# Nuclear's Unclear Future

Samantha Stephens
SRI Analyst

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Nuclear power makes up about 9% of global electricity generation, with 443 reactors and 385 GW of capacity in operation today. This includes reactors in 31 countries, with Belarus and the United Arab Emirates currently constructing their first (World Nuclear Organization 2016).

Debates over the future of nuclear have been underway for years. On one hand, its very low lifecycle carbon emissions, consistent power production, and scalability are attractive in many markets and contexts. As a result, many of the climate scenarios compatible with limiting the most severe effects of climate change include nuclear power in no small part.

However, atomic energy has struggled to attain public acceptance. The meltdowns at Three Mile Island, Chernobyl, and Fukushima Daiichi led to major safety concerns, while the governance and physical risks many reactors still face today have provided little reassurance. New technologies have faced severe delays and cost overruns, not necessarily renewed enthusiasm. Further apprehension comes from challenges in managing nuclear's end-of-life.

From an investor's point of view, a distinction can be made between existing and new nuclear. Beyond what are often tenuous financial situations, the attractiveness of existing nuclear is principally determined by an estimation of its exposure to physical, technological, and governance risks. While new nuclear builds might mitigate some of these risks up-front, there are other options with lower sustainability risks, sometimes at a similar price point: renewables.

Renewables are without comparable negative externalities and have consistently decreasing costs, making them increasingly fierce competitors for nuclear's share of the low-carbon energy mix.

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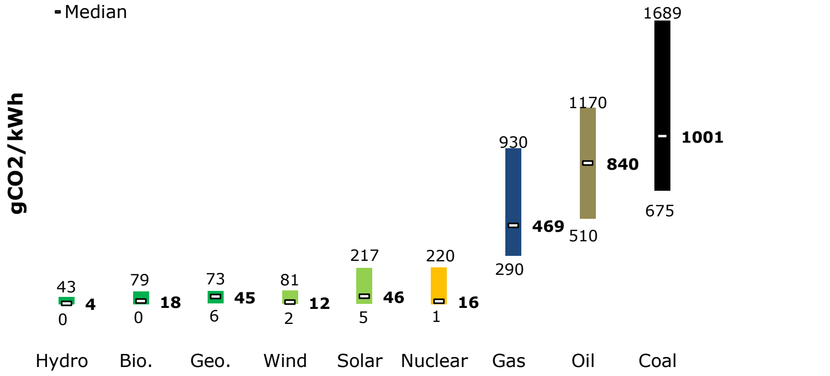
As countries attempt to address their emissions reduction commitments, the power sector has often been the focus of new regulation. From this perspective, nuclear would seem poised to experience its long-discussed-but-never-realized renaissance in the coming years; it produces zero greenhouse gas emissions during power generation and has lifecycle emissions on par with wind and solar.

*Nuclear produces zero greenhouse gas emissions during power generation, with lifecycle emissions on par with wind and solar.*

**1: Lifecycle Carbon Intensity of Fuels**
**(g$CO_2$ emitted per kilowatt-hour generated)**




*Source: Mirova / IPCC 2014*

But, this potential remains challenged by other factors currently shaping the future of nuclear power, namely:

- Security, including accidents, health, and handling of materials
- End-of-life, including decommissioning and waste storage
- Cost, which is affected by the two aforementioned factors

# 1. Overview

## 1.1 The Basics

Nuclear fission is the splitting of an unstable heavy atom's nucleus into two lighter nuclei under the impact of a sub-atomic particle called a neutron. Following impact, more neutrons are emitted and a large quantity of energy is released. The emitted neutrons then split new heavy atoms, creating a self-sustaining chain reaction. To prevent the reaction from running away and becoming explosive, as in nuclear weaponry, the emitted neutrons must be controlled so that they hit only one heavy nucleus. Control of the reaction is maintained via the presence of control rods, which absorb some of the neutrons.

In a nuclear power plant, the heavy nuclei in question are usually uranium. The energy released during atomic fission produces heat, which is used to convert water into steam. This steam is used to drive a turbine, which produces electricity.

## 1.2 The Nuclear Fuel Cycle

The nuclear fuel cycle is long and complex; the construction of a nuclear power plant alone takes 5 to 7 years. It includes many steps from the extraction of ores to the production of electricity and calls for heavy investments, especially downstream (enrichment, operation, reprocessing).

*The nuclear fuel cycle is long and complex, comprising: extraction, concentration, conversion, enrichment, fabrication, use, and recycling / disposal.*

First, for uranium ore to become nuclear fuel, it must follow these steps:

1. *Extraction*;
2. *Concentration* of the ore: processing and purification;
3. *Conversion and Enrichment*: after the uranium concentrate is converted into uranium hexafluoride ($UF_6$), the proportion of U-235 is increased to between 3 and 5% (U-235 is the most fissionable type of uranium, but it makes up only 0.7% of natural uranium);
4. *Fabrication*: creating pellets and fuel rods from the enriched uranium, followed by assembling fuel rods into bundles.

The produced fuel is then charged in the reactor for approximately four years. Afterwards spent fuel is managed in one of two ways: in an "open" cycle, the spent fuel is considered to be waste. In a "closed" cycle (or more accurately, partially closed), the fuel is reprocessed and reused one or more times prior to it becoming waste.

### 1.3 The World Nuclear Market

#### Industrial Players

The nuclear industry consists of seven main types of players:

- *Extraction, conversion, enrichment,* and/or *fabrication* as previously described within the fuel cycle,
- *Reactors*, or the companies which manufacture reactors and provide maintenance services,
- *Operators*, typically utilities responsible for the operation of the reactor and the generation of electricity,
- *End-of-Life*, players involved in waste reprocessing, waste storage, decommissioning, etc.

#### Institutional Players

The nuclear industry is among the most regulated industries in the world. On the international level, the International Atomic Energy Agency (IAEA) is the foremost institutional player. It is responsible for promoting peaceful applications of atomic energy and limiting its military use.

States which operate nuclear power plants must also have their own regulatory bodies responsible for day-to-day plant operations, including setting safety standards, end-of-life provisioning, disaster preparedness, licensing, reacting to incidents, and more. Some examples of local regulators are the Autorité de Sûreté Nucléaire (ASN) in France, the Nuclear Regulatory Commission (NRC) in the United States, the Chinese Atomic Energy Authority (CAEA) / National Nuclear Safety Administration (NNSA), and the Russian Ministry for Atomic Energy (Minatom).

## 2. Security

Since the first reactor reached criticality in late 1942, about 16,870 reactor-years[1] have taken place along with three major meltdown accidents: Chernobyl, Fukushima Daiichi, and Three Mile Island. Each was a milestone in nuclear power history, providing a key lesson going forward.

[1] *One reactor year = one nuclear reactor which operates for one year.*

- Three Mile Island (USA): in 1979, a partial meltdown occurred due to a mechanical failure in a secondary system followed by human error. Some radioactive gas was released, but few environmental or human health impacts were observed.

- Chernobyl (Ukraine, then-USSR): during a 1986 stress test, reactor design flaws plus improper actions by operators led to uncontrolled reaction conditions, a steam explosion, and a fire. This was the worst nuclear plant accident in history in terms of cost and casualties. It also had major economic impacts as it has rendered large zones of Ukraine and Belarus uninhabitable for humans.

- Fukushima Daiichi (Japan): after an earthquake struck in March 2011, emergency generators were flooded, disabling cooling systems. Partial meltdowns took place in three reactors, leading to explosions. Since then, contaminated water continues to leak into the Pacific Ocean, and the vicinity has been declared a no-go area.

These accidents have drawn attention to the fact that one total core meltdown has taken place every 3704 reactor-years, significantly more often than predicted (on the order of one accident every 10,000) (Leveque 2013, Rose & Sweeting 2016). But, this figure might not accurately represent risk going forward. The present failure rate is derived from a small sample size (about 15,000 reactor-years). Whether accidents will be more or less frequent in the future depends on a variety of factors not taken into consideration in these statistics; locations and plants do not experience the same level of human error, operations, technology, or natural disaster risk.

Since the stakes are high, nuclear risk must be treated carefully and proactively. At the plant-scale, sophisticated probabilistic assessments are used to identify sources of potential danger. No comprehensive accident database is available to external stakeholders, but approximations can be made to identify the main indicators of environmental and social risk on a plant-by-plant basis.

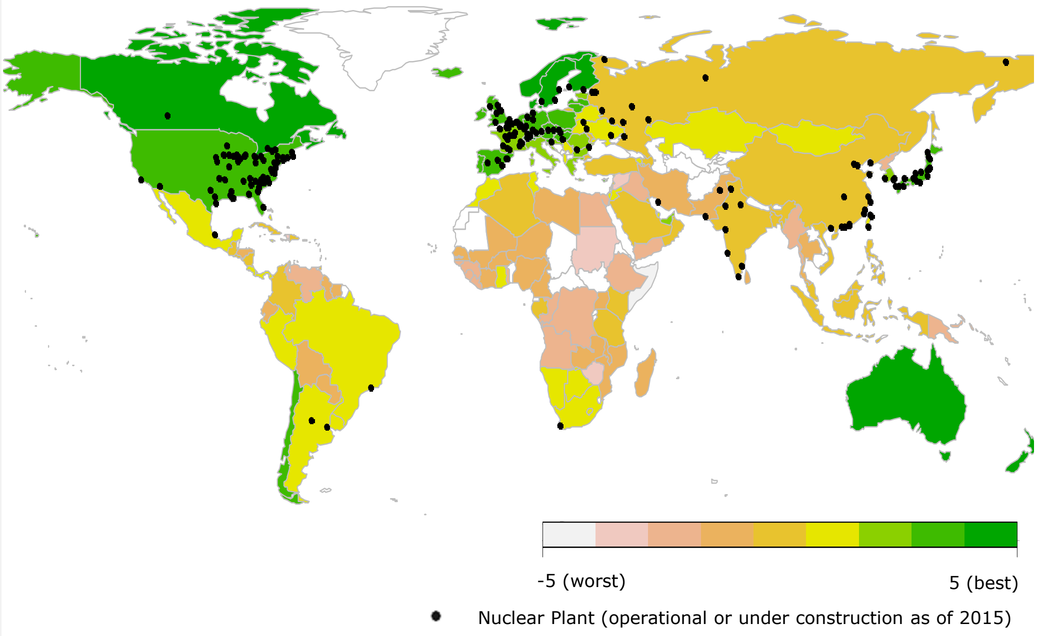
## 2.1 Country Risk

One potential source for plant/operator risk misstep comes from regulatory quality and governance, encompassing worker and community safety, susceptibility to corrupt or unethical practices, and adherence to all relevant international standards and treaties.

The process of country risk evaluation can be split into general governance (indicators adapted from the World Governance Indicators, WGI, published by the World Bank) and nuclear-specific governance. The World Governance Index captures the quality of a country’s governance through six dimensions: voice & accountability, political stability and lack of violence, government effectiveness, regulatory quality, rule of law, and control of corruption). Nuclear-specific governance assesses the physical security of nuclear materials in each country.

Based on these pillars, we created a composite indicator to compare country risk from one country to another. In figure 2, reactors locations were overlaid atop the resulting values.

**2: Reactor Locations (2016)**




**Detailed Descriptions of Indicators Used within Composite**

**Overall Governance (from WGI)**

- *Voice and Accountability:* the extent to which a country's citizens are able to participate in selecting their government, freedom of association, and a free media speaks volumes about the availability of accurate and reliable information about nuclear risk management and incidents.
- *Political Stability and Absence of Violence:* a country with politically motivated violence and/or terrorism also has a greater risk of its nuclear facilities being targeted for theft or sabotage.
- *Government Effectiveness:* a state with high quality, independent public and civil services with credible and implementable policies is more likely to have adequate control over its nuclear activities.
- *Regulatory Quality:* given that nuclear risk is highly location-dependent, the stringency and quality of the local regulator is of utmost importance.
- *Rule of Law:* a high level of confidence in and abidance by the rules of society (including the quality of contract enforcement, the police, and the courts) ensures that no laws or regulations are circumvented during the construction and/or operation of nuclear reactors.
- *Control of Corruption:* if public power is exercised for private gain, nuclear plant operators may not act in accordance with the best interests of their workers and/or nearby populations.

**Nuclear Governance (partially adapted from Nuclear Threat Initiative, NTI)**

- If a state is *signatory to major nuclear-related international treaties* (Convention on the Physical Protection of Nuclear Material, Conv. on Early Notification of a Nuclear Accident, Joint Conv. on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, Nuclear Non-Proliferation Treaty, etc.) and has undertaken additional voluntary commitments it is likely to take key issues into account during the regulatory process.
- The greater a state's ability to enforce norms through an *independent nuclear regulatory body*, the more effective its regulation is.
- A *robust set of nuclear-specific rules* leads to greater control and less potential for misuse.

*Source: Mirova / NTI 2016 / World Bank 2015 / World Nuclear Association 2016 / IAEA 2016*

According to this data (NTI 2016, World Bank 2015, and World Nuclear Association 2016), some specific areas of attention include:

- OECD member countries generally have high composite scores due to their political stability and regulatory quality, coupled with strong nuclear regulatory norms, adherence to international nuclear safety and security treaties, and lack of groups potentially interested in obtaining nuclear materials.

  However, there are some states with nuclear operations which stand out in terms of their approach to nuclear governance:

  - Spain's relatively poor nuclear governance assessment is derived from its limited implementation of mandatory cybersecurity and physical security controls. Though Iberdrola and Endesa/Enel (both publicly traded) envision reducing their exposure to nuclear going forward, they currently own most of the Spanish nuclear fleet.

  - Hungary withdrew from the Convention on the Physical Protection of Nuclear Material and the Convention on Early Notification of a Nuclear Accidents, which strongly contributes to its low nuclear governance assessment. Hungary's nuclear plants are operated by the 100% state-owned MVM Group.

  - Mexico's nuclear governance is considered limited because it has few physical and cybersecurity controls. Few plans are in place to protect nuclear facilities in the event of a natural disaster, and key areas are accessible to non-vetted personnel. Mexico's plants are owned and operated by Mexico's Comision Federal De Electricidad, which is 100% state-owned.

- Russia has a well-developed nuclear regulatory system but is exposed to corruption, poor levels of regulation concerning worker health and safety, and a lack of government effectiveness (according to the WGI). Russian nuclear plants are owned and operated by the state-owned Rosenergoatom.

- China and India's scores fall behind others' both in their general and nuclear-specific governance. Lack of voice and accountability is of particular concern in China, while the Indian regulator is not adequately stringent, empowered, or independent. Chinese plants are owned by a variety of majority state-owned companies; Indian reactors are similarly owned and operated by the national Nuclear Power Corporation of India.

- Many countries with relatively poor assessments overall (including the aforementioned Mexico, Hungary, Russia, China, and India), have nuclear fleets largely owned by state-owned entities, which leads to limited visibility on their practices and a greater emphasis on country-wide governance. There are two plants which stand out as being owned by publicly-traded companies within this scope, however: Angra (Brazil, owned by Electrobras), and Koeberg (South Africa, owned by Eskom).

## 2.2 Natural Disaster

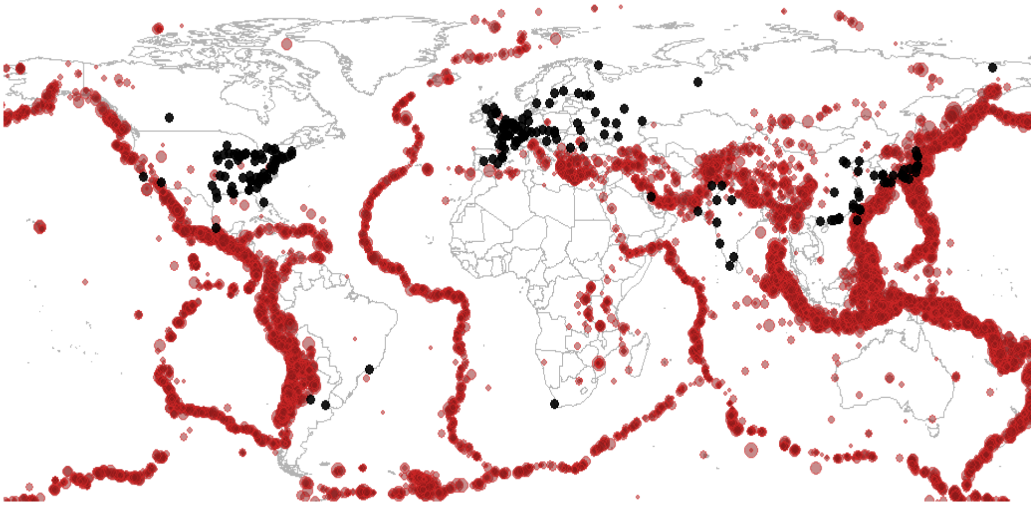
The Fukushima Daiichi accident emphasized the importance of strong natural disaster risk management practices from both regulatory and operational perspectives. Prior to the 2011 accident, Fukushima Daiichi's operator received several warnings that the seawall was not sufficient to withstand a powerful tsunami. The operator failed to rectify these shortcomings, instead embroiled in controversy over 16 years of falsified inspection records and hidden flaws. Meanwhile, the regulator neglected to perform thorough inspections. Despite having cited reports indicating that Fukushima Daiichi was exposed to seismic risk factors nearly identical to those which ultimately caused the accident, the Japanese regulator approved license renewal for the plant about one month before the disaster (Starr 2012).

*Around the world, the Fukushima accident spurred new regulation focused on increasing safety measures in the context of natural disasters.*

Around the world, this incident spurred new regulation focusing on increasing safety measures. It underscores the importance of local regulator quality, especially since seismic and weather behavior is so site specific. Best practices now include additional probabilistic assessments and hazard analyses, plus frequent re-evaluation. The most severe natural phenomena historically reported in the area (plus a generous margin of error) must be considered, as well as the capacity for workers to respond.

The enormous variation in natural disaster risk that can come with small changes in displacement means that it is difficult for external stakeholders to assess these risks on a plant-by-plant basis unless site data is accessible. However, trends in historically disaster affected areas allow for some identification of plants potentially exposed to seismic risk today (see figure 3).

**3: Plant Locations and Magnitude 5+ Earthquakes (2005-2015)**



**Earthquakes:** Magnitude 5 ⟷ Magnitude 8

Nuclear Plant (operational or under construction as of 2015)

*Plants located in zones of high seismic activity can face earthquake and tsunami risk. Most plants are located far from zones of concern in Europe and the United States.*

*Source: Mirova / USGS 2016 / World Nuclear Association 2016*

Based on past incidents and identified areas of natural disaster risks, some specific areas of attention include:

- East Asia: Japanese and Taiwanese reactor locations remain exposed to seismic and tsunami events (specific plants include Fukushima Daini, operated by TEPCO, and Hamaoka, operated by Chubu Electric Power Co.). Though China's most seismically active zones are in its interior, many of its reactors are on the east coast where there is flooding risk (e.g. Ningde, Daya Bay, Fangjiashan, Yangjiang, Tianwan, Ling Ao, and Qinshan, all of which are state-owned). The expansion of its nuclear fleet and limited space on the east coast has led to plans for plants in interior regions, which would necessitate special attention to earthquake precautions.

- South Asia: the reactors on India's west coast are in cyclone and tsunami-susceptible areas (notably Madras, owned by the Nuclear Power Corporation of India), while those in the north are exposed to earthquakes. Pakistan's coastal plants are also highly exposed to seismicity (Kanupp, in particular, owned by the Pakistan Atomic Energy Commission). All plants in this region are state-owned.

- North America: a plant in the northeast (Indian Point, owned by Entergy) has been identified as prone to earthquakes, while the last nuclear plant on the similarly-exposed west coast (Diablo Canyon, owned by PG&E Corp) will voluntarily close in 2025. Plants located along the Gulf coast (Turkey Point and St. Lucie, owned by a subsidiary of NextEra Energy) could also face flooding or loss of power due to hurricanes. Most plants are owned and operated by publicly-traded companies, including the aforementioned as well as Exelon, Duke Energy, Progress Energy, NRG Energy, and Xcel Energy.

## 2.3 Technology

Historical safety performance has varied somewhat depending on reactor type, but only once has it decisively led to disaster: inherent flaws in Light Water Graphite Reactors (LWGR, also known as RBMK) were a major contributor to the Chernobyl accident. Otherwise, no reactor type has been identified as intrinsically less safe than the others.

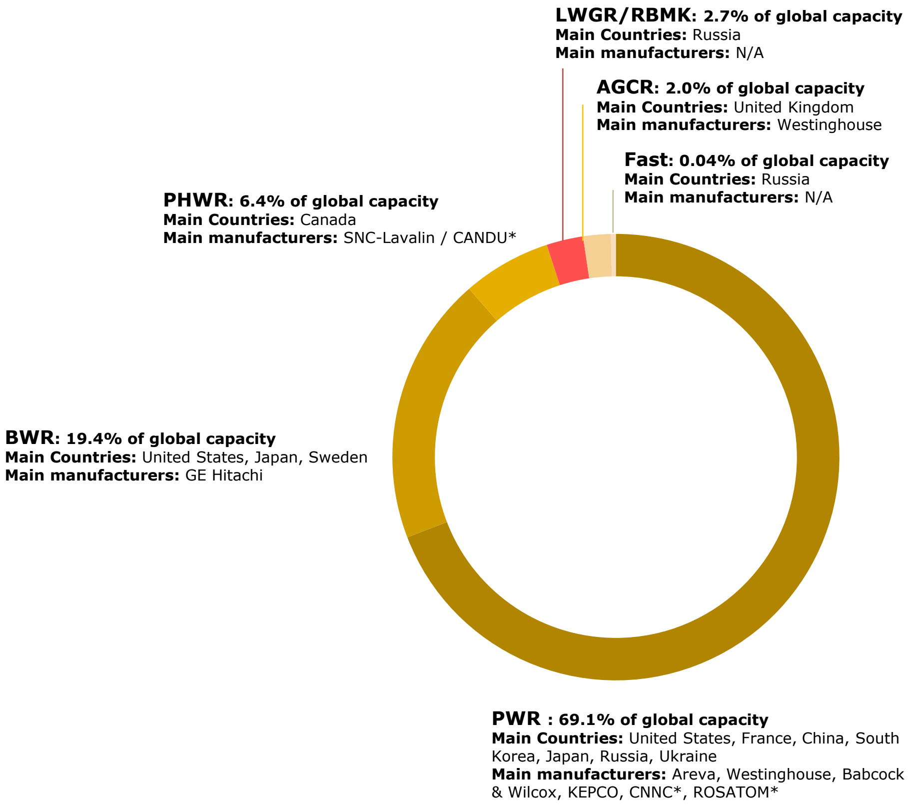
Reactor technologies are nonetheless dependent upon additional plant components (i.e. cooling mechanisms, generators) which must also be implemented and maintained correctly under the watchful eye of the local regulator. Flooding of the critical backup generators placed in susceptible areas led to the meltdown at Fukushima rather than direct reactor malfunction, and Three Mile Island was the result of failure in a secondary cooling system. Since detailed information about the existence and upkeep of such systems is typically not publicly available, technology history coupled with governance considerations can act as a proxy.

### The Majority: Pressurized and Boiling Water Reactors

Today, the Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) are by far the dominant technologies employed, together comprising just below 90% of total installed capacity (World Nuclear Association 2016).

About half of the remaining capacity is made up of Pressurized Heavy Water Reactors (PHWR), favored in Canada and its export partners. In the U.K., Advanced Gas Cooled Reactors (AGCR) make up the bulk of the country's capacity. Fast reactors, once considered promising, now comprise only a miniscule portion of today's capacity.

**4: Overview of Main Technology Types (2016)**




**state-owned*

*Source: Mirova / World Nuclear Association 2016*

## Historically Problematic: Light Water Graphite Reactors

*Unlike Three Mile Island and Fukushima, the link between reactor technology, costs, and fatalities is clear for Chernobyl's LWGR.*

Light Water Graphite Reactors (LWGR/RBMK) were manufactured in the Soviet Union and make up 3% of today's capacity, all in Russia. Unlike Three Mile Island and Fukushima, the link between reactor technology, costs, and fatalities is clear for Chernobyl's LWGR. These reactors are now known to have been intrinsically unsafe, lacking a containment structure and processes to prevent meltdowns. These technological deficiencies were further compounded by the scant Soviet attention to worker safety at the time. Because of the design's shortcomings, no new LWGR have been built since 1990. All LWGR reactors outside of Russia have been permanently closed, and the ones in Russia (15 reactors in total, comprising 10 GW of state-owned capacity) have implemented more comprehensive safety measures (World Nuclear Association 2016).

## The Future: Next-Generation Nuclear Reactors

The next generation of reactors promises a variety of safety improvements, better efficiency, and more standardized designs. Even so, they have not succeeded in renewing ardor for nuclear power in Europe and the United States, where construction of new reactors has stagnated. Only a few

*Several generation III reactors have experienced delays and cost overruns, therefore failing to succeed in renewing global enthusiasm for nuclear.*

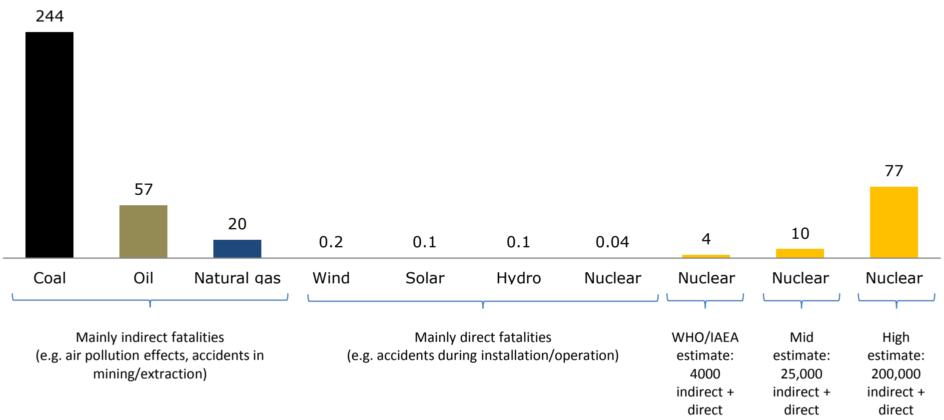
generation III reactors have been built so far, in South Korea and Japan (World Nuclear Association 2016). Several more generation III "EPR" are under construction (e.g. Olkiluoto 3, Flamanville 3, Taishan 1&2), but all have been the subject of controversy due to lengthy delays and cost overruns (European Commission 2016).

## 2.4 Health Impacts

Despite these safety concerns, nuclear's direct health impacts have probably been positive. Though proximity to nuclear plants tends to cause community concern, living or working near a nuclear plant is not known to cause negative health effects - barring accidents - as all radiation is contained in the reactor. For fossil fuels, however, health effects arise through air pollution, fuel extraction hazards, and one day, climate change.

According to a study by Kharecha and Hansen (2013), using nuclear in lieu of fossil fuels has led to well over a million deaths avoided since 1970. The disparity between the deaths caused by nuclear power and those caused by fossil fuels is attributable to the near-zero air pollution generated by nuclear plants, as well as particularly stringent safety standards within the atomic power value chain.

**5: Approximate Fatalities per Terawatt-Hour by Energy Type (2016)**




*This data is based on historical fatalities and power generation. If only direct deaths are taken into account, nuclear is the least fatal energy type. When various estimations of Chernobyl's impacts are taken into account, it becomes more comparable to fossil fuels.*

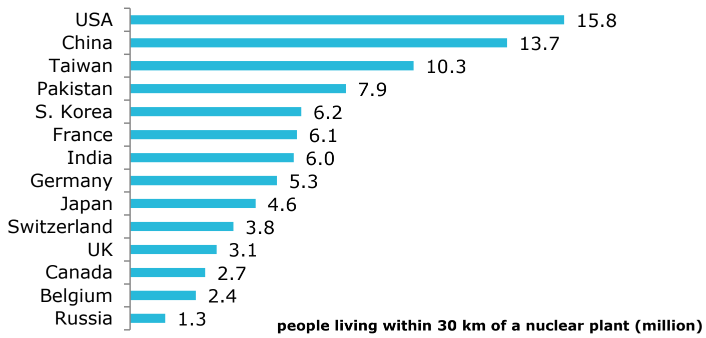
*Source: Mirova / Kharecha & Hansen 2013 / IAEA 2005 / Yablokov & Nesterenko 2010*

*Uncertainty in nuclear's health impacts comes from difficulties in estimating indirect effects plus the unknown severity and location of future accidents.*

Nevertheless, these conclusions depend almost entirely on assessments of Chernobyl's indirect health impacts. Estimations of cumulative deaths due to the disaster range from 4,000 (International Atomic Energy Agency, IAEA, 2005) to 985,000 (Yablokov & Nesterenko 2010), though most are in the tens to low hundreds of thousands. Evidently, it has not been possible to accurately and decisively identify the fatalities caused by this nuclear meltdown, as relocations, the dissolution of the USSR, and difficulties in gathering data have led to many lost records. The reliability of the International Atomic Energy Agency (IAEA)'s estimate has further been disputed since its explicit mission is to promote nuclear power.

The extent to which nuclear did or did not prevent past fatalities remains uncertain due to the range of indirect death estimates. While the long-term health effects of nuclear power remain nebulous, the principal source of uncertainty does not arise from ambiguity in health impacts sustained as a result of exposure to radiation. Instead, it comes from the unknown severity and location of future incidents. If the next meltdown were to take place near a population center, for instance, it could have far more consequential health impacts than any accident observed so far.

**6: Countries with > 1 Million People Living Within 30km of a Nuclear Plant (as of 2010)**




*Source: Mirova / SEDAC 2016 / NASA 2016*

As the nuclear fleets age, there has been speculation that risks will only increase. Insufficiently secure waste storage or transportation could also lead to severe and widespread effects.

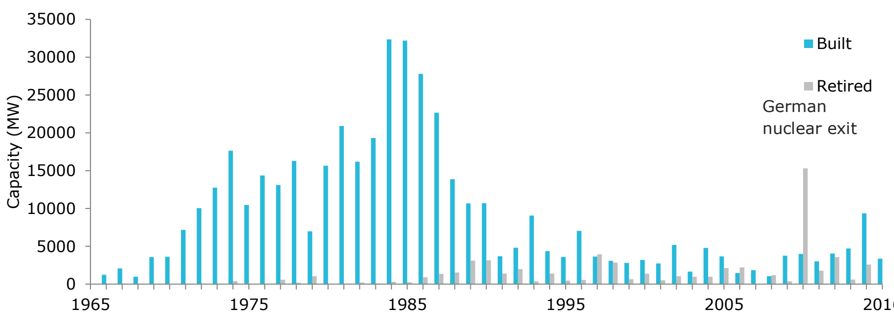
# 3. End-of-Life

Because of the potential negative health impacts of radioactive materials, reactors' end of life is a controversial subject. All radioactive material must be removed from the plant site safely and waste must be stored for as long as hundreds of thousands of years; both are daunting tasks.

## 3.1 Dismantling, Decommissioning, and Restoration

Once a plant is retired, removing radioactive materials and making sure that the location is returned to a usable and safe state requires time and substantial funds. Generally, nuclear plants have a lifetime of 40 years, sometimes with the possibility of a 20-year extension. Given that today's nuclear fleet averages nearly 30 years old, there will be a substantially increased need for decommissioning in the relatively near future, with or without regulatory intervention.

**7: Global Nuclear Capacity Additions and Retirements (1965-2016)**




*Of the nearly 150 reactors which have ceased to generate power, less than 20 have undergone complete decommissioning. The process remains in progress for over 100 reactors.*

*Source: World Nuclear Association 2016*

There are three types of decommissioning:

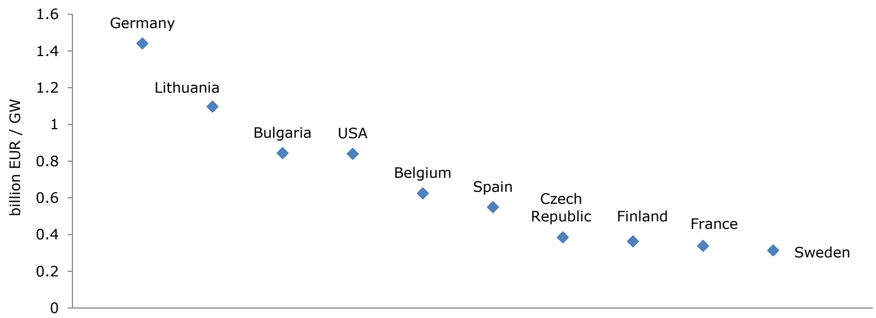
- *Safe enclosure* is the main method, postponing the final removal of controls for a longer period, usually from 40 to 60 years. The facility is placed into a safe storage configuration until the eventual dismantling and decontamination activities occur. Most stopped reactors are currently in this state.
- *Immediate dismantling* implies that the facility is quickly removed from regulatory control after its regulated activities end. Dismantling and decontaminating activities begin shortly afterward, typically taking five years or more. So far, only a few plants have undergone complete, immediate decommissioning.
- *Entombment* is seldom used. It places the facility into a condition that will allow the remaining radioactive material to remain on-site indefinitely. This involves reducing the size of the area where the material is located and then encasing the facility in concrete. The destroyed unit at Chernobyl is one example of a reactor decommissioned this way.

*Decommissioning takes place over long timeframes, making it difficult to estimate costs and, in some cases, assign liabilities.*

No matter how, decommissioning typically takes place over long timeframes, making it difficult to estimate costs and, in some cases, assign liabilities. There have been relatively few instances of complete decommissioning from which to accrue learning effects and wider experience, but based on the limited set of examples available, complete decommissioning costs have varied widely, from 0.2 – 4 billion EUR per GW, or about 1.4 billion EUR/GW on average (World Nuclear Association 2016, European Commission 2016, US NRC 2015, OECD-NEA 2016).

Though the data in figure 8 represents the estimated cost of decommissioning, it is still necessary for the utility/plant/government (depending on location) to accrue the funds necessary. For example, in the United States, only about $50 billion has been accumulated so far out of a total $80 billion needed. In addition, such funding estimates are also often subject to critique. France’s €0.3 billion/GW assumption, for instance, has been criticized for being too low, with some estimations reaching two or three times greater. German decommissioning is projected to be extremely expensive because of the country’s sudden nuclear exit in 2011; this implies less time preparatory time for dismantlement and waste storage.

**8: Estimated Decommissioning Costs by Country, 2016**




*Decommissioning costs are estimated by companies, governments, or other associations. Above, the European estimates are derived from state responses to a questionnaire designed by the European Commission’s Decommissioning Funding Group, if available. The U.S. estimate is provided by the U.S. Nuclear Regulatory Commission. Differences in methodology, the state of certain preparations (waste storage, for instance), and specificities of local regulation lead the figures to vary sizably from country to country.*

*Source: Mirova / European Commission 2016 / US NRC 2015*

Provisions for the end of a nuclear plant's life are set aside through different mechanisms depending on the country and its regulator. In general, operators of nuclear power plants are responsible for financing decommissioning and waste management costs. To ensure that sufficient funds are available when needed, these provisions are set aside on the balance sheet, put into an internal fund (administered by the company), or added to an external fund (administered by the government or independent trustees). Given that cost estimates are subject to some uncertainty, some countries/regulators require supplemental provisions in case of extra charges incurred during the decommissioning process.

## 3.2 Waste Management

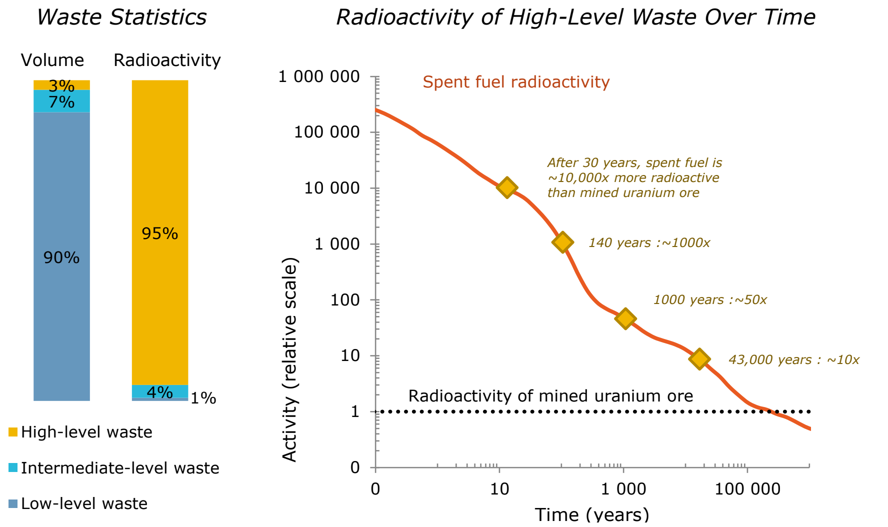
Waste is also a highly controversial aspect of nuclear power given its long lifetime and the associated dangers. There are three main types:

*Since spent fuel remains dangerous for up to 300,000 years, financing secure storage and making sure it does not impose a burden on future generations still presents a major challenge.*

- *Low-level waste* consists of materials contaminated with small amounts of radioactivity, disposed with general household waste once it becomes safe to handle.
- *Intermediate-level waste* contains non-negligible amounts of radioactivity and requires some shielding. It is typically solidified in concrete or bitumen for disposal.
- *High-level waste* arises directly from burning uranium in a reactor and thus contains the products generated in the reactor core. It is highly radioactive and hot, so cooling and shielding are required.

Each year, nuclear power generation facilities worldwide produce about 200,000 m$^3$ of low-/intermediate-level waste and about 10,000 m$^3$ of high-level waste, together almost enough to fill a football stadium. Since high-level waste is still dangerous for as much as hundreds of thousands of years, financing secure storage and making sure it does not impose undue burdens on future generations still presents a major challenge.

**9: Nuclear Waste**




*Source: Mirova / US NRC 2015 - Waste / World Nuclear Association Nuclear Fuel Cycle 2016*

Today, the main option for disposing of spent fuel is *geological disposal*. After 40-50 years of surface storage, waste radioactivity drops by a factor of almost 1000. This makes handling more feasible. Only then will the material will then be moved from surface storage to a geological repository, where it will remain for as long as 300,000 years.

In most cases, the 40-50 year storage window has not yet passed. Some countries are therefore in the process of selecting appropriate deep geological repositories for their high-level waste (e.g. Bure in France, Yucca Mountain in the U.S.), while others (e.g. Onkalo in Finland) have begun construction on theirs. Several low-level and intermediate-level waste storage facilities are already in operation.

Some places have opted for *aqueous reprocessing,* which removes the reusable parts of spent fuel prior to its disposal. The resulting material then takes about 9000 years to become as safe as mined uranium ore. Advanced reprocessing techniques could render this material's lifespan even shorter, but the technology is still being developed (US NRC 2015 - Waste, World Nuclear Association Nuclear Fuel Cycle 2016).

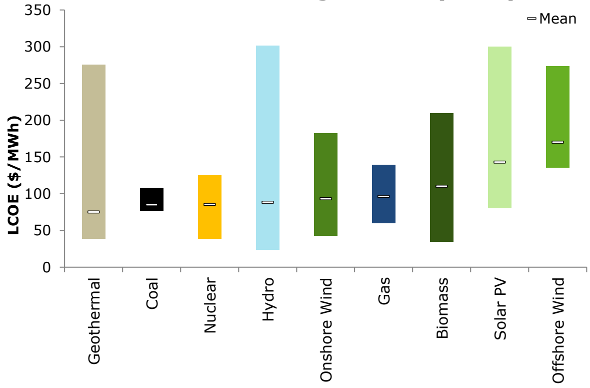
All forms of energy carry some potential for negative health impacts, but nuclear-associated risks will clearly last longer than human civilization has existed. With this arises a unique set of challenges: how will we communicate with people thousands of years in the future to deter disruption of waste repositories? How can we ensure that these repositories will remain structurally intact during this time period?

# 4. Going Forward

## 4.1 Costs

Social concerns aside, nuclear power has historically been a reliably low-cost and low-carbon electricity source. Since the levelized cost of electricity (LCOE) accounts for all lifetime costs incurred per unit of electricity produced, nuclear's high construction costs are offset by its low operating costs. Coupled with its high power output, nuclear's LCOE has historically been relatively low.

**10: Global Average LCOEs (2014)**




*Renewables have become economically competitive with nuclear in some regions, and their costs are still falling.*

*LCOE stands for "levelized cost of electricity," a measure of a system's total lifetime cost over its total electricity output. Using LCOE instead of total capital expenditures, for instance, allows for comparability of power sources with different cost structures.*

*Faced with tightening climate regulation, coal LCOEs are tending higher. Nuclear LCOEs are also going up, especially in Europe, due to concern over insufficient decommissioning provisions and other regulation. At the same time, decreasing capital costs for turbines and photovoltaic modules mean that wind and solar LCOEs are decreasing.*

*Source: Mirova / IPCC 2014 / IEA Projected Costs of Generating Electricity 2015*

However, its sensitivity to financing cost and regulation leads (new) nuclear to be more economically viable in some areas than others. In Europe and the U.S., for instance, costs and cost projections have increased in recent decades because of provisioning requirements, regulation, and the delays in generation III reactors. Renewables have thus become economically competitive with new nuclear in these locations.

Some studies indicate that new nuclear costs substantially less in Korea and China due to standardization, learning effects, less exigent provisioning requirements, and less rigorous regulations overall (Lovering et al. 2015, IEA 2016). In these locations, while safety concerns have been neither assuaged nor realized, the outlook for growth in local nuclear power seems more positive.

**11: Selected Results of Recent Tenders and Auctions**

| Nuclear | | Solar | | Wind | |
|---|---|---|---|---|---|
| **United Kingdom:** New Gen. III nuclear (2016) | 110 € / MWh | **Germany**: 4th pilot tender for ground-mounted PV (2016) | 75 € / MWh | **Germany**: average onshore wind (2016) | 65 € / MWh |
| **Finland**: New Gen. III nuclear (2016) | 95 € / MWh | **Dubai** : 1 GW Mohammed bin Rashid Al Maktoum tender (2016) | 30 € / MWh | **France**: average onshore wind (2016) | 85 € / MWh |
| **China**: New Gen. III nuclear (2016) | 45 € / MWh | **France**: CRE3 800 MW ground-mounted PV tender (2015) | 70-200 € / MWh | **Morocco**: 850 MW onshore wind tender (2016) | 30 € / MWh |

*Based on recent tenders and auctions, the price of solar and wind have been below the LCOE of new nuclear in Europe. These prices have also been falling steadily in recent years, primarily due to reductions in capital costs, improved turbine/panel efficiencies, and mastery of connection and installation practices. In some regions with particularly good resource (see Dubai solar or Moroccan wind), recent renewable LCOEs have even proven below those of the most inexpensive nuclear.*

*It is worth noting that in both figures 10 and 11, the nuclear LCOEs do not take dismantling and decommissioning costs into account, while the renewable LCOEs do not include costs associated with intermittence.*

*Source: Mirova / Parkinson 2016 / Commission éolienne du SER 2015 / Hirtenstien 2016 / l'Echo du Solaire 2015 / Morris 2016 / German Mechanical Engineering Industry Association 2016 / Lecomte, Mario, & Vignon 2015 / Cour des comptes 2015*

The true ensemble of costs which should be attributed to nuclear remains uncertain because of the unknown costs associated with waste storage and decommissioning. Waste storage must be maintained to very high standards for unfathomably long timespans, leading to questions of liability, as well as more existential questions of permanence and feasibility. Similarly, very little of the global nuclear capacity retired thus far has been dismantled and decommissioned. The decommissionings that have taken place took substantially longer and were more expensive than expected. As a result, nuclear's role as the most cost-effective power source is no longer certain either.

## 4.2 Outlook

Many countries are involved in nuclear power, though in different ways and for different reasons. The outlook for nuclear also varies greatly from region to region; nuclear is stagnant in the United States, set to be phased out in Germany and (to some extent) France, the United Kingdom is embracing new nuclear, and China and India are looking to expand their capacity substantially in order to meet growing demand and decarbonization objectives.

**Figure 12: Nuclear Capacity and Generation, by Country (2016)**

| Country | Capacity (MW) | Share of Power Generation |
|---|---|---|
| USA | 98 708 | 20% |
| France | 63 130 | 72% |
| Japan | 39 752 | 2% |
| Russia | 28 707 | 17% |
| China | 25 443 | 4% |
| South Korea | 23 017 | 30% |
| India | 13 524 | 3% |
| Canada | 13 107 | 16% |
| Ukraine | 10 799 | 52% |
| UK | 9 651 | 20% |
| Sweden | 8 883 | 40% |
| Germany | 7 121 | 13% |
| Spain | 5 913 | 21% |
| Belgium | 5 308 | 52% |
| Czech Rep. | 5 032 | 29% |
| Taiwan | 3 904 | 14% |
| Switzerland | 3 333 | 34% |
| Finland | 2 752 | 34% |
| Hungary | 1 926 | 51% |
| Slovakia | 1 889 | 54% |
| Argentina | 1 884 | 6% |
| Pakistan | 1 860 | 4% |
| Bulgaria | 1 814 | 35% |
| Brazil | 1 627 | 3% |
| South Africa | 1 445 | 7% |
| Romania | 1 300 | 17% |
| Mexico | 915 | 6% |
| Iran | 690 | 2% |
| Slovenia | 688 | 35% |
| Netherlands | 482 | 3% |
| Armenia | 375 | 31% |
| *all others* | 0 | 0% |

*Source: Mirova / World Nuclear Association 2017, (Reactor Database) 2016*

## Selected Countries

### United States

Nuclear power accounts for about 20% of the United States' power generation, with over 100 GW in capacity.

Most reactors were constructed prior to 1974 and no new reactors entered operation between 1977 and 2013, in part due to heightened fear following the Three Mile Island accident in 1979. Despite the advanced age of the fleet, there are only two reactors under construction today.

The U.S. uses an open fuel cycle. Commercial reprocessing was banned from 1978 to 1981 due to military concerns, and few new investments followed in reprocessing facilities or research. In general, little effort has since been made to convert to a closed fuel cycle, though interest has grown in recent years.

| Selected Actors | Area(s) of Involvement |
|---|---|
| **Neutron Energy** | Mining |
| **United States Enrichment** | Enrichment |
| **General Atomics** | Conversion, Fabrication |
| **GE, Westinghouse** | Reactors |
| **EnergySolutions** | End-of-Life |

*More than 75% of France's electricity is generated from its 58 nuclear reactors, making it the most nuclear-reliant country in the world.*

### France

More than 75% of France's electricity is generated from its 58 nuclear reactors, making it the most nuclear-reliant country in the world. As a result, it has among the lowest carbon footprints of electricity generation in the OECD.

The majority of the reactors were constructed after 1974 as France sought to increase its energy independence following the 1973 oil crisis. After the 2011 Fukushima accident, however, support for atomic power has dropped. The Energy Transition law enacted in 2016 implies a nuclear phase-out to a 50% of the electricity mix by 2035.

France is unique in terms of its domestic capacity through much of the nuclear value chain, from enrichment to reprocessing. It has an active nuclear reprocessing program, allowing it to treat its own fuel as well as sell reprocessing services to other countries.

| Selected Actors | Area(s) of Involvement |
|---|---|
| **AREVA** | Extraction, Conversion, Enrichment, Fabrication, Reactors, Reprocessing |
| **Electricité de France** | Operators |

### India

India currently has 22 reactors in operation representing about 3% of its electric capacity. Given its ambitious $CO_2$ emissions reduction targets under the Paris Agreement, growing energy demand, and reliance on imported coal, India is looking to significantly expand its nuclear capacity in the coming years.

India's ability to benefit from international cooperation regarding nuclear power is limited because it did not sign the Nuclear Non-Proliferation Treaty and independently developed nuclear weapons. However, several bilateral agreements (including the 2006 U.S.-India Civil Nuclear Agreement) have helped to develop its nuclear industry.

In part because it has limited domestic uranium reserves, India is a major proponent of thorium-based fuels, which could prove more recyclable than the existing uranium.

| Selected Actors | Area(s) of Involvement |
|---|---|
| **Nuclear Power Corporation of India, National Thermal Power Corporation** | Operators |
| **Uranium Corporation of India** | Extraction, Conversion |
| **Nuclear Fuel Complex** | Fabrication |

### United Kingdom

The United Kingdom currently has 15 reactors generating about 20% of its electricity, but almost half will be retired by 2025. No new reactors have been built since 1995 due to lack of public agreement and no consistent nuclear energy policy.

However, there are currently several reactors under construction or expected to begin construction soon. The most well-known is Hinkley Point C, which struck a divisive subsidy contract with the government that guarantees it twice the wholesale price of electricity for 35 years.

Following the U.K.'s decision to withdraw from the European Union, it notified the European Atomic Energy Community of its intention to withdraw as well. Going forward, this will likely have negative impacts on the country's nuclear industry and governance through changes in regulation, research, access to nuclear materials, and several cooperation agreements.

| Selected Actors | Area(s) of Involvement |
|---|---|
| **BHP Billiton** | Extraction |
| **Urenco Group** | Extraction, Conversion, Enrichment, Fabrication |
| **EDF Energy, Horizon (Hitachi)** | Operators |
| **Magnox Ltd, Sheffield Ltd** | Operators, End-of-Life |

### Germany

*Germany has 8 reactors in operation today, but all will be closed by 2022 following a 2011 government decision to cease nuclear power operations.*

Germany has eight reactors in operation today, but all will be closed by 2022 following a 2011 government decision to cease nuclear power operations.

As a result, German utilities have been forced to figure out how to accrue adequate funds for decommissioning earlier than anticipated, as well as how to replace the generation capacity of their now- or soon-to-be-mothballed nuclear power plants. Waste storage became a similarly contentious subject, with the German nuclear plant operators agreeing to pay €17.4 billion to transfer their waste liabilities to the state.

Though closing these plants was in an effort to avoid future social risk, it also led some of the country's nuclear generation capacity to be replaced by coal, with detrimental climate impacts.

| Selected Actors | Area(s) of Involvement |
|---|---|
| **Bilfinger Berger Power Services** | Reactors |
| **E.ON, EnBW, RWE, Vattenfall** | Operators |
| **Cameco (Nukem Energy)** | Reprocessing |
| **GNS Gesellschaft für Nuklear-Service** | End-of-Life |
| **Siemens** | Reactors |

### China

Of the 64 reactors under construction today, 22 are in China, and more are yet to come. China has ambitious targets to increase its nuclear capacity, to 58 GW by 2020 and 150 GW by 2030, largely in an effort to mitigate the pollution effects of its coal-fired plants.

*China has ambitious targets to increase its nuclear capacity, to 58 GW by 2020 and 150 GW by 2030, largely in an effort to mitigate the pollution effects of its coal-fired plants.*

China uses a closed fuel cycle and has a robust and complete nuclear supply chain. It is self-sufficient in terms of reactor design and construction, and has achieved relatively low-cost nuclear builds relative to the rest of the world. Overall, China's involvement in nuclear power is set to continue to ramp-up as it begins to export its nuclear technology and supply chain components more and more.

Some concerns do exist, however, regarding nuclear risk management in China. It is unclear whether regulatory oversight is adequate to prevent natural disaster-related issues, and there is apprehension stemming from the perception of a relatively undeveloped local safety culture.

| Selected Actors | Area(s) of Involvement |
|---|---|
| China Guangdong Nuclear Power Group | Operators |
| China National Nuclear Corporation | Conversion, Enrichment, Fabrication, Reactors, Reprocessing, End-of-Life |
| China Nuclear Engineering and Construction Corporation | Construction |
| China Nuclear International Uranium Corporation | Extraction |

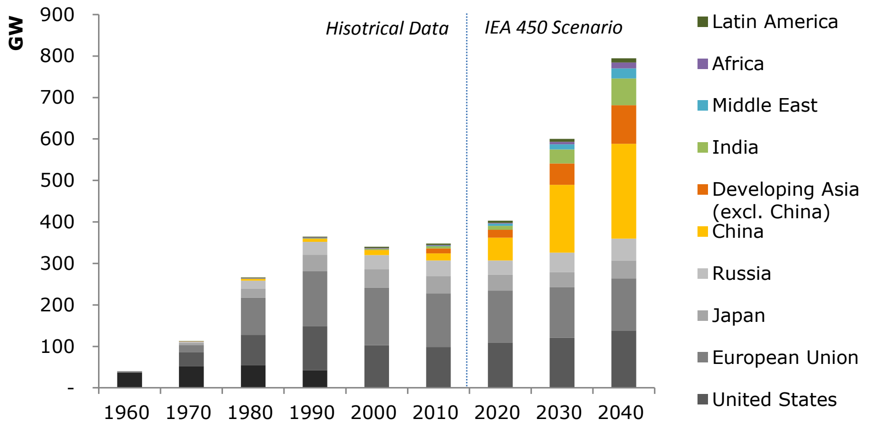
## Global Outlook

Many companies, agencies, and organizations produce energy projections, including the International Energy Agency, the U.S. Energy Information Administration, BP, ExxonMobil, Greenpeace, Négawatt, and many more. Some describe likely pathways based on today's policies and historical trends, while others define pathways to achieve certain climate goals.

According to the International Energy Agency's (IEA) scenario compatible with a 2°C rise in global temperature, nuclear will make up 18% of electricity generation in 2040 (as opposed to 12% if the current trajectory is maintained and 9% today). Based on the same scenario, nuclear capacity will increase from 385 GW today to 614 GW in 2040 (IEA World Energy Outlook 2016). This increase reflects the low carbon intensity of nuclear power and its ability to generate large, constant amounts of electricity in the face of growing global demand for low-carbon energy.

*Nuclear will continue to play a sizeable role in decarbonizing the global energy mix according to the International Energy Agency's 2° C compatible scenario.*

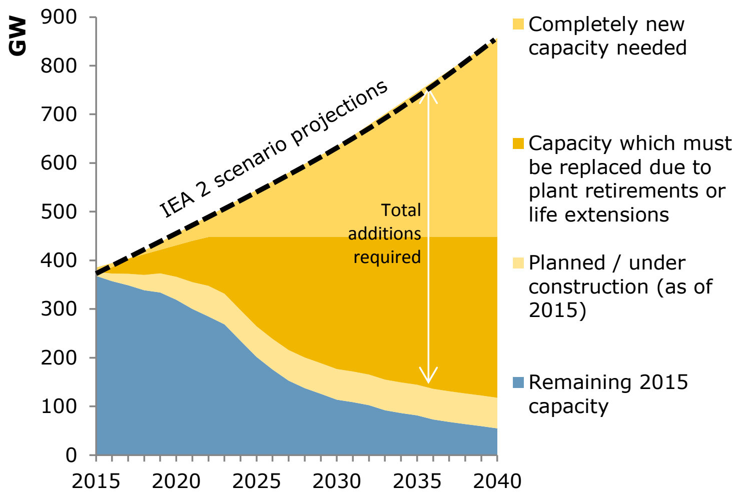
**13: Nuclear Power According to the IEA's 450 (2°) Scenario**




*Source: Mirova / IEA World Energy Outlook 2016 / World Nuclear Association 2016*

Since the current nuclear fleet averages about 30 years old, large-scale replacement of retiring plants while simultaneously adding new capacity would be necessary in order to achieve this particular pathway to 2°C. Retirements alone would mandate the installation of 330 GW of capacity by 2040 in developed countries with large existing nuclear fleets like the United States, France, Russia, and Japan. This seems unlikely, in our view. The remaining 230 GW of new capacity would come from developing countries, namely China and India (IEA World Energy Outlook 2016).

**14: Global Nuclear Retirements and Additions According to the IEA's 450 (2°) Scenario**




*Source: Mirova / IEA World Energy Outlook 2016 / World Nuclear Association 2016*

Until grid solutions (e.g. storage) are developed that harmonize renewables' intermittence with the existing grid, low-carbon baseload power remains a necessity. Nuclear plays this role well. But, this is only true as long as storage remains prohibitively costly, more flexible hydro and/or biomass plants are unable to act as replacements, and nuclear remains comparatively inexpensive. None of this is certain.

As investors, investments in new nuclear are less attractive than ever. Nuclear power leads to sizeable, dangerous, and ambiguous levels of risk over its very long lifetime. Meanwhile, renewables are becoming increasingly cost competitive, even before nuclear's end-of-life costs are taken into account. The existing nuclear park could even potentially be sufficient to support decarbonization objectives in some regions if renewables and energy efficiency measures are ramped-up with sufficient speed (Association negaWatt, 2017). So, the certainty renewables afford in terms of cost, climate benefit, and long-term social impact has thus become more and more appealing overall, to both the general public and investors.

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Regulated by AMF under n°GP 02-014
RCS Paris n°394 648 216
Registered Office: 21 quai d'Austerlitz – 75 013 Paris - Tel.: +33 (0)1 78 40 80 00
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Limited liability company
Regulated by AMF under n°GP 90-009
RCS Paris n°329 450 738
Registered Office: 21 quai d'Austerlitz – 75 634 Paris Cedex 13 Tel. +33178408000

**NATIXIS GLOBAL ASSET MANAGEMENT S.A.**
RCS Paris 453 952 681
21 quai d'Austerlitz, 75013 Paris
S.A. / Share Capital: €156 344 050

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