully failure-proof system. In other words, it is unrealistic to expect that there will never be another failure caused by yet another unforeseen triggering event. As the number of reactors increases, it appears inevitable that over the course of the decades-long lifetimes of thousands of reactors, another accident will occur sooner or later. In summary, we should expect that the likelihood of accidents, while much lower than before, will be nonzero; and while it is unlikely that there will be another event like Fukushima or Chernobyl, there will likely be some scares at the scale of Three Mile Island.

Proliferation

Weapons risk will likely get worse as the sheer amount of fissile material and spent fuel around the world increases.

History demonstrates that any state actor with the interest and wherewithal to make nuclear weapons has succeeded in doing so. History has also shown that economic sanctions and relegation to pariah status have not prevented bad state actors from leveraging their nuclear arms to perpetrate major atrocities within and outside their national borders. If nuclear power is to become globally mainstream, the number of reactors will need to grow by an order of magnitude. This will mean a dramatic increase in the amount of nuclear material both fissile and spent. While some technologies and fuel cycles are more efficient than others, all nuclear reactors produce byproducts and waste products that are dangerous. As thoughtful as current measures are, it is hard to believe any future measures can prevent bad actors, state or nonstate, from getting their hands on enough fissile material and enrichment equipment to make nuclear weapons of some scale. At the same time, while current containment measures have seemingly prevented spent fuel from being exploited for dirty bombs, it will become that much harder as the amount of radioactive waste also increases by an order of magnitude.

Regulation

The current institutional and regulatory infrastructure is geared towards pre-Gen 4 technology and assumptions about access to nuclear energy being limited to a small number of countries.

Over the next two decades the nuclear power ecosystem will get significantly more complex with respect to the geographic spread of reactors, public vs private control of facilities, the amount of nuclear material being extracted, processed, transported and stored, the amount of nuclear waste, and the types of fuel. There is broad recognition across the nuclear power ecosystem that the current framework is not equipped to support this step-change in complexity. The IAEA is working towards a harmonized global regulatory safety/security framework for Gen 4 advanced reactors, and there are a number of other multilateral initiatives attempting to address different aspects of the rapidly emerging ecosystem. It is reasonable to assume that, across these initiatives, a technically robust set of frameworks will emerge. It is also reasonable to assume that with the emergence of more globalized initiatives, like the International Framework for Nuclear Energy Cooperation (IFNEC) and regional forums like the [African/Asian/LatAm] Nuclear Business Platforms, the new frameworks will be more inclusive than those developed in earlier eras.

However, two big challenges remain: First, as nuclear power and associated technical knowledge becomes commoditized and more accessible, it could become a free-for-all depending on how robust and inclusive the global regulatory framework (and compliance) is. Second, there will inevitably be a tradeoff between inclusivity of perspectives and ensuring the new frameworks are not so watered-down as to be toothless. Both these challenges, if not adequately addressed, will increase the risk of accidents and proliferation.

Public trust

In the public psyche, the word "nuclear" evokes images of nuclear explosions, nuclear accidents like Chernobyl and Fukushima, and post-apocalyptic nightmares. Likewise, to "go nuclear" has come to mean resorting to extreme measures.

Without separating the public from such associations, it will be hard for nuclear power to become a mainstream global reality. The history of nuclear power, from bombs to accidents, have justifiably raised public fears. Public backlash combined with the hope that renewables would rapidly emerge as the default option led to anti-nuclear policies in many OECD countries. Fictional depictions of nuclear Armageddon further hardened public opposition especially juxtaposed with the wholesome associations enjoyed by solar and wind. As an increasing number of people immersed in climate and energy policy are realizing, the absolute pause on nuclear power over recent decades has proven counterproductive. This realization among experts needs to percolate to the broader public which will require sustained, creative, multi-platform public engagement. The arc of successful, albeit too-little-too-late, public engagement on topics like climate change and pandemics (also, incidentally, popular topics in post-apocalyptic fiction) can offer valuable lessons on how to shape the conversation on nuclear power.

Cost

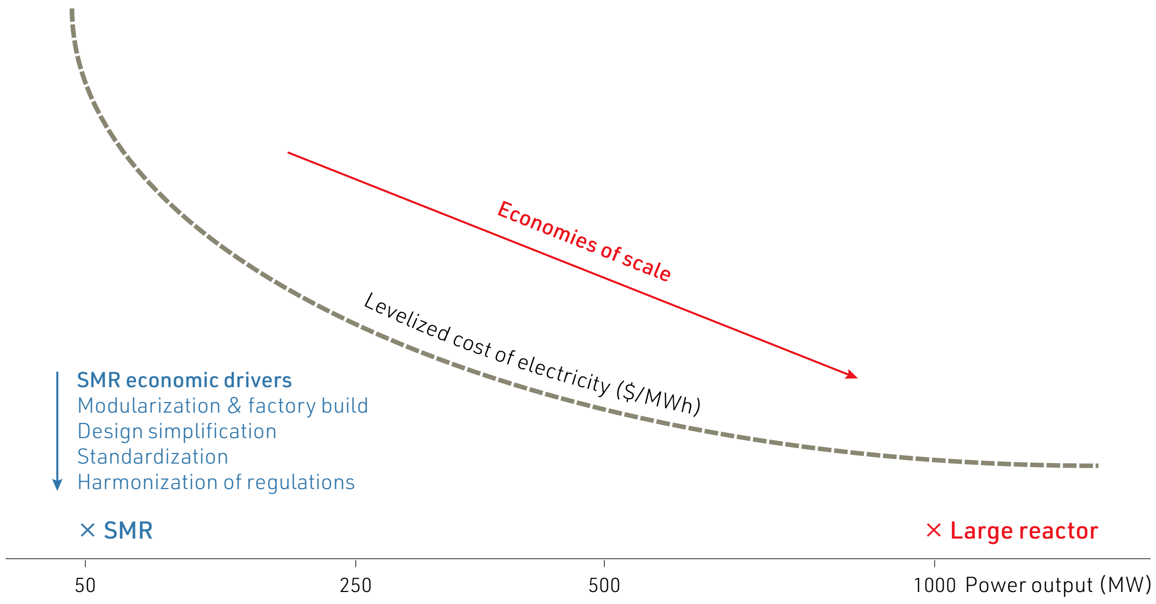
The LCOE of Gen 4 nuclear power can be lower than that of earlier generations, but it is too early to tell.

Either way, it will be higher than other power sources including renewables. For economies of scale to materialize, the field will have to winnow to a few winners. To paraphrase a recent article in The Atlantic,[35] the real challenge with large earlier-generation nuclear plants was not making them safe but doing so at a reasonable cost. Large nuclear plants custom-built for individual sites, capacities, and other specifications, needed customized safety mechanism. Retrofitting safety mechanisms in existing plants added further costs. In many ways, the pause in construction of nuclear power plants in OECD countries created an opening for thinking anew towards Gen 4 reactors. The key driver of Gen 4 cost reduction is via SMR designs which benefit from five different levers: modularization & factory build, design simplification, standardization, regulatory harmonization (discussed below), and in principle, economies-of-scale by virtue of large production volume.[36] By comparison, the only lever for LCOE reduction in large reactors is maximizing reactor/plant capacity. **Exhibit 8** from the OECD/NEA illustrates these factors. As things stand, there are dozens of promising SMR designs. The economic benefits of mass manufacturing will materialize only if a few of them survive and win enough market share. Paradoxically, therefore, the greater the number of SMR companies with compelling designs, the harder it will be for the SMR concept to realize the economies of scale needed to make SMR a cost-effective reality. Assuming a small number of companies reach the scale needed to be successful, the LCOE of SMRs will likely be lower than the lowest cost of nuclear power plants currently operating. Indeed, some companies have begun making LCOE projections showing substantial cost reduction. Terra Power, for example, projects LCOE in the $50-60/MWh range, presumably based on startup-optimistic assumptions that can only be validated over time. Indeed, NuScale, one of the other SMR startups mentioned above recently revised its estimates—for a second time—from $55/MWh in 2016 to $58/MWh in 2021, and then to $89/MWh in 2023.[37] Compared to the costs shown in Exhibit 4b earlier, this is about half the lowest-end of the LCOE range for current nuclear power. Even these optimistic, unvalidated projections are higher than actual LCOE of utility-scale solar and wind.

Another risk facing nuclear power innovations is path dependence, an economic phenomenon in which

EXHIBIT 8

Illustrative economics of conventional/large vs. SMR reactors. Whereas conventional reactors rely on the large capacity of individual reactors to achieve cost savings, SMRs have multiple cost-reduction levers. However, they will need to manufacture and sell enough units to achieve benefits of scale. (Source: OECD/NEA[38])



early events and decisions can constrain later developments. In the 1970s, the nuclear industry created a path dependence toward large-scale LWRs, building expertise, infrastructure, and regulations focused on that reactor type, with other types unable to progress. Going forward in the emerging SMR market, if conventional pressurized light water reactors dominate before the newer (inherently safer) Gen 4 reactor designs become a reality, the newer designs can be blocked out.

How much the world can, or will, rely on nuclear power will depend in considerable part on how soon solutions for affordable grid-scale energy storage become available. As that situation evolves, the following scenarios are likely to emerge in different parts of the world (referring back to **Exhibit 6** which showed the mix of electricity sources):

- In OECD and upper-middle income countries (UMICs), nuclear power will likely continue its comeback and complement renewables in gradually displacing fossil fuel sources. The mix of sources will depend on both the speed with which energy storage solutions emerge and public acceptance of nuclear power.
- For most lower-middle income countries (LMICs), it will be a long while before nuclear power becomes affordable. As such, the urgent need to ramp up energy infrastructures will likely be met through renewables with a number of countries continuing or even increasing use of fossil fuel sources. Incentives from multilateral agencies will be critical to encouraging them to prioritize clean power. However, as the cost of nuclear power decreases over time, LMICs will likely invest in it as a potent symbol of national advancement.
- Low-income countries (LICs) currently depend heavily on hydro power with fossil fuels constituting a small share of electricity sources. While they are unlikely to invest in nuclear power for the foreseeable future, renewables supported by multilateral funding agencies will offer them an attractive option to bypass the conventional development pathway of relying on fossil fuels.

As such, one key investment decision philanthropic funders will need to make is how much to bet on nuclear power vs. innovations in grid-scale energy storage solutions for renewables. This report does not take a position on the relative merits of each. Instead, it offers the following guidance for those who have decided to invest in accelerating the timeline for nuclear power.

INVESTMENT AVENUES FOR PHILANTHROPIC FUNDERS

Until recently, nuclear power has been in the exclusive domain of governmental agencies and large companies with a history of contracting with governments, e.g., GE and Westinghouse in the US, and Areva in France. Historically, the main point of engagement from foundations and civil society on nuclear power has been on the specific topics of nonproliferation and waste management. In recent years, however, several things have changed in the philanthropic foundation landscape: there are many more philanthropies and philanthropists willing and able to write big checks to advance their beliefs; climate change has become a central issue for more of them; and more of them are betting on technology innovation as a key lever for advancing their strategic objectives. This brief is intended for a subset of those foundations in a position to contribute US$25-50 million towards making next-generation nuclear power a reality at the level of the industry and ecosystem as a whole, rather than as a profitable investment in an individual company.

Based on the above analysis, we recommend that such funders invest in one of the following three ways:

1. Co-create a large (US$500 million to 1 billion) "challenge" pool of funds with stage-gated investment in a shrinking pool of companies. As of Q1 2023 most Gen 4 projects and companies are nascent which means that it is too early to place bets on individual companies without insider knowledge. The ones that have made more progress already have substantial funding from governments and/or extremely wealthy individuals and are on track to get more as they demonstrate more success. Either way, a $25-50m investment at this stage. while potentially being a make-or-break proposition for any individual company, is unlikely to move the broader industry as a whole. Therefore, rather than finding individual companies to invest in, a more optimal approach for philanthropic funders interested in de-risking a high-potential technology would be to co-create a "challenge" pool with like-minded funders. Through a robust, stage-gated evaluation process, such a pool can concentrate funds towards a continuously winnowed-down list of highest-potential companies. By highlighting these companies, the pool can also catalyze additional external funding towards them, thereby further increasing the chance of their success. Over time, this will ensure that the best technologies and companies gain the market traction needed to create economies-of-scale and drive down costs to become affordable in developing countries. There will also likely be investment opportunities in technologies for producing new types of nuclear fuel as an alternative to conventional low enriched uranium fuel rods and potentially also in reprocessing of spent fuel for reuse. In addition, as the amount of fissile material increases along with its geographic spread, there will likely be a need for innovations in tracking nuclear fuel across the cycle creating another valuable avenue for philanthropic investment.

2. Support civil society groups in ensuring the emerging regulatory framework takes into account not just the priorities of governments and private companies but the needs of the global public. As things stand, there is considerable effort being put into creating international regulatory frameworks for the emerging nuclear power landscape. It is not clear, however, if the dominant voices will speak for the range of stakeholders. While there is no doubting the technical expertise of the various institutions involved, recent global agreements such as the UNFCCC climate change talks leave much to be desired on an optimal tradeoff balance between private interests, national security interests, and the greater public good. With a topic as complex and fraught as nuclear power, it is very important to have strong voices from civil society to ensure public interests are adequately represented. As such, philanthropic funders should consider supporting organization with the right mix of technical depth and global advocacy capabilities.

3. Engage the public in a long-term initiative. Just as public fears in many countries led to a pause in the last era of nuclear power expansion, public support will be necessary to start the new one. While those steeped in the topic are increasingly optimistic, the broader public has not been brought along. Given the complexity of the topic and its vulnerability to oversimplification in the age of social media, a sustained, thoughtful, and creative public engagement effort will be required. This will likely require investment across several forms of media and platforms reaching across geographies and age groups. As such, rather than a one-off, it will require a long-term funding commitment to developing and implementing a public engagement strategy.

The US and France offer contrasting models of public engagement on nuclear energy: whereas many of France's nuclear power plants have visitor centers to educate the public, those in the US tend to resemble unwelcoming militarized facilities. Unsurprisingly, public support for nuclear power in France has been considerably higher than in the US.

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