Columbia Business School
Climate Knowledge Initiative

23 September 2025

Reenergizing Nuclear

Quint Houwink, Adele Teh, Hinako Arai, Vedant Bhansali, Khande-Jaé Fisher, Brenda Rain, Christian Sandjaja, Clara Zibell, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner

Columbia Business School
Climate Knowledge Initiative

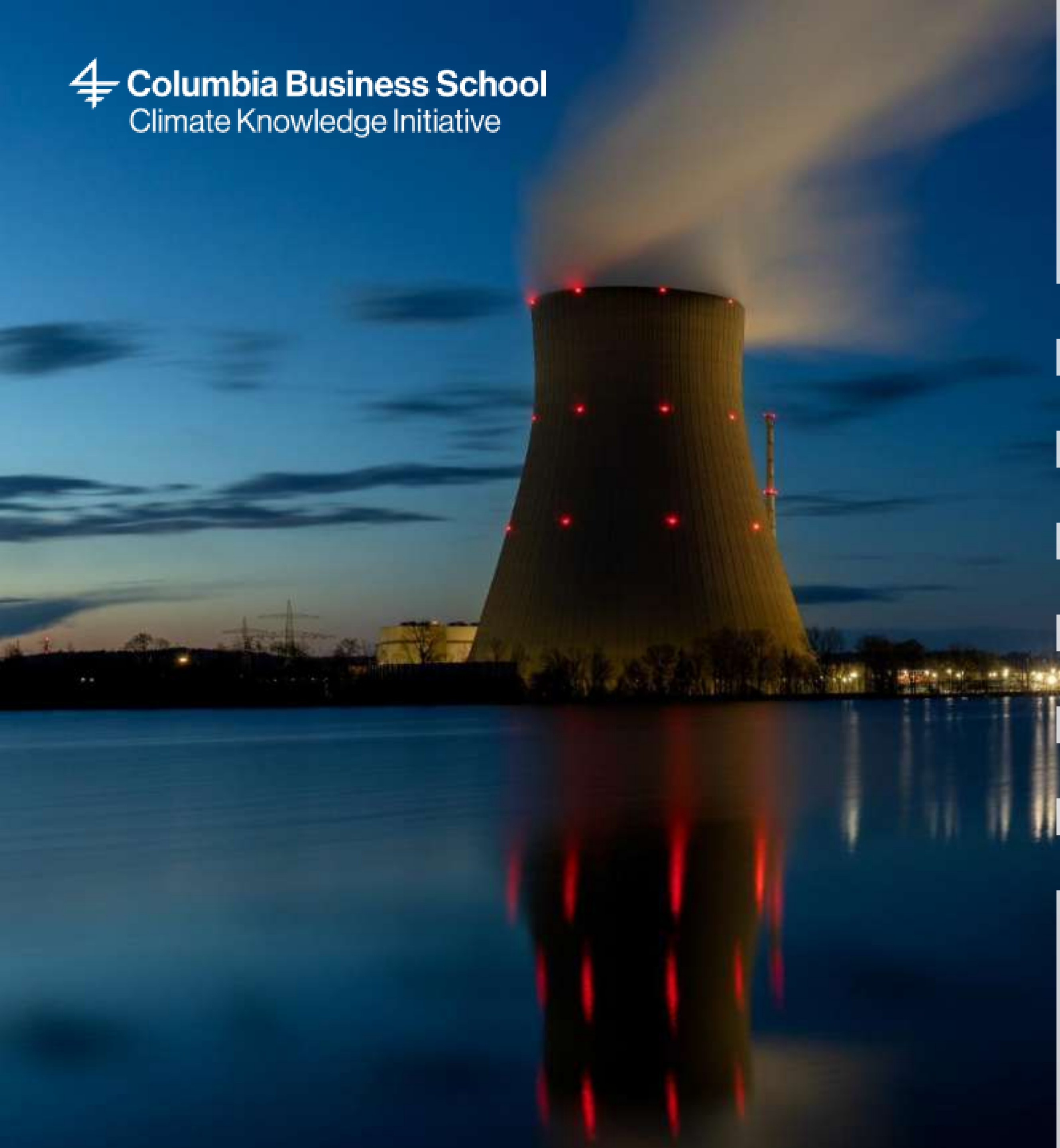
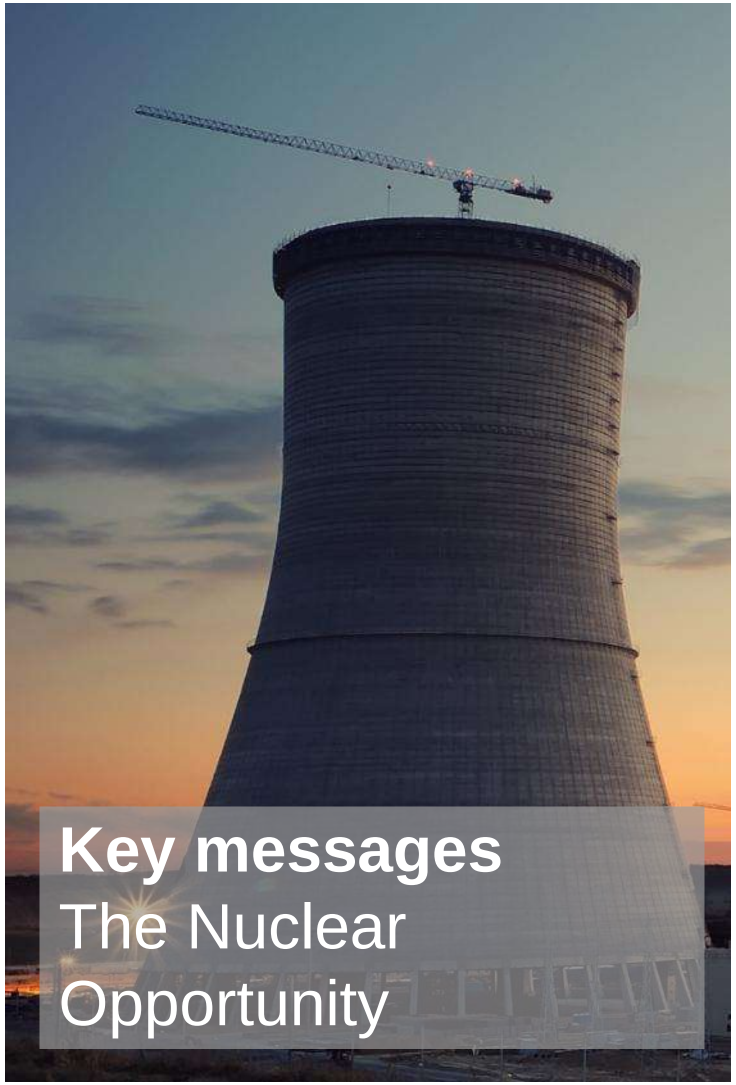


Table of contents

Columbia Business School
Climate Knowledge Initiative

The Nuclear Opportunity



Key messages
The Nuclear Opportunity

Properly managed nuclear is safe, land efficient, and low waste compared with other energy sources.

- Highly radioactive waste represents less than 0.25% of total nuclear waste.

Nuclear energy use has decreased from its peak of 17% to 9% today, and deployments have moved from Europe and the United States to India and China.

Nuclear is expected to generate 7% to 11% of global electricity by 2050, growing capacity 1.5 to 3x.

- Nuclear has the lowest carbon intensity of all energy sources at 5 grams CO_2e/kWh, even lower than solar photovoltaic (PV) and wind.

There are four pathways for the future of nuclear power:

- Extending the lifetime of nuclear plants, which has the lowest LCOE and can be safe.
- Building new large reactors, which would significantly reduce emissions but is costly and time intensive.
- Building small modular reactors (SMRs), which provide more flexible nuclear power, but LCOE is still highly uncertain.
- Nuclear fusion, which addresses many of nuclear’s problems, if the technology can be commercialized.

The average age of nuclear power plants has doubled to 31 years since 2000, indicating the potential of extending their lifetime beyond 40 years.

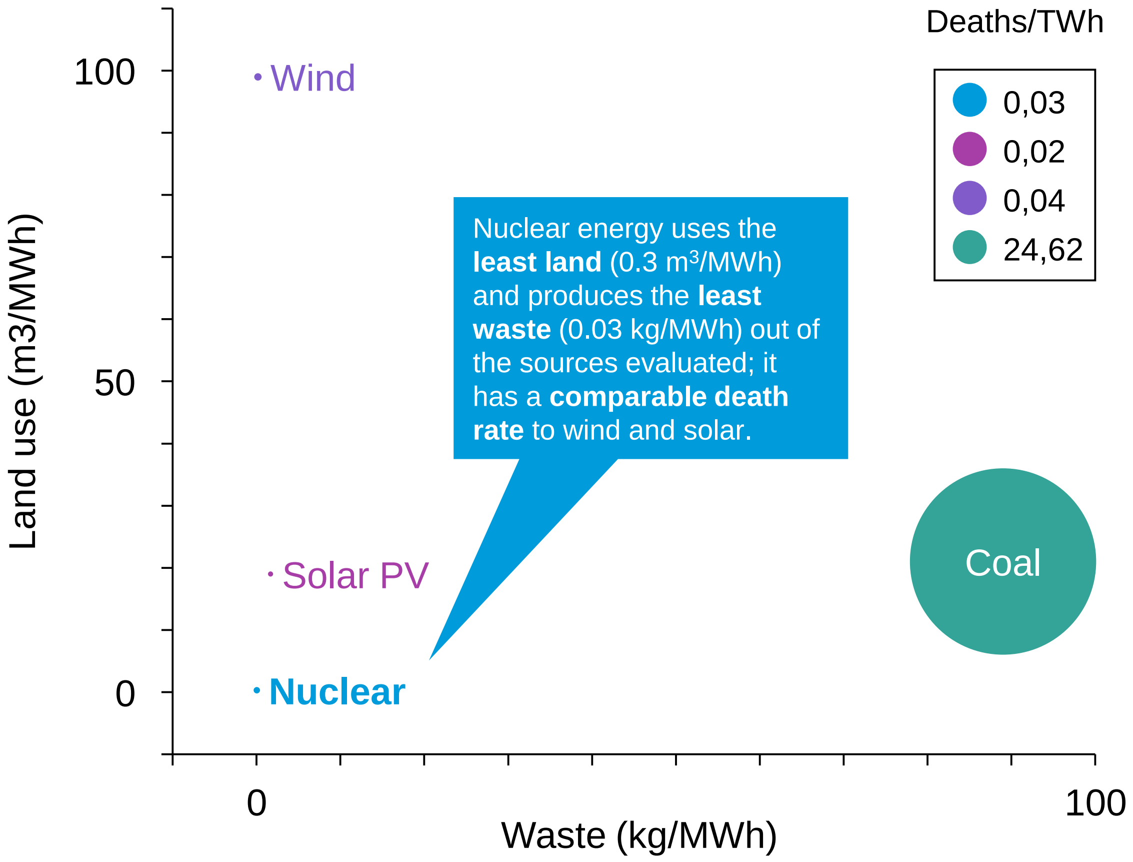
- Extending the lifetime of all nuclear plants by 10 years generates an additional ~30,000 TWh

Global nuclear capacity is set to double if all announced and initiated plants materialize; China is responsible for ~30% of all new plants.

Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

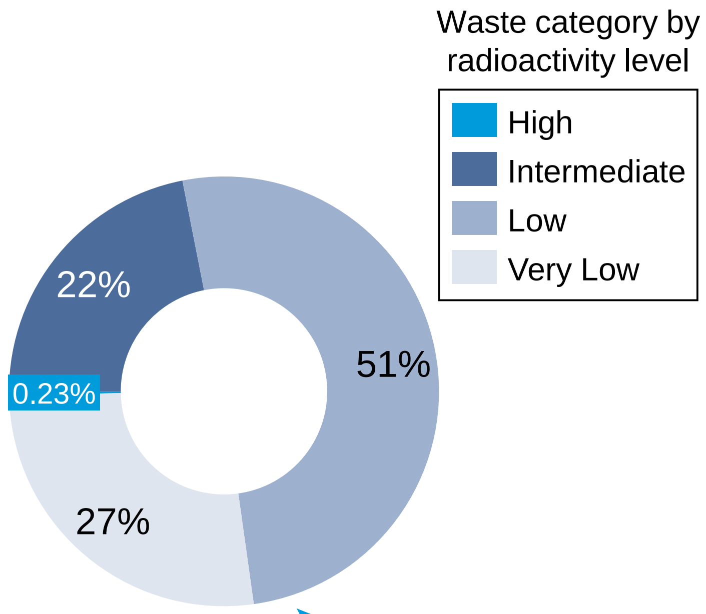
Properly managed, nuclear energy is as safe and low waste as renewables and more land efficient

Waste[1], land use, and death rates by energy source[2], 2023



Nuclear energy uses the **least land** (0.3 m³/MWh) and produces the **least waste** (0.03 kg/MWh) out of the sources evaluated; it has a **comparable death rate** to wind and solar.

Radioactivity of nuclear waste, 2023



High radioactive-level nuclear waste includes used fuel and has 95% of radioactivity but makes up only ~0.2% of total nuclear waste.

Observations

- Very low and low radioactive-level waste types are **78% of total nuclear waste** by volume and have a **radioactivity of <1%.**
- Nuclear is the only energy source that fully accounts for all its waste throughout its entire lifecycle, with **producers paying for nuclear waste disposal,** which is about 10% of total costs.[3]
- Fossil fuel operators typically do not internalize the full environmental costs of CO_2 emissions, pollution, and methane leaks, making the energy source appear artificially cheaper.
- Solar panels and wind blades are often landfilled at end of life.

---

[1] Refers to physical material waste, not GHG pollution. [2] See Appendix for further details on waste, land use, and safety comparison. [3] Decommissioning costs as a share of total costs varies by country.

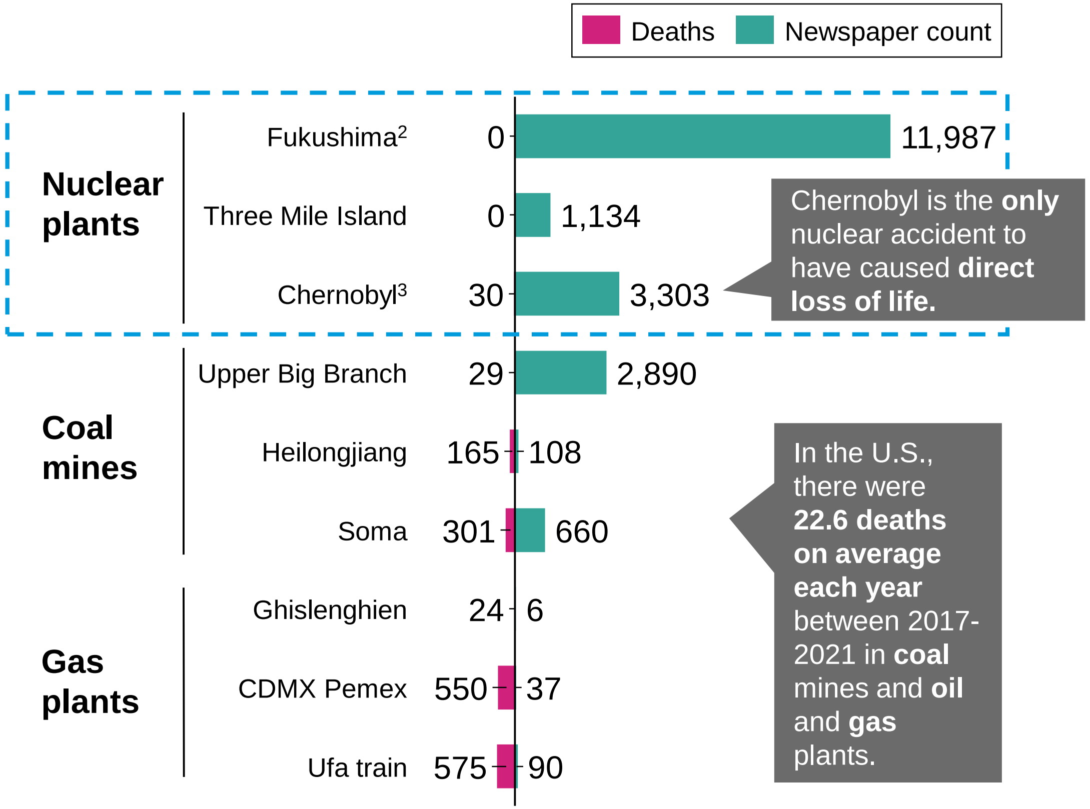
Sources: IAEA, Radioactive Waste Summary (2023); Our World in Data, Death rates per electricity production (2016); Our World in Data, How does the land use of different energy sources compare? (2022); World Nuclear Association, Radioactive Waste Management (2022); World Nuclear Association, Radioactive Waste: Myths and Realities (2025); Sustainability by Numbers, How much waste do solar panels and wind turbines produce? (2023).

Credit: Clara Zibell, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Columbia Business School
Climate Knowledge Initiative

Disproportionate media coverage of nuclear accidents influences public opinion and policy at the expense of nuclear deployment

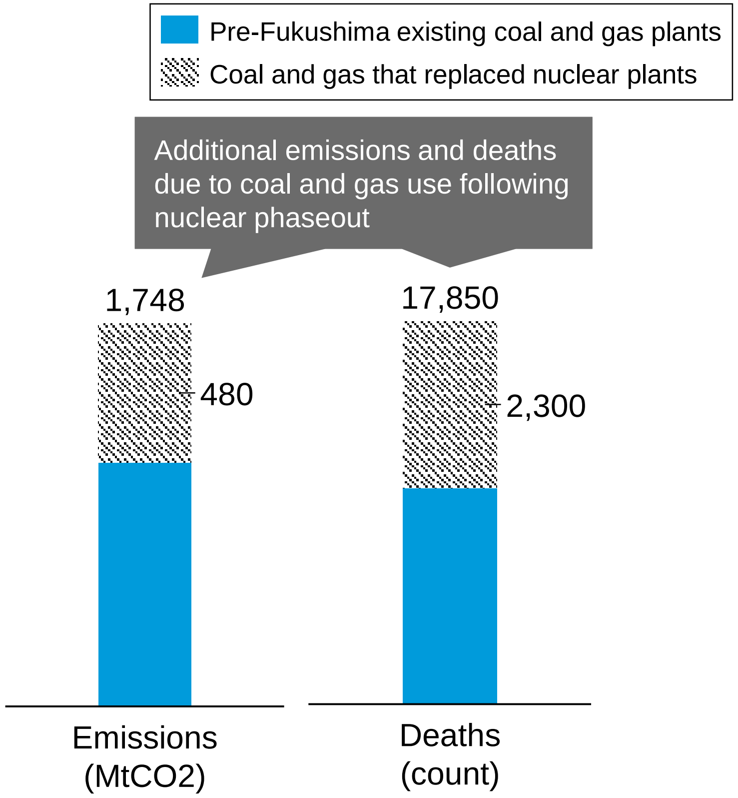
Direct deaths vs. newspaper coverage 30 days post deadliest power plant accidents,[1] 1980-2018



Chernobyl is the **only** nuclear accident to have caused **direct loss of life.**

In the U.S., there were **22.6 deaths on average each year** between 2017-2021 in **coal** mines and **oil** and **gas** plants.

Total emissions and pollution-induced deaths following Japan's nuclear phaseout, 2011-2017



Additional emissions and deaths due to coal and gas use following nuclear phaseout

Observations

- **Gas and coal** replaced lost nuclear following Japan's 2011 Fukushima accident, **adding 480 $MtCO_2$** cumulative emissions and an estimated **2,300 air pollution-induced deaths** in the country (through 2017).
- A 20-point **perception gap** leads people to believe general support for nuclear is lower than it really is: 56% perceived vs. 78% actual support.
- **Safety is at the forefront of new reactors;** a defense-in-depth approach layers backup systems to prevent or contain accidents at every stage.
- **Lack of a containment structure at Chernobyl** resulted in 30 immediate deaths and thousands more long term.

---

[1] Includes only direct deaths. [2] >2,300 disaster-related deaths from post-evacuation stress, in addition to ~19,500 who died in earthquake and tsunami. [3] Controversy exists regarding total deaths from Chernobyl; an additional 19 non-direct radiation exposure deaths occurred between 1984 and 2004.

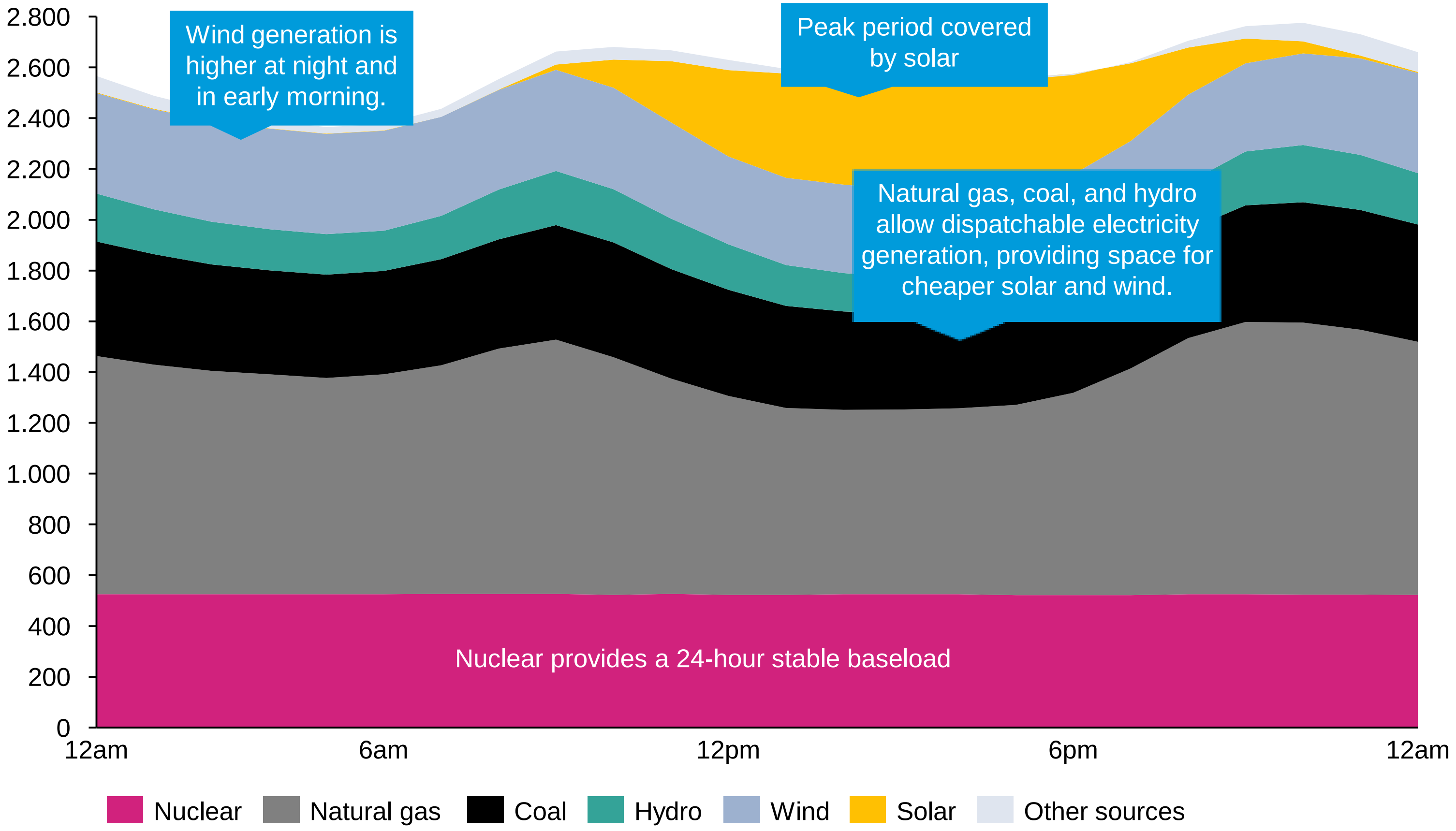
Sources: WNA, World Nuclear Performance Report (2024); WNA, Chernobyl Accident 1986 (2025); WNA, Fukushima Daiichi Accident (2024); IEA, Evolution of nuclear power generation by region, 1972-2026 (2024); IAEA, A Pioneer in Nuclear Power (1984); Wang et al., Analysis on accident types of coal mine in global major coal producing countries (2023); Bisconti Research National Nuclear Energy Public Opinion Survey (2023); WNA, Safety of Nuclear Power Reactors (2025); Kharecha et al., Implications of energy and CO2 emission changes in Japan and Germany after the Fukushima accident (2019); NRC, Defense-in-Depth (2020); U.S. Bureau of Labor Stats, Mining fatalities rose 21.8% from 2020 to 2021 (2023).

Credit: Clara Zibell, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Houwink et al., "Nuclear Transition" (23 September 2025).

Columbia Business School
Climate Knowledge Initiative

Nuclear is a proven source of stable baseload power, offering a more cost-competitive and reliable solution than renewables

U.S. hourly electricity generation by source, GWh; Feb. 27–March 4, 2025; ISO NE



Wind generation is higher at night and in early morning.

Peak period covered by solar

Natural gas, coal, and hydro allow dispatchable electricity generation, providing space for cheaper solar and wind.

Nuclear provides a 24-hour stable baseload

Observations

- Nuclear power’s **high-capacity factor ensures a stable and continuous electricity supply and** accommodates fluctuations from renewable sources.
- Standalone solar and wind are cheaper, but **the need for large-scale storage** and grid upgrades raises **their true cost significantly**, setting premium for solar at $162/MWh and wind at $177/MWh, compared with SMR projections of $69-$120/MWh.
- The energy storage requirement to decarbonize with renewables alone is vastly **more expensive and unattainable with today's technology.**
- Upfront nuclear costs are offset by high-capacity factors, grid stability, and long asset life. **This generates a viable alternative to renewables with storage.**
- To replace nuclear as a baseload source, the United States would need **313 GW of new solar and wind** and 992 GWh per day of storage (**~10x increase of current storage capacity**).

Sources: Lazard, LCOE+ (2025); EIA, Hourly Electric Grid Monitor (2025); WNA, Nuclear Power in the USA (2025).

Credit: Christian Sandjaja, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Nuclear comparable to batteries and geothermal in baseload and grid-stability properties; outperforms in capacity and discharge duration

Nuclear vs. lithium-ion batteries for grid stability

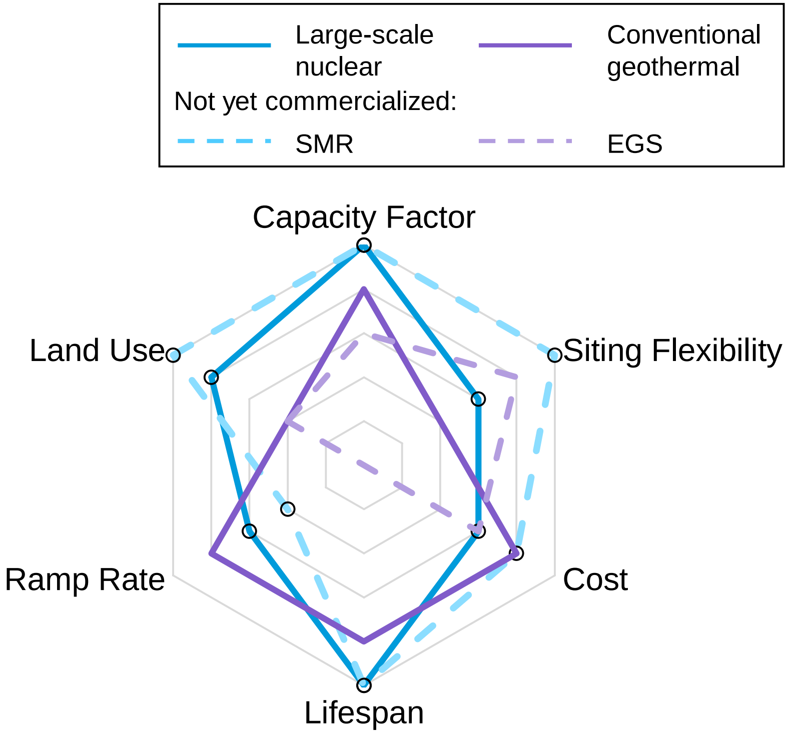
Performance

Low | Moderate | High

	Large-scale nuclear plus storage	SMRs	Li-ion battery
Discharge duration	24/7	24/7	2-10 hours
Capacity	1,000 MWe+ (CF: 90%)	Up to 300 MWe (CF: 70-90%)	100+ MW (utility scale) (CF: up to 20%)
Ramp rate	Up to 12%/min	Up to 10%/min	Instantaneous
Lifespan	40+ years	40-80 years (estimated)	10-15 years
LCOE/LCOS	High uncertainty (Pilot/demo stage)	$50-$120/MWh (uncertain)	$44-$131/MWh (Wind/solar plus storage)
Load following	Medium	Medium-High	High

Coupling nuclear with thermal storage enhances maneuverability and allows for quicker response to fluctuating demand; standalone nuclear load following is not economically efficient though currently employed in France.

Nuclear vs. geothermal for baseload energy



Observations

- SMRs with superior ramping capabilities can provide **longer duration energy support** for intermittency than batteries.
- **Staggering SMRs could surpass the capacity factor of large-scale nuclear** (>90%), although this has not yet been proved.
- Large-scale nuclear and SMRs stand out against geothermal for their **higher capacity, longer lifespan, and lower land-use intensity.**
- In the United States, large-scale nuclear plants typically provide baseload power, but France’s nuclear fleet is designed to meet grid demand (load following). **New reactor designs improve ramp rates:**
  - EPR: +/- 5% of total power per minute between 60% and 100% of total reactor power.
  - AP1000: +/- 10% step load changes between 25% and 100% of full power.

[1] Points at the extremities of the radar chart show the most desirable features (5=most desirable). See Appendix for reasoning behind scale.

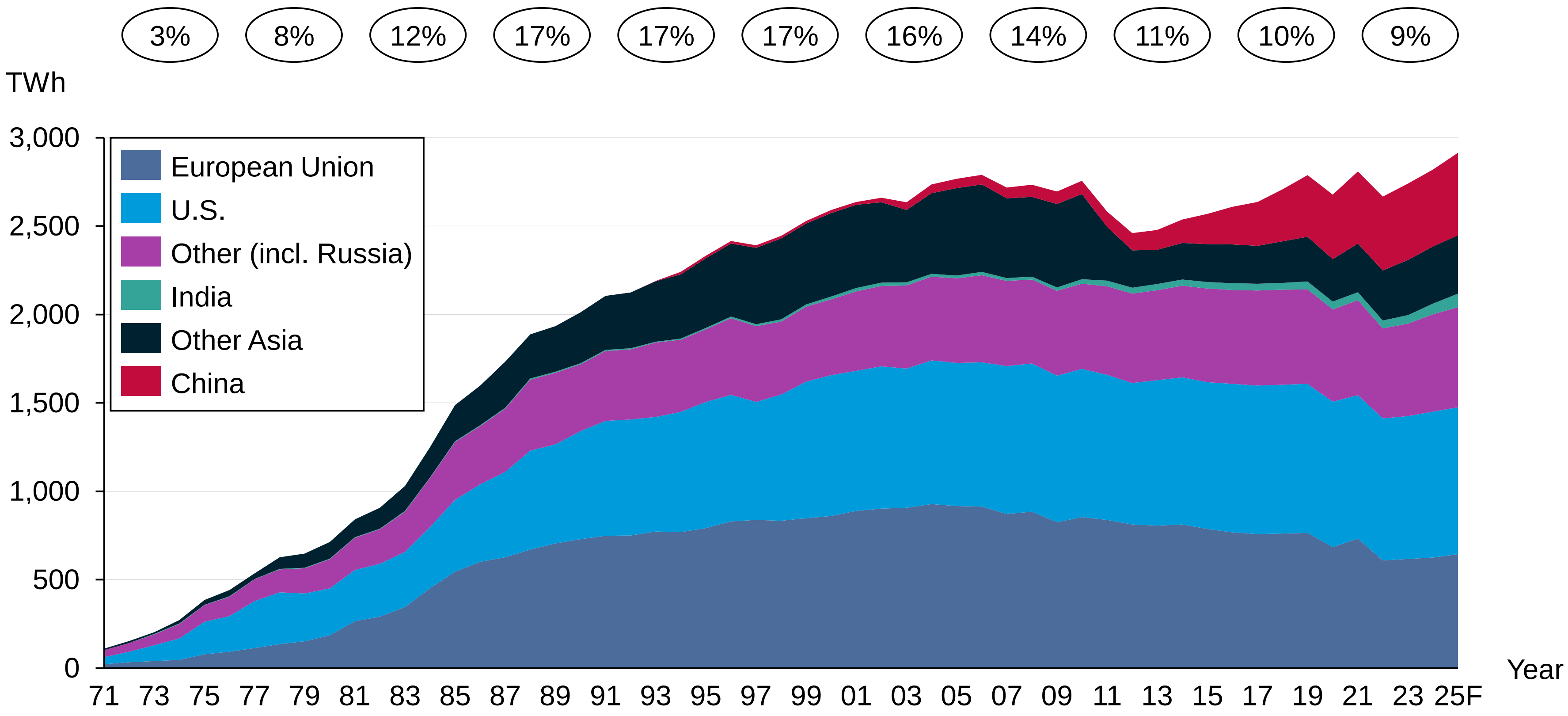
Sources: Lazard, LCOE+ (2025); NREL, Annual Technology Baseline: Batteries (2024); DOE, Grid Energy Storage Technology Cost and Performance Assessment (2022); IAEA, Non-Baseload Operation in Nuclear Power Plants (2023); IAEA, What are SMRs (2023); DOE, Benefits of SMRs (2025); EIA Nuclear FAQ (2025); Feutry et al. Nuclear Power Plant Flexibility at EDF (2019); NREL, Annual Technology Baseline: Nuclear (2024); Detering, Nuclear is a Dispatchable Energy Source (2023); Lovering et al., Land Use Intensity of Electricity Production (2022); IEA, The Future of Geothermal Energy (2024); DOE, What is generation capacity (2025); SLB, Beyond Levelized cost: What’s the true value of geothermal energy? (2024).

Credit: Clara Zibell, Khande-Jaé Fisher, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Nuclear energy has decreased from its peak of 17% of global power to 9% today as supply moves from the West to APAC

Nuclear power generation, 1971-2025, TWh

x% **Fraction of global power demand**, %



Observations

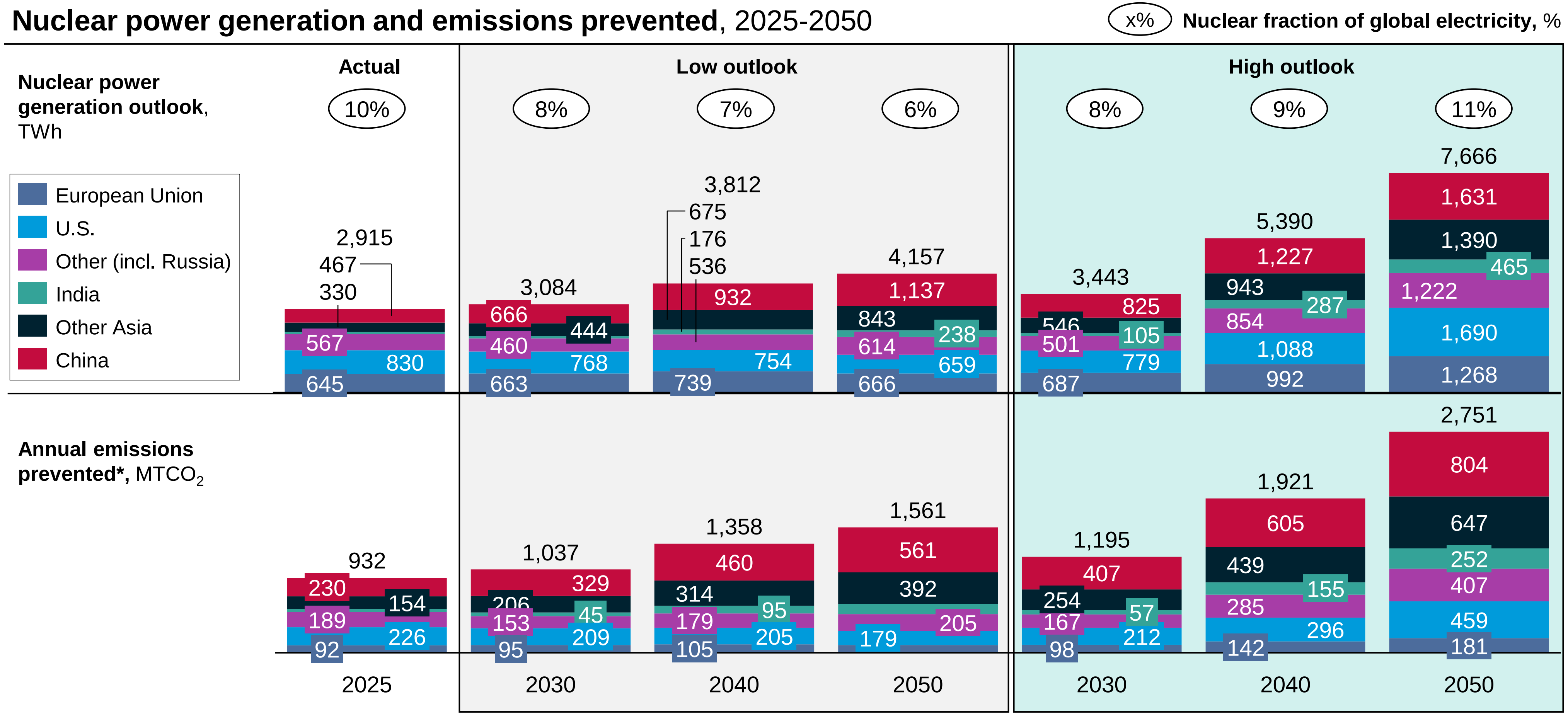
- Very early after the first power plant was connected to the grid in 1954, **nuclear power became a significant fraction of global power generation, producing 10% to 20% of the total.**
- Where growth was driven by Europe and the United States during the first 30 years, **China and India have been responsible for the most growth in nuclear over the past 20 years.**
- **Despite having historic nuclear power production in 2025 at 2,915 TWh,** the share of nuclear is decreasing due to the exponential growth in global power demand**.**

Sources: WNA, World Nuclear Performance Report (2024); IEA, Evolution of nuclear power generation by region, 1972-2026 (2024); IAEA, A Pioneer in Nuclear Power (1984).

Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Nuclear projected to generate 6-11% of global electricity by 2050 and prevent 1 to 3 GT CO_2 annually until 2050

Nuclear power generation and emissions prevented, 2025-2050



Observations

- **Current nuclear power production is expected to grow 1.5x to 3x until 2050** depending on the scenario.
- **Growth will be driven by the United States and emerging economies**, which will be responsible for over half of nuclear power by 2050.
- Emissions prevented increase with nuclear power. **The true impact decreases as grids decarbonize in other ways.**

(*) Assumes average grid carbon intensity per region in 2024. As the average includes nuclear, the actual emissions prevented will be slightly higher until 2030 and lower after 2030 as renewables grow.
Sources: IAEA, Climate Change and Nuclear Power (2022); Enerdata, Total electricity generation (2024); IAEA, Energy, Electricity and Nuclear Power Estimates for the Period up to 2050 (2024); Eneroutlook, CO2 intensity of electricity generation (2022).
Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Columbia Business School
Climate Knowledge Initiative

Life extension is most economically favorable option; new smaller reactors are costlier yet safer and less wasteful

	Pathway	Life extension	New large reactors	New smaller reactors		Fusion
Technology	**Type**	**Water reactors**	**Mostly water reactors**	**Water reactors**	**Gas, liquid metal, molten salt reactors**	**MCF or ICF**
	TRL	9	Varies	3-8	Most 2-3	3-4
	Size	> 1,000 MW	> 1,000 MW	XMR (<50 MW) | Small (< ~400 MW)	XMR (<50 MW) | Small (< ~400 MW)	< 500 MW
	Construction or deployment time	Immediate	10-12 years	3-5 years	3-5 years	Earliest by mid-2030s
	Potential application	Grid services	Grid services	Grid services, district heating, mining, desalination, data centers	Grid services, hydrogen, hard-to-abate industries, data centers	Grid services
	Financing	Mostly public funding, some commercial debt	Mostly public funding	Mostly public-private partnership, but MAG-7 and private offtakers increasing	Mostly public-private partnership, but MAG-7 and private offtakers increasing	Public funding and VC, MAG-7 and private offtakers
Policies and regulation	**Waste management**	Conventional	Varies	Less waste	Less waste, reprocessing, extended use	Minimal waste
	Safety	Active	Active or passive	Mainly passive	Mainly passive	Naturally the safest
	Proliferation	LEU < ~5%	Mainly LEU	LEU < ~5%	20% > HALEU > 5%	Almost free
	Supply chain	Mature for fuel but challenging to replace outdated hardware	Mature for water reactors	Mature for fuel but less for hardware of novelty of designs	Immature for fuel and hardware	Highly immature
Economic viability	**Initial cost****	450-950 USD/kWe for 10-20 years of extension	1,800-4,300 USD/kWe, but 1-5x cost overruns	~ 4,000 USD/kWe, highly uncertain (HU)	6,000-7,000 USD/kWe, HU	4,000-8,000 USD/kWe, HU
	LCOE	$30-$40/MWh*	$138-$222/MWh	$50-$120/MWh, HU	$50-$120/MWh, HU	$20-$100/MWh, HU

Less favorable

More favorable

(*) Based on a 20-year extension and 7% real discount rate. (**) Extending life and build of large reactors for 2020, smaller reactors from 2019, fusion from 2023.

Sources: IEA, Nuclear Power and Secure Energy Transitions (2022); IAEA, Climate Change and Nuclear Power (2020, 2024); Fusion Industry Association, The global fusion industry (2024); Lazard, LCOE (2025); NUCNET, Nuclear Fusion (2021); IES, Literature Review of Advanced Reactor Cost Estimates (2020); IEA, Projected costs of generating electricity (2020); IEA, The path to a new era for nuclear energy (2025); Smoliski et al., From conception to technological implementation – SMR's technology readiness levels (2025).

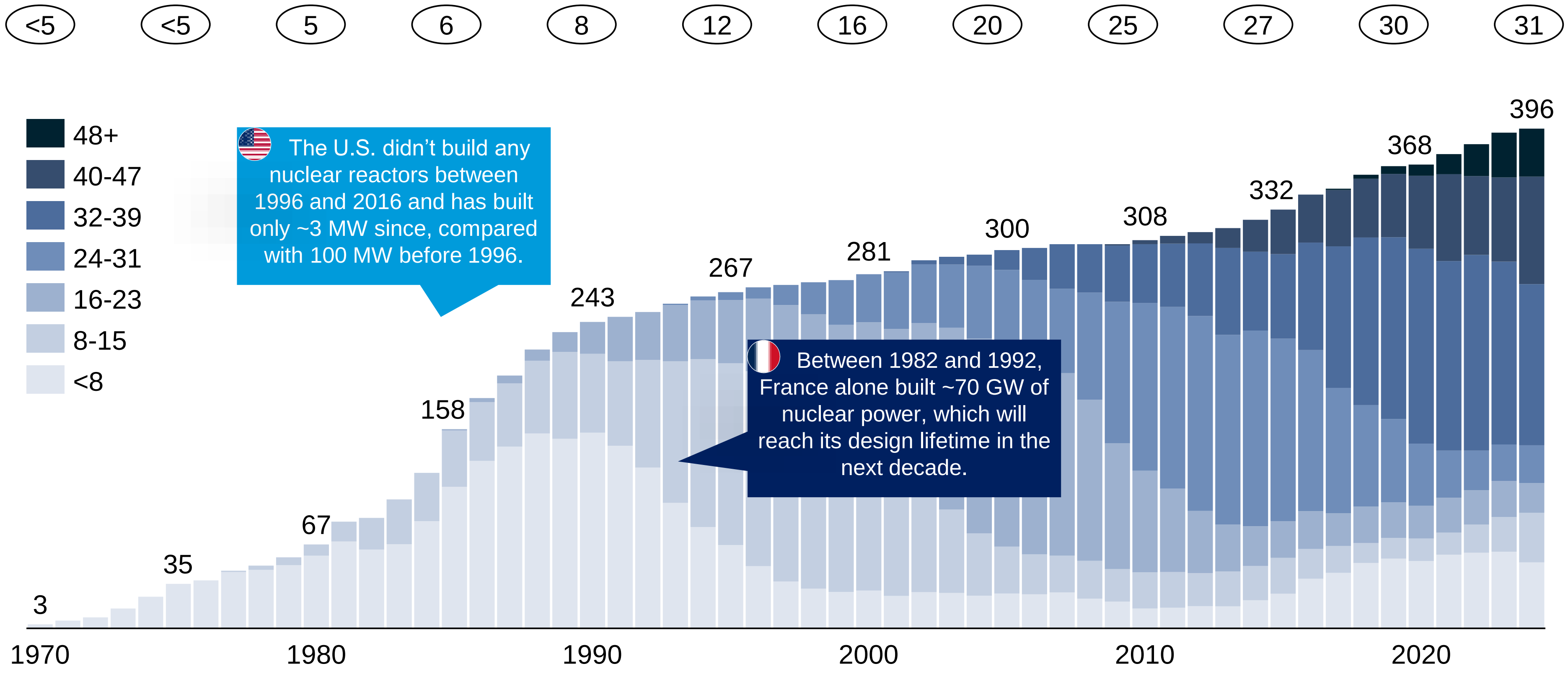
Credit: Brenda Rain, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Columbia Business School
Climate Knowledge Initiative

The average age of nuclear power plants doubled since 2000 to 31 years, indicating the need to extend their lifetime beyond 40 years

Nuclear plant capacity by age of reactor, GW, 1970-2024

xx **Average age of nuclear plant,** years in operation



The U.S. didn't build any nuclear reactors between 1996 and 2016 and has built only ~3 MW since, compared with 100 MW before 1996.

Between 1982 and 1992, France alone built ~70 GW of nuclear power, which will reach its design lifetime in the next decade.

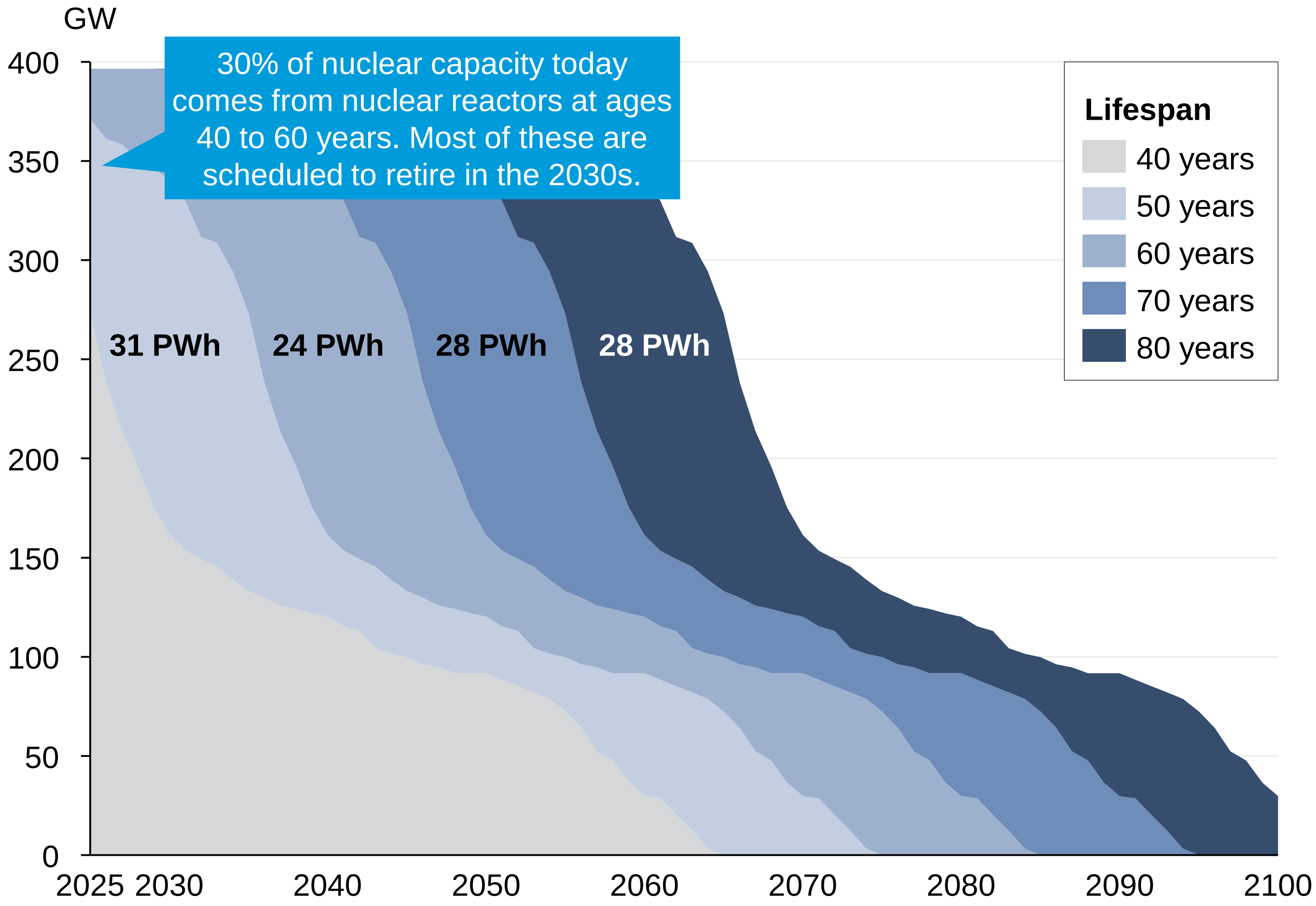
Observations

- **Global capacity of operational nuclear plants grew rapidly to 243 MW in 1990,** which then gradually grew to 396 MW today.
- **Between 2000 and 2010, few new plants were constructed**, leading to a rapid increase in average age that corresponded to the number of years passed (+9 years in 10 years' time).
- **Since 2010**, new plants have become operational, **stabilizing the increase in average plant age.**
- **With >250 MW capacity at >24 years of age, extending plants' lifetime is extremely promising.**

Sources: WNA, World Nuclear Performance Report (2024); Global Energy Monitor, Global Nuclear Power Tracker (2024).
Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Columbia Business School
Climate Knowledge Initiative

Extending the lifetime of all nuclear plants by 10 years adds ~30,000 TWh and saves ~950 $MtCO_2e$ but comes with uncertainty



30% of nuclear capacity today comes from nuclear reactors at ages 40 to 60 years. Most of these are scheduled to retire in the 2030s.

Observations

- The 130 GW nuclear capacity coming from **nuclear plants at ages over 40 years prove the feasibility of extending lifetimes, although this is uncharted terrain.**
- **Extending plants' lifetime is cheap and believed to be safe.**
- **An extension of just 10 years of all existing nuclear power generates ~31,000 TWh, which saves 950 $MTCO_2e$*.**
- This is equivalent to ~2% of annual emissions today. **Extending nuclear reactors can thus abate 0.2% of global emissions.**

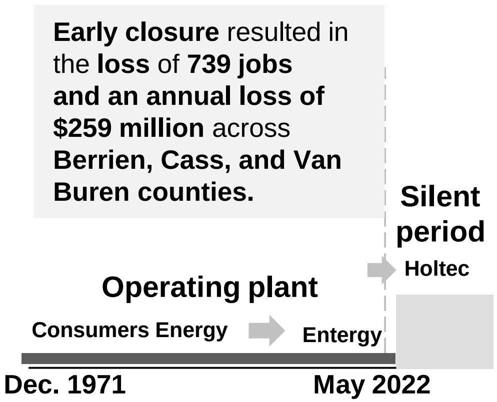
Case study: Bruce Power

- In 2015, Bruce Power agreed to invest in refurbishing and extending the lifetime of its nuclear fleet until 2066.
- This meant increasing the lifespan for 2 GW power from 40 years to 80 years.
- Bruce Power thereby reduces a total of 73 $MTCO_2e$.

(*) Assumes 2025 carbon intensity of grids respective to global distribution of nuclear power today. (**) Assumes Canada's carbon grid intensity in 2022 (100 g CO_2e/kWh).
Sources: IAEA, Climate Change and Nuclear Power (2020); Global Energy Monitor, Global Nuclear Power Tracker (2024); WNA, Global Nuclear Industry Performance (2024); Bruce Power, Life-Extension Program & MCR Project (2023); CEC, Provincial and Territorial Energy Profiles – Canada (2022).
Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Palisades restart driven by state-level support for nuclear and workforce advances, but technical and regulatory barriers remain

Palisades project's milestones (2023-2025)



Early closure resulted in the **loss** of **739 jobs and an annual loss of $259 million** across **Berrien, Cass, and Van Buren counties.**

2023

June
- Submitted application to DOE's LPO for federal funding
- Received approval of federal loan to be delivered in 2024 ($150M)

Sept.
- Signed multi-decade PPA with nonprofit rural cooperative (Wolverine)

Oct.
- Filed submission to NRC to reauthorize plant operation

2024

March
- Received conditional commitment of $1.52B loan guarantee of LPO to support the plant's resumption

Aug.
- Upgraded heat exchanger (cooling system)
- 26 former Palisades operators completed their requalification, ensuring human capital is available by 2026
- Started initial training accreditation

Sept.
- Holtec closed $1.52B DOE loan to restart Palisades; in March 2025, it is reconfirmed
- Received $1.3B of support from USDA to help regional cooperatives with the PPA

2025

Feb.
- NRC draft Environmental Assessment completed; didn't find significant impact from resumed power operations

April
- Received full accreditation for its Operation Training Program from NNAB

May
- Received accreditation for its Maintenance and Technical Training Program

June
- Successfully completed emergency preparedness exercises
- Completed startup readiness assessment to ensure highest safety and operation procedures are implemented

Aug.
- Waiting for response about regulatory submittals

September; expected operation by last quarter of 2025

Project details

- **Capacity:** 805 MW
- **Location:** Michigan
- **Technology:** PWR
- **Extension period:** ~26 years (2051)
- **Owner:** Holtec, previously Entergy
- **Other considerations:** Plans to include two additional SMRs; 300MW to benefit from site permits and skilled workforce

Tailwinds

- **State's climate commitment in Public Act 235:** 80% of energy must come from carbon-free sources by 2035.
- **Market and political momentum:** Two executive orders approved in January 2025 (14154, 14156) favor nuclear financial outlook.
- **Regulatory support structures:** NRC has established a dedicated panel to guide the restarting.

Headwinds

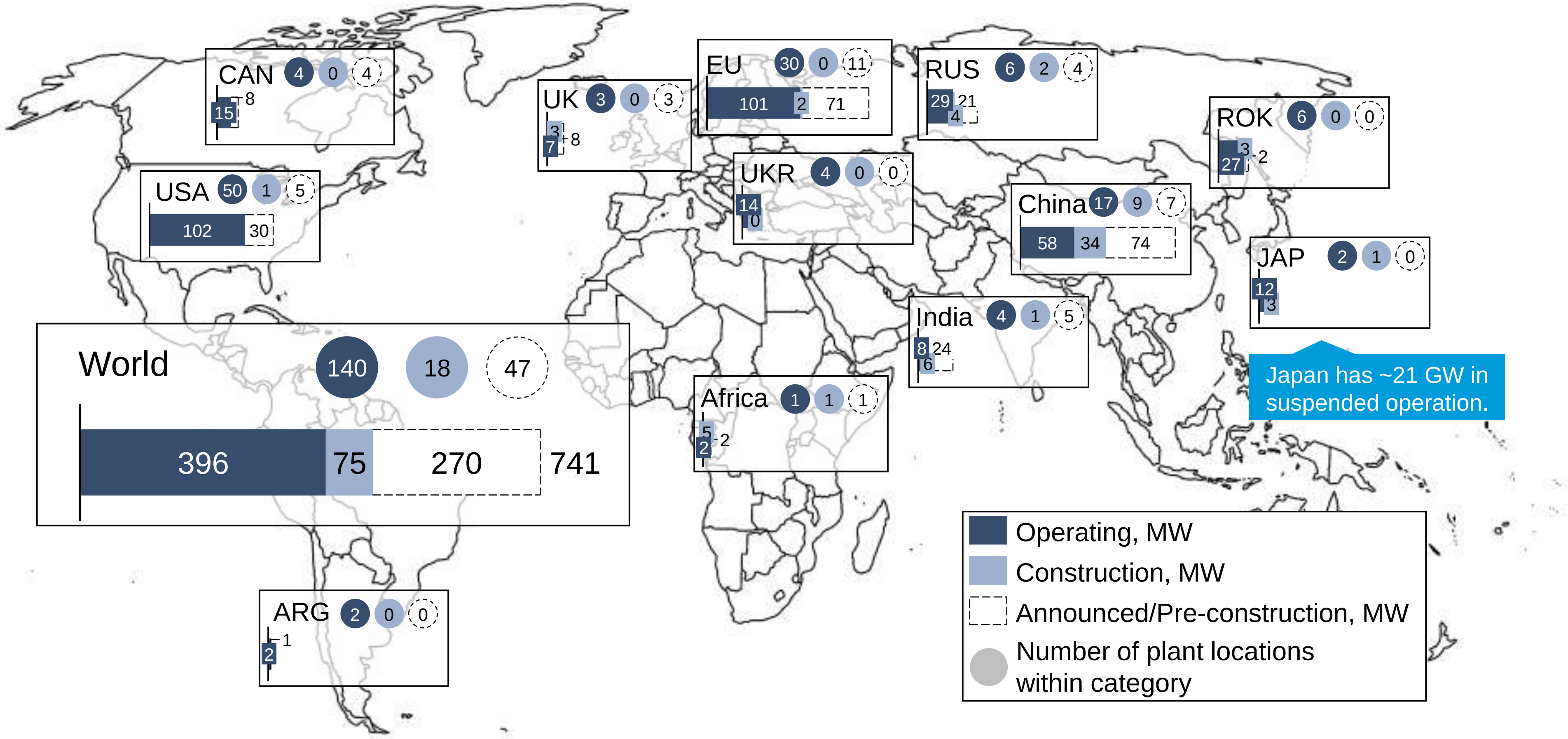
- **Aging infrastructure and repairs raise safety concerns:** Adequate performance of steam generation tubes and control-road seal issues requires a more thorough analysis to ensure the required performance.
- **Regulatory hurdles:** NRC moved the estimated completion from July 31 to September 30, **increasing completion risk.**

Sources: Holtec, Holtec and Wolverine ink historic PPA (2023); Holtec, Palisades restart program – now in the inspections and maintenance phase (2024); Holtec, Palisades cooling system upgraded (2024); Holtec, Historic repowering of Michigan's Palisades, Holtec obtains up to 1.52B in conditional loan commitment from the DOE (2024); Holtec, Holtec closes $1.52B DOE loan to restart Palisades (2024); DSIRE, NC Clean Energy technology center, Renewable Energy standard (2024).

Credit: Brenda Rain, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Global nuclear capacity set to double if all announced and initiated plants materialize; China responsible for ~30% of new plants

Global distribution of nuclear capacity, GW and plant count, 2024



Japan has ~21 GW in suspended operation.

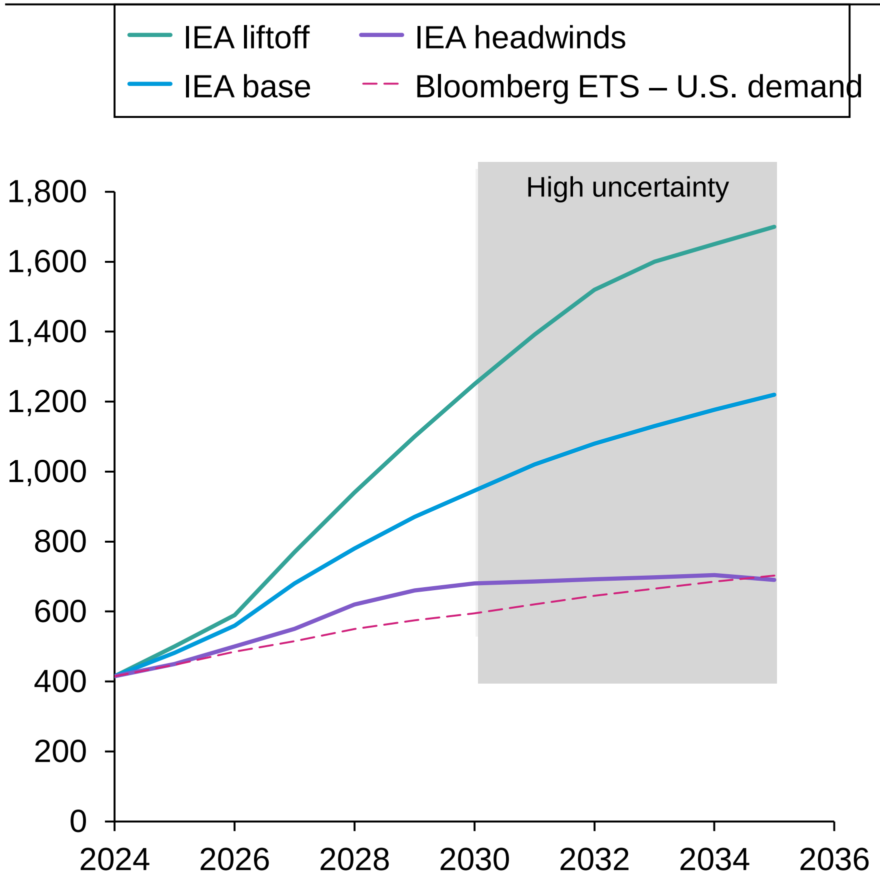
Observations

- Global nuclear capacity today is **396 GW**, with an additional **75 GW** under construction and **270 GW** in pre-construction or announced.
- Today, most of the capacity is in the **United States and Europe, representing ~50% of all reactors.**
- However, **China is leading by far in the number of nuclear plants being built,** representing nearly half of all plants under construction.
- **Europe has announced 71 new plants,** nearly equaling China's 74 planned plants.
- Typical development time for a plant in China is five to eight years vs. eight to 12 years in Europe, India, and the U.S.

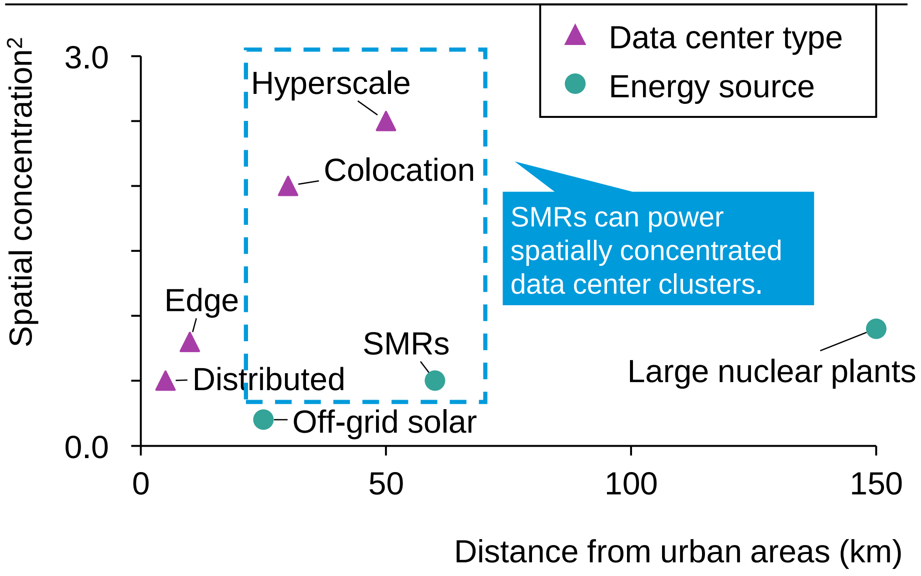
Sources: Global Energy Monitor, Global Nuclear Power Tracker (2024); IEA, The Path to a New Era for Nuclear Energy (2025); IEA, Nuclear Power and Secure Energy Transitions (2022).
Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Off-grid SMRs are a mid- to long-term solution for increased energy demand from hyperscale and colocation data centers

Projected global data center energy demand[1] (TWh)



Urban proximity and spatial concentration[2]



SMRs can power spatially concentrated data center clusters.

Data center types

	Training AI	Inference AI
Hyperscale	Primary	Common
Colocation	Limited	Common
Edge	Not suitable	Primary
Distributed	Not suitable	Primary

Observations

- Long timelines for transmission connection, gas turbines (more than seven years), and power supply stress the need for **off-grid solutions.**
- **Off-grid solar is a strong option for training-only data centers,** when uptime requirements are slightly relaxed.
- The **small size and modularity of SMRs** allow these to be sited closer to data centers. This is ideal for **inference AI** workloads, which have **low-latency and high-redundancy** requirements.
- The data center construction timeline is up to seven years in the United States. SMR technology is expected to be deployed after 2030.

---

[1] IEA Scenarios are based on projected AI uptake, energy sector bottlenecks, and efficiency improvements. [2] Spatial concentration = electrical output/land area used.

Sources: IEA, Energy and AI (2025); IEA, Electricity (2025); Baranko et al., Fast, scalable, clean, and cheap enough (2024); Ember, Global Electricity Review (2025); BNEF, How AI Influences US Data Center Power Demand (2025); Gartner, Power Shortages Will Restrict 40% of AI Data Centers by 2027 (2024); Last Energy, On-Site Nuclear Power (2023).

Credit: Clara Zibell, Khande-Jaé Fisher, Isabel Hoyos, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Columbia Business School
Climate Knowledge Initiative

Technological Developments

Key messages
Technological Developments

Reactors are similar in their mechanics, although they use different coolants; small modular reactors (SMRs) simplify the existing design.

There are four main types of coolant: water, gas, metal, and molten salt.

- **Pressurized water reactors (PWR) are most common,** but they are complex due to the high pressure needed to keep the water liquid.
- **Boiling water reactors (BWR) are simpler than PWR,** and therefore modern reactors are typically BWR; however, they do have to deal with radioactive steam.
- **Gas-cooled reactors have higher thermal efficiency** but need specialized materials.
- **Liquid metal reactors have high thermal efficiency** but also have chemically reactive materials that could cause explosions when leaks occur.
- **Molten salt reactors (MSR) have higher thermal efficiency** and fuel cycle flexibility but need special tubing to deal with corrosion.

Water-cooled reactors have evolved significantly over four generations to become safer, standardized, more efficient, and more modular.

Nuclear-produced “pink” hydrogen offers an emission-free, cost-competitive, and subsidized option, but scaling remains a challenge.

Credit: Vedant Bhansali, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Emerging SMR technology is small and flexible, providing an off-grid and off-site solution for nuclear power

Desirability

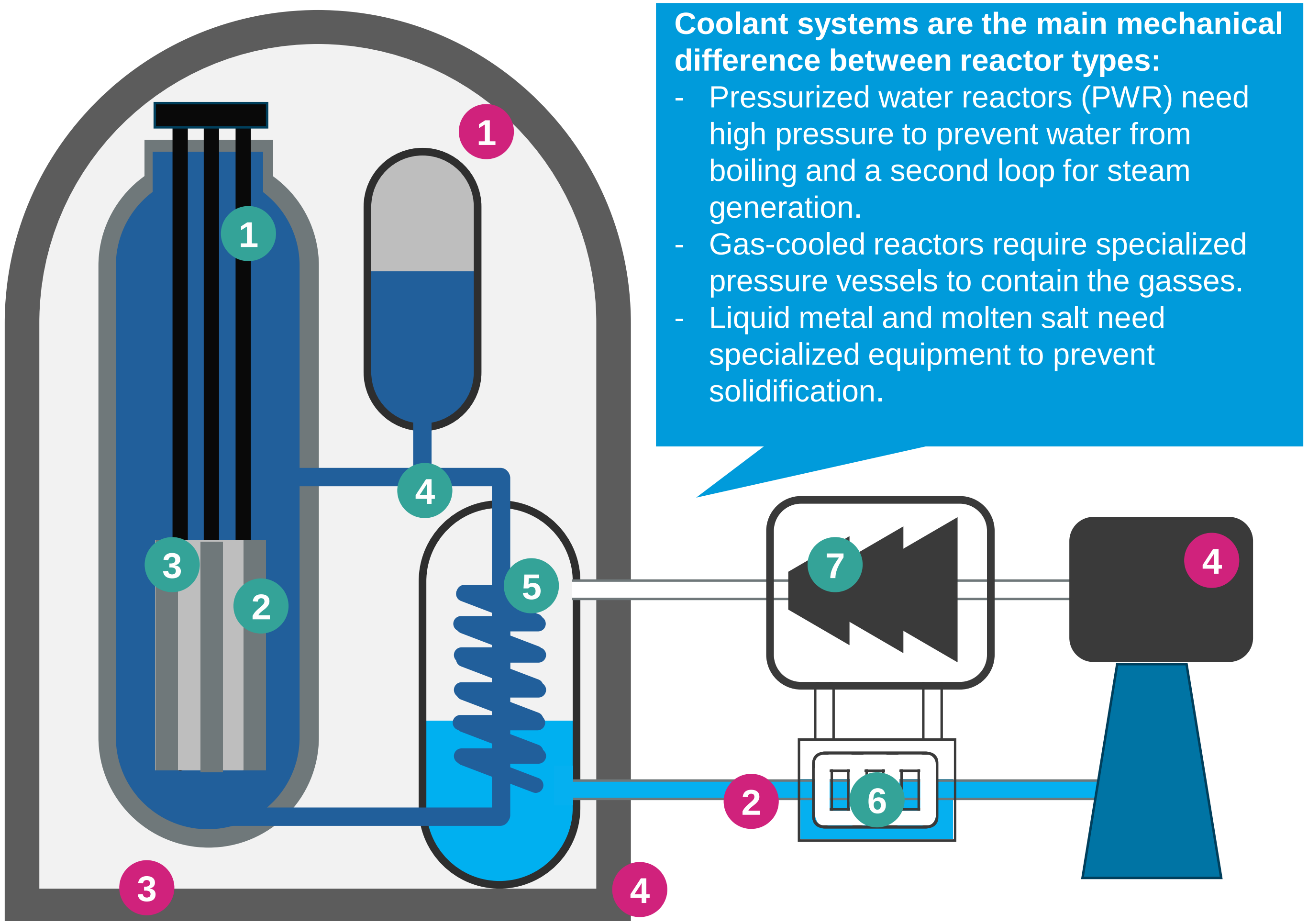
🟩 *High*	🟨 *Medium*	🟥 *Low*

	Description	Large-size nuclear power plants	Small modular reactors
Technical specifications	Electrical capacity (MWe/unit)	🟨 >1,000	🟨 Up to 300
	Fuel	🟨 Typically light water reactors	🟩 May use various coolants and fuel types
	Refueling frequency	🟥 Every 1-2 years	🟩 Every 3-7 years, even up to 30 years
	Safety features	🟥 Active systems (operator or power dependent)	🟩 Passive systems (self-shutdown)
	Land area requirement (square miles)	🟥 1.3	🟩 0.01
	Construction approach	🟥 Custom built on-site	🟩 Factory fabricated and shipped to sites for modular assembly
	Siting flexibility	🟥 Low; large dedicated sites required	🟩 High; suitable for remote, urban, and industrial areas
Economics	Construction time	🟥 10 years, often with overruns	🟩 3-5 years
	Cost to build ($)	🟥 10B-15B	🟩 2B-4B
	Cost structure	🟨 Economies of scale; high upfront investment with high financial risk	🟨 Economies of series; lower initial capital, but costs per MW may initially be high
	LCOE ($/MWh)	🟥 140-220	🟩 50-120 (uncertain)
Operations	Use case	🟨 Baseload power for national grids	🟨 Flexible: remote/off-grid
	Waste management	🟨 Established waste management protocols in place, but long-term disposal continues to face public and political resistance	🟨 Some studies suggest higher radioactive waste per MWh, though advanced modular reactors may improve waste handling
	Deployment status	🟩 Mature, globally deployed	🟥 First-of-a-kind stage, few operational units; commercial viability yet to be proved
	Supply chain readiness	🟩 Mature, although often highly specialized and slow moving	🟥 Emerging; key components still under development and supplier confidence is needed to scale up
	Standards and regulations	🟩 Established framework	🟥 Adapting existing frameworks and emerging regulatory approaches

Sources: European Commission, Small Modular Reactors Explained (2025); NEI, Nuclear Plant's Footprint (2025); IAEA, What are SMRs? (2023); Statista, Construction Time for Nuclear Reactors Worldwide (2024); Holtec, SMR FAQs (2025); CNBC, GE Vernova Deploying SMRs (2024).

Credit: Adele Teh, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

All reactor types use similar mechanics and different coolants; small modular reactors simplify the existing design



Coolant systems are the main mechanical difference between reactor types:

- Pressurized water reactors (PWR) need high pressure to prevent water from boiling and a second loop for steam generation.
- Gas-cooled reactors require specialized pressure vessels to contain the gasses.
- Liquid metal and molten salt need specialized equipment to prevent solidification.

How a typical reactor works

1. **Fuel rods contain fissile material** (e.g., U-235) where fission reactions occur, generating heat.
2. **Moderator rods slow down fast neutrons from fission events** to increase the probability of further fission.
3. **Control rods control the speed of the reaction** by absorbing excess neutrons.
4. **Pressurizer maintains coolant pressure to prevent boiling (for PWR).**
5. **Heat transfers to secondary water loop**, producing steam.
6. **High-pressure steam flows to spin turbine blades.**
7. **The generator converts mechanical energy into electricity.**

How SMRs are different

1. **Compact, integrated containment structure**
2. **Simplified, passive cooling systems** without external pumps
3. **Factory-fabricated modules** that allow for faster construction and deployment
4. **Modular and built from components** to be factory manufactured and then transported and assembled at the final site

Sources: U.S. DOE, NUCLEAR 101: How Does a Nuclear Reactor Work?, 2023; NEA, The NEA Small Modular Reactor (SMR) Strategy (2025); IN, Advanced Small Modular Reactors (2025).
Credit: Vedant Bhansali, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Columbia Business School
Climate Knowledge Initiative

Water-cooled reactors dominate today's nuclear landscape; advanced coolant types offer efficiency and safety gains

	Pressurized water	Boiling water	Gas cooled	Liquid metal	Molten salt
Description	Water as coolant and moderator; water stays liquid under pressure	Water as coolant and moderator; water boils inside the reactor core	Gas (CO_2 or helium) as coolant	Liquid metals (e.g., sodium, lead) as coolant	Molten fluoride or chloride salts used as coolant and sometimes fuel; includes both liquid-fueled and solid-fueled designs (e.g., Kairos FHR); high thermal efficiency and strong passive safety
Global capacity, GW, 2024	950	200	~30	<1	<1
LCOE*, 2024	$50–$100 per MWh	$50–$100 per MWh	$70–$120	$80–$140	$90–$150
Pros	Most common reactor type globally; proven safety systems; high capacity for grid-scale power	Simpler system than PWRs; direct steam cycle (no steam generator needed); good operational flexibility	High thermal efficiency (~41%); uses diverse fuels; passive safety features (low pressure, high heat tolerance)	Very high thermal efficiency (~40–45%); can "breed" more fuel than consumed; operates at low pressure	Highest thermal efficiency (~45–50%); strong passive safety (negative temp coefficient); fuel cycle flexibility (e.g., thorium)
Cons	High-pressure operation increases system complexity; large infrastructure footprint	Steam is radioactive (direct contact with core); more turbine contamination risk	Needs specialized materials for high temp; higher capital and maintenance costs	Coolants are chemically reactive; material corrosion risks	Corrosion and material compatibility challenges; no standard regulatory path yet
Scalability	H	H	M	M	H
Maturity	H	H	M	M	L

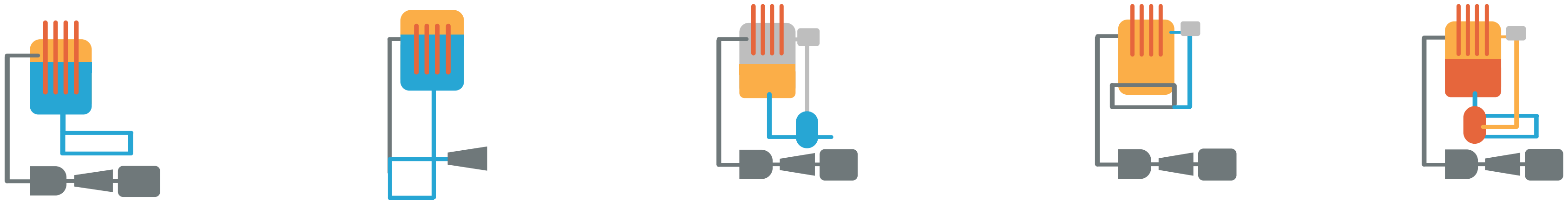
(*) LCOE values are highly uncertain. They depend on assumptions about learning rates, deployment scale, financing costs, and regulatory environment.
Sources: IET, Nuclear Reactor Types (2024); WNA, Nuclear Power Reactors (2025); IAEA, Comparative Evaluation of Nuclear Energy System Options (2023).
Credit: Vedant Bhansali, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

HTGRs, LMRs, and MSRs have higher efficiency, produce less nuclear waste, and have versatile industrial applications

Key metrics comparing different types of nuclear reactors

Performance

Low	Moderate	High



	Water-cooled reactor		High-temperature gas-cooled reactor (HTGR)	Liquid metal reactor (LMR)	Molten salt reactor (MSR)
	Pressurized water reactor (PWR)	Boiled water reactor (BWR)			
Coolant	Pressurized light water	Light water	Helium or CO_2 (remains gas)	Liquid sodium or lead, no moderator	Molten salt with dissolved fissile material
Thermal efficiency	33-37%	33%	~50%	33-43%	45-50%
Safety	Active safety	Active safety	Passive safety	Passive safety	Passive safety, lower risk of explosion
Waste volume	High	Higher than PWR	Low	Low	Low
Operating temperature	About 315°C, high pressure	285°C, medium pressure	750-950°C, low pressure	480-550°C, low pressure	~700°C, low pressure

Sources: Quadrennial Technology Review, Advancing Clean Electric Power Technologies (2015); IAEA, High Temperature Gas Cooled Reactor Fuels and Materials (2010); Idaho National Laboratory, Baseline Concept Description of a Small Modular High Temperature Reactor (2014); Terrestrial Energy, Molten salt reactor technology (2024); IAEA, Molten salt reactors (2024); WNA, Molten salt reactors (2024); Generation IV International Forum, Molten salt reactors (MSR) – Criteria and technologies (2024); Pacific Northwest National Laboratory, Technical report on molten salt reactors (2020); Moltex Energy, Moltex demonstrates reactor's unique capability to consume nuclear waste and close the fuel cycle (2024); WNA, Nuclear Power Reactor Characteristics (2016).

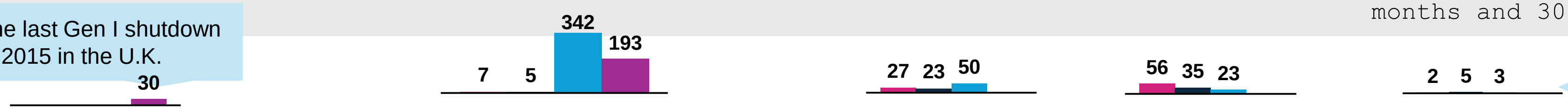
Credit: Hinako Arai, Vedant Bhansali, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Water-cooled reactors have evolved significantly over time to become safer, standardized, more efficient, and more modular

Key differences in reactors by generation

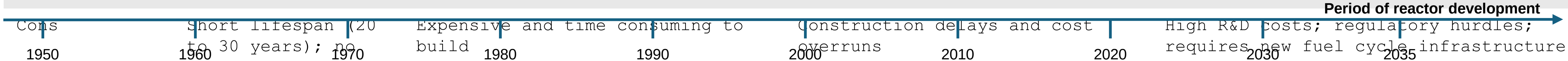
Advanced reactors

	Gen I	Gen II	Gen III	Gen III+	Gen IV
Description	Early reactor protype	Commercial power reactors, usually LWR	Advanced light water reactors		Advanced reactors
Efficiency	30%	33%	39%		45%
Fuel	Low-enriched uranium (LEU) (2-	LEU (3-5%)	LEU (4-5%) and mixed oxide (MOX) fuel		HALEU (>5%), thorium, MOX, recycled fuels, and refueling cycles between 30 months and 30 y
Status of commercial reactors					
Global installed capacity	0 GW	271-348 GW	48 – 125 GW		~0.2 GW
Ratio in US	0%	97.8%	2.2%		0%
Pros	Demonstrated the civil use of nuclear fission	Used for large, commercial-scale power generation; relies on active safety systems; based on a set of design principles; has prolonged lifetime	Improved design and economic; streamlined licensing from standardized designs and mass-produced parts; enhanced safety		Improved safety; reduced waste and OpEx
Cons	Short lifespan (20 to 30 years); no standardized designs; small capacity	Expensive and time consuming to build	Construction delays and cost overruns		High R&D costs; regulatory hurdles; requires new fuel cycle infrastructure



The last Gen I shutdown in 2015 in the U.K.

The first Gen IV reactors started commercial operation in 2023 in China, **highlighting the economic uncertainty about these models.**



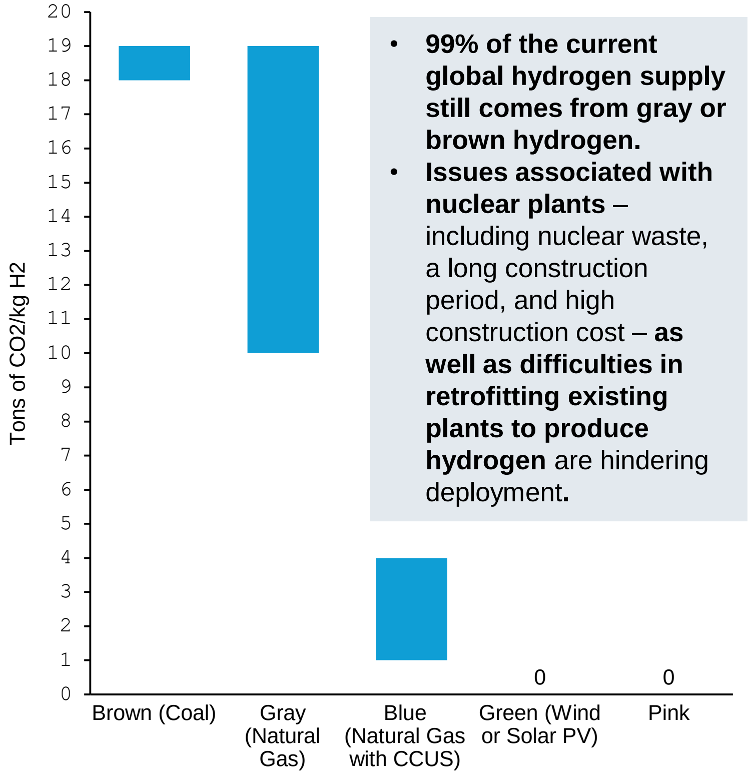
Sources: Global Energy Monitor, Global Nuclear Power Tracker (2024); WNA, Economics of nuclear power (2023); WNA, Advanced Nuclear Power Reactors (2021); Columbia University Center on Global Energy Policy, The Uncertain Costs of New Nuclear Reactors (2023); U.S. DOE, Pathways to Commercial Liftoff: Advanced Nuclear (2023); Cleantech Group, Advanced Nuclear Fission's Role in the Energy Transition (2020); Reuters, China starts up world's first fourth-generation nuclear reactor (2023); Center for Advanced Nuclear Energy Systems, 2024 Total Cost Projection of Next AP1000 (2024); Reinberger et al., The Technological Development of Different Generations and Reactor Concepts (2019).

Credit: Hinako Arai, Vedant Bhansali, Brenda Rain, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Nuclear-produced ‘pink’ hydrogen offers an emission-free, cost-competitive, and subsidized option; scaling remains a challenge

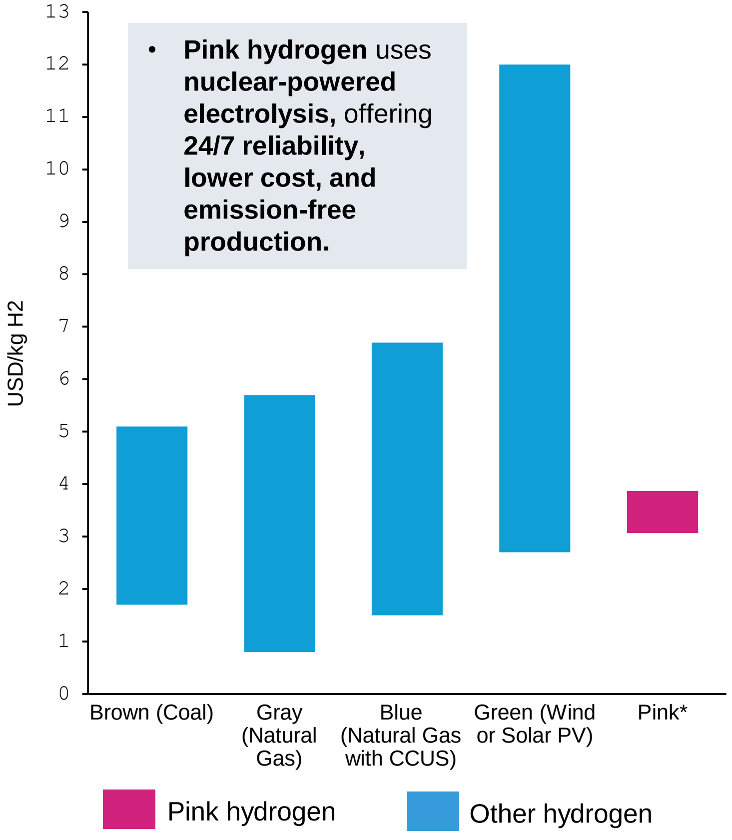
Comparison by types of hydrogen production

Carbon intensity (2024)



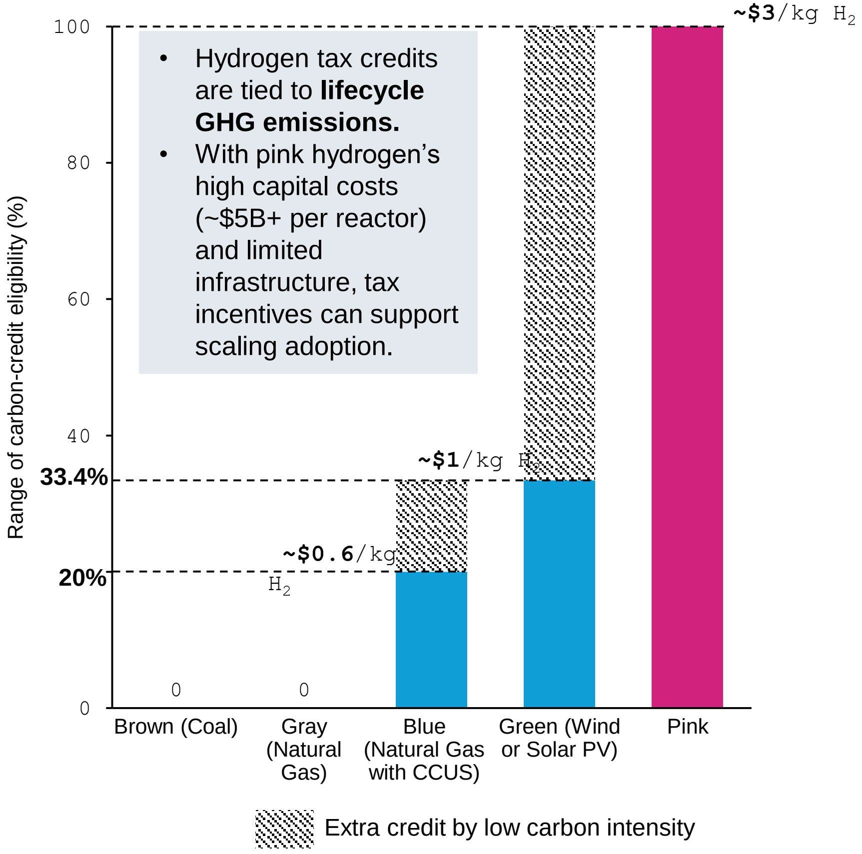
- **99% of the current global hydrogen supply still comes from gray or brown hydrogen.**
- **Issues associated with nuclear plants** – including nuclear waste, a long construction period, and high construction cost – **as well as difficulties in retrofitting existing plants to produce hydrogen** are hindering deployment**.**

Levelized cost of hydrogen (2023)



- **Pink hydrogen** uses **nuclear-powered electrolysis,** offering **24/7 reliability, lower cost, and emission-free production.**

Subsidy under IRA (Section 45V)



- Hydrogen tax credits are tied to **lifecycle GHG emissions.**
- With pink hydrogen’s high capital costs (~$5B+ per reactor) and limited infrastructure, tax incentives can support scaling adoption.

(*) LCOH of pink hydrogen is from Lazard; other LCOH is from IEA.

Sources: National Grid, Hydrogen colour spectrum explained (2023); Hydrogen Insight, Nuclear hydrogen makes a lot of intellectual sense: U.S. energy loans head (2023); Harvard Kennedy School, Belfer Center for Science and International Affairs, The colors of hydrogen (2024); WNA, Hydrogen production and uses (2024); U.S. DOE, Production cost of high-temperature electrolysis (2020); IEA, Global Hydrogen Review 2024 (2024); CTVC, Final Hydrogen Tax Credits Get Greenlight #228 (2025); Lazard, LCOE+ (2024).

Credit: Vedant Bhansali, Quint Houwink, Brenda Rain and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

TerraPower leads in advanced reactors, breaking ground in 2024 for its 345 MW natrium reactor planned for 2030

2006 **TerraPower founded** by Bill Gates to develop **advanced nuclear power**

2010 For its first years, TerraPower focused on a **traveling wave reactor (TWR)**, which has much higher fuel efficiency, theoretically requiring no fuel replacements for its lifetime

2015 Starts a **JV with Chinese CNNC** to build a 600 MW TWR prototype in **China**

2018-19 The U.S. **stops all partnerships** with China on nuclear, **killing the JV**

2020 Pivots to developing a a **natrium reactor** together with **GE Hitachi**

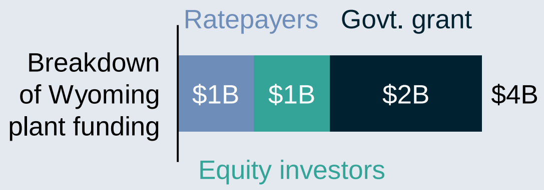
2021 Selects Kemmerer, **Wyoming,** as its **first reactor site**

2024 **TerraPower Isotopes** starts commercial-scale production of actinium, which is used in clinical trials for cancer research

2024 **Breaks ground** in Wyoming for the 345MW, $4 billion FOAK reactor

2030 The Wyoming plant to deliver its first power to the market

TerraPower's approach to funding*



- The $4 billion Wyoming plant is a first of a kind (**FOAK)**, meaning its **costs are higher** than for subsequent reactors.
- Rather than assigning all those costs to ratepayers, **TerraPower charges regular electricity prices** and covers the difference with a $2 billion federal grant and $1 billion equity investment.
- It believes that **investors and the government will benefit** from the **IP gained** in the FOAK.

TerraPower's unique design

- For its design, TerraPower uses the metal **sodium** (Latin name: natrium) **as its coolant.**
- Where **water requires high pressure** to prevent boiling above 100°C, **sodium doesn't boil until 883°C,** ideal for a reactor operating at ~500°C.
- Sodium is **highly reactive with water and oxygen; a leak can cause explosions.** Historically, liquid **metal reactors have been more expensive.**
- TerraPower believes sodium will allow **modular fabrication** and have **non-nuclear systems**, bringing down construction and regulatory costs.
- Beyond its unique cooling system, TerraPower includes **salt heat storage**, which should help the plant **react to power demand peaks.**

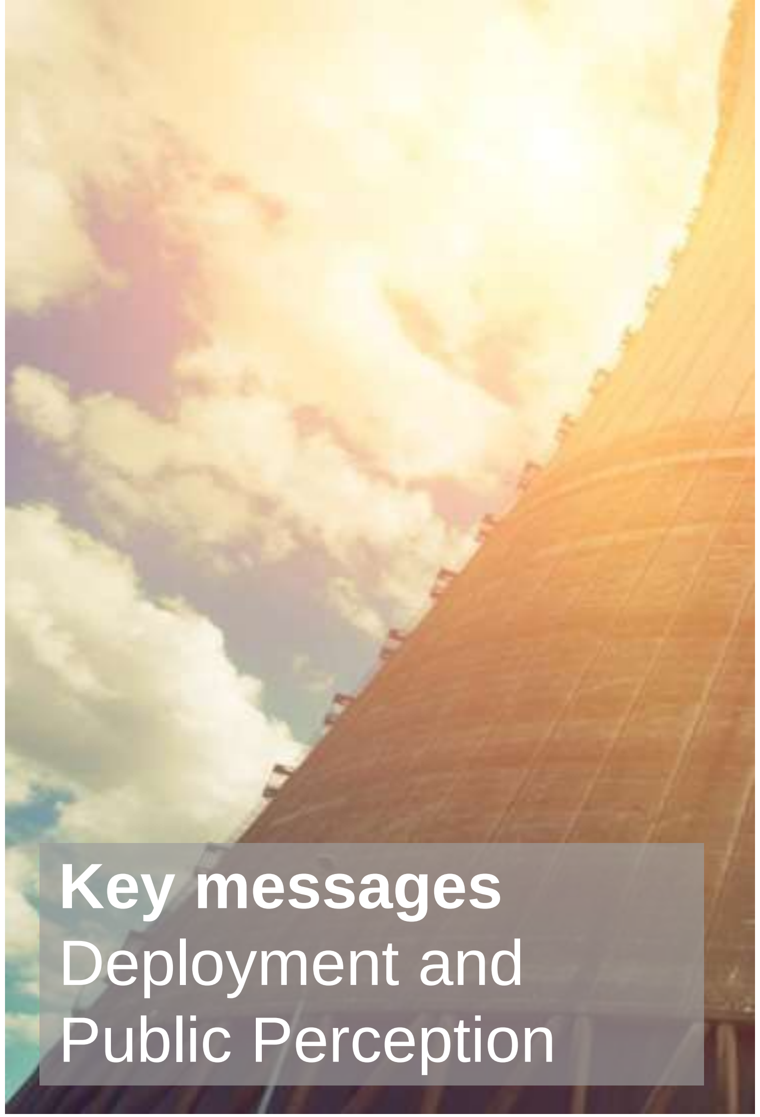
(*) Numbers represent rough estimate from CEO interviews.

Sources: TerraPower, About TerraPower (2025); Businesswire, TerraPower Isotopes Brings Actinium-225 to Market (2024); Reuters, Bill Gates' $4 bln high-tech nuclear reactor set for Wyoming coal site (2021); WNN, TerraPower, CNNC team up on travelling wave reactor (2015); Neutron Bytes, TerraPower to Leave China, but Bill Gates Is Still in the Game (2019).

Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Columbia Business School
Climate Knowledge Initiative

Deployment and Public Perception



Key messages
Deployment and Public Perception

At an LCOE of $182/MWh, nuclear is far above gas or renewables with storage solutions; reactor life extension is the cheapest option at $30-$40/MWh.

- Nuclear LCOE has increased 49% since 2009, making it the least affordable energy source option.
- Addressing the capital cost of nuclear will be key in achieving a commercially viable energy transition.

SMR projects are facing severe cost overruns and delays, highlighting scale and execution challenges for first-of-a-kind (FOAK) reactors.

- SMR projects so far have adjusted cost projections upward by up to 400% and increased timelines from four to 12 years.
- This is typical in FOAK projects and doesn’t indicate SMRs are less feasible than other reactor types.

Nuclear energy becomes cost competitive when full system costs are counted; matching renewable reliability can increase costs to $162-$177/MWh due to the necessity for storage.

- Nuclear complements intermittent renewable sources by providing low-carbon and reliable baseload power.

Many nuclear power plants store their waste using interim dedicated on-site disposal.

- Deep geological disposal will be needed to dispose of high-level nuclear waste.

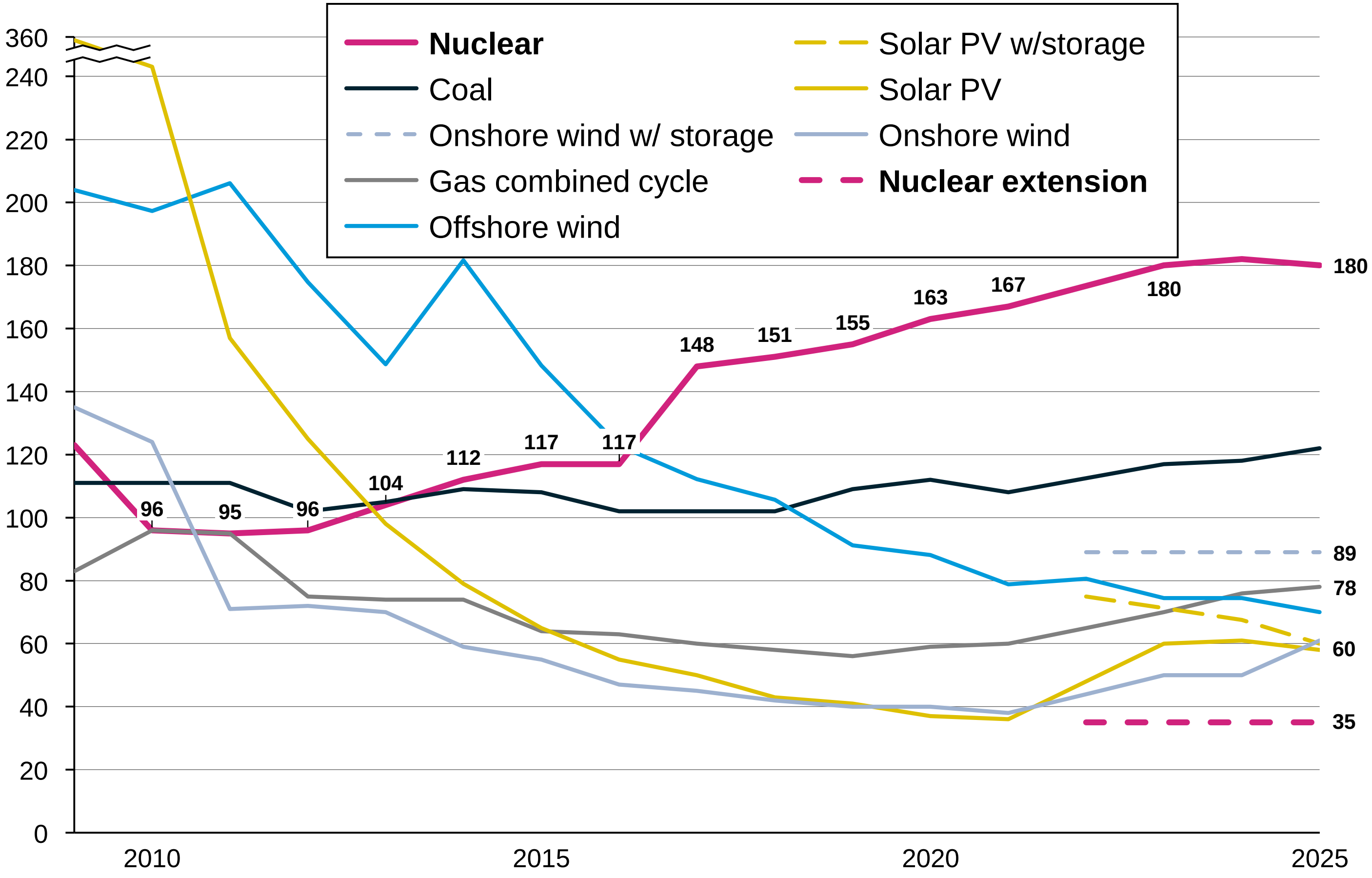
The majority of the public supports nuclear energy deployment, driven by a strong preference for energy reliability.

- There is a strong correlation between the number of reactors operational in a country and public support.
- 46% of survey respondents support the use of nuclear energy, while 28% oppose it.

Credit: Christian Sandjaja, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

At an LCOE of ~$182/MWh, nuclear is far above gas or renewables with storage solutions; reactor life extension is cheapest option

LCOE by technology, $/MWh



LCOE range (U.S.), $/MWh, 2025

$141-$220	**Nuclear**
$67-$179	Coal
$47-$170	Gas
$45-$133	Onshore w/storage
$70-$157	Offshore
$33-$131	Solar w/storage
$20-$57	Solar
$37-$86	Onshore wind
$30-$40	**Nuclear life extension**

Observations

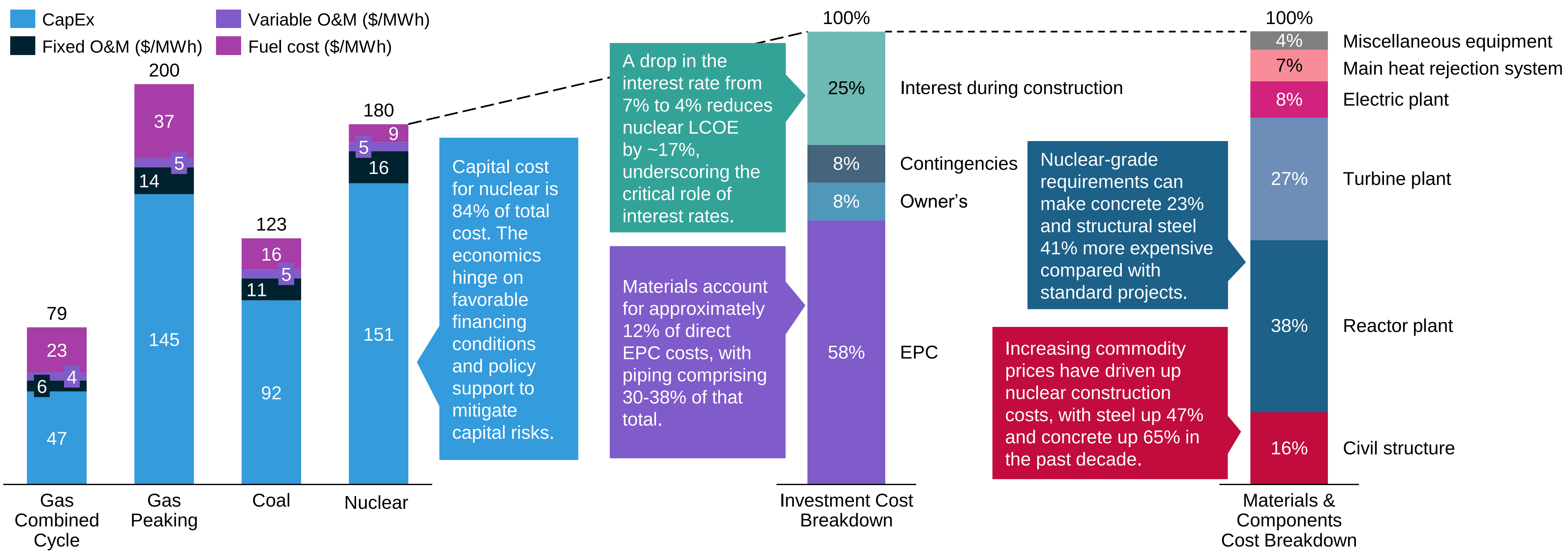
Factors that influence nuclear LCOE increases:

- Capital cost – **Nuclear power plants have high upfront capital costs**, which significantly impacts their LCOE.
- Construction delays – **Median construction time is 11 years**, with most countries experiencing at least one year of delay compared with scheduled startup dates.
- Financing cost – **High interest rates have particularly affected capital-intensive projects** like nuclear power plants.
- **Renewables with** four-hour **storage** aids grid flexibility but **can't ensure 24/7 reliability**, underscoring the **need for firm sources like nuclear** as renewables grow.
- Nuclear LCOE should be assessed against solar and wind **with storage**, as it provides continuous power.

Sources: Lazard, LCOE+ (2025); Statista, Construction Time for Nuclear Reactors Worldwide (2024).
Credit: Christian Sandjaja, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Lowering capital cost, which account for ~80% of LCOE component costs, is key to scaling nuclear technologies

LCOE cost components*, $/MWh



Capital cost for nuclear is 84% of total cost. The economics hinge on favorable financing conditions and policy support to mitigate capital risks.

A drop in the interest rate from 7% to 4% reduces nuclear LCOE by ~17%, underscoring the critical role of interest rates.

Materials account for approximately 12% of direct EPC costs, with piping comprising 30-38% of that total.

Nuclear-grade requirements can make concrete 23% and structural steel 41% more expensive compared with standard projects.

Increasing commodity prices have driven up nuclear construction costs, with steel up 47% and concrete up 65% in the past decade.

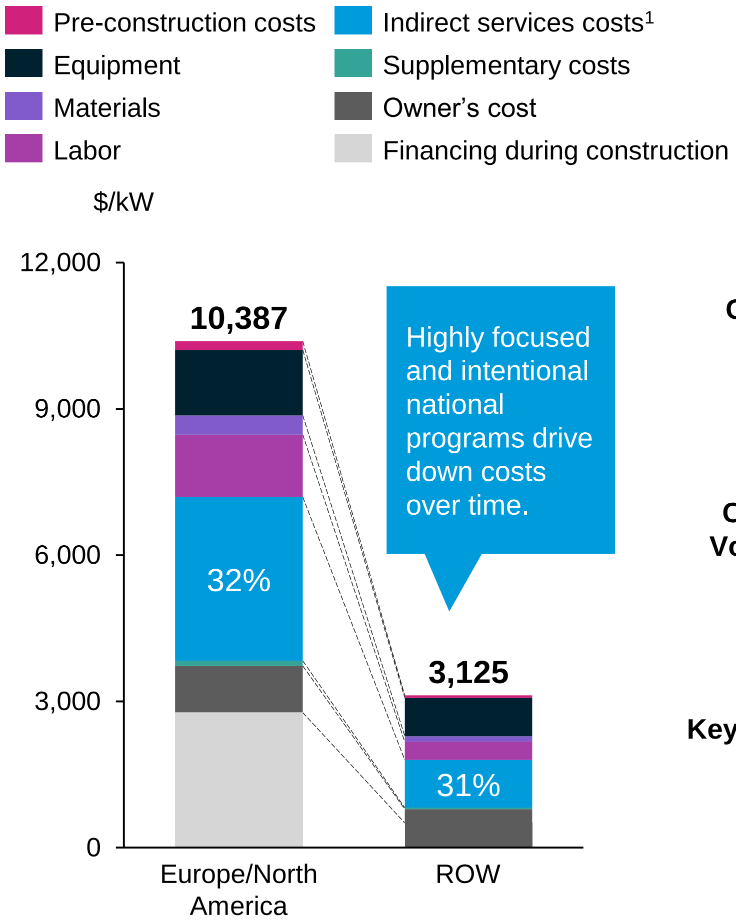
**Self-analysis based on Lazard LCOE+*

Sources: Lazard, LCOE+ (2025); World Nuclear Association, Economics of Nuclear Power (2024); OECD Nuclear Energy Agency, Unlocking Reductions in the Construction Costs of Nuclear (2020); Statista, PPI of concrete products in U.S. 1926-2023 (2024); Institute for Progress, Why Does Nuclear Power Plant Construction Cost So Much? (2023); U.S. Bureau of Labor Statistics, Producer Price Index by Industry (2024); U.S. Bureau of Labor Statistics, Producer Price Index by Commodity: Metals and Metal Products: Iron and Steel (2024).

Credit: Christian Sandjaja, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

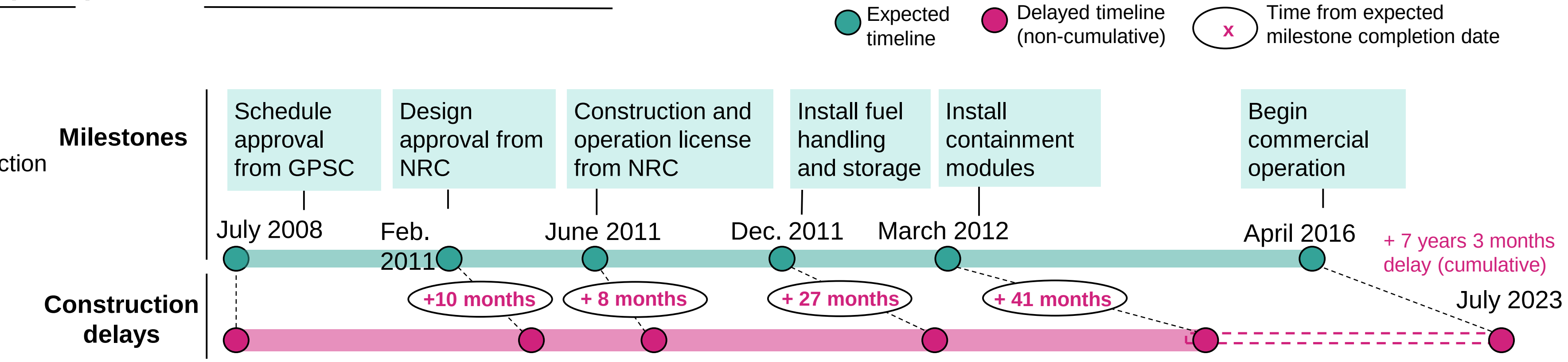
Poor project management among key drivers of time and cost overruns in new European and North American large reactor builds

Cost comparison of conventional nuclear plants in Europe and North America vs. rest of world (ROW)



Highly focused and intentional national programs drive down costs over time.

Case study: Voglte Unit 3



Milestones	Schedule approval from GPSC	Design approval from NRC	Construction and operation license from NRC	Install fuel handling and storage	Install containment modules	Begin commercial operation
Expected timeline	July 2008	Feb. 2011	June 2011	Dec. 2011	March 2012	April 2016
Construction delays		+10 months	+ 8 months	+ 27 months	+ 41 months	July 2023

+ 7 years 3 months delay (cumulative)

Cost drivers Vogtle 3 and 4

- NRC updated safety requirements to protect plants against aircraft impacts.
- **Sixty license amendment requests** were made to NRC since construction start.

- **FOAK AP1000** is first project in 30 years.
- **Supply of knowledgeable engineers**, superintendents, crafts, and other key personnel was limited.
- Submodule and rebar installation for the nuclear island did not fit design specifications.

- **Unclear governance structure:** Westinghouse acted as the 1) nuclear system supplier, 2) plant design engineer, and 3) consortium leader.
- Westinghouse declared **bankruptcy** in 2017.

Key challenges

Construction start with incomplete design

Immature supply chain and untrained workforce

Unclear project governance and project development

---

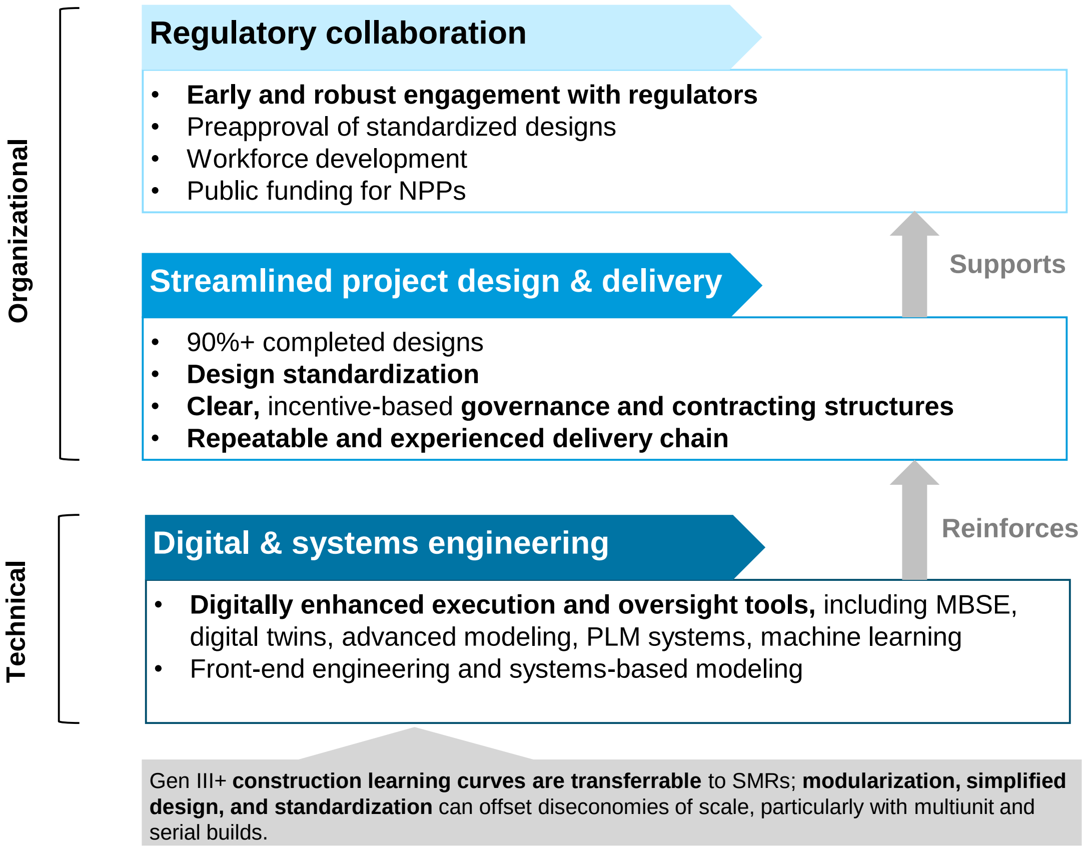
[1] Indirect services cost includes onsite and offsite project and construction management and design services.

Sources: Energy Technologies Institute, The ETI Nuclear Cost Drivers Project: Full Technical Report (2020); Nuclear Energy Agency, Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders (2020); Georgia Power, Nuclear Plant Voglte (2024).

Credit: Clara Zibell, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Employing digital tools, streamlined program design, and regulatory collaboration, effective project management cuts complexity, cost overruns

Enablers and strategies for reducing project complexity



Regulatory collaboration

- **Early and robust engagement with regulators**
- Preapproval of standardized designs
- Workforce development
- Public funding for NPPs

Streamlined project design & delivery

- 90%+ completed designs
- **Design standardization**
- **Clear,** incentive-based **governance and contracting structures**
- **Repeatable and experienced delivery chain**

Digital & systems engineering

- **Digitally enhanced execution and oversight tools,** including MBSE, digital twins, advanced modeling, PLM systems, machine learning
- Front-end engineering and systems-based modeling

Gen III+ **construction learning curves are transferrable** to SMRs; **modularization, simplified design, and standardization** can offset diseconomies of scale, particularly with multiunit and serial builds.

Case studies

Horizon (U.K.)

- Horizon and U.K. regulators codeveloped “papers of principle” to align on safety case revisions; there was a **>20% overnight cost reduction** for twin-unit ABWR.

KEPCO APR1400 (Korea)

- **Streamlined delivery time and efficiency** through an **integrated delivery chain; received standard design approval** from U.S. NRC in 2019.
- Barakah plant completed construction for the first unit **in five years;** Unit 3 was delivered four and five months faster than Unit 2 and 1, respectively.

Galois (U.S.)

- Leveraged **MBSE** to develop a digital instrumentation and control system with **enhanced traceability and optimized timelines** in under nine months; developed at a fraction of the cost of traditional control systems.

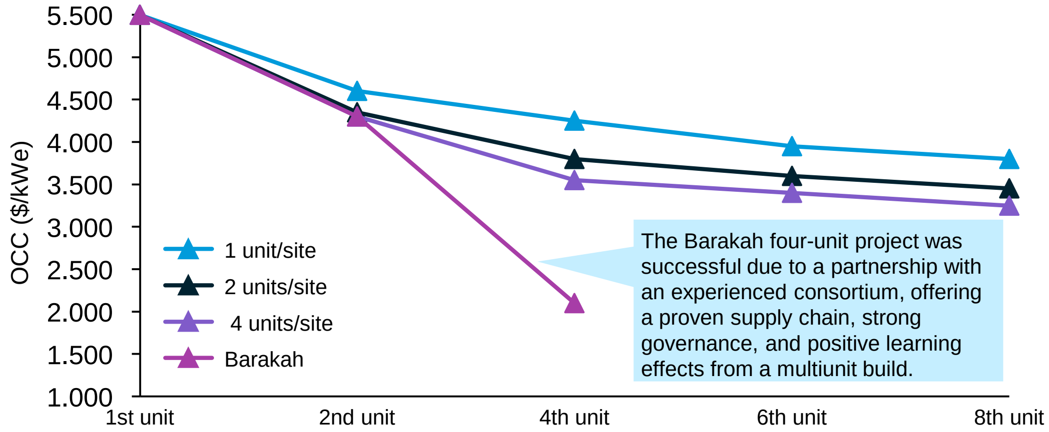
Definitions: ABWR: advanced boiling water reactor; MBSE: model-based systems engineering; NPP: nuclear power plant; PLM: product lifecycle management.

Sources: OECD, NEA, Unlocking Reductions in the Construction Costs of Nuclear (2020); Galois, Demonstrating Rigorous Digital Engineering for Nuclear Power Plant Systems (2024); Galois, How Do You Modernize Safety Critical Designs in Nuclear (2024); The Nuclear Institute, Why Nuclear Projects Suffer from Poor Predictability (2019); Locatelli, Why Are Megaprojects Delivered Over Budget and Late? (2018); ETI, Nuclear Cost Drivers Report (2018); Lyons, Production Learning in an SMR Supply Chain (2019); ENEC, Unit 4 start-up at Barakah Plant accelerates UAE towards net zero (2024).

Credit: Khande-Jae Fisher, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

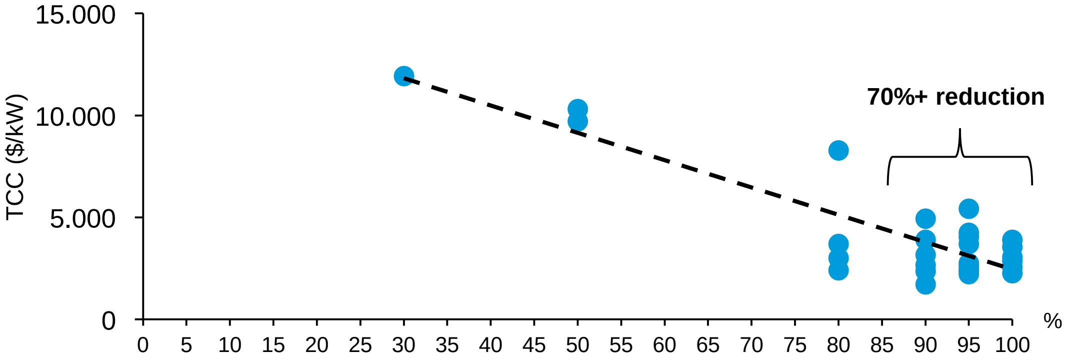
Improvements in design and delivery of NPPs lower the risk profile and significantly reduce costs across the nuclear project lifecycle

Standardization decreases unit costs in multiunit builds like the ENEC Barakah nuclear plant

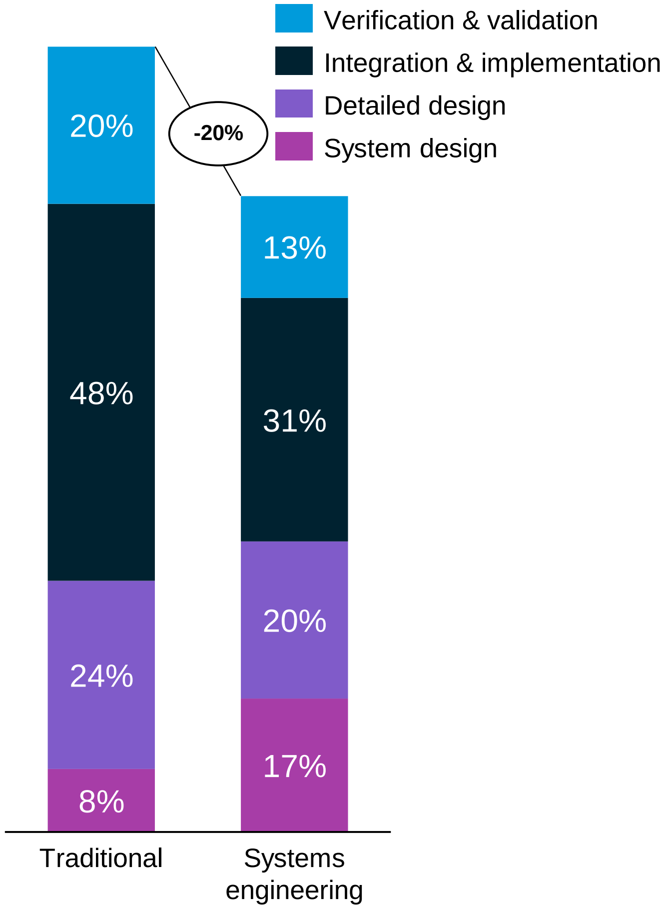


The Barakah four-unit project was successful due to a partnership with an experienced consortium, offering a proven supply chain, strong governance, and positive learning effects from a multiunit build.

Design completion of 90%+ at construction reduces total capital costs by up to 70%



Systems engineering reduces time and budget costs by up to ~20%



Observations

- Countries that report lower project costs, such as Korea and Japan, typically begin construction with designs 90%+ completed and plan for standardized, repeatable designs through multiunit and/or serial builds.
- Multiunit sites reduce complexity and unit costs by sharing resources and site-specific regulatory, planning, and infrastructure expenses.
- Systems engineering enables effective coordination between teams, saving up to 19% in overall time and costs.
- Notable companies that have used a 90%+ design completion approach include GE Hitachi, which reduced rework for projects by up to 20x.

Sources: OECD, NEA, Unlocking Reductions in the Construction Costs of Nuclear (2020); Galois, Demonstrating Rigorous Digital Engineering for Nuclear Power Plant Systems (2024); The Nuclear Institute, Why Nuclear Projects Suffer from Poor Predictability (2019); Locatelli, Why Are Megaprojects Delivered Over Budget and Late? (2018); ETI, Nuclear Cost Drivers Report (2018)

Credit: Khande-Jae Fisher, Isabel Hoyos, Helen Kim, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

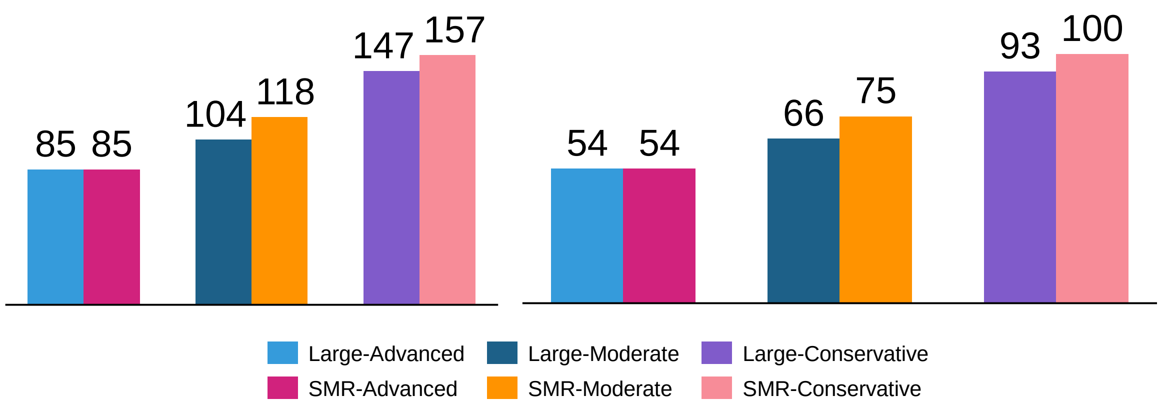
SMRs have the potential to close the cost gap with large reactors but only if shorter construction times are achieved

Current status: Early-stage deployment, no commercial ops

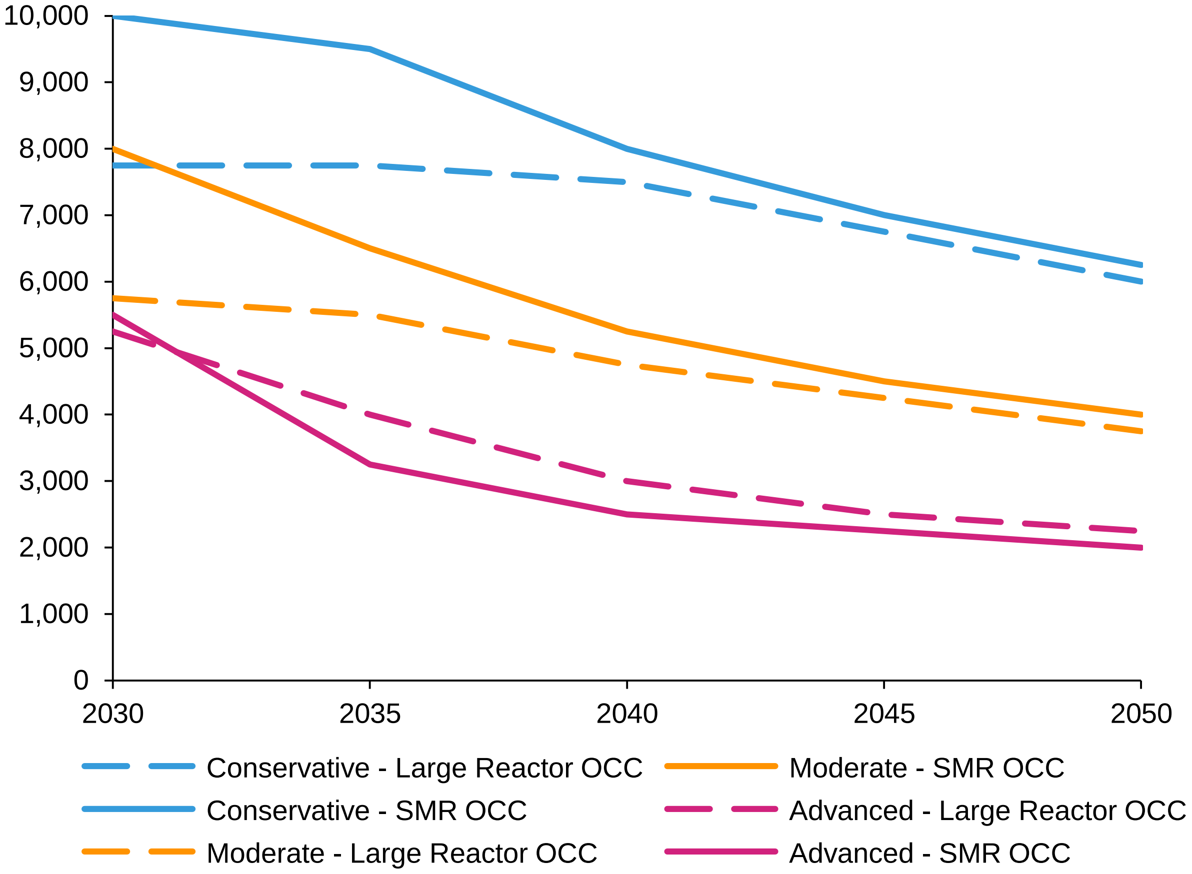
- No SMRs have been commercially deployed in the United States as of May 2025; all cost and learning estimates are based on literature, not real-world data.
- SMRs are expected to enable **faster learning rate** and **cost reductions** through modularity, factory fabrication, and the production of many standardized units.
- Faster learning rates (9.5% vs. 8%) and shorter construction times (55 vs. 82 months) are projected to **reduce both OCC per kWe and LCOE** over time.
- Despite these advantages, **SMRs are currently projected to have higher initial OCC** ($8,000/kWe) than large reactors ($5,750/kWe) by 2030.
- However, SMRs' shorter construction **reduces financing costs, which narrows the LCOE gap.** SMRs can be potentially more competitive under higher financing rates.

Est. 2030 LCOE; $/MWh, 7.5% WACC

Est. 2030 LCOE; $/MWh, 7.5% WACC + 40% ITC



Overnight capital cost evolution, 2022 $/kWe

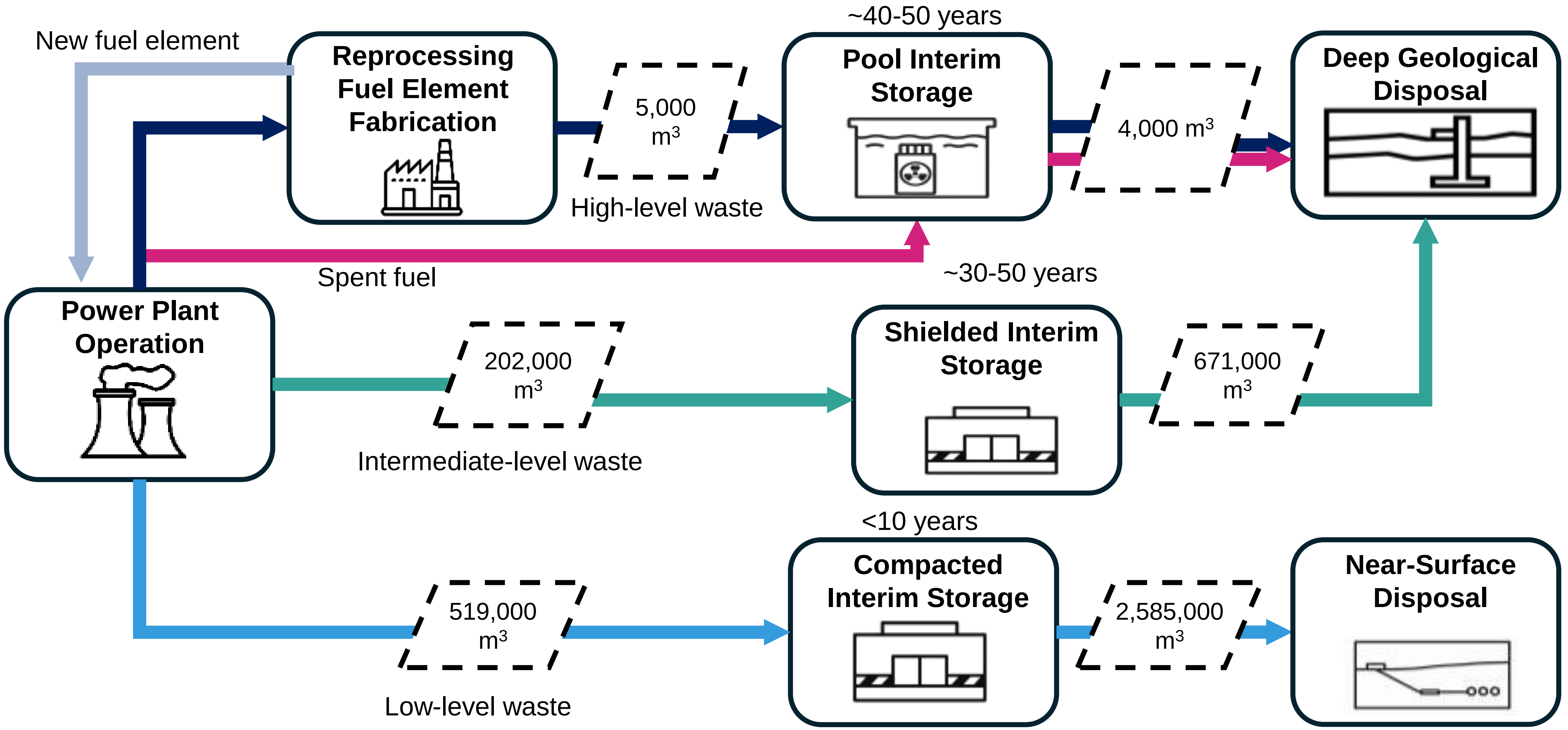


Sources: GAIN, Meta-Analysis of Advanced Nuclear Reactor Cost Estimations (2024); Institute for Energy Economics, Small Modular Reactors: Still Too Expensive, Too Slow and Too Risky (2024).

Credit: Christian Sandjaja, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Deep geological disposal remains the preferred option for high-level (radioactive) nuclear waste management

Cumulative nuclear waste supply (2019-2023)



High- and intermediate-level (radioactive) waste is stored in deep isolation for non-human intervention. Deep geological disposal (DGD) involves storing hazardous materials deep underground in stable geological formations, typically **200 to 1,000 meters below the surface.**

Legend:

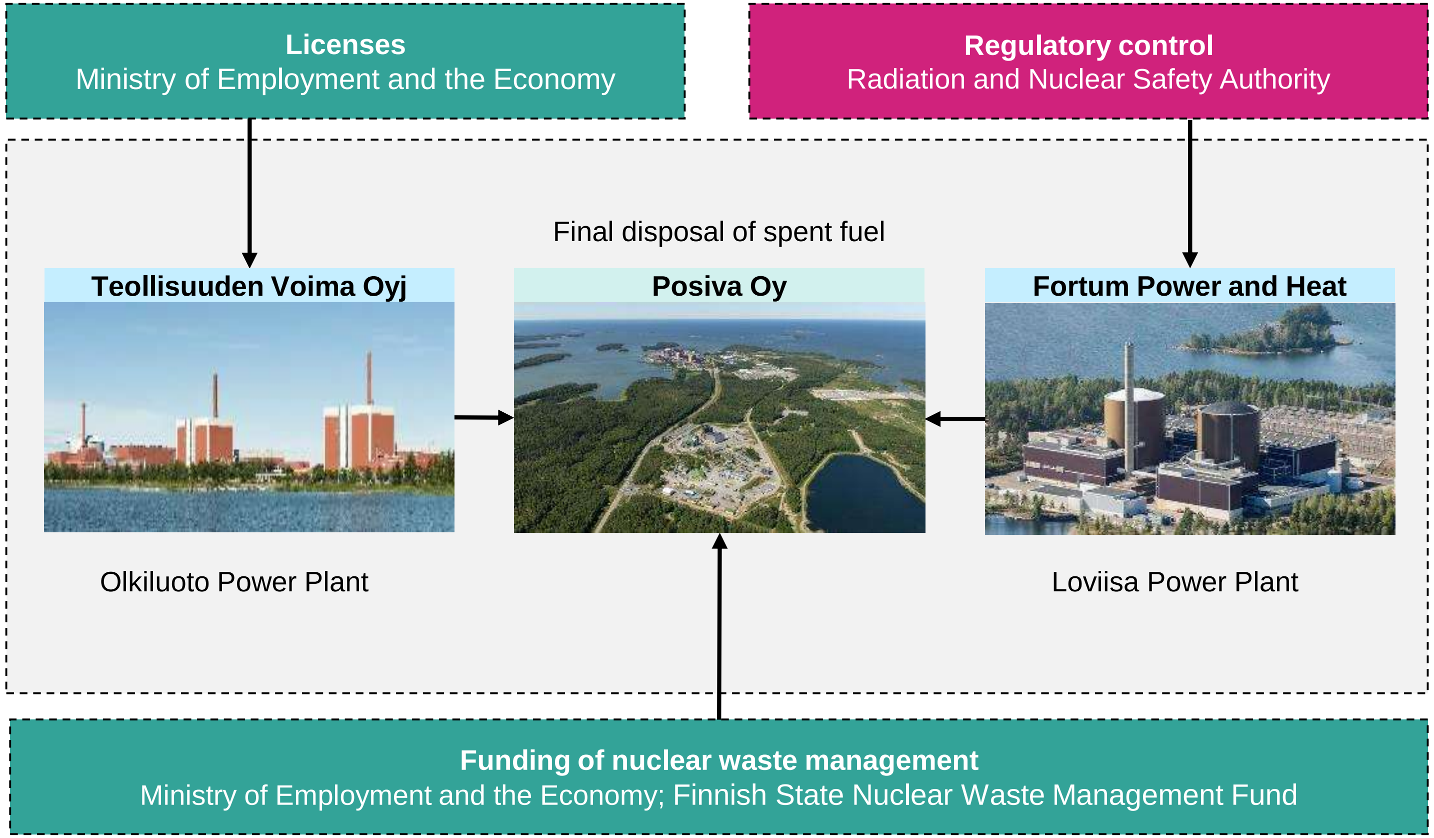
▱ Cumulative nuclear waste volume

Sources: DoE, Pathways to Commercial Liftoff: Advanced Nuclear (2023); World Nuclear Association, Radioactive Waste: Myths and Realities (2022); World Nuclear Association, Storage and Disposal of Radioactive Waste (2022).

Credit: Christian Sandjaja, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

While Onkalo operates only for Finland’s waste, it created a blueprint for global precedent

Onkalo licensing, oversight, and funding structure



Licenses
Ministry of Employment and the Economy

Regulatory control
Radiation and Nuclear Safety Authority

Final disposal of spent fuel

Teollisuuden Voima Oyj

Posiva Oy

Fortum Power and Heat

Olkiluoto Power Plant

Loviisa Power Plant

Funding of nuclear waste management
Ministry of Employment and the Economy; Finnish State Nuclear Waste Management Fund

Project Overview

- Onkala, the **world's first permanent deep geological disposal repository** for spent nuclear fuel, represents a **significant improvement over the temporary storage methods** that have dominated global nuclear waste management.
- It addresses the **mismatch** between the **extremely long hazardous lifetime** of the waste and the **temporary nature of existing storage** solutions.
- Olkiluoto and Loviisa account for **39% of Finland’s domestic electricity consumption**, raising the demand for a long-term disposal solution.

Timeline

2004	**2024**	**2025-26**	**2120**
Construction begins	Trial run starts	Expected operation	Repository closing

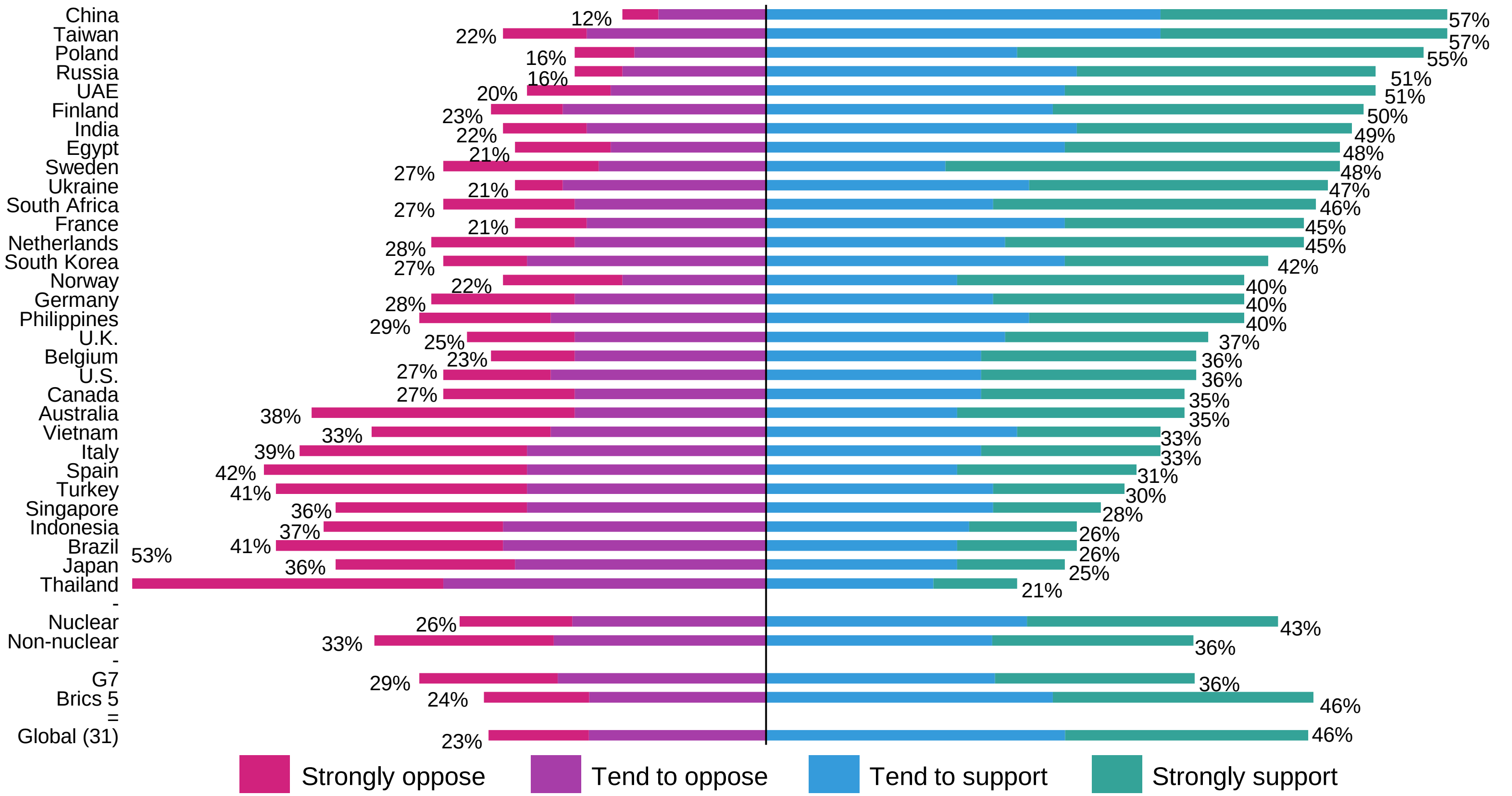
Challenges and considerations

- Long-term safety: Designed to isolate waste for >100,000 years
- Public support: Benefited from existing nuclear facilities in the area
- Strategic location: Close proximity to Olkiluoto and Loviisa power plants

Sources: Science, Finland built a tomb to store nuclear waste. Can it survive 100,000 years? (2024); Posiva, Introducing ONKALO and its principle of operation (2024); American Nuclear Society, Finland begins trial run of Onkalo repository (2024); World Nuclear Association, WNA Nuclear Fuel Cycle Royal Commission Issues Paper 4 Submission (2015); Pacific Northwest National Laboratory, Nuclear Waste: Challenges for the Next Generation (2007); Posiva, Olkiluoto: A Safe Home for Spent Nuclear Fuel (2011); IAEA/Posiva, Characterization of Spent Fuel for the Management of Final Disposal (2011).
Credit: Christian Sandjaja, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

A majority of the public supports nuclear energy deployment, driven by a strong preference for energy reliability

% of people who oppose or support nuclear energy's use in their country



Observations

- **46% of survey respondents support** the use of nuclear energy, while 23% oppose it.
- **22 out of 31 countries surveyed have net support** for nuclear energy.
- Notable country highlights:

  China – Majority support
  Nuclear is central to China's strategy to **reduce dependence on coal** and **meet its carbon neutrality target** by 2060. It is reflected in government incentives that have resulted in competitive cost ($70/MWh).

  Russia – Majority support
  Russia **leverages nuclear exports for peaceful geopolitical influence**, with state-owned Rosatom building around 20 reactors abroad. Nuclear energy, linked to Soviet-era prestige, enjoys strong public support as a **symbol of technological strength.**

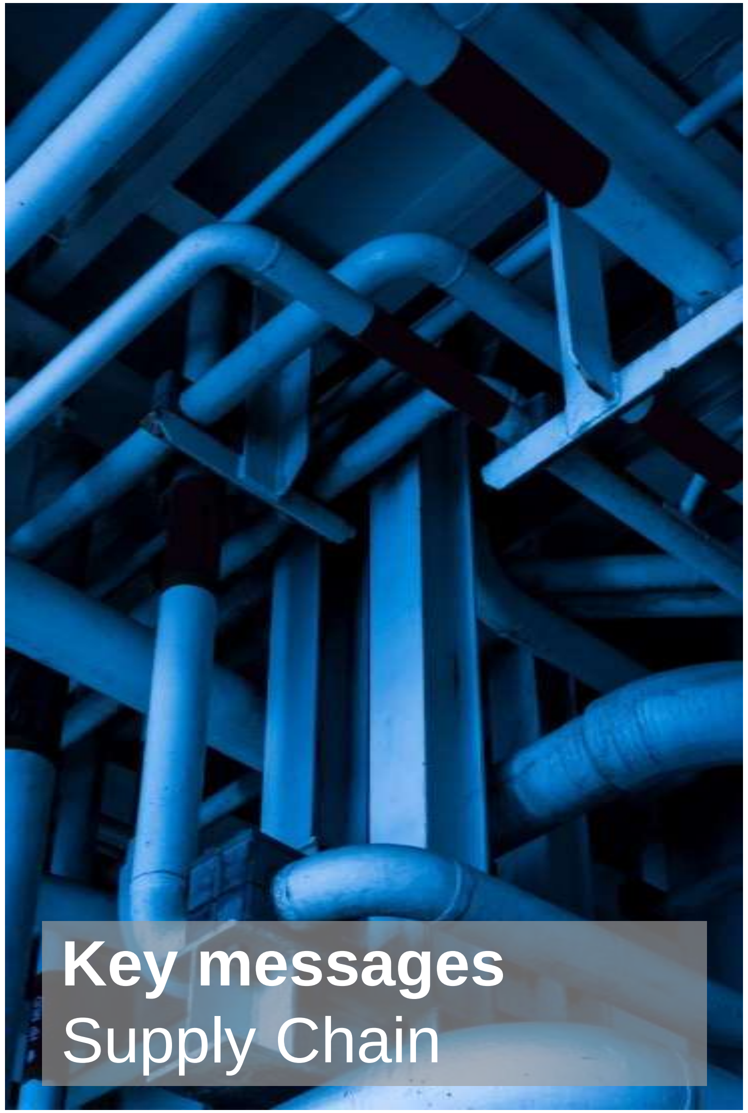
  Thailand – Majority oppose
  Skeptical due to safety concerns; favors renewables. This is seen in its unsuccessful attempt to reintroduce nuclear power in its Power Development Plan in 2007 and 2010.

Sources: Radiant Energy Group, Public Attitudes Toward Clean Energy 2024 – Nuclear (2025); World Nuclear News, American Nuclear Society, Surveys reveal public support for, but some concerns on, nuclear energy (2024); Nuclear Business Platform, China's Nuclear Power Program: A Blueprint for Global Competitiveness (2023); ECNS, China to build 10 new nuclear power units in 2024 (2025); Nuclear energy and international relations: the external strategy of Russia's Rosatom (2024); Political Science and Security Studies Journal, Nuclear technologies as an instrument of geopolitical confrontation on the borderlands of the Heartland/Rimland (2022); IEEE Xplore, The evaluation of economic and social effect from the revised nuclear power plant planning in Thailand (2011); Hunton, Navigating the Nuclear Landscape: Understanding Thailand's Laws and Approach (2025).

Credit: Christian Sandjaja, Quint Houwink, Brenda Rain, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Columbia Business School
Climate Knowledge Initiative

Supply Chain



Key messages

Supply Chain

Despite 60% of nuclear power plants being in the West, more than 50% of OEM and critical component capacity is in China today.

Historically, countries that are actively building new nuclear reactors have also had the largest reactor OEMs.

- During the 1970’s nuclear reactor boom in the West, Westinghouse, GE, and Framatome accounted for 90% of new-build reactors.
- Today, most new reactors are built by CNNC, Rosatom, and Atomenergomash.

Uranium producing and consuming countries have almost no overlap, as most uranium resources are situated in Kazakhstan, Canada, and Australia.

- The world requirement for uranium ore was 68 kilotonnes in 2023. This is significantly more than the 55 kt produced. The difference is made up using stockpiles and recycled uranium.
- The West is highly dependent on Canada and Kazakhstan for its uranium ore.

Mining and enrichment are dominated by a few businesses mostly in Kazakhstan and Russia, while fuel is produced typically in the country where the reactor is located.

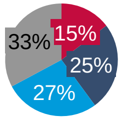
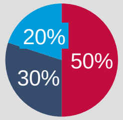
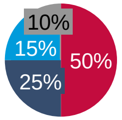
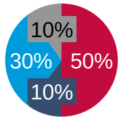
- Europe and the United States must invest in uranium enrichment facilities if they want to reduce their dependency on Russia and China.
- Only a few commercial businesses reprocess nuclear fuel. The United States closed its reprocessing plants in the 1970s.

Credit: Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

The traditionally Western nuclear supply chain is increasingly dominated by Chinese players

Supply chain tiers nuclear power plants

🟥 China ⬛ U.S. 🟦 EU ▨ Other ⬜ Deep dive next

Tier	⓪ **Operators**	① **OEMs**	② **Major components**	③ **Specialized components**	④ **Subcomponents**	**Nuclear fuel**
Description	Mostly electrical utility companies operating nuclear power plants	Design, engineer, and construct the reactors	Produce the large parts of the power plant such as pressure vessels, generators, and reactor vessels	Produce niche components that aren't specific to nuclear but require high standards, such as electronics, valves, and piping	Supply the low-tech components required for a nuclear power plant such as the steel frame, fasteners, and concrete foundation	Mostly uranium to keep the nuclear plants running
Number of players	~200	10-15	20-30	500-1,000	1,000+	1,000+
Regional market share, 2024					Local suppliers	Depends on fuel production stage — see deep dive
Example players	exelon DUKE ENERGY EDF 中广核 CGN	GE HITACHI framatome Westinghouse MITSUBISHI HEAVY INDUSTRIES ROSATOM 中核集团 CNNC AtkinsRéalis	BWXT KSB JSW CURTISS-WRIGHT	framatome ULTRA Schneider Electric FLOWSERVE	Many	orano CGN KAZATOMPROM Cameco UEC Centrus

Observations

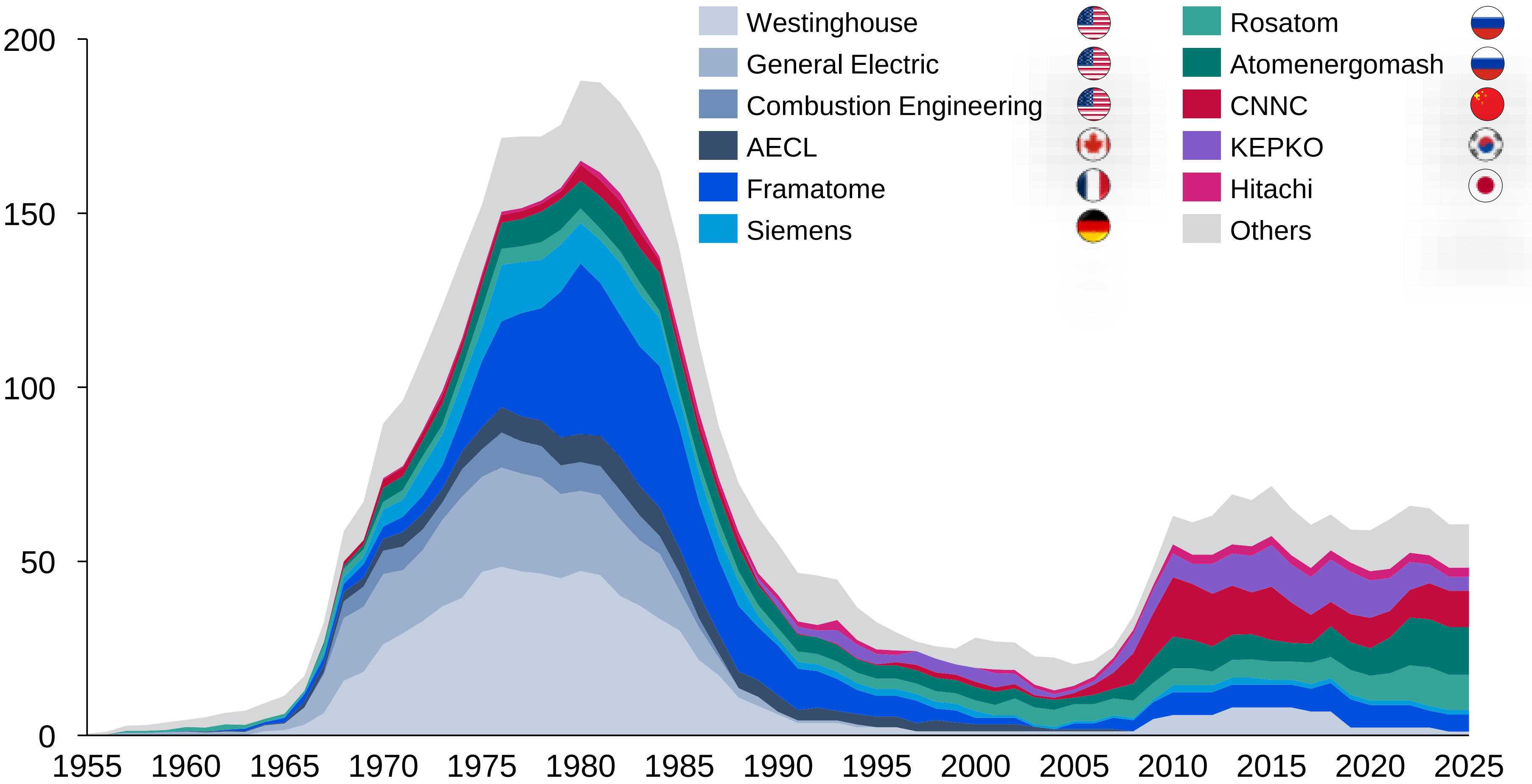
- China **hosts 15% of existing nuclear plants** but accounts for 30% of new global constructions. It also leads in **manufacturing.**
- Building a nuclear power plant requires highly specialized knowledge. **It is for this reason that the nuclear supply chain is highly concentrated.**
- **This concentration allows a few players to benefit from the learning curve.** Framatome benefitted from this learning curve when France was building its nuclear fleet in the 1970s and 1980s. Today, CNNC and other Chinese OEMs benefit from the nuclear boom in China.
- OEMs have provided fuel, parts, and support for 80+ years, creating **lasting technical and geopolitical dependence**.

Sources: Global Energy Monitor, Global Nuclear Power Tracker (2024); NIA, The Essential Guide to Nuclear Supply Chain (2010); EOG, Top 9 Nuclear Power Companies Leading the Global Energy Future (2024).

Credit: Quint Houwink, Clara Zibell, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Reactor manufacturing has shifted from the U.S. and Europe to Russian and Chinese OEMs

Nuclear reactors under construction by OEM, GW, 1955-2025



Observations

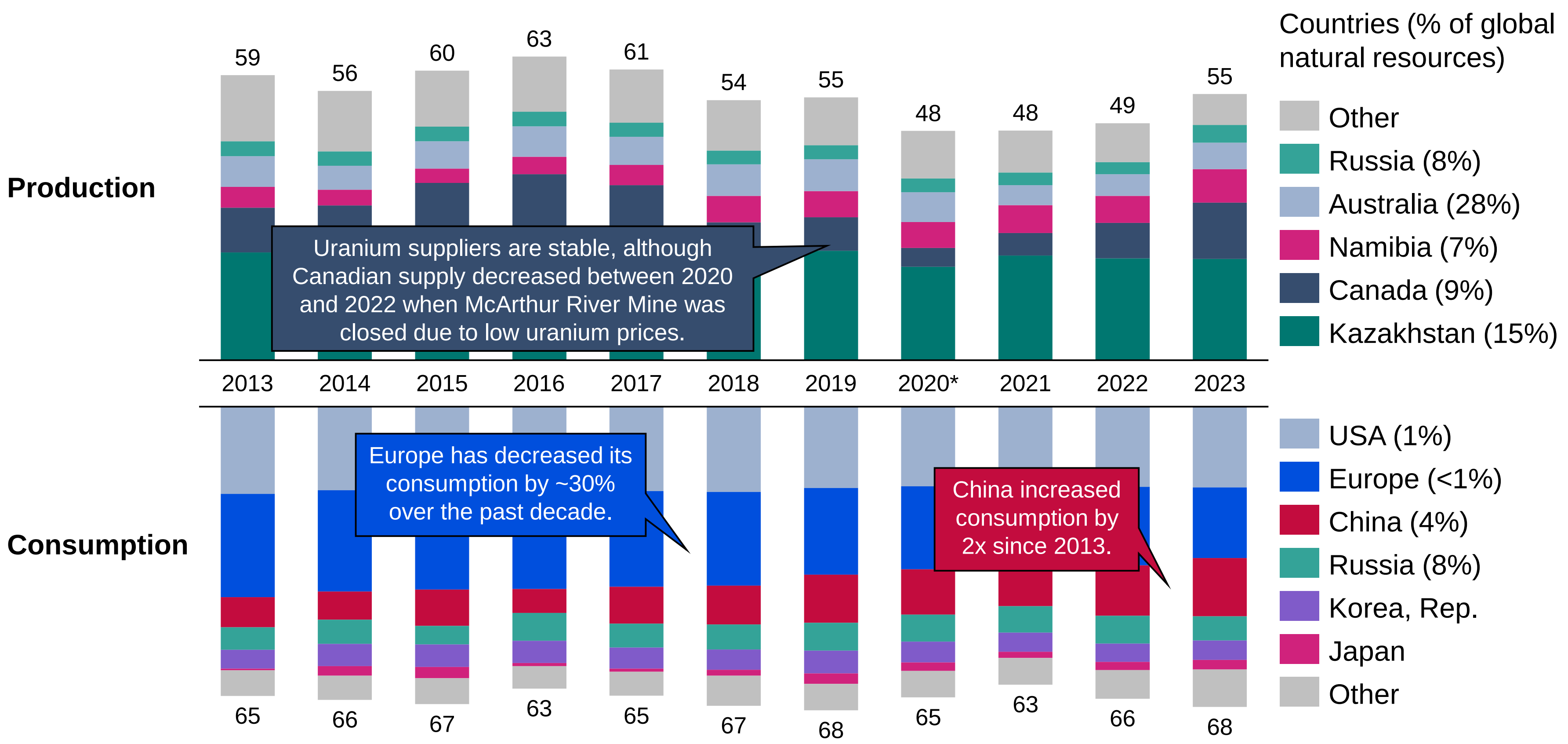
- During the nuclear boom of the **1970s and 1980s, ~80% of all new nuclear reactors were built by American** (Westinghouse, GE) **and European** (Framatome, Siemens) **OEMs.**
- Since the reemergence of reactors **in the past two decades, ~80% of reactors are built by Russian and Chinese manufacturers.**
- As Western OEMs haven't built a significant number of new reactors recently, **a lot of the know-how has been lost**, growing the barriers for new reactors.

Source: IAEA, Nuclear Power Reactors in the World (2024).
Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Columbia Business School
Climate Knowledge Initiative

Uranium producing and consuming countries have little overlap, as most uranium resources are in Kazakhstan, Canada, and Australia

Global uranium production and consumption, kt, 2013-2023



Uranium suppliers are stable, although Canadian supply decreased between 2020 and 2022 when McArthur River Mine was closed due to low uranium prices.

Europe has decreased its consumption by ~30% over the past decade.

China increased consumption by 2x since 2013.

Observations

- **The world requirement for uranium ore was 68 kilotonnes in 2022.** This is significantly more than the 55 kilotonnes produced.
- The gap is covered by stockpiles and re-enrichment.
- Countries with the highest uranium consumption (United States, Europe, and China) have hardly any uranium production or resources.
- This makes the West and China dependent on uranium ore imports. As this is considered a national security risk, countries keep **large stockpiles of uranium (the United States keeps ~480 tonnes of unirradiated highly enriched non-military uranium).**

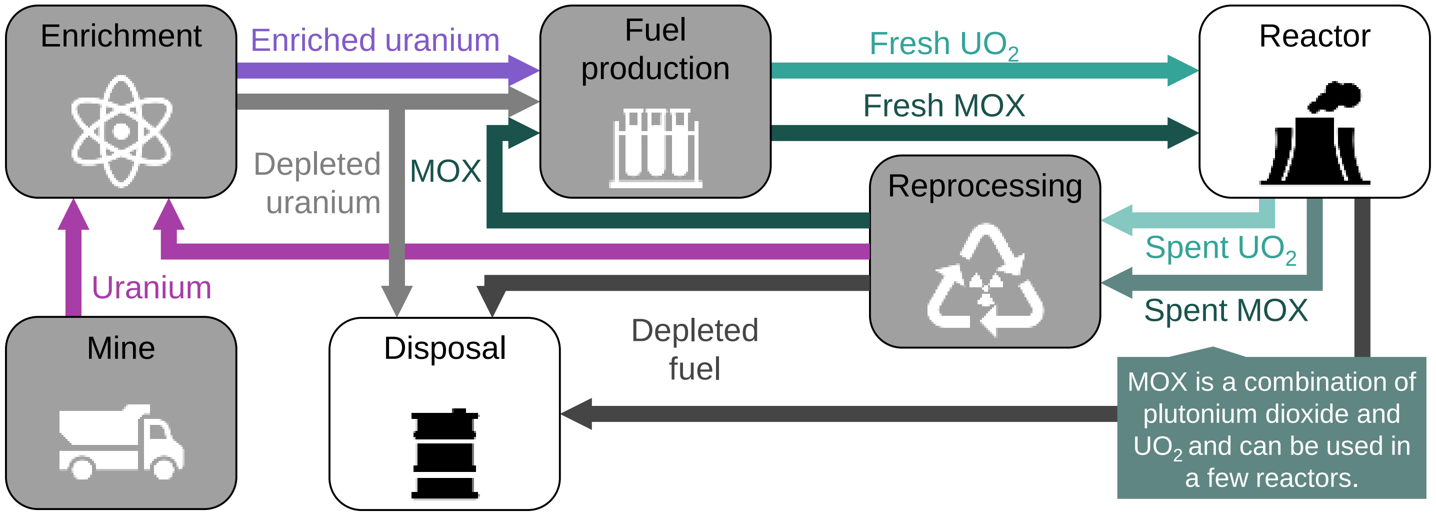
(*) Interpolated due to lack of data.
Sources: DoE, Nuclear Energy Supply Chain Deep Dive Assess (2022); WNA, Uranium Enrichment (2024); Storm van Leeuwen, Materials for nuclear power (2019); BGR, Energy Study (2014-2024); International Panel on Fissile Materials (2025).

Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Mining and enrichment are dominated by few businesses in non-Western countries; fuel fabrication is more decentralized

Overview of the nuclear fuel cycle

Material flows



MOX is a combination of plutonium dioxide and UO_2 and can be used in a few reactors.

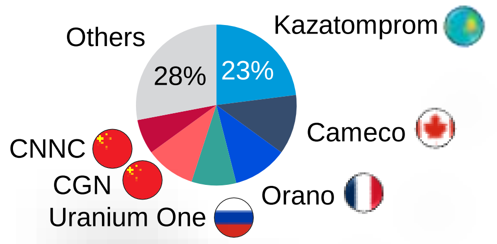
Observations

- Getting from mined uranium to nuclear fuel is an **extensive process involving specialized facilities.**
- **Enrichment is concentrated 4 businesses** around the world, with Russian Rosatom enriching 43% of global uranium.
- **Fuel production is more decentralized**, with most countries with reactors having their own facilities.
- **Only a few commercial businesses reprocess nuclear fuel**. The U.S. closed it reprocessing plants in the 1970's.
- **41% of fuel costs** come from **mining** the uranium, **45% enrichment** and only **14% fuel production.**

Market share, 2024

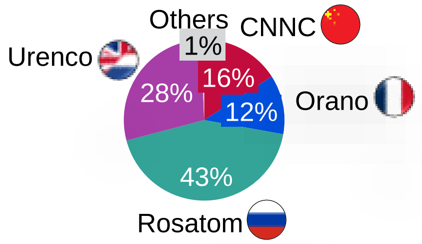
Mining

Total: 55 kt uranium



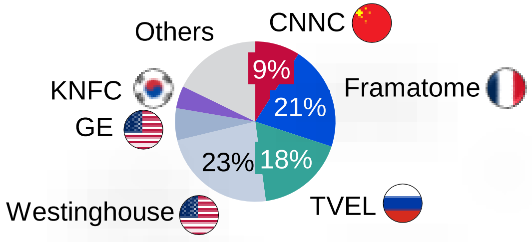
Enrichment

Total: 62,900 SWU/year



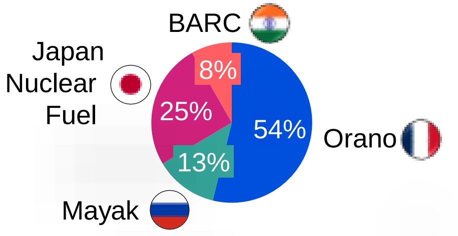
Fuel production*

Total: 15 t LWR fuel



Fuel recycling

Total: 3,860 t



(*) Refers to rod/assembly part of fuel production. Percentages differ slightly for pelletizing.

Sources: DoE, Nuclear Energy Supply Chain Deep Dive Assess (2022); WNA, World Uranium Mining Production (2024); Storm van Leeuwen, Materials for nuclear power (2019); The World Nuclear Industry, Status Report (2023); WNA, Nuclear Fuel and its Fabrication (2021); WNA Uranium Enrichment (2025); WNA, Nuclear Fuel and its Fabrication (2021); WNA Processing of Used Nuclear Fuel (2024); WNA, Nuclear Power Economics and Structuring (2024).

Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Columbia Business School
Climate Knowledge Initiative

Global Policy

Key messages
Global Policy

Governments have regained interest in nuclear power as a crucial emission-free, reliable energy source to achieve their net-zero targets and a key factor in energy security.

– At COP29 in 2024, 26 countries agreed to triple their nuclear energy capacity by 2050.

Policies for countries pursuing nuclear power include **increasing investment in new reactors, extending the operating lifetime of existing ones, and restarting retired plants.**

– 63 reactors were under construction at the end of 2024, which is expected to generate more than 70 GW.

– In the past five years, the lifetimes of 66 reactors in 13 countries were extended.

– While there are limited cases of the reopening of nuclear plants, Japan has the most experience.

– Overall investment in nuclear was $60 billion in 2023, which is a nearly 50% increase from 2020.

Countries have varying policy stances on nuclear energy.

– U.S.: The Inflation Reduction Act extends tax credits, making existing reactors economical and incentivizing construction. Government also actively supports development of advanced nuclear reactors.

– EU: Countries are divided on nuclear energy policy. France plans to increase nuclear power and boost the development of advanced reactors. Germany has shut down all its reactors, though there is now discussion about potentially reversing that policy.

– APAC: China is leading the global increase in nuclear capacity and development in new nuclear technologies. Japan, Korea, and India aim to increase nuclear capacity to enhance energy security and reduce reliance on fossil fuel.

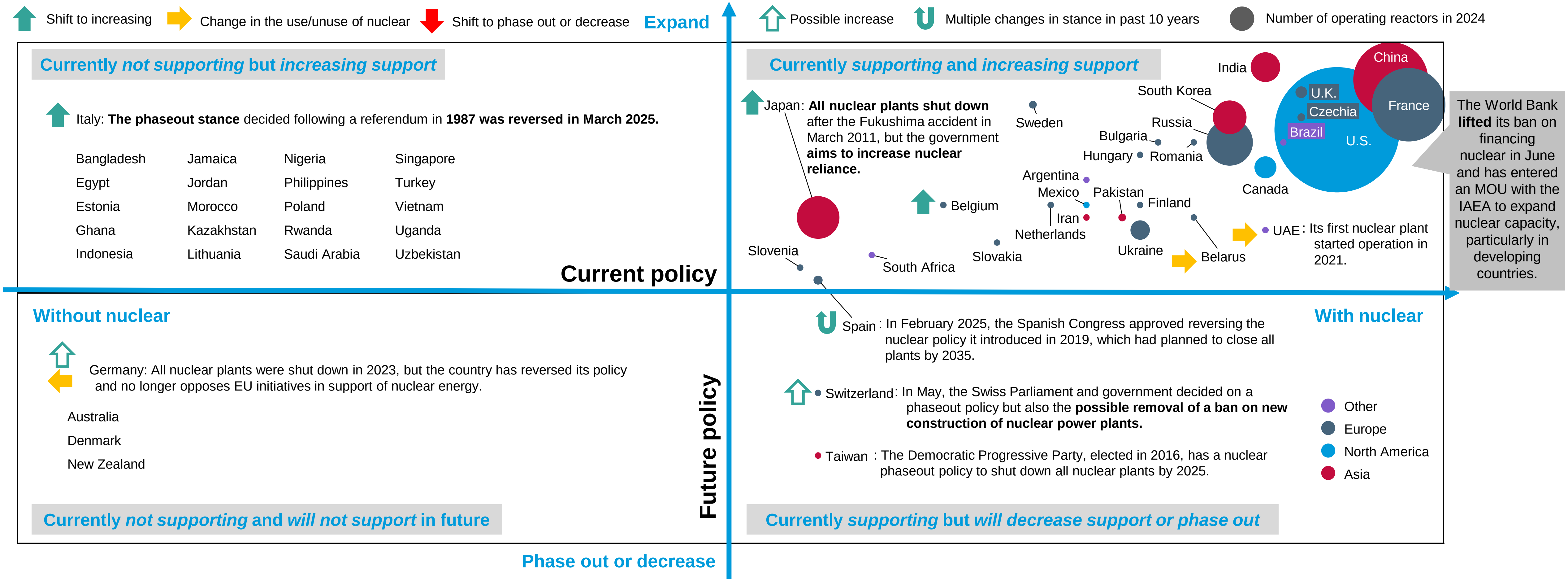
– Emerging nuclear energy countries: Many African countries are considering including nuclear power in their future energy mix; eight plants are planned or under construction.

Advanced economies that have not been building new reactors for the past two decades, including rebuilding the skills and industrial base for construction, **face deployment challenges.**

Source: IEA, The Path to a New Era for Nuclear Energy (2025).
Credit: Hinako Arai, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Governments have regained interest in nuclear power as a crucial emission-free energy source and a key factor in energy security

Changes in nuclear power policy by country during 2014-2024



Arrows indicate changes in policy stance between quadrants

- Shift to increasing
- Change in the use/unuse of nuclear
- Shift to phase out or decrease
- Possible increase
- Multiple changes in stance in past 10 years

Bubble size

● Number of operating reactors in 2024

Currently *not supporting* but *increasing support*

Italy: **The phaseout stance** decided following a referendum in **1987 was reversed in March 2025.**

Bangladesh
Egypt
Estonia
Ghana
Indonesia
Jamaica
Jordan
Morocco
Kazakhstan
Lithuania
Nigeria
Philippines
Poland
Rwanda
Saudi Arabia
Singapore
Turkey
Vietnam
Uganda
Uzbekistan

Currently *supporting* and *increasing support*

Japan: **All nuclear plants shut down** after the Fukushima accident in March 2011, but the government **aims to increase nuclear reliance.**

UAE: Its first nuclear plant started operation in 2021.

The World Bank **lifted** its ban on financing nuclear in June and has entered an MOU with the IAEA to expand nuclear capacity, particularly in developing countries.

Germany: All nuclear plants were shut down in 2023, but the country has reversed its policy and no longer opposes EU initiatives in support of nuclear energy.

Australia
Denmark
New Zealand

Currently *not supporting* and *will not support* in future

Spain: In February 2025, the Spanish Congress approved reversing the nuclear policy it introduced in 2019, which had planned to close all plants by 2035.

Switzerland: In May, the Swiss Parliament and government decided on a phaseout policy but also the **possible removal of a ban on new construction of nuclear power plants.**

Taiwan : The Democratic Progressive Party, elected in 2016, has a nuclear phaseout policy to shut down all nuclear plants by 2025.

● Other
● Europe
● North America
● Asia

Currently *supporting* but *will decrease support or phase out*

Sources: WNA, Country Profiles (2025); IEA, The Path to a New Era for Nuclear Energy (2025); Japan Atomic Energy Commission, White Paper on Nuclear Energy 2020 (2021, only in Japanese); World Nuclear News, Belgium Retires Oldest Nuclear Plant Reactor (2025), World Nuclear News, Feasibility Study for Belarus New Nuclear (2024).; Clean Energy Wire, Economy Minister Confirms end of Germany's resistance to nuclear power at EU level (2025).
Credit: Hinako Arai, Khande-Jae Fisher, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Ongoing policy support continues to propel China’s rapid capacity expansion; renewed political backing expected to spur U.S. growth

Key policy drivers across main nuclear players

Level of policy support: H = High M = Medium L = Low

	U.S.	EU	China
Nuclear capacity (GW)	**97**	**98**	**56**
LCOE ($/MWh)	**180**	**160**	**70**
Main policies	Federal: **Inflation Reduction Act; Advanced Reactor Demonstration Program; May 25 Nuclear EO Package** H	**Net-Zero Industry Act** M	**14th Five-Year Plan (2021-2025)** H
Policy focus	Lifetime extension, building new reactors, developing advanced reactors	Decision on whether to use nuclear energy left to member countries, nuclear safety	Rapidly construct large-scale plants and advanced reactors
2050 target capacity (GW)	**400** H	**150** M	**554** H
Incentives	- Federal: **Tax credits** on production and investment **DOE loans** now nuclear focused - State: **Zero emissions credits, state-backed loans** and **funds** - Total public commitment to date is **>$40B** H	- **Eurotom Research and Training Programme** funds nuclear research and innovation, provides financial support for **decommissioning** - An estimated **~€241B** in investments needed to reach target capacity M	- **Feed-in tariff** to decrease the price of nuclear power; **VAT refunds** to nuclear operators - Latest government study* revealed **~CNY 8.7T (~US$1.3T)** needed to lift nuclear capacity to 554 GW by 2050 H
Lifetime extension	Initial 40-year operating license **extended by 20 years**, with possible extension of **another 20 years** H	No overarching rule; European Commission investigates and approves extension plans of member countries M	Not a priority for China due to relatively new fleet; first lifetime extension in 2021 extended 30-year-old plants by **20 years** L
Development of advanced reactors	$3.2B in SMRs and other advanced reactor designs; $3.4B in federal funding for the HALEU availability program H	Advanced nuclear reactors included in scope of net-zero technologies eligible for financial support M	Start operation of ACP100 SMR by 2026, develop floating offshore nuclear power plants H

China has fastest growing fleet.

China’s LCOE is less than half that of U.S. and EU.

U.S. and China have ambitious targets of 4x and 10x current capacity, respectively; EU 1.5x.

Significant additional capital commitments required to reach capacity goals.

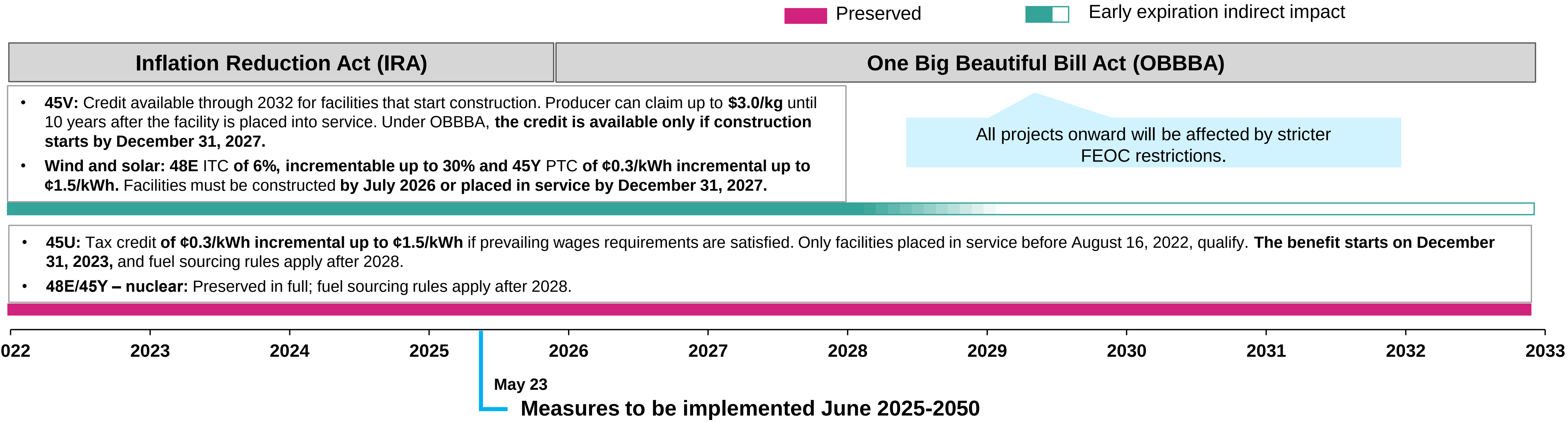
*The latest Chinese government study mentioned by World Nuclear Association was released in October 2018.

Sources: World Nuclear Association, Nuclear Power in the USA (2025); Lazard, LCOE (2025); Nuclear Europe, Pathways to 2050 (2025); World Nuclear Association, Nuclear Power in China (2025); ForoNuclear, EU recognizes value of nuclear (2025); IEA, The Path to a New Era for Nuclear Energy (2025); ITIF, How Innovative Is China in Nuclear Power? (2024); World Nuclear Association, Economics of Nuclear Power (2023); NEA, Projected Costs of Generating Electricity 2020 Edition (2020); Nuclear Business Platform, China’s Nuclear Power Program (2024).

Credit: Hinako Arai, Adele Teh, Quint Houwink, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Houwink et al., “Nuclear Transition” (23 September 2025).

Columbia Business School
Climate Knowledge Initiative

OBBBA preserves IRA 45U incentives until 2033; foreign entity of concern (FEOC) fuel sourcing rules apply after 2028



🟥 Preserved

🟩 Early expiration indirect impact

Inflation Reduction Act (IRA)

One Big Beautiful Bill Act (OBBBA)

- **45V:** Credit available through 2032 for facilities that start construction. Producer can claim up to **$3.0/kg** until 10 years after the facility is placed into service. Under OBBBA, **the credit is available only if construction starts by December 31, 2027.**
- **Wind and solar: 48E** ITC **of 6%, incrementable up to 30% and 45Y** PTC **of ¢0.3/kWh incremental up to ¢1.5/kWh.** Facilities must be constructed **by July 2026 or placed in service by December 31, 2027.**

All projects onward will be affected by stricter FEOC restrictions.

- **45U:** Tax credit **of ¢0.3/kWh incremental up to ¢1.5/kWh** if prevailing wages requirements are satisfied. Only facilities placed in service before August 16, 2022, qualify. **The benefit starts on December 31, 2023,** and fuel sourcing rules apply after 2028.
- **48E/45Y – nuclear:** Preserved in full; fuel sourcing rules apply after 2028.

Measures to be implemented June 2025-2050

The U.S. government plans to deploy 400 GW of U.S. nuclear energy capacity by 2050.

- **Executive Order 14299, Deploying Advanced Nuclear Reactor Technologies for National Security:** Applies specifically to Gen III+ reactors, SMRs, microreactors, and mobile reactors. Some provisions include deploying techs at military stations, defining critical sites for data centers and providing them with nuclear energy, building up a fuel bank, easing environmental review processes, and promoting nuclear exports.
- **EO 14300, Ordering the Reform of the Nuclear Regulatory Commission:** Includes structure, personnel, regulations, and basic operations.
- **EO 14301, Reforming Nuclear Reactor Testing at the Department of Energy:** Includes updating NEPA rules and establishing a DOE pilot program to allow companies to build test reactors outside of partnerships with national laboratories.
- **EO 14302, Reinvigorating the Nuclear Industrial Base:** Outlines how to strengthen the recycling of nuclear waste and prioritize new nuclear projects.

Sources: IEA, The Path to a New Era for Nuclear Energy (2025); Cres Forum, The Issue Brief: Key Federal Policies Fueling Nuclear Innovation and Reinvestment (2025); IRS, Zero-Emission Nuclear Power Production Credit (2025); DOE, The Hydrogen Production Tax Credit Explained for Nuclear Power Plants (2025); Farr & Gallagher, Tax Credit Opportunities for Nuclear Energy (2024); Congress, One Big Beautiful Bill Act (2025); CGEP Assessing the Energy Impacts of the One Big Beautiful Bill Act (2025); American Action Forum, Trump's nuclear executive orders: Overview and analysis (2025); Hunton, Recent nuclear executive orders to accelerate US nuclear renaissance (2025).

Credit: Hinako Arai, Brenda Rain, Clara Zibell, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

EU countries are divided on nuclear energy policy, with some having phased out or planning to phase out nuclear power

EU governments’ policy stance on nuclear energy

🟦 EU member states with operating and/or under-construction nuclear power plant (as of July 2022)
🟪 EU member states without nuclear power plants
🟦 Non-EU countries with operating and/or under-construction nuclear power plants
⬜ Non-EU countries without nuclear power plants

Observations

- Nuclear energy accounted for about **one-fifth of the EU’s electricity** in 2024, with **12 EU countries** including nuclear in their energy mix.
- The decision to incorporate nuclear power into a country’s energy mix is made by each government.
- The European Commission supports countries that use nuclear energy by providing **guidance on nuclear safety** and advancing **the development of next-generation nuclear reactors.**
    - **Euratom Safeguards:** Under the Euratom Treaty, the EC established **a nuclear material supervision system**.
    - **Euratom Research and Training Programme (2021-2025):** €1.38 billion allocated to nuclear research and innovation, including fusion research and development.
    - **European Industrial Alliance on SMRs (February 2024):** Aims to accelerate the deployment of SMRs and strengthen the EU supply chain, including a skilled workforce.
    - **Net-Zero Industry Act:** Seeks to boost European manufacturing of net-zero technologies, including nuclear fission, by addressing production barriers and enhancing competitiveness.

Sources: IEA, The Path to a New Era for Nuclear Energy (2025); WNA, Nuclear Power in the European Union (2025); European Commission, In focus: EU nuclear energy policy – why it matters to us all (2024); European Commission, Nuclear Safety (2025); European Commission, Euratom Safeguards (2025); European Commission, Small Modular Reactors (2024).
Credit: Hinako Arai, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

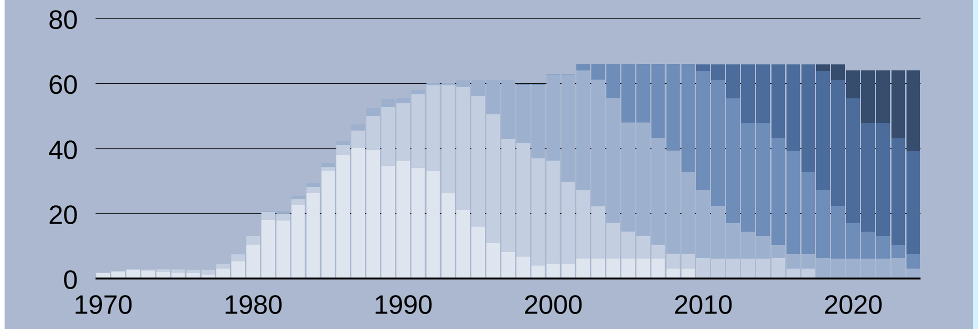
France is expanding nuclear power and developing advanced reactors; Germany is considering reversing its phaseout

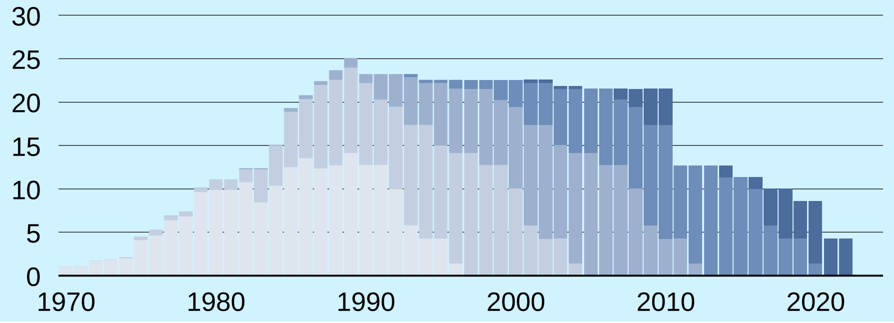
	France	Germany
Policy stance	• 70% of its electricity from nuclear power • Actively developing new-generation nuclear reactors	• No nuclear power; phaseout concluded in 2023 • Chancellor Friedrich Merz is in favor of restarting nuclear power plants, sparking a possible reversal of the phaseout policy.
Specific policies	• ***Grande Carenage* program:** Extend the lifetime of all nuclear reactors beyond 40 years, totaling 1.3 GW • **France 2030 investment plan:** 1 billion euros has been allocated to support the development of innovative reactors, including SMRs, with the goal of commissioning the first SMR by 2035 • Plans to construct six EPR2 reactors and assess the potential need for an additional eight	• **Decision to phase out:** In 2002, the Atomic Energy Act was amended to phase our nuclear plants. This phaseout was reversed by a new government in 2009 but reinstated in 2011, leading to the immediate shutdown of eight reactors and a plan to close all remaining reactors by the end of 2022. • **Completion of phaseout:** The last three nuclear power plants were shut down April 15, 2023. Originally scheduled to close December 31, 2022, their operation was extended due to the energy crisis, but no new fuel elements were allowed. They ceased operation by mid-April 2023.

Nuclear capacity (MW)

Lifespan

■	48+	■	16-23
■	40-47	■	8-15
■	32-39	■	<8
■	24-31		

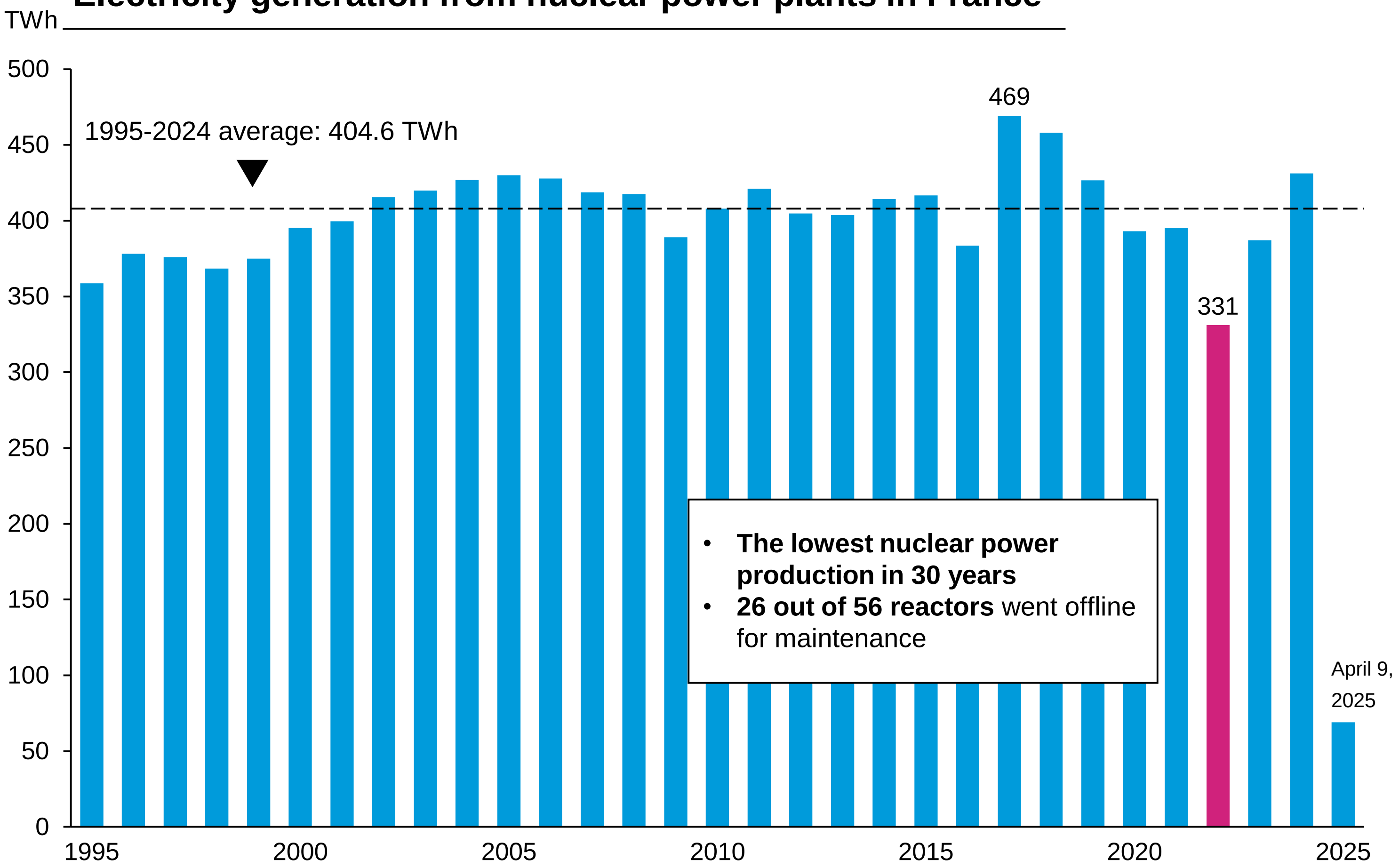




Sources: IEA, The Path to a New Era for Nuclear Energy (2025); WNA, Nuclear Power in the European Union (2025); WNA, Nuclear Power in Germany (2024); WNA, Nuclear Power in France (2025); EIA, Germany extends the life of its last three operating nuclear power plants until April (2023); Bundestag, The Nuclear Phase-out in Germany (2024).
Credit: Hinako Arai, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

More than half of the nuclear power plants in France went off the grid in the summer of 2022 due to maintenance nuclear shutdowns

Electricity generation from nuclear power plants in France



- **The lowest nuclear power production in 30 years**
- **26 out of 56 reactors** went offline for maintenance

Observations

Reasons for shutdown:

- **Corrosion:** In December 2021, inspections at Civaux 1 revealed pipe corrosion; similar defects at other units required part replacements and plant shutdowns.
- **Maintenance delays:** COVID-19 and a shortage of nuclear workers — linked to weak policy support — postponed scheduled outages and extended downtime.
- **Cooling restrictions:** Regulated use of river water and unusually high water temperatures forced output cuts at operating reactors.

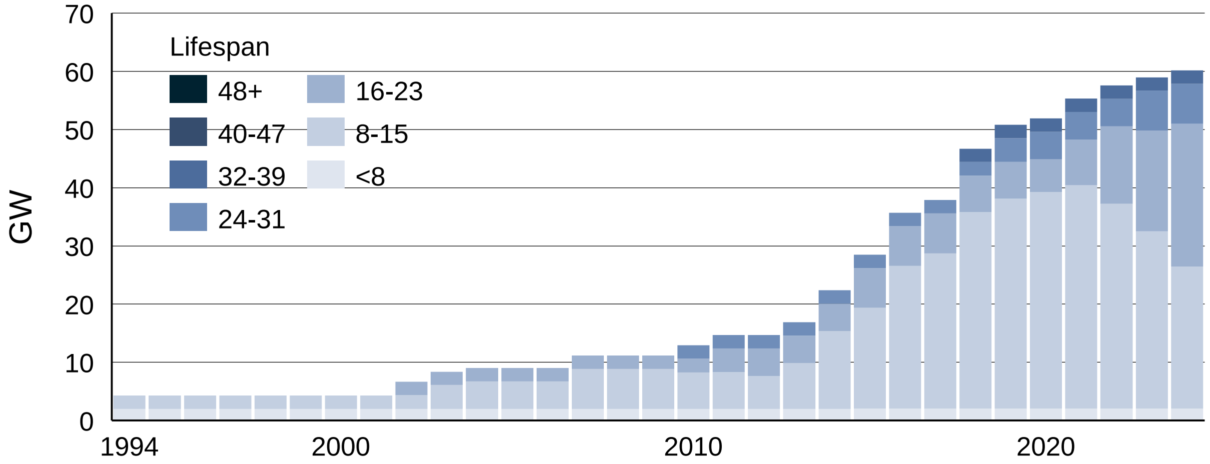
Policy implications:

- Revealed risk of **high nuclear reliance.**
- In the long term, **standardizing and modularizing nuclear plant components** — rather than undertaking bespoke, labor-intensive fixes — **can improve reliability** and streamline future maintenance.

Sources: RTE, Generation – Nuclear (2025); WNA, Nuclear Power in France (2025); Clean Air Task Force, The 2022 French nuclear outages: Lessons for nuclear energy in Europe (2023); Bundestag, The Nuclear Phase-out in Germany (2024).
Credit: Hinako Arai, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

China is leading the global increase in nuclear capacity and development in new nuclear technologies

Nuclear capacity in China



Policy tools used by the Chinese government:

- Nuclear plants typically benefit **from guaranteed price premiums and priority dispatch.**
- Major state-owned nuclear operators (e.g., China National Nuclear Corporation, China General Nuclear Power Group) gain access to **low-cost loans** through state-owned banks.
- Central and provincial governments facilitate site development by **securing land and organizing grid interconnections for new nuclear projects.**

	2011-2015 (12th Five-Year Plan)	**2016-2020 (13th Five-Year Plan)**	**2021-2025 (14th Five-Year Plan)**
Plan	• Begin construction at coastal and inland sites to **add 25 GW** of nuclear capacity by 2015, bringing **total capacity to 40 GW** • Develop **multipurpose water-pressurized SMR, ACP100**, with a capacity of 125 MW	• Increase nuclear capacity from 27 GW to **58 GW** by the end of 2020 • Complete four Gen III reactors (U.S.-developed AP1000) and build demonstration units using **Chinese-developed technology (Hualong One, CAP1400, etc.)**	• Targets capacity of **70 GW by 2025** • **Mandates and increases the use of Gen III or more advanced technologies** • Develop ACP100 SMR by 2026 and floating offshore nuclear power plants
Progress	• Following the March 2011 Fukushima accident, **approvals for new nuclear plants suspended**, delaying the projects but order revoked in 2012 • Preliminary design of ACP100 completed in 2014	• Four AP1000 reactors completed in 2018 at Sanmen and Haiyang • **ACP100 SMR passed the IAEA safety review** in 2016, making it the world's first SMR to achieve this milestone	• **First Hualong One reactor put into commercial operation** in 2021, and two in Pakistan • First **ACP100 construction began** in 2021 in Hainan

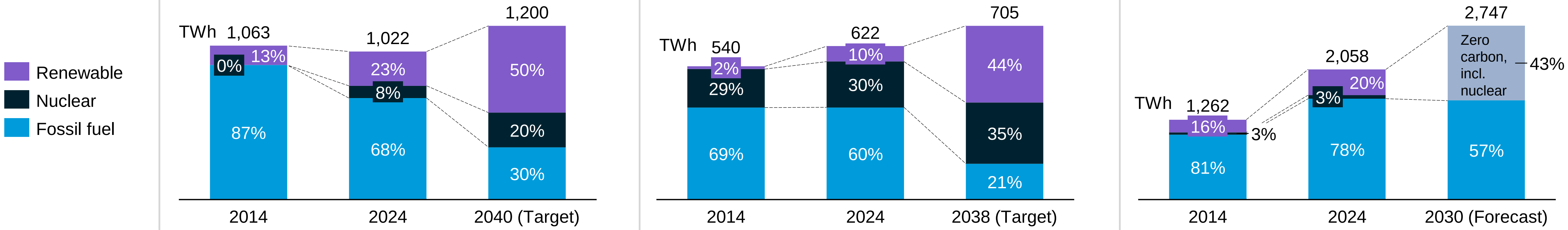
Sources: WNA, World Nuclear Performance Report (2024); IEA, The Path to a New Era for Nuclear Energy (2025); WNA, Nuclear Power in China (2025); WNN, Nuclear Growth Revealed in China's New Five-Year Plan (2016); Oxford Institute of Energy Studies, Guide to Chinese Climate Policy (2022); NucNet, China/First Hualong One Reactor Begins Commercial Operation at Fuqing (2021).

Credit: Hinako Arai, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Japan, Korea, and India all aim to increase nuclear capacity to enhance energy security and reduce reliance on fossil fuel

	Japan restarting plants that shut down after March 2011 accident	**Korea's nuclear power phaseout plan reversed by former president**	**India rapidly expanding nuclear capacity, developing Indian SMRs**
Legislative policy	• **The 7th Strategic Energy Plan** • **Electricity Business Act**	• **11th (2024-2038) Basic Plan for Long-Term Electricity Supply and Demand**	• **National Electricity Plan of 2023** • **Nuclear Energy Mission for Viksit Bharat**
Trend observed	• Of the 54 nuclear reactors that operated before the Fukushima Daiichi accident, **14 have resumed operation, and 12 are scheduled to begin operation.** • Restarting these nuclear plants is key to increasing energy self-sufficiency and reducing GHG emissions to achieve net zero.	• The nuclear phaseout policy, introduced by former President Moon Jae-in in 2017, was reversed in March 2022 by then-President Yoon Suk Yeol. • **The country formed a public-private partnership** comprising 42 entities to advance SMR development. • The target is to build two large nuclear reactors and 700 MW of SMRs by 2038.	• India will provide funds to construct at least five Indian-designed SMRs, to be operational by 2033. • **It aims to reach 100 GW of nuclear capacity by 2047.** • A new program focused on development of SMRs, called the Nuclear Energy Mission, was introduced in the 2025-2026 Union Budget.

Energy mix



Sources: WNA, World Nuclear Performance Report (2024); IEA, The Path to a New Era for Nuclear Energy (2025); METI, Agency for Natural Resources and Energy, Energy in Japan (2025) (available only in Japanese); WNA, South Korea Confirms Need for New Reactors (2025); IEEFA, South Korea's 11th Power Plan Makes Partial Progress Towards Decarbonization (2025); BloombergNEF, India's Clean Power Revolution (2020); WNA, Indian Budget Launches Nuclear Energy Mission (2025); Impact and Policy Research Institute, Nuclear Energy Mission for Vikasit Bharat 2025 (2025); Ember, Electricity Data Explorer (2024).

Credit: Hinako Arai, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Since 2013, Japan has restarted 14 nuclear reactors (~13 GW) under new, stricter safety standards

Political, financial, and energy conditions

- Following the 2011 **Fukushima** accident, Japan's abrupt suspension of its nuclear fleet led to **increased dependence on imported fossil fuels** and **higher electricity prices.**
  - **90%** of energy demand was met by **imported fossil fuels.**
  - Shares of Tokyo Electric Power Co. (Tepco) **fell ~70% and it reported $27B+ in losses in 2011.**
- In 2013, Japan began **prioritizing energy independence**, setting the conditions for a nuclear renaissance.

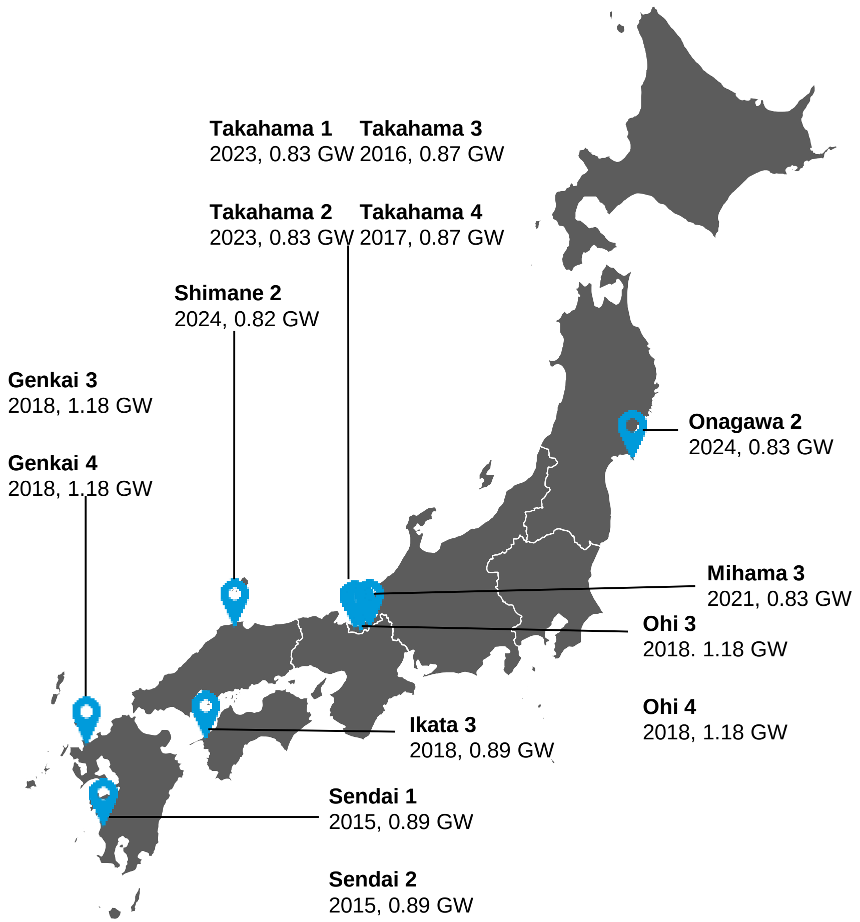
Key policy and finance levers

- Japan created the Nuclear Regulation Authority, **establishing new safety and regulatory requirements for nuclear plants in 2013**, with revisions in 2019.
  - **Tsunami protection, seismic approval, and local government consent** were included.
- The country's **2014 Strategic Energy Plan reintroduced nuclear as a baseload power source**, reinstating it as critical for domestic energy self-sufficiency.
  - By contrast, the previous administration had declared a zero-nuclear future in 2012.
- Implementation was **financed by a combination of private funding and government incentives. Total costs were estimated at $700M-$1B per plant.**

Impact

- Nuclear now **supplies ~8.5%** of Japan's energy demand (compared with ~29% in 2010), with a target of **20% by 2040.**
- A 2023 survey showed that **50%+ of the population supports restarting plants.**
- **Tepco's shares have seen a 200%+ share increase** since their lowest point ($1.50 in November 2012).

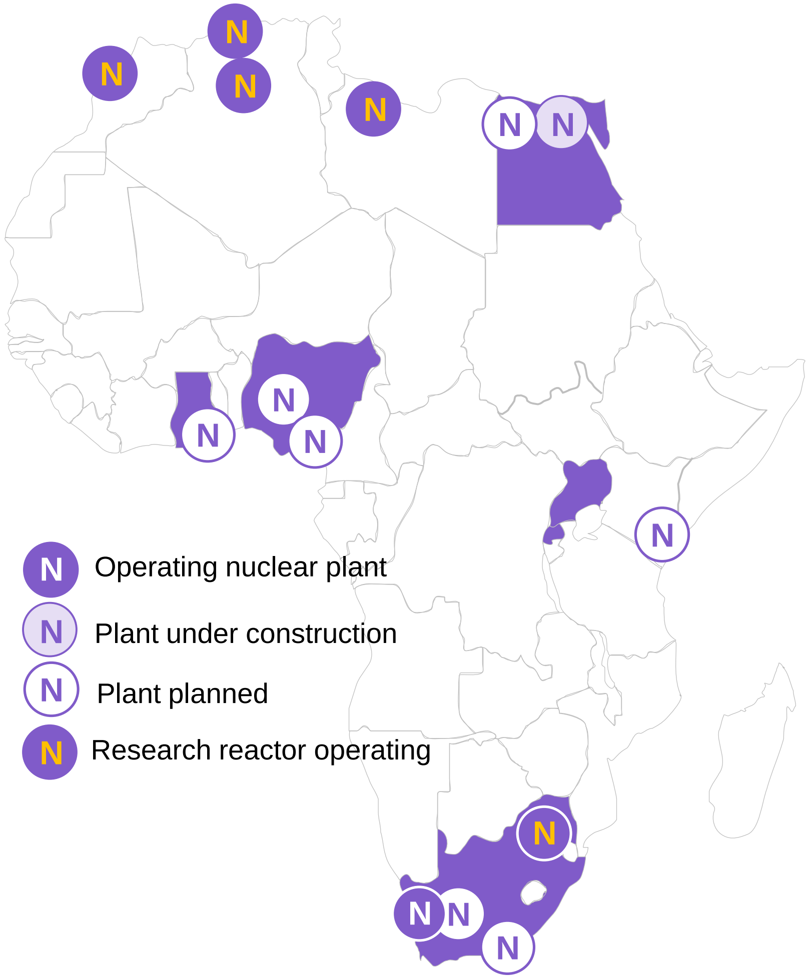
Japan's restarted nuclear reactors



Sources: EIA, Since Fukushima, Japan has restarted 14 nuclear reactors (2025); WNA, Nuclear Power in Japan (2025); Reuters, Tokyo Electric set to receive $5.9B financing (2013); Google Finance, TKECY (2025); IAEA, Japan (2025); Journal of Energy, Japan's 2014 Strategic Energy Plan (2017).

Credit: Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Many African countries are considering including nuclear power in their future energy mix; 8 plants are planned or under construction



Ghana

- Under the **Ghana Nuclear Power Program**, the country is in a preparatory work for the construction of its first nuclear power plant.
- It signed an agreement with a U.S. SMR developer, Regnum Technology Group, in 2024, to **deploy 12 SMRs.**

Nigeria

- The country aims to have **29.7 GW** of energy capacity by 2030, of which it plans to power 8% from nuclear power.
- **It is constructing its first nuclear power plant,** partnering with key nuclear leading countries such as Russia and China.

South Africa

- **Two reactors are in operation**, with a nuclear capacity of 1.8 GW.
- The operational lifetime of the Koeberg Unit 1 nuclear plant was extended for 20 years, until 2044.
- Plan to develop two SMR designs.

Egypt

- Aims to have 9% of electricity generated by nuclear by 2030.
- **4.8 GW power plant began construction** in November 2022 and is expected to be complete in 2028. The plant uses four large Russian reactors.

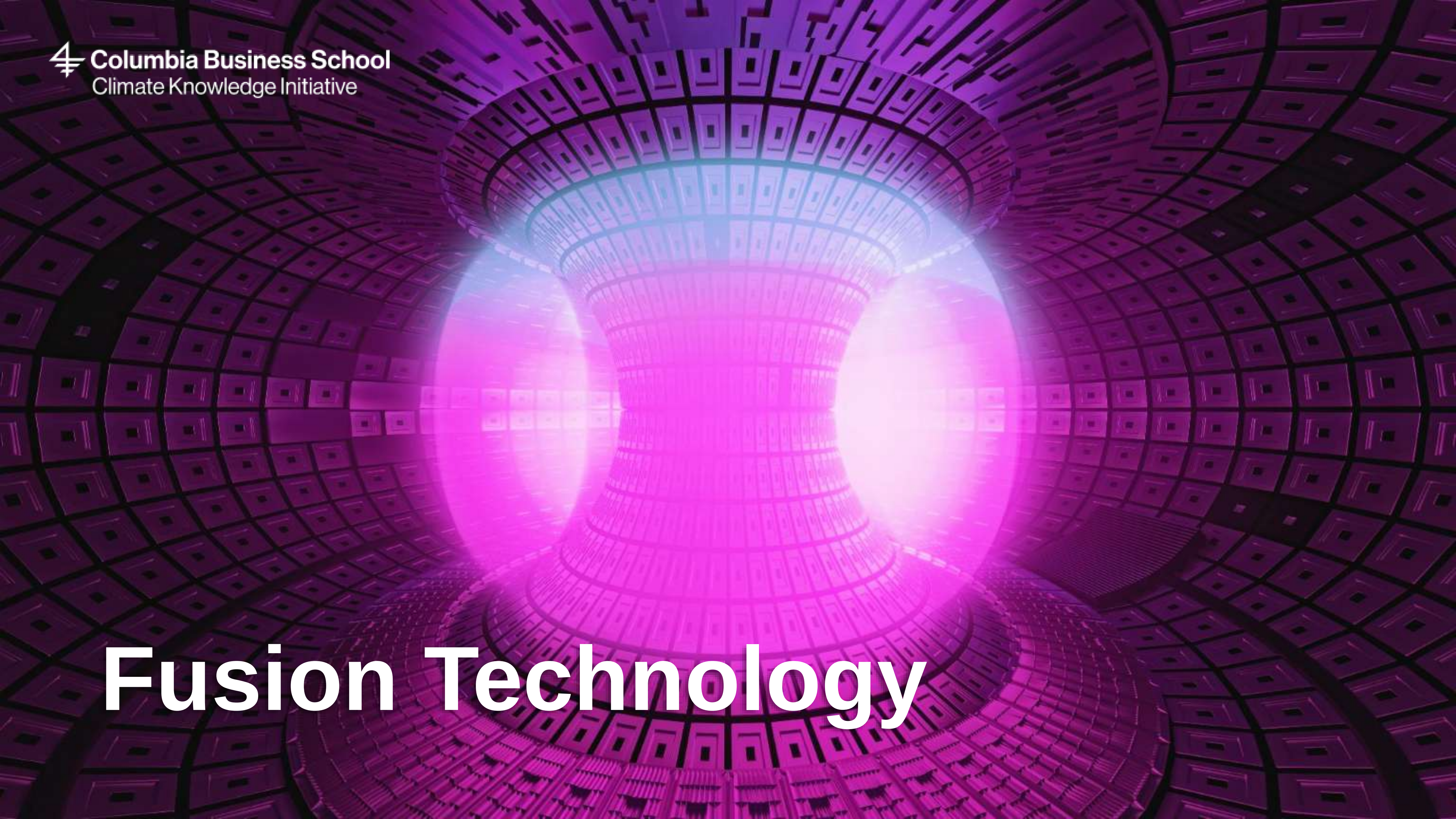
Uganda

- **Uganda Vision 2040**, created in April 2013, lays out the development of significant nuclear capacity for the country's future energy mix.
- Uganda has signed agreements with both Russia (Rosatom) and China (China National Nuclear Corporation).

Rwanda

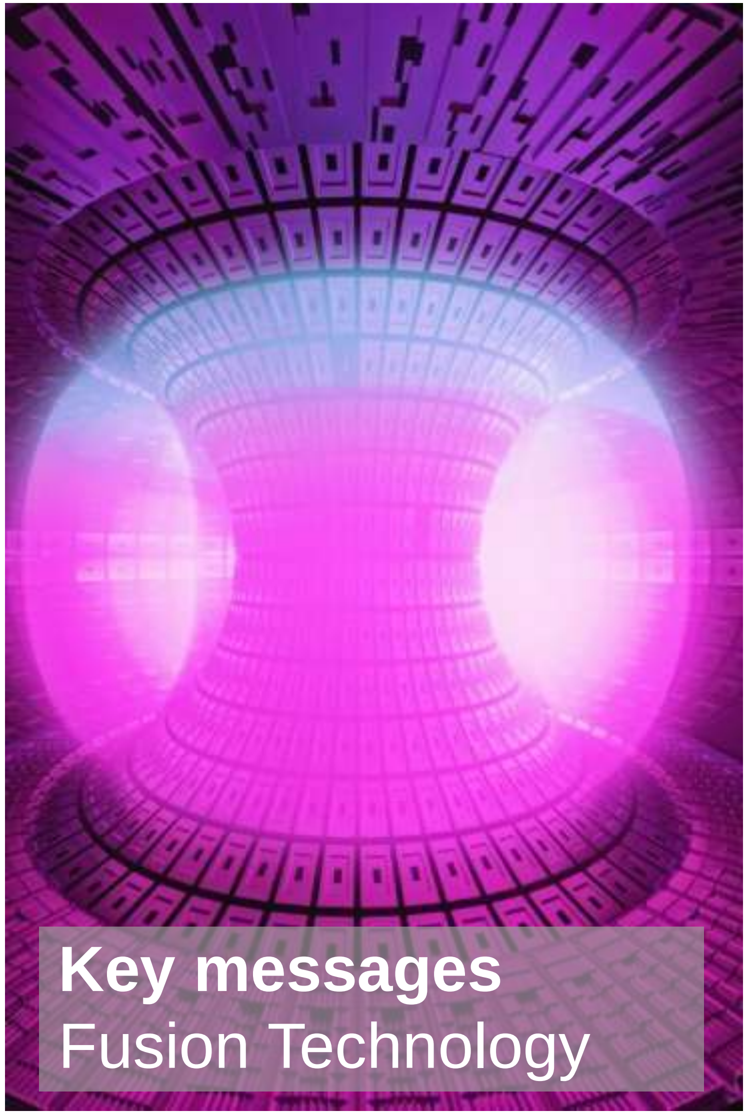
- In 2019, Rwanda decided to **collaborate with Russia** to build its first nuclear power plant.
- In September 2023, Rwanda's atomic energy board **signed a deal with a Canadian-German startup,** Dual Fluid Energy, to build a demonstration nuclear reactor.

Sources: IEA, The Path to a New Era for Nuclear Energy (2025); IAEA, Argentina Country Highlight (2024); African Energy Newsletter, More African governments consider nuclear power, but costs could scupper plans (2024); Energy for Growth Hub, 2023 Update: Who in Africa Is Ready for Nuclear Power? (2023); World Nuclear News, Permit Granted at El Dabaa (2025); Reuters, Ghana signs agreement to build small NuScale nuclear reactor (2024); Nuclear Business Platform, Nigeria's Path to Nuclear Energy (2024).
Credit: Hinako Arai, Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).



Columbia Business School
Climate Knowledge Initiative

Fusion Technology



Key messages
Fusion Technology

Fusion provides energy by fusing two nuclei instead of splitting an atom as in fission.

- Fusion can generate 8x as much energy as fission from 1 kilogram of fuel and without carbon emissions.
- It could theoretically be deployed anywhere in the world, as fuel (deuterium-tritium) is found in seawater and could be produced as a byproduct of fusion.

There are six stages to get to commercial fusion; the world is currently in phase four:

1. **Fusion starts by forming a plasma,** the fourth form of matter besides gas, liquid, and solid.
2. **The plasma needs to reach 100 million °C** to ensure sufficient energy to enable fusion.
3. **The plasma needs to become sufficiently dense and be sustained.**
4. **The reaction should get to a net energy gain;** the energy output exceeds the energy input needed to start and sustain the plasma.
5. **The reactor then has to generate exportable electricity.**
6. **Finally, fusion energy needs to be commercially competitive.**

There are two main approaches to fusion energy: magnetic confinement fusion (MCF) and inertial confinement fusion (ICF).

- MCF uses magnets to confine and control the plasma as it heats up to the point of fusion.
- ICF uses lasers to heat up a fuel pellet and create enough density to create a plasma and initiate fusion.

Recent years have seen an enormous increase in commercial fusion businesses, from 23 startups in 2021 to 43 in 2024, with a total of $7.1 billion in funding.

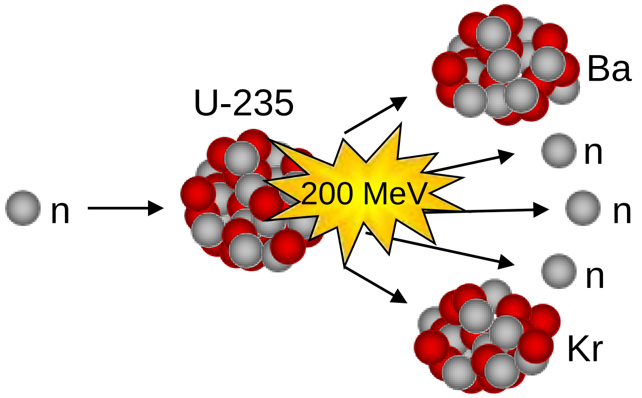
- Commonwealth Fusion Systems has received ~$2 billion in funding and is leading in MCF technology.
- Marvel Fusion has received ~$350 million in funding and is leading in ICF technology.

Most companies hope to have commercial fusion technology by 2035, although experts are skeptical.

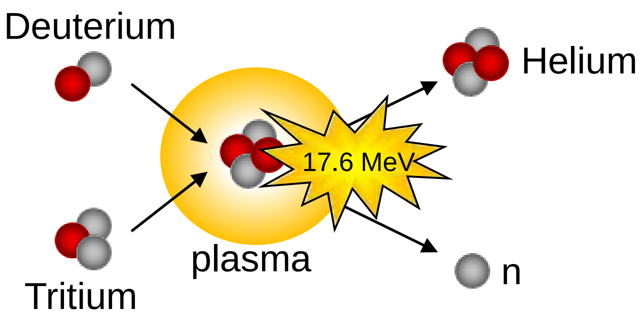
Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

In fusion, two light nuclei fuse release energy without highly radioactive byproducts or emissions

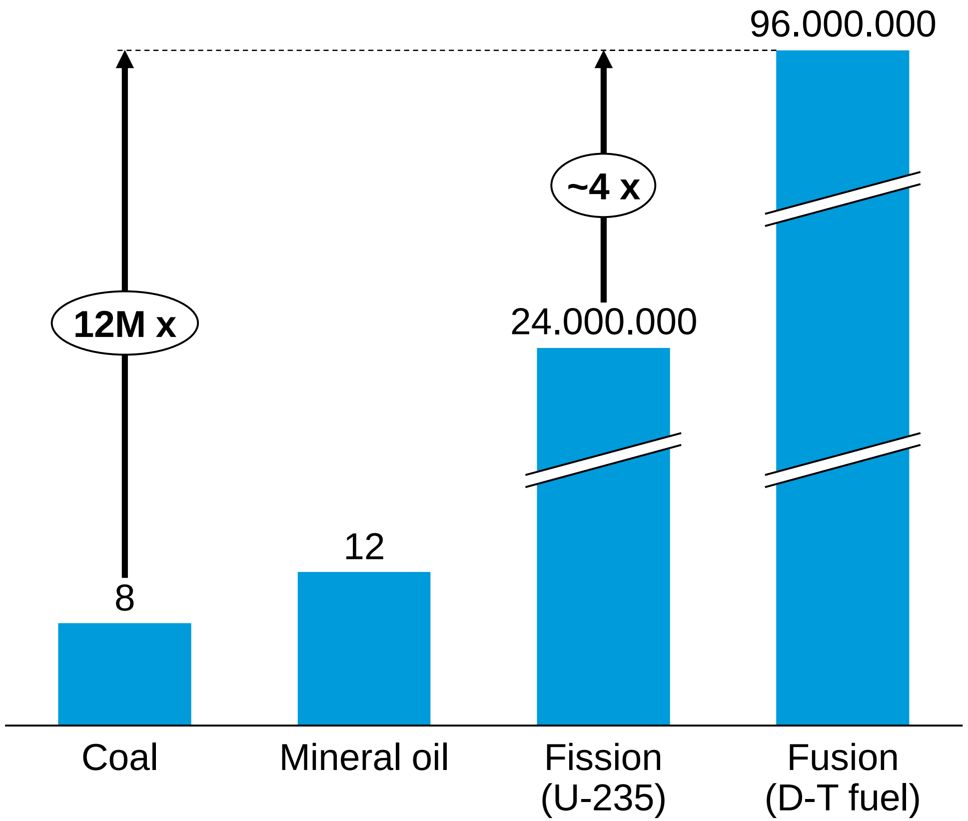
In fission, one heavy atom is split…



…while in fusion, two light nuclei are fused



Energy density for different energy sources, kWh



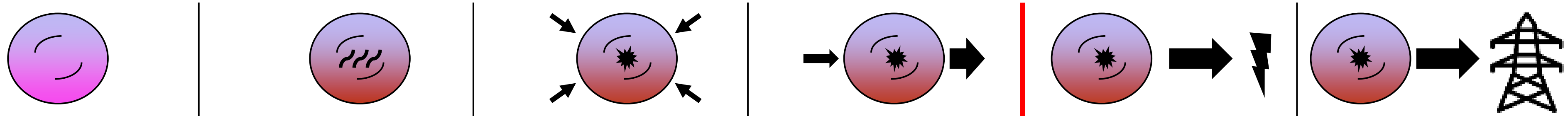
Observations

- The two nuclear energy types, **fission and fusion, split and fuse nuclei**, respectively, to release energy.
- Out of all energy sources, nuclear **fusion produces the most energy per kilogram of fuel,** even more than uranium-235.
- Unlike fossil fuels but like fission, fusion generates **zero CO_2 emissions during operation.**
- Fusion reactors **cannot melt down or explode** and **produce no long-lived radioactive waste,** making them **safer** than fission and fossil fuel plants.
- In theory, **fusion fuel could be generated anywhere in the world from seawater.**
- **Deuterium isotopes are naturally present in seawater.**
- **Tritium** (hydrogen isotopes) **is a byproduct of some fission reactors** and **could be a byproduct of fusion,** although experiments are still underway for this.

Sources: European Nuclear Society, Fuel comparison (2025); University of Leipzig, Energy fundamentals (2025); Greenly, Will nuclear fusion help solve our future energy needs? (2024); Baojie Nie, Nuclear fusion energy research (2024); ITER, Advantages of fusion energy (2025); ITER Tritium Breeding; DOE, DOE Explains...Deuterium-Tritium Fusion Fuel.

Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Fusion energy has achieved four of the six milestones to get to commercial viability



Stage	① Create plasma	② Heat plasma to 100 million °C	③ Reach sufficient density, be sustained	④ Achieve net energy gain	⑤ Generate exportable electricity	⑥ Achieve commercial viability
Description	**Plasma,** the fourth form of matter besides gas, liquid, and solid, **is needed for nuclei** (the positive ions) **to fuse.** Plasma is an extremely hot mix of negative electrons and positive ions.	**Plasma needs to reach 100 million °C to ensure sufficient ions collide.** Plasma is typically heated using lasers or radio waves, or by running a current through the plasma.	Plasma must reach **sufficient density and be sustained** in a fixed space. This is where advanced devices are required to contain and control the plasma.	A net gain means **the fusion energy output exceeds the energy input.** At this point, called ignition, the fusion can **sustain itself** (in theory, but in practice, obstacles remain).	After achieving net gain, **the machine as a whole needs to reach a net gain.** Typically, efficiency losses in the powerplant radically reduce the total gain.	**LCOE estimates for fusion range between $25 and $100 per MWh, but this range is extremely uncertain.** Like fission, costs are mostly driven by the high capital costs of the reactor.
Progress	Plasma has been was **identified in the 19th century.**	Plasma was first sufficiently heated **in the 1960s,** at Los Alamos National Laboratory.	The Joint European Torus (JET) was the first to take this step in **1991.**	In **2022**, the National Ignition Facility in California was able to get **3.15 MJ output** using **2.05 MJ input.**	Most continuous operating prototype power plants are scheduled for the **early 2030s.**	Most commercial companies hope to sell fusion energy by the **mid-2030s.**

Today

Sources: Fusion Industry Association, The Global Fusion Industry in 2024 (2024); ITER, Fusion Energy (2025); DoE, National Laboratory Makes History by Achieving Fusion Ignition (2022); McCabe, A timeline for fusion energy (2023); EU-Startups, Marvel Fusion bags additional €50 million for nuclear fusion and prototype facility (2025).
Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

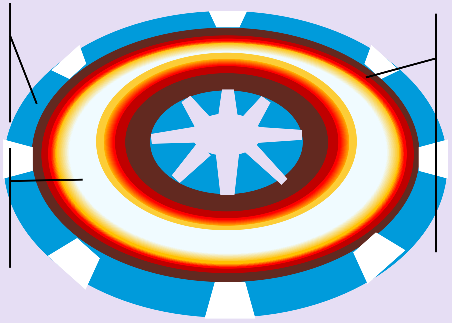
Columbia Business School
Climate Knowledge Initiative

Magnetic and laser-based confinement are in competition as companies take the fusion baton from flagship research projects

Magnetic confinement fusion (MCF)

Electromagnets confine and control the plasma.

The plasma is heated using EM waves or a current.



There are two leading magnet configurations: donut (**tokamak**) and a twisted donut (**stellarator**).

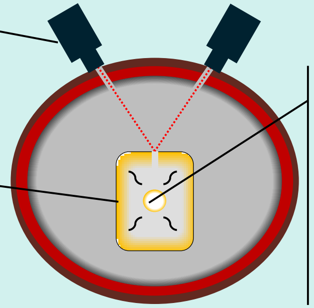
- ⊕ Can theoretically **sustain the fusion reaction indefinitely**, using the heat from the reaction to continue the plasma
- ⊕ Has seen the most research over the past decades; **~65% of startups use MCF**
- ⊖ **Instability issues plague MCF,** as it can cool down the plasma and damage the vessel wall
- ⊖ **A substantial amount of energy** (~20%) **is lost** in cooling the vessel and powering the electromagnets

ITER is the leading MCF research project in the world. This tokamak in France has received ~$18 billion in funding and is expecting to commence operations in the mid-2030s.

Inertial confinement fusion (ICF)

Powerful lasers send **high-frequency pulses** toward the target.

Either a fuel pellet is hit **directly** or ICF uses a **cavity** that heats up and emits X-rays hitting the fuel pellet **indirectly.**



As the outside of the pellet heats up, it compresses the inside to become plasma, **starting the fusion reaction.**

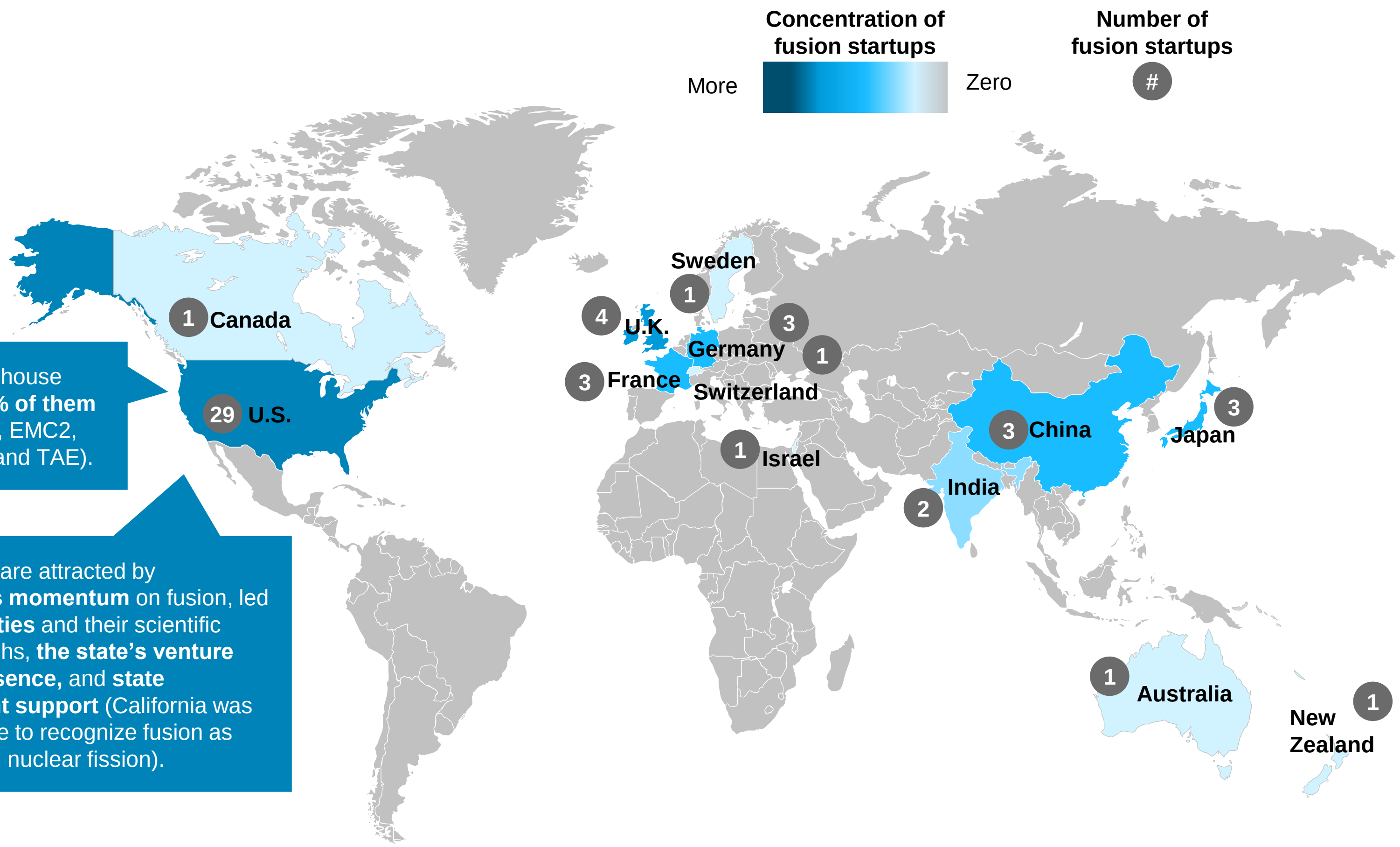
- ⊕ Can theoretically **reach higher densities and temperatures,** leading to better gains from the reaction itself
- ⊕ Is easier to manufacture in components and operate for short periods of time, **improving the operational flexibility**
- ⊖ **Requires extreme precision from the lasers** to fire on the tip of a pencil within a billionth of a second
- ⊖ **Low efficiencies** in the laser (<1% today) and the cavity X-ray conversion (<50%) need to be overcome to get an overall net gain

The Nation Ignition Facility in California was able to achieve a net gain (3.2 MJ from 2.1 MJ laser energy) for the first time in 2022 using ICF.

Sources: IAEA, Magnetic Fusion Confinement with Tokamaks and Stellarators (2021); NHSJS, Nuclear Fusion: Overview of Challenges and Recent Progress (2024); U.S. Fusion Energy, Approaches to Fusion (2025); Fusion Industry Association, The Global Fusion Industry in 2024 (2024); Kramer, National Ignition Facility surpasses long-awaited fusion milestone (2022).
Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Over half of fusion startups based in U.S., ~one-third in California

Private global fusion ecosystem landscape in 2025



10 out 50 U.S. states house **fusion startups**; **~30% of them are in California** (e.g., EMC2, Fuse, Helicity Space, and TAE).

Companies are attracted by **California's momentum** on fusion, led by **universities** and their scientific breakthroughs, **the state's venture capital presence,** and **state government support** (California was the first state to recognize fusion as distinct from nuclear fission).

Observations

- **Fusion has received a total of $9.7B** funding to date; **27% in 2025** and **92%** from **private sources.** Commonwealth Fusion Systems, TAE Technologies, and Helion Energy have all received over $1B.
- Most companies **(47%)** are **MCF** and use **deuterium-tritium as fuel (68%).**
- **Most fusion startups are backed by public-private partnerships**, with **the United States** being the country that provides the **most support** through the Department of Energy, including:
  1. **Milestone-based fusion development program:** Supports the development of a fusion pilot plant and fusion power commercialization.
  2. **Innovation network for fusion energy (INFUSE):** Provides access to national laboratories.
  3. **INCITE:** Provides **access to the DOE's supercomputing facilities.**
  4. **Chadwick:** Contributes **to the development of advanced materials for the first wall of fusion materials.**

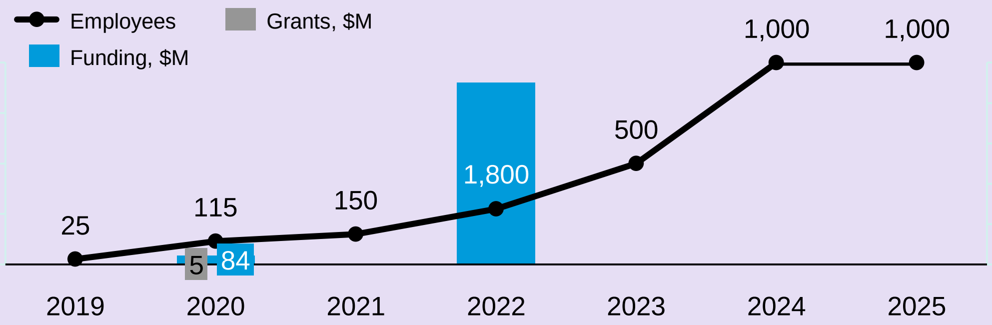
Sources: PitchBook, Company profiles (2025); MIT, MIT spinout Commonwealth Fusion Systems unveils plans for the world's first fusion power plant (2024); WNN, Germany's Marvel Fusion raises further EUR113 million (2025); Fusion Industry Association, The global fusion industry in 2025 (2025); Nuclear Engineering International, California recognises fusion energy as distinct from nuclear fission (2023).

Credit: Brenda Rain, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

The two leading startups in MCF and ICF are Commonwealth Fusion Systems and Marvel Fusion, respectively

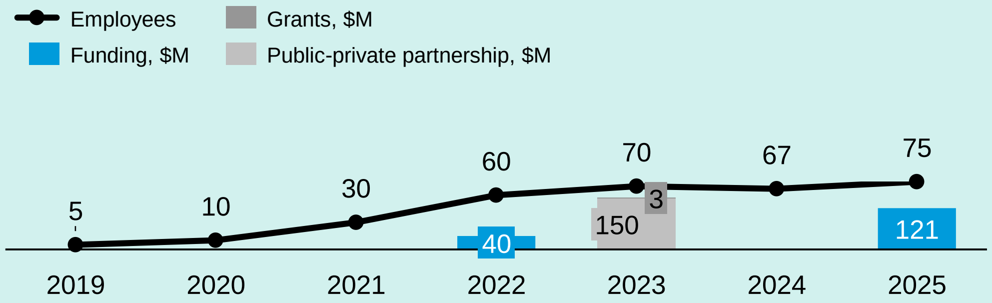
Commonwealth Fusion Systems

- Founded in 2018 as a spin-off from **MIT**, CFS is by far the best funded fusion company in the world with **~$2 billion in total funding.**
- CFS believes it can revolutionize fusion engineering employing its research into **high-temperature superconducting magnets.**
- The company aims to build a more compact tokamak, named **ARC, in the early 2030s with ~400 MW clean power.**
- Before that, CFS is developing SPARC to pave the way for ARC. **SPARC is expected to produce plasma in 2026 and have a net gain shortly after.**



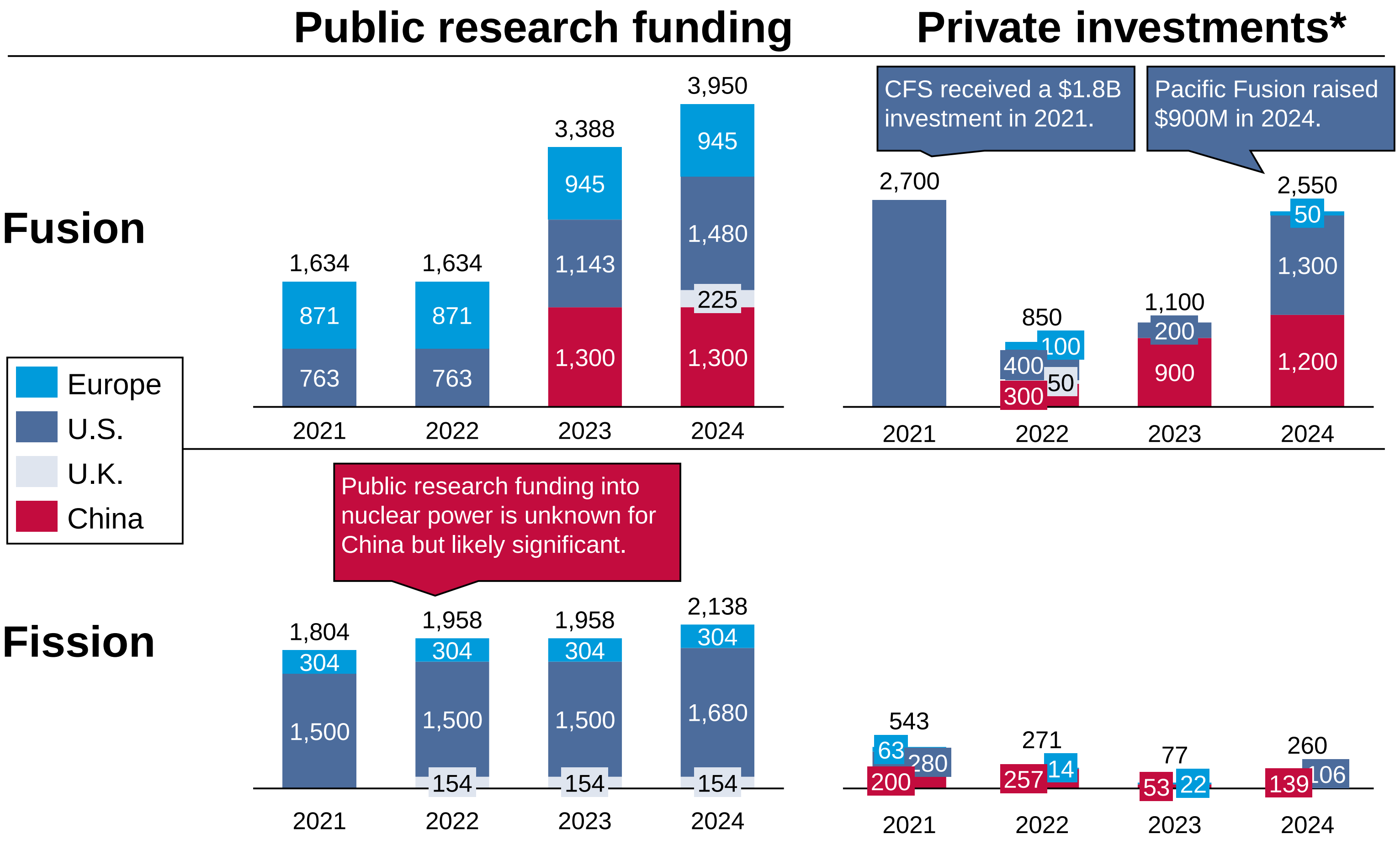
MarvelFusion

- **Marvel was founded in 2019 following the Nobel Prize in physics in 2018 for breakthrough laser technologies.**
- Using this novel laser technology and new fuel pellets, Marvel believes it can **improve the efficiency of NIF** to reach commercially viable fusion energy by the mid-2030s.
- The company is building a **$150 million proof of technology with Colorado State University** to test the new laser technology by 2027.
- Marvel aims to build its **first power plant prototype** with **Siemens Energy** by **2032** and have **commercial power by 2035.**



Sources: PitchBook, Company profiles (2025); MIT, MIT spinout Commonwealth Fusion Systems unveils plans for the world's first fusion power plant (2024); WNN, Germany's Marvel Fusion raises further EUR113 million (2025).
Credit: Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Despite a long timeline to commercialization, fusion is collecting significantly more funding than fission, driven by ambitious policy



CFS received a $1.8B investment in 2021.

Pacific Fusion raised $900M in 2024.

Public research funding into nuclear power is unknown for China but likely significant.

Nuclear fusion policy around the world

Governments worldwide have designed policies on how to regulate fusion and how to incentivize it.

United States

- Fusion **regulated as particle accelerators**, making it easier to develop than fission power plants
- **Approved $790M annual research funding**, including $40M for private firms under milestone-based program

European Union

- **Fusion regulations the same as that for fission** reactors
- **Funds fusion** under the Euratom Treaty **at $871M annually;** Germany has had additional funding since 2023

United Kingdom

- Fusion **regulated by the Environmental Agency**, not the nuclear regulator
- **Subsidizes £410M** for STEP tokamak project until 2027

China

- **Aims to lead fusion tech through its ~$1.5B annual fusion spend**, but regulations similar to that for fission
- Has deployed the **only new tokamak since 2019**

(*) Does not include PE investments or state enterprises.

Sources: PitchBook, Nuclear power deal flow (2025); Fusion Industry Association, The Global Fusion Industry in 2024 (2024); Gov.uk, Government announces up to £650 million for UK alternatives to Euratom R&T (2023); Neutron Bytes, Mixed Messages from Congress on Funding Nuclear Energy (2021); EC, Euratom (2025); CFS, The race to lead the world in fusion has begun (2025); Gov.uk, Plan for Change to deliver jobs and growth in UK leading fusion industry (2025); Utility Dive, The answer is a fusion moonshot (2024); AIP, FY23 Budget Outcomes: National Nuclear Security Administration (2023); FIA, FIA Urges Prioritization of Commercializing Fusion Energy (2024); WNN, Germany stepping up investment in fusion (2023).

Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

CKI Nuclear Team

Quint Houwink

Master of Business Administration

CKI Fellow

Khande-Jaé Fisher

Masters of Science in Sustainability Science

CKI Fellow

Isabel Hoyos

Master of Sustainability Management

Staff Associate, Climate Knowledge Initiative

Adele Teh

Master of Business Administration

CKI Fellow

Brenda Rain

Master of Sustainability Management

CKI Fellow

Hyae Ryung (Helen) Kim

PhD in Sustainable Development

Senior Research Fellow

hk2901@columbia.edu

Hinako Arai

Master of International Affairs

CKI Fellow

Christian Sandjaja

Master of Sustainability Management

CKI Fellow

Gernot Wagner

Senior Lecturer, Columbia Business School

Faculty Director, Climate Knowledge Initiative

gwagner@columbia.edu

Vedant Bhansali

BA Financial Economics

CKI Fellow

Clara Zibell

BA Sustainable Development

CKI Fellow

Attribution: Houwink et al., "Reenergizing Nuclear" Columbia Business School Climate Knowledge Initiative (2025).

Columbia Business School
Climate Knowledge Initiative

Appendix

Comparison of current and upcoming nuclear and geothermal technologies for clean baseload electricity supply

Scale of 1-5 (least to most desirable)

	Nuclear		Geothermal	
	Large-scale nuclear	**SMRs**	**Conventional geothermal**	**Enhanced geothermal systems (EGS)**
Capacity factor (CF)	●●●●● 92.3%	●●●●● Potential to stagger SMRs for greater CF but not yet proven	●●●●○ 70-90%	●●●○○ Geothermal energy potential increases with depth (higher temps)
Siting flexibility	●●●○○ Specific siting requirements according to safety, environment, seismicity, etc.	●●●●● Possible to site in remote areas or smaller grids	●●○○○ Limited to naturally occurring reservoirs	●●●●○ More flexible than conventional geothermal
Cost (LCOE)[1]	●●●○○ $141-$228/MWh, high CapEx	●●●●○ $50-120/MWh (lower though uncertain)	●●●●○ $66-$109/MWh	●●●○○ $200/MWh; costs based on initial demonstration
Lifespan	●●●●● 32 years on average, possible to extend up to 80 years	●●●●● 6 to 80 years expected (yet unproven)	●●●●○ 25 years, extendable	○○○○○ Uncertain
Ramp rate	●●●○○ 5-10% per minute depending on reactor design	●●●○○ 5% per minute (expected)	●●●●○ 15% per minute, full range 0-100%	○○○○○ Uncertain
Land use[1]	●●●●○ 2.4km^2/TWh per year, 500 acres	●●●●● Modular, 35 acres per site	●●○○○ 7.5km^2/TWh per year, larger surface infrastructure	●●○○○ Like conventional but more complex engineering

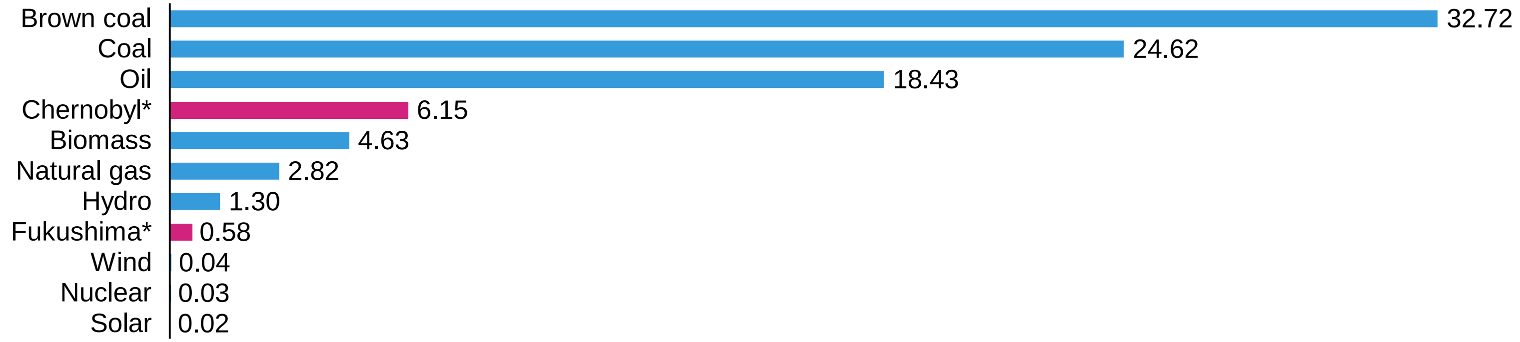
[1] Note that axes are inverted so that lowest values reflect desirability (i.e., lower price = more desirable → score = 5)

Sources: IAEA, Non-Baseload Operation in Nuclear Power Plants (2023); IAEA, What are SMRs (2023); DOE, Benefits of SMRs (2025); EIA, Nuclear FAQ (2025); Feutry et al., Nuclear Power Plant Flexibility at EDF (2019); NREL, Annual Technology Baseline: Nuclear (2024); Detering, Nuclear Is a Dispatchable Energy Source (2023); Lovering et al., Land Use Intensity of Electricity Production (2022); IEA, The Future of Geothermal Energy (2024); , What is generation capacity (2025).

Credit: Clara Zibell, Isabel Hoyos, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Traditional reactors have a proven safety track record, while SMRs take it further with built-in passive protections

Death rates per TWh electricity produced



SMR vs. traditional plant safety difference

Feature	Small modular reactor	Traditional plant
Safety systems	Passive cooling systems, simpler design ✚	Active cooling systems, complex design
Radioactive inventory	Smaller inventory	Larger inventory ✚
Containment structures	Less robust	More robust ✚
Emergency planning zones	Reduced (e.g., site boundary)	Larger zones (10+ miles) ✚
Risk from natural hazards	Underground siting reduces some risks ✚	Above-ground siting increases exposure
Cumulative risk (multiple units)	Higher if many modules are used	Centralized risk in single reactor ✚

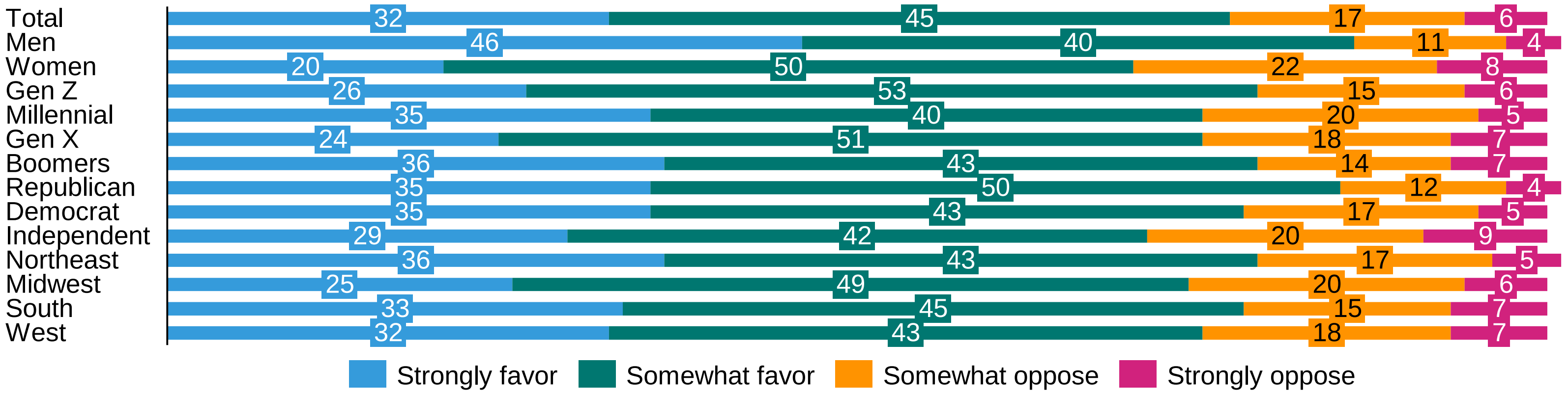
Observations

- Nuclear energy stands out as **one of the safest energy sources**, significantly lower than fossil fuels like coal and oil.
- This stark contrast **underscores nuclear's potential to deliver clean and safe energy** at scale.
- SMRs build on this safety advantage with **passive systems**, **smaller radioactive inventories**, and **underground siting**.
- However, **less robust containment and scalability risks** mean that safety gains depend on strong regulatory oversight.
- SMRs are particularly suited for **remote or rural regions** with limited grid infrastructure, **industrial sectors requiring heat or electricity**, and **nuclear first-timer countries** that try to adopt nuclear energy.

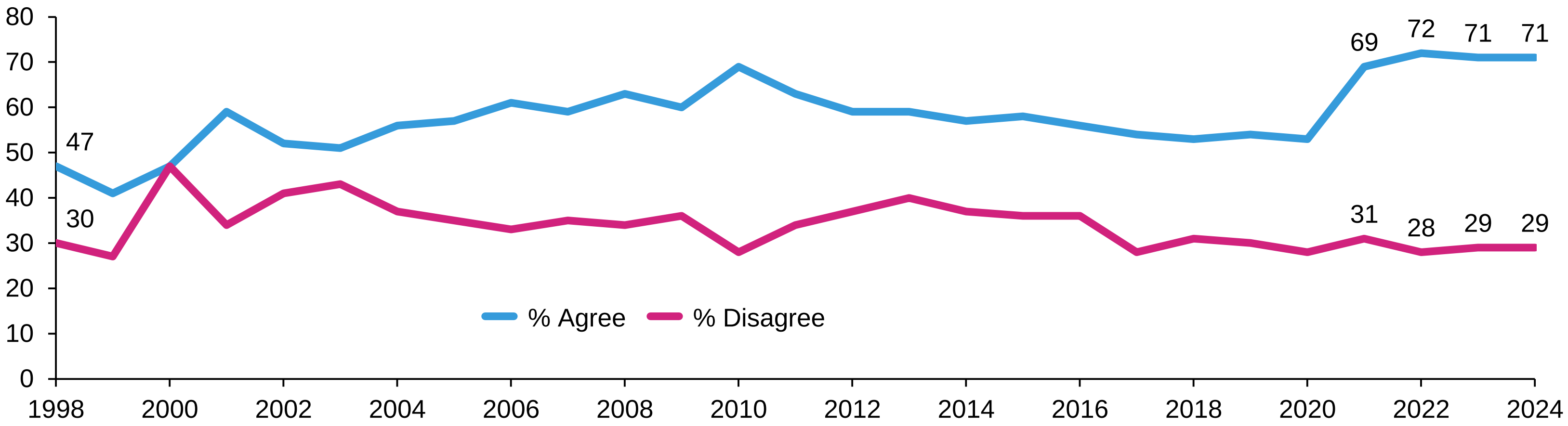
Sources: Nuclear Innovation Alliance, Safety (2021); European Commission, Small Modular Reactors Explained (2024); Union of Concerned Scientists, Small Modular Reactors (2013); NuScale Power, Nuclear Power and Safety (2025); Our World in Data, Death rates per unit of electricity production (2016).
Credit: Christian Sandjaja, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Various U.S. demographic groups support including nuclear in the energy mix and favor expanding nuclear capacity

U.S. sentiment toward using nuclear in energy mix by demographic



U.S sentiment toward building more nuclear power plants



Observations

- Nuclear's mortality rate is **significantly lower** than other energy sources, making it one of the safest energy source options.
- A few **notable nuclear accidents**:
    - **Chernobyl** – A **critical design flaw**, compounded by operator errors and a poor safety culture, resulted in an uncontrollable fission reaction and subsequent steam explosions.
    - **Fukushima** – **Loss of both off-site power and backup generators** due to flooding eliminated the ability to pump coolant to the reactor, making it impossible to cool the fuel even after shutdown.
- Modern nuclear reactors **incorporate major advancements in safety principles,** which supports positive sentiment.
- Due to increased safety, more U.S. power plants renewed their licenses, **backed by local community support.**

Sources: DOE, Pathways to Commercial Liftoff: Carbon Management (2023); Energy Research & Social Science, Establishing Leadership in Bringing CCUS to Scale (2025); Our World in Data, Death rates from energy production per TWh (2021); Bisconti, Record High Support for Nuclear Energy (2024); Nuclear Innovation Alliance, Safety (2025).

Credit: Christian Sandjaja, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Nuclear waste is much smaller in volume and has significantly fewer negative externalities than any other energy source

Waste management by energy source

Energy source	Nuclear	Solar PV	Wind	Coal
Operational waste products	Spent fuel rod and unprocessed uranium (radiotoxic)	End-of-life solar panels	Turbine blades	Coal ash (contains arsenic, lead, mercury) and greenhouse gases
Volume (kg/MWh)	0.03	1.67	0.16	89
Waste management	Near-surface disposal for LLW and deep geological disposal for ILW and HLW	Landfills or recycling (14% global recycling rate**)	Landfills and incineration most common	Landfills and reuse in other materials (concrete or wallboard)
Waste risks and challenges	Long-term disposal of HLW remains a challenge	Trace amounts of lead in solar PV solders	Microplastics pollution from blade degradation	Contaminates soil, water, and air sources, posing threats to human health
Toxicity	L H*	M	L	H
Recyclability	M **	M **	H	L

Observations

- **Waste** from nuclear energy **is strictly regulated and contained** while waste from other sources is disposed into the environment.
- While coal releases greenhouse gases directly into the atmosphere, nuclear, solar PV, and wind also generate some emissions throughout their lifecycle (manufacturing, mining, installation).
- Coal and nuclear generate operational waste, while waste for solar and wind is end of life.

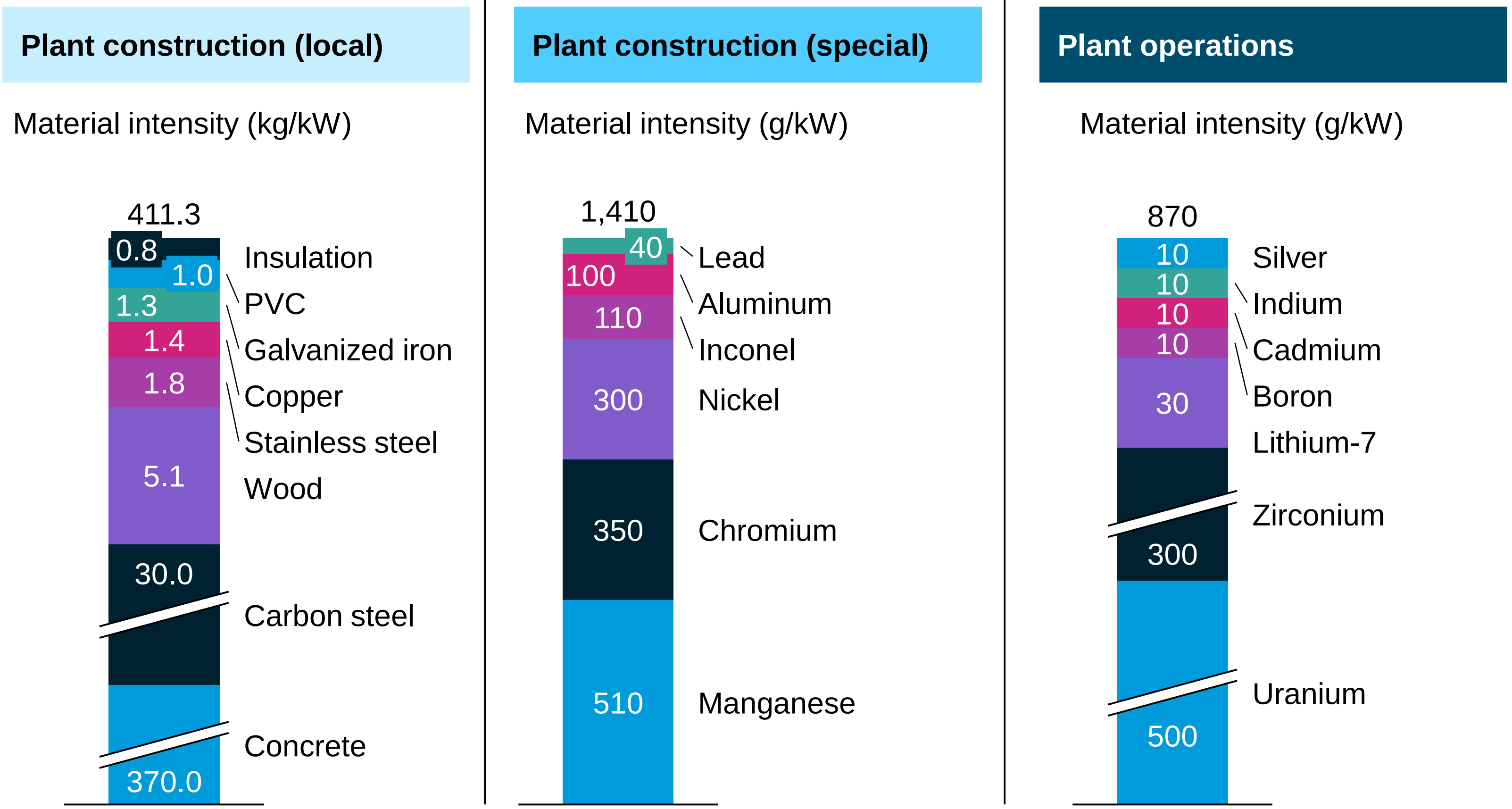
(*) Radiotoxicity is harmful only in the event of improper waste management. (**) Varies by region.

Sources: Sustainability by numbers, How much waste do solar panels and wind turbines produce? (2023); MDPI, The End of Life of Solar PV Systems (2023); Science Direct, End-of-life solar voltaic waste management (2024); MDPI, Waste Management of Wind Turbine Blades (2024); EPA, Coal Ash Basics (2025).

Credit: Clara Zibell and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Nuclear power operations are highly dependent on strategic elements such as lithium-7, uranium, zirconium, and indium

Overview of material intensity by type


Plant construction (local) | **Plant construction (special)** | **Plant operations**

Observations

Concrete

- Safety considerations are the main factor determining the amount of concrete needed in a nuclear plant.
- After safety incidents and the 9/11 attacks, the regulations for nuclear plants were tightened and concrete requirements nearly doubled since the 1960s.
- In Gen IV reactors, the concrete requirement has decreased fivefold due to smarter design.

Zirconium

- Zirconium is used in fuel cladding to encase uranium fuel pellets in reactors.
- Low neutron absorption allows efficient reactions; it is highly corrosion-resistant.
- Zirconium must be purified to remove hafnium, which absorbs neutrons.

Uranium (recoverable)

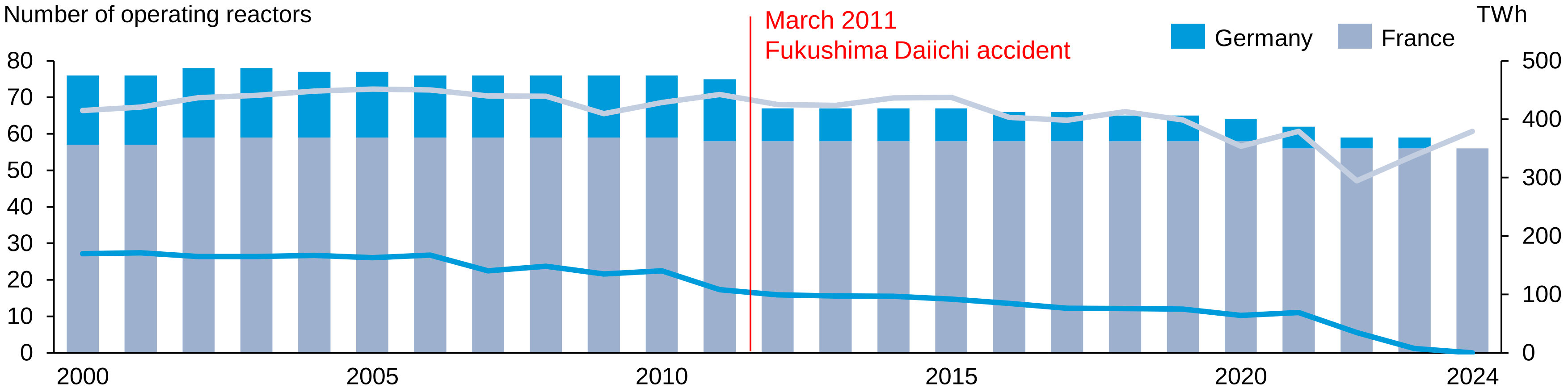
- It is a primary fuel source in nuclear reactors, with uranium-235 undergoing fission to generate energy.
- Uranium is typically processed into uranium dioxide (UO_2) pellets and encased in zirconium fuel rods.
- It has a heavily fluctuating price.

Sources: DoE, Nuclear Energy Supply Chain Deep Dive Assess (2022); Ashby, Materials and the Environment Ch. 12 (2013); WNA, Advanced Nuclear Power Reactors (2021); Peterson *et al*., Metal And Concrete Inputs For Several Nuclear Power Plants (2005).

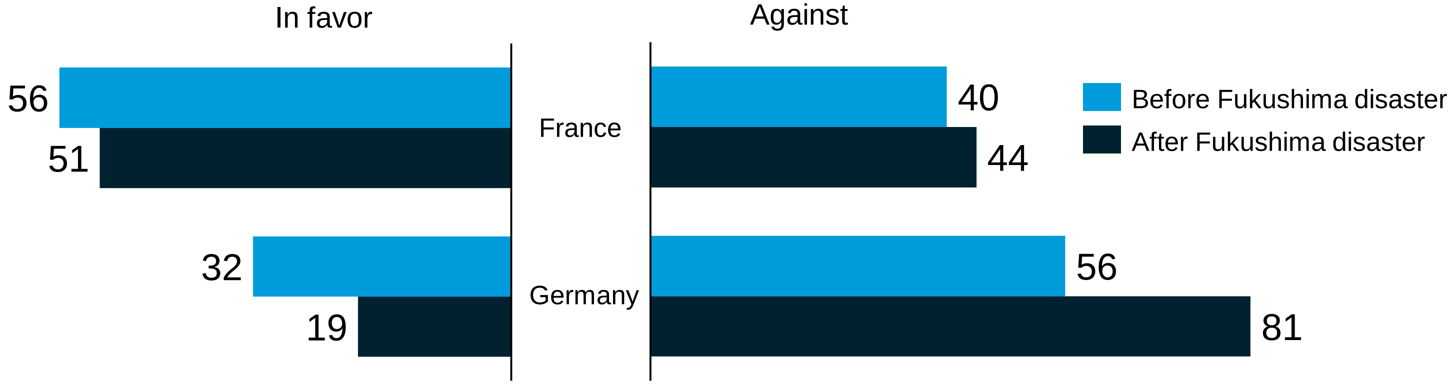
Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Post-Fukushima, Germany quickly decided to shut down reactors; France maintained policy stance given its high reliance on nuclear

Electricity generation from nuclear power and number of operating reactors



Public perception on the use of nuclear energy (%)



Observations

In response to the Fukushima Daiichi disaster in March 2011, France and Germany followed a diverging policy path.

- **France:** Then-President Nicolas Sarkozy stood steadfast on using nuclear power plants given that **74% of the country's electricity supply came from nuclear** at that time. Despite large anti-nuclear protests, the government focused on securing jobs by keeping the plants open.
- **Germany:** Germany had its nuclear phaseout policy from 2002 but decided in 2010 to extend the operating life to continue using nuclear energy while shifting to renewable energy. However, three days after the Fukushima accident in 2011, Germany declared **a three-month nuclear moratorium.** All plants constructed pre-1980 were shut down immediately and all other operating plants underwent stress testing.

Sources: Ember, Electricity Data Explorer (2024); Columbia K=1 Project Center for Nuclear Studies, France: A Study of French Nuclear Policy After Fukushima (2012); Asahi Shimbun, Opposition to Nuclear Growing (2011); Bundestag, The Nuclear Phase-out in Germany (2024); Willsher, Nicolas Sarkozy makes €1bn Commitment to Nuclear Power (2011).

Credit: Hinako Arai, Quint Houwink, and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Glossary

ADR	Advanced modular reactor
APAC	Asia Pacific
AI	Artificial intelligence
ARG	Argentina
BWR	Boiling water reactor
CAN	Canada
CapEx	Capital expenditures
CCUS	Carbon capture, utilization, and storage
CFS	Commonwealth Fusion Systems
COP	Conference of the Parties
CO_2	Carbon dioxide
D-T fuel	Deuterium-tritium fusion fuel
DGD	Deep geological disposal
DOE	Department of Energy
EM	Electromagnetic
EPC	Engineering, procurement, and construction
EPR	European pressurized reactor
EU	European Union
ETS	Emissions Trading System
FOAK	First of a kind
GHG	Greenhouse gas
GT	Gigatonnes
HALEU	High-assay low-enriched uranium
HTGR	High-temperature gas-cooled reactor
HLW	High-level waste
IAEA	International Atomic Energy Agency
ICF	Inertial confinement fusions
IDC	Interest during construction
IEA	International Energy Agency
ILW	Intermediate-level waste
IRA	Inflation Reduction Act
ITC	Investment Tax Credit
JAP	Japan
JET	Joint European Torus
kWh	Kilowatt-hour
LCOE	Levelized cost of energy
LCOH	Levelized cost of hydrogen
LEU	Low-enriched uranium
LMR	Liquid metal reactor
LLW	Low-level waste
LULCF	Land use, land-use change, and forestry
LWR	Light water reactors
MCF	Magnetic confinement fusion

Columbia Business School
Climate Knowledge Initiative

Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Glossary (cont.)

MeV	Megaelectron volts
MJ	Megajoules
MSR	Molten salt reactor
MOX	Mixed oxide fuel
MWe	Megawatt electrical
NIF	National Ignition Facility
NRC	National Regulatory Commission
O&M	Operations & maintenance
OCC	Overnight capital costs
OEM	Original equipment manufacturer
PDP	Power Development Plan
PTC	Production Tax Credit
PV	Photovoltaic
PWR	Pressurized water reactor
R&D	Research & development
ROK	Republic of Korea
RUS	Russia
SMRs	Small modular reactors
STEPS	Stated Policies Scenario (IEA)
U-235	Uranium-235
UKR	Ukraine
UO_2	Greenhouse gas
VAT	Value-added tax
VLLW	Very low-level waste

Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).

Units, Calculations, and References

One watt equates to one **joule** of energy per second.
In electrical systems, power (**watts**) is calculated by multiplying voltage (**volts**) by current (**amps**).

Kilowatt (kW)	1,000 (1 thousand) watts
Megawatt (MW)	1,000,000 (1 million) watts
Gigawatt (GW)	1,000,000,000 (1 billion) watts
Terawatt (TW)	1,000,000,000,000 (1 trillion) watts

Credit: Quint Houwink and Gernot Wagner. Share with attribution: Houwink et al., "Reenergizing Nuclear" (23 September 2025).