MEEN 40090: Energy Systems & Climate Change
28th October 2025

Nuclear Energy (1)

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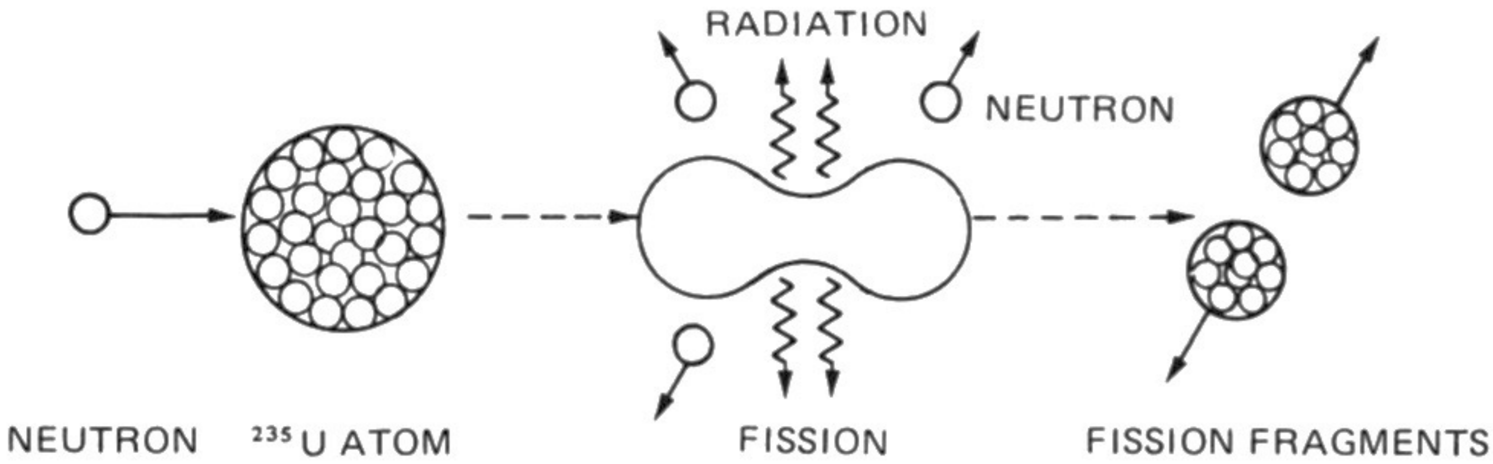
Nuclear energy – Outline

- Brief overview of the evolution and current status of nuclear energy.
- The nuclear fuel cycle, physics of nuclear fission processes and fundamentals of thermal fission reactor design.
- Evolution of reactor design (Generation I to Generation IV).
- Outlook of nuclear power in the medium and long term (contribution to reduction of CO_2 emissions, availability of resources, cost of nuclear energy, management of waste).

Nuclear energy - Overview

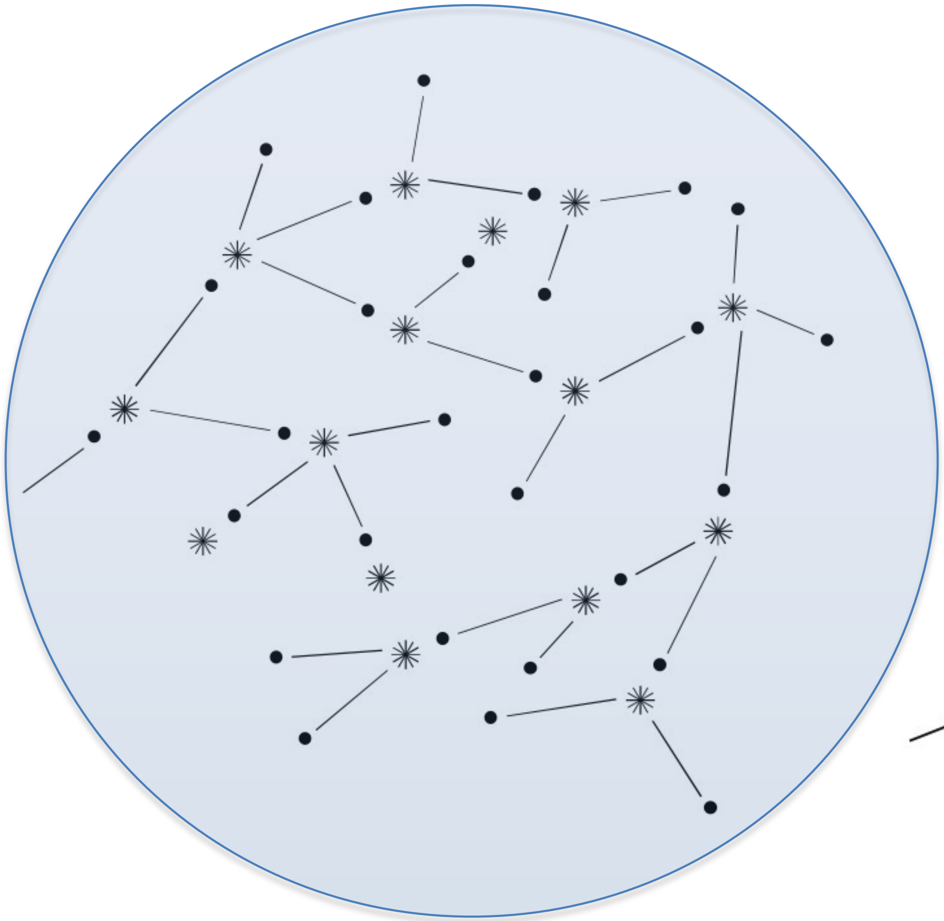
As an energy source, can deliver substantial amounts of energy without any significant emission of greenhouse gases.



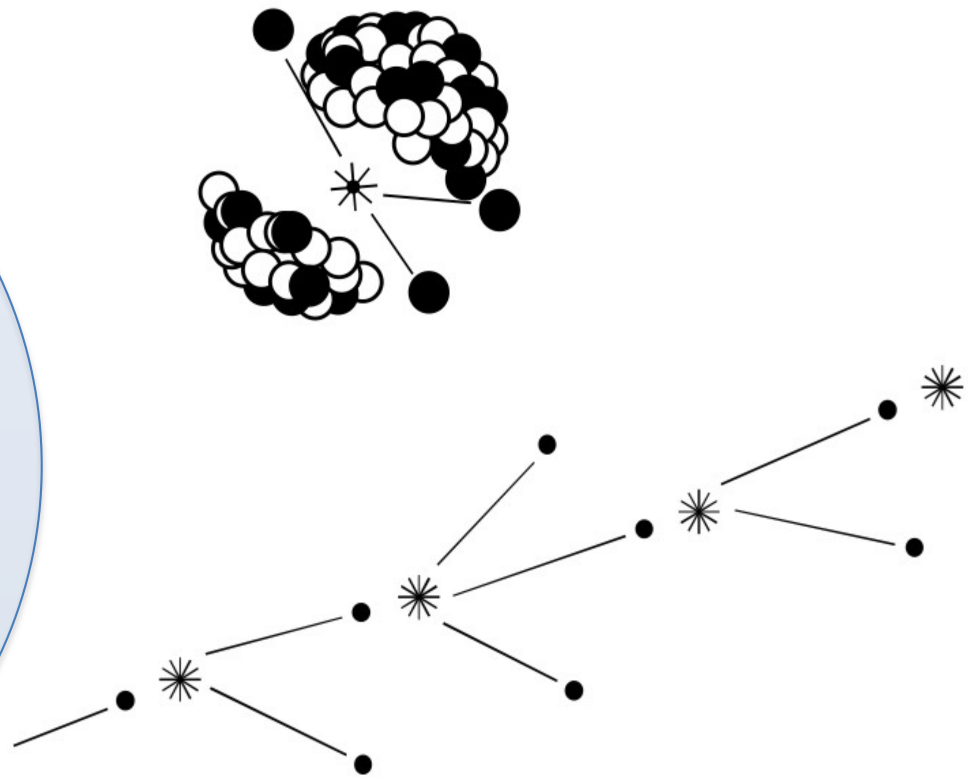
Source: Knief,2008

- major advantage: each such splitting provides one hundred million times as much energy as the 'burning' of one carbon atom in a fossil fuel, without the emission of CO_2.

- Production of more neutrons during the fission process, means that there is a potential to set up a self-sustaining chain reaction.



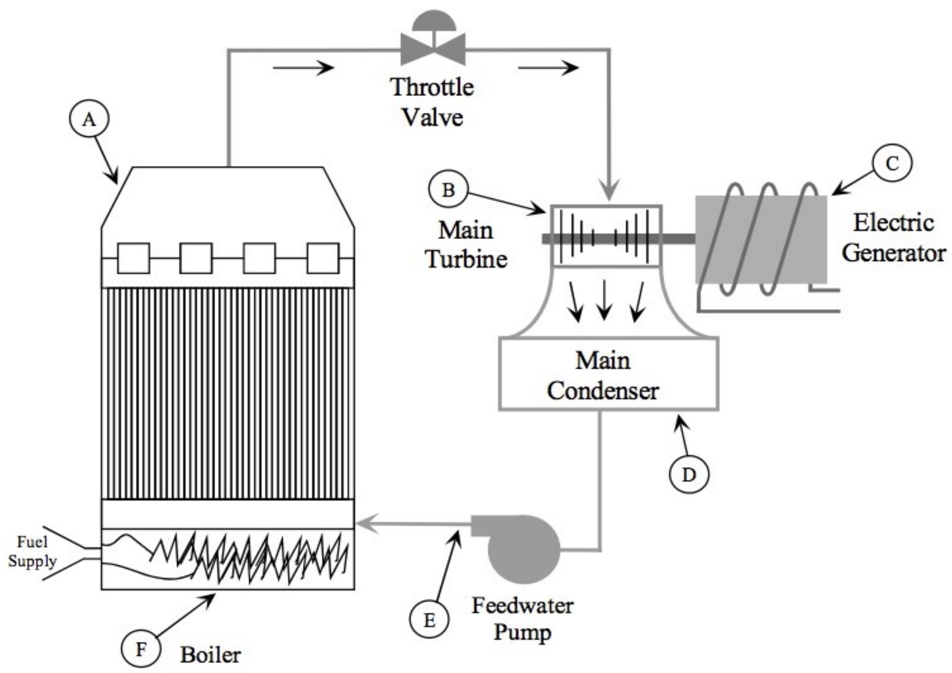
Chain reaction



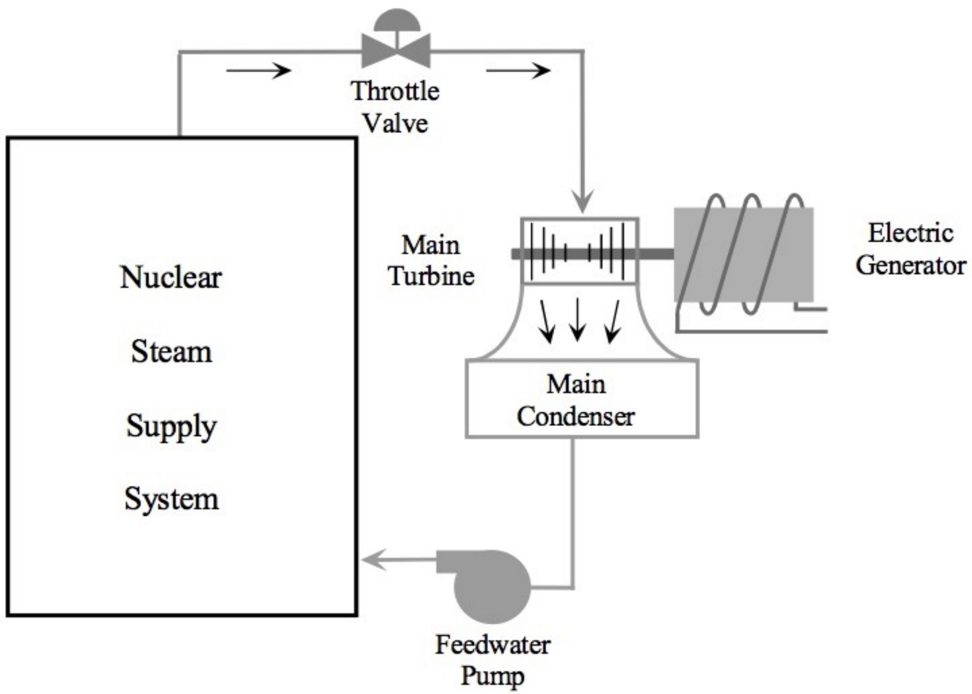
Steady state power generation (criticality)

Source: USNRC

- Working principle similar to other electrical generating facilities (e.g., conventional fossil fuel plants), except that the steam boiler is replaced by a nuclear steam supply system.



Fossil fuel steam plant



Nuclear power plant

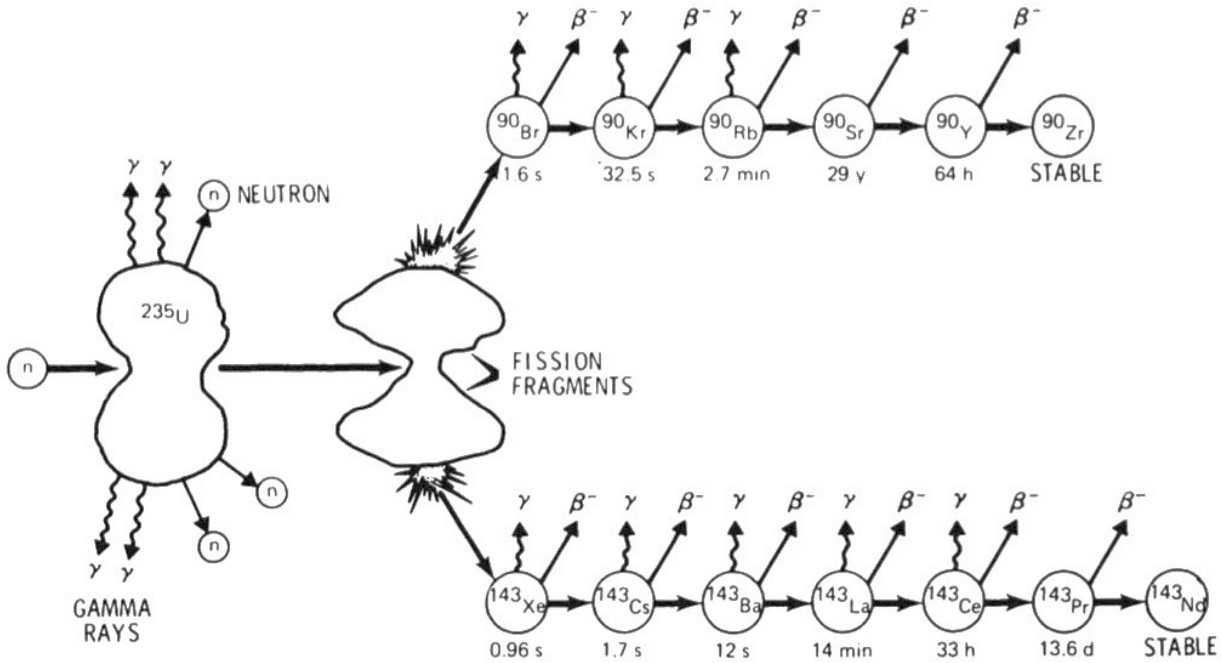
Source: USNRC

Nuclear energy – Advantages

- Nuclear power plants can deliver very large amounts of power per mass of fuel consumed, providing a highly concentrated form of energy – easily and cheaply transportable in comparison with fossil fuels;
- Nuclear energy emits no CO_2 during the end-use stage of its life cycle;
- Nuclear energy is not affected by the intermittency and grid integration challenges of renewable energies (e.g., wind, PV solar).

Nuclear energy – Disadvantages

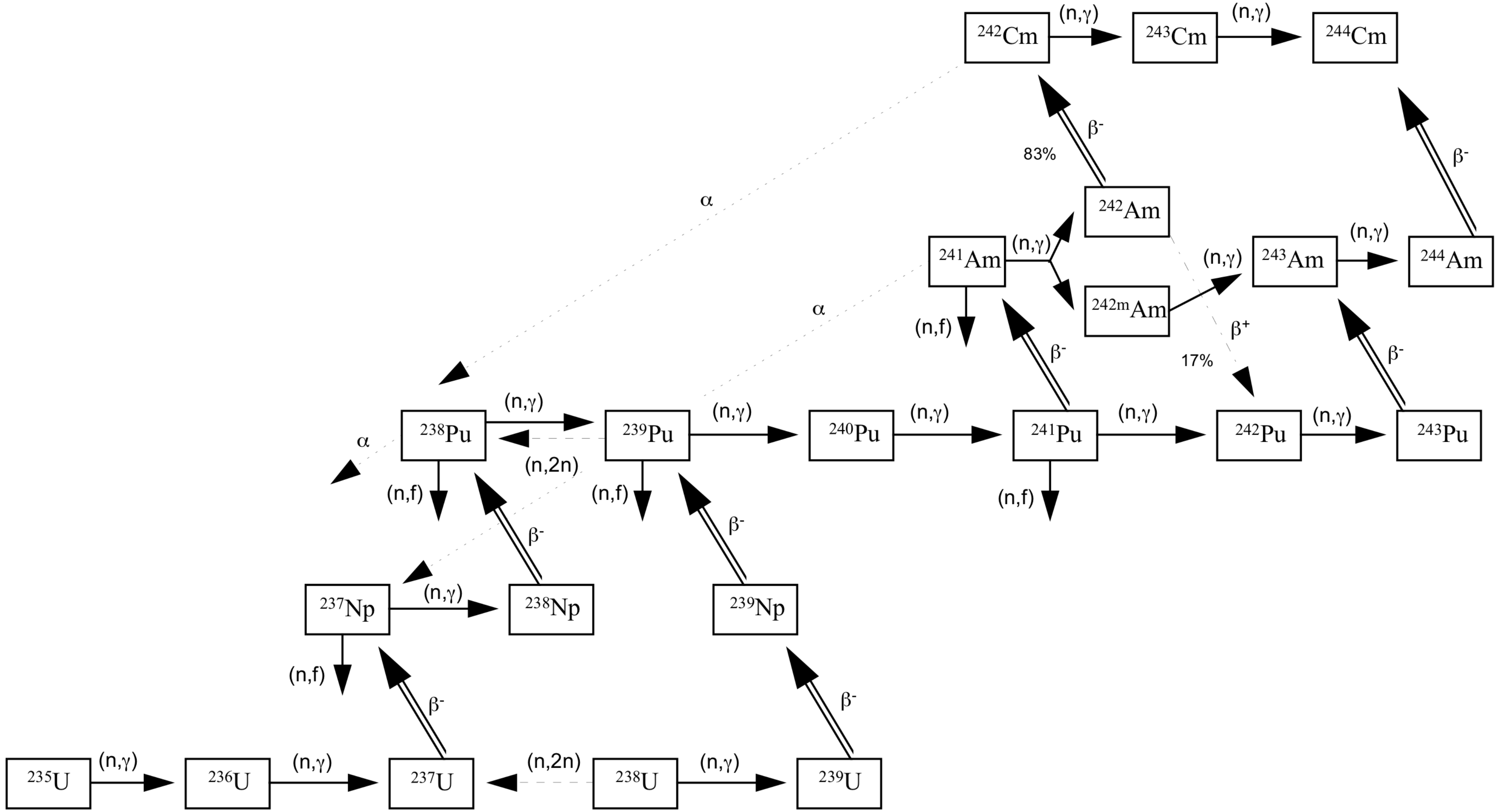
- Generation of intense radiation at time of fission, and presence of radioactive by-products with varying half-lives.



Source: Knief,2008

Requires shielding of reactors, containment of fuel, careful transport of by-products, and management of high-level nuclear waste that includes isotopes that remain radioactive for thousands of years.

Nuclear energy – Disadvantages



Simplified reaction chain for the production of transuranium isotopes in a thermal fission nuclear reactor

Source: Schultz,1976; NEA, 1989

Nuclear energy – Disadvantages (cont'd)

- Vulnerability of nuclear power plants to low-probability, high-consequence accidents;
- Perceived reactor safety risk becomes a public acceptance issue;
- Relative small availability of primary fuel in comparison with other sustainable resources (e.g., solar, wind), which will require exploitation of more expensive uranium resources, or the development of alternative fission reactor designs (fast fission and breeder reactors);
- Potential for the diversion of produced fissile material (e.g. Pu) for the development of nuclear weapons;
- High capital costs, with danger of long construction periods and delays resulting in rapidly scalating costs.

Drawbacks are not exclusive to nuclear energy ...

- high capital costs
- effects of inundating large extensions of land

- intermittency
- grid integration challenges
- visual and auditory effects

- intermittency
- grid integration challenges
- use of toxic materials

- energy – Food/water aspects
- emissions of NOx and SOx
- transportation and processing

Source: World Energy Council, 2013

A brief history of nuclear energy

Following the discovery of the neutron by Chadwick in 1932, Fermi and his co-workers in Rome carried out a number of neutron irradiation experiments in the mid-1930s, including the slow neutron irradiation of uranium.

The expected reaction was

$$^{238}\mathrm{U} + \mathrm{n} \rightarrow {}^{239}\mathrm{U} + \gamma$$

with the nuclide ^{239}U possibly exhibiting β decay.

Fermi and co-workers in Rome

They indeed observed a number of β decays with different half-lives, and believed that transuranic elements with Z = 93, 94, 95, 96, … were being produced.

Although preliminary chemical tests seemed to confirm this hypothesis, more elaborate tests in the late 1930s by Hahn, Meitner and Strassmann in Germany showed that elements from the middle of the periodic table were, in fact, the products, e.g., barium and lanthanum.

They bombarded solutions of uranium salts with **thermal** neutrons and found that after bombardment a number of new radionuclides were present.

Hahn and Meitner in the laboratory

By 1939, after numerous tests, Hahn and Strassmann positively identified one of these elements as **barium**.

A mechanism that could explain how a middle mass element such as barium (Z = 56) could be produced in this fashion did not exist! Hahn and Strassmann were confounded.

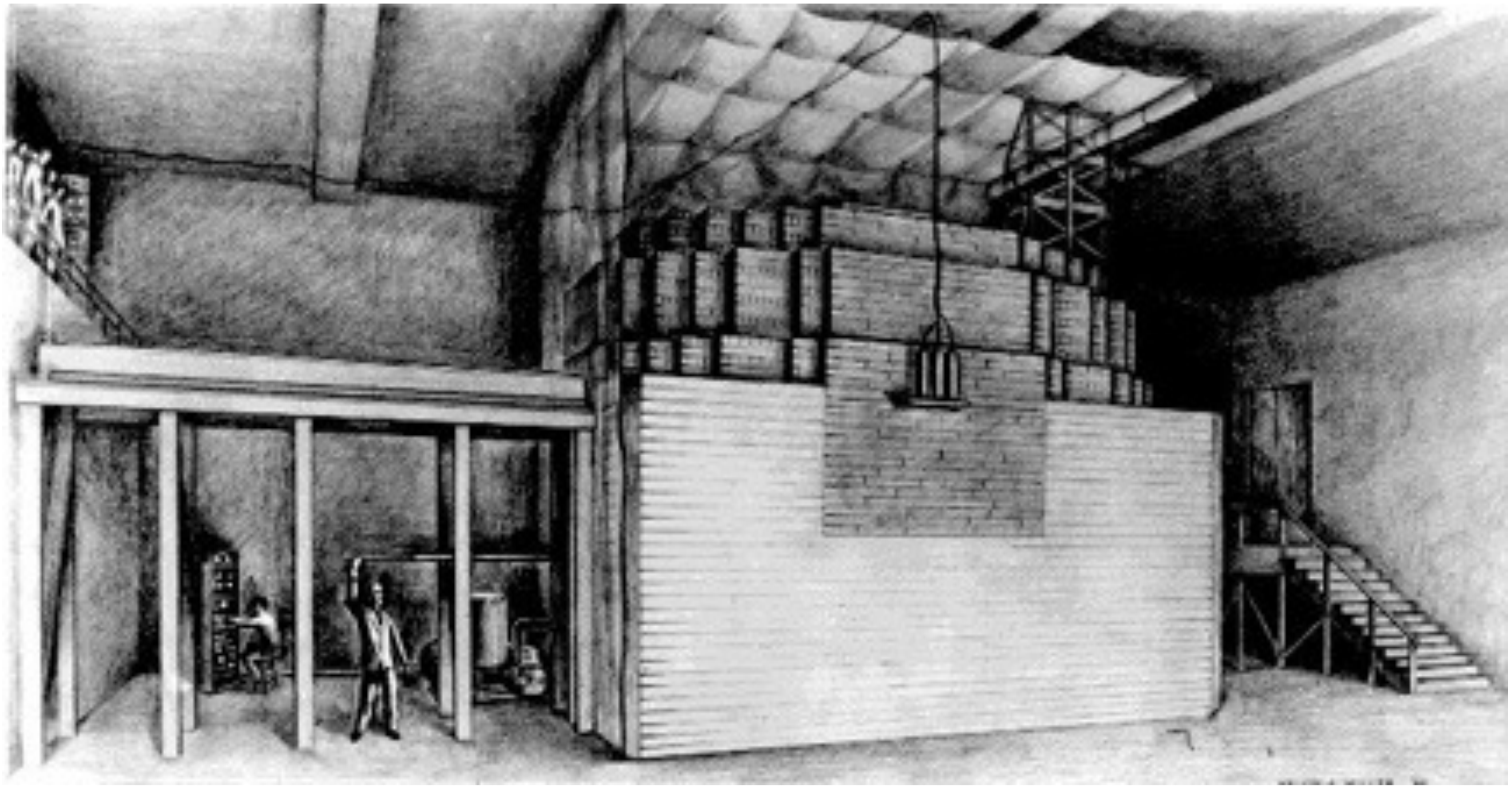
However, the puzzle was solved within a few weeks by Meitner and her nephew Otto Frisch.

Using the liquid drop model proposed by Bohr, they proposed the mechanism by which a uranium nucleus, having absorbed a thermal neutron, could split, with the release of energy, into two roughly equal fragments, one of which might well be barium. Frisch name the process **fission**.

Otto Frisch and his idea of the fission process

A brief history of nuclear energy

December 2, 1942: CP-1 at University of Chicago



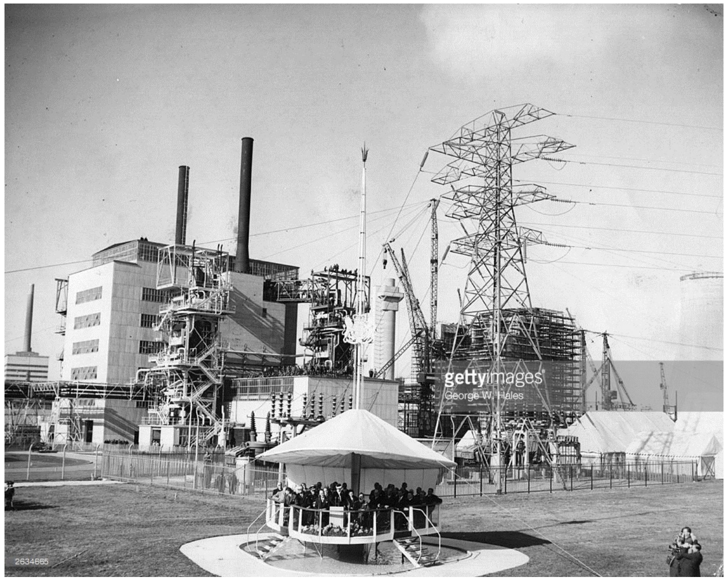
The Fermi experimental pile, the first controlled chain reaction

Early development after World War II

- Several pre-commercial research and test reactors and facilities were constructed at the National Reactor Testing Station at Idaho (US). **1951:** electricity generated for use inside a building;

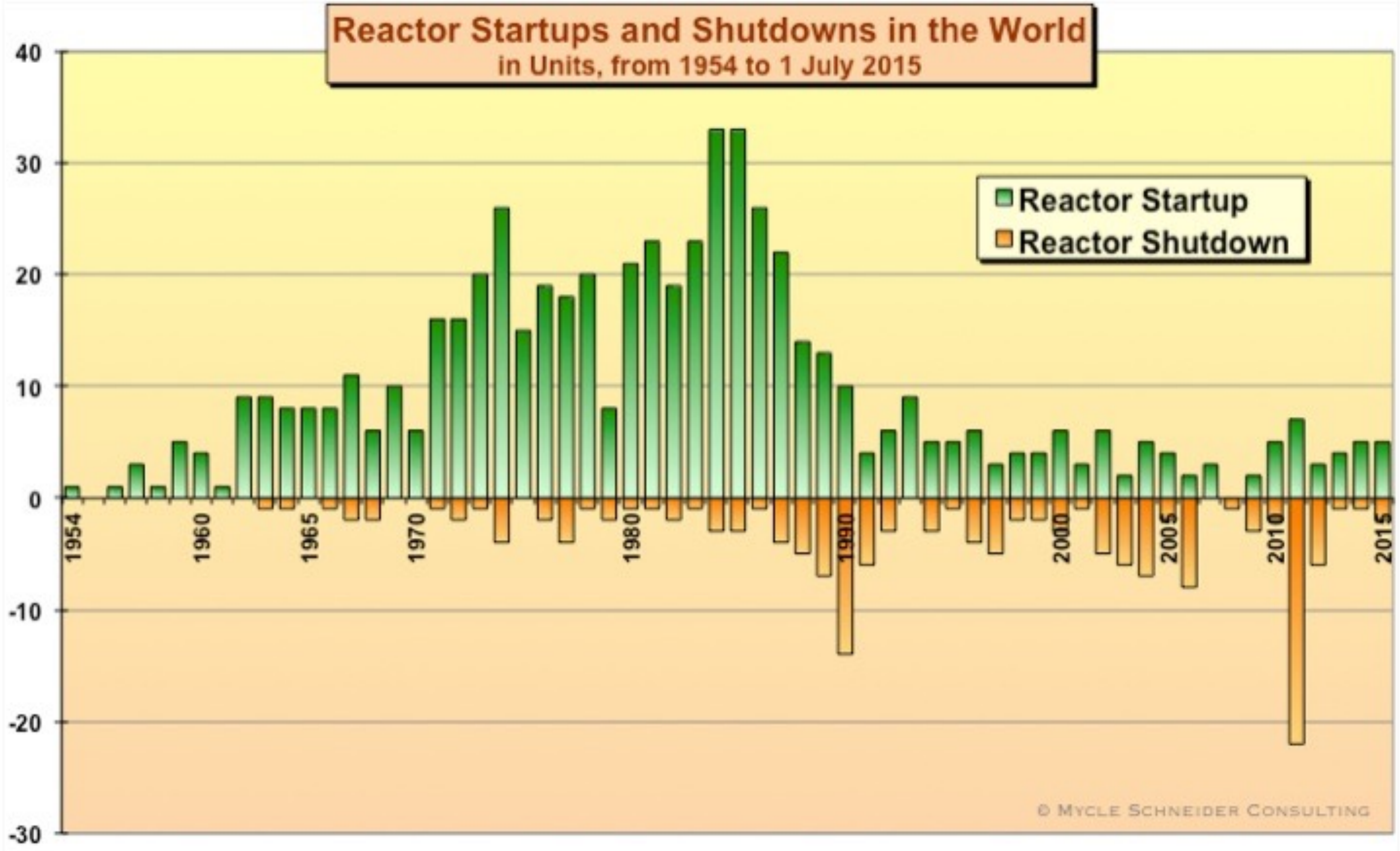
- **1954:** A 5-MW reactor at Obninsk (USSR) delivers power to the grid for the first time;

- **1956:** First commercial nuclear plant (50-MW) begins operations at Calder Hall (UK).



A period of significant growth (1960s – 1980s)

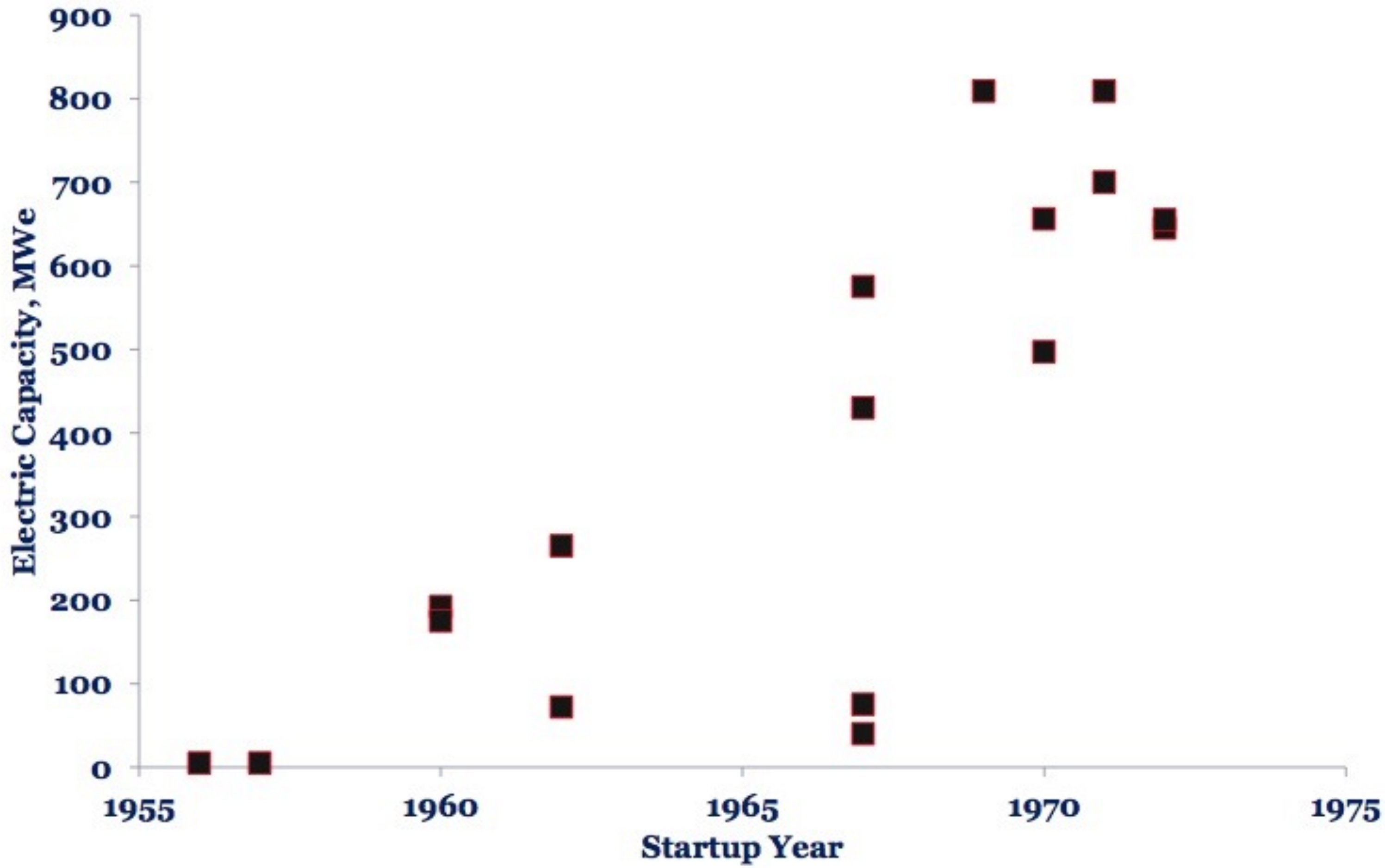
- Rapid expansion until the late 1980s, with peaks in 1974 and 1984/5.
- Growth slowed down by the Three Mile Island (1978) and Chernobyl (1986) accidents.



Nuclear power reactor grid connections and shutdowns, 1954-2015

Sources: IAEA-PRIS, World Nuclear Industry Status Report (2015)

Early technology scale-up – Electric capacity evolution

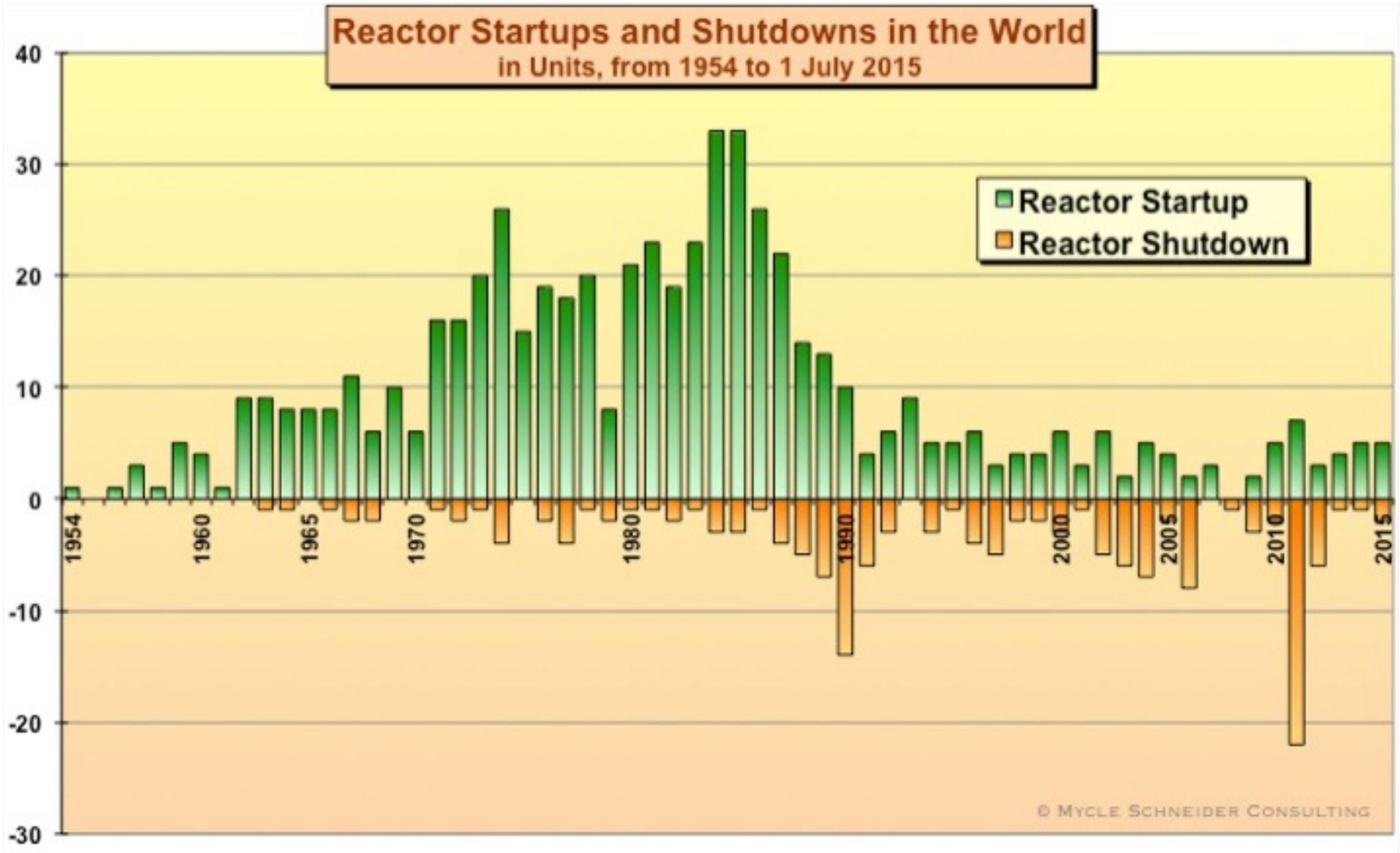


US reactor electric capacity as a function of startup date

Sources: NAMP (2015)

Decline in growth (1990s – present)

- 1991-2000 showed more startups than shutdowns (52/30)
- 2001-2010 startups outweighed by shutdowns (32/35)
- 2011-2015 trend of previous decade has continued (24/32) - Fukushima

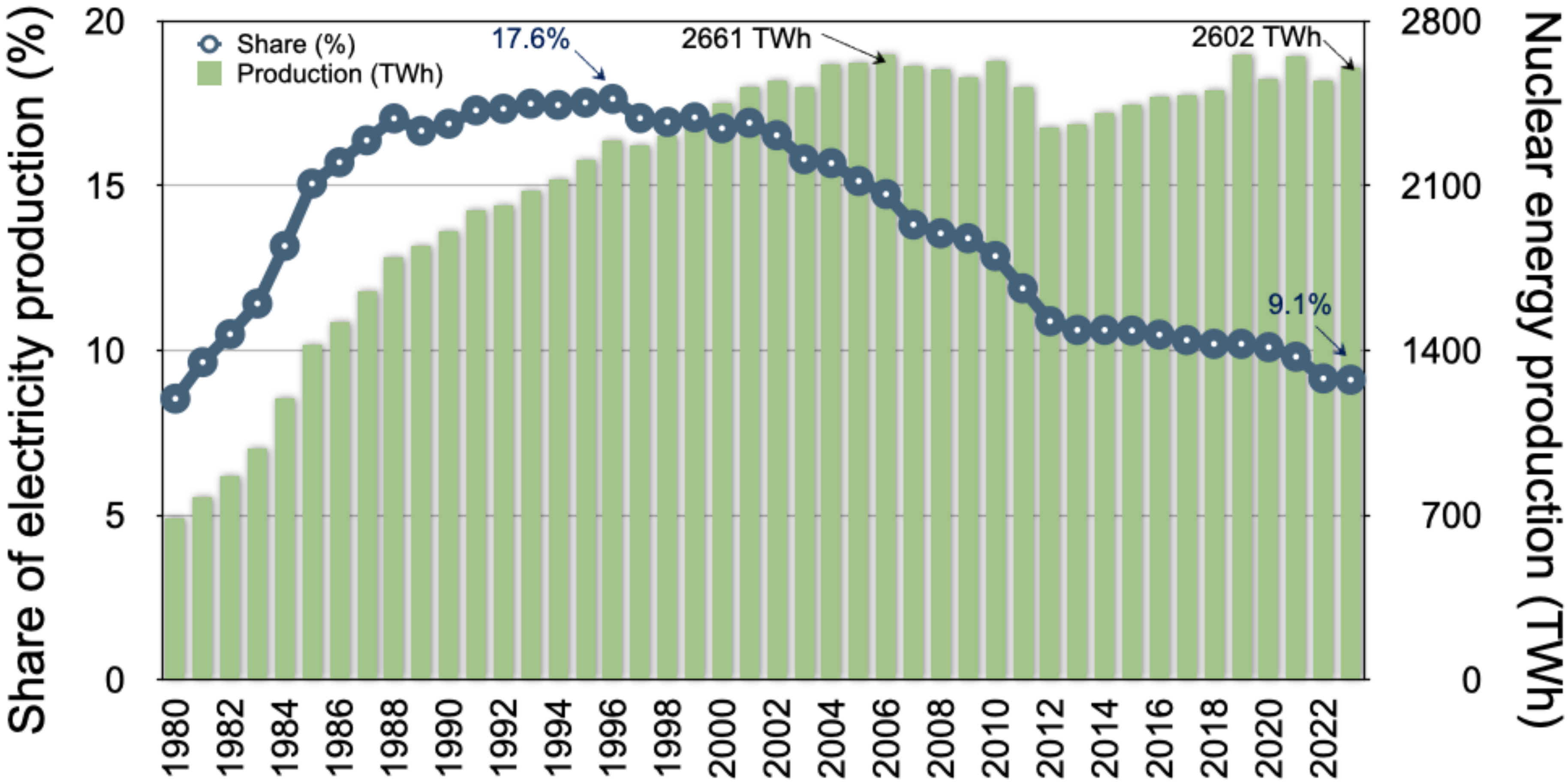


Nuclear power reactor grid connections and shutdowns, 1954-2015

Sources: IAEA-PRIS, World Nuclear Industry Status Report (2015)

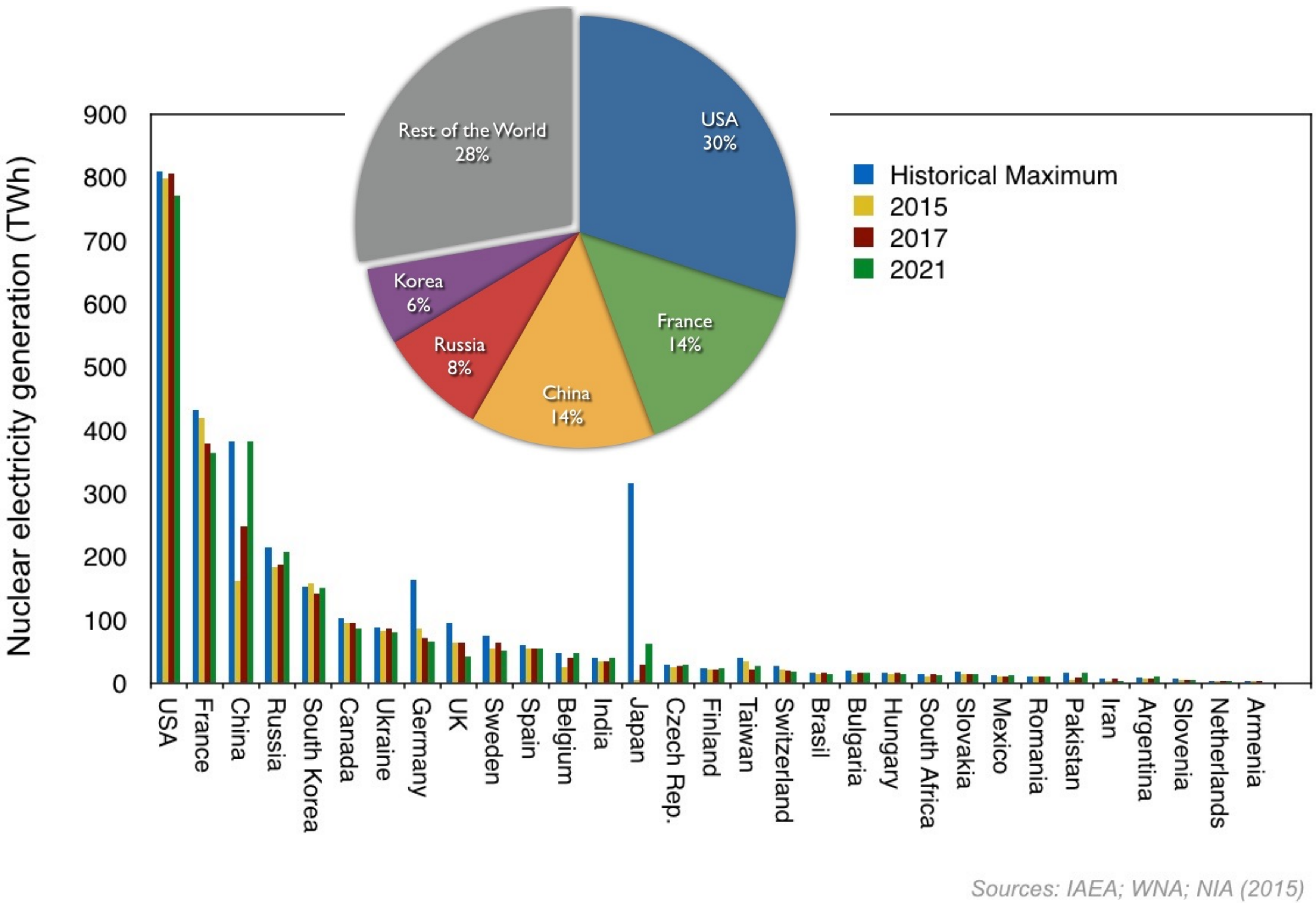
Current status of nuclear energy

- As of end of 2024, 31 countries generating nuclear power

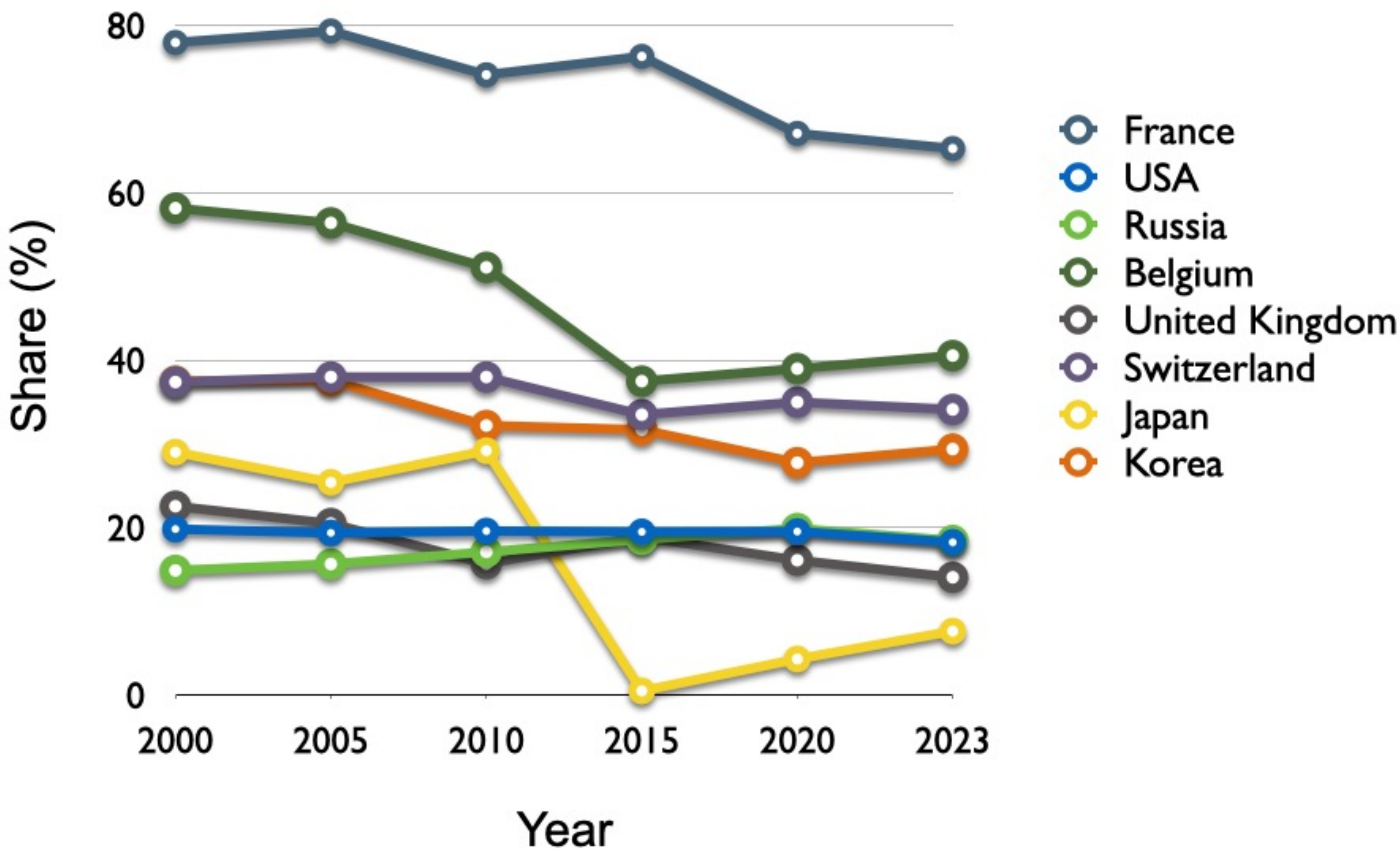


Sources: IAEA PRIS; EIA, 2015; BP Energy Charting Tool

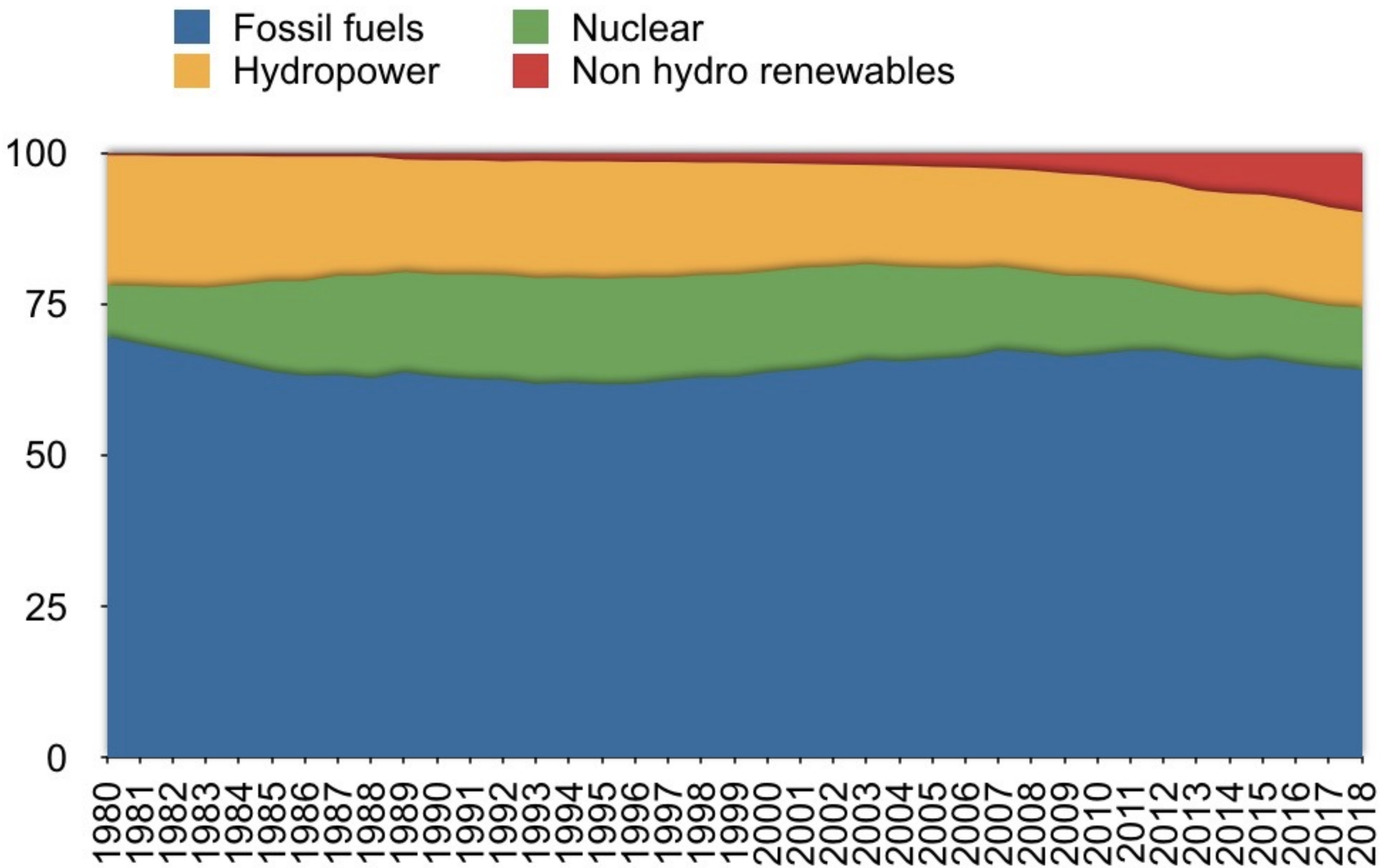
World's Nuclear electricity generation



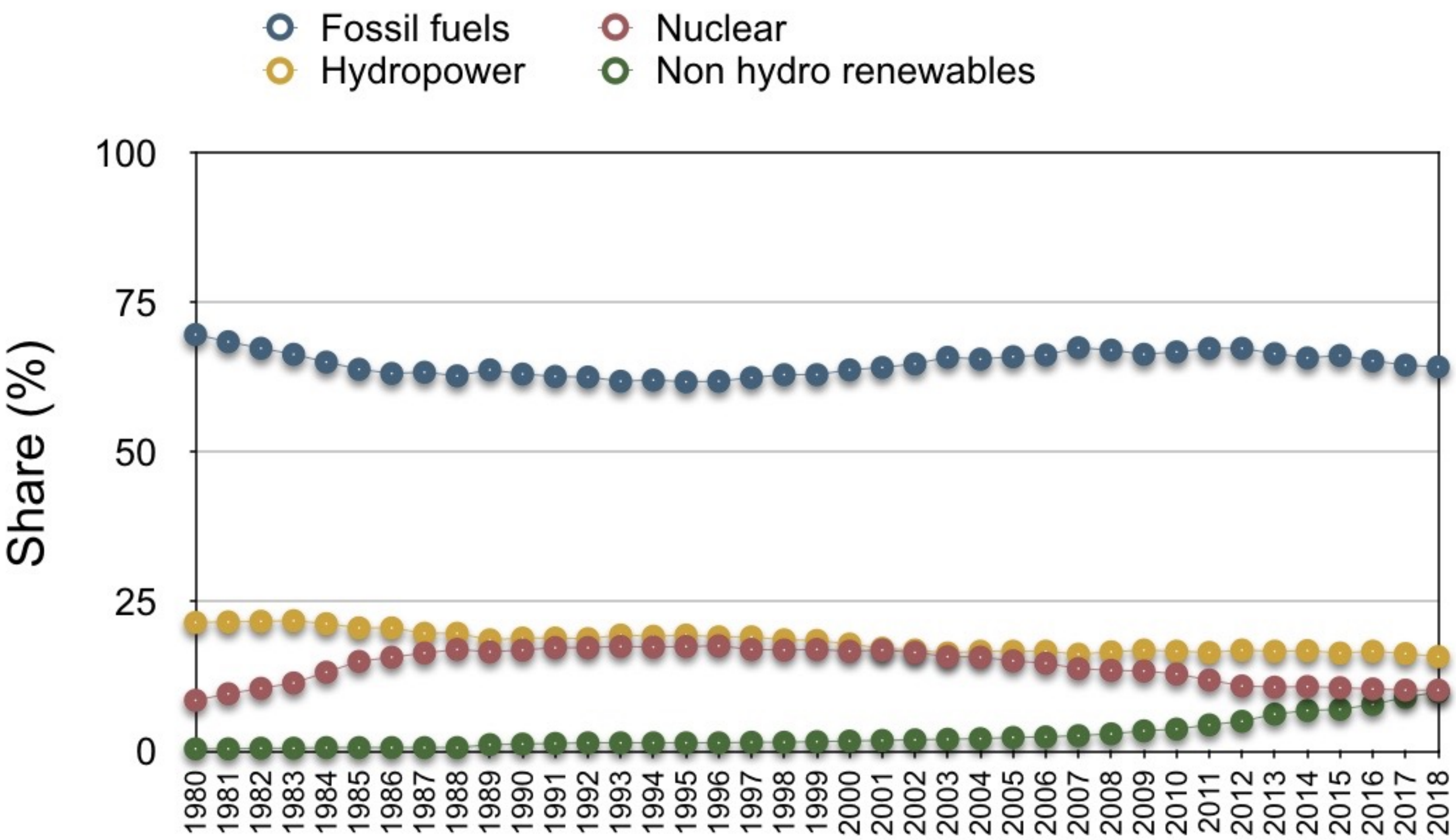
Nuclear electricity production by country in 2015/17/21
and historical maximum



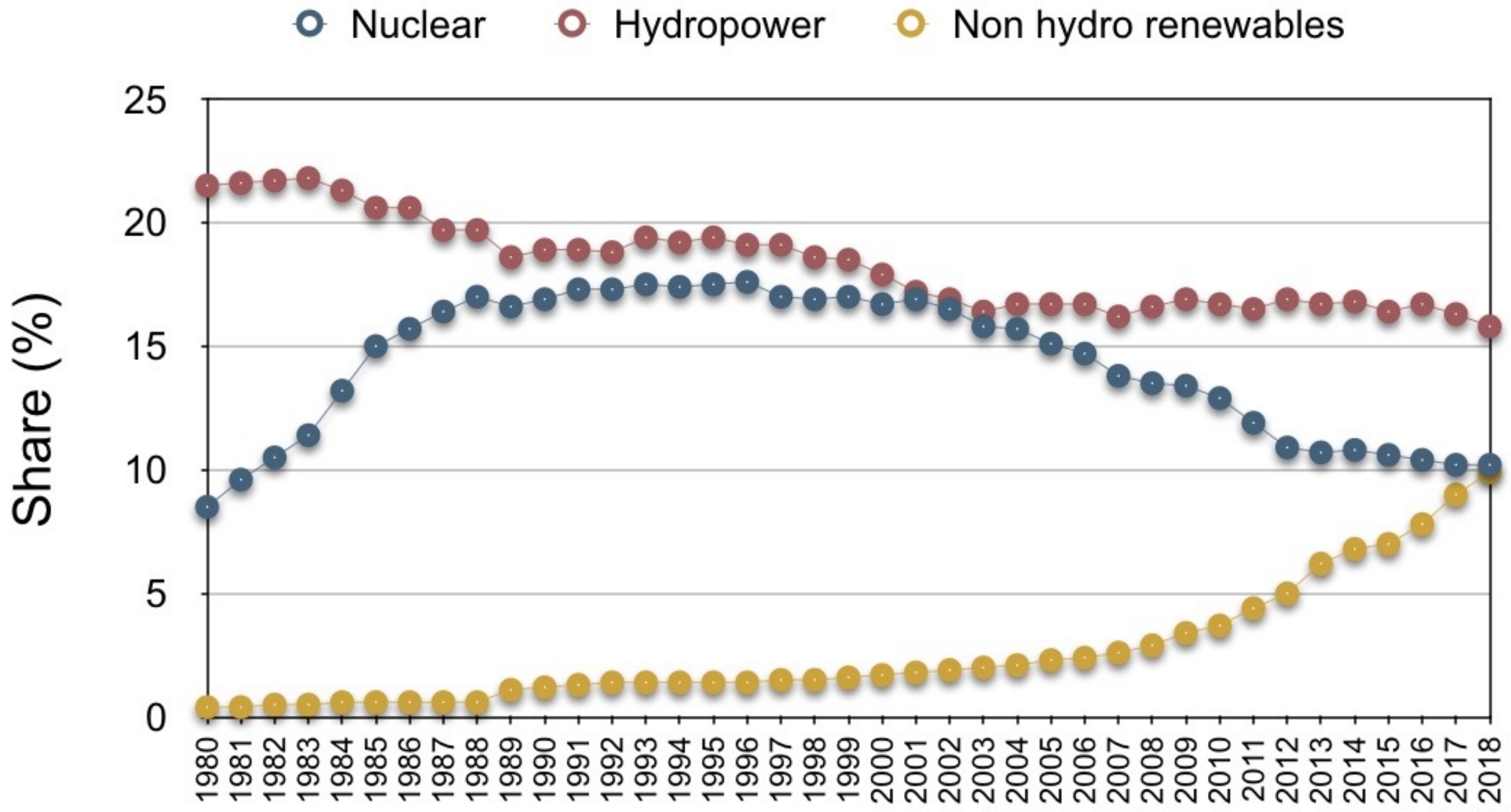
Nuclear's share of the total electricity market for some selected countries (Source: IAEA PRIS; EIA)



World’s share of total electricity generation by source



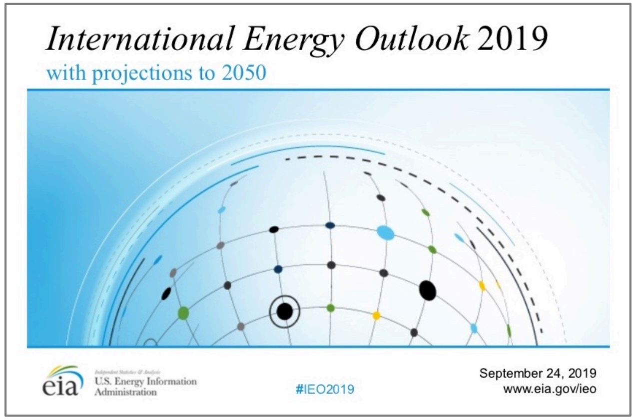
World's share of total electricity generation by source

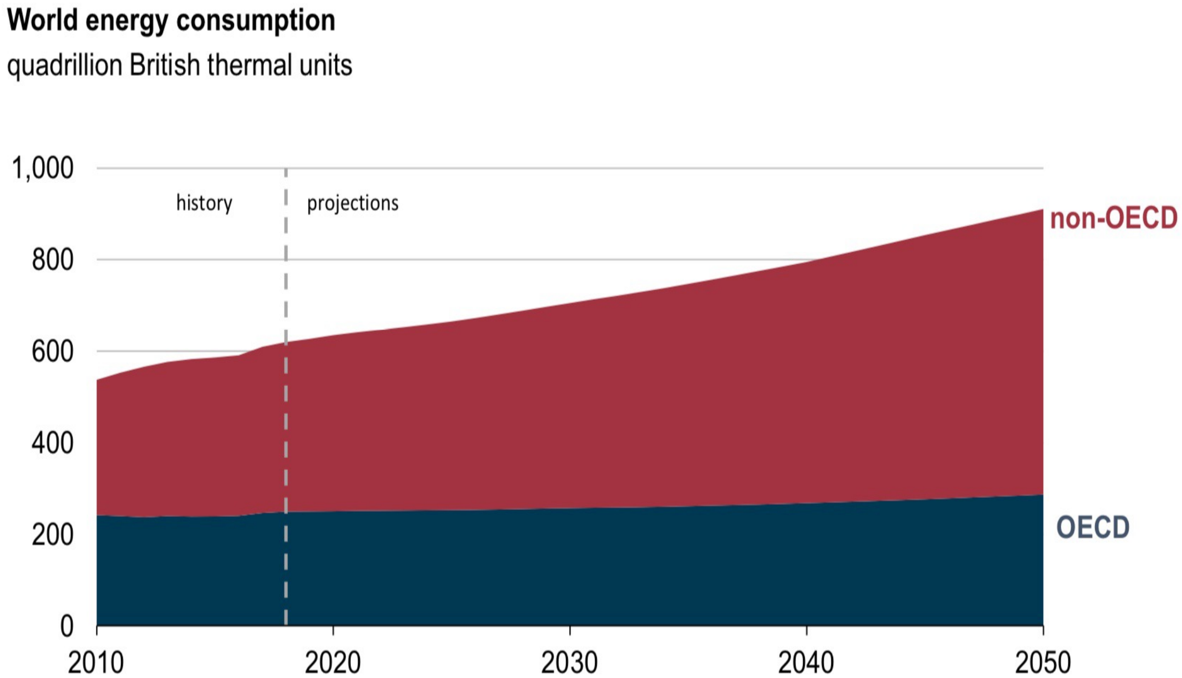


World’s share of total electricity generation by source (excl. fossil fuels)

International Energy Outlook reports

Considerable growth still predicted in World Energy Consumption from 2018 to 2050, with much of the growth in non-OECD nations.



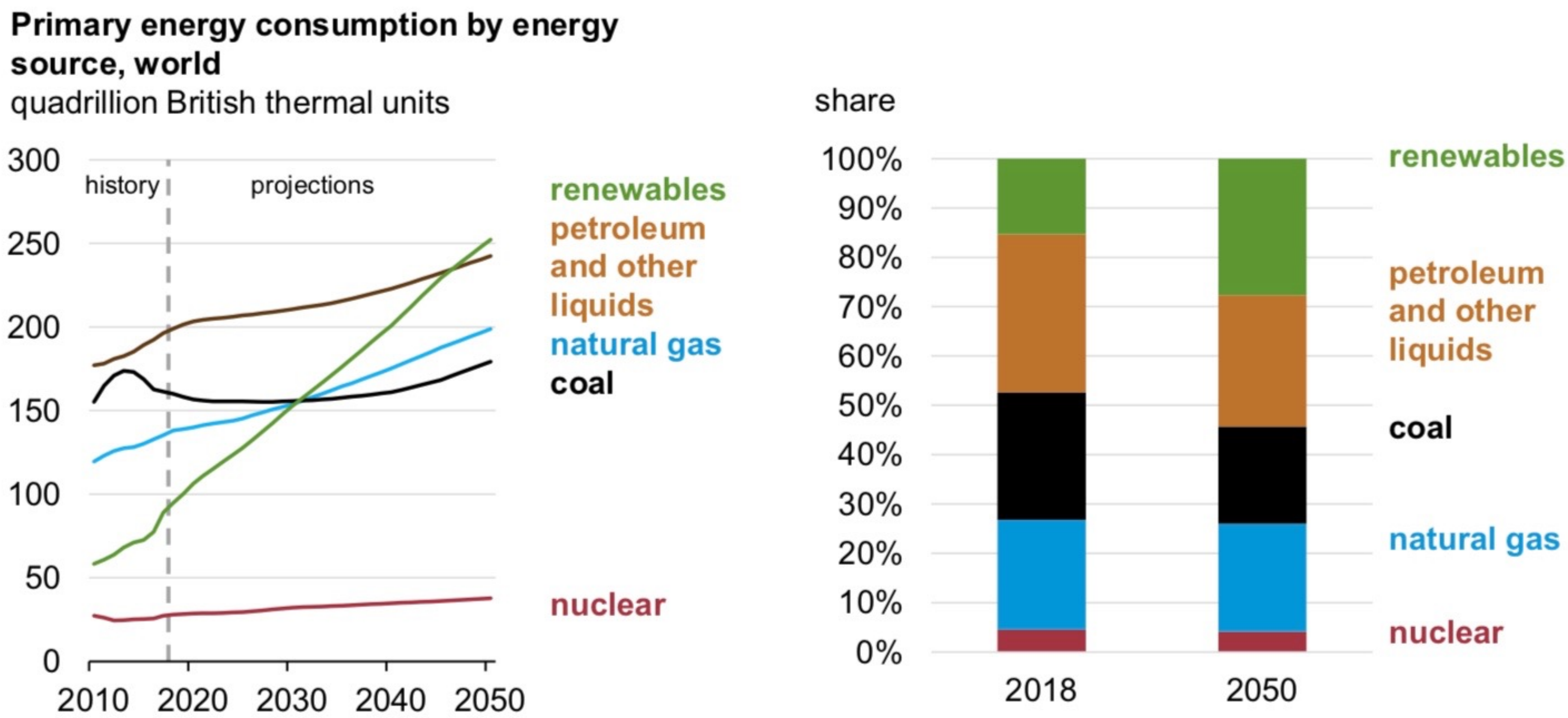


World energy consumption, 1990–2040 (quadrillion Btu)

Note: 1 quadrillion Btu = 45 million tons of coal = 170 million barrels of crude oil = 293 TWh

International Energy Outlook reports

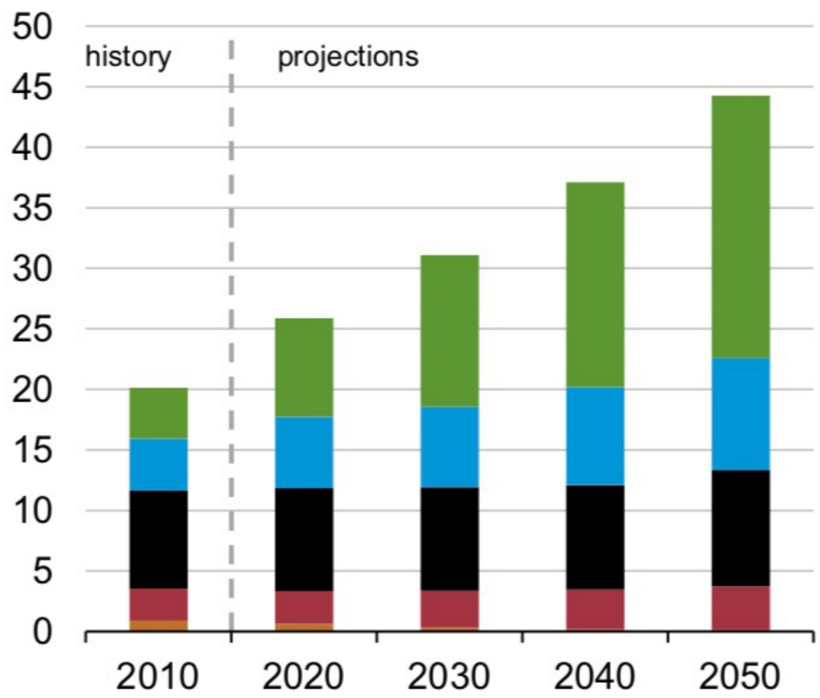
In the reference case considered, fossil fuels continue to supply almost 70% of world energy use through 2050, but renewables become the leading source of primary energy consumption.



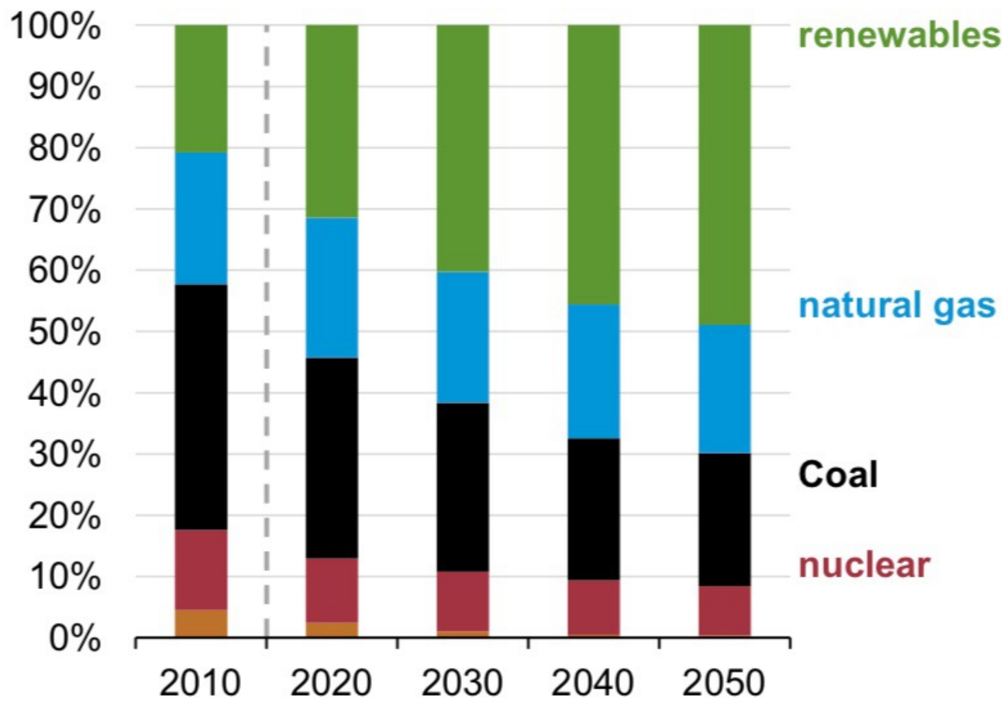
World energy consumption by fuel type, 2010–2050 (quadrillion Btu)

International Energy Outlook reports

Net electricity generation by fuel, world
trillion kilowatthours

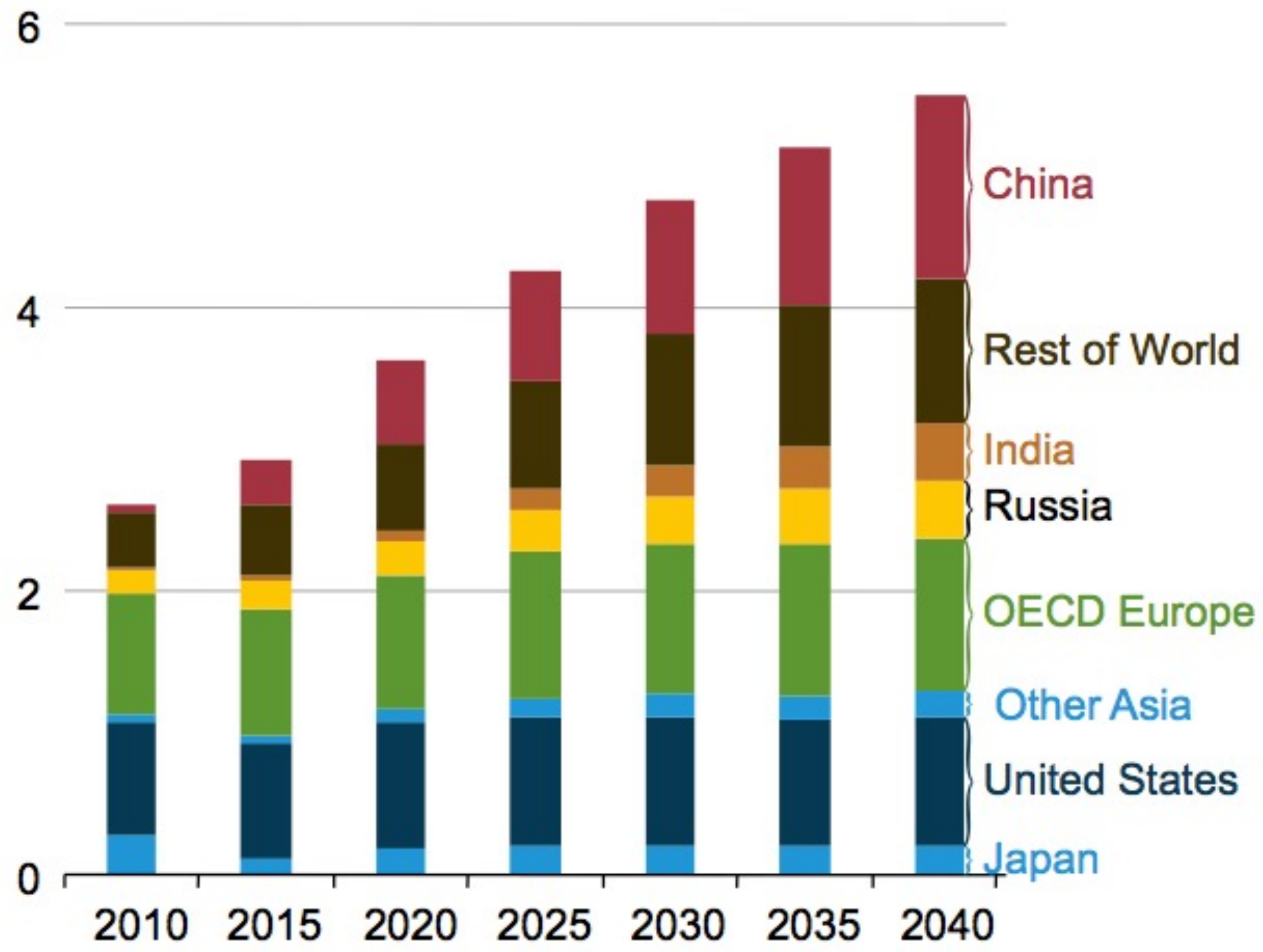


Share of net electricity generation, world
percent



World net electricity generation by energy source, 2010–2050 (trillion kWh = TWh)

International Energy Outlook reports



World net electricity generation from nuclear power by region, 2010–2040 (trillion kWh = TWh)

As of September 2025, there were 416 nuclear power plants worldwide (31 countries) with an installed electric capacity of ~376 GW, and a further 63 plants, with an installed capacity of ~66 GW, were under construction in 15 countries.

Nuclear Power Plants, 2011-08-07