

BOOK 10

Nuclear Industry Fundamentals

Christian GUERITTE
Professor TPA

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TPA

Sharing Experience

Building bridges between the oil industry and academic circles by delivering technical or business-related presentations by professors or experts.



OIL & GAS and ENERGY GLOBAL ISSUES

A Toolbox to understand the World of Energy in the Global Economy

The Toolbox is updated twice a year and benefits from the contributions of TPA Professors:

Coordination: GUÉRITTE Christian

LUC Benoît, PERSILLON Philippe, CORDIER Jean-Pierre, PAPÉE Jean, MULLER Isabelle, DEUTSCH Denis, FOURCADE Bernard, MICHAUD Olivier, SAINCRY Daniel, FOURNIÉ François, CHOUX Jean-Claude, BERA Jean, GUYS Philippe, DE MERVILLE Eric, DUMAY Jean-Michel, VALDELIÈVRE Michel, FONTAINE Jean-Marc, FERRIER Jérôme, BITEAU Jean-Jacques, PETTEAU Pascal, NOSJEAN Nicolas



Nuclear energy



OVERALL TABLE OF CONTENTS

BOOK 1 Projects Economic Evaluation and Investment Decision

BOOK 2 Energy Industry Fundamentals

BOOK 3 Climate Change Problematic

BOOK 4 Oil Industry Fundamentals

BOOK 5 Gas Industry Fundamentals

BOOK 6 Unconventional Hydrocarbons

BOOK 7 Renewables (except hydropower)

BOOK 8 Hydropower

BOOK 9 Coal Industry Fundamentals

BOOK 10 Nuclear Industry Fundamentals



TABLE OF CONTENTS

- 1. What is nuclear energy ?**
- 2. What are uranium resources ?**
- 3. The world nuclear industry: past and present**
- 4. Future evolution**
- 5. The world nuclear industry and the energy and oil & gas industry: interest from stakeholders?**



TABLE OF CONTENTS

1. What is nuclear energy ?

- 1. Uranium**
- 2. The Chain Reaction**
- 3. Natural and Artificial Radiation**
- 4. The Uranium Cycle**
- 5. Zero CO₂ Emissions for Nuclear Plants**

2. What are uranium resources ?

- 1. Uranium Resources**
- 2. Uranium Requirements and Production**
- 3. Uranium Mines and Mining Companies**
- 4. Trends in Capital Expenditures**
- 5. Uranium Prices**



TABLE OF CONTENTS

3. The world nuclear industry: past and present

- 1. Nuclear Reactors Types**
- 2. Spent Fuel Management**
- 3. Worldwide Nuclear Industry**
- 4. The Competition**
- 5. The Dismantlment**
- 6. Risk Management**
- 7. Waste Management**



TABLE OF CONTENTS

4. Future Evolution

- 1. Past Evolution and Perspectives**
- 2. A Zoom on Middle East**
- 3. A Zoom on China**
- 4. A Zoom on Japan**
- 5. A Zoom on Germany**
- 6. A Zoom on France**
- 7. A Zoom on UK**
- 8. A Zoom on Russia**
- 9. Some Scenarios**
- 10. The Competitiveness of Nuclear Energy – The LCOE**
- 11. The Generation IV International Forum (GIF)**



TABLE OF CONTENTS

5 . The world nuclear industry and the energy and oil & gas industry: interest from stakeholders?



1

What is nuclear energy ?

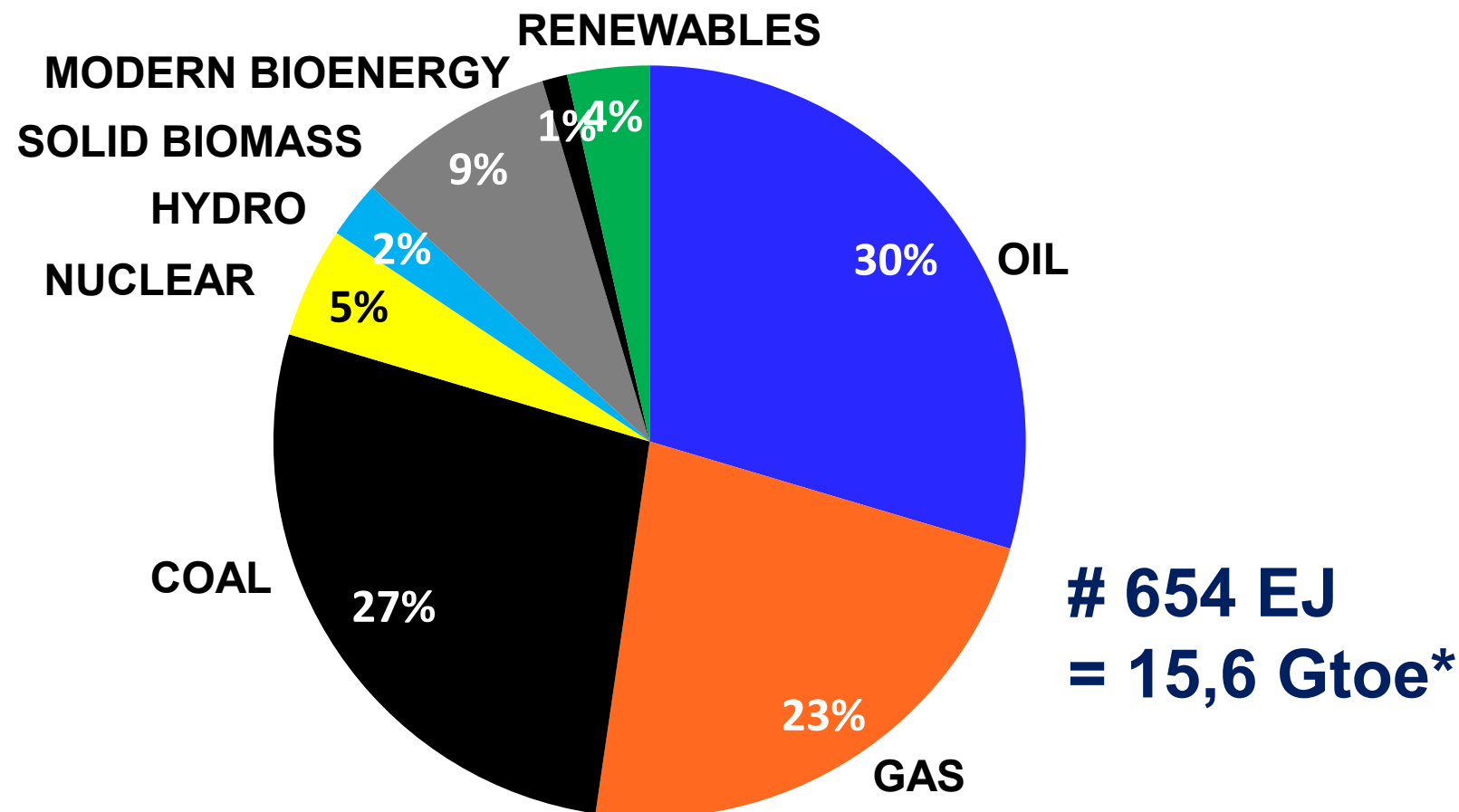


TABLE OF CONTENTS

- 1. What is nuclear energy ?**
- 2. What are uranium resources ?**
- 3. The world nuclear industry: past and present**
- 4. Future evolution**
- 5. The world nuclear industry and the energy and oil & gas industry: interest from stakeholders ?**



World Primary Energy Demand – 2024 + 2,0% vs 2023



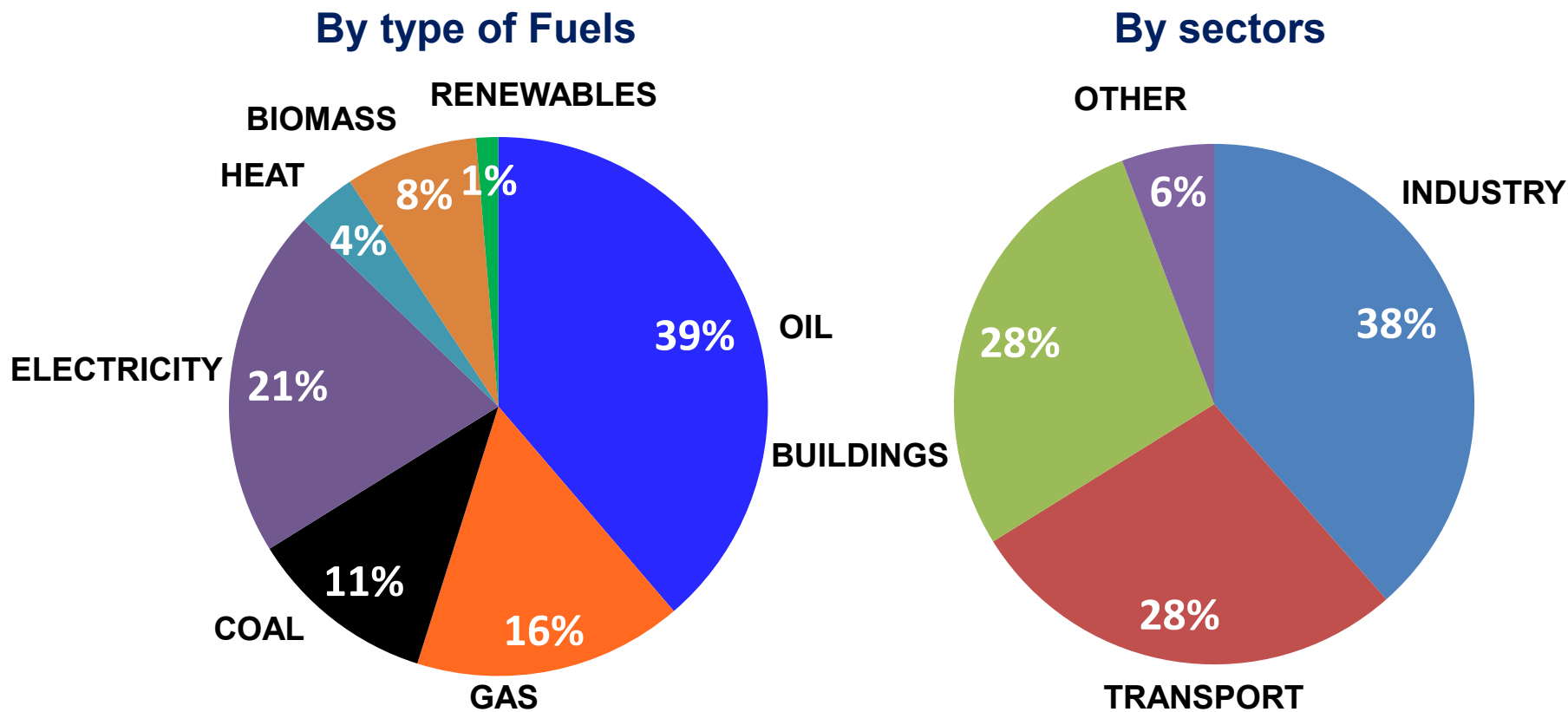
* out of which electricity generation # 6,5 Gtoe # 31 100TWh (eq. Primary Energy)

Source: Data from IEA WEO 2025. Nota: Sums might not be equal to 100% due to rounding

Solid Biomass: tradit. wood & charcoal & solid residues. Modern Bioenergy: liquid & gaseous bioenergy (biofuels & biogases) Renewables: Solar, Wind, Geothermal, Marine Energy,...



Total Final Consumption – 2024 + 2,0% vs 2023



452 EJ = 10,8 Gtoe

Nota: Sums might not be equal to 100% due to rounding

OTHER relates to agricultural sector & other non-energy use

Source: Data from IEA WEO 2025



1-1

Uranium



U in the Periodic Table of Elements

Nuclear Industry elements are part of Actinides

PERIODIC TABLE OF THE ELEMENTS

<http://www.periodni.com>

Legend:

- Metal
- Semimetal
- Nonmetal
- Alkali metal
- Alkaline earth metal
- Transition metals
- Lanthanide
- Actinide
- Chalcogens element
- Halogens element
- Noble gas

STANDARD STATE (25 °C; 101 kPa)

Ne - gas
Hg - liquid
Fe - solid
Ts - synthetic

PERIOD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H HYDROGEN	2 He HELIUM																
2	3 Li LITHIUM	4 Be BERYLLIUM																
3	11 Na SODIUM	12 Mg MAGNESIUM																
4	19 K POTASSIUM	20 Ca CALCIUM	21 Sc SCANDIUM	22 Ti TITANIUM	23 V VANADIUM	24 Cr CHROMIUM	25 Mn MANGANESE	26 Fe IRON	27 Co COBALT	28 Ni NICKEL	29 Cu COPPER	30 Zn ZINC	31 Ga GALLIUM	32 Ge GERMANIUM	33 As ARSENIC	34 Se SELENIUM	35 Br BROMINE	36 Kr KRYPTON
5	37 Rb RUBIDIUM	38 Sr STRONTIUM	39 Y YTTRIUM	40 Zr ZIRCONIUM	41 Nb NIOSIUM	42 Mo MOLYBDENUM	43 Tc TECHNETIUM	44 Ru RUTHENIUM	45 Rh RHODIUM	46 Pd PALLADIUM	47 Ag SILVER	48 Cd CADMIUM	49 In INDIUM	50 Sn TIN	51 Sb ANTIMONY	52 Te TELLURIUM	53 I IODINE	54 Xe XENON
6	55 Cs CAESIUM	56 Ba BARIUM	57-71 La-Lu Lanthanide	72 Hf HAFNIUM	73 Ta TANTALUM	74 W TUNGSTEN	75 Re RHENIUM	76 Os OSMIUM	77 Ir IRIDIUM	78 Pt PLATINUM	79 Au GOLD	80 Hg MERCURY	81 Tl THALLIUM	82 Pb LEAD	83 Bi BISMUTH	84 Po POLONIUM	85 At ASTATINE	86 Rn RADON
7	87 Fr FRANCIUM	88 Ra RADIUM	89-103 Ac-Lr Actinide	104 Rf RUTHERFORDIUM	105 Db DUBNIUM	106 Sg SEABORGIUM	107 Bh BOHRNIUM	108 Hs HASSIUM	109 Mt MEITNERIUM	110 Ds DARMSTADIUM	111 Rg ROENTGENIUM	112 Cn COPERNICIUM	113 Uut UNUNTRIUM	114 Fl FLEROVIUM	115 Uup UNUNPENTIUM	116 Lv LIVERMORIUM	117 Uus UNUNSEPTIUM	118 Uuo UNUNOCTIUM

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(1) Pure Appl. Chem., 81, No. 11, 2135-2156 (2009)
Relative atomic masses are expressed with five significant figures. For elements that have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element. However three such elements (Tl, Pa and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

LANTHANIDE

57 138.91 La LANTHANUM	58 140.12 Ce CERIUM	59 140.91 Pr PRASEODYMIUM	60 144.24 Nd NEODYMIUM	61 (145) Pm PROMETHIUM	62 150.36 Sm SAMARIUM	63 151.96 Eu EUROPIUM	64 157.25 Gd GADOLINIUM	65 158.93 Tb TERBIUM	66 162.50 Dy DYSPROSIUM	67 164.93 Ho HOLMIUM	68 167.26 Er ERBIUM	69 168.93 Tm THULIUM	70 173.05 Yb YTTERIUM	71 174.97 Lu LUTETIUM
---------------------------	------------------------	------------------------------	---------------------------	---------------------------	--------------------------	--------------------------	----------------------------	-------------------------	----------------------------	-------------------------	------------------------	-------------------------	--------------------------	--------------------------

ACTINIDE

89 (227) Ac ACTINIUM	90 232.04 Th THORIUM	91 231.04 Pa PROTACTINIUM	92 238.03 U URANIUM	93 (237) Np NEPTUNIUM	94 (244) Pu PLUTONIUM	95 (243) Am AMERICIUM	96 (247) Cm CURIUM	97 (247) Bk BERKELIUM	98 (251) Cf CALIFORNIUM	99 (252) Es EINSTEINIUM	100 (257) Fm FERMIUM	101 (258) Md MENDELEVIUM	102 (259) No NOBELIUM	103 (262) Lr LAWRENCIUM
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U History (1)

79 : Uranium oxide used to add a yellow color to ceramic glazes in the Bay of Naples.

Middle Ages : Pitchblende extracted from the silver mines in Joachimsthal (Jachymov), Bohemia, as a coloring agent in the glassmaking industry.

1789 : Berlin chemist Martin Heinrich Klaproth precipitates a yellow salt by dissolving pitchblende in nitric acid and he reduces it to a black powder (UO_2) which he names urane after the planet Uranus discovered 8 years earlier (named after Ouranos, the ancient Greek deity of the sky).

1841 : French chemist Eugène-Melchior Pélégot (CNAM) isolates the first sample of uranium metal (U).

1896 : French physicist Henri Becquerel (Nobel prize 1903) discovers the phenomenon of natural radioactivity (invisible rays emitted by uranium) by leaving a sample of a uranium salt on top of a photographic plate which becomes fogged.

1898 : Physicists Pierre and Marie Curie (Nobel prize 1903) discover two new elements (polonium and radium) by using several tonnes of pitchblende.



U History (2)

1905 : American chemist Bertram Boltwood concludes that lead and helium are decay product of uranium.

1906 : British physicist Ernest Rutherford (Nobel prize 1908) suggests the geological time-keeping potential of radioactivity.

1934 : Italian physicist Enrico Fermi (Nobel prize 1938) observes that bombarding uranium with neutrons produces the emission of beta rays (electrons).

1938 : Berlin physicists Otto Hahn (Nobel prize 1944) and Fritz Strassmann discover that uranium is able to break apart (fission) into lighter elements with release of enormous energy.

1939 : French scientists Frédéric Joliot and wife Irène Curie (Nobel prize 1935) discover that uranium fission produces neutrons which in turn generate new fission (nuclear chain reaction).

1942 : Enrico Fermi achieved the first induced nuclear chain reaction in Chicago by piling 50 000 graphite bricks + 53 tonnes of uranium oxide + 5.5 tonnes of uranium metal.



U Uses

- ❑ Unlike the metals which have been in demand for centuries, uranium was used only to **colour glass** as from as **79 AD**.
- ❑ Then deposits were mined during the **early 20th** century in order to obtain its decay product, **radium** which was used in **luminous** paint, particularly on the **dials** of watches and aircraft instruments, and in medicine for the treatment of disease.
- ❑ From the **1940s**, virtually all of the uranium that was mined was used in the production of nuclear **weapons**.
- ❑ This ceased to be the case in the late **1970s** when a serious non-military demand materialised with the significant nuclear **electricity** generation development, because uranium-**235** is the **only** naturally-occurring material which can sustain a **fission** chain reaction, releasing large amounts of energy.
- ❑ Heat from nuclear fission is also being used for **research** reactor, for **industrial** process **heat**, for naval propulsion (**submarine** and **ice-brakers**), for **space** exploration, and for making **medical** and industrial **radio-isotopes**.
- ❑ In the **future**, nuclear power will also be used for **desalination** of sea water and may be for other **process heat applications**.



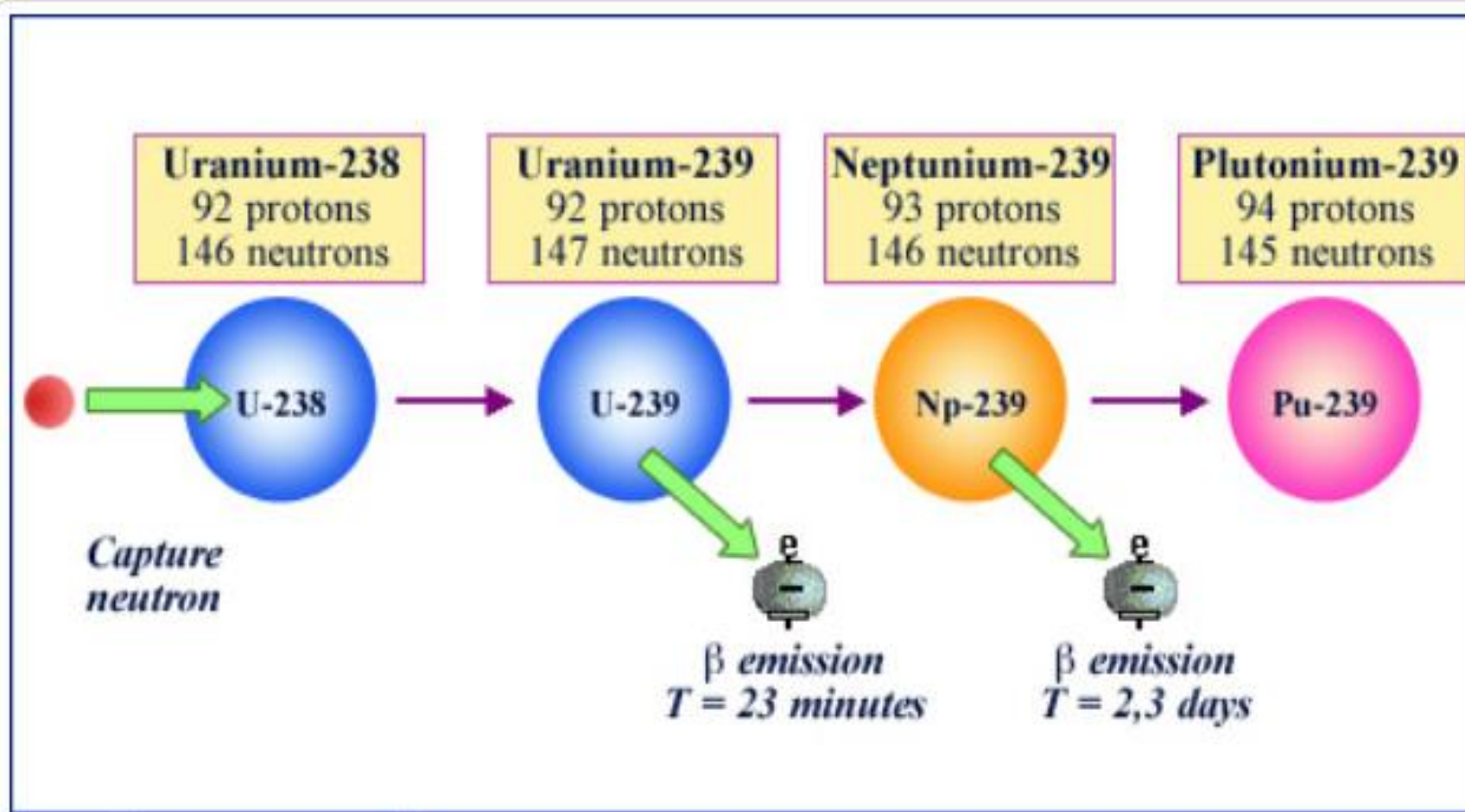
U_{238} & U_{235} & P_{239}

- Uranium₂₃₈ and Uranium₂₃₅ are chemically identical.
- The nucleus of U_{238} & U_{235} do not contain the same number of neutrons:
 - ❖ U_{238} : 92 protons & 146 neutrons – Atomic mass: 238
 - ❖ U_{235} : 92 protons & 143 neutrons – Atomic mass: 235
- U_{235} is the main isotope of Uranium which is fissile and used in nuclear plants.
- The difference in mass allows the isotopes to be separated and makes it possible to increase, to enrich the percentage of U_{235}
- All present and historical processes, directly or indirectly, make use of this small mass difference, through gas diffusion or centrifugation.
- Other fissile actinide: Plutonium₂₃₉
 - ❖ P_{239} : 94 protons & 145 neutrons – Atomic mass: 239



Plutonium Generation

To be used in Fast Breeder Reactors



Plutonium-239 is a good nuclear fuel: split by fast neutrons, it releases an average of 2,30 secondary neutrons per neutron captured.

Of these secondary neutrons, one is required to maintain the chain reaction. Then 1,30 remains available.

Source: Radioactivity.EU.com



1-2

The Chain Reaction



Nuclear Fission

Uranium was the **first** element that was found to be **fissile** :

- **Uranium-235** has the distinction of being the **only naturally** occurring fissile isotope. Upon bombardment with **slow neutrons**, the U235 isotope will most of the time divide into **two smaller nuclei**, releasing energy (**heat**) and **more neutrons**. If these neutrons are **absorbed** by other U235 nuclei, a **chain** reaction occurs.
- **Uranium-238**, being capable of being **transmuted** to fissile **plutonium-239**, is called **fertile** uranium.
- **Uranium-233**, an **artificial fissile** isotope, can be produced from **natural** thorium-232.

The **high probability** of uranium-**235** to fission when bombarded with **slow neutrons** generates the heat in used as a source of power and bears ability of uranium to produce a sustained nuclear **chain** reaction. If there is nothing to **absorb** some neutrons and **slow** the reaction, the reaction is **explosive**. Fission of uranium produces **plutonium** (Pu), other **transuranic** elements (Np, Am, Cm, ...) and **fission** products (Cs, I, Zr, Sr, Ba, Tc, Sn, Xe, Kr, ...).

NB : on the opposite, thermo-nuclear **fusion** is a reaction in which two light atomic nuclei (e.g. deuterium, tritium, helium) fuse together to form a **heavier nucleus** and in doing so release a large amount of energy.

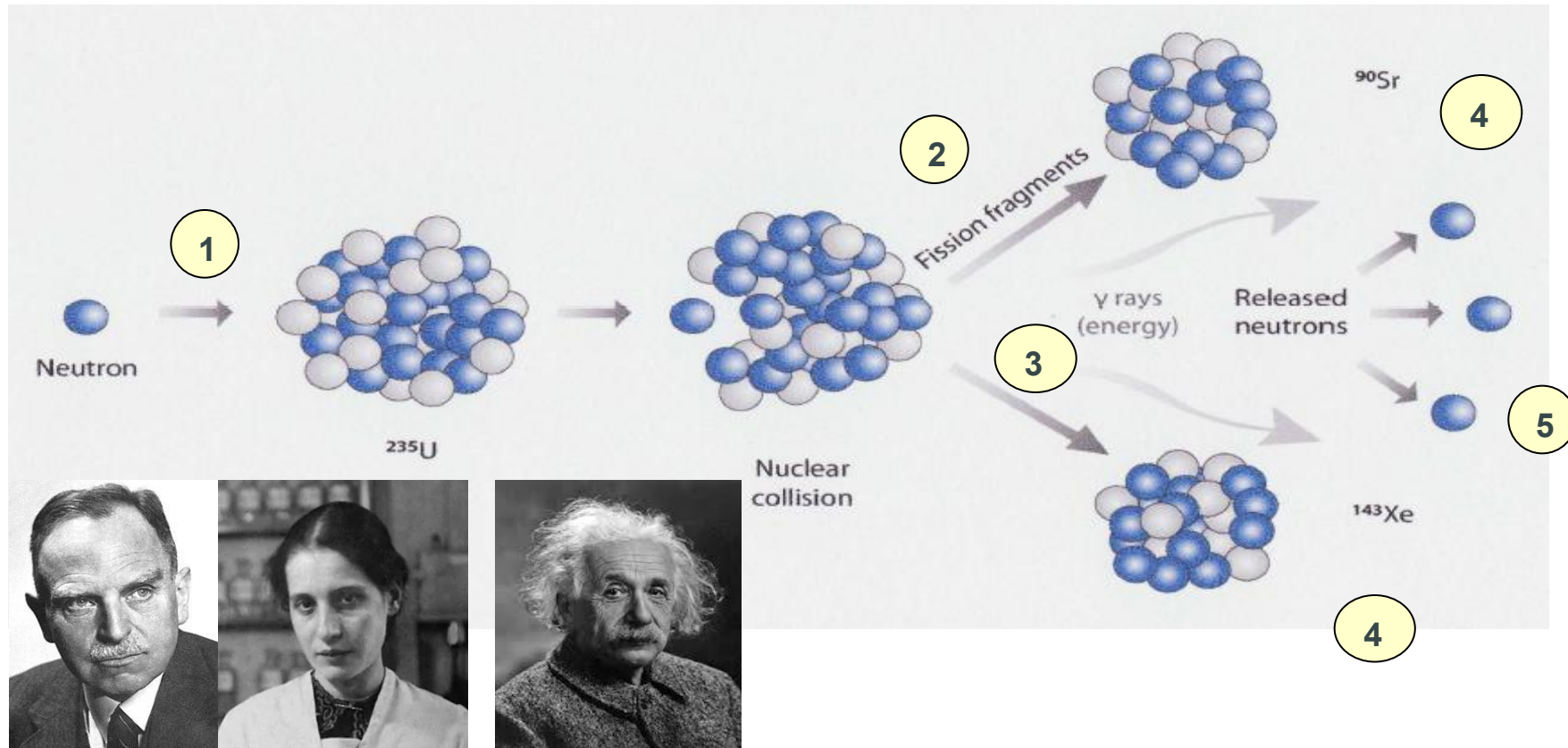


A Typical Fission Reaction

- A nuclear chain reaction needs a critical mass of fissile material.
- The critical mass is the smallest amount of fissile material needed for a sustained nuclear chain reaction. It depends upon material properties : density, shape, enrichment, purity, temperature, and surroundings. Critical mass is dependent on the effective neutron multiplication factor k , the average number of neutrons released per fission event that go on to cause another fission event rather than being absorbed or leaving the material. When $k = 1$, the mass is critical, and the chain reaction is self-sustaining.
- When a chain reaction is self-sustaining, the mass is said to be in a critical state in which there is no increase or decrease in power, temperature, or neutron population.
- Startup neutron source: Californium-252 or Plutonium-238 : metallic elements inserted into the reactor with new nuclear fuel to initiate the reaction. Due to spontaneous fission a supercritical mass will generate a chain reaction. For example, a spherical critical mass of pure U_{235} with a mass of about 52 kilograms would experience around 15 spontaneous fission events per second.



A Typical Fission Reaction

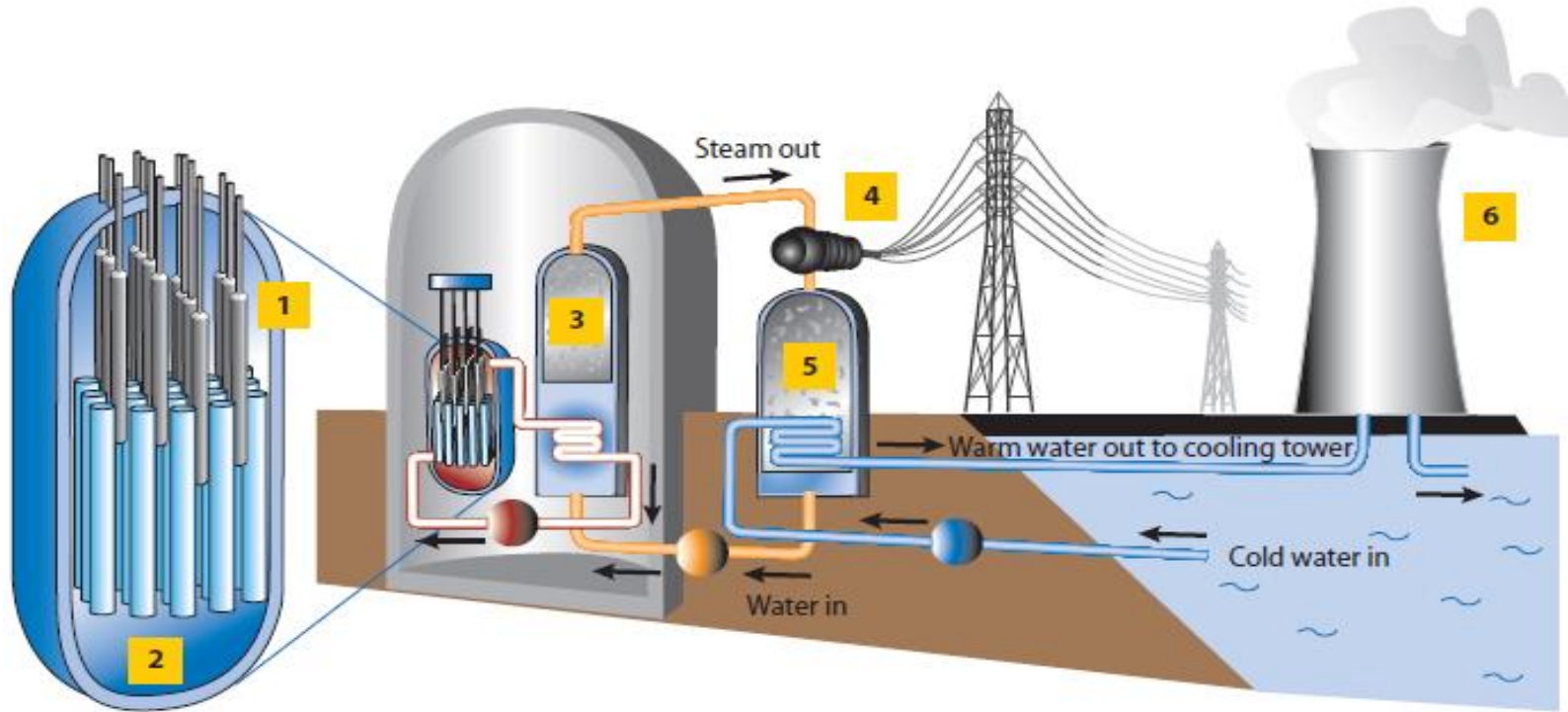


- 1 A neutron hits the nucleus of a uranium atom (U_{235})
- 2 The uranium nucleus splits (fission) into several smaller atoms, releasing heat and several more neutrons
- 3 The chain reaction begins: the neutrons hit other nuclei, causing them to fission, and so on....
- 4 The total mass of the products of the reaction is less than the original mass of the nucleus and impacting neutron. The difference has been converted into energy according to Einstein formula $\Delta E = \Delta mc^2$
- 5 Fission products kinetic energy is immediately converted into heat



Basic Components of a Nuclear Reactor

Pressurized Water Reactor (PWR)



Source: New Scientist.

- 1 Reactor: fuel heats up water. Control rods absorb neutrons to control or halt the fission process
- 2 Coolant and moderator: fuel and control rods are surrounded by water (serves as coolant and moderator)
- 3 Steam generator/secondary circuit: water heated by the nuclear reactor
- 4 Turbo-generator set: drives the turbine and alternator to produce electricity
- 5 Condenser: removes heat to convert steam back to water
- 6 Cooling tower: removes heat from the cooling water



Energy Equivalence Natural Uranium vs toe

- In current Pressurized Water Reactors (PWR), without recycling of plutonium, 1 tonne of Natural U generates 420 000 GJ:
1 t Natural U # 10 000 toe
- With a Fast Breeder Reactor (FBR), and complete recycling:
1 t Natural U # 500 000 toe

Nota: A Fast Breeder Reactor generates 50 times more energy, potential transmutation process, possibility to reduce High Level Waste (HLW) by a factor 10Currently, at the level of R&D or demonstration.....



1-3

Natural and Artificial Radiation

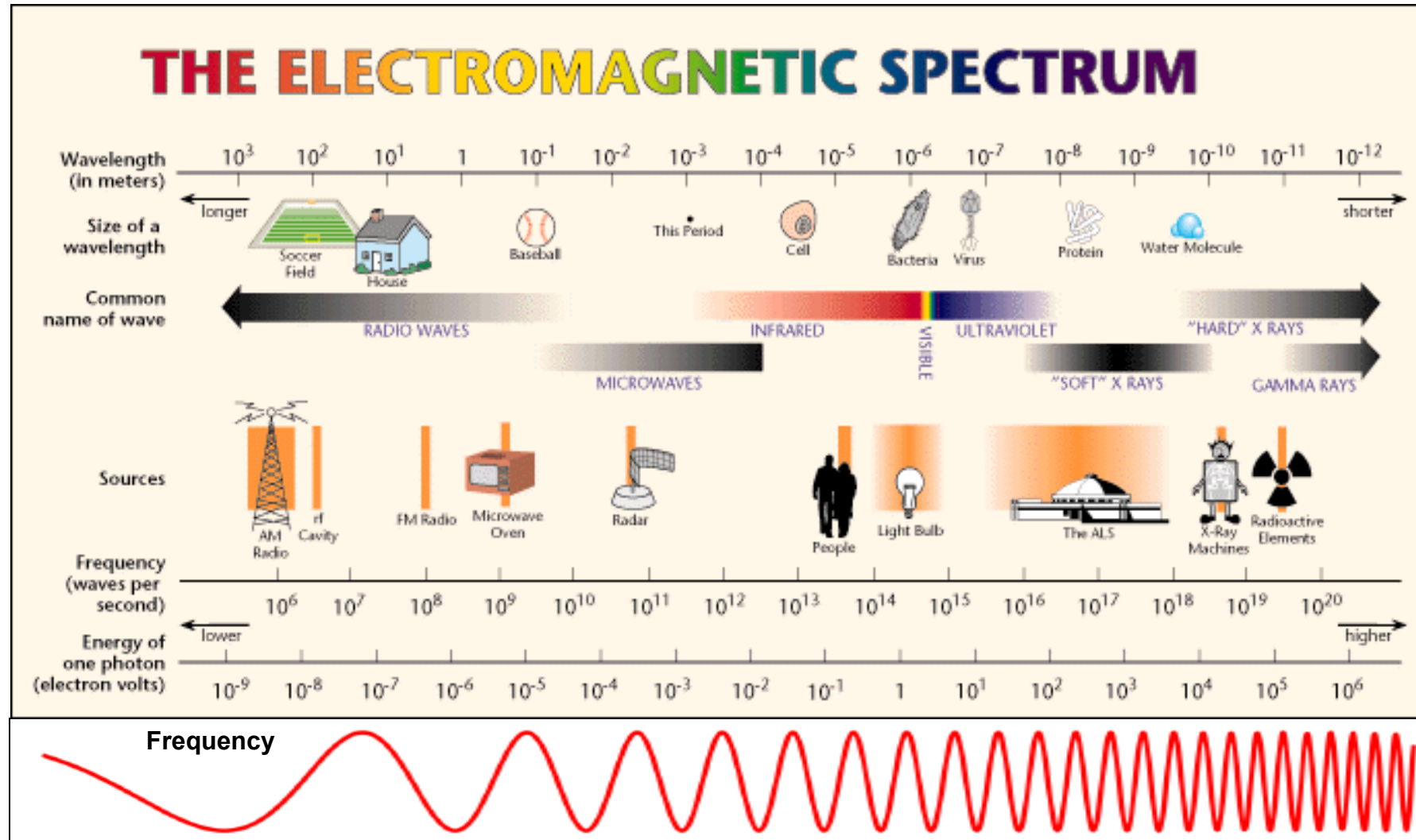


Radioactivity or radioactive decay :

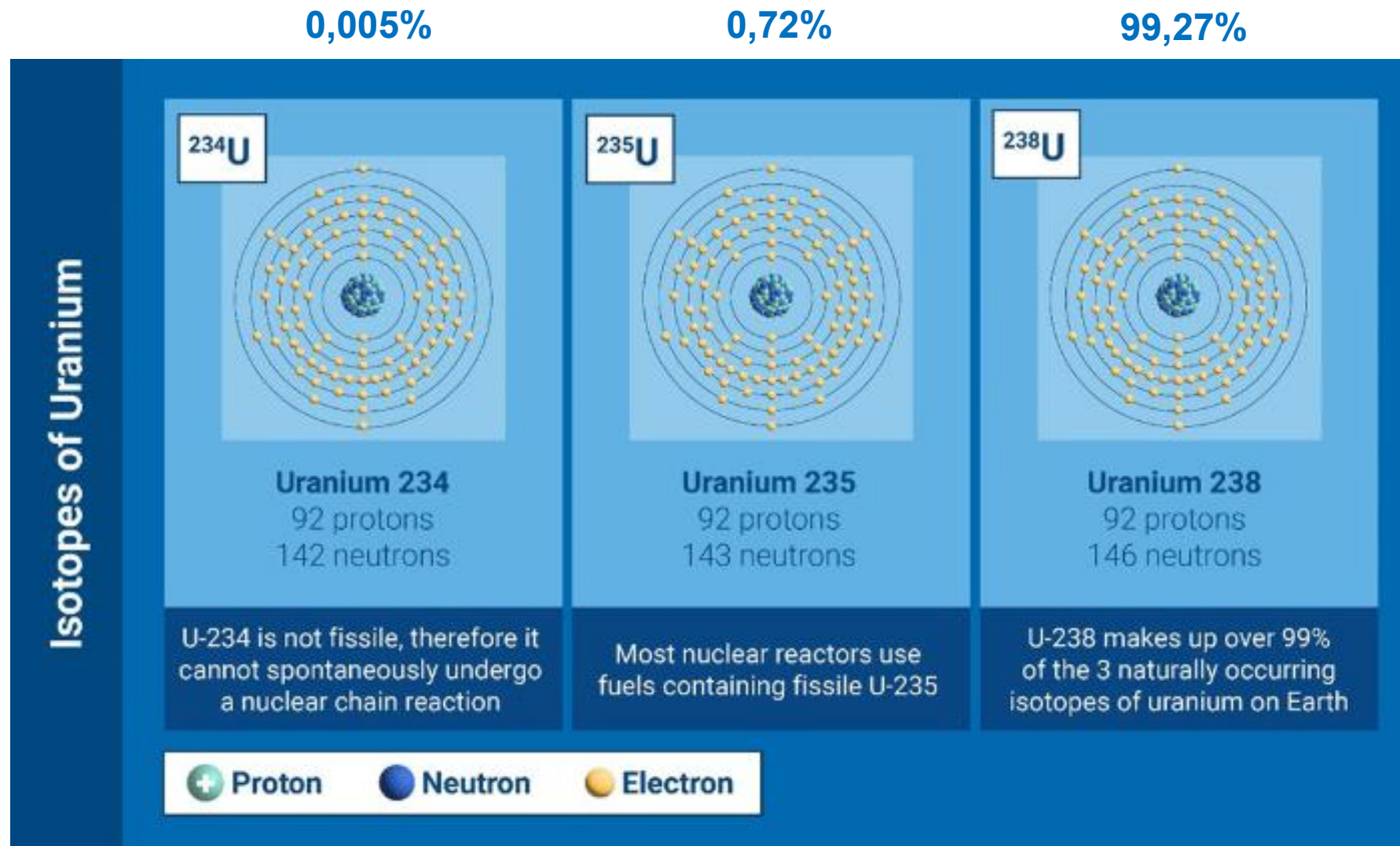
Process in which an unstable atomic nucleus loses energy by emitting radiation



Reminder: The Electromagnetic Spectrum From Radio Waves to Gamma Rays.....



Isotopes of Uranium



Key Uranium isotopes radioactive properties

Radioactive Properties of Key Uranium Isotopes and Associated Radionuclides

Isotope	Half-Life	Natural Abundance (%)	Specific Activity (Ci/g)	Decay Mode	Radiation Energy (MeV)		
					Alpha (α)	Beta (β)	Gamma (γ)
U-232	72 yr	0	22	α	5.3	0.017	0.0022
U-233	160,000 yr	0	0.0098	α	4.8	0.0061	0.0013
U-234	240,000 yr	0.0055	0.0063	α	4.8	0.013	0.0017
U-235	700 million yr	0.72	0.0000022	α	4.4	0.049	0.16
Th-231	26 hr		540,000	β	-	0.17	0.026
U-236	23 million yr	0	0.000065	α	4.5	0.011	0.0016
U-238	4.5 billion yr	>99	0.00000034	α	4.2	0.010	0.0014
Th-234	24 days		23,000	β	-	0.060	0.0093
Pa-234m	1.2 min		690 million	β	-	0.82	0.012

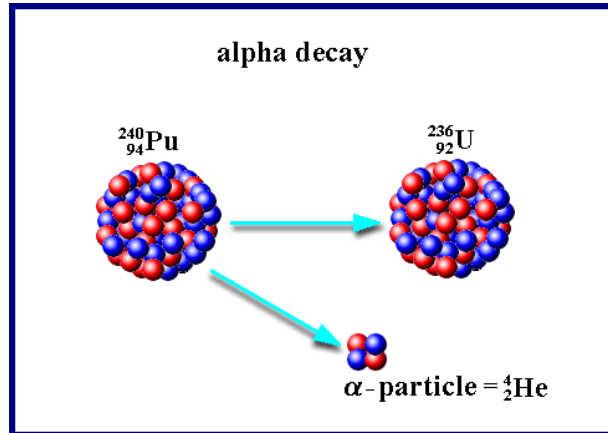
- Natural uranium is constituted primarily of uranium-238 with 0.7% uranium-235 and a small amount of isotope 234.
- Three isotopes, uranium 236, 233 and 232, are also produced by reactors from uranium-235 and thorium.
- These three natural isotopes and these three artificial isotopes are alpha emitters.

Source: Radioactivity.EU.com
Ci/g: Curie/gramme
MeV: MegaelectronVolt



Radioactive Decay (1)

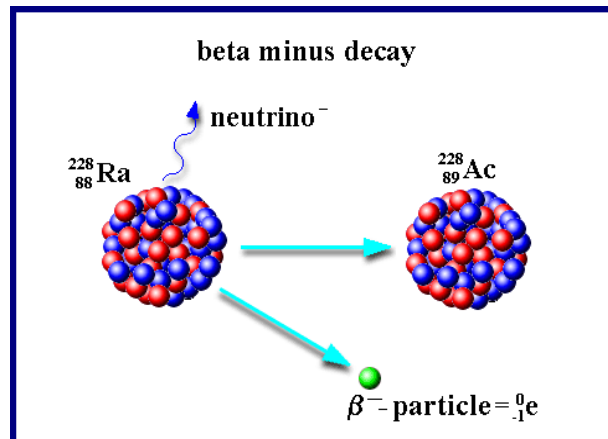
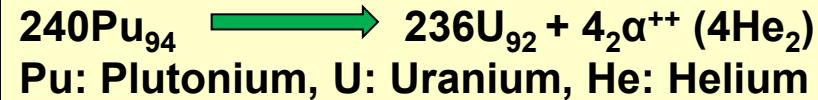
Atomic nuclei that are not stable tend to approach stable configuration via radioactivity. Atoms are radioactive because the ratio proton/neutron is not ideal. Through radioactive decay, the nucleus approaches a better balance proton/neutron.



Alpha decay occurs when the neutron to proton ratio is too low.

Alpha decay emits an Alpha particle made of 2 protons and 2 neutrons, the same as a helium nucleus.

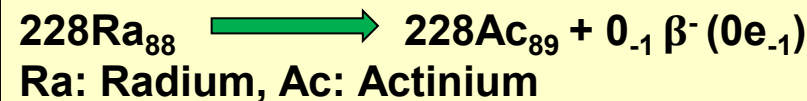
Example:



Beta decay occurs when the neutron to proton ratio is too high.

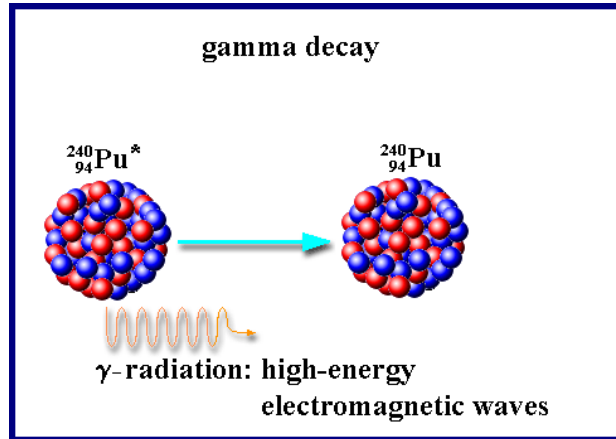
Beta decay emits a Beta particle made of 1 electron to reach a better balance.

Example:



Radioactive Decay (2)

Atomic nuclei that are not stable tend to approach stable configuration via radioactivity. Atoms are radioactive because the ratio proton/neutron is not ideal. Through radioactive decay, the nucleus approaches a better balance proton/neutron.

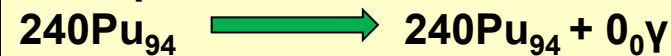


Gamma rays form a high electromagnetic radiation., higher than X rays.

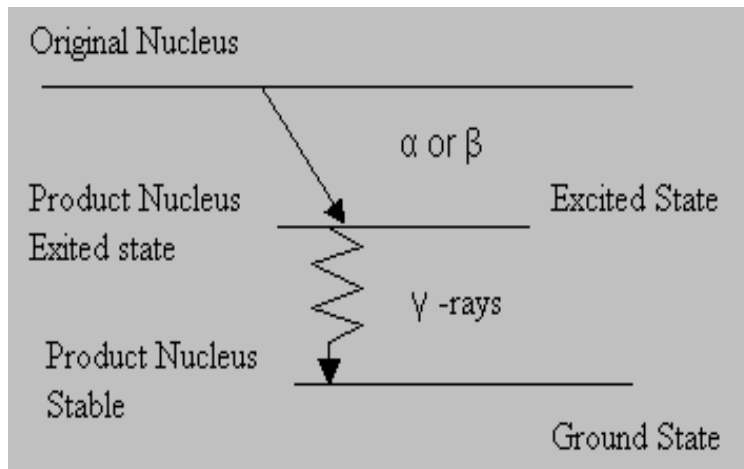
Gamma rays are released when an atomic nucleus releases its excess energy.

Atomic mass and Atomic number remain the same.

Example:



Pu: Plutonium

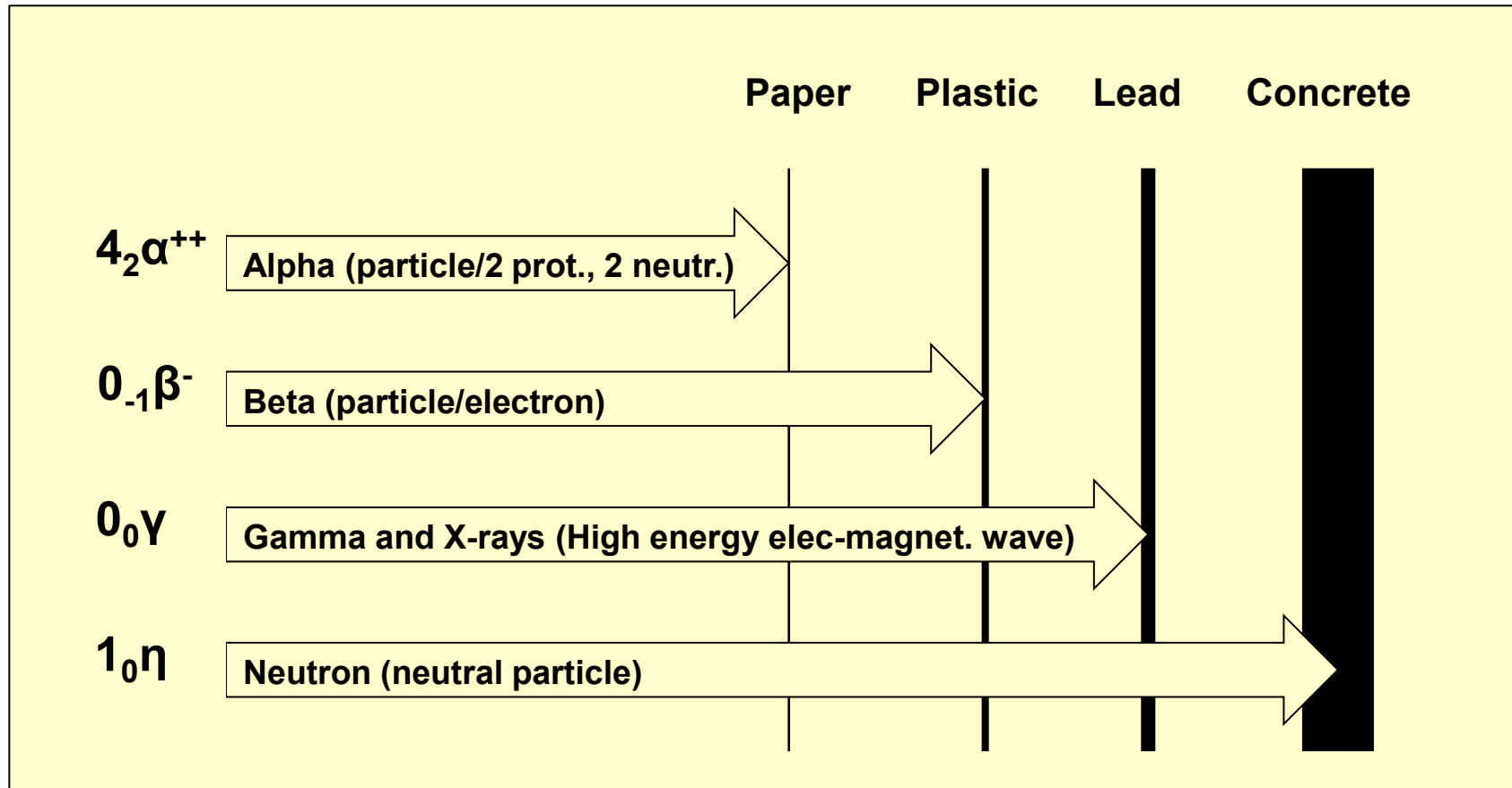


After α or β decay, the resulting nucleus is in a unstable state.

It reaches a stable state after γ emission.



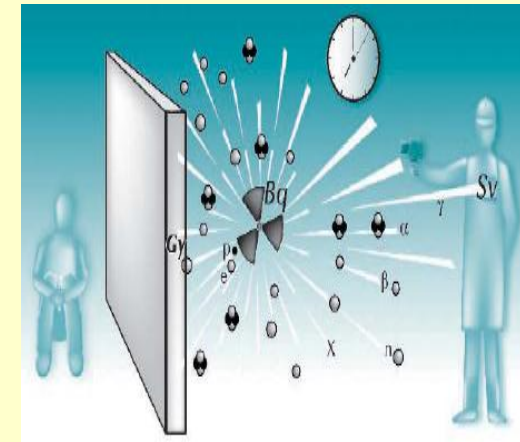
Penetrating distances for different Radiation types



Effects caused by an exposure to radiation

Sievert, Rem, Gray, Rad: Energy/Mass = Velocity²

- **Units:**
- **Becquerel: Raw physical unit measuring actual radioactivity in material**
1 Becquerel (Bq) = 1 disintegration/s
(Human body 75kg = 8 000 Becquerels)
- **Gray: Radiation energy absorbed by a mass of material**
1 Gray (Gy) = 1J/kg of tissues (m²s⁻²)
1 Gy = 100 Rad (Old unit)
- **Sievert : International unit indicating the biological damage in the human body caused by an exposure to radiation**
1 Sievert (Sv) (m²s⁻²) = 100 Rem (Old unit)
(Sleeping next to someone = 0,05 μSv)



Note: Rad: Radiation absorbed dose

36

Rem: Roentgen equivalent man or Radiation equivalent man

TPA Toolbox Energy Book 10 – Nuclear



Effects caused by an exposure to radiation

Sievert, Rem, Gray, Rad: $\text{Energy/Mass} = \text{Velocity}^2$

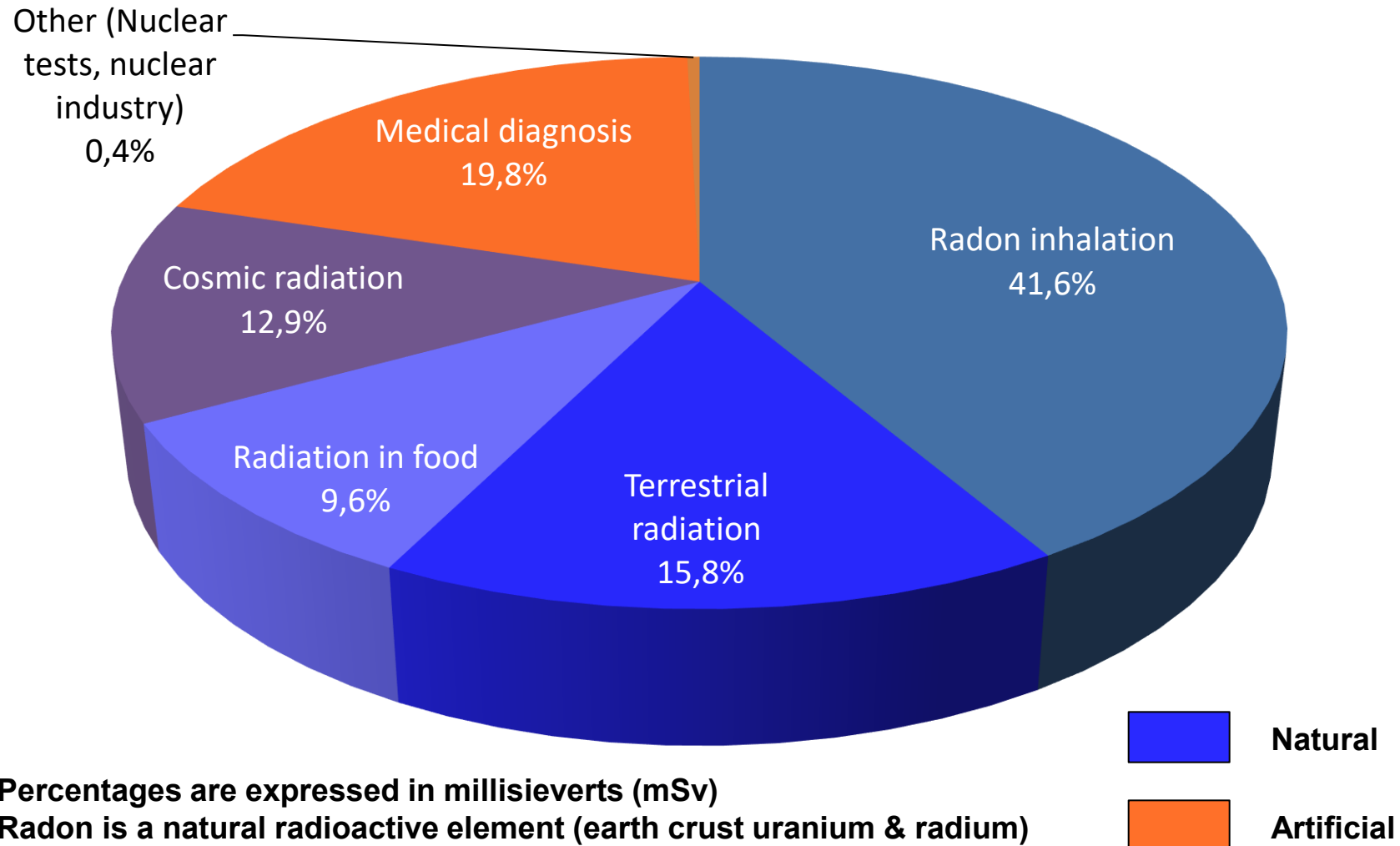
Comparative effects:

- ❖ β and γ radiation : 1 Sv
- ❖ Neutron radiation: 5 to 20 Sv
- ❖ α radiation : 20 Sv

- ❖ For X-rays, γ rays:
1 rad $\longrightarrow$ 1 rem = 10 mSv
- ❖ For neutron (linked to energy level):
1 rad $\longrightarrow$ 5 to 20 rem = 50 to 200 mSv
- ❖ For α radiation:
1 rad $\longrightarrow$ 20 rem = 200 mSv



Average Human Radioactivity exposure (3 mSv/year)



Source: Data from UNSCEAR, United Nations 2015³⁸
United Nations Scientific Committee on the Effects of Atomic Radiation



1-4

The Uranium Cycle



Common Units and Conversion Table for Uranium Compounds

Unités usuelles pour l'uranium Common units for uranium

	kg U	lb U ₃ O ₈	Short Ton U ₃ O ₈
1 kg U	1	2,5998	1,2999.10 ⁻³
1 lb U ₃ O ₈	0,3846	1	0,5.10 ⁻³
1 Short Ton U ₃ O ₈	769,3	2 000	1

Table de conversion pour les composés de l'uranium Conversion table for uranium compounds

	U	UO ₂	UO ₃	U ₃ O ₈	UF ₄	UF ₆	UNH ⁽¹⁾
Poids moléculaire	238,03	270,03	286,03	842,01	314,02	352,02	502,13
U	1	0,881	0,832	0,848	0,758	0,676	0,474
UO ₂	1,134	1	0,944	0,962	0,860	0,767	0,538
UO ₃	1,202	1,059	1	1,019	0,911	0,813	0,570
U ₃ O ₈	1,179	1,040	0,981	1	0,894	0,797	0,559
UF ₄	1,319	1,163	1,098	1,119	1	0,892	0,625
UF ₆	1,479	1,304	1,231	1,254	1,121	1	0,701
UNH ⁽¹⁾	2,110	1,860	1,756	1,789	1,599	1,426	1

(1) Nitrate d'uranyle : UO₂ (NO₃)₂, 6 H₂O



Billion of years ago, natural reactors existed in Africa

Natural reactors in Oklo (Gabon)

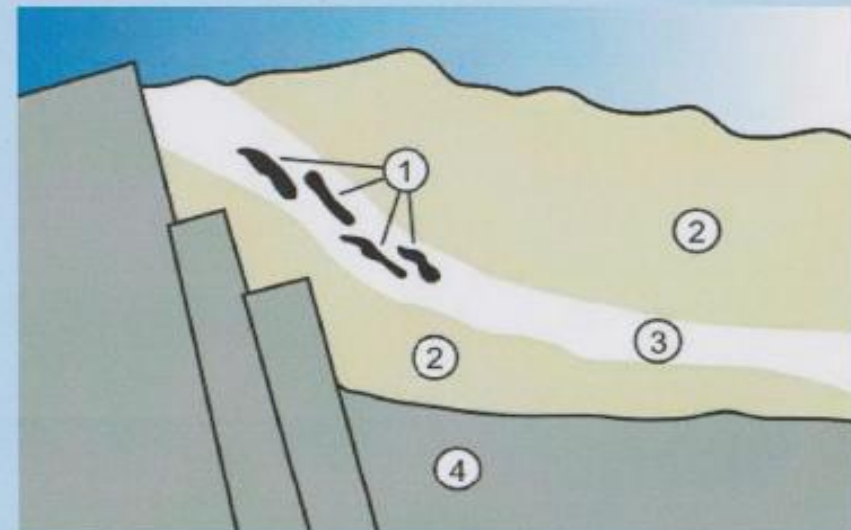
At the **Oklo** uranium mine it was discovered in 1972 that in **Precambrian** time (- **1.7** billion years) **17** natural nuclear **reactors** were operating in a **rich** deposit of uranium ore.

Each operated at 20 to 100 kW of power output. At that time the concentration of **U235** in all natural uranium was **3.7%** (comparable to enriched uranium used **today** in civil nuclear reactors) instead of **0.7%** today, because U235 decays much **faster** than U238 (whose half-life is the same as the age of earth).

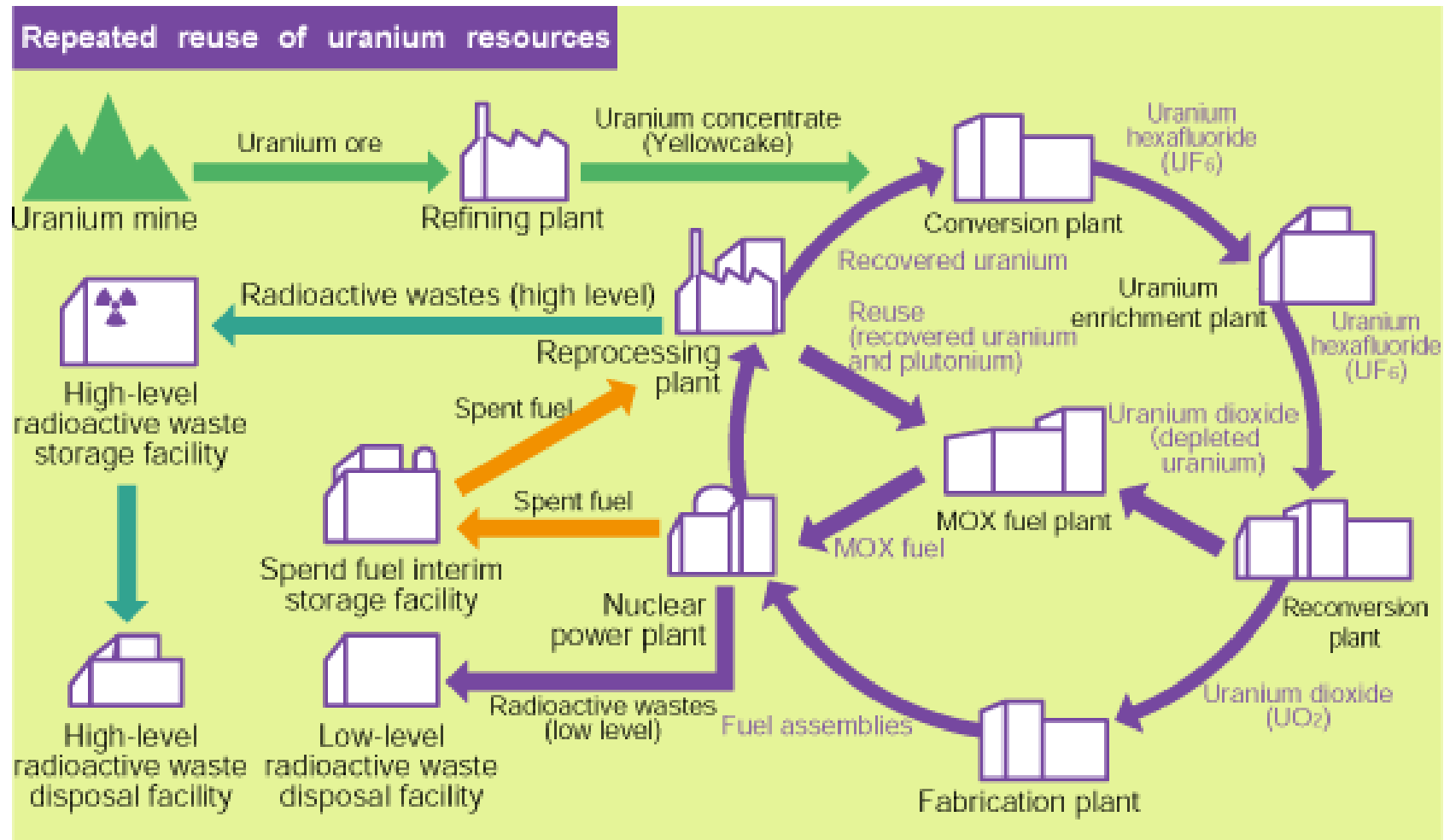
These naturally **self-sustaining chain** reactions started by the presence of **water** acting as a **neutron moderator** and continued for **2 million** years before finally dying away.

During this long reaction period, about 5.4 tonnes of **fission products** as well as 1.5 tonnes of **plutonium** together with other **transuranic** elements were generated in the orebody. Most of the initial radioactive products have long since **decayed** into **stable** elements, but there was **little movement** of radioactive long live **waste** during and after the nuclear reactions : the waste was held in place deep under Oklo in **rocks** (granite, sandstone, clays) surrounding the reactors' areas. Plutonium and the other transuranic isotopes has moved less than **10 feet** from where it was formed almost two billion years ago.

1. Nuclear reactor zones.
2. Sandstone.
3. Uranium ore layer.
4. Granite.

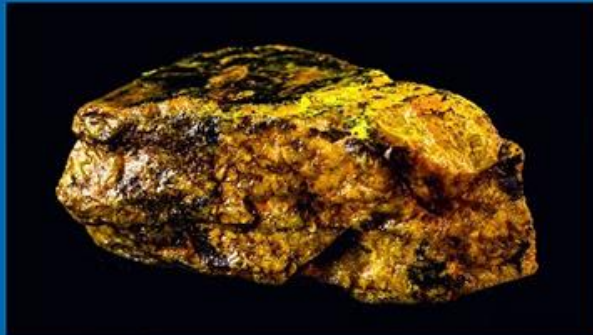


Simplified scheme of Uranium Cycle



MOx: Mixed Oxide (8,5% PuO₂, 91,5% UO₂)

Simplified scheme of Uranium Cycle



1

Uranium ore



2

Yellowcake



3

Hexafluoride



4

Dioxide



5

Fuel pellets

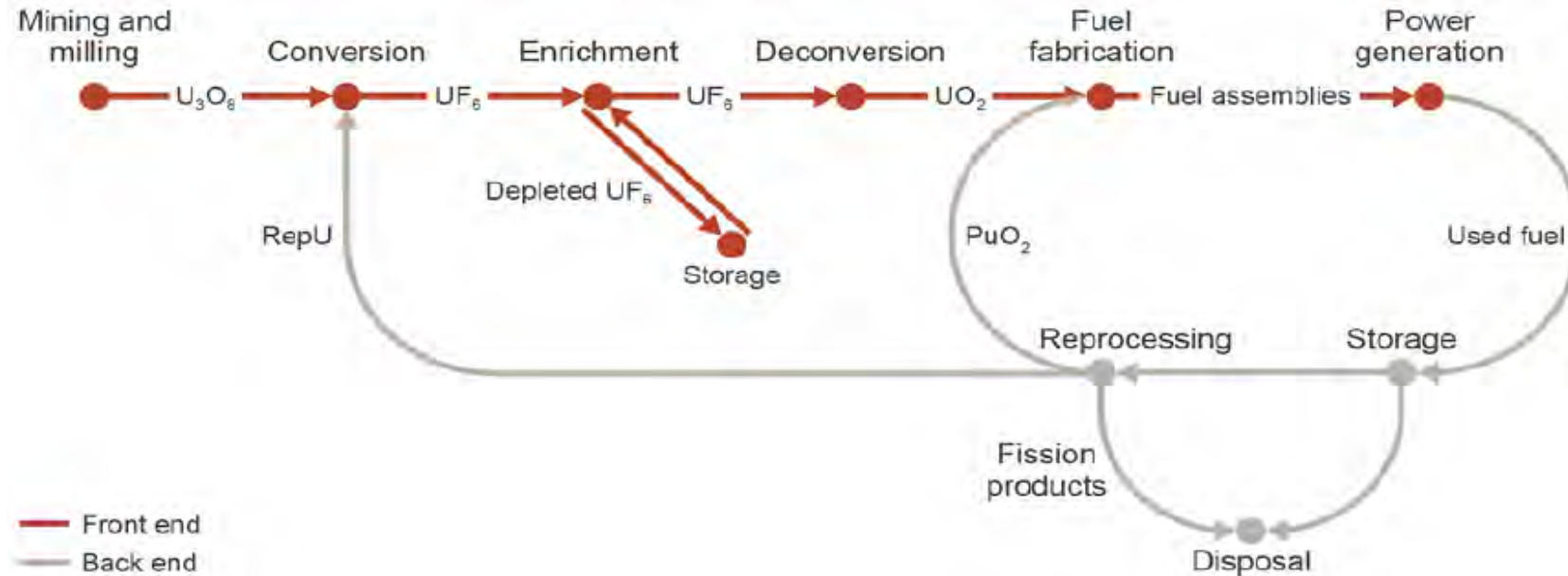


6

Fuel assemblies

MOx: Mixed Oxide (8,5% PuO_2 , 91,5% UO_2)

Simplified scheme of Uranium Cycle



The fuel cost in nuclear power has historically been a minor element in the total production cost. Fuel costs of new nuclear plants are usually under 20% of the total operational costs, compared with up to 80% in fossil fuel-fired plants.

Uranium supply can be characterized by two main categories: primary and secondary supply. Primary supply refers to uranium that is newly mined and processed, while secondary supply includes uranium received after reprocessing and returned back to the fuel cycle.

Source: WNA The Nuclear Fuel Report, Expanded Summary
April 2022



The cycle of Nuclear Fuel

- Extraction of uranium ore (example: pitchblende, the ore may contain less than 1% of uranium) →
- Concentration of ore on the site (up to 90% - 75% uranium : yellow cake/ U_3O_8) →
- Conversion of natural uranium (99,3% U_{238} + 0,7% U_{235}) into UF_6 (Uranium Hexafluoride) by fluorination →
- Isotopic enrichment of UF_6 (U_{238} into U_{235}) →
- Fabrication of fissible fuel (UF_6 into UO_2 , U_{235} concentration = **3,5 %**) →
- Loading of fuel into the reactor (UO_2 in fuel rods) →
- Chain reaction (Production of plutonium), Generation of electricity →
- Downloading of used fuel →
- Management and recycling of used nuclear fuel

$$1\text{kg U (U}_{238}\text{)} = 1,18 \text{ kg U}_3\text{O}_8 = 2,60 \text{ lb U}_3\text{O}_8$$



Uranium Mine



Source: Ranger Uranium Mine – Australia
Photo: Alberto Otero Garcia, Creative Commons

Pitchblende: Uranium Oxide U_3O_8



Source: B.Estève

Production of Uranium Ore



Most uranium is extracted using conventional mining techniques.

Source: NEA

Yellow Cake

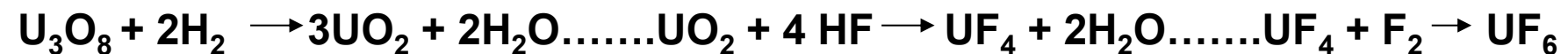


Major Uranium Hexafluoride Conversion Plants

Uranium Oxyde $\longrightarrow$ UF₆

Estimated world primary conversion capacity and UF₆ production 2022

Company	Country	Location	Licensed capacity (tU)	UF ₆ production (tU)
Cameco	Canada	Port Hope	12,500	10,600
CNNC (est.)*	China	Lanzhou & Hengyang	15,000	10,500
ConverDyn	USA	Metropolis	7000	0
Orano	France	Pierrelatte, Malvesi	15,000	8900
Rosatom (est.)	Russia	Seversk	12,500	12,000
Total			62,000	42,000



Depleted Uranium and Deconversion Plants

Depleted Uranium $\longrightarrow$ UF_6 $\longrightarrow$ U_3O_8 $\longrightarrow$ UF_4

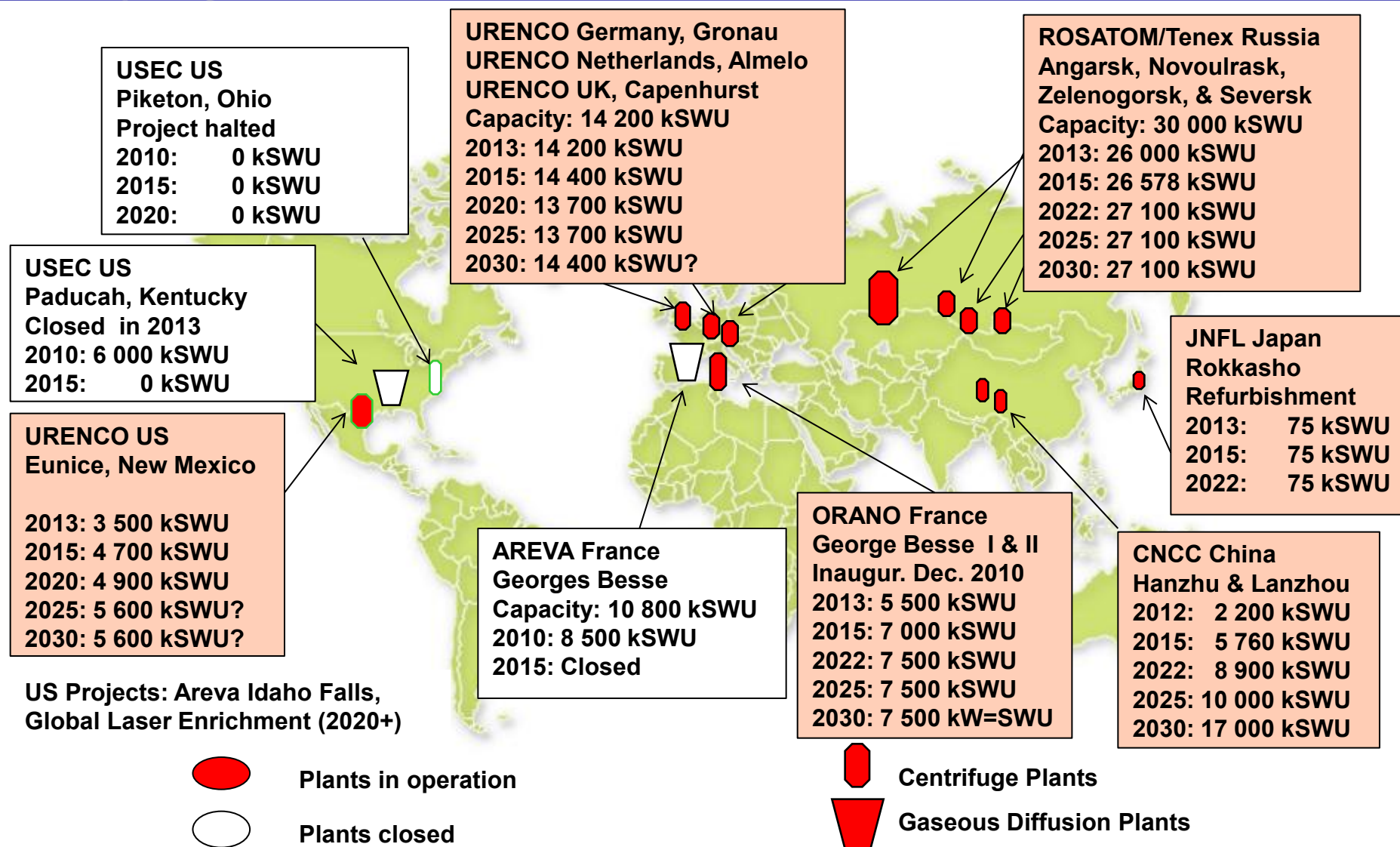
Uranium deconversion plants

Operator	Location	Capacity tU/yr
Orano	Tricastin, France	20,000
	Richland, Washington, USA	small
Urenco ChemPlants	Capenhurst, UK	10,000
Mid America Conversion Services	Portsmouth, Ohio, USA	13,500
	Paducah, Kentucky, USA	18,000
INIS Fluorine Products	Hobbs, New Mexico, USA	6500 (construction on hold)
Tenex	Zelenogorsk, Russian Federation	10,000



Major Uranium Enrichment Plants

World Capacity: 61,5 MSWU in 2022 - 62,9 MSWU in 2025 - 70,3 MSWU forecasted in 2030



Source: Data from CEA Memento 2018/WNA Updated June 2025
AREVA became ORANO
Nota: SWU : Separative Work Unit

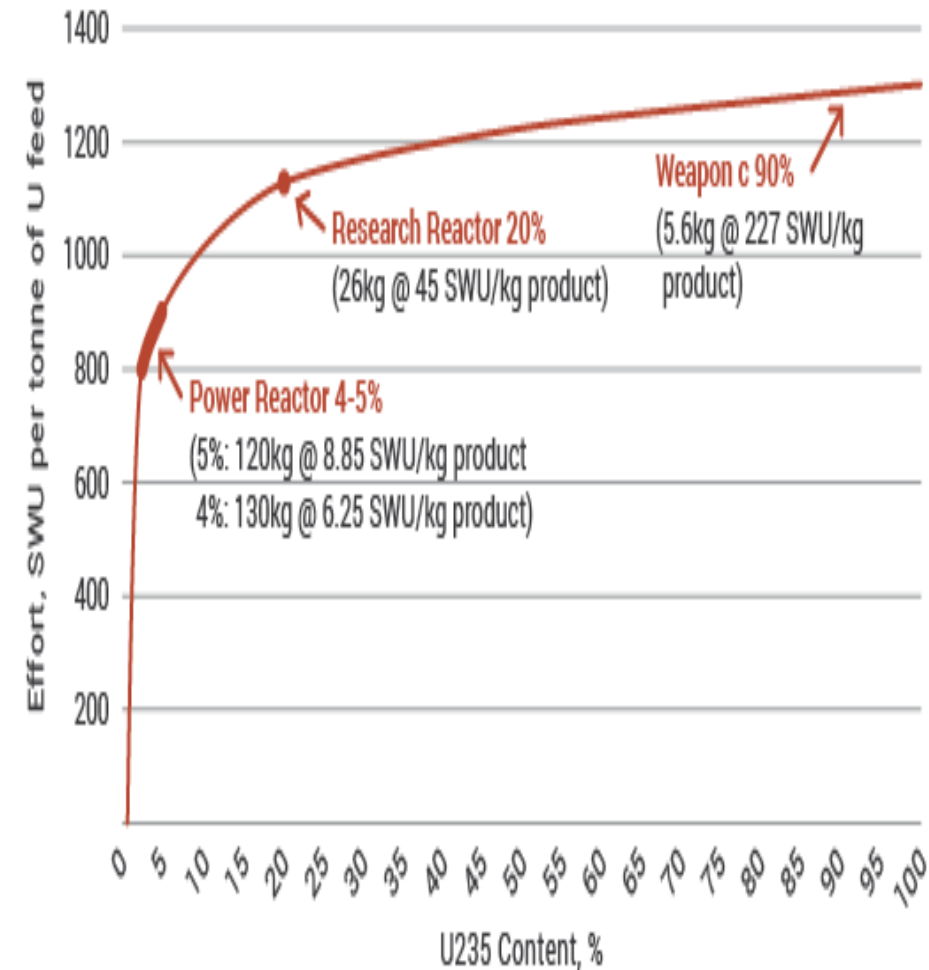
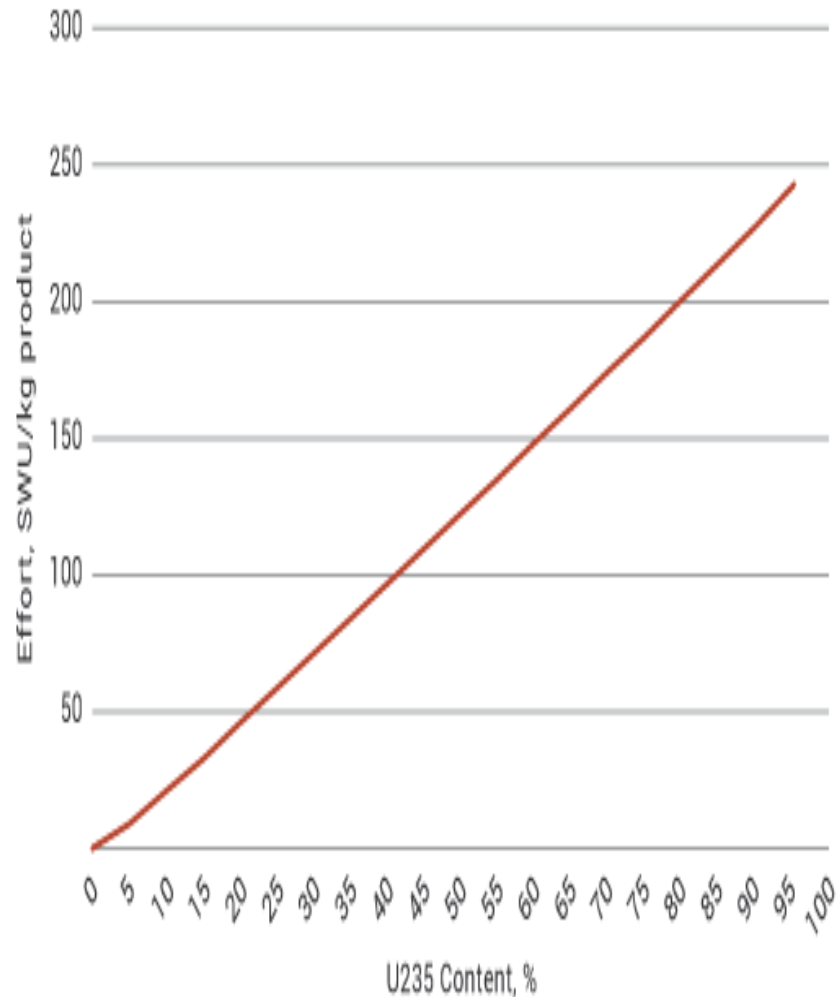
Note: 100 000 SWU are needed to feed the fuel for a nuclear reactor
of 1 000 MWe

TPA Toolbox Energy Book 10 – Nuclear

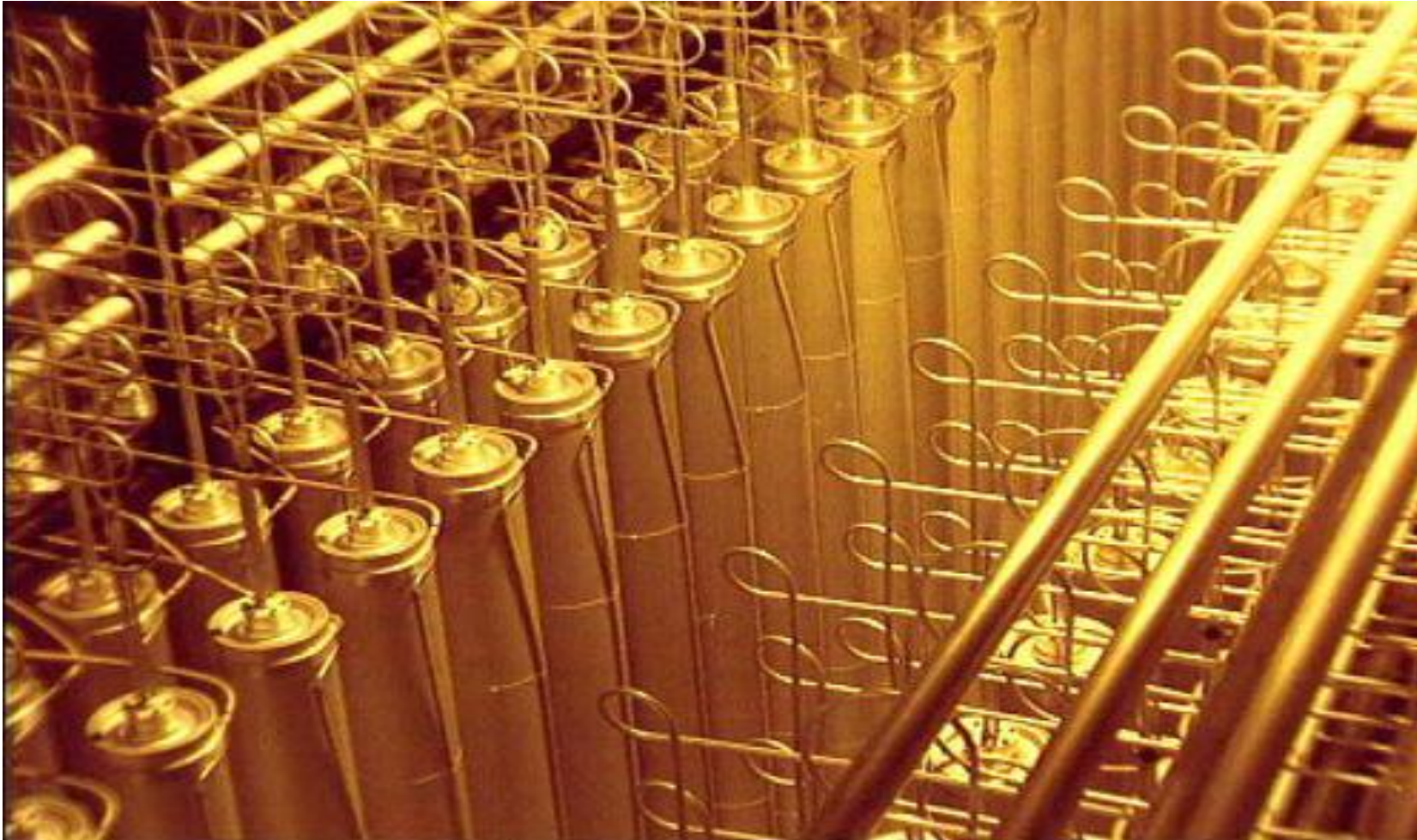


Uranium Enrichment and Uses (4% Enrichment)

1t U₂₃₈ → 800 SWU/6,25 → 130 kg U₂₃₅



A bank of centrifuges at Urenco plant



Source: WNA 2018

Tricastin Enrichment Plant - France



George Besse I enrichment plant at Tricastin site (beyond cooling towers) was shut down in 2012. Most of the output from the nuclear power plant was used to power the enrichment facility. Gaseous diffusion plants have been replaced by the much more energy-efficient centrifuge enrichment technology.



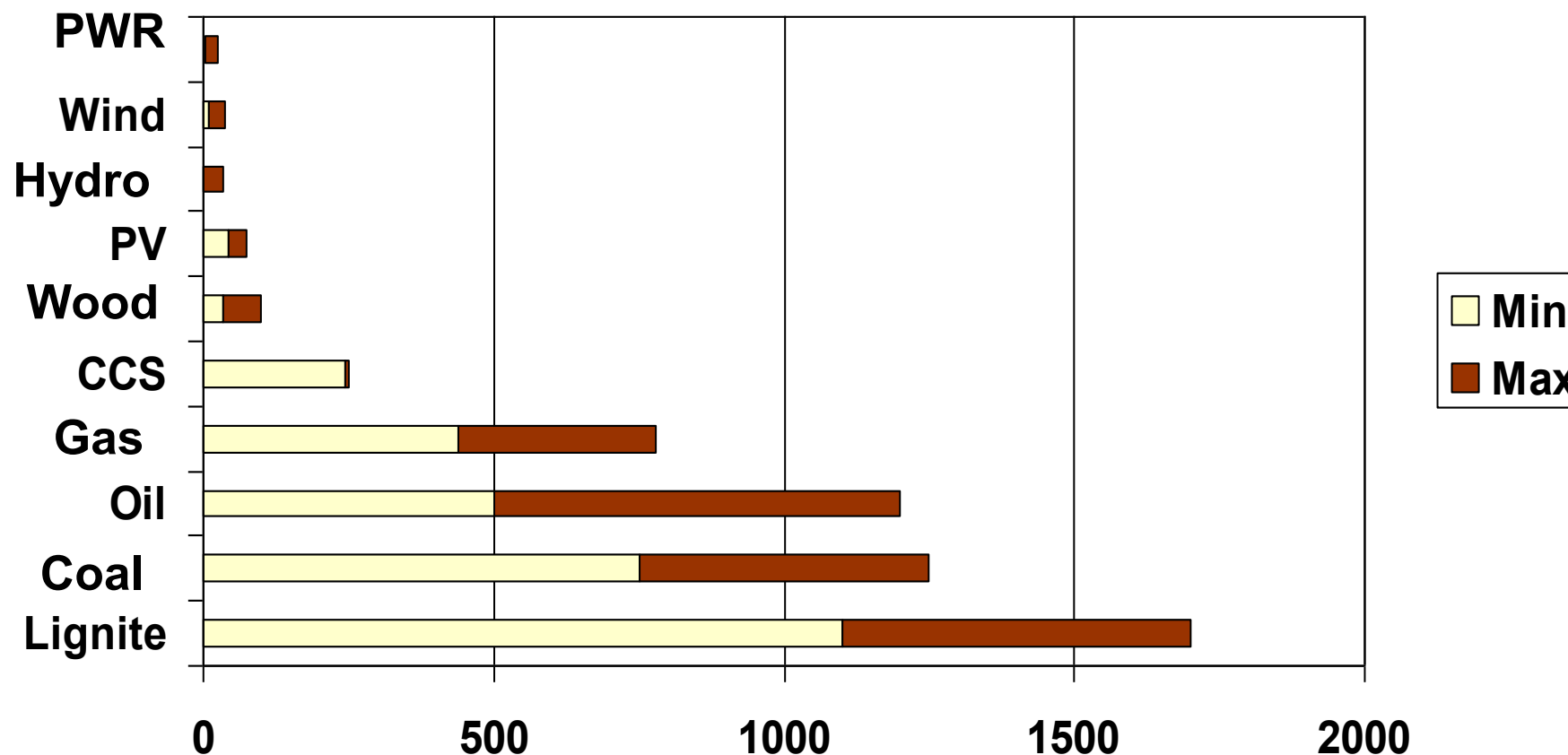
1-5

Zero CO₂ Emissions for Nuclear Plants



Life Cycle GHG Emissions, g CO₂eq per kWh_e (View 1)

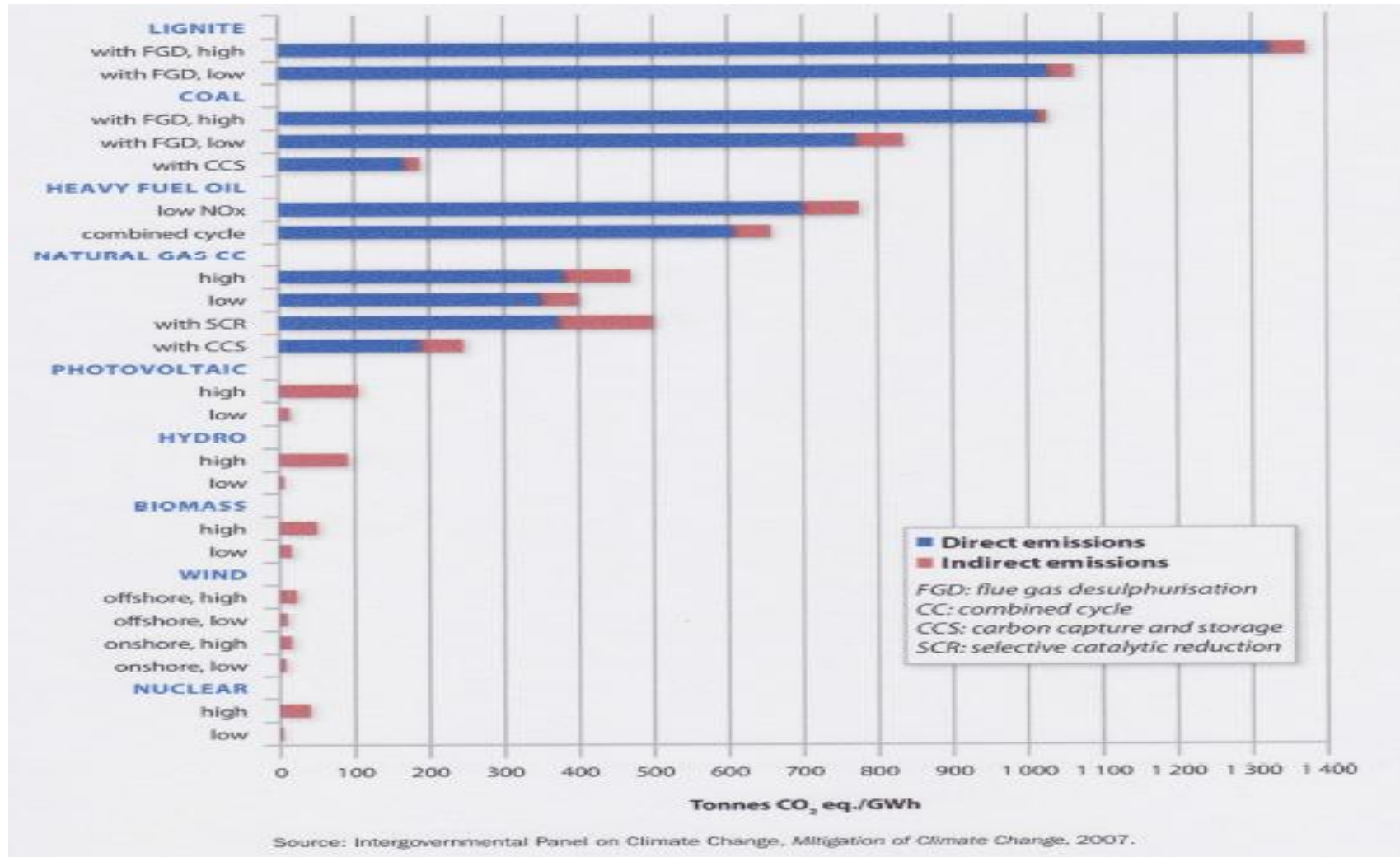
D. Weisser IAEA May 2006



Ranges reflect differences in assessment technology, conversion efficiency, assessment boundary, etc.



Life Cycle GHG Emissions, g CO₂eq per kWh_e (View 2)



2

What are uranium resources ?



TABLE OF CONTENTS

1. What is nuclear energy ?
2. What are uranium resources ?
3. The world nuclear industry: past and present
4. Future evolution
5. The world nuclear industry and the energy and oil & gas industry: interest from stakeholders ?



2-1

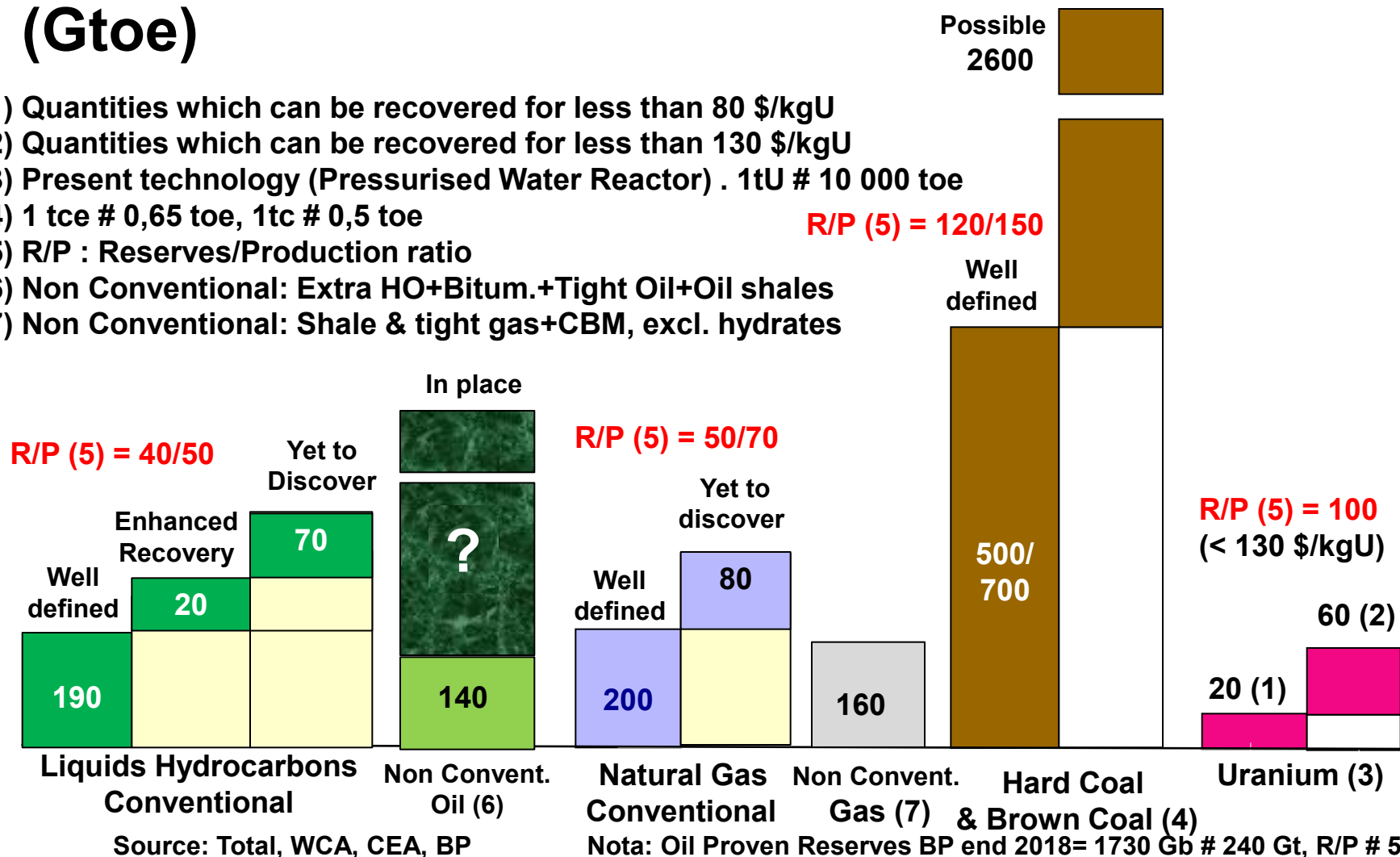
Uranium Resources



World Resources (Gtoe) – A Vision 01/01/2019

(Gtoe)

- (1) Quantities which can be recovered for less than 80 \$/kgU
- (2) Quantities which can be recovered for less than 130 \$/kgU
- (3) Present technology (Pressurised Water Reactor) . 1tU # 10 000 toe
- (4) 1 tce # 0,65 toe, 1tc # 0,5 toe
- (5) R/P : Reserves/Production ratio
- (6) Non Conventional: Extra HO+Bitum.+Tight Oil+Oil shales
- (7) Non Conventional: Shale & tight gas+CBM, excl. hydrates



R/P varies vs sources. Not at scale



Some definitions, classifications, conversion factors

		Identified resources		Undiscovered resources	
Decreasing economic attractiveness ↓	Recoverable at costs	<USD 40/kgU	Reasonably assured resources	Inferred resources	Prognosticated resources
		USD 40-80/kgU	Reasonably assured resources	Inferred resources	Prognosticated resources
		USD 80-130/kgU	Reasonably assured resources	Inferred resources	Prognosticated resources
		USD 130-260/kgU	Reasonably assured resources	Inferred resources	Prognosticated resources
		Speculative resources			
Decreasing confidence in estimates →					

1 short ton U ₃ O ₈	=	0.769 tU
1% U ₃ O ₈	=	0.848% U
1 USD/lb U ₃ O ₈	=	USD 2.6/kg U
1 tonne	=	1 metric ton

Source: OECD NEA/IAEA Uranium 2022
Resources, Production and Demand - OECD 2023/NEA 7634
Nota: RAR = Reasonably Assured Resources
Inferred Resources = Additional expected Resources



Global World Distribution of identified recoverable conventional Uranium Resources (<130 US\$/kg U) as of 01/01/2023

(<USD 130/kgU as of 1 January 2023)



The global distribution of identified recoverable conventional uranium resources in the <USD 130/kgU cost category among 15 countries, which are either major uranium producers or have significant plans for growth of nuclear generating capacity, illustrates the widespread distribution of these resources. Together, these 15 countries are endowed with over 95% of the global resource base as specified above (the remaining resources in this cost category are distributed among another 23 countries). The widespread distribution of uranium resources is an important geographic aspect of nuclear energy in light of security of energy supply.

* Secretariat estimate or partial estimate.

Source: OECD NEA/IAEA Uranium 2024
Resources, Production and Demand - OECD 2025/NEA 7683

Nota: RAR = Reasonably Assured Resources
Inferred Resources = Additional expected Resources

Typical Natural Uranium Concentrations

Very high-grade ore (Canada) – 20% U	200,000 ppm U
High-grade ore – 2% U	20,000 ppm U
Low-grade ore – 0.1% U	1000 ppm U
Very low-grade ore* (Namibia) – 0.01% U	100 ppm U
Granite	3-5 ppm U
Sedimentary rock	2-3 ppm U
Earth's continental crust (av)	2.8 ppm U
Seawater	0.003 ppm U

ppm = parts per million



World Uranium Resources at 01/01/2021 and 01/01/2023 (tU)

Resource category	2021	2023	Change ^(a)	% change
Total Identified resources				
<USD 260/kgU	7 917 500	7 934 500	17 000	0.2
<USD 130/kgU	6 078 500	5 925 700	-152 800	-2.5
<USD 80/kgU ^(b)	1 990 800	1 881 100	-109 700	-5.5
<USD 40/kgU ^(b)	775 900	666 900	-109 000	-14.0
Reasonably assured resources				
<USD 260/kgU	4 688 300	4 778 700	90 400	1.9
<USD 130/kgU	3 814 500	3 868 800	54 300	1.4
<USD 80/kgU ^(b)	1 211 300	1 180 700	-30 600	-2.5
<USD 40/kgU ^(b)	457 200	364 700	-92 500	-20.2
Inferred resources				
<USD 260/kgU	3 229 200	3 155 700	-73 500	-2.3
<USD 130/kgU	2 263 900	2 056 900	-207 000	-9.1
<USD 80/kgU ^(b)	779 600	700 400	-79 200	-10.2
<USD 40/kgU ^(b)	318 700	302 200	-16 500	-5.2

* Totals may not sum exactly, or exactly match totals reported in other tables of this report, due to rounding.

(a) Changes might not equal differences between 2021 and 2023 because of independent rounding. (b) Totals for <USD 40/kgU and <USD 80/kgU cost ranges should be regarded with some caution as certain countries do not report low-cost resource estimates, whereas other (non-producing) countries may underestimate mining costs.

Source: OECD NEA/IAEA Uranium 2024

Resources, Production and Demand - OECD 2025/NEA 7683

Nota: RAR = Reasonably Assured Resources

Inferred Resources = Additional expected Resources



World Uranium Identified Resources vs in situ & vs costs Estimated Recovery Factor at 01/01/2023 (tU)

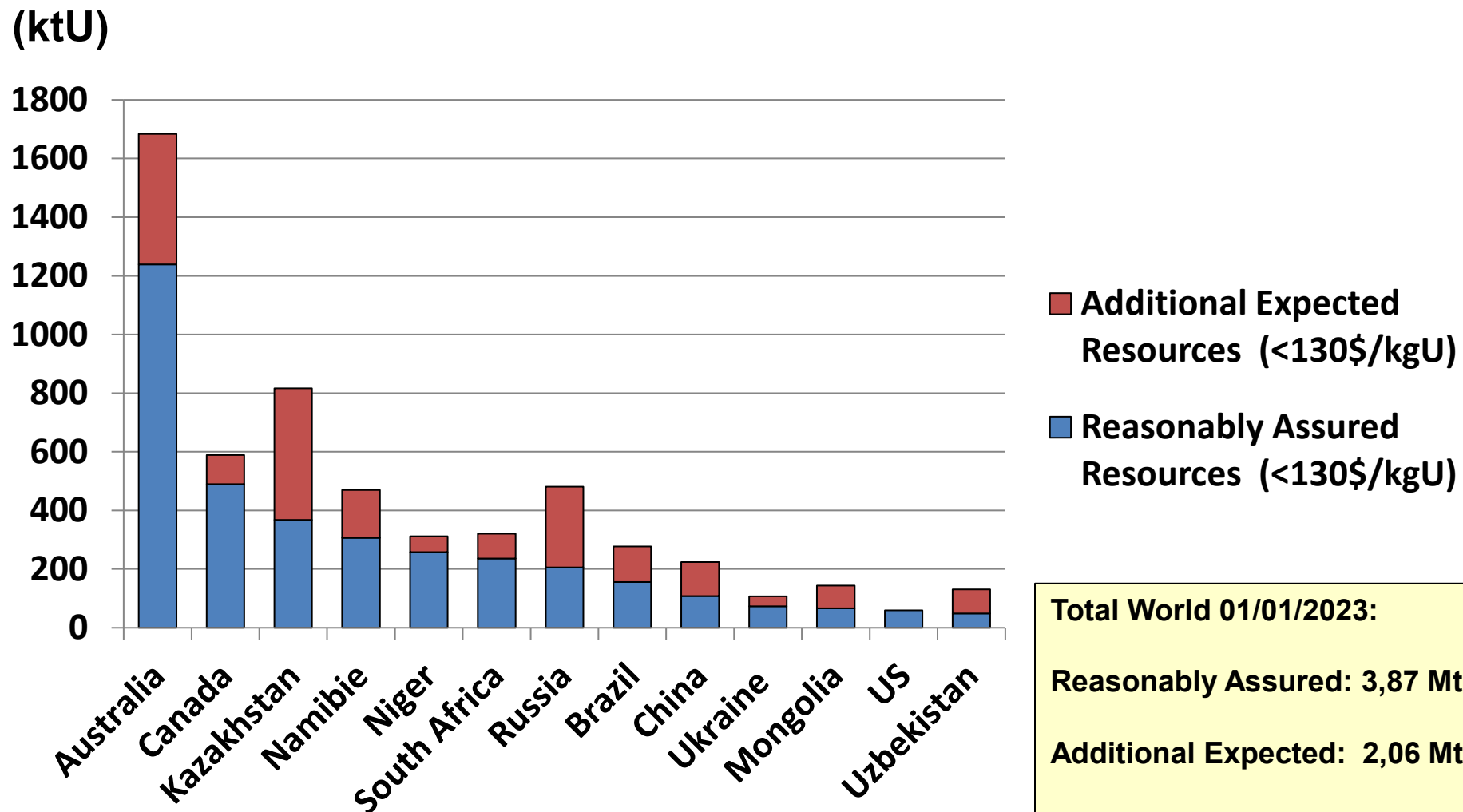
(as of 1 January 2023, tonnes U, rounded to nearest 100 tonnes[†])

Identified resources	Cost ranges			
	<USD 40/kgU	<USD 80/kgU	<USD 130/kgU	<USD 260/kgU
Total in situ	808 300	2 313 000	7 943 700	10 714 400
Total recoverable	666 900	1 881 100	5 925 700	7 934 500
Difference	141 400	431 900	2 018 000	2 779 900
Difference %	17.5	18.7	25.4	25.9
Recovery %	82.5	81.3	74.6	74.1

Source: OECD NEA/IAEA Uranium 2024
Resources, Production and Demand - OECD 2025/NEA 7683
Nota: RAR = Reasonably Assured Resources
Inferred Resources = Additional expected Resources



World Most Important Uranium Resources at 01/01/2023 (<130 \$/kgU)



Total World 01/01/2023:

Reasonably Assured: 3,87 Mt

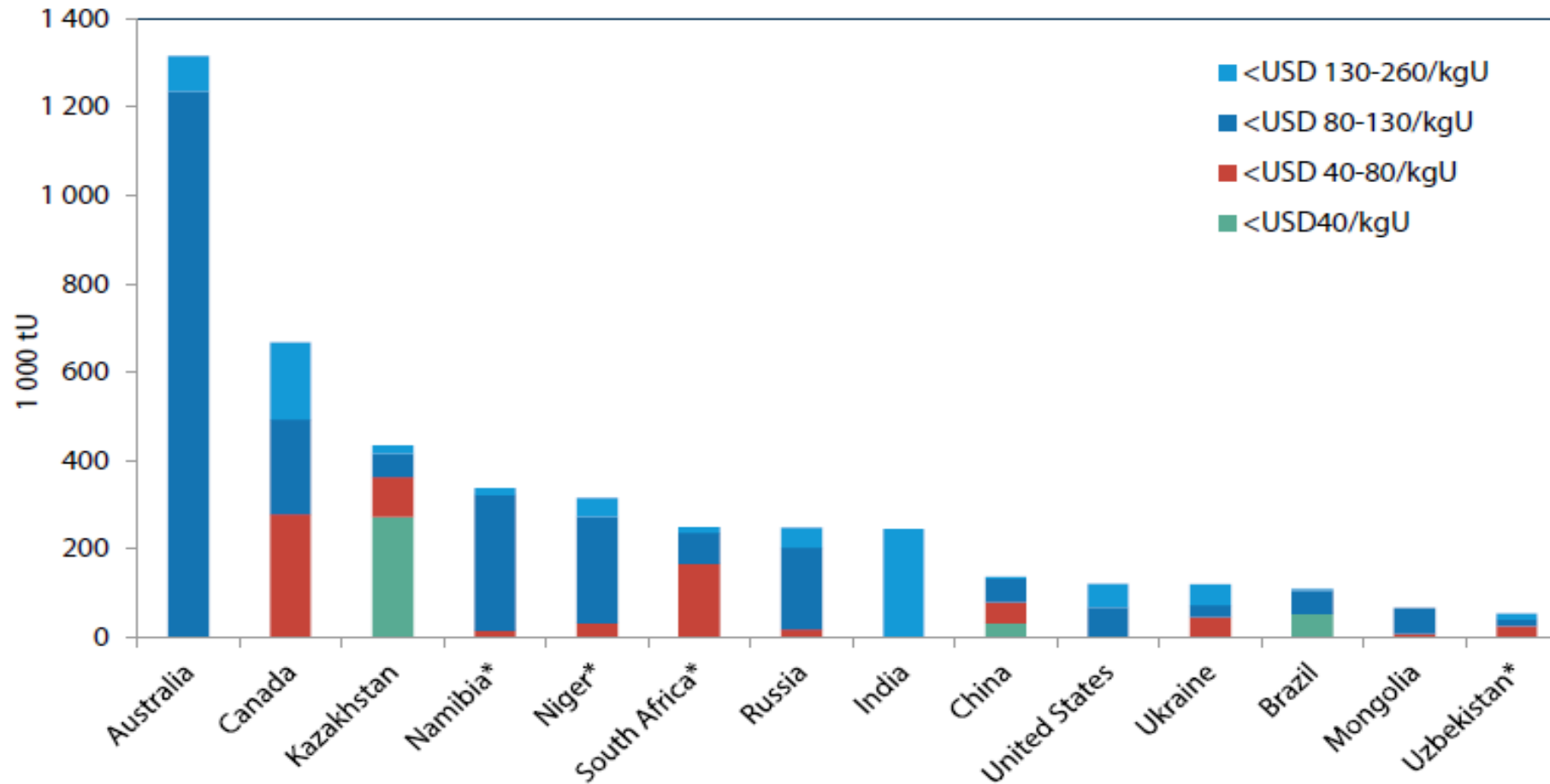
Additional Expected: 2,06 Mt

Total: 5,93 Mt

Source: Data from OECD NEA/IAEA Uranium 2024
 Resources, Production and Demand - OECD 2025/NEA 7683
 Nota: RAR = Reasonably Assured Resources
 Inferred Resources = Additional expected Resources



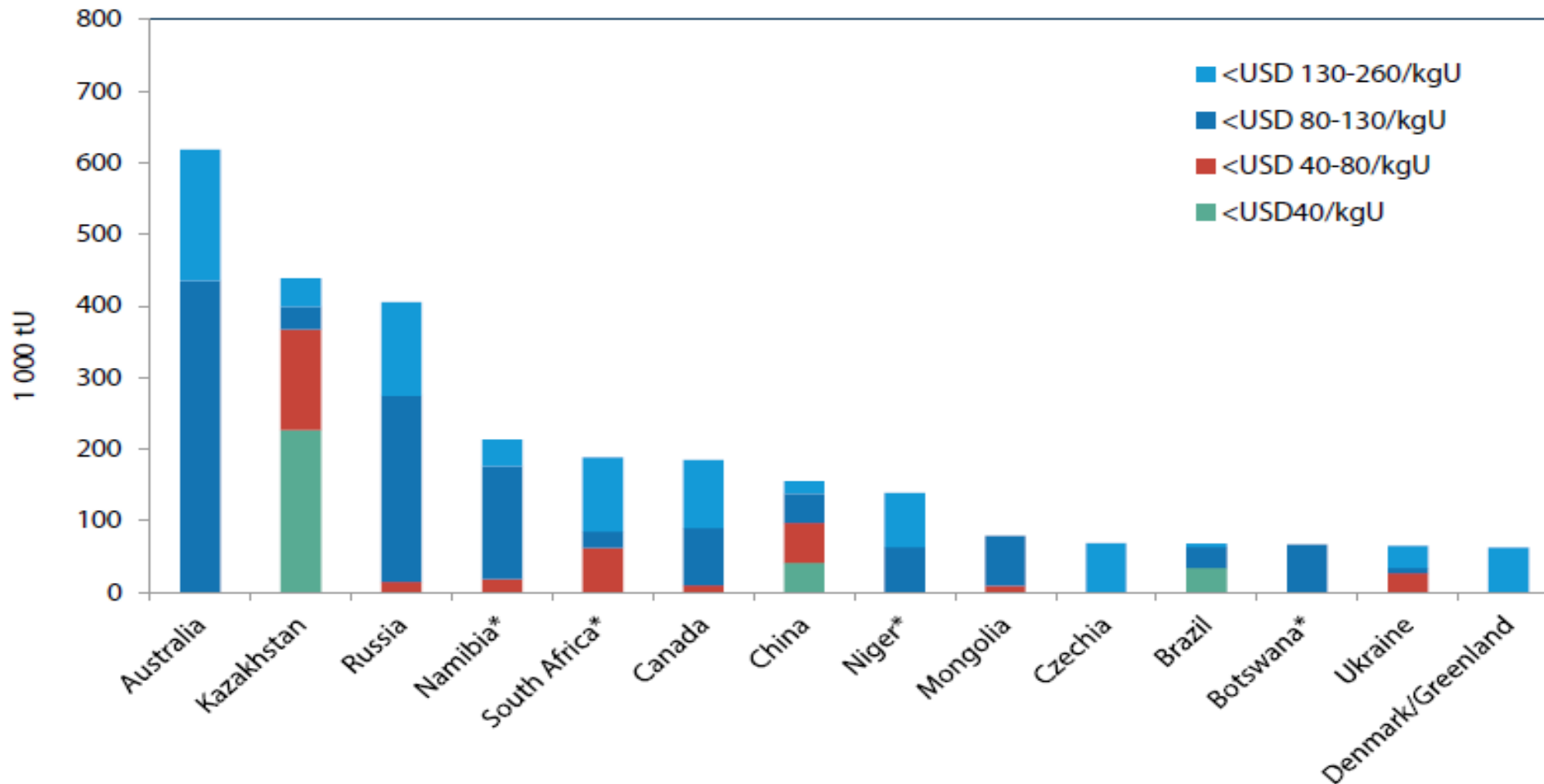
Distribution of RAR by countries & costs



* Secretariat estimate or partial estimate.

Source: OECD NEA/IAEA Uranium 2024
 Resources, Production and Demand - OECD 2025/NEA 7683
 Nota: RAR = Reasonably Assured Resources
 Inferred Resources = Additional expected Resources

Distribution of Additional Expected (Inferred) Resources by countries & costs



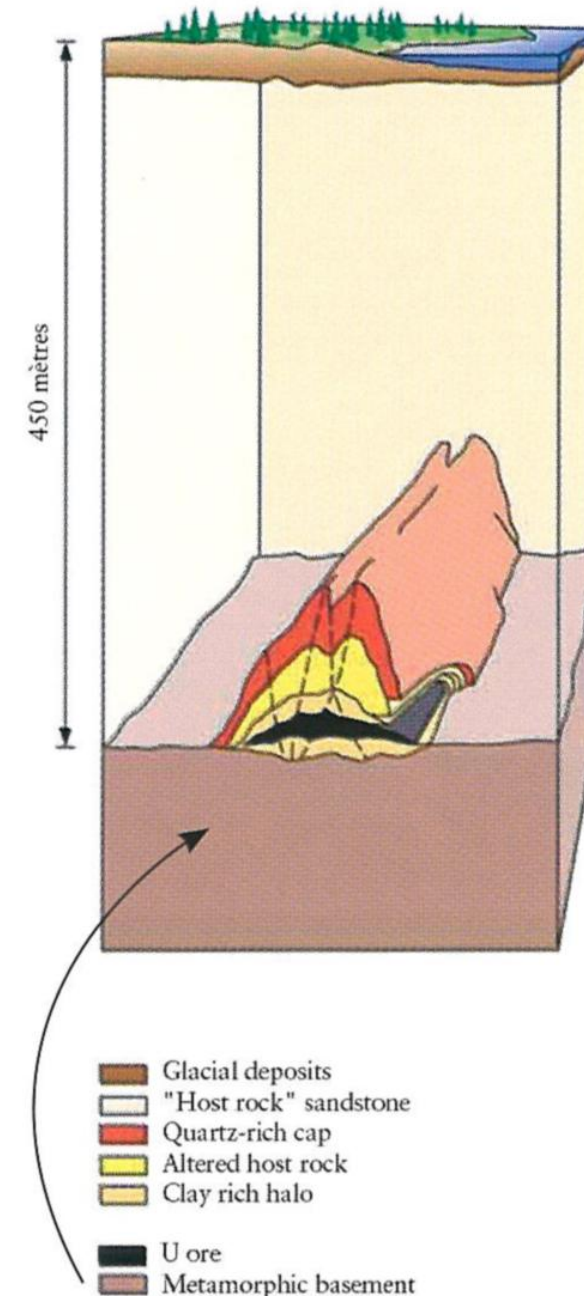
* Secretariat estimate or partial estimate.

Source: OECD NEA/IAEA Uranium 2024
 Resources, Production and Demand - OECD 2025/NEA 7683
 Nota: RAR = Reasonably Assured Resources
 Inferred Resources = Additional expected Resources



Cigar Lake: A « Monster » uranium deposit in Canada.

- Athabasca Canada
- 150 000 tons
- Uranium content: 10/50%
- Depth: 450 m

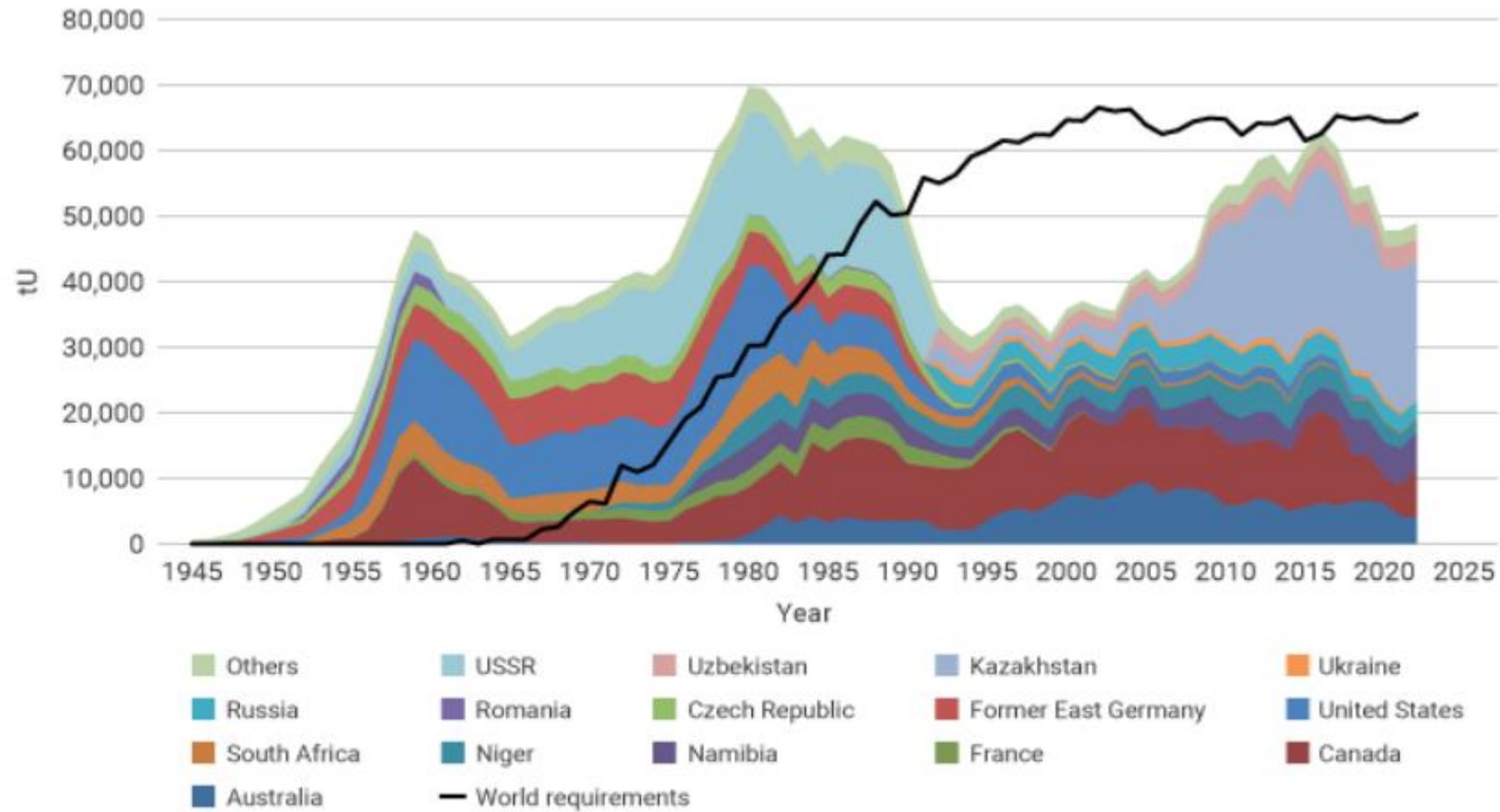


2-2

Uranium Requirements and Production



World Uranium Requirements and Production Historical Evolution 1945 - 2022

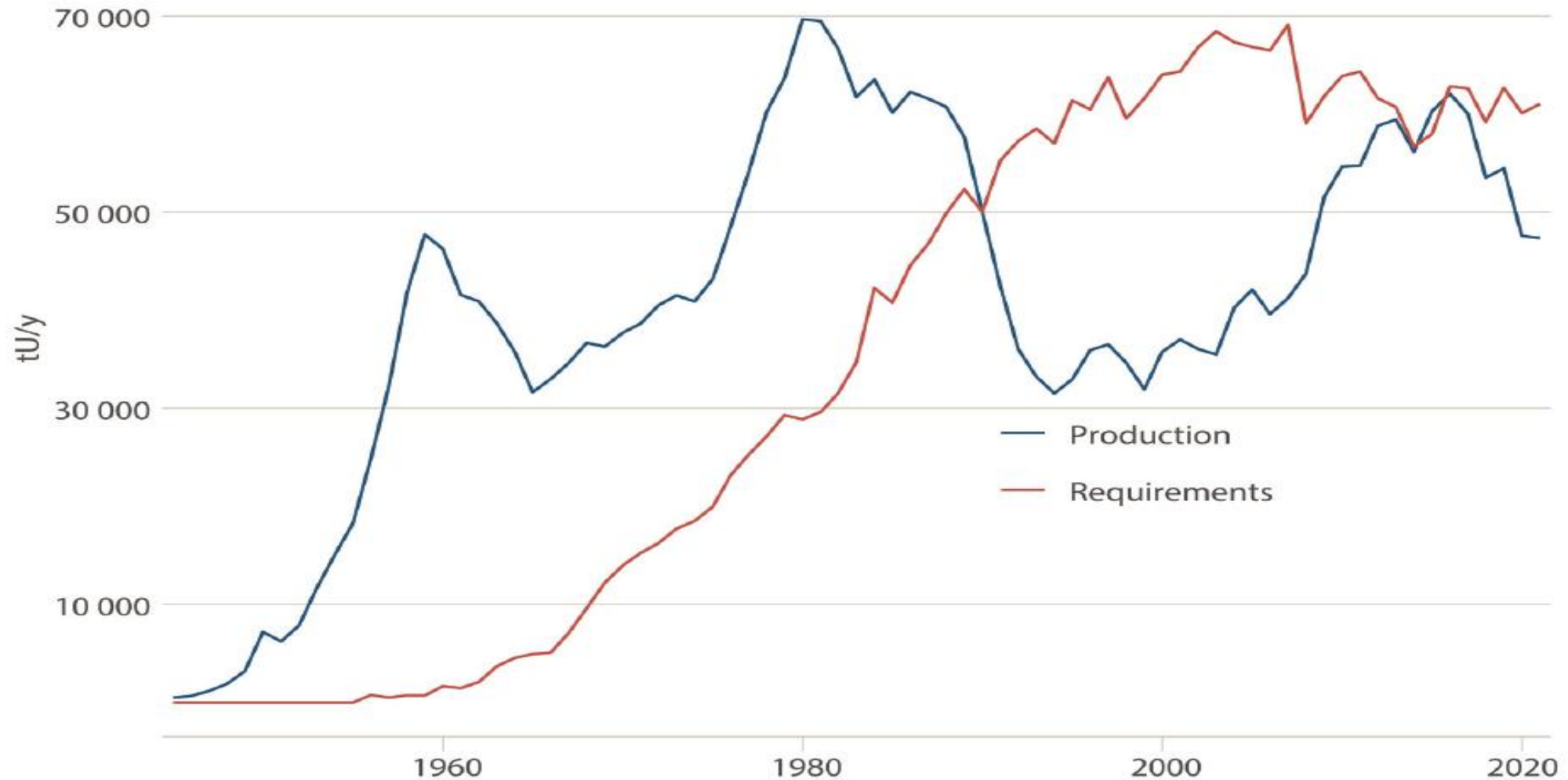


Source: OECD-NEA, IAEA, World Nuclear Association

Source: WNA Nuclear Fuel Cycle/Uranium markets - Updated August 2024



World Uranium Consumption and Production Past and Present Requirements by OECD/NEA



Source: OECD NEA/IAEA Uranium 2024
Resources, Production and Demand - OECD 2025/NEA 7683



World Uranium Production - Historical Evolution 2015 – 2024 (tU)

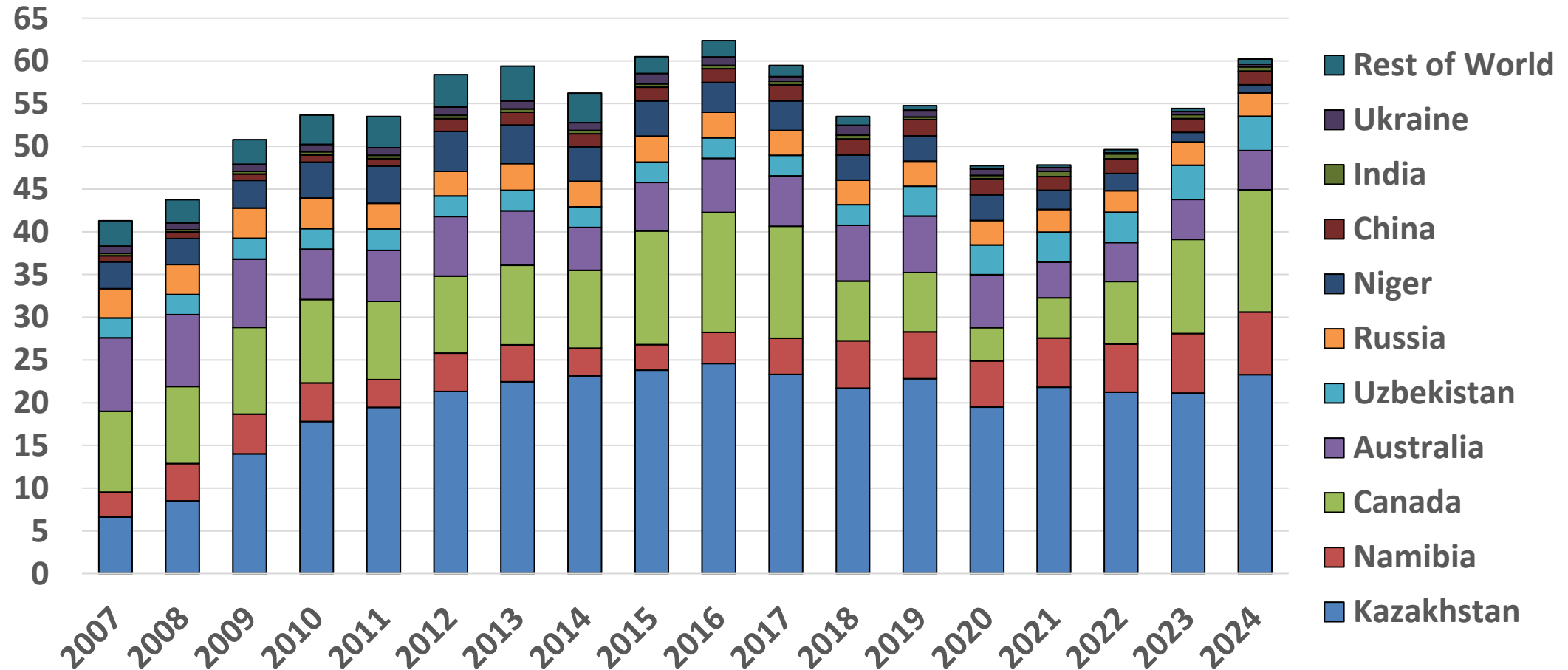
Country	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Kazakhstan	23,607	24,689	23,321	21,705	22,808	19,477	21,819	21,227	21,109	23,270
Canada	13,325	14,039	13,116	7001	6938	3885	4693	7351	11,001	14,309
Namibia	2993	3654	4224	5525	5476	5413	5753	5611	6986	7333
Australia	5654	6315	5882	6517	6613	6203	4192	4553	4693	4598
Uzbekistan (est.)	2385	3325	3400	3450	3500	3500	3516	3561	4000	4000
Russia	3055	3004	2917	2904	2911	2846	2635	2508	2710	2738
China (est.)	1616	1616	1692	1885	1885	1885	1600	1700	1600	1600
Niger	4116	3479	3449	2911	2983	2991	2248	2020	1130	962
India (est.)	385	385	421	423	308	400	600	600	485	500
South Africa (est.)	393	490	308	346	346	250	192	200	200	200
Ukraine (est.)	1200	808	707	790	800	744	455	100	340	288
USA	1256	1125	940	582	58	6	8	75	19	260
Others	357	277	85	116	116	131	95	108	161	155
World total tU	60,342	63,207	60,462	54,154	54,742	47,731	47,805	49,614	54,433	60,213
World total tU3O8	71,158	74,536	71,299	63,861	64,554	56,286	46,374	58,507	64,190	71,006
% of world demand	98%	96%	93%	80%	81%	74%	76%	76%	83%	90%



World Uranium Production in the recent years

In 2024: N°1 Kazakhstan, N°2 Canada, N°3 Namibia

(ktU)



Source: ChG/Data from WNA Facts & figures - Updated September 2025



World Uranium Consumption and Production

Past and Present Requirements by WNA/NEA/IAEA

tU	2000	2005	2010	2015	2017	2020	2021	2022	2023	2024	2025
Consumption In reactors	60 000	67 000	70 000	66 000	65000	60 000	61 000	60 000	65 000	67 000	69 000
Production from mining	35 000	45 000	54 000	60 000	59000	48 000	48 000	49 000	55 000	60 000	60 000
Secondary sources	25 000	22 000	16 000	6 000	6000	12 000	13 000	11 000	10 000	7 000	9 000

Secondary sources: Recycled Uranium & Plutonium, Re-enriched depleted uranium tails, ex-military weapons-grade uranium, civil stockpiles, ex-military weapons-grade plutonium

Source: Requirements & Production past and projections WNA
Facts & figures/NEA/IAEA Uranium 2024. Rounded numbers.
2024 - 2025 assumptions: high requirements



World Uranium Consumption and Production

Past and future Requirements by NEA/IAEA

(tonnes U per year)

Region	2022	2025 low	2025 high	2030 low	2030 high	2035 low	2035 high	2040 low	2040 high	2045 low	2045 high	2050 low	2050 high
European Union	13 720	11 703	14 252	14 851	16 303	14 505	18 690	14 746	20 016	15 695	22 007	13 390	21 900
North America	17 705	17 088	17 138	17 120	17 267	17 440	17 885	18 445	19 670	16 765	20 189	14 123	22 603
East Asia	16 401	18 125	22 953	20 060	25 448	23 648	30 788	26 736	40 624	29 136	48 784	33 936	56 624
Europe (non-EU)	7 525	8 810	8 820	9 648	10 362	11 446	13 104	14 116	15 704	14 616	16 204	14 616	17 532
Central and South America	530	568	568	873	961	1 656	2 108	1 244	2 240	1 335	2 783	1 335	3 238
Middle East, Central and South Asia	2 843	3 192	3 702	4 649	5 565	7 549	9 622	9 126	13 870	10 838	15 438	10 838	16 366
South Eastern Asia	0	0	0	0	0	0	0	0	640	0	800	0	1 120
Africa	294	294	294	470	646	998	1 168	1 478	2 928	1 808	3 088	1 808	3 248
Pacific	0	0	0	0	0	0	0	0	0	0	0	0	0
World Total	59 018	59 779	67 728	67 671	76 552	77 242	93 365	85 891	115 692	90 192	129 293	90 045	142 631

* NEA/IAEA estimate (rounded to nearest whole number). Because of rounding, totals may not add up.



World Uranium projected Requirements and Production Scenarios by OECD/NEA 2025 – Production costs < 130\$/kgU

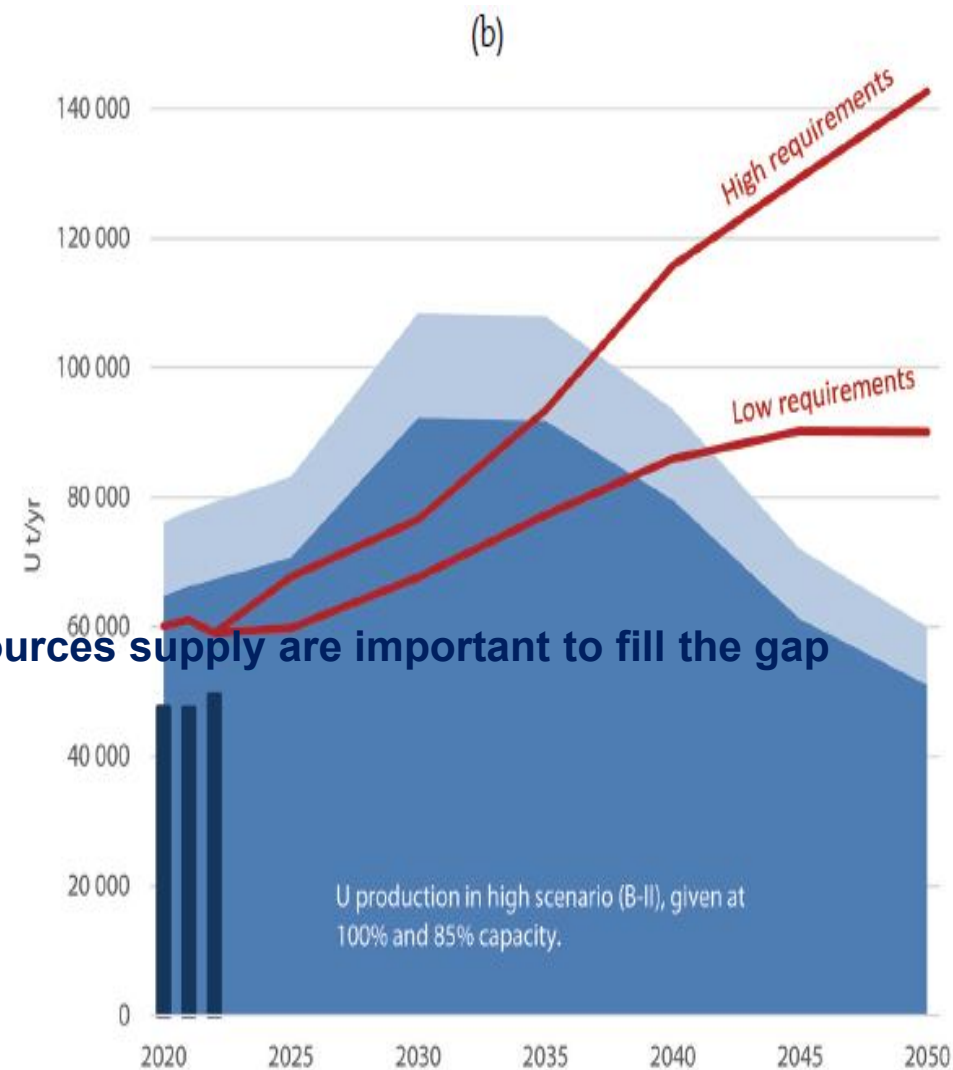
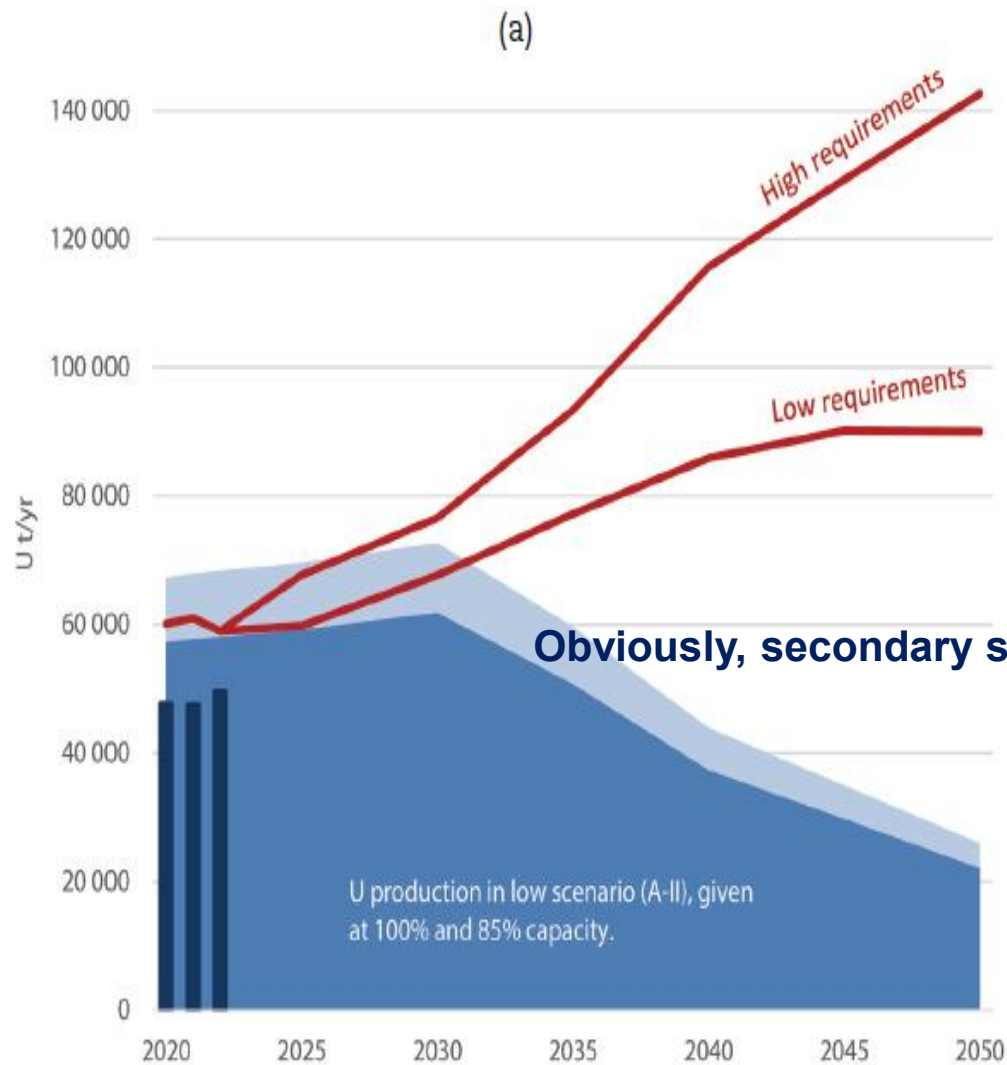


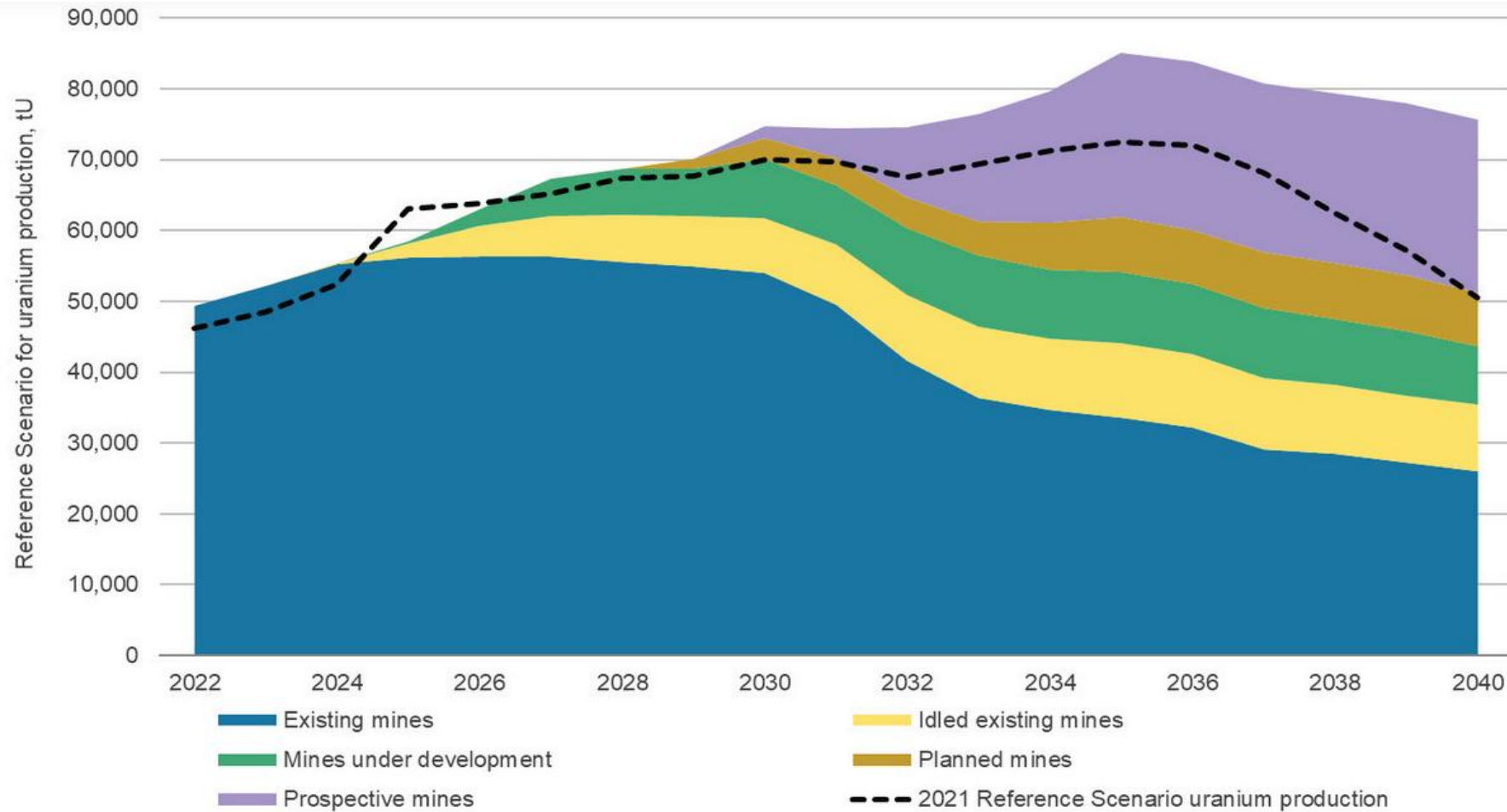
Figure a) illustrates the A-II case (production capability of existing, idled and committed centres supported by RAR and inferred resources recoverable at <USD 130/kgU). Figure b) illustrates the B-II case (production capability of existing, idled, committed, planned and prospective centres supported by RAR and inferred resources recoverable at <USD 130/kgU). Both figures illustrate two production capacities per case: the light shaded area represents 100% of production capacity, the darker shade represents 85% of the production capacity. Dark blue bars show the production values for 2020-2022.

Note that figures do not include the secondary supply forecast, which has in the past filled the gap between primary production and demand.



Uranium Production Perspectives

A WNA Reference Scenario

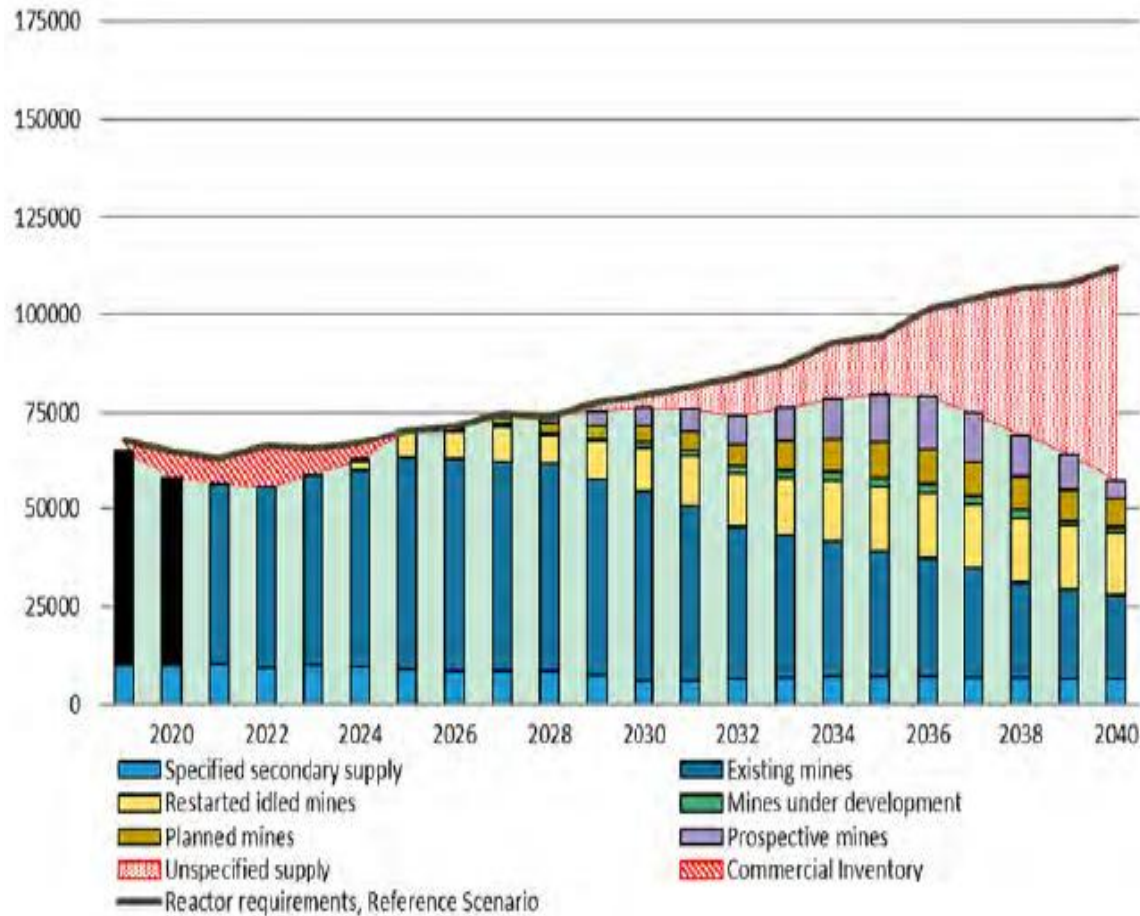


Source: The Nuclear Fuel Report, World Nuclear Association

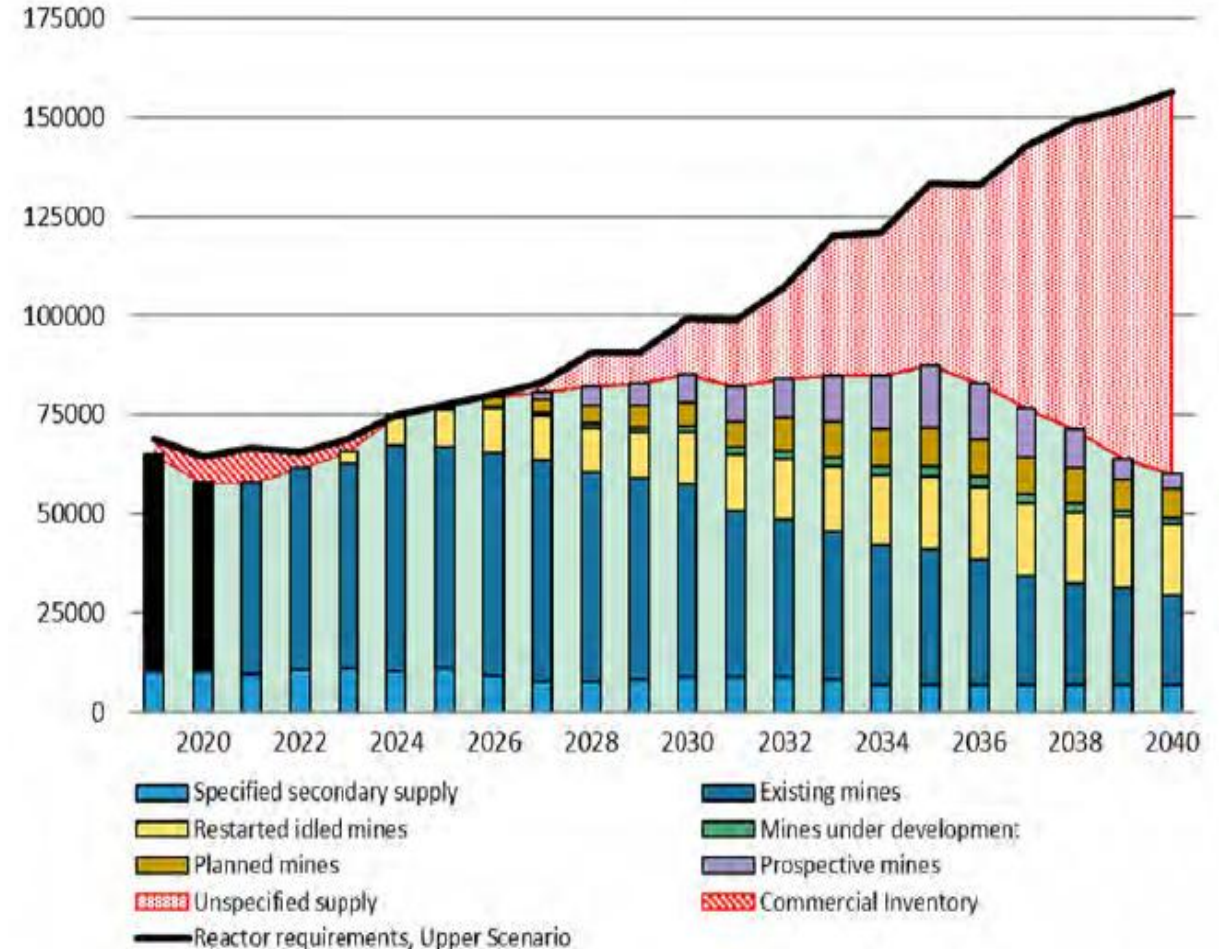


Uranium Production & Requirements Perspectives (tU) WNA Scenarios

Reference Scenario



Upper Scenario



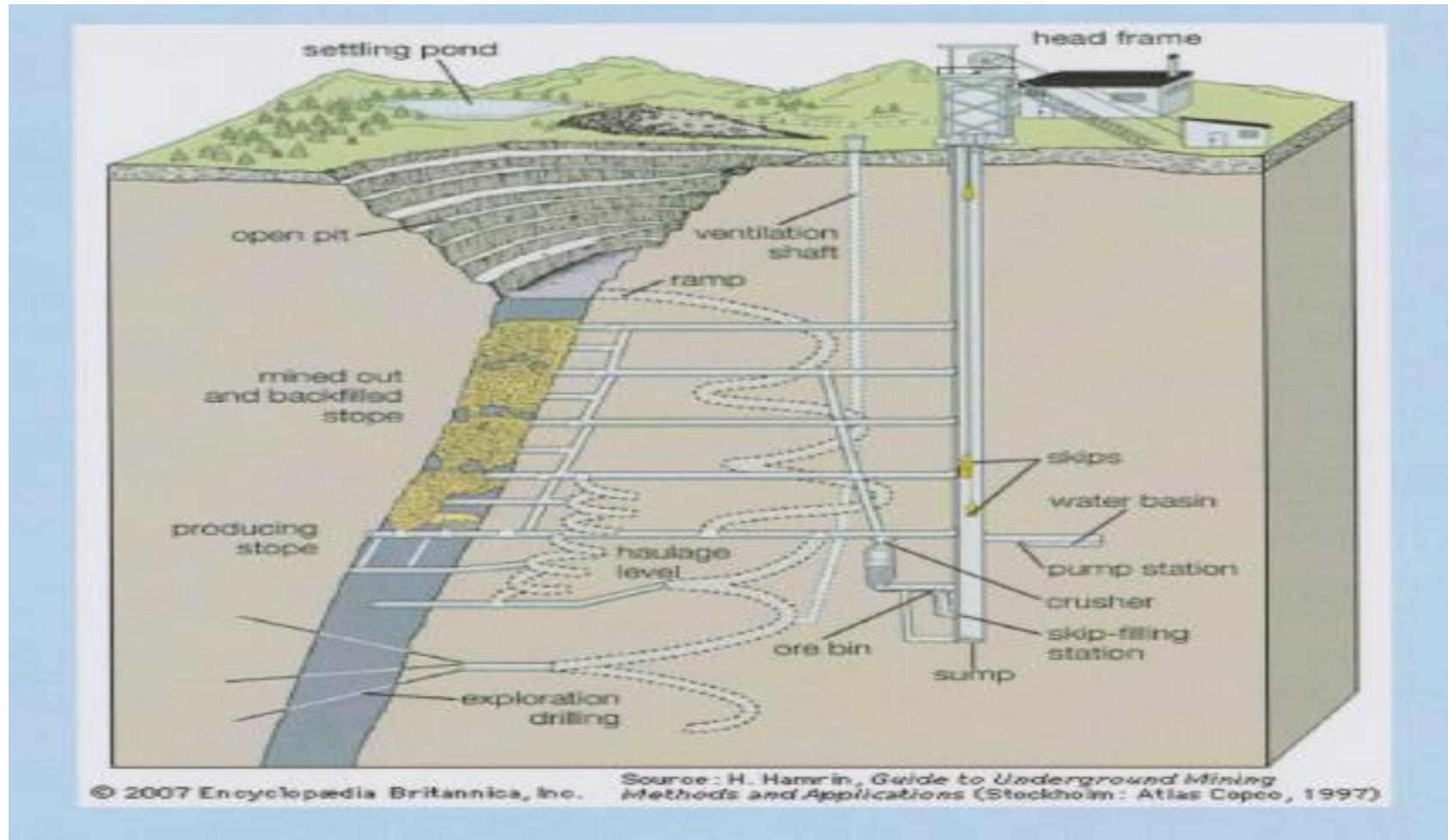
Source: WNA The Nuclear Fuel Report, Expanded Summary April 2022

2-3

Uranium Mines and Mining Companies

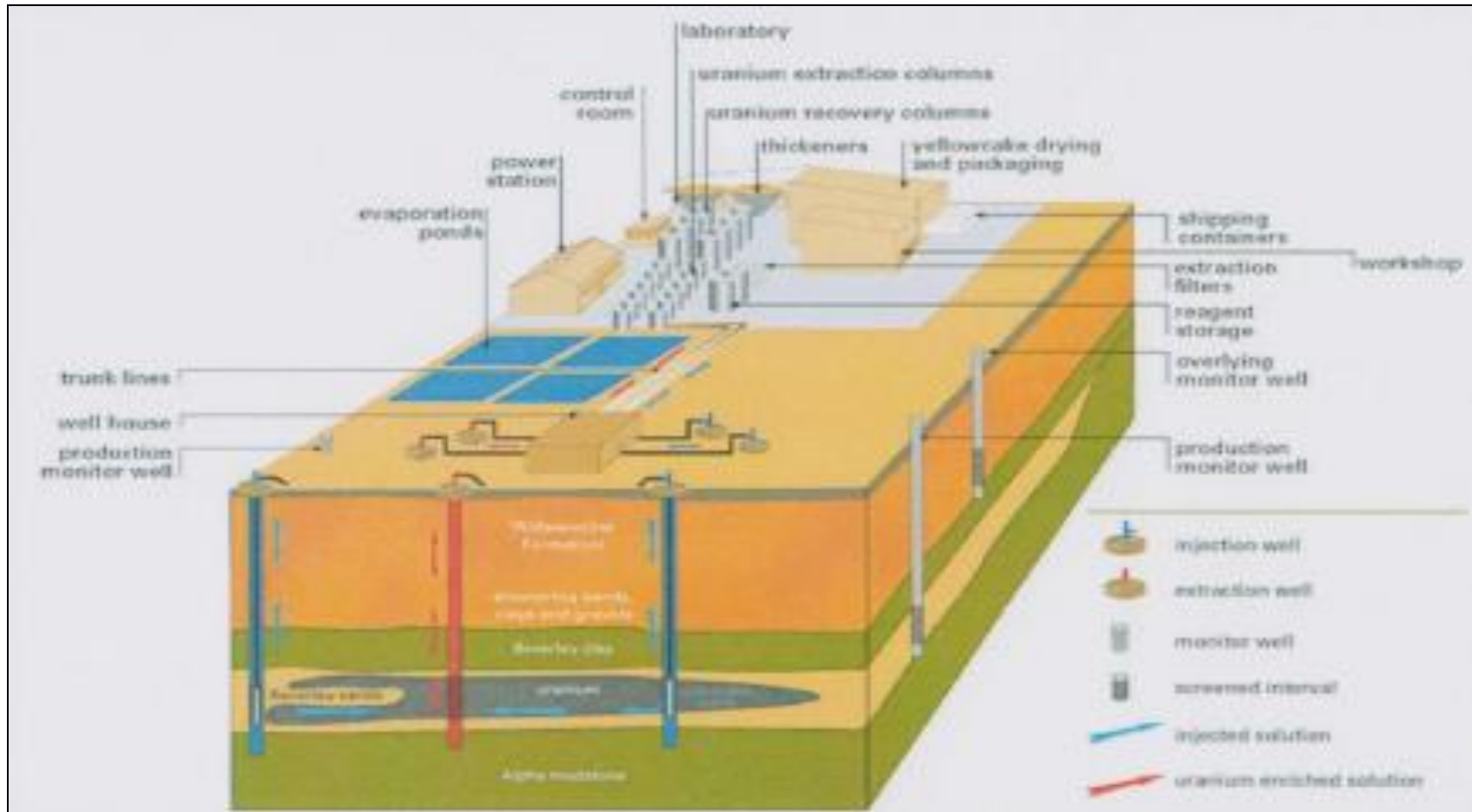


Conventional Techniques: Open Pit & Underground



In Situ Leaching (ISL)

The Uranium ore is dissolved in acid or alkaline reagents injected into the aquifer by means of well fields



Mining Methods 2024

Method	%
In situ leach (ISL)	52%
Underground & open pit (except Olympic Dam)	44%
By-product	4%

Source: WNA World Uranium Mining Production Updated September 2025



Top Ten Uranium Mines 2024

Mine	Country	Main Owner	Mine type	Product. (ktU)	% of World Total
McCartur River/Key Lake	Canada	Cameco	Underground	7,81	13
Cigar Lake	Canada	Cameco/Orano	Underground	6,50	11
Husab	Namibia	Swakop Uranium (CGN)	Open Pit	4,44	7
Budenovskoye 2 Karatau	Kazakhstan	Kazatomprom/ Uranium One	ISL	3,30	5
Inkai, sites 1-3	Kazakhstan	Kazatomprom/ Cameco	ISL	2,99	5
Akdala & South Inkai 4	Kazakhstan	Kazatomprom/ Cameco	ISL	2,80	5
Olympic Dam	Australia	BHP/Billiton	By Product/Undergr.	2,69	6
Moinkum & Tortkuduk	Kazakhstan	Orano/Kazatomprom	ISL	2,39	4
Rössing	Namibia	CNCC	Open Pit	2,21	4
Khorassan 1	Kazakhstan	Kazatomprom/Uranium One	ISL	2,03	3
Total 10				37,16	62



New mine in Kazakhstan: South Tortkuduk



- **Katco is a Joint-Venture Orano/Kazatomprom (51%/49%)**
- **Katco exploits 2 uranium mines: Muyunkum & Tortkuduk, 1000 km south of Astana. Technology used: ISL (In Situ Leach) – injection of acid solution to dissolve uranium.**
- **South Tortkuduk contains 45000 t of reserves.**



Leading Uranium Mining Companies 2024 Production

Company	Production (ktU)	World Share (%)
Kazatomprom	12,46	21
Cameco	10,19	17
Orano (ex Areva)	6,82	11
CGN	5,76	10
Uranium One	5,83	10
Navoi Mining	4,00	7
CNNC	3,29	6
ARMZ	2,74	5
BHP	2,69	5
General Atomics/Quasar	1,81	3
Others	4,63	8
World Total	60,22	100

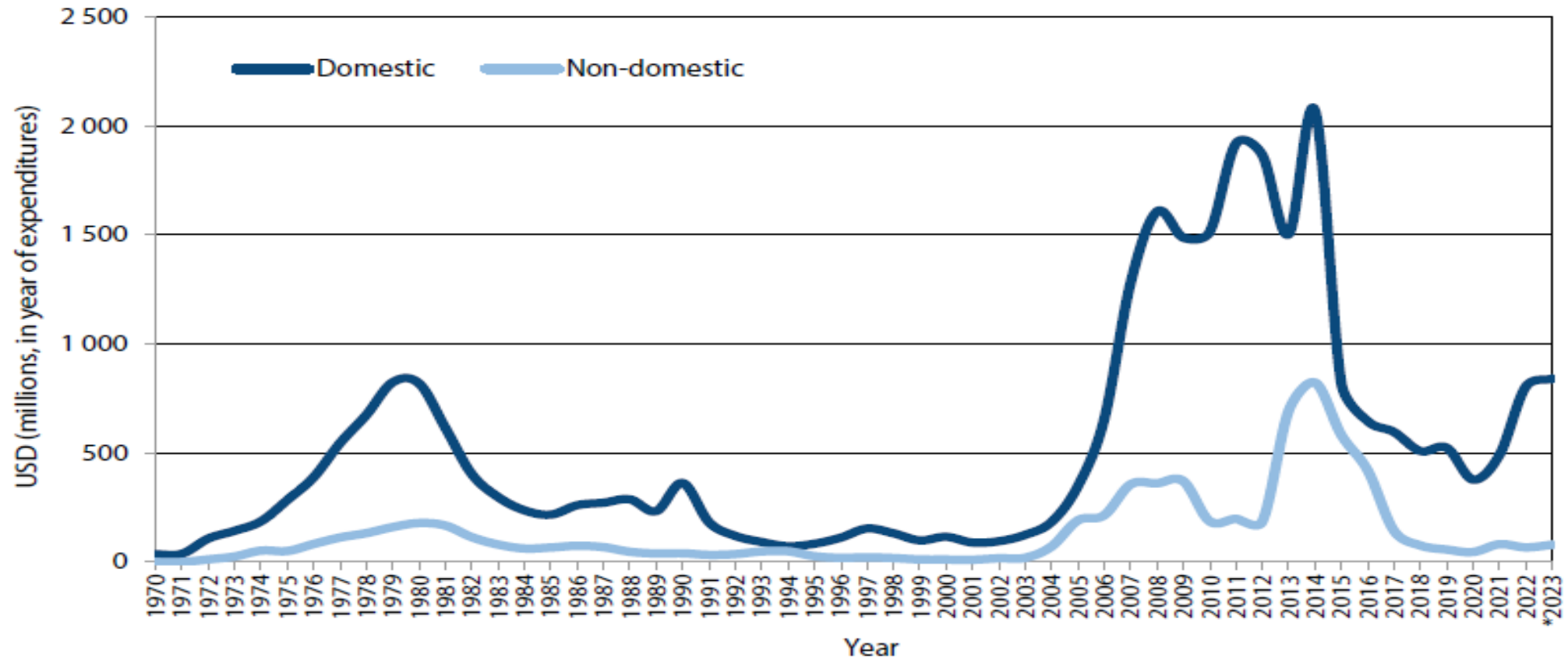


2-4

Trends in Capital Expenditures



Trends in Exploration & Development Expenditures



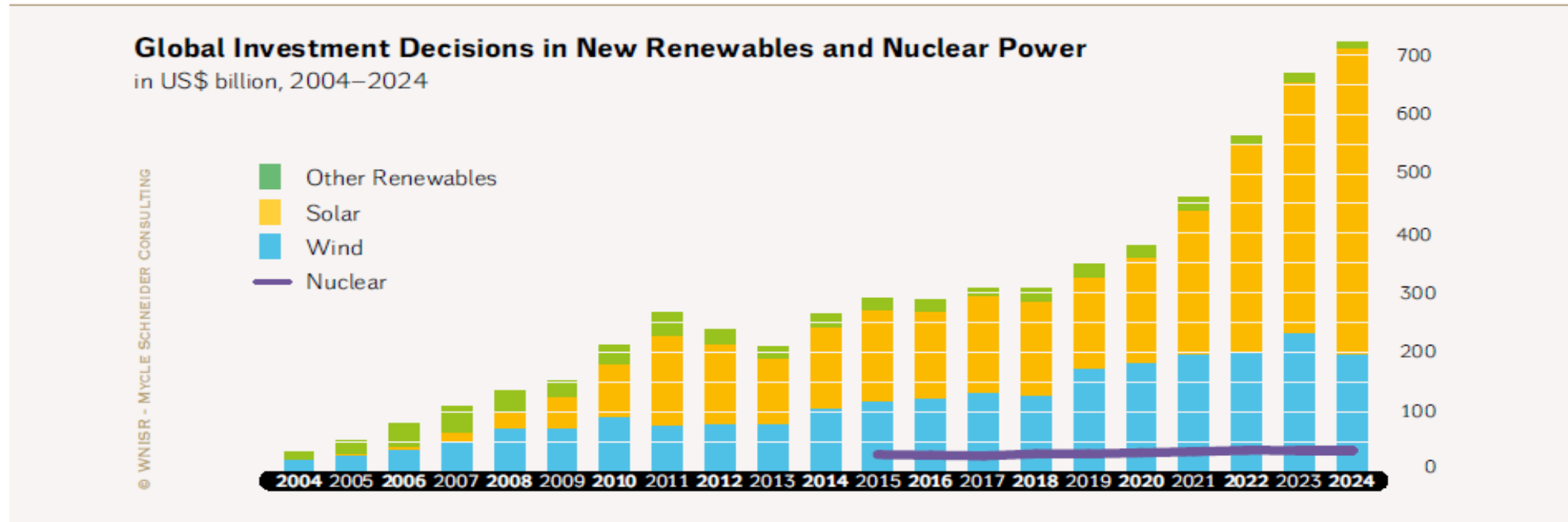
Note that expenditures for some significant producing countries were not available at the time of data collection and writing for this edition. Data prior to the early 1970s is incomplete or aggregated across multiple prior years, and thus cannot be properly represented in this chart.

* Preliminary data.

Source: OECD NEA/IAEA Uranium 2024
Resources, Production and Demand - OECD 2025/NEA 7683

Global Investment Decisions Nuclear vs Renewables

Nuclear spendings remain limited



Source: BloombergNEF, 2025

Notes:

As of the 2025 edition, WNISR is using BloombergNEF data as source for nuclear as well as renewables investments and is thus abandoning its own calculations. The BloombergNEF nuclear investment data series is only available from 2015 onwards.

BloombergNEF notes: “Nuclear power investment data covers reactors under construction or major refurbishment. It excludes funding for research and development and capex investment during refueling outages. We also exclude spending to bring back retired reactors to operation, such as in Japan, and at Palisades and Three Mile Island in the US.” Whereas WNISR’s nuclear investment numbers were based on the total estimated investment sum and allocated to the construction-start year, BNEF has opted “to spread the investment cost of each project equally over the construction period”. As shown in WNISR2024, when cumulated over several years, BloombergNEF and WNISR analyses were in the same order of magnitude.

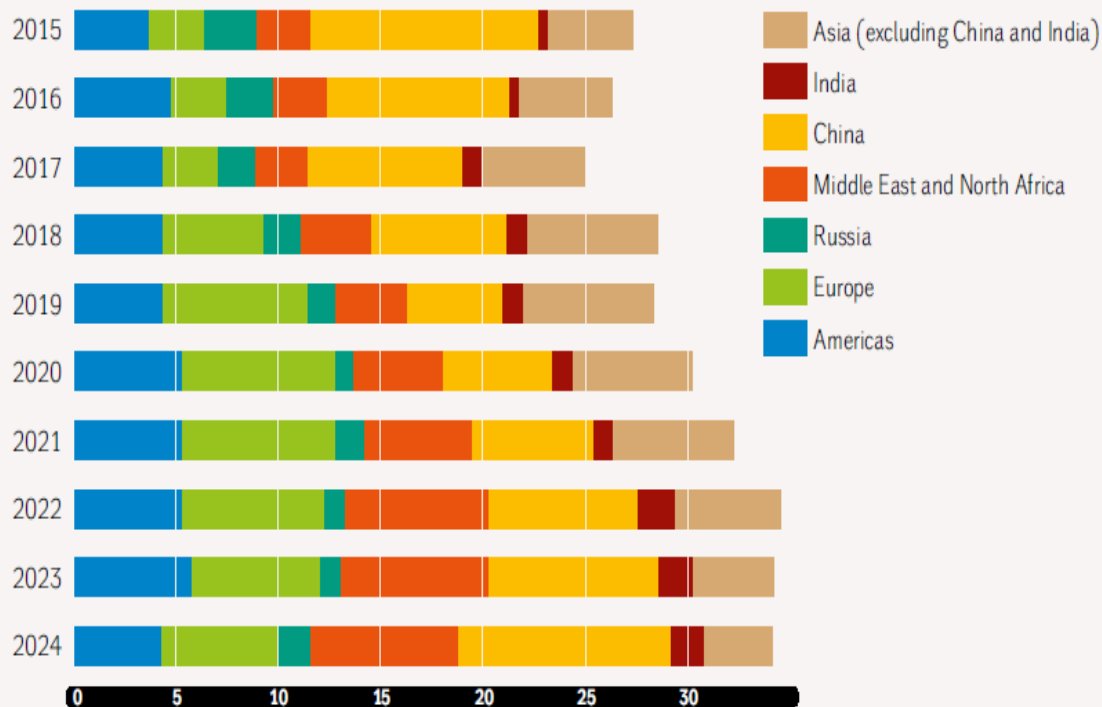
Source: Mycle Schneider
WNISR September 2025

Global Investment Decisions Nuclear vs Renewables

Nuclear spendings remain limited

Regional Breakdown of Nuclear Power Plant Investments

in US\$ billion, 2015–2024

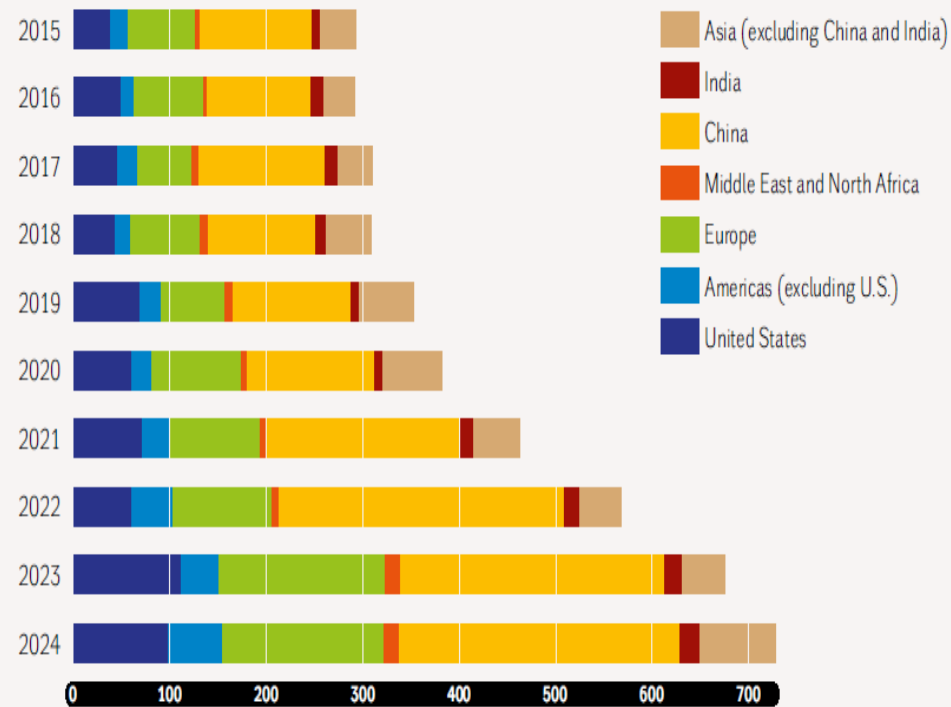


© WNISR - MYCLE SCHNEIDER CONSULTING

Source: BloombergNEF, 2025

Regional Breakdown of Renewable Energy Investments

in US\$ billion, 2015–2024



© WNISR - MYCLE SCHNEIDER CONSULTING

Source: BloombergNEF, 2025

Notes: Europe includes the EU27, the U.K., and the rest of EMEA (Europe, Middle East, Africa) as presented in Table 18.

Source: Mycle Schneider
WNISR September 2025

TPA Toolbox Energy Book 10 – Nuclear



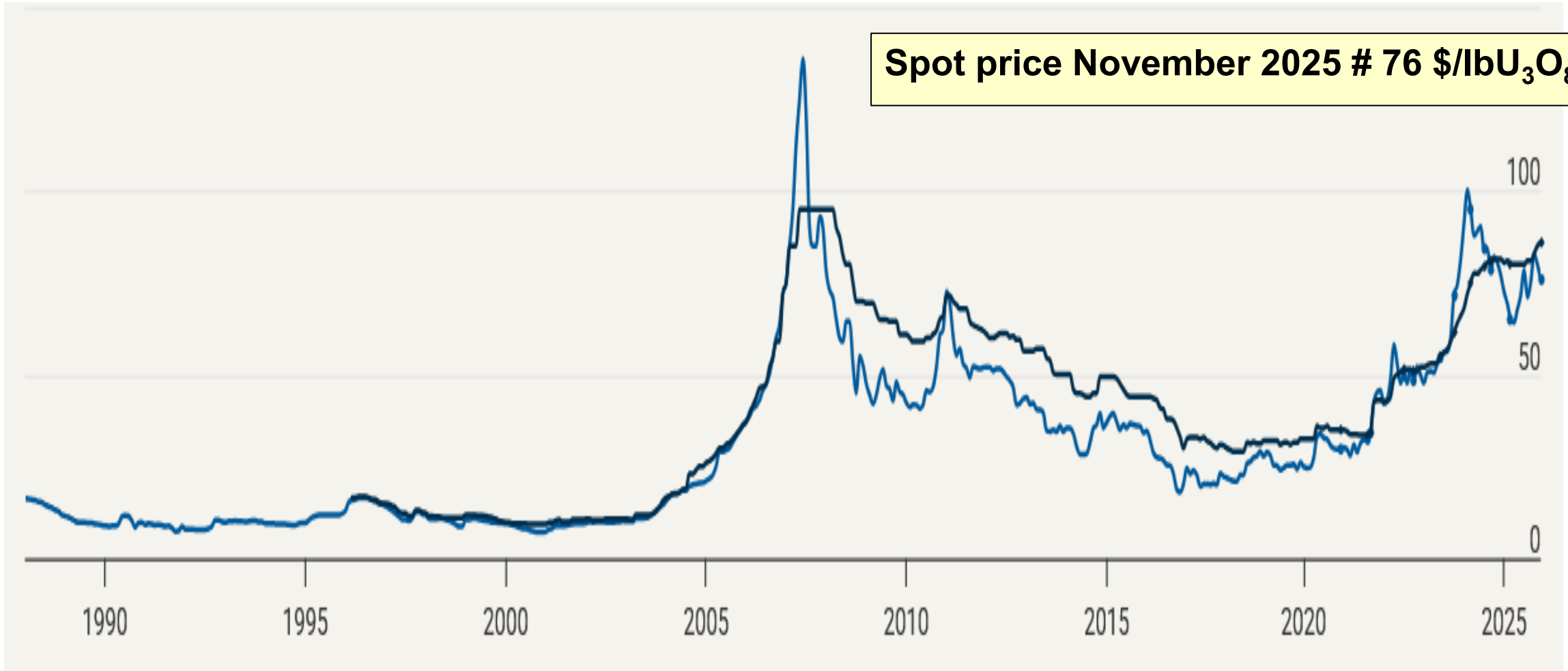
2-5

Uranium Prices



Uranium spot and long-term Prices evolution (1988 – 2025) (US\$/lbU₃O₈)

Spot price November 2025 # 76 US\$/lbU₃O₈



— Uranium Spot Price — Long-term Uranium Price

Source: Cameco November 2025



Uranium spot price (US\$/lb U₃O₈)

After a peak at 105 \$/lb beginning 2024, 82 \$/lb at 29/12/2025



The world nuclear industry: past and present



TABLE OF CONTENTS

1. What is nuclear energy ?
2. What are uranium resources ?
3. The world nuclear industry: past and present
4. Future evolution
5. The world nuclear industry and the energy and oil & gas industry: interest from stakeholders ?

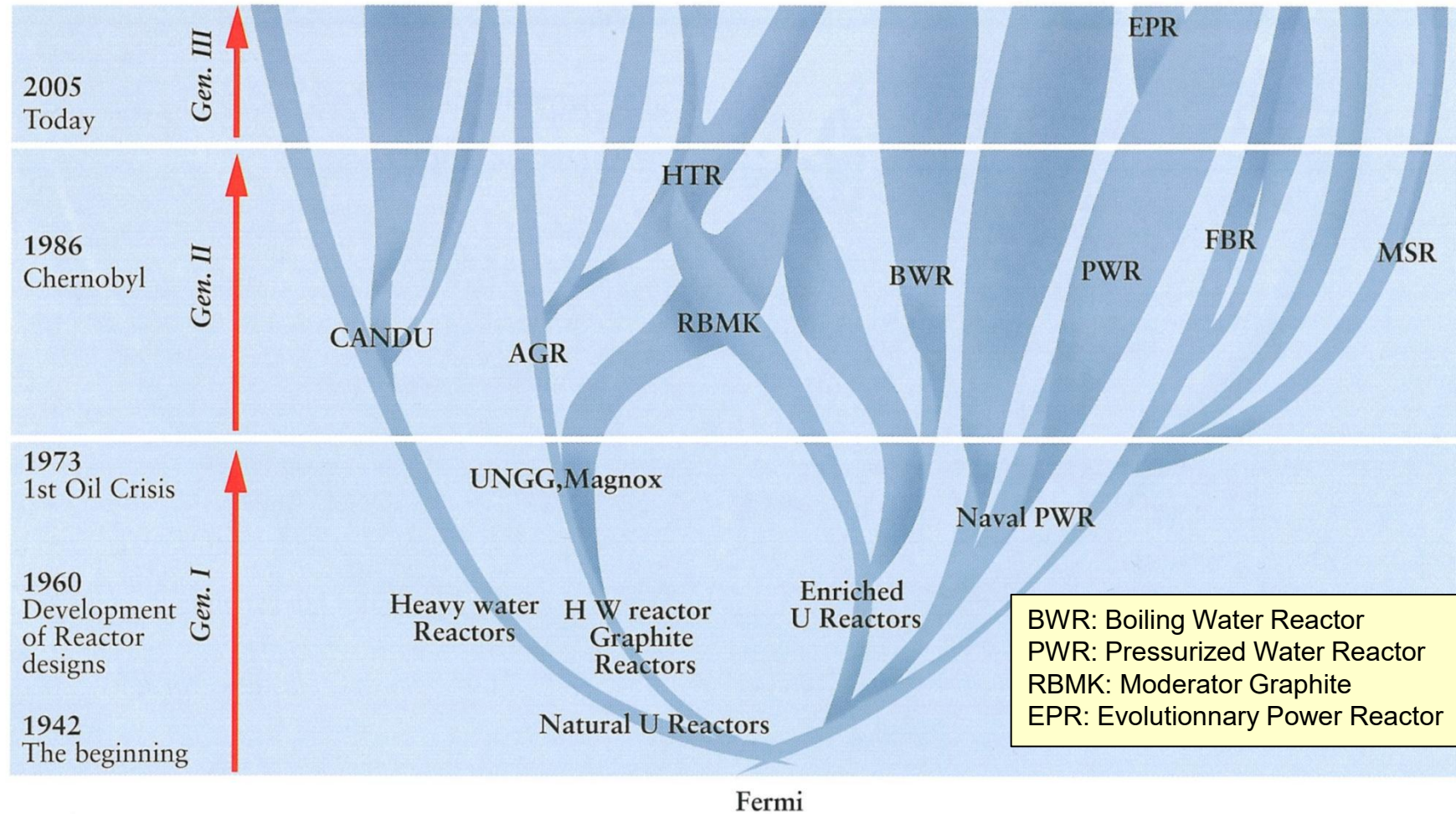


3-1

Nuclear Reactors Types



Nuclear Reactors phyllogenic tree since 1942



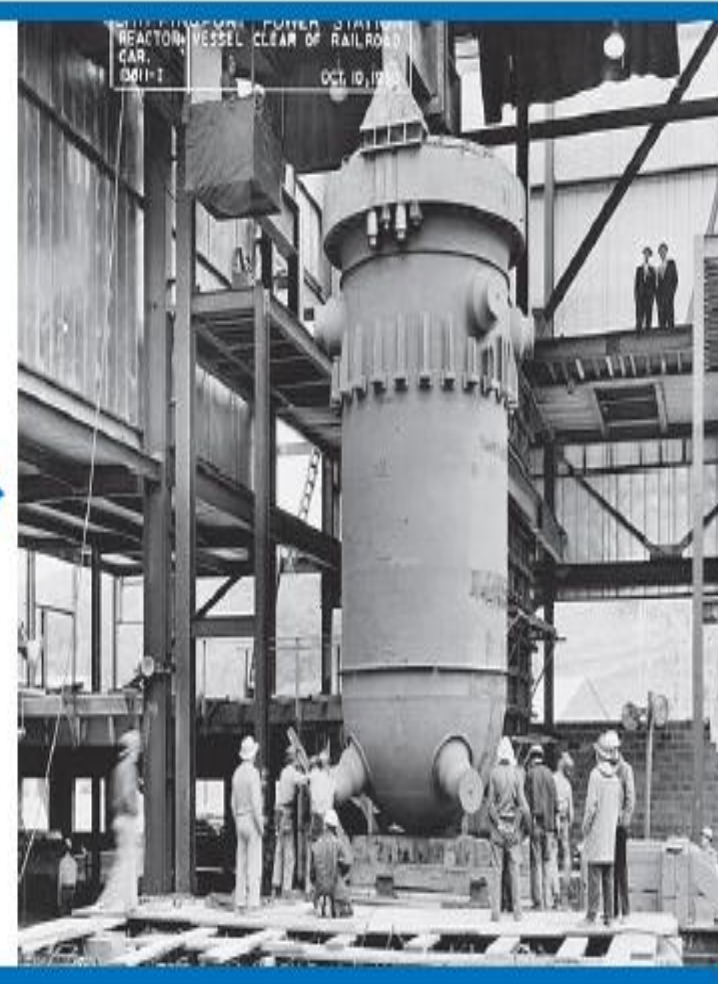
First Nuclear Power Plants



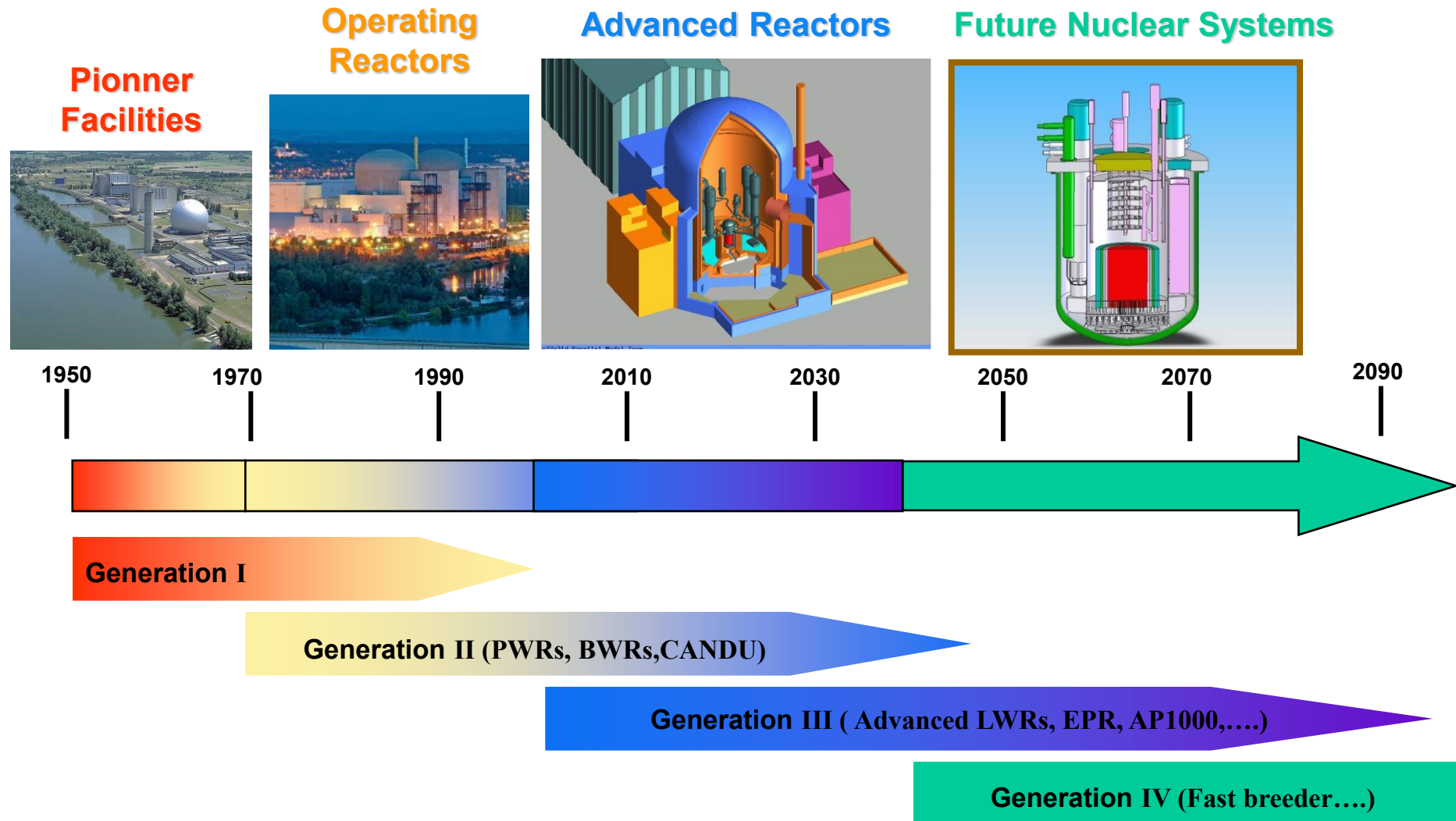
First nuclear power plants
in the world

◀ Obninsk APS-1,
Russia
1954.

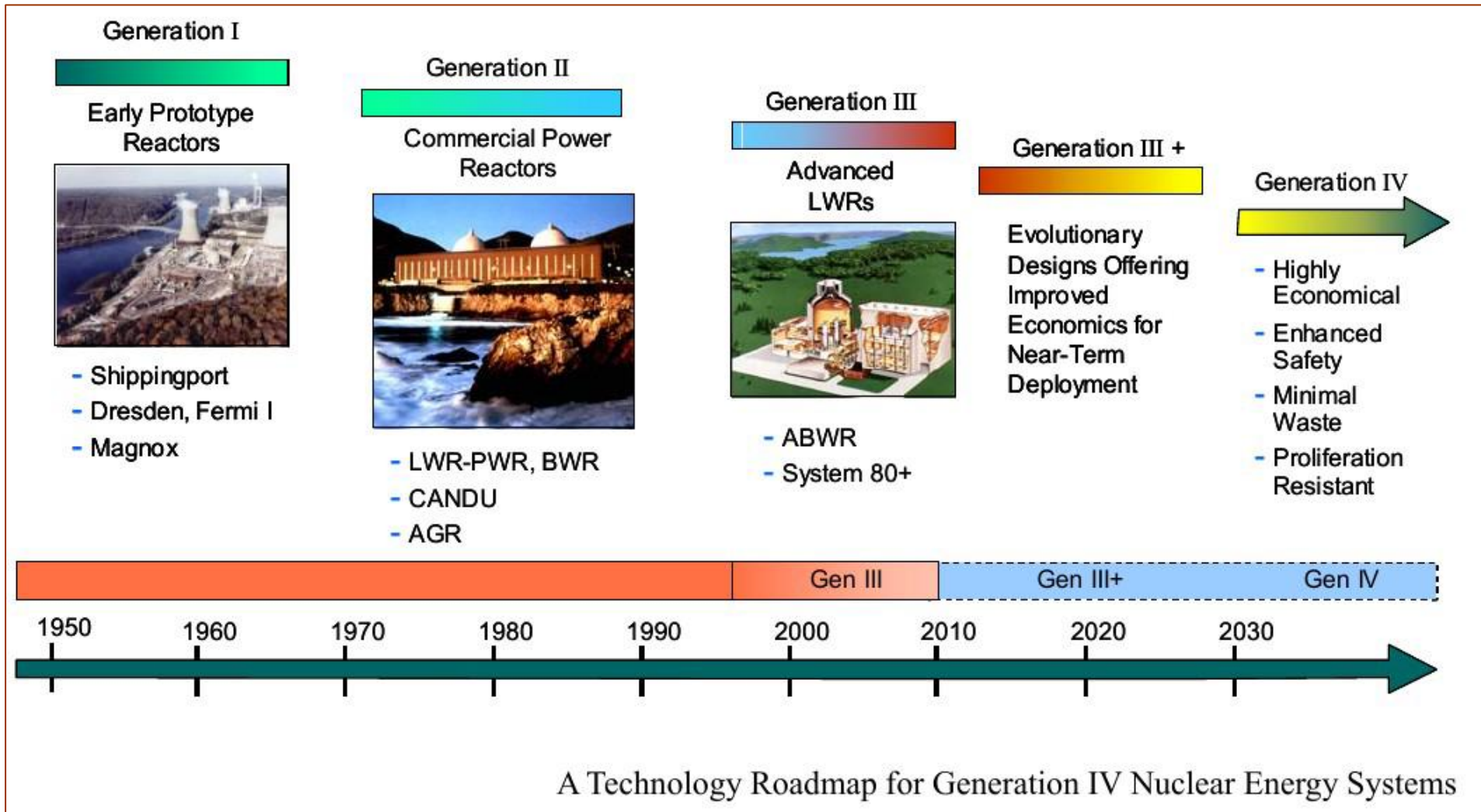
Shippingport, ▶
United States,
1956.



Nuclear reactors « Generations »



Evolution of Nuclear reactors



GENERATION I : early prototypes

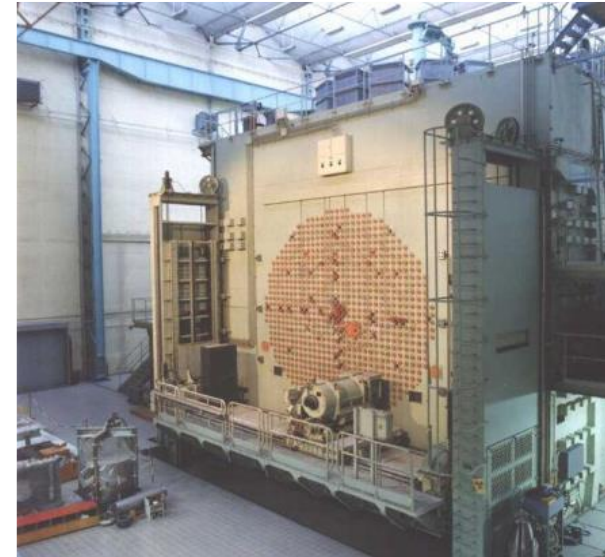
1942 : Fermi Pile, Chicago USA: *first critical chain reaction*



1951 : EBR-I reactor USA :
*first breeder reactor (NaK)
and first electricity
generating reactor, 200 kWe*

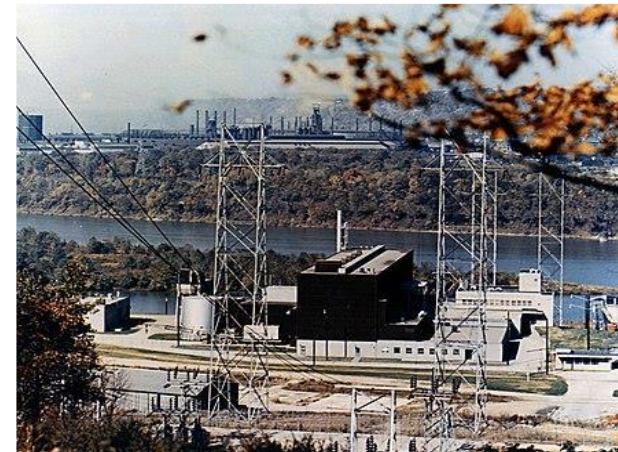


**1957 : Shippingport Atomic
Power Station, USA :** *first
demonstration PWR, 60 MWe*



**1956 : BR1 reactor Mol
Belgium:** *first European
research reactor*

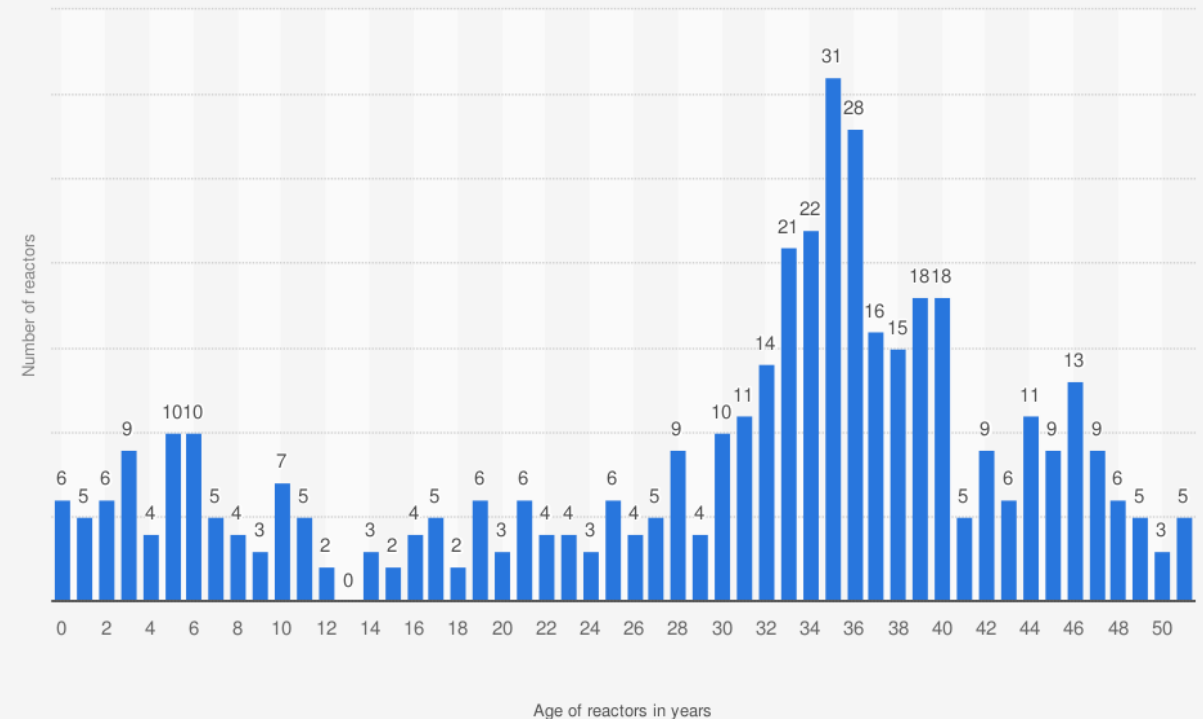
1954 : Obninsk, Russia :
*first nuclear plant connected
to the electricity grid,
demonstration of RBMK,
5 MWe*



GENERATION II

- ◆ Commercial reactors
- ◆ In use for up to 50 years
- ◆ Different types / different characteristics:
 - Fuel : Uranium (enriched or not), Plutonium, MOx (principle 1 : enough fissile fuel to reach critical mass)
 - With or without moderator of neutrons (fast or thermal) (principle 2 : fission is easier with slow neutrons)
 - Moderator : H₂O, D₂O, C, ...
 - Coolant : Water (H₂O, D₂O), gas (air, CO₂, He), liquid metal (Na, Pb, Lead Bismuth, NaK, Hg), molten salt... (principle 3: need to extract the heat to produce steam for the turbine)
 - Safety design: emergency stop, guaranteed cooling, control systems, protection against external 'attacks', ..

Number of nuclear reactors in operation worldwide as of December 2021, by age



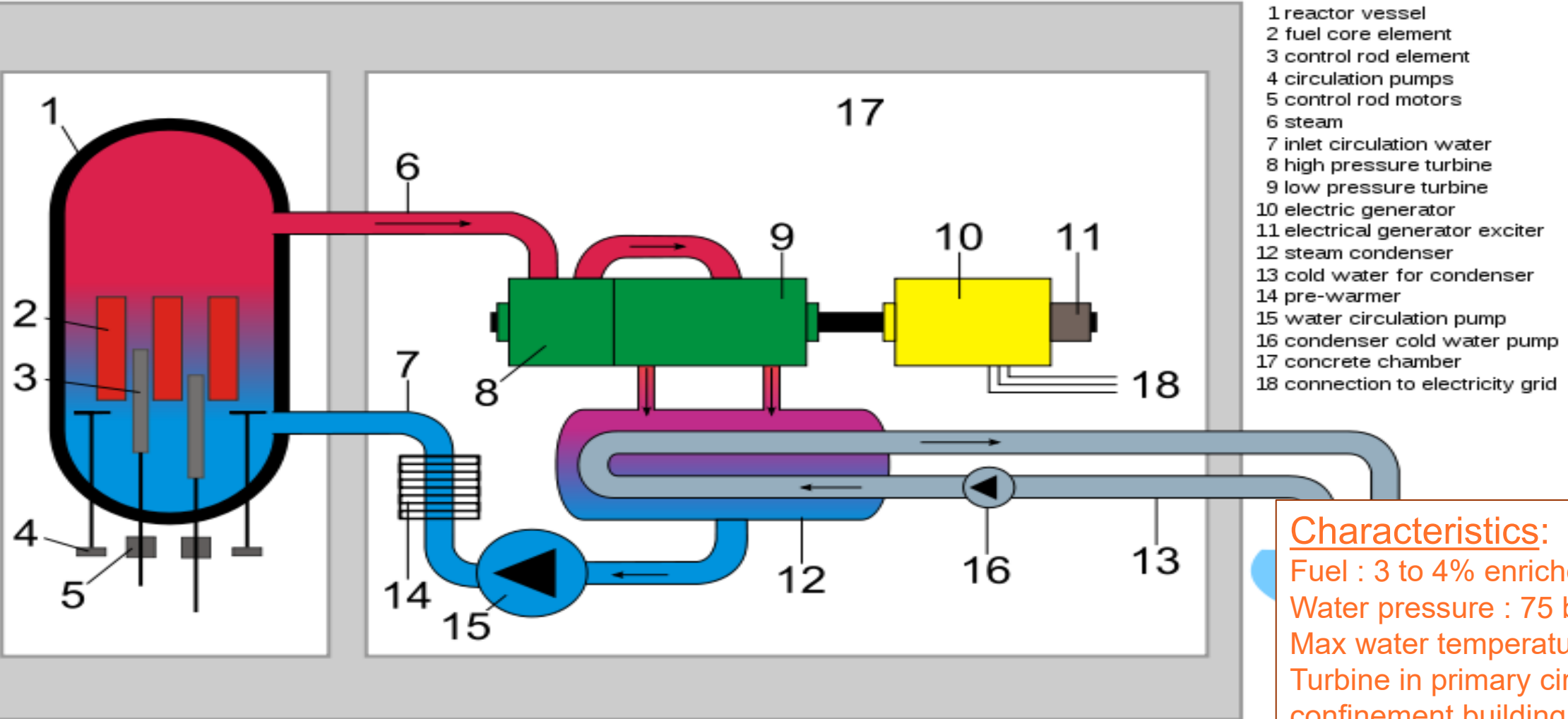
Source
IAEA
© Statista 2022

Additional Information:
Worldwide; December 31, 2021



GII : Boiling Water Reactor (BWR)

Accident (level 7):
• Fukushima 2011
(cooling system)



Characteristics:
Fuel : 3 to 4% enriched
Water pressure : 75 bar
Max water temperature: 285 °c
Turbine in primary circuit in
confinement building



Basic Components of a Nuclear Reactor

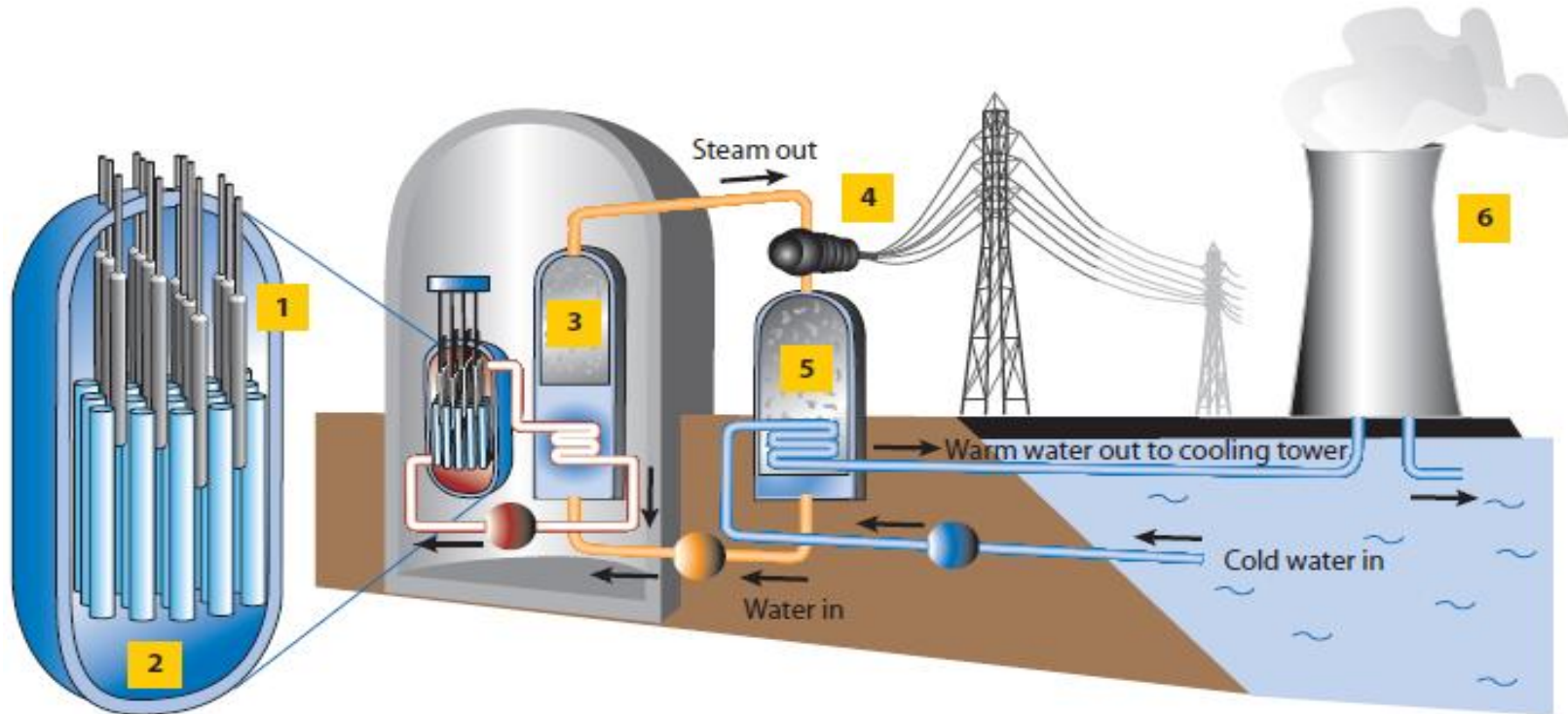
Pressurized Water Reactor (PWR)

Accidents (level 5):

- 3 Mile Island 1979 (cooling system)



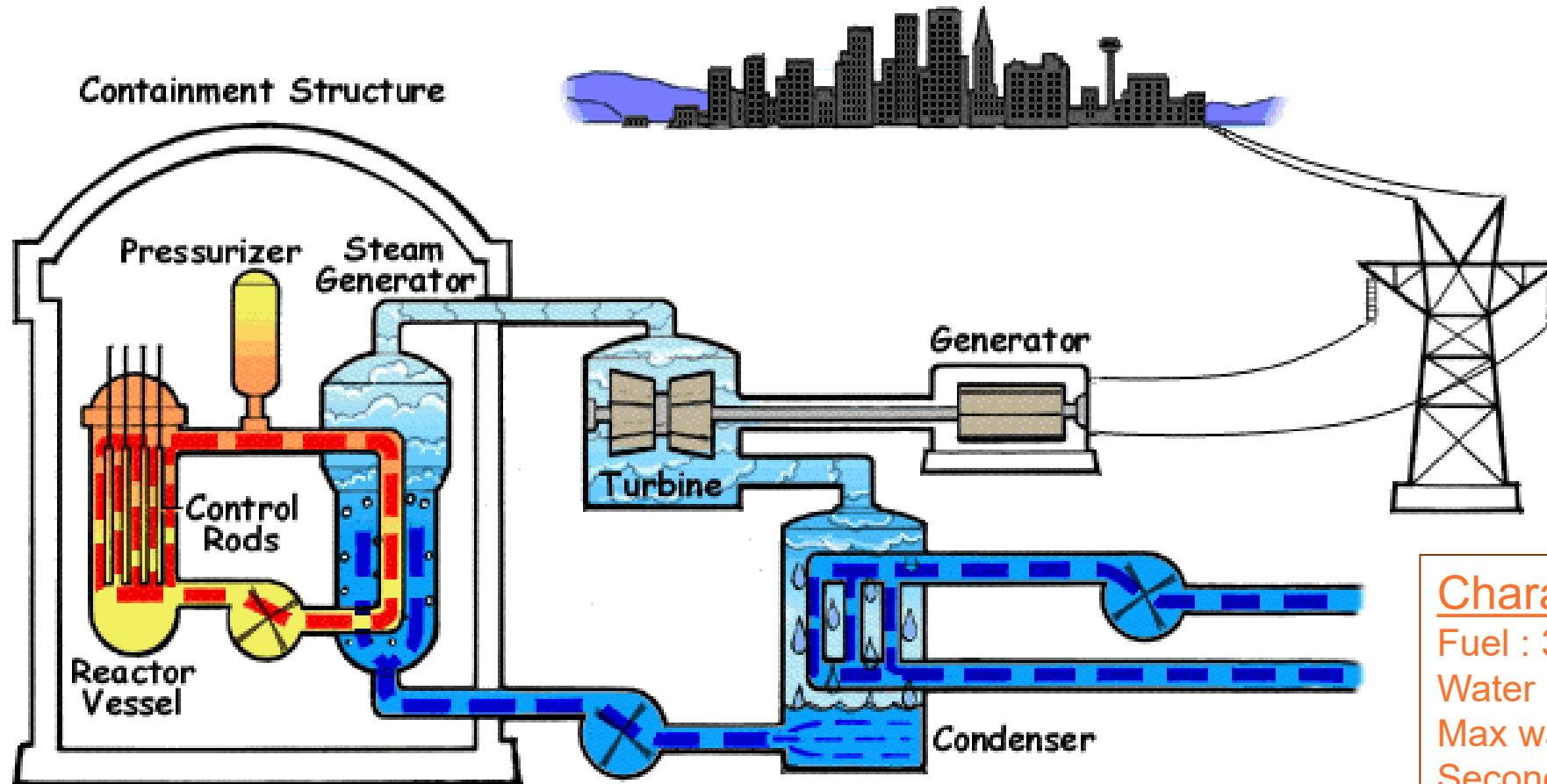
Fuel assembly



Source: New Scientist.

- 1 Reactor: fuel heats up water. Control rods absorb neutrons to control or halt the fission process
- 2 Coolant and moderator: fuel and control rods are surrounded by water (serves as coolant and moderator)
- 3 Steam generator/secondary circuit: water heated by the nuclear reactor
- 4 Turbo-generator set: drives the turbine and alternator to produce electricity
- 5 Condenser: removes heat to convert steam back to water
- 6 Cooling tower: removes heat from the cooling water

GII : Pressurized Water Reactor (PWR)



Characteristics:

Fuel : 3 to 4% enriched

Water pressure : 150 bar

Max water temperature: 320 °c

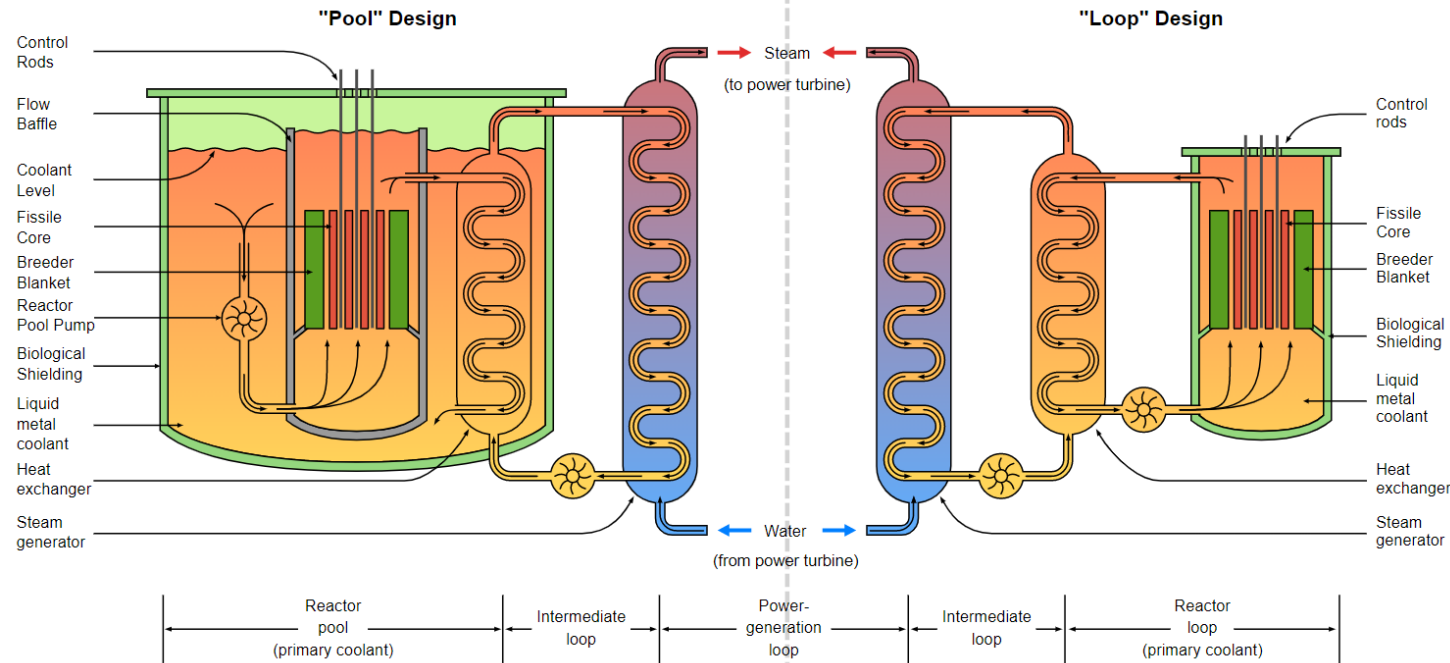
Secondary circuit: not radioactive

Extra emergency stop: injection of boric acid



GII : Fast Breeder Reactor (FBR)

Liquid Metal cooled Fast Breeder Reactors (LMFBR)

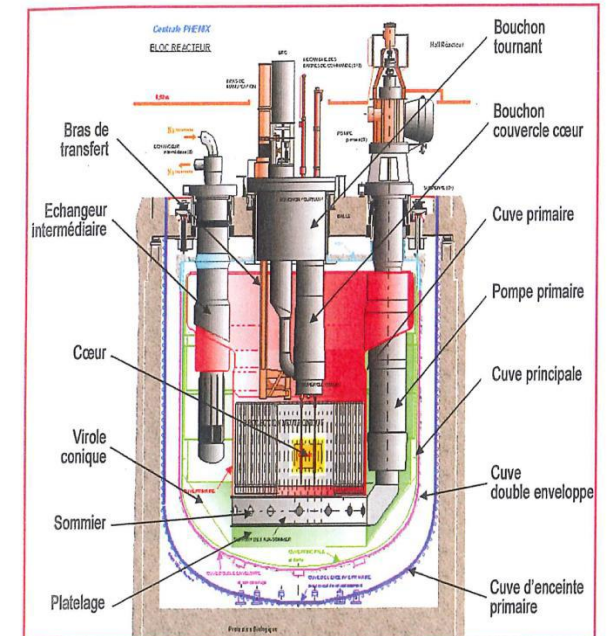


Characteristics:

- Coolant : Na
- No moderator
- Fuel : MOx
- Temperature : 560 °c
- Na becomes radioactive (intermediate cooling circuit needed)

- + re-use of 'spent' fuel of PWR reactors
- + reduction of waste (transmutation)
- Production of Pt
- Proliferation?

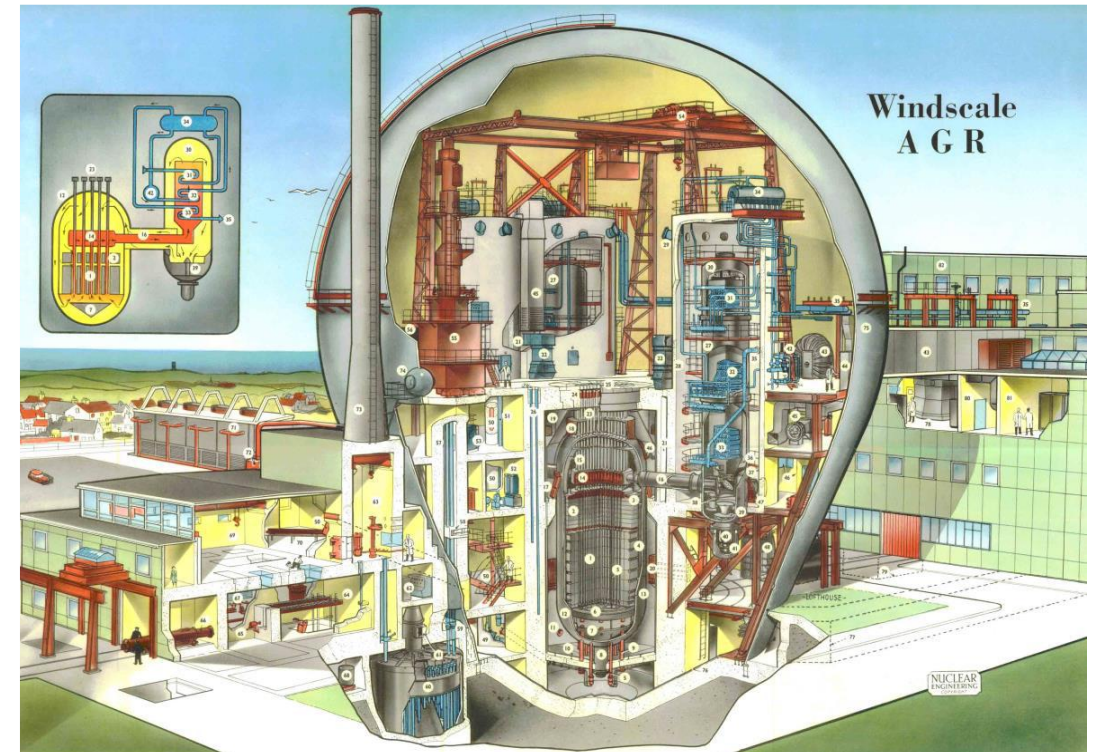
1973 : Marcoule, France:
Phenix, 233 MWe



GENERATION II : status

- 437 reactors (2021)
- By reactor type:
 - **PWR** **303** Pressurized Water Reactor
 - BWR 61 Boiling Water Reactor
 - PHWR 47 Pressurized Heavy Water Reactor
 - LWGR 11 Light Water Graphite Reactor (RMBK)
 - GCR 11 Gas Cooled Reactor
 - FBR 3 Fast Breeder Reactor
 - HTGR 1 High Temperature Gas cooled Reactor

1961 : Windscale, UK:
Advanced gas Cooled Reactor, 33 MWe



Generation III : EPR

CHINA :

Taishan 1 : 1750 MWe : start-up 2018

Taishan 2 : 1750 MWe start-up 2019

Total cost : 12,2 G€

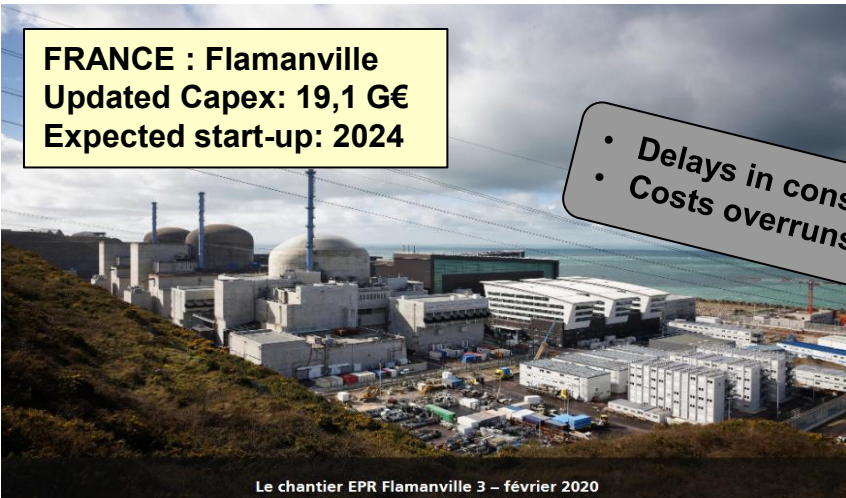


Image: CGN – China General Nuclear Power Corp.

FRANCE : Flamanville

Updated Capex: 19,1 G€

Expected start-up: 2024



Le chantier EPR Flamanville 3 – février 2020

- Delays in construction (12 yrs)
- Costs overruns

Source: EdF

FINLAND : Olkiluoto 3

1600 MWe : start-up 04/2023

Total Cost : ~ 8.8 G€



Source: Usine Nouvelle

- Delays in construction (13 yrs)
- Costs overruns

UK : Hinkly Point C 1,2

2 x 1500 Mwe : expected start-up 2027

Total Cost : ~30 G€



- Delays in construction
- Costs overruns (x2)

Source: Wikipedia



Generation III : AP1000 (Westinghouse)

- ◆ Same principles and power as PWR
- ◆ Simplification on safety
- ◆ Stand-by during 72 hrs without electricity
- ◆ Less expensive than EPR
- ◆ Also some costs overruns and delays



AP1400 : KEPCO ~1400 MWe
Korea: 3 in operations, 3 under construction
UAE: Barakah 1 (2020), Barakah 2 (2021),
Barakah 3 (2023) [less than 10 yrs]



- Delays in construction (China, US)
- Costs overruns (US)

AP1000 : ~1000 MWe

Sanmen 1,2 (China : 2018)

Haiyang 1,2 (China, 2018-2019)

Vogtle (Georgia, USA)

- Vogtle3 : 07/2023, 6 yrs delays, x M\$ overruns
- Vogtle 4 : 2023 ?

Source : UDA Energucht



Main characteristics of reactor types

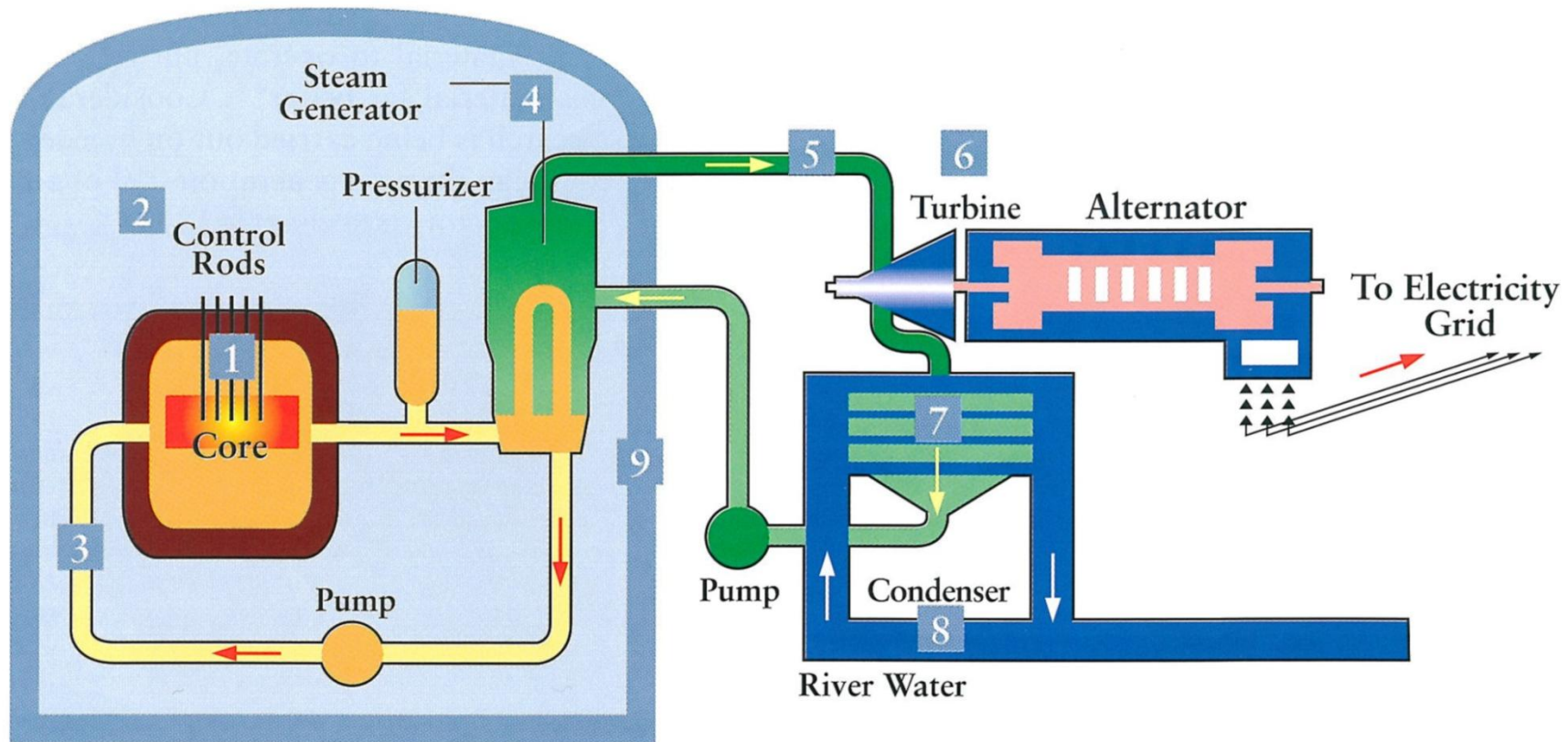
Reactor type groups	Type	Coolant	Moderator	Fuel
Gas – Graphite	AGR	CO2 - Advanced gas cooled	Graphite	Enriched UO2
	MGUNGG	CO2 - Magnox gas cooled	Graphite	Naturel U
	HTRGCR (GT-MHR, PBMR)	He - High temperature	Graphite	UO2, UC2, ThO2,...
Heavy water	PHWR	Heavy water - Pressurized	Heavy water	Natural or enriched UO2
Light water	BWR (ABWR)	Light water - Boiling	Light water	Enriched UO2 +/- Mox
	PWR (APWR, EPR, WWER)	Light water - Pressurized	Light water	Enriched UO2 +/- Mox
Fast reactor	Breeder	Sodium		UO2 Enriched, PuO2
Water Graphite	RBMK (LWGR)	Light water - Boiling	Graphite	Enriched UO2
Light water – Heavy water	HWLWR (ATR)	Light water - Boiling	Heavy water	UO2 Enriched, PuO2

ABWR, APWR, AGR, GT-MHR, PBWR: Advanced reactor type, EPR: Evolutionary Pressurized Reactor

Source: CEA 2017 Energy Handbook/Elecnucl 2019



A PWR Nuclear Plant (Pressurized Water Reactor)



Nuclear Materials & Process

- ❑ The following figures indicate the order of magnitude of the nuclear material required to manage the annual operation of a typical **1 000 MWe** nuclear power reactor :
- ❖ **Mining** : 200 000 tonnes of uranium ore of grade **0.1%** (1000 ppm)
- ❖ **Milling** : 230 tonnes of uranium oxide concentrate, containing **195** tonnes of uranium.
- ❖ **Conversion** : 288 tonnes uranium hexafluoride **UF₆**, containing **195 t U**.
- ❖ **Enrichment** : **35 t** enriched UF₆, containing **24 t** enriched U, + 253 t depleted UF₆ (tails).
- ❖ **Fuel assemblies** : **27** tonnes **UO₂**, containing 24 t enriched U.
- ❖ **Reactor** : **8 640** million kWh (8.64 TWh) of electricity at full output. (360 days)
- ❖ **Spent fuel** : **27** tonnes containing 23 t uranium (0.8% U²³⁵), 240 kg plutonium, plus other transuranic elements (Am, Np , ...), and 720 kg fission products.



Example of nuclear fuel management

PWR 1300 MWe

- Net electric power : 1300 Mwe
- Net Thermal power : 3800 MWth
- Efficiency : 34-35%
- Number of fuel assemblies : 193
- Number of rods per assembly : 264
- Weight of uranium per assembly : 538 kg
- Initial loading:
- Weight of enriched uranium : 104 t
- Average initial enrichment : 2,3%
- Natural uranium requirements : 423 t (assuming 0,25% tail assay, no losses)
- Enrichment requirements : 294 000 SWU (Separative Working Unit)
- Equilibrium reload (Reload by 1/3 core, annually):
- Number of assemblies per reload : 64
- Weight of heavy metal : 34,5 t
- Enrichment : 3,1%
- Natural uranium requirements : 235 t (assuming 0,3% tail assay, no losses)
- Enrichment requirements : 124 000 SWU
- Fuel residence time : 38 months



Typical PWR Fuel Assembly



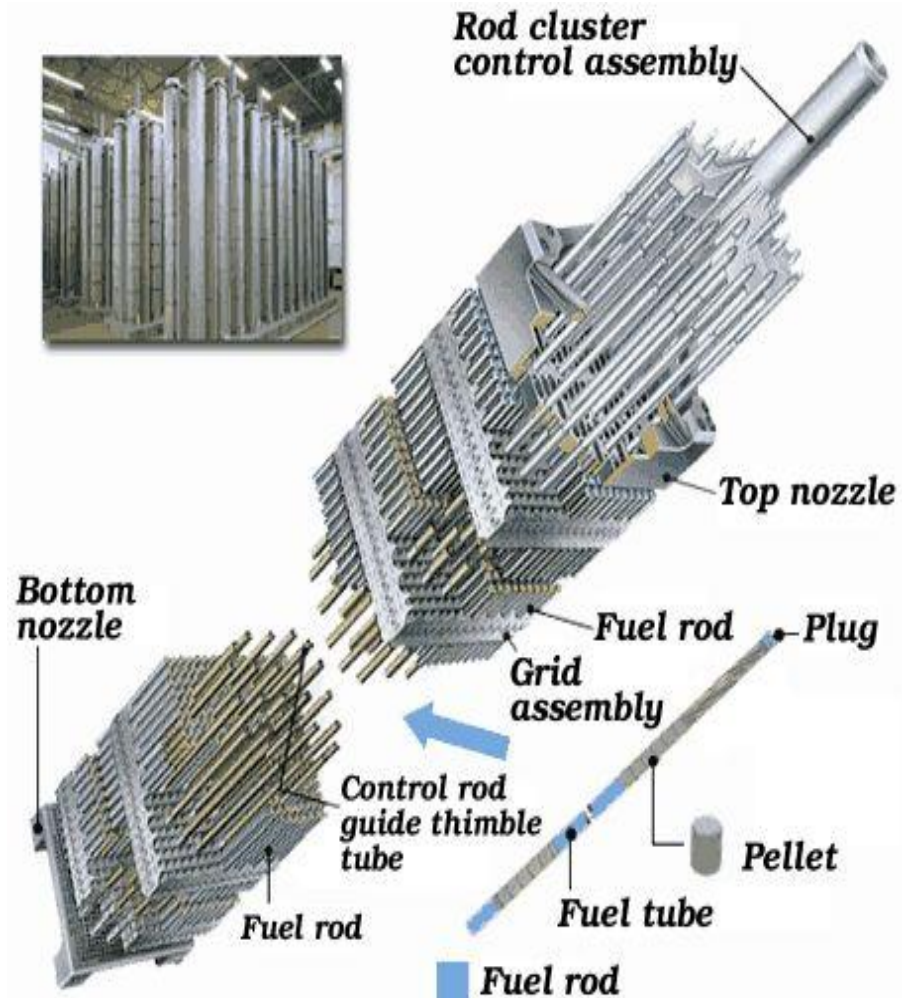
Source: B.Barre, P.R.Bauquis Ed. Hirle



TPA Toolbox Energy Book 10 – Nuclear

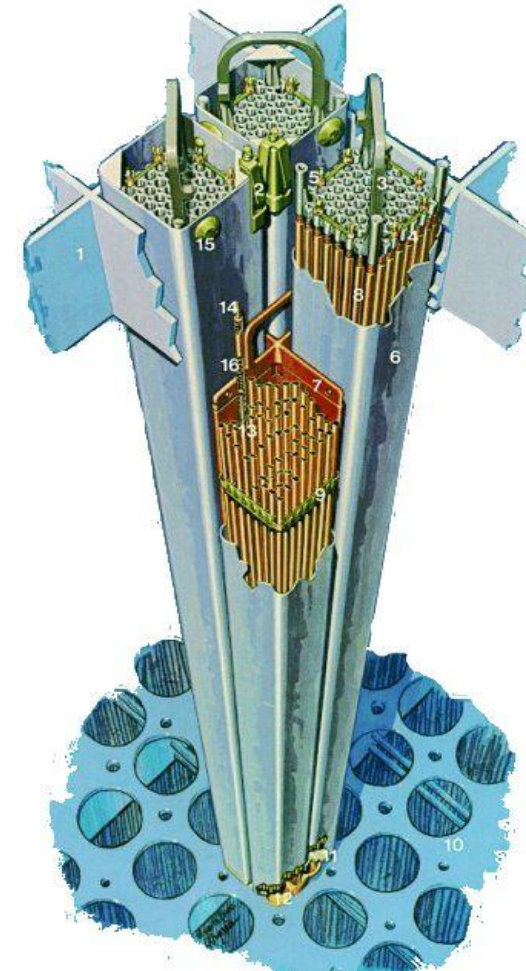


Other Typical PWR & BWR Fuel Assembly



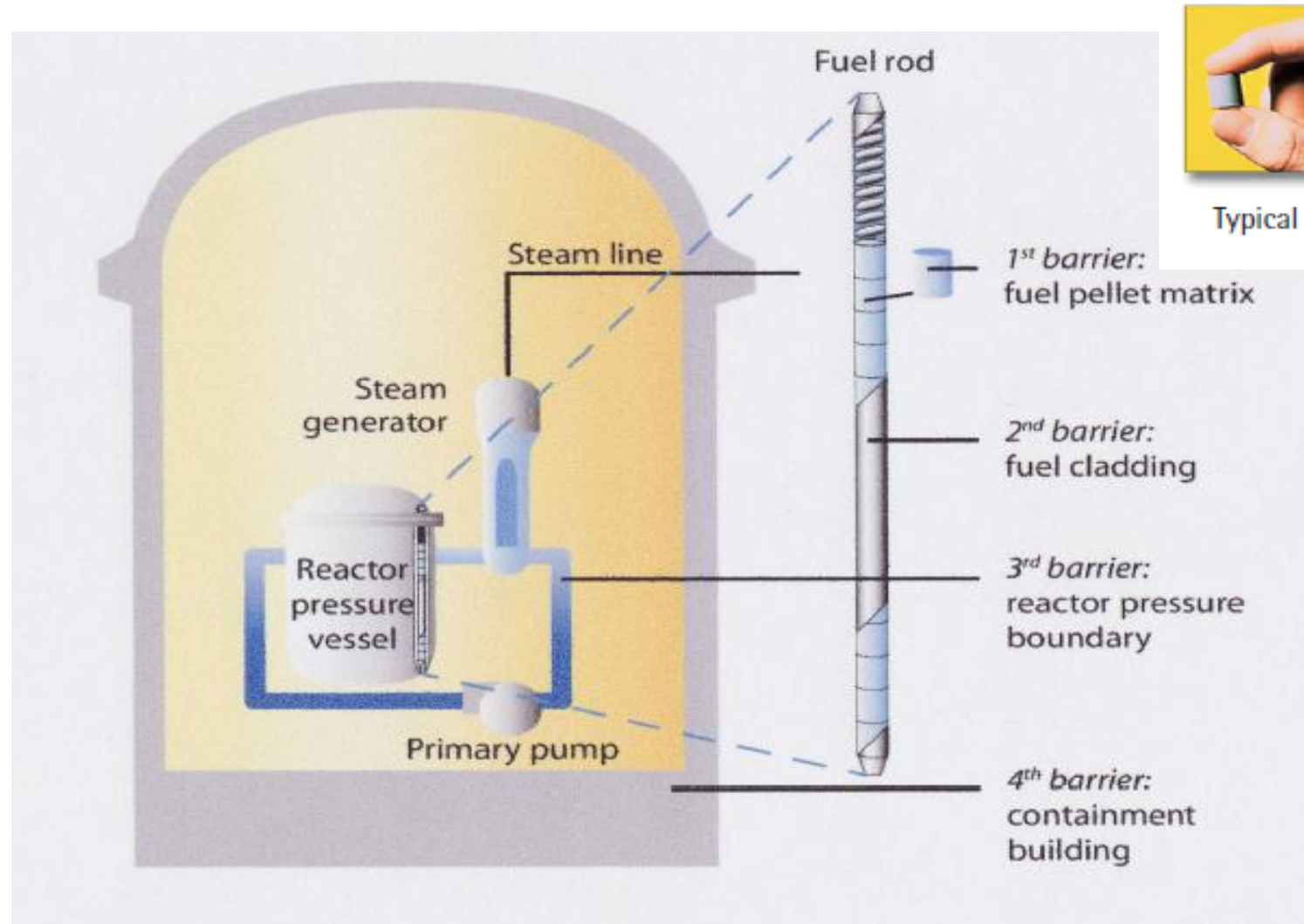
BWR/6 FUEL ASSEMBLIES & CONTROL ROD MODULE

- 1.TOP FUEL GUIDE
- 2.CHANNEL FASTENER
- 3.UPPER TIE PLATE
- 4.EXPANSION SPRING
- 5.LOCKING TAB
- 6.CHANNEL
- 7.CONTROL ROD
- 8.FUEL ROD
- 9.SPACER
- 10.CORE PLATE ASSEMBLY
- 11.LOWER TIE PLATE
- 12.FUEL SUPPORT PIECE
- 13.FUEL PELLETS
- 14.END PLUG
- 15.CHANNEL SPACER
- 16.PLENUM SPRING



Source: WNA 2018

Typical Barriers Confining Radioactive Materials



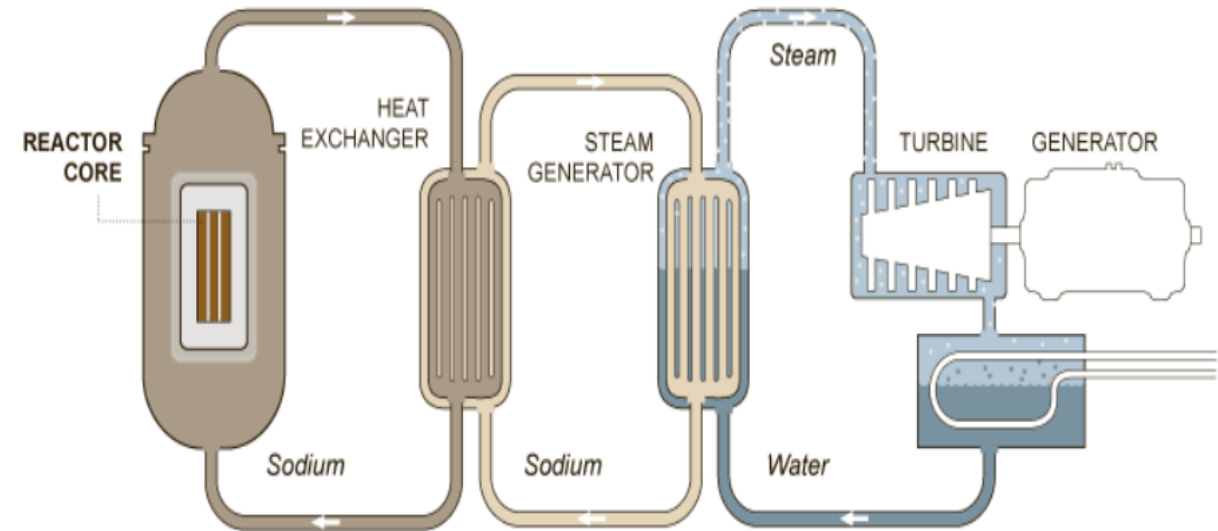
Typical fuel pellet.



Fast Breeder Reactor (FBR)

General principles

- A Fast Breeder Reactor is a nuclear reactor that generates more fissile material than it consumes.
- These reactors can be fueled with more-commonly available isotopes of uranium and thorium, such as U_{238} (fertile uranium) and Th_{232} , as opposed to fissile U_{235} which is used in conventional reactors (only 0,7% of natural uranium before enrichment)
- FBR create more fissile fuel than they use. They have no moderator and relies on fast neutrons to cause fission (instead of slow neutrons in a conventional reactor) using plutonium (Pu_{239}) as its basic fuel.
- They offer a more efficient use of uranium resources and the ability to burn actinides which are otherwise the long-lived component of high-level nuclear waste.



Fast Breeder Reactors (FBR) – History & current status

E = experimental, D = demonstration or prototype, C = commercial, R = research

	MWe	MW (thermal)	Operation
USA			
EBR 1	0.2	1.4	1951-63
EBR II (E)	20	62.5	1963-94
Fermi 1 (E)	61	200	1963-75
SEFOR		20	1969-72
Fast Flux Test Facility (E)		400	1980-93
UK			
Dounreay FR (E)	15	65	1959-77
Prototype FR (D)	250	650	1974-94
France			
Rapsodie (E)		40	1967-83
Phenix* (D)	250	563	1973-2009
Superphenix (C)	1240	3000	1985-98
Germany			
KNK 2 (E)	20	58	1972-91

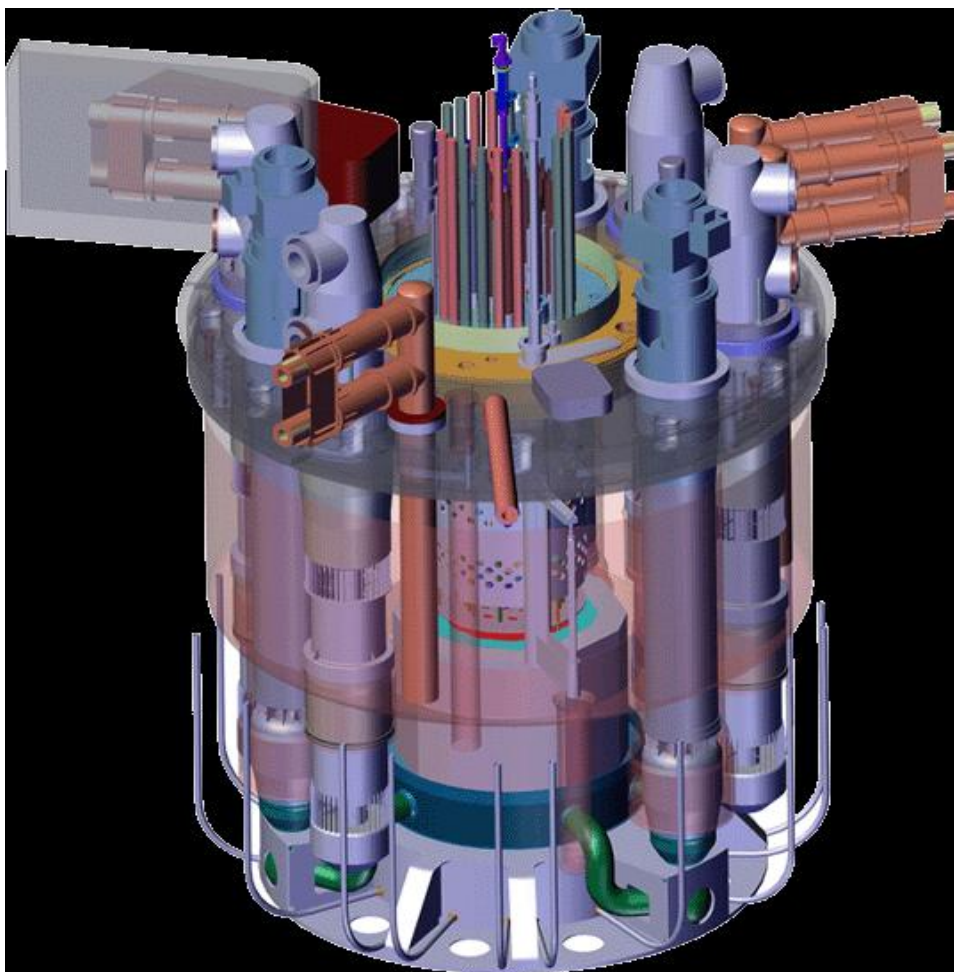
	MWe	MW (thermal)	Operation
India			
FBTR (E)	13	40	1985-
PFBR (D)	500	1250	under const.
Japan			
Joyo (E)		50, 75, 140	1978-2007 2021 restart?
Monju (D)	280	714	1994-96, 2010.
Kazakhstan			
BN-350* (D)	135	750	1972-99
Russia			
BR 1/2 (E)		1/0.1	1955, 1956
BR 5 Obninsk (R)		5	1958-71
BOR 60 Dimitrovgrad (R)	12	60	1969-
BR 10 Obninsk (R)		8	1973-2002
BN-600* Beloyarsk 3 (D)	600	1470	1980-
BN-800 Beloyarsk 4 (E)	864	2100	2014-
MBIR (E)	40	150	under const.
China			
CEFR (E)	20	65	2010-
CFR600 (D)	600	1500	under const.

Source: World Nuclear Association Updated August 2021



Fast Breeder Reactor

ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) – Marcoule (Gard – France)



- Astrid: prototype Fast Breeder Reactor (FBR), coolant: sodium (Na) – Generation IV
- Unlike in typical nuclear reactors where neutrons are slowed down by a moderator to optimize the fission reaction, in FBR the neutrons are not slowed down and can provoke the fission of all heavy nuclei, U235, U238, Plutonium,.....
- Na has a great reactivity with oxygen and water, challenge to be solved.
- Project developed by CEA in cooperation with Japan.
- Main characteristics: Power: 600 MW, Expected Start-up: 2040, cost: 5 G€
- **Mid 2019, CEA announced that the project is abandoned.....until 2050....**



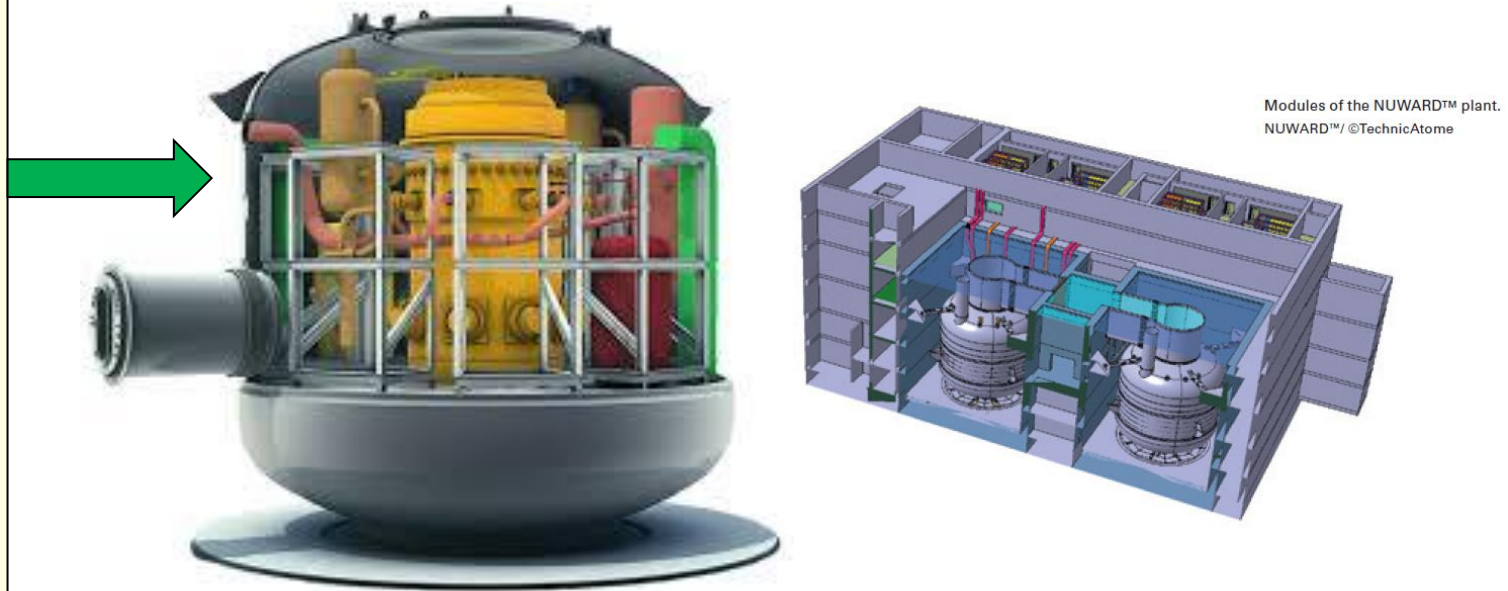
Small Modular Reactors

- **Small Modular Reactors (SMR) are fission nuclear reactors characterized by a power between 10 and 400 MW, less than for conventional reactors.**
- **They can be manufactured in specific plants and be transported and installed on their operational site.**
- **Cost and construction delays are less than for conventional reactors due to standardisation.**
- **Many countries are studying SMR: France, Argentina, Canada, China, India, Russia, South Korea, UK, US. More than 150 different models under study.**



Small Modular Reactors (SMR)

- Nuward, the French SMR
- Joint Venture CEA/EDF, Naval Group, TechnicAtom
- Technology PWR
- Nominal Power: 2x170 MW
- Small size/Compacity
- Safety standards # Generation III
- Demonstration unit construction scheduled for 2030



Source: EdF, Technicatome, Naval Group

Status of projects:

- Russia : fast breeder SMR for 2026
- USA : 6 PWR for 2028 (ARDP)
- Canada: Candu SMR in 2028 (300 MWe)
- Canada: 4th generation SMR in 2030
- China, UK, France, ...



Recent reshaping of Nuward project

 **NUWARD** relaunches the development of its SMR to support the energy transition in Europe and beyond.



 The studies conducted in recent months have been decisive: NUWARD has refined its SMR strategy to fully meet the expectations of the utilities and industry. The NUWARD SMR will deliver 400 MW of power and offer an option for cogeneration, up to approximately 100 MWth. It will rely on well-known and perfectly mastered technological building blocks within the nuclear sector to offer a safe product adapted to market needs.

The added value of NUWARD will be based on **simplicity**, **modularity** and **prefabrication**, with the aim of optimising competitiveness and construction times.

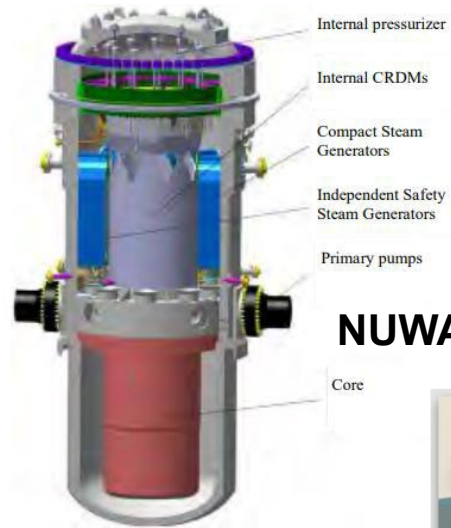
 The ambition is to finalise the conceptual design of the reactor by mid-2026 and market a product for the 2030s, with a First-Of-A-Kind (FOAK) built in France.



SMR : EXAMPLES : LIGHT WATER REACTORS



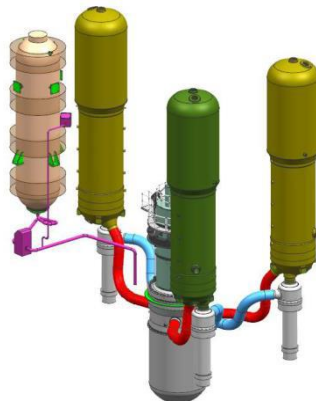
BWRX-300



NUWARD



NuScale VOYGR



Rolls-Royce SMR



RITM-200

As of 2023, there are more than 8 modular reactor designs and yet unfinished demonstration projects, and the first SMR units are in operation in Russia and China.
Source : Nuclear Engineering International. Retrieved 24 January 2023.

Source : SCK CEN



The first floating nuclear plant

Pevek Harbor/Tchoukotka peninsula - Russia

Floating nuclear power plant

Akademik Lomonosov

Length 110m
Width 30m

Storage of spent fuel and radioactive waste

Hydrotechnical structures

Heat distribution centre



Two KLT-40S nuclear reactors (35MW each)

Steam turbines

Electric transmission unit

Hot water tanks



**Academic Lomonossov: 144 m length, 30 m width. Displacement: 21500 t.
2 PWR reactors, 35 MW each. Will feed a 200 000 inhabitants city. Operator Rosatom.
Destination 2019: Tchoukotka peninsula eastern Siberia.**



Land-based SMR in Russia – 55 MW

Nuclear regulator Rostekhnadzor has granted a licence to build the country's first land-based small modular reactor (SMR), in the Republic of Sakha (also known as Yakutia) in Russia's Arctic north.



April 2023 - Rosatom and the Corporation for the Development of the Far East and the Arctic signed a cooperation agreement relating to the construction of the plant, saying "the project will provide a clean, cost-effective and stable source of energy to the remote Arctic territories of Yakutia with a decentralised energy supply. The electric power of the station will be at least 55 MW, the service life of non-replaceable equipment will be up to 60 years".



Four example of SMR start-up

Here are some example of start-up developing SMR on different concept than PWR:

- ◆ Jimmy Energy : High Temperature reactor of small power (10 MW) aimed at heat generation
- ◆ Naarea : Salt reactor of 40 MW with CO₂ as a coolant
- ◆ Tansmutex : reactor using Subcritical Transmuting Accelerated Reactor Technology
- ◆ Renaissance fusion : based on nuclear fusion

A lot of innovation necessary



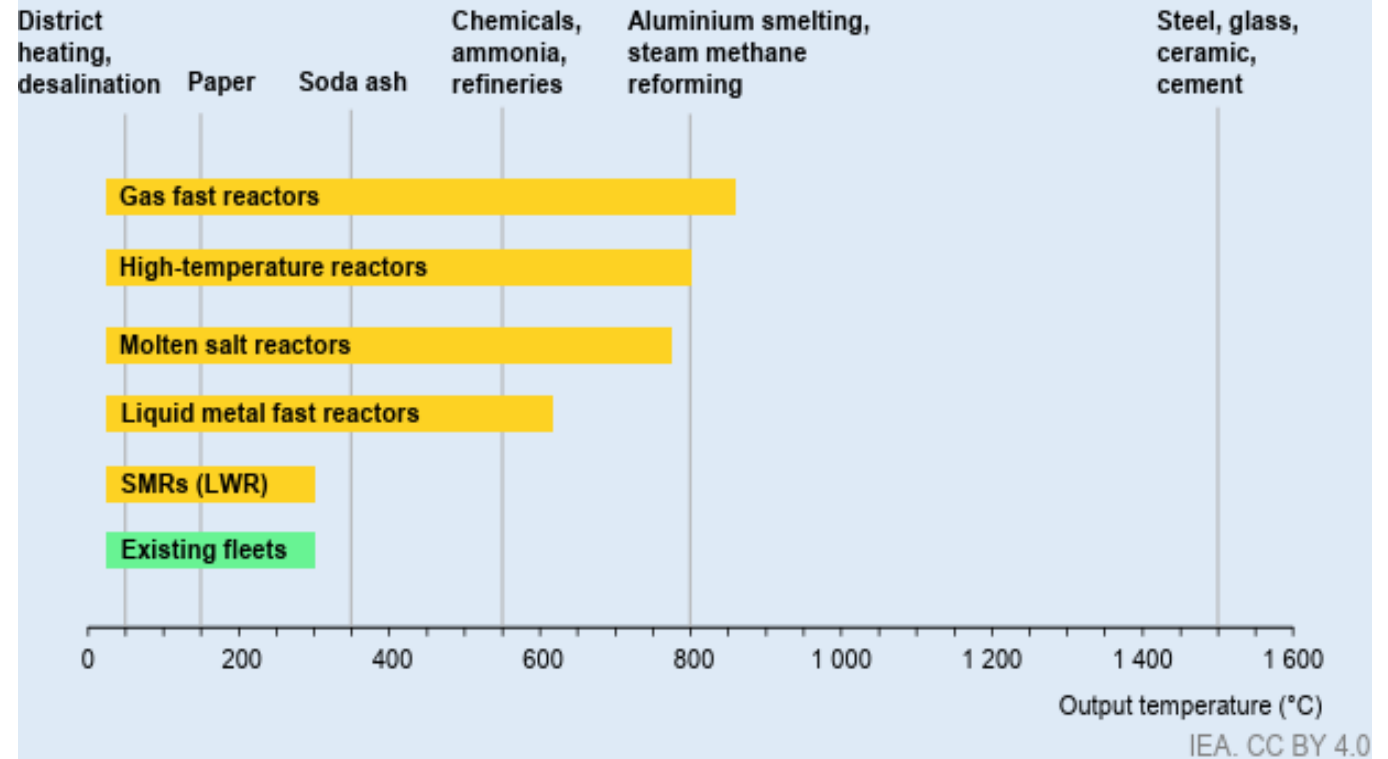
Small Modular Reactors

HTR : Heat only rather than Electricity



- A new company, JIMMY, proposes a 10 to 20 MW reactor to produce Heat to Heat intensive industries
- A project for a sugar company is planned in France in 2026

Figure 1.9 Nuclear CHP applications by temperature ranges and reactor types



Nuclear Energy

Atomic Mass, Mass Defect, Binding Energy, Aston Curve



Nuclear Energy

- **Atoms are constituted of protons, neutrons, and electrons which orbit around the nucleus.**
- **The nucleus of an atom is constituted of protons and neutrons, known collectively as nucleons.**
- **Protons carry a positive electric charge, electrons have a negative charge, neutrons have no electric charge. At rest, atoms are electrically neutral.**
- **Nucleons are attracted to each other by a strong nuclear force.**
- **Nuclear Binding Energy is the minimum Energy which is required to disassemble the nucleus of an atom into its constituents, protons and neutrons.**
- **The mass of an atomic nucleus is less than the mass of its constituents. The difference in mass (Mass Defect) corresponds to the Binding Energy (BE), calculated according to the Einstein formula: $E = \Delta mc^2$.**
- **Elements can be ranked by Binding Energy per nucleon.**



Nuclear Energy – Some key numbers

Avogadro Number	NA	Number of particles contained in one mole	$6,02214076 \times 10^{23}$
Atomic mass of an atom	am	In SI unit of Mass	Kg
Atomic mass unit	amu	1/12 of the mass of a single ^{12}C atom at rest	1
Atomic mass unit	kg	1/12 of the mass of a single ^{12}C atom at rest	$1,660539 \times 10^{-27}$
Defect mass	amu - kg	Mass protons + mass neutrons + mass electrons – mass atom = Δm	
Binding Energy	J - MeV	= $\Delta m \cdot c^2$	
Speed of light	m/s	Speed of light in vacuum	$2,997925 \times 10^8$
1 MeV	MeV	=	$1,602177 \times 10^{-13} \text{ J}$

Element	kg	amu
Mass proton	$1,672623 \times 10^{-27}$	1,007365
Mass neutron	$1,674929 \times 10^{-27}$	1,008754
Mass electron	$9,109400 \times 10^{-31}$	0,000549



Nuclear Energy – Table Mass Defect & Binding Energy

Atomic Number	Name of Element	Symbol	Atomic Mass Nb	Atomic Mass	Number Protons	Number Neutrons	Mass Protons	Mass Neutrons	Mass Protons	Mass Neutrons	Mass Electrons	Mass Defect	Mass Defect	Binding Energy (BE)	Binding Energy	Number Nucleons	BE/ Nucleon
Z			A	u	Z	A-Z	kg	kg	amu	amu	amu	amu	kg	J	MeV	A	MeV
0	Neutron	n	1	1,008754	0	1	0,000000E+00	1,674929E-27	0,000000	1,008754	0,000000	0,000000	0,000000E+00	0,000000E+00	0,0	1	0,00
1	Hydrogen	1H	1	1,007825	1	0	1,672623E-27	0,000000E+00	1,007365	0,000000	0,000549	0,000089	1,473698E-31	1,324494E-14	0,1	1	0,08
1	Deuterium	2H	2	2,014102	1	1	1,672623E-27	1,674929E-27	1,007365	1,008754	0,000549	0,002566	4,260437E-30	3,829089E-13	2,4	2	1,19
1	Tritium	3H	3	3,016049	1	2	1,672623E-27	3,349858E-27	1,007365	2,017508	0,000549	0,009373	1,556364E-29	1,398790E-12	8,7	3	2,91
2	Helium	3He	3	3,016029	2	1	3,345246E-27	1,674929E-27	2,014730	1,008754	0,001097	0,008552	1,420167E-29	1,276382E-12	8,0	3	2,66
2	Helium	4He	4	4,002603	2	2	3,345246E-27	3,349858E-27	2,014730	2,017508	0,001097	0,030732	5,103234E-29	4,586558E-12	28,6	4	7,16
3	Lithium	6Li	6	6,015121	3	3	5,017869E-27	5,024787E-27	3,022095	3,026262	0,001646	0,034882	5,792307E-29	5,205866E-12	32,5	6	5,42
3	Lithium	7Li	7	7,013360	3	4	5,017869E-27	6,699716E-27	3,022095	4,035016	0,001646	0,045397	7,538355E-29	6,775136E-12	42,3	7	6,04
4	Beryllium	9Be	9	9,012180	4	5	6,690492E-27	8,374645E-27	4,029460	5,043770	0,002195	0,063245	1,050203E-28	9,438758E-12	58,9	9	6,55
6	Carbon	11C	11	11,011434	6	5	1,003574E-26	8,374645E-27	6,044191	5,043770	0,003292	0,079818	1,325413E-28	1,191222E-11	74,4	11	6,76
6	Carbon	12C	12	12,000000	6	6	1,003574E-26	1,004957E-26	6,044191	6,052524	0,003292	0,100006	1,660642E-28	1,492510E-11	93,2	12	7,76
6	Carbon	13C	13	13,003355	6	7	1,003574E-26	1,172450E-26	6,044191	7,061278	0,003292	0,105405	1,750293E-28	1,573085E-11	98,2	13	7,55
7	Nitrogen	14N	14	14,006700	7	7	1,170836E-26	1,172450E-26	7,051556	7,061278	0,003840	0,109974	1,826159E-28	1,641270E-11	102,4	14	7,32
8	Oxygen	16O	16	15,999400	8	8	1,338098E-26	1,339943E-26	8,058921	8,070032	0,004389	0,133942	2,224152E-28	1,998968E-11	124,8	16	7,80
13	Aluminium	27Al	27	26,981540	13	14	2,174410E-26	2,344901E-26	13,095747	14,122555	0,007132	0,243894	4,049955E-28	3,639918E-11	227,2	27	8,41
16	Sulfur	32S	32	31,972071	16	16	2,676197E-26	2,679886E-26	16,117842	16,140063	0,008778	0,294612	4,892150E-28	4,396845E-11	274,4	32	8,58
16	Sulfur	34S	34	33,967867	16	18	2,676197E-26	3,014872E-26	16,117842	18,157571	0,008778	0,316324	5,252684E-28	4,720877E-11	294,7	34	8,67
20	Calcium	40Ca	40	39,962591	20	20	3,345246E-26	3,349858E-26	20,147302	20,175079	0,010973	0,370763	6,156663E-28	5,533333E-11	345,4	40	8,63
20	Calcium	43Ca	43	42,958767	20	23	3,345246E-26	3,852337E-26	20,147302	23,201341	0,010973	0,400849	6,656251E-28	5,982340E-11	373,4	43	8,68
22	Titanium	47Ti	47	46,951763	22	25	3,679771E-26	4,187323E-26	22,162033	25,218849	0,012070	0,441188	7,326102E-28	6,584372E-11	411,0	47	8,74
22	Titanium	48Ti	48	47,947946	22	26	3,679771E-26	4,354815E-26	22,162033	26,227603	0,012070	0,453759	7,534847E-28	6,771983E-11	422,7	48	8,81

Source: Ch.Guéritte/Data from various sources



Nuclear Energy – Table Mass Defect & Binding Energy

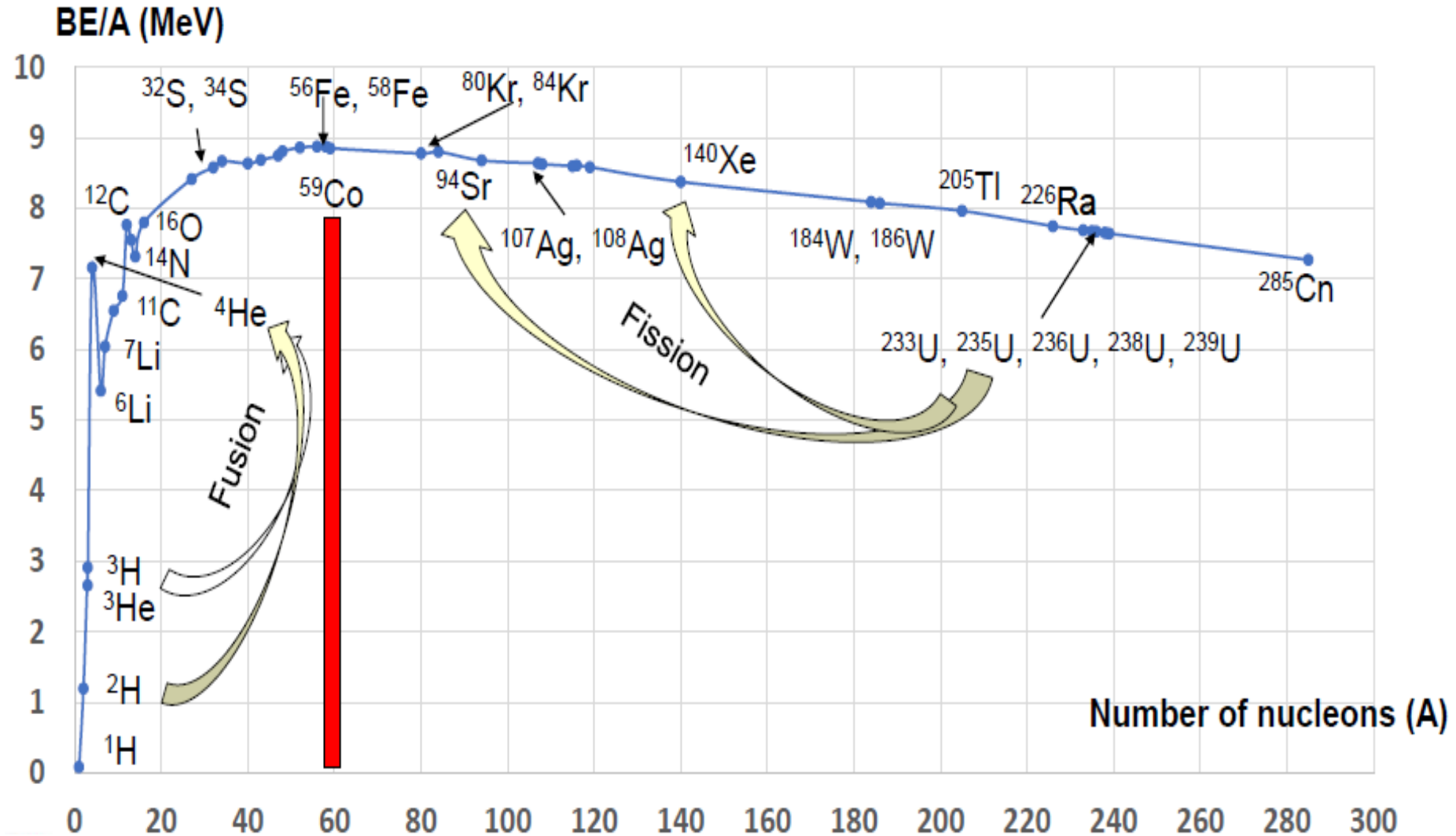
Atomic Number	Name of Element	Symbol	Atomic Mass Nb	Atomic Mass	Number Protons	Number Neutrons	Mass Protons kg	Mass Neutrons kg	Mass Protons amu	Mass Neutrons amu	Mass Electrons amu	Mass Defect amu	Mass Defect kg	Binding Energy (BE) J	Binding Energy MeV	Number Nucleons	BE/ Nucleon MeV
Z			A	u	Z	A-Z	kg	kg	amu	amu	amu	amu	kg	J	MeV	A	MeV
24	Chromium	52Cr	52	51,940508	24	28	4,014295E-26	4,689801E-26	24,176763	28,245110	0,013167	0,494532	8,211906E-28	7,380493E-11	460,7	52	8,86
26	Iron	56Fe	56	55,934937	26	30	4,348820E-26	5,024787E-26	26,191493	30,262618	0,014264	0,533439	8,857962E-28	7,961139E-11	496,9	56	8,87
26	Iron	58 Fe	58	57,933276	26	32	4,348820E-26	5,359773E-26	26,191493	32,280126	0,014264	0,552608	9,176269E-28	8,247219E-11	514,8	58	8,88
27	Cobalt	59Co	59	58,933200	27	32	4,516082E-26	5,359773E-26	27,198858	32,280126	0,014813	0,560597	9,308941E-28	8,366459E-11	522,2	59	8,85
36	Krypton	80Kr	80	79,916379	36	44	6,021443E-26	7,369688E-26	36,265144	44,385174	0,019751	0,753690	1,251531E-27	1,124820E-10	702,1	80	8,78
36	Krypton	84Kr	84	83,911507	36	48	6,021443E-26	8,039659E-26	36,265144	48,420189	0,019751	0,793577	1,317766E-27	1,184349E-10	739,2	84	8,80
38	Strontium	94Sr	94	93,915362	38	56	6,35597E-26	9,3796E-26	38,279875	56,490221	0,020848	0,875582	1,453938E-27	1,306734E-10	815,6	94	8,68
47	Silver	107Ag	107	106,905097	47	60	7,861328E-26	1,004957E-25	47,346161	60,525237	0,025786	0,992086	1,647398E-27	1,480607E-10	924,1	107	8,64
47	Silver	108Ag	108	107,905956	47	61	7,861328E-26	1,021707E-25	47,346161	61,533991	0,025786	0,999981	1,660508E-27	1,492390E-10	931,5	108	8,62
50	Tin	115Sn	115	114,903342	50	65	8,363115E-26	1,088704E-25	50,368256	65,569007	0,027431	1,061352	1,762417E-27	1,583981E-10	988,6	115	8,60
50	Tin	116Sn	116	115,901751	50	66	8,363115E-26	1,105453E-25	50,368256	66,577760	0,027431	1,071697	1,779595E-27	1,599420E-10	998,3	116	8,61
50	Tin	119Sn	119	118,903308	50	69	8,363115E-26	1,155701E-25	50,368256	69,604022	0,027431	1,096402	1,820618E-27	1,636290E-10	1021,3	119	8,58
54	Xenon	140Xe	140	139,921647	54	86	9,03216E-26	1,44044E-25	54,397716	86,752839	0,029626	1,258535	2,089846E-27	1,878260E-10	1172,3	140	8,37
74	Tungstene	184W	184	183,950931	74	110	1,237741E-25	1,842422E-25	74,545019	110,962934	0,040599	1,597620	2,652912E-27	2,384318E-10	1488,2	184	8,09
74	Tungstene	186W	186	185,954364	74	112	1,237741E-25	1,875920E-25	74,545019	112,980442	0,040599	1,611695	2,676283E-27	2,405324E-10	1501,3	186	8,07
81	Thallium	205Tl	205	204,974428	81	124	1,354825E-25	2,076912E-25	81,596575	125,085489	0,044439	1,752075	2,909389E-27	2,614829E-10	1632,0	205	7,96
88	Radium	226Ra	226	226,025410	88	138	1,471908E-25	2,311402E-25	88,648131	139,208045	0,048279	1,879044	3,120227E-27	2,804320E-10	1750,3	226	7,74
92	Uranium	233U	233	233,039635	92	141	1,538813E-25	2,361650E-25	92,677591	142,234306	0,050474	1,922736	3,192779E-27	2,869527E-10	1791,0	233	7,69
92	Uranium	235U	235	235,043930	92	143	1,538813E-25	2,395148E-25	92,677591	144,251814	0,050474	1,935949	3,214720E-27	2,889246E-10	1803,3	235	7,67
92	Uranium	236U	236	236,04557	92	144	1,538813E-25	2,411898E-25	92,677591	145,260568	0,050474	1,943065	3,226536E-27	2,899866E-10	1810,0	236	7,67
92	Uranium	238U	238	238,050788	92	146	1,538813E-25	2,445396E-25	92,677591	147,278076	0,050474	1,955353	3,246940E-27	2,918205E-10	1821,4	238	7,65
92	Uranium	239U	239	239,05429	92	147	1,538813E-25	2,462146E-25	92,677591	148,286830	0,050474	1,960602	3,255657E-27	2,926038E-10	1826,3	239	7,64
112	Copernicium	285Cn	285	285,177126	112	173	1,873338E-25	2,897627E-25	112,824893	174,514433	0,061446	2,223647	3,692452E-27	3,318611E-10	2071,3	285	7,27

Source: Ch.Guérutte/Data from
various sources



Nuclear Energy – Aston Curve

Binding Energy (BE) per nucleon vs number of nucleons (A)



Source: Ch.Guérutte



Nuclear Energy

Nuclear Fission, Nuclear Fusion

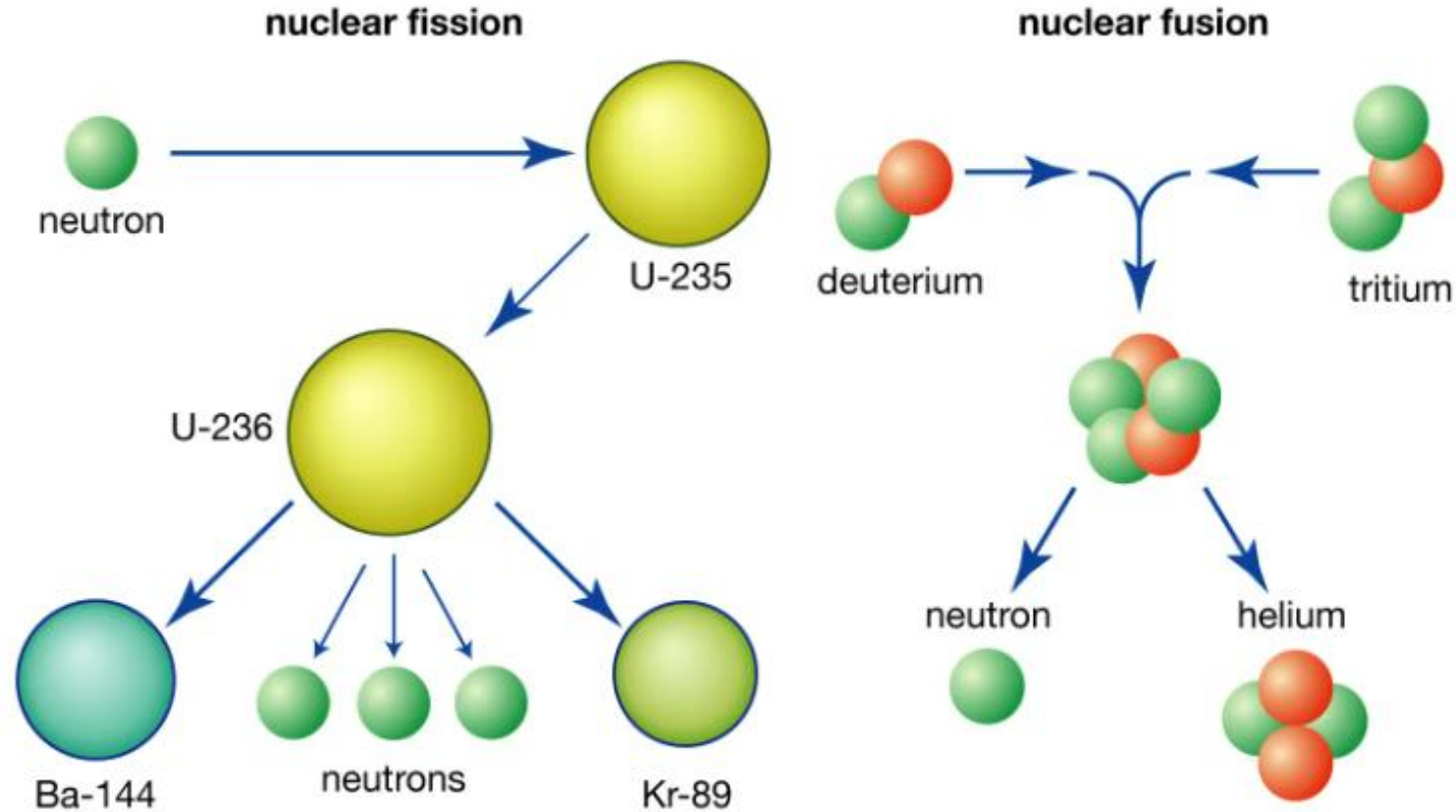
- **Fusion:** two atomic nuclei fuse together to produce a heavier nucleus.
- **Fission:** the breaking of a heavy nucleus into lighter nuclei.
- The Aston curve represents the Binding Energy per nucleon as a function of the number of nucleons. High values correspond to the more stable nuclei, where the nucleons are more tightly bound. The maximum is reached for $^{56}\text{Fe}/^{58}\text{Fe}$ (8,88 MeV).
- BE/A is greater for medium-class nuclei than heavy nuclei and light nuclei.
- Energy is released if the products of a nuclear reaction have a greater binding energy per nucleon (BE/A) than the parent nuclei.
- In a Fusion elementary reaction, deuterium and tritium fuse together to produce ^4He , a heavier component, generating an important quantity of energy:
$$^2\text{H} + ^3\text{H} \longrightarrow ^4\text{He} + ^1_0\text{n} + 17,5 \text{ MeV}$$
- In a Fission elementary reaction, ^{235}U nuclei can be split into Xenon and Strontium nuclei, lighter components, generating an important quantity of energy:
$$^{235}\text{U} + ^1_0\text{n} \longrightarrow ^{140}\text{Xe} + ^{94}\text{Sr} + 2^1_0\text{n} + 184,6 \text{ MeV}$$



The Future: Nuclear Fusion?



Nuclear Fission & Nuclear Fusion



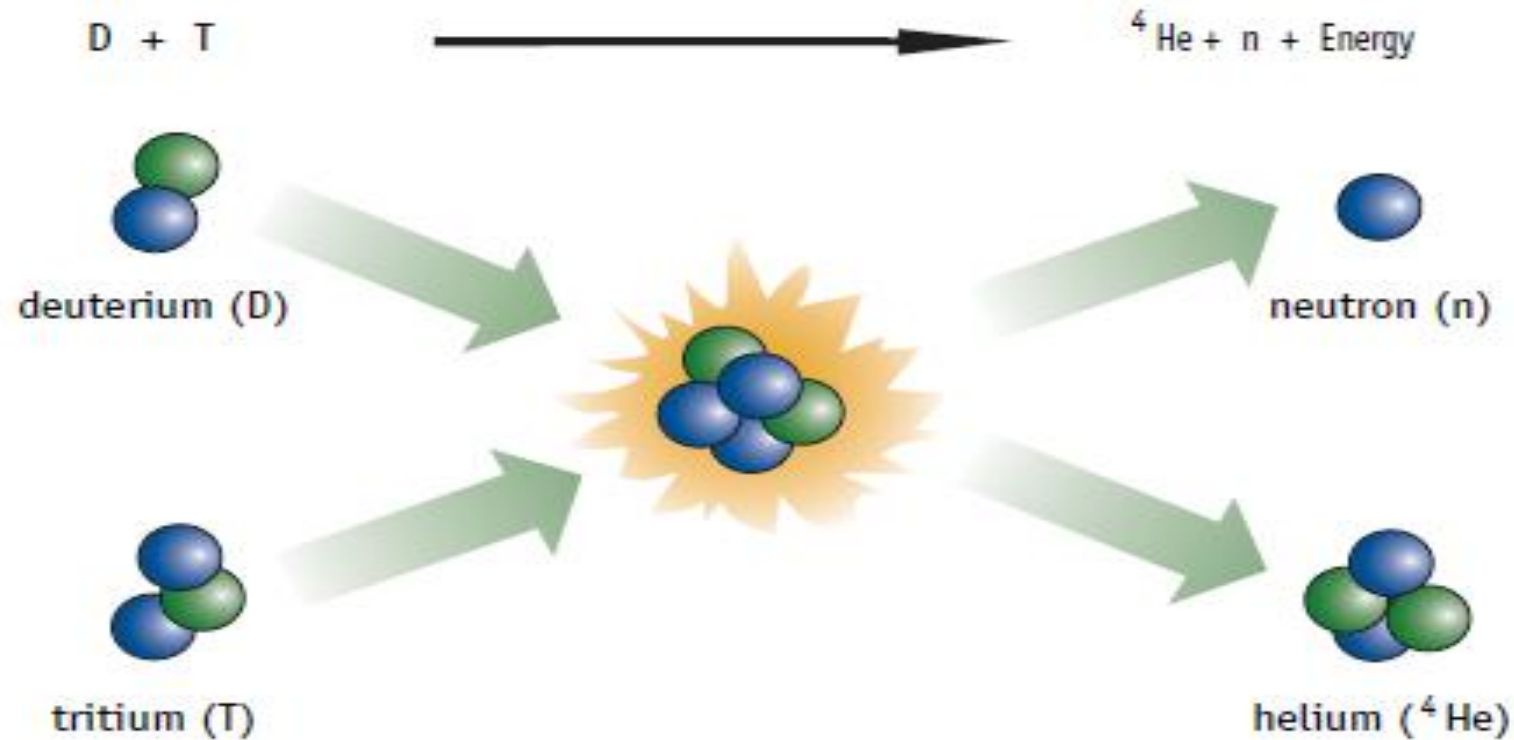
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Note: Deuterium and Tritium are two isotopes of hydrogen

Nuclear fusion consists in assembling two light atomic nuclei into a heavier nucleus. Huge scientific and technological challenge. Needs extreme temperature conditions: > 100 millions °C.....



The Fusion Reaction: has been researched for decades

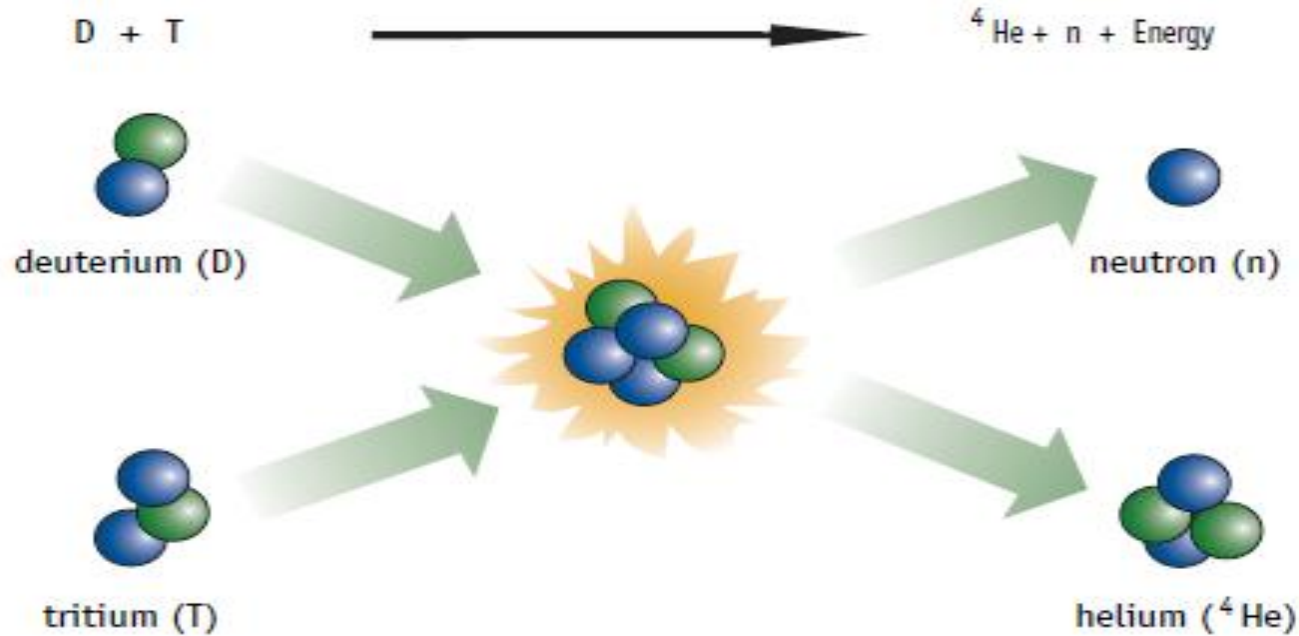


Source: Joint European Torus.

Note: Deuterium and Tritium are two isotopes of hydrogen
Nuclear fusion consists in assembling two light atomic nuclei into a heavier nucleus. Huge scientific and technological challenge. Needs extreme temperature conditions: > 100 millions °C.....



The Fusion Reaction



Source: Joint European Torus.

Note: Deuterium and Tritium are two isotopes of hydrogen
Nuclear fusion consists in assembling two light atomic nuclei into a heavier nucleus.
Huge scientific and technological challenge. Needs extreme temperature conditions: > 100 millions °C.....

STATUS

- R&D for decades (70 yrs)!
- Used in the H bomb (fusion initiated by fission)
- Coalition of most 'nuclear' countries to develop a fusion program together (ITER program)
- Slow progress due to political constraints
- Separate efforts before demo unit: China, Korea, ...
- **NEW** : private companies are now interested (6 Bn \$): 3 competing technologies
 - SPARC (MIT + private)
 - STEP (Oxford + private)
 - Helion (for Microsoft)
- Timing could improve???

Sources : UDA Energucht + Fabrice Louche ERM



Nuclear Fusion

International Thermonuclear Experimental Reactor ITER Project - Cadarache



Nuclear Fusion : ITER

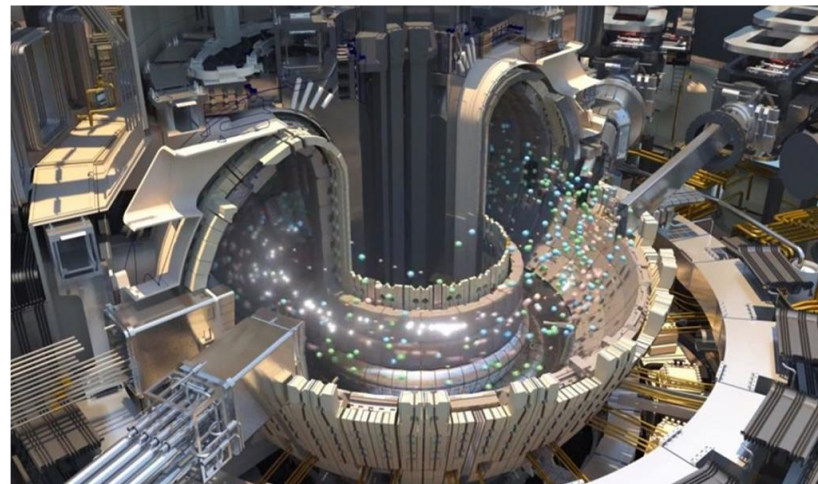
International Thermonuclear Experimental Reactor



Source: Futura Science 2018

ITER:

- Russia, China, South Korea, USA, Japan, India, Kazakhstan, UE (45.5%)
- Objective: net production of energy
- Large Tokamak (diameter: 30 m): plasma
 - >150 million °C
 - High particle density
 - Duration
- 500 MW
- No electricity production
- Cadarache (Aix en Provence) / France



Timing:

- Dec 2025 : first plasma
- 2025-2026 : increase power
- 2035: operation in deuterium-tritium
- 2040? Demonstration unit (electricity prod.)
- 2050? Industrial prototype

Source : UDA Energucht

2023: welding problems → potential delays



Nuclear Fusion

International Thermonuclear Experimental Reactor Iter Project

- **1st experimental Tokamak: Tore Supra, CEA Cadarache, Iter predecessor.**
- **Iter: The matter must be in a plasma state.**
- **Fuel is confined thanks to supraconducting modules in solenoid magnets.**
- **Temperature # 110 million °C.**
- **Construction of the world's largest Tokamak with ten times the plasma volume of the largest Tokamak operating today.**
- **Production of deuterium-tritium plasma scheduled for 2035.**
- **Power: 500 MW.**
- **Location: Cadarache, France.**
- **Partnership: EU, China, Switzerland, India, Korea, Russia, US.**
- **Original budget: 5 G€.**
- **Current budget: 19 G€.**



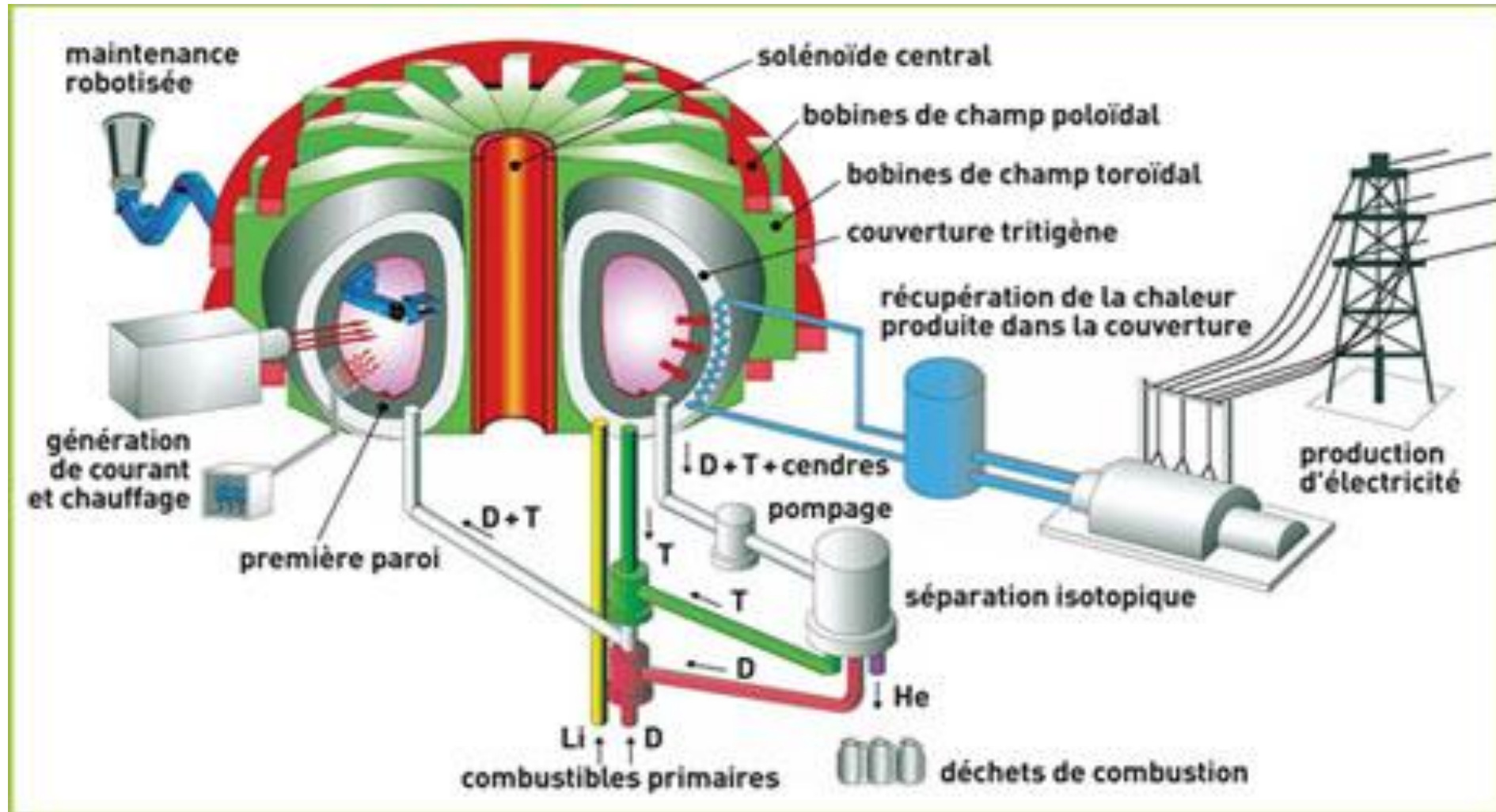
Tokamak
Russian origin:
« тороидальная камера с магнитными катушками »
« *toroidalnaïa kamera s magnitnymi katouchkami* »
Chambre toroïdale avec bobines magnétiques



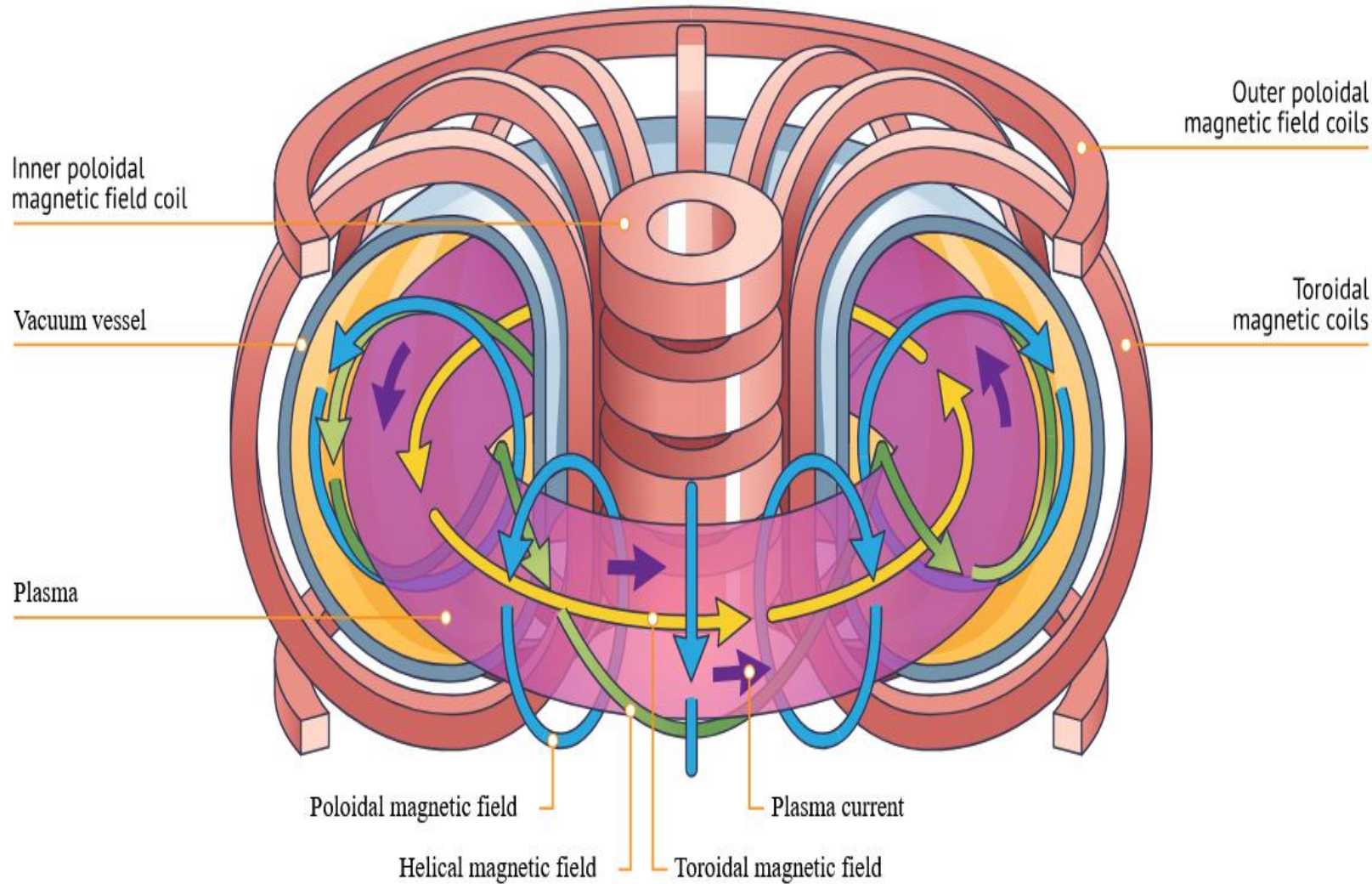
Nuclear Fusion

Tokamak basic principle

Iter Project - Cadarache



Nuclear Fusion - Tokamak basic principle



- The donut-shaped chamber encircled by toroidal magnetic coils is the basic design of a tokamak.
- In the magnetic cage in a form of a torus, a combination of poloidal and toroidal magnetic fields enable the isolation of the hot plasma current from the vessel walls.
- The plasma current can be heated up to fusion temperature (> 100 millions $^{\circ}\text{C}$) and can ignite thermonuclear fusion.
- The plasma is created by the introduction of hydrogen ($\text{D} + \text{T}$ isotopes) Electric current is generated in gas and particles, electrons and ions collide together and temperature increases.
- Heating efforts combined in the plasma current, the temperature can reached levels above 100 millions $^{\circ}\text{C}$.



2021/2022 Significant technical problems appears on Iter Project

ITER NEWSLINE -

21 NOV, 2022

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Machine assembly

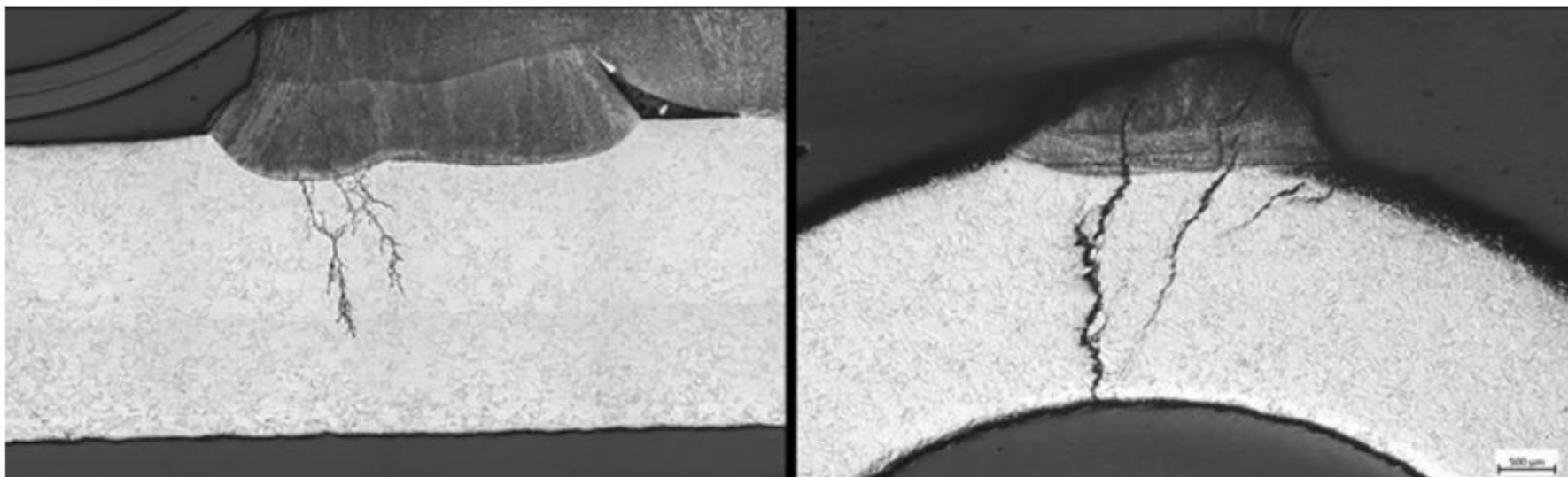
KEY COMPONENTS TO BE REPAIRED

When building a machine as large and as complex as ITER, difficulties and setbacks do not come as surprises—they are an integral part of manufacturing, assembling and installing first-of-a-kind components. From the first stages of fabrication to the final insertion in the Tokamak pit, component challenges are a constant and familiar companion. Sometimes, however, in the midst of ordinary, almost daily issues, a concern of a larger dimension arises—one which demands in-depth examination, creativity in devising corrective actions, and time and budget to repair. Two-and-a-half years into its machine assembly phase, ITER is facing a concern of this nature: defects have been identified in two key tokamak components, the thermal shields and the vacuum vessel sectors.



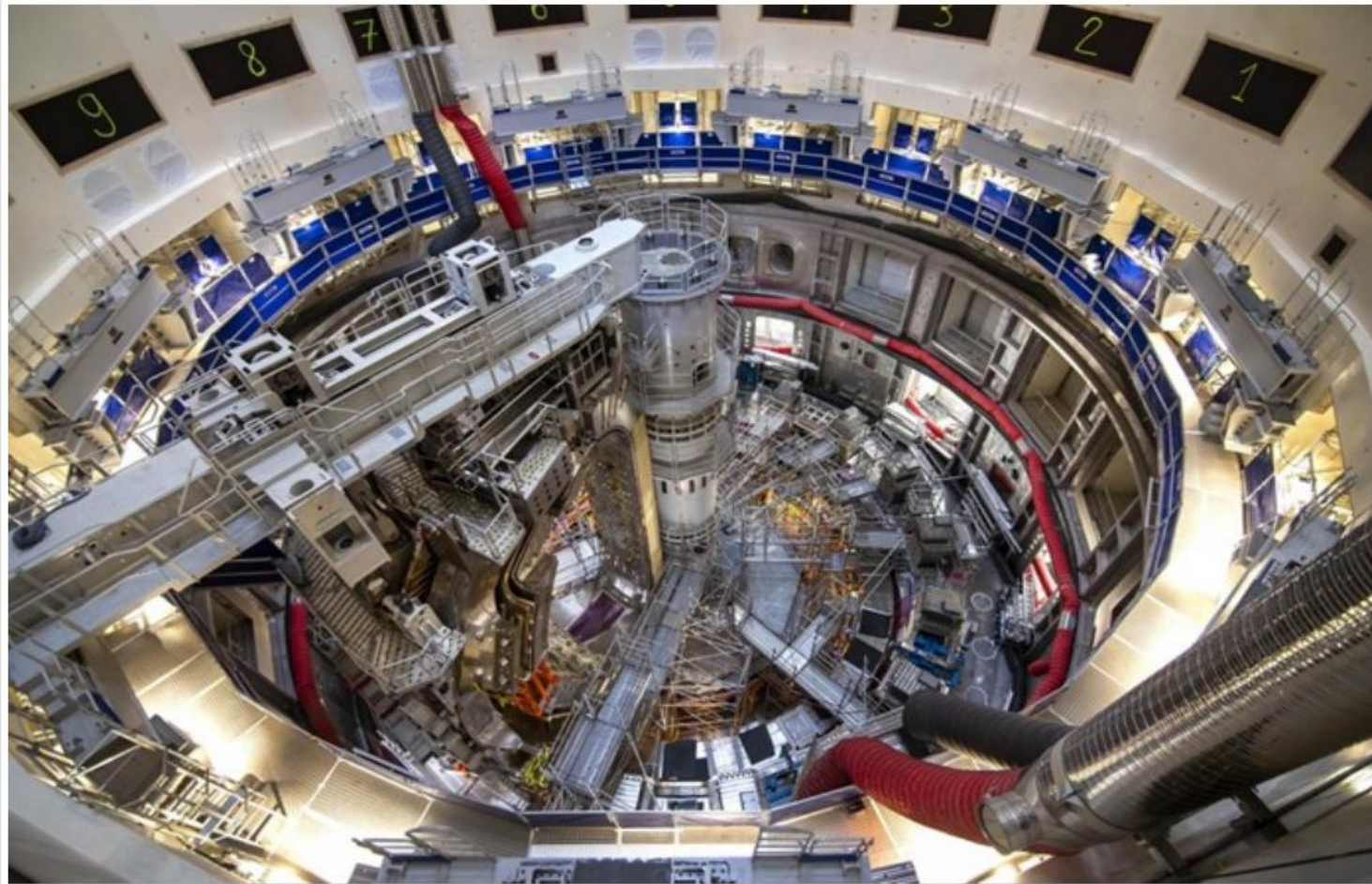
2021/2022 Significant technical problems appears on Iter Project

In November 2021, helium tests detected leaks on an element of the vacuum vessel thermal shield that had been delivered a year and a half earlier. Working groups with experts from different ITER partners were rapidly established to investigate, and they were able to identify the root cause for the leaks—stress caused by the bending and welding of the cooling fluid pipes to the thermal shield panels, compounded by a slow chemical reaction due to the presence of chlorine residues¹ in some small areas near the pipe welds. This reaction had generated what is called "stress corrosion cracking" and, over time, cracks up to 2.2 millimetres deep had developed in the pipes. A crucial question therefore arose: was the issue a one-off problem, limited to the elements examined, or was it systemic, affecting all thermal shield components?



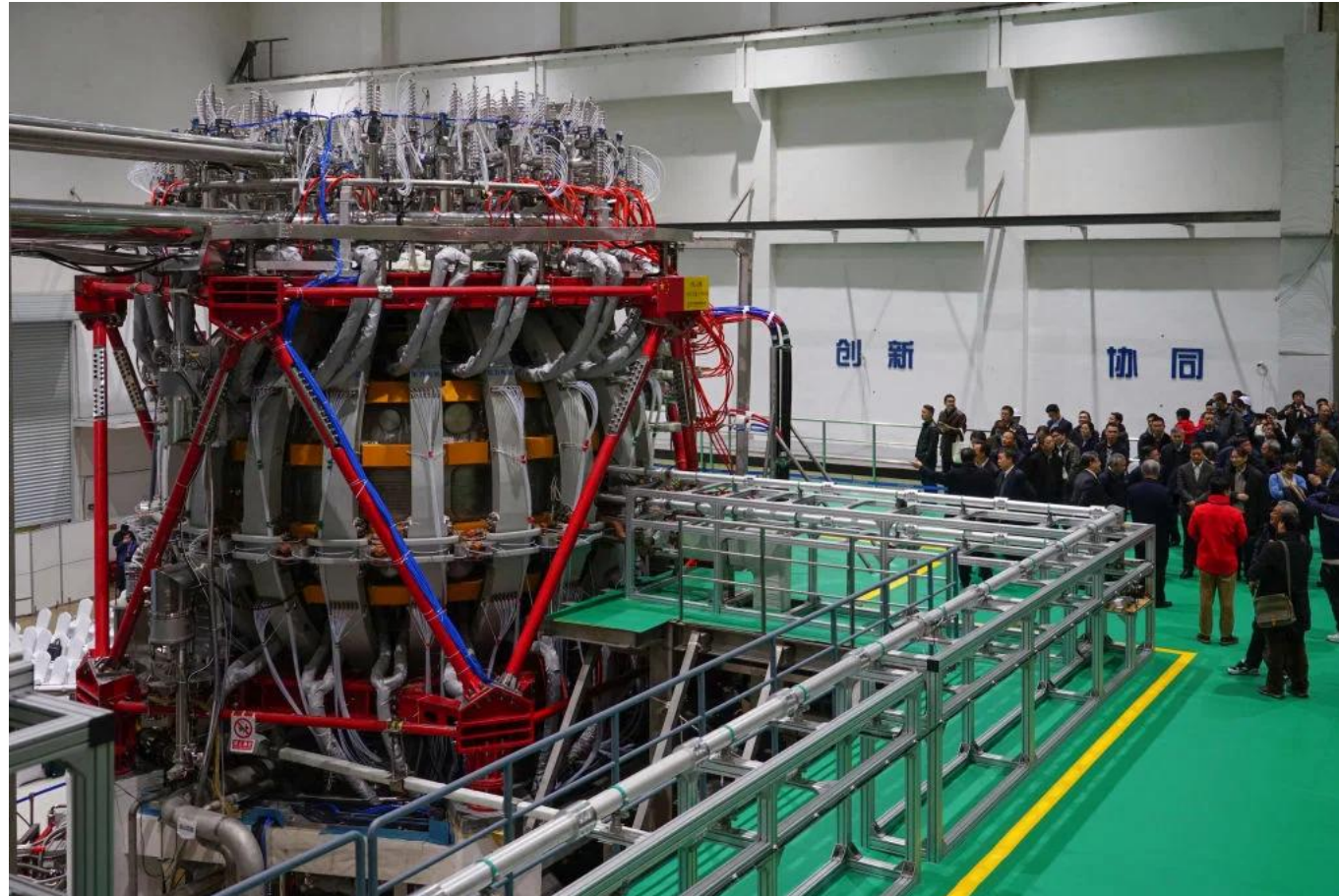
Investigative techniques (high-resolution CT scanning, scanning electron microscope, energy-dispersive X-ray spectrometer, and metallographic observation) revealed cracks in thermal shield cooling pipes such as the ones pictured here. At left, the crack is 1.5 mm deep. At right it is 2.2 mm deep and crosses the full width of the pipe.

2021/2022 Significant technical problems appears on Iter Project



In order to deal efficiently with both thermal shield piping and vacuum vessel issues, the decision was taken to lift the module already installed in the machine pit (Sector #6, shown here) and disassemble it in order to proceed with the repairs. The consequences on schedule and cost "will not be insignificant" according to ITER Director-General Pietro Barabaschi.

China Nuclear Fusion device HL-2M Tokamak « Artificial Sun » 1st plasma discharge at the Southwestern Institute of Physics – Chengdu/Sichuan – China - December 2020



Nuclear Fusion : EAST

(Experimental Advanced Superconducting Tokamak)
China

Separate effort leading
to a DEMO unit



中国工程物理研究院
CHINA ACADEMY OF ENGINEERING PHYSICS

铸国防基石 做民族脊梁



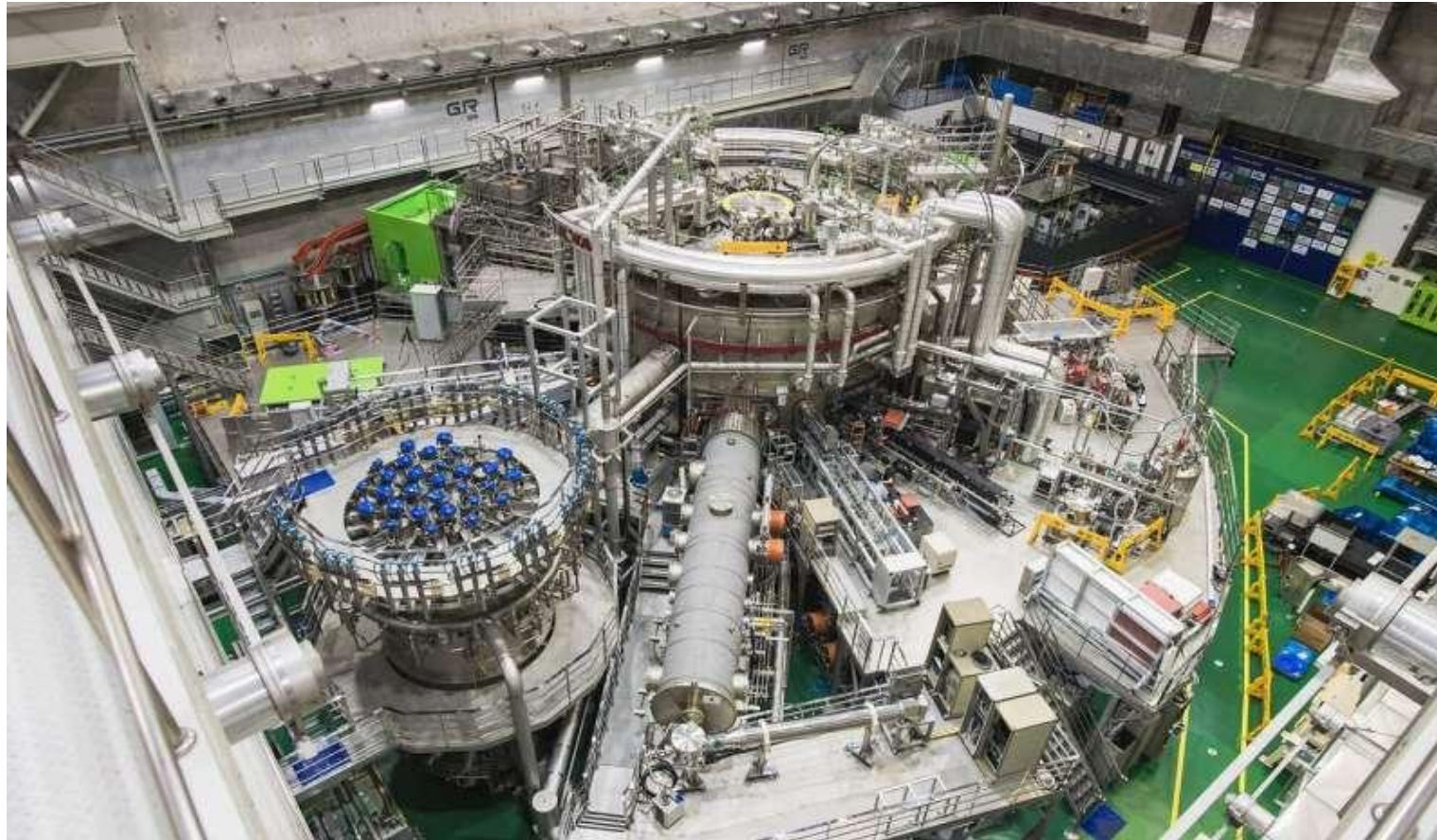
Z-FFR 总体结构示意图

EAST:

- Mix fusion - fission
- Apr 2021
 - 70 million ° C
 - 17 sec continuous
 - Plasma operation
- China
- Next objective:
 - 2028 : industrial reactor!
 - 2035 : stable production

Source : UDA Energucht

South Korea Nuclear Fusion KSTAR (Korea Superconducting Tokamak Advanced Research) Reactor « Artificial Sun »
Continuous operation of plasma for 20 seconds at temperature > 100 millions degrees
Korea Institute of Fusion Energy – Daejeon/Korea - December 2020



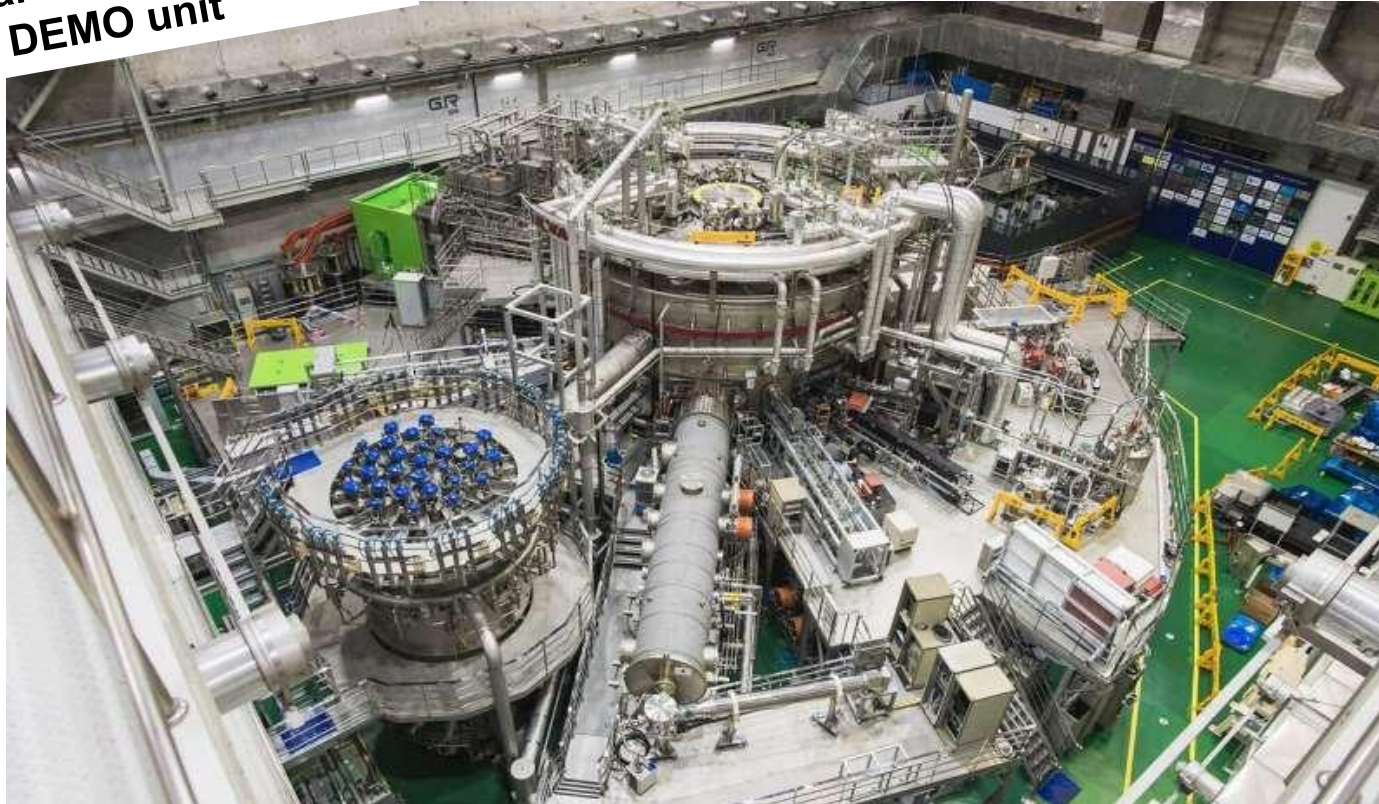
Source: National Research Council
for Science and Technology



Nuclear Fusion : KSTAR

(Korea Superconducting Tokamak Advanced Research)
Reactor « Artificial Sun »

Separate effort leading
to a DEMO unit



Source: National Research Council for
Science and Technology

KSTAR:

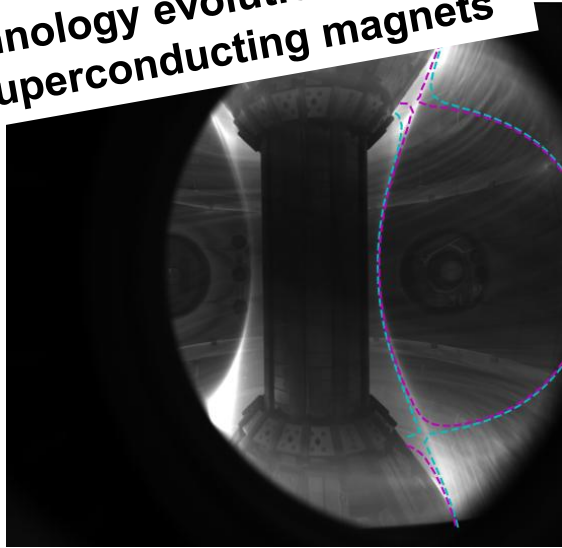
- Built in 2007
- Dec 2020
 - >100 million °C
 - 20 sec continuous
 - Plasma operation
- Daejeon / South Korea
- Next objective:
 - 200 million °C
 - 300 seconds
 - 2026

Source : UDA Energucht



Nuclear Fusion : Spherical Tokamak

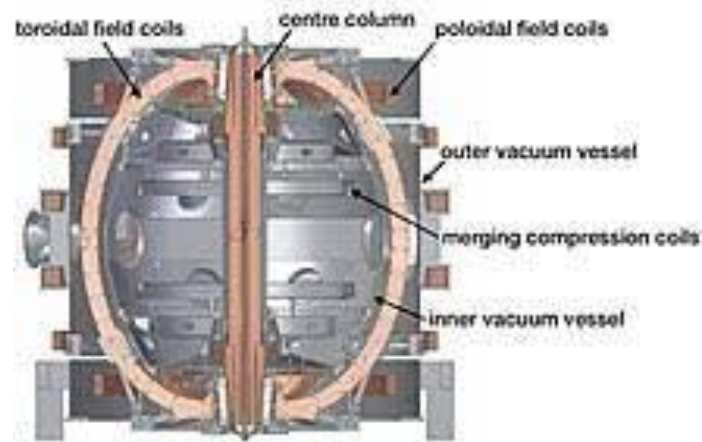
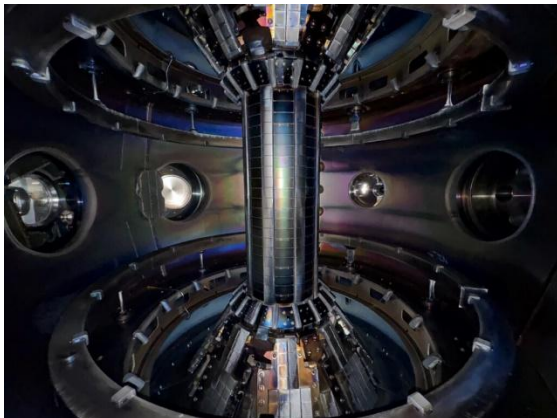
Technology evolution thanks to superconducting magnets



Source: Tokamak Energy

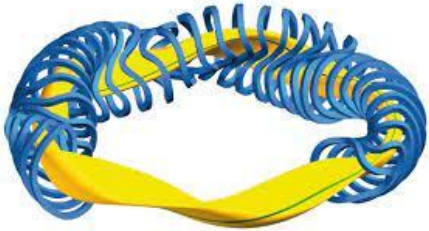
Tokamak Energy :

- **Smaller**
- **More compact**
- **High Field Supraconducting Magnets (new)**
- **Oxford, UK**
- **Private company**

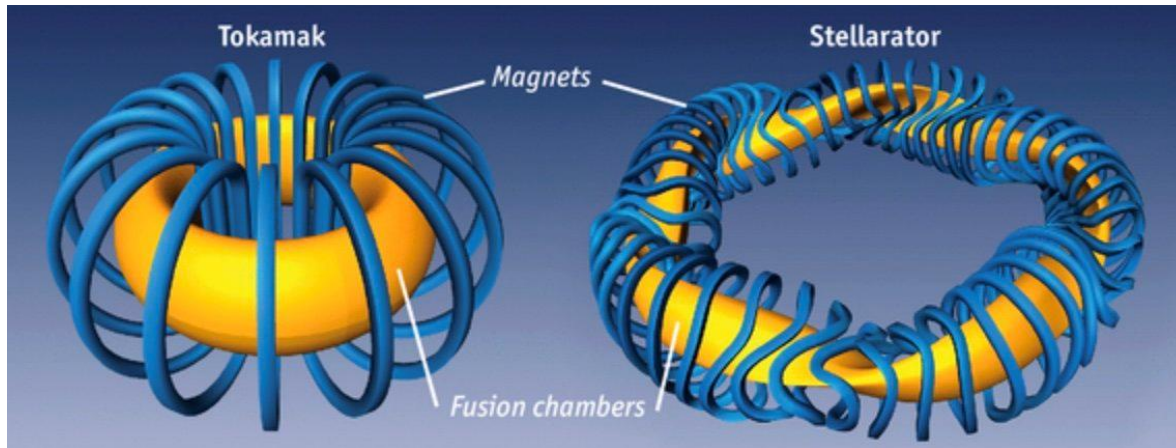


Nuclear Fusion : Stellarator

Alternative technology



Source : Wikipedia



Source : Ian Hogarth

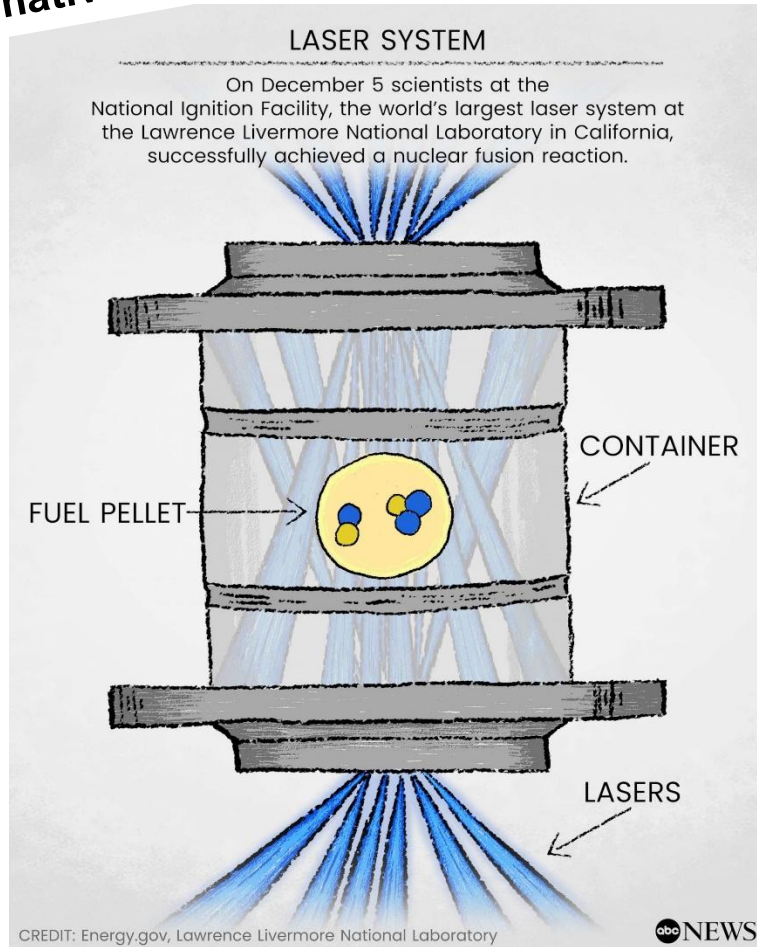
Proxima Fusion:

- Twisted Torus
- No need of a plasma current
- Stability of the plasma
- More difficult to design
- München, Germany
- Private Company (Max Planck Institut)
- Present
 - 300 sec of plasma
- Next objectives:
 - 30 min of plasma
 - 2031 : prototype
 - 2040 : operational reactor



Nuclear Fusion : Inertial Fusion (laser technology)

Alternative technology



Source : Lawrence Livermore Laboratory with ABC News

Lawrence Livermore Laboratory:

- Laser technology
- High density / short confinement time
- California, US
- Present
 - 192 lasers
 - 3 MJ produced with 2 MJ injected
- Next objectives:
 - 200-300 lasers
 - 10 times per second



Nuclear Fusion: Conclusion

- ◆ Technically complex (very high T)
- ◆ Slow progress of international cooperation (ITER)
- ◆ Initiatives from some countries
- ◆ NEW : private initiatives (other technologies)
- ◆ Timing :
 - 2060 for industrial electricity production?
 - Earlier due to private push in other technologies? 2050?
 - If it works...

Objectives:

- Generate fusion
- Maintain fusion during time
- Produce more electricity than used
- Recover electricity

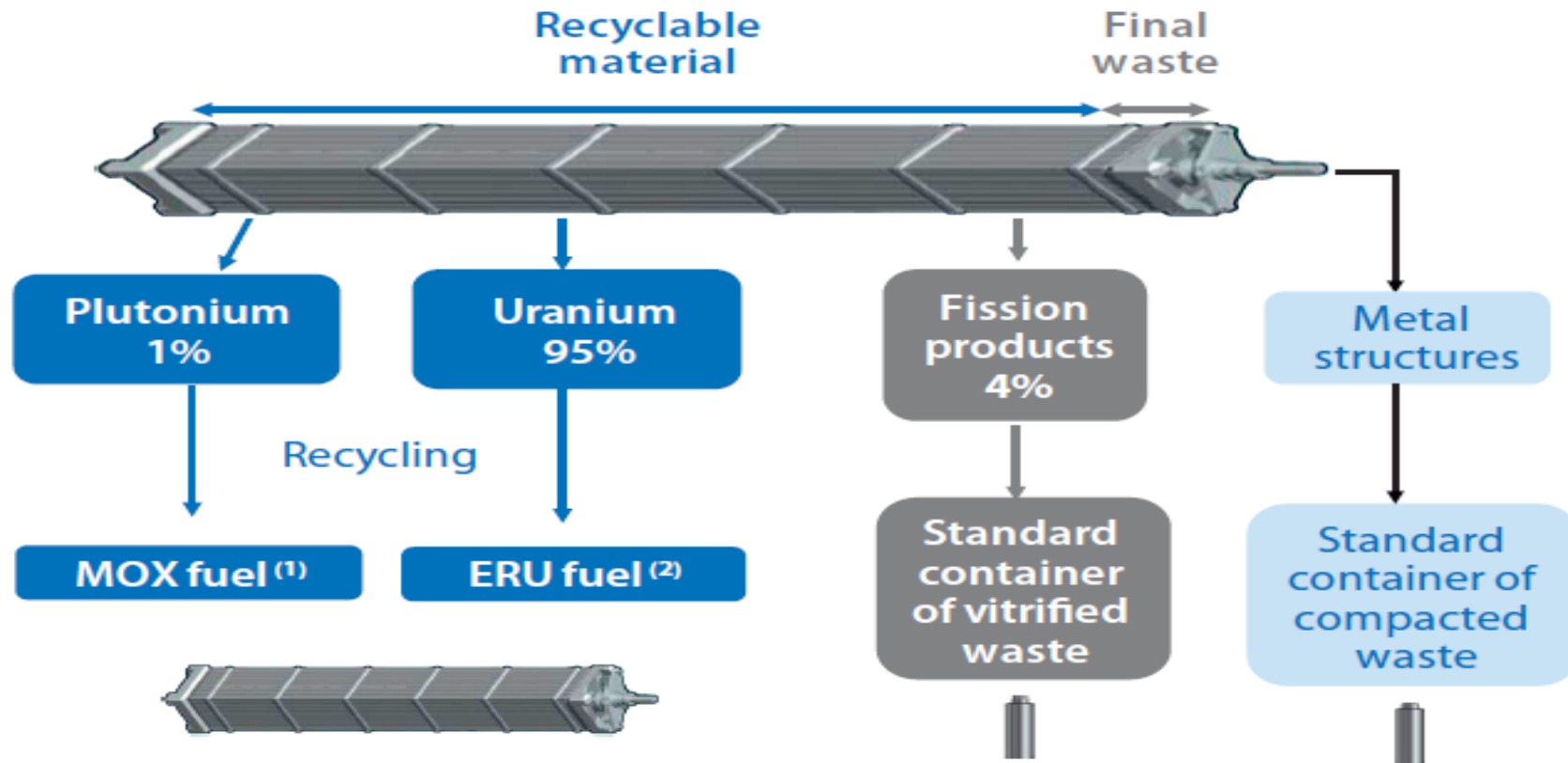


3-2

Spent Fuel Management



Composition and Reprocessing of Spent Fuel



(1) MOX : mixed oxide.

(2) Enriched recycled uranium.

Source: AREVA.

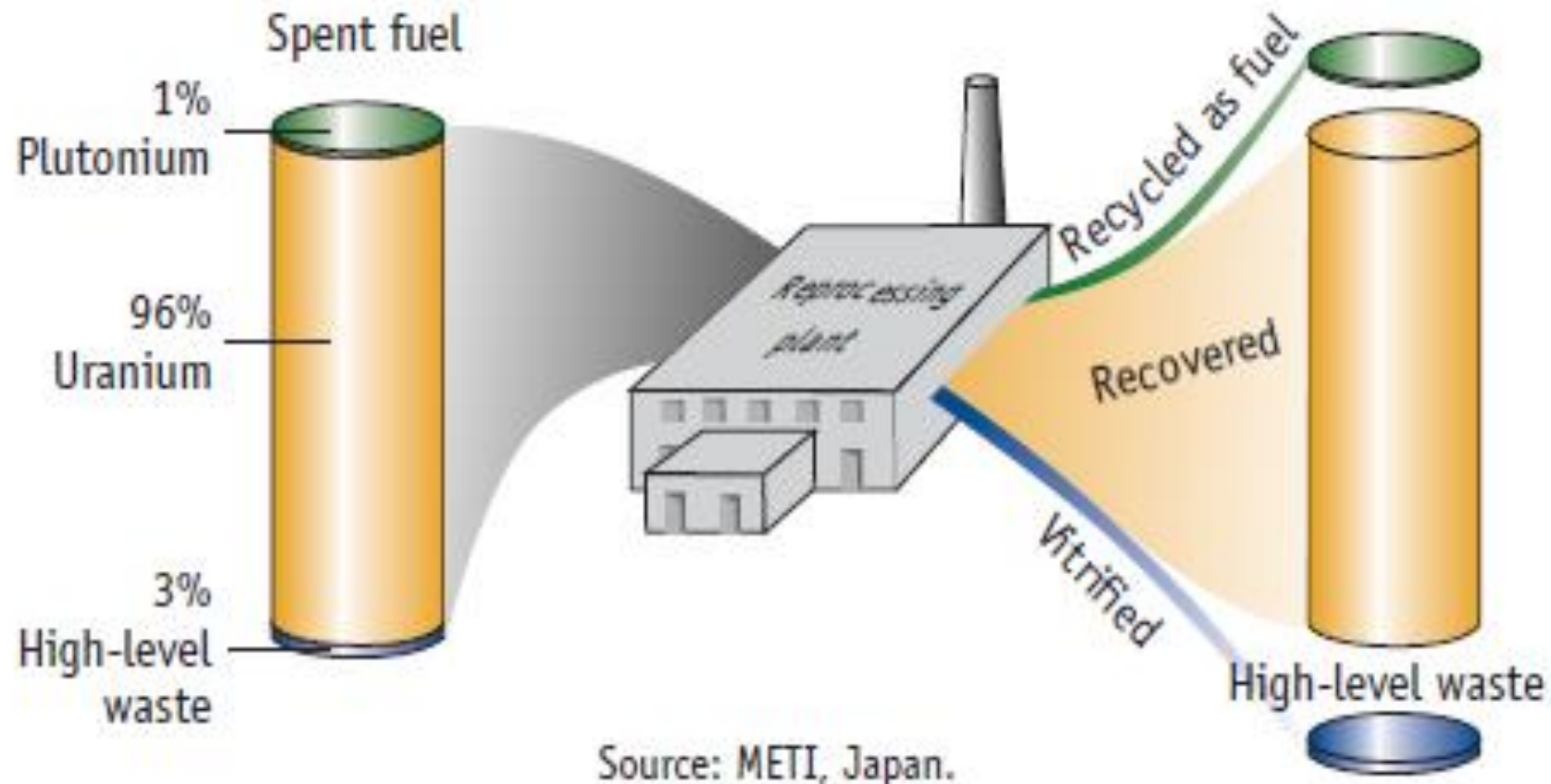
RU: Recycled Uranium

ERU: Enriched Recycled Uranium

1/8 RU → ERU (Usable in PWR, BWR)

7/8 RU → ERU (Usable in Fast Neutrons Reactors)

Composition and Reprocessing of Spent Fuel



Facilities for Spent Fuel Management

Typical spent nuclear fuel storage pool.



Dry storage of spent fuel.



Source:NEA

Major LWR* and other Spent Fuel Reprocessing Plants 2020 - Total Capacity : 3860 tU

LWR fuel	France, La Hague	1700
	Russia, Ozersk (Mayak)	400
	Japan (Rokkasho)	800*
	Total LWR (approx)	2100
Other nuclear fuels	UK, Sellafield (Magnox)	1500
	India (PHWR, 4 plants)	260
	Total other (approx)	1760
Total civil capacity		3860

Nota: LWR : Light Water Reactor * Planned to start in 2022

Source: WNA Processing of Used Nuclear Fuel Updated August 2024



The Thermal Oxyde Reprocessing Plant (THORP) at Sellafield - UK



3-3

Worldwide Nuclear Industry



Worldwide Nuclear Industry - Sources

A Mycle Schneider Consulting Project
Paris, September 2025



The World Nuclear Industry Status Report 2025



Nota: According to sources, number of nuclear reactors can differ between **Operable (connected to the grid) and **Operational in use** reactors.
The difference correspond to number of reactors under suspended operations**



In 2024, 70 Years of Nuclear Power

- ◆ 417 operational reactors (440 operable) in 31 countries as of 31/12/2024 (60% in OECD) - 23 reactors were in suspended operations.
- ◆ Net installed operable capacity of # 398 GWe (378 GWe operational + 20 GWe on suspended operations) as of 31/12/2024
- ◆ Average world fleet age : 32 years
- ◆ # 2 670 TWh/year
- ◆ ~ 57% Hydro-power
- ◆ 9% Electricity
- ◆ 5% Primary energy
- ◆ 62 reactors (78 GWe) under construction (42 in Asia, 28 in China) as of 31/12/2024
- ◆ 15 countries are currently building new reactors



Nuclear Power 2007/2024 – Capacities & Electricity Generation

Selected Countries - Operable Plants

Country	GWe*	TWh nets	Units*	%Elec
USA	99/97	807/782	104/94	19/18
France	63/63	420/364	59/57	77/67
Japan	48/32	267/85	55/33	28/8
Russia	22/27	148/202	31/36	16/18
S. Korea	18/26	137/179	20/26	35/32
Germany	20/0	133/0	17/0	26/0
Canada	13/13	88/81	18/17	15/13
Ukraine*	13/13	87/50	15/15	48/52
Sweden	9/7	64/49	10/6	46/29
China	9/58	59/418	11/59	2/5
WORLD	372/398	2608/2620	439/440	15/9

Data from IAEA PRIS (International Atomic Energy Agency)/WNA Facts and Figures - Updated
 September/November 2025. Capacities at year-end.
 Operable: Connected to the grid. Ukraine *: Estimate



Operable Reactors worldwide by types end 2024

	Africa	Asia	East Europe & Russia	North America	South America	West & Central Europe	Total
BWR		19		33		8	60
FNR			2				2
GCR						8	8
HTGR		1					1
LWGR			10 (-1)				10 (-1)
PHWR		24 (+1)		17 (-2)	3	2	46 (-1)
PWR	2	109 (+3)	41	63 (+1)	2	96 (+1)	313 (+5)
Total	2	153 (+4)	53 (-1)	113 (-1)	5	114 (+1)	440 (+3)

Source: World Nuclear Association, IAEA PRIS



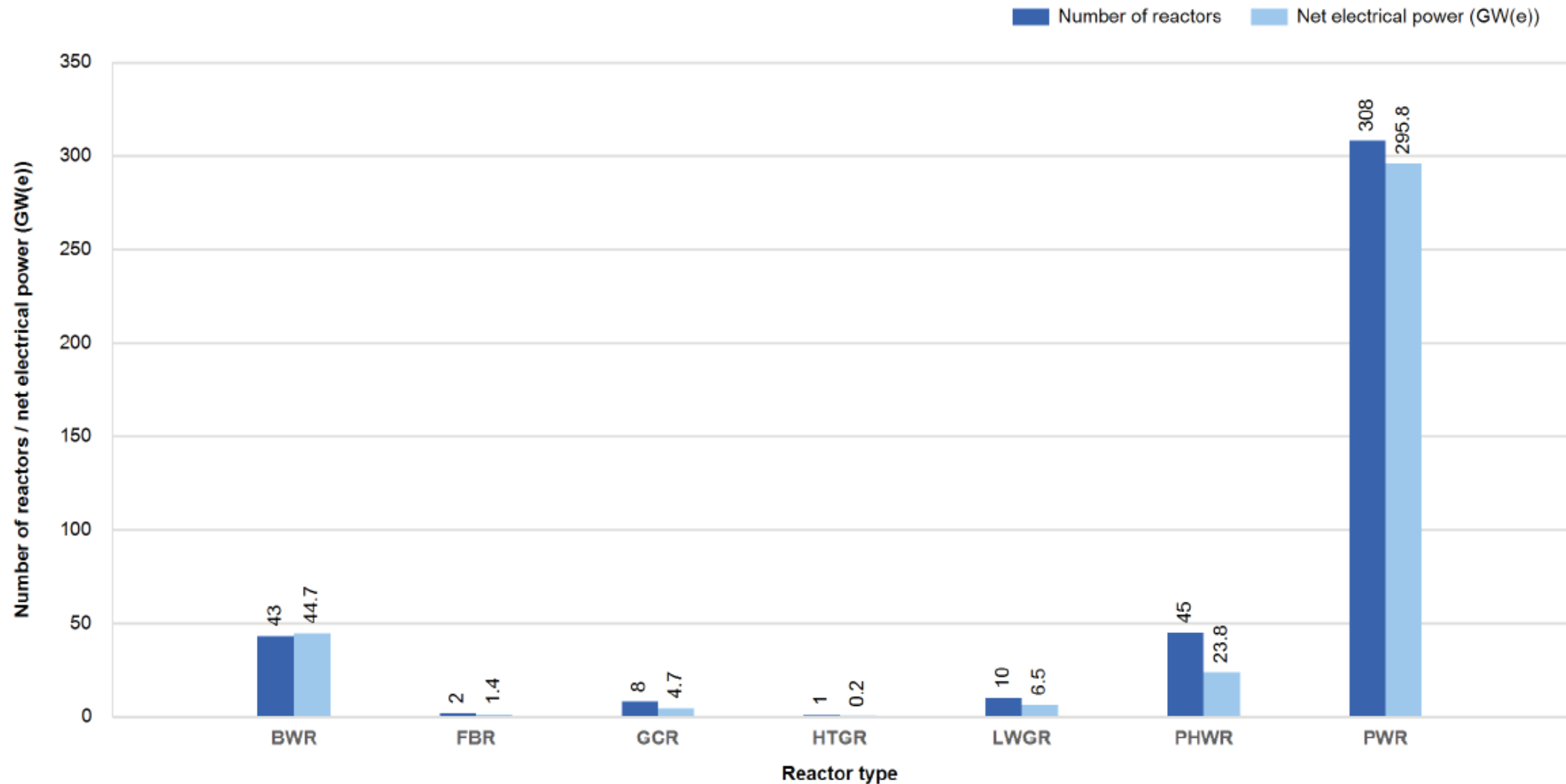
Operational Reactor types in use worldwide end 2024

Type Code	Type	Under construction	Operational	Suspended Operation	Shutdown
BWR	Boiling Light-Water Cooled and Moderated Reactor	2	43	17	53
FBR	Fast Breeder Reactor	4	2		8
GCR	Gas Cooled, Graphite Moderated Reactor		8		44
HTGR	High Temperature Gas Cooled Reactor		1		4
HWGCR	Heavy-Water Moderated, Gas Cooled Reactor				3
HWLWR	Heavy-Water Moderated, Boiling Light-Water Cooled Reactor				2
LWGR	Light-Water Cooled, Graphite Moderated Reactor		10		14
PHWR	Pressurized Heavy-Water Moderated and Cooled Reactor	2	45	2	12
PWR	Pressurized Light-Water Moderated and Cooled Reactor	54	308	4	70
SGHWR	Steam Generating Heavy-Water Reactor				1
X	Other				2
TOTAL		62	417	23	213

Source: IAEA PRIS: International Atomic Energy Agency/Power Reactors Information System
2025 Edition – Nuclear Power Reactors in the World



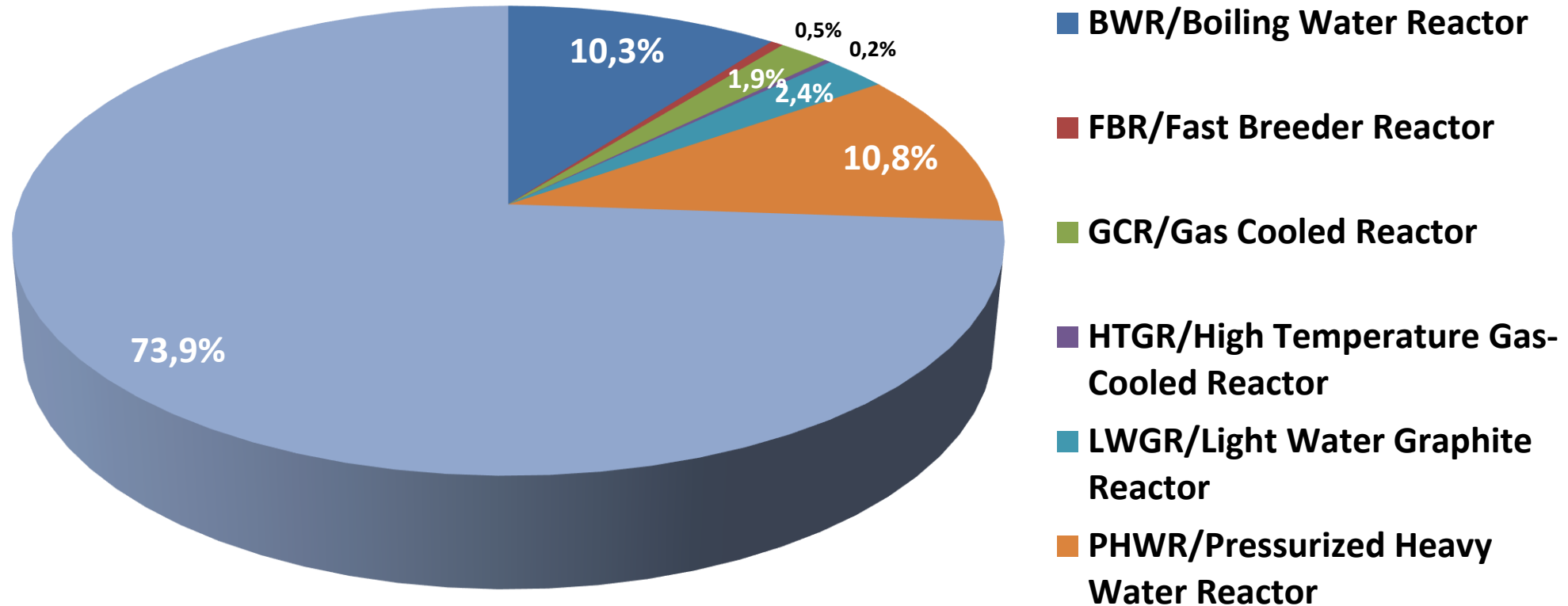
Number of Reactors by types & Net Power worldwide end 2024



Source: IAEA PRIS: International Atomic Energy Agency/Power Reactors Information System
2025 Edition – Nuclear Power Reactors in the World



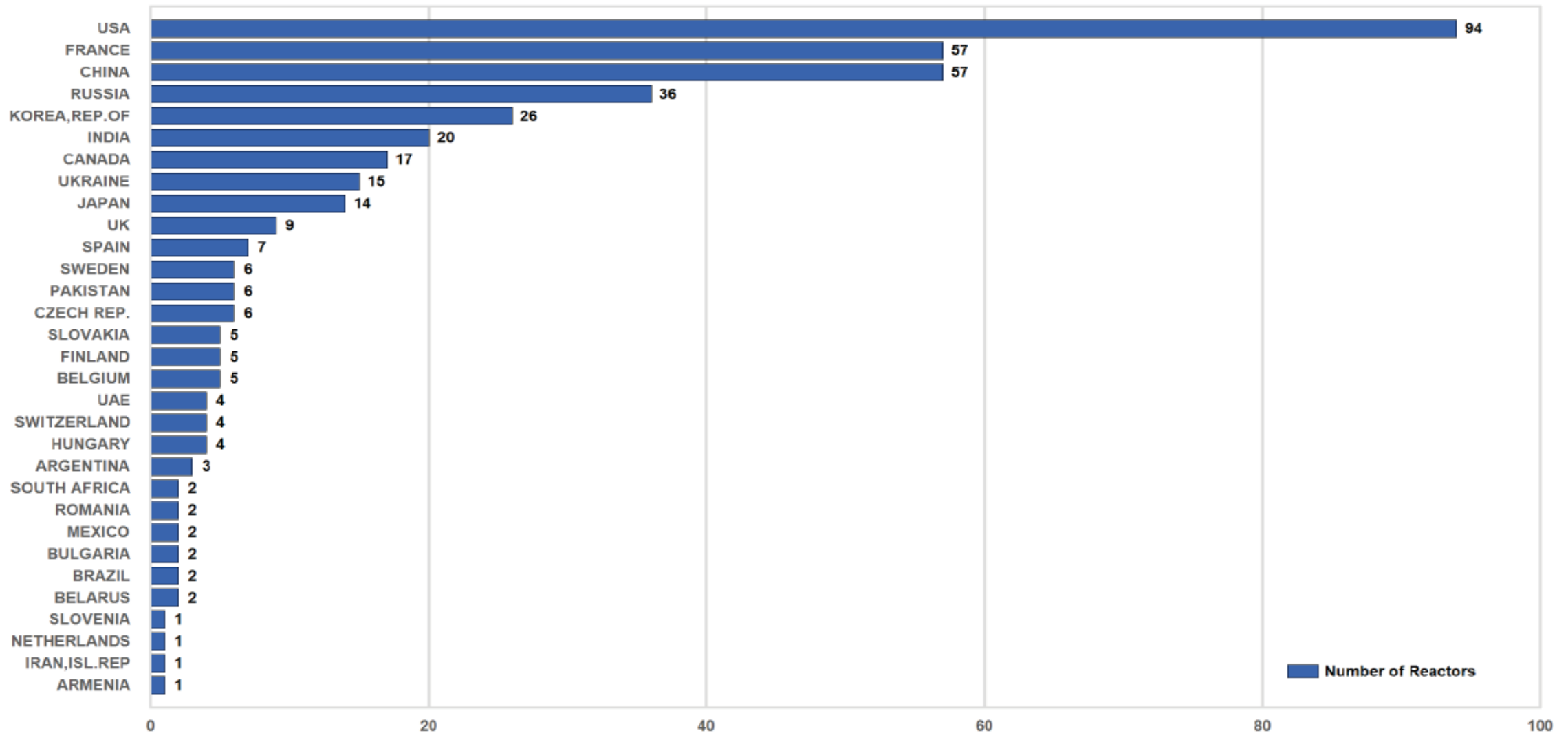
Reactor types in use worldwide end 2024: 417 Operational Plants



Source: IAEA PRIS: International Atomic Energy Agency/Power Reactors Information System
2025 Edition – Nuclear Power Reactors in the World



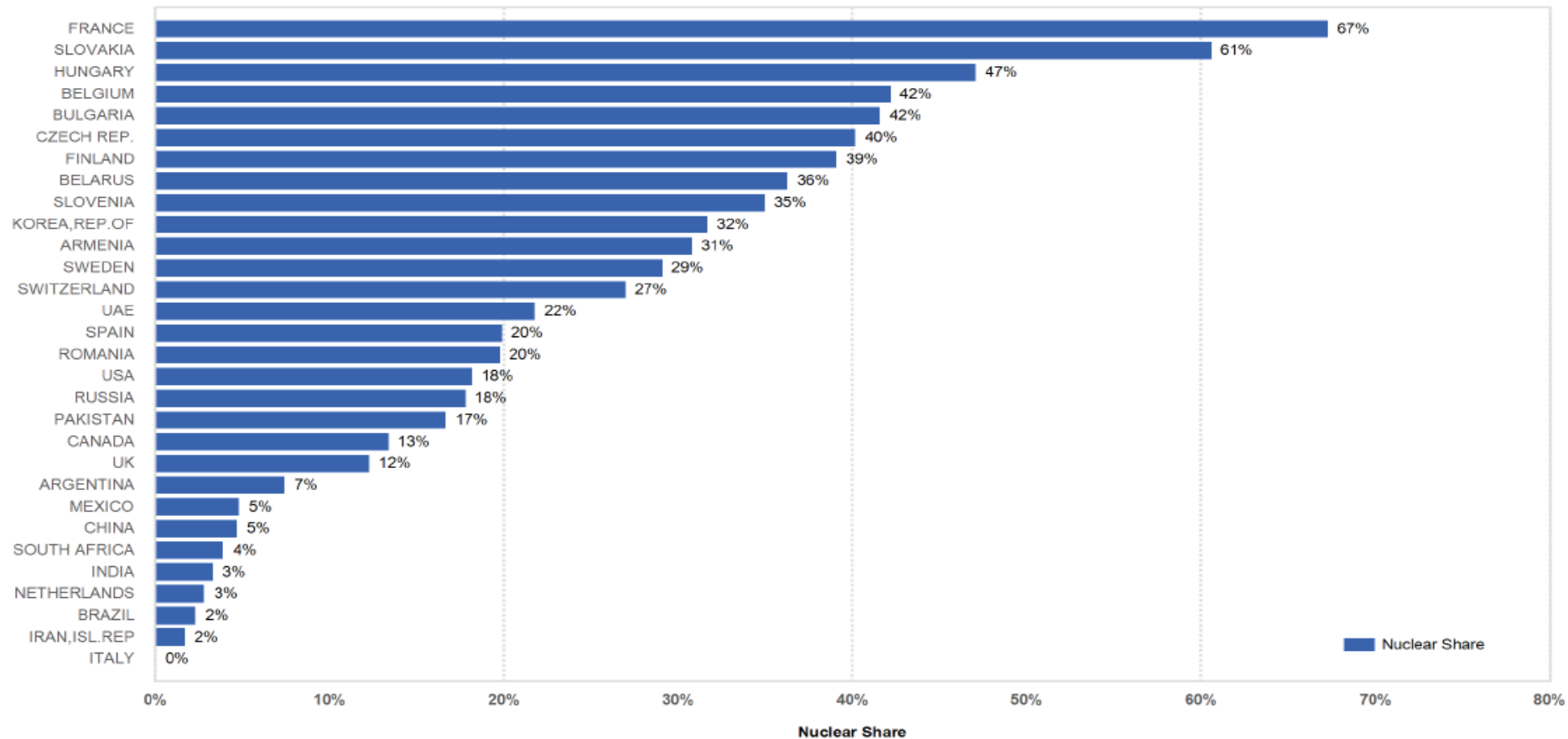
Number of Reactors in operation worldwide end 2024



Source: IAEA PRIS: International Atomic Energy Agency/Power Reactors Information System
2025 Edition – Nuclear Power Reactors in the World



Nuclear share of Electricity Generation end 2024



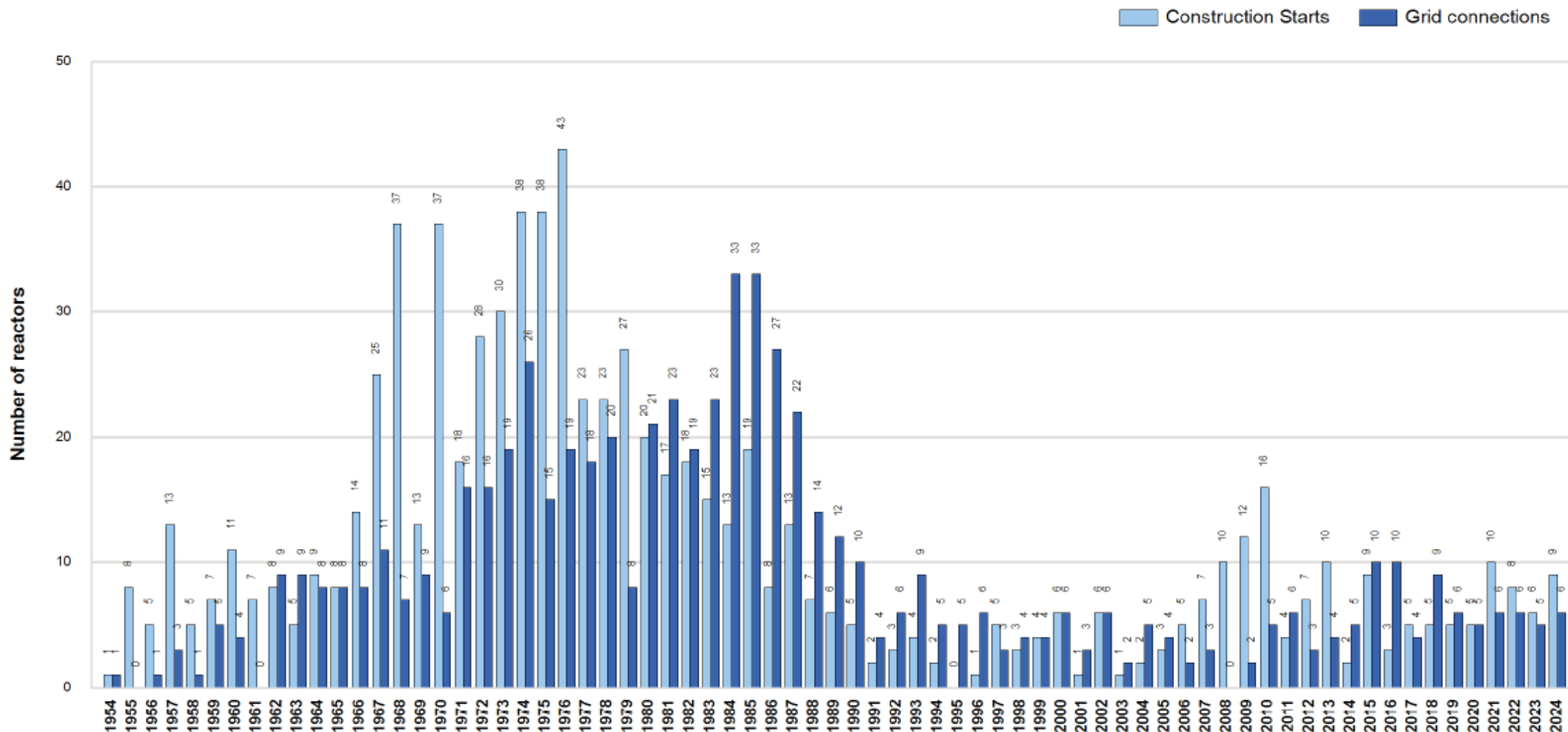
Note:

1. The nuclear share of electricity supplied in Taiwan, China was 4.6% of the total.
2. The graph does not include the nuclear share from Japan as country energy data were not submitted for the year 2024 by the time of publication. The nuclear share in 2023 was 5.6%.
3. The graph does not do not include the nuclear share from Ukraine as 2022, 2023 and 2024 country energy data were not reported by the time of publication.

Source: IAEA PRIS: International Atomic Energy Agency/Power Reactors Information System
2025 Edition – Nuclear Power Reactors in the World



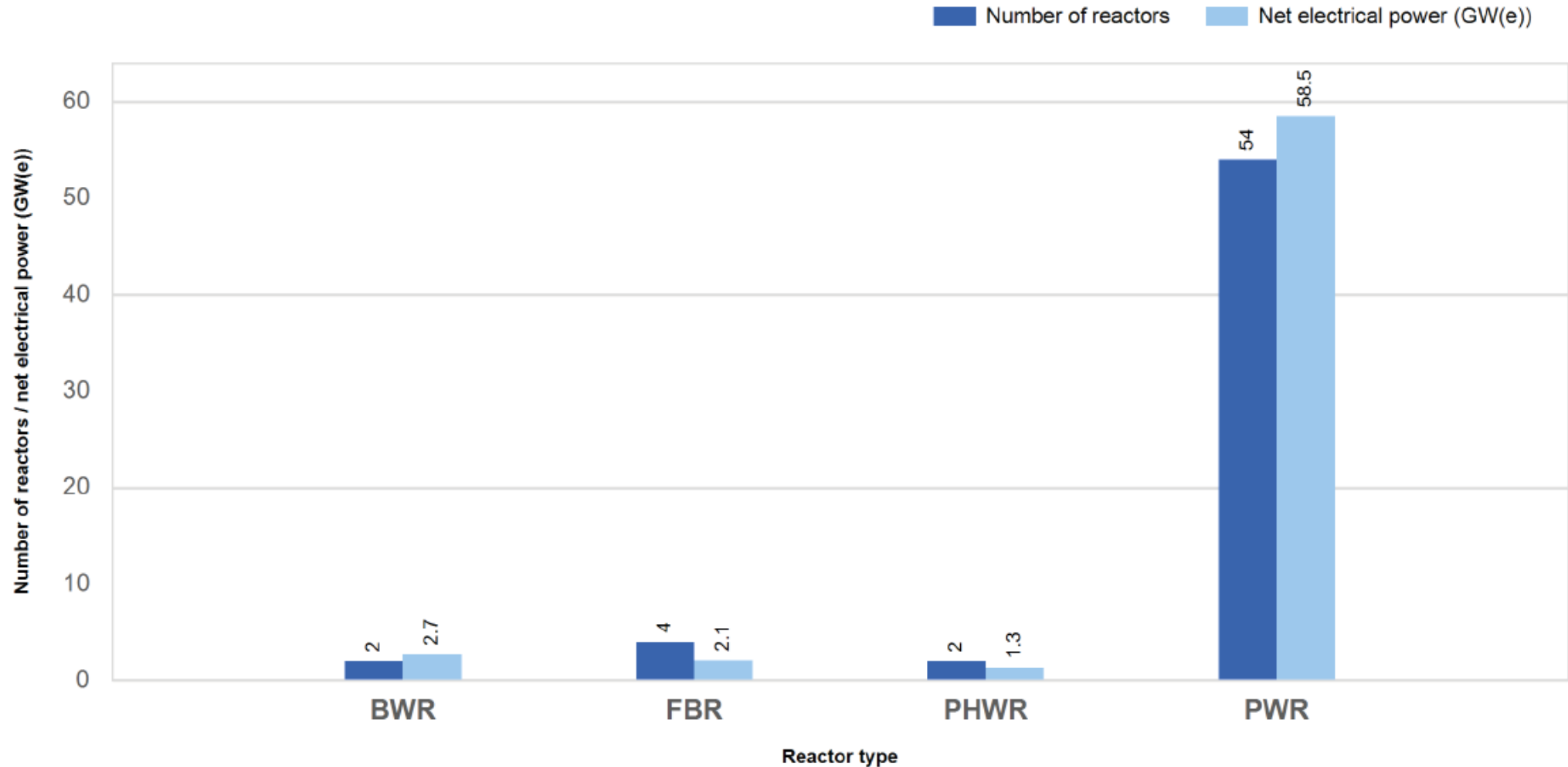
Annual Construction starts & Grid connections- 1954 - 2024



Source: IAEA PRIS: International Atomic Energy Agency/Power Reactors Information System
2025 Edition – Nuclear Power Reactors in the World



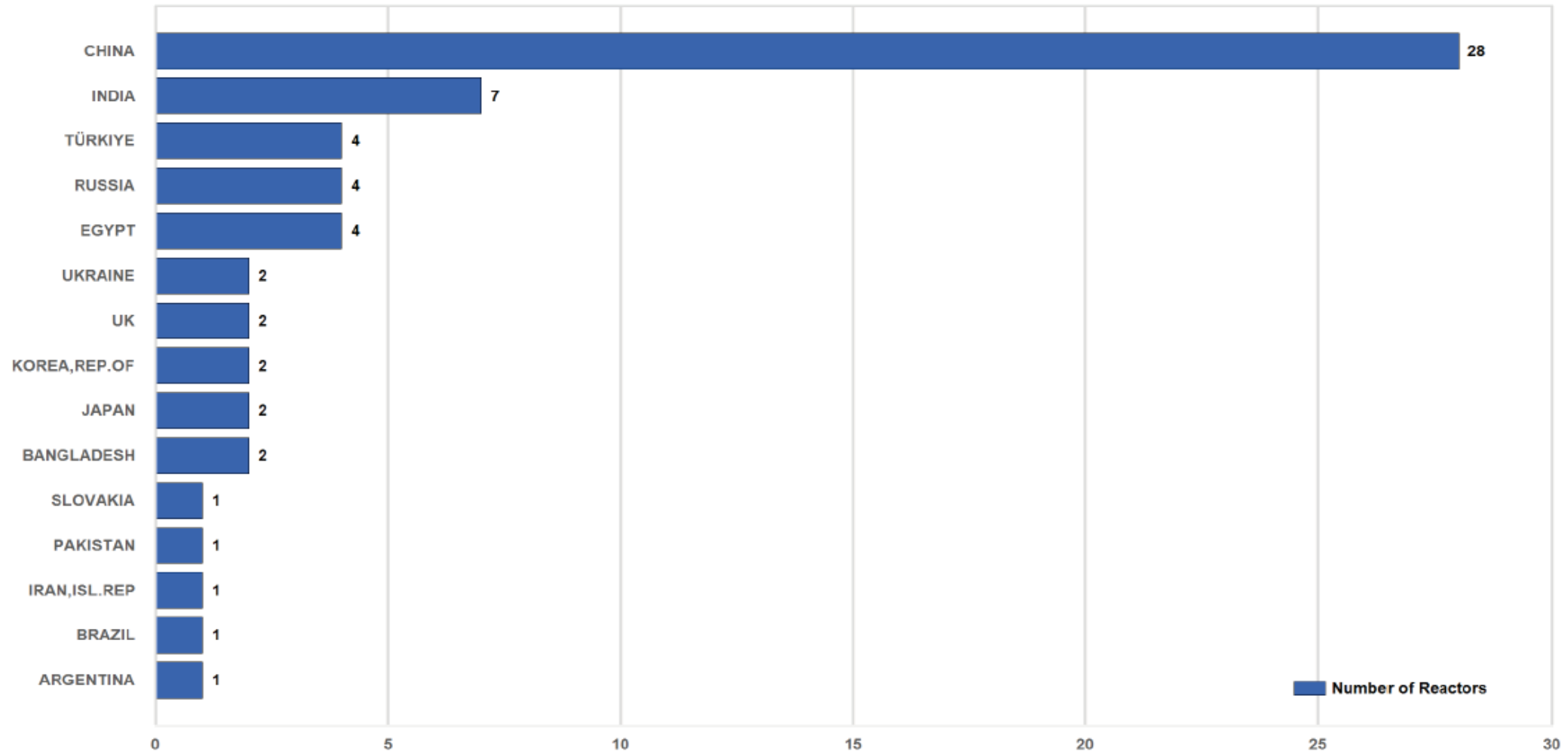
Number of Reactors under construction & Net Power worldwide end 2024



Source: IAEA PRIS: International Atomic Energy Agency/Power Reactors Information System
2025 Edition – Nuclear Power Reactors in the World



Number of Reactors under construction worldwide end 2024



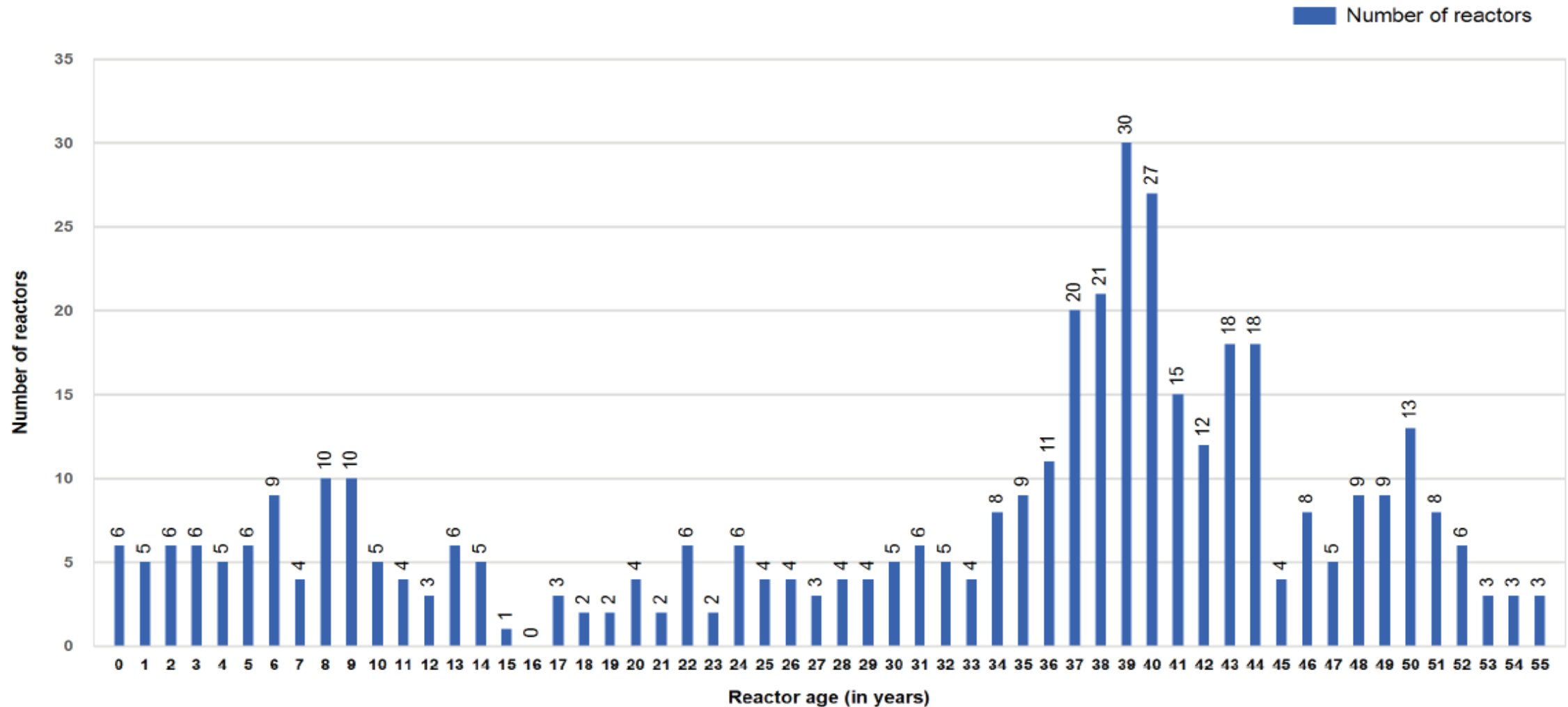
Source: IAEA PRIS: International Atomic Energy Agency/Power Reactors Information System
2025 Edition – Nuclear Power Reactors in the World



Nuclear Industry – Reactors by age



Number of operational Reactors by age end 2024



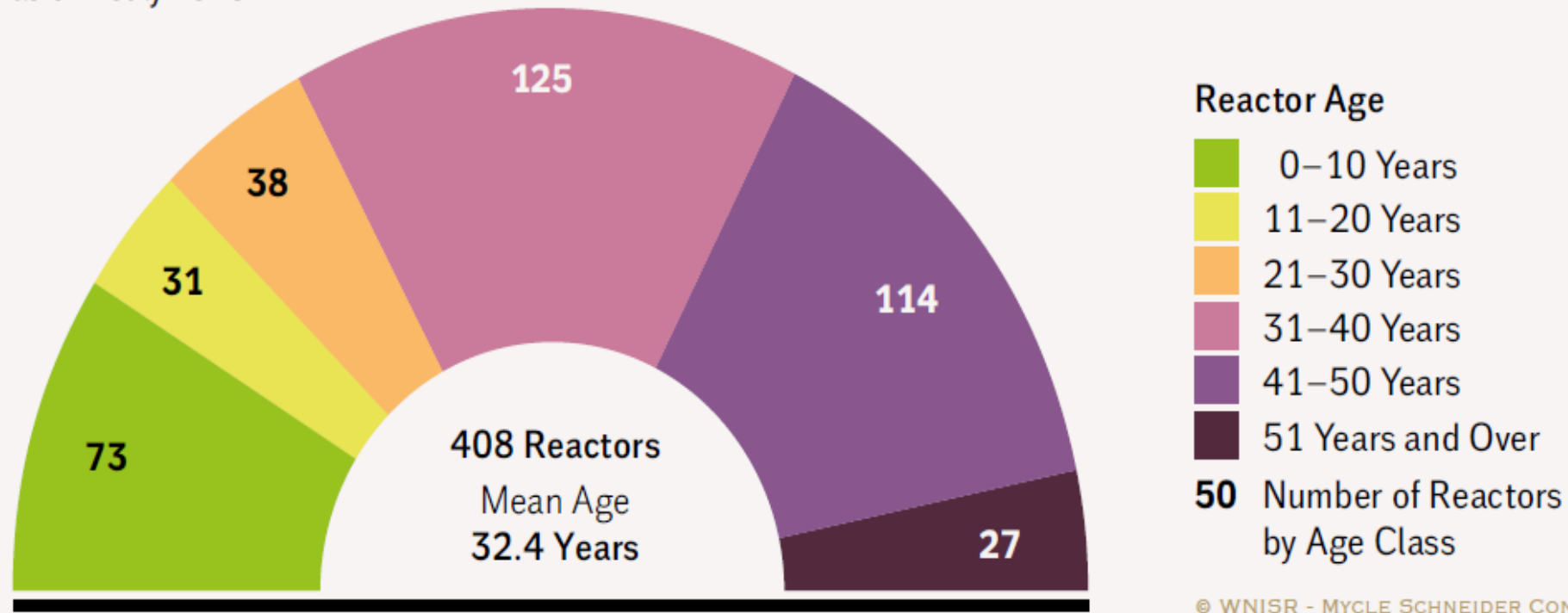
Source: IAEA PRIS: International Atomic Energy Agency/Power Reactors Information System
2025 Edition – Nuclear Power Reactors in the World



Age of Nuclear Reactors as of 1st July 2025

Mean Age: 32 years

Age of World Nuclear Fleet
as of 1 July 2025

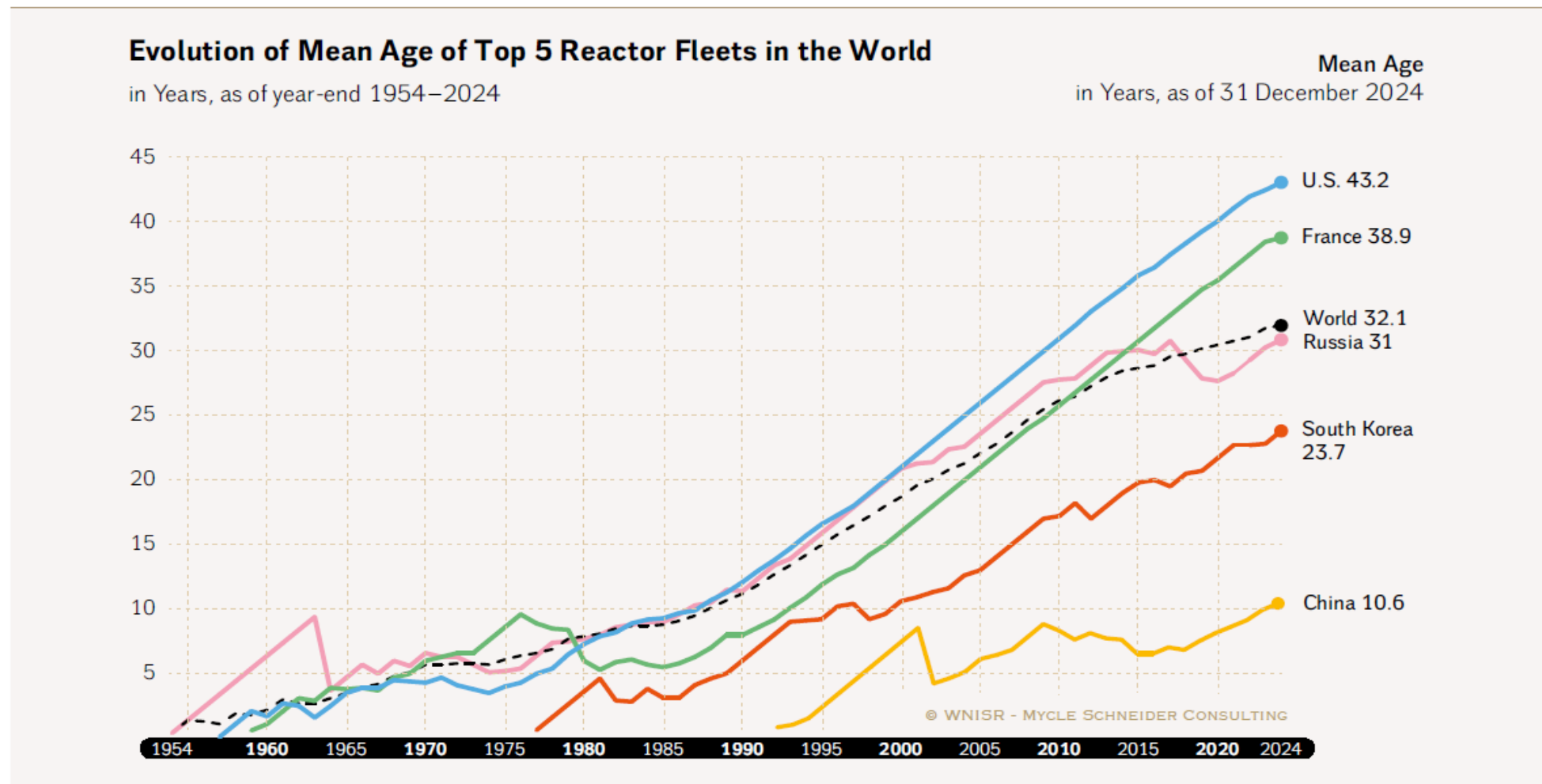


Sources: WNISR, with IAEA-PRIS, 2025

Source: Mycle Schneider
World Nuclear Industry Status Report (WNISR) IAEA-PRIS September 2025



Evolution of Mean Age of Nuclear Reactors



Sources: WNISR with IAEA-PRIS, 2025

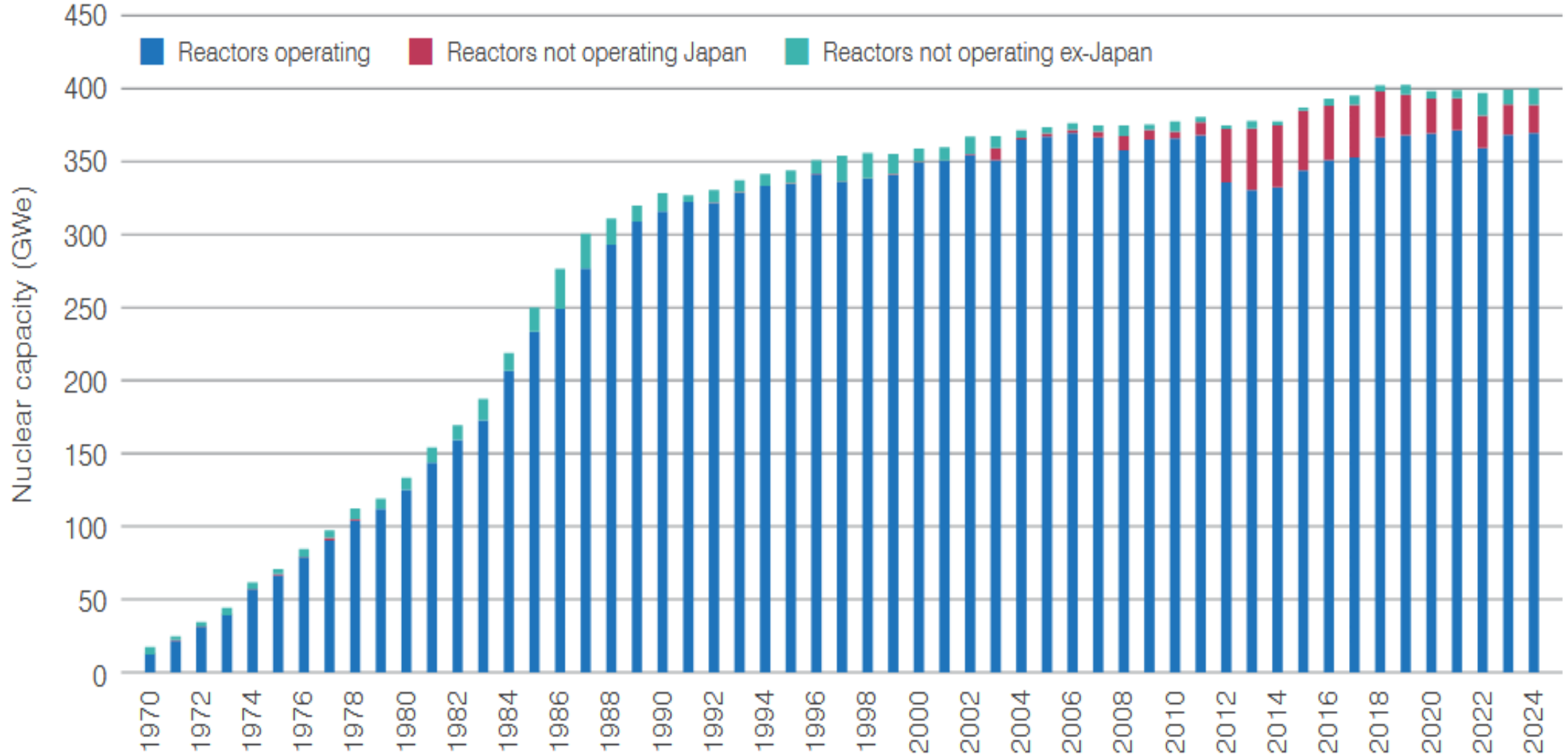
Source: Mycle Schneider
World Nuclear Industry Status Report (WNISR) IAEA-PRIS September 2024



Nuclear Industry - Capacity & Generation



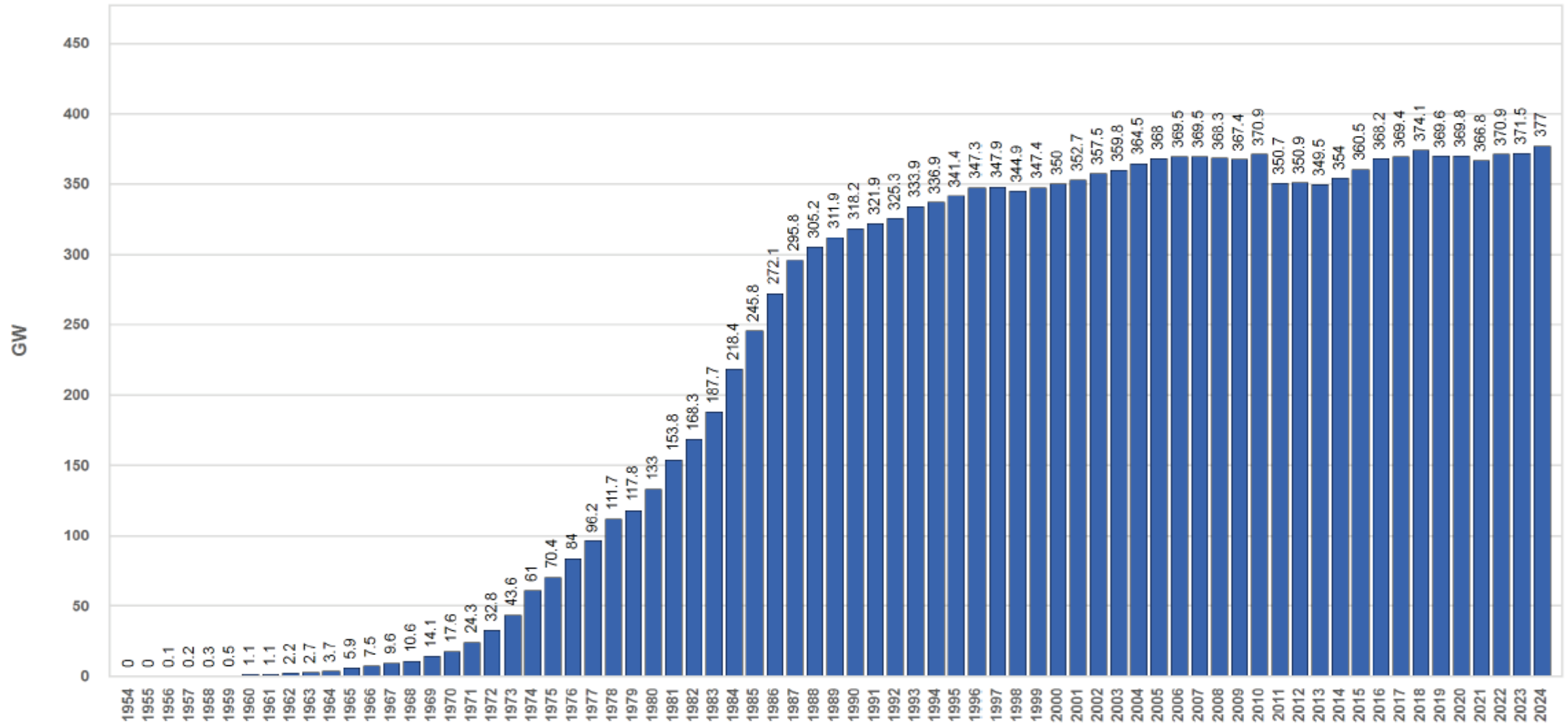
Historical evolution of worldwide Operable Nuclear Power Capacity



Source: World Nuclear Association, IAEA PRIS



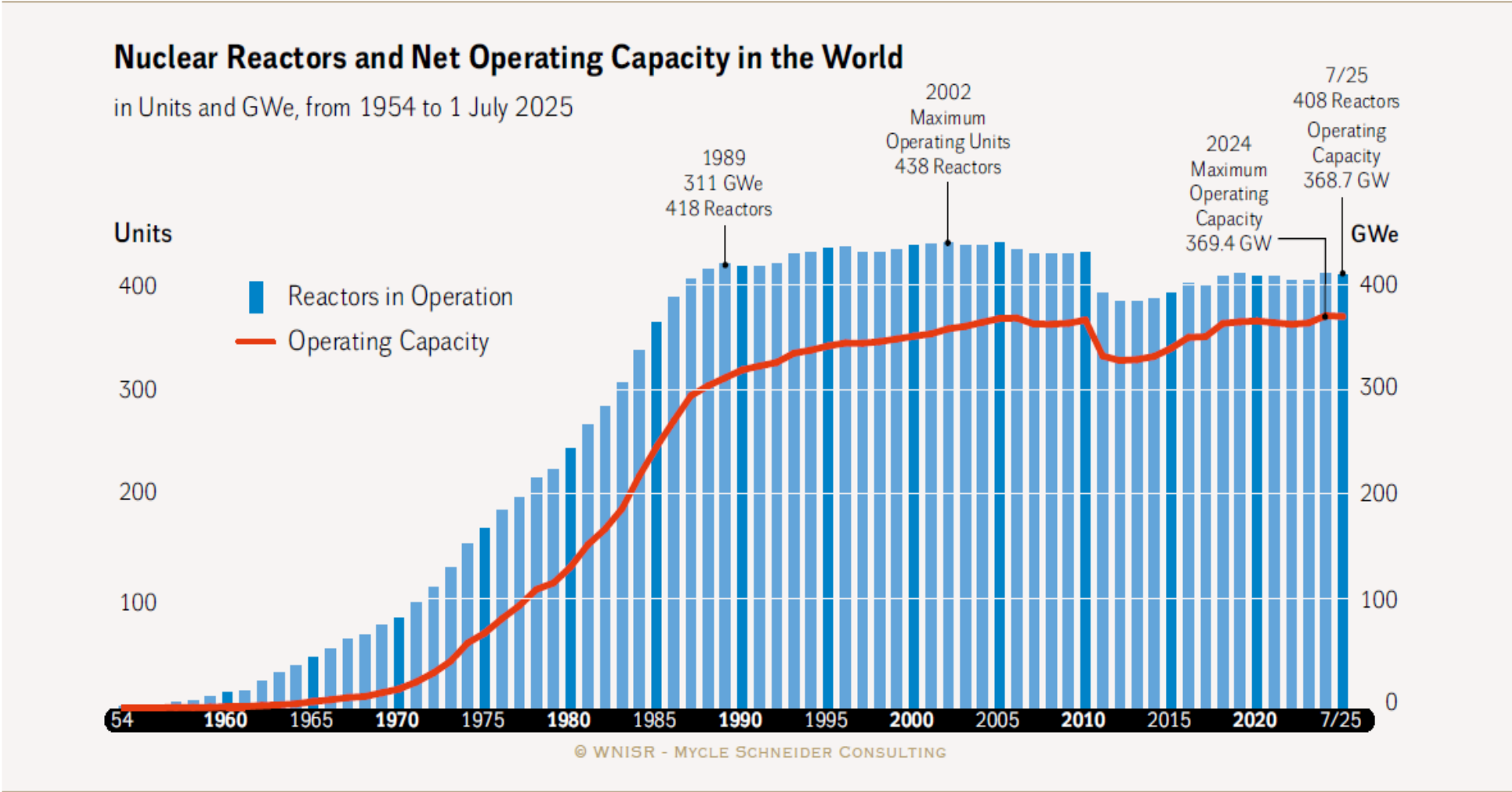
Historical evolution of worldwide Operational Nuclear Power Capacity



Source: IAEA PRIS: International Atomic Energy Agency/Power Reactors Information System
2025 Edition – Nuclear Power Reactors in the World



Nuclear Generation Capacity (Net) 1954 – July 2025



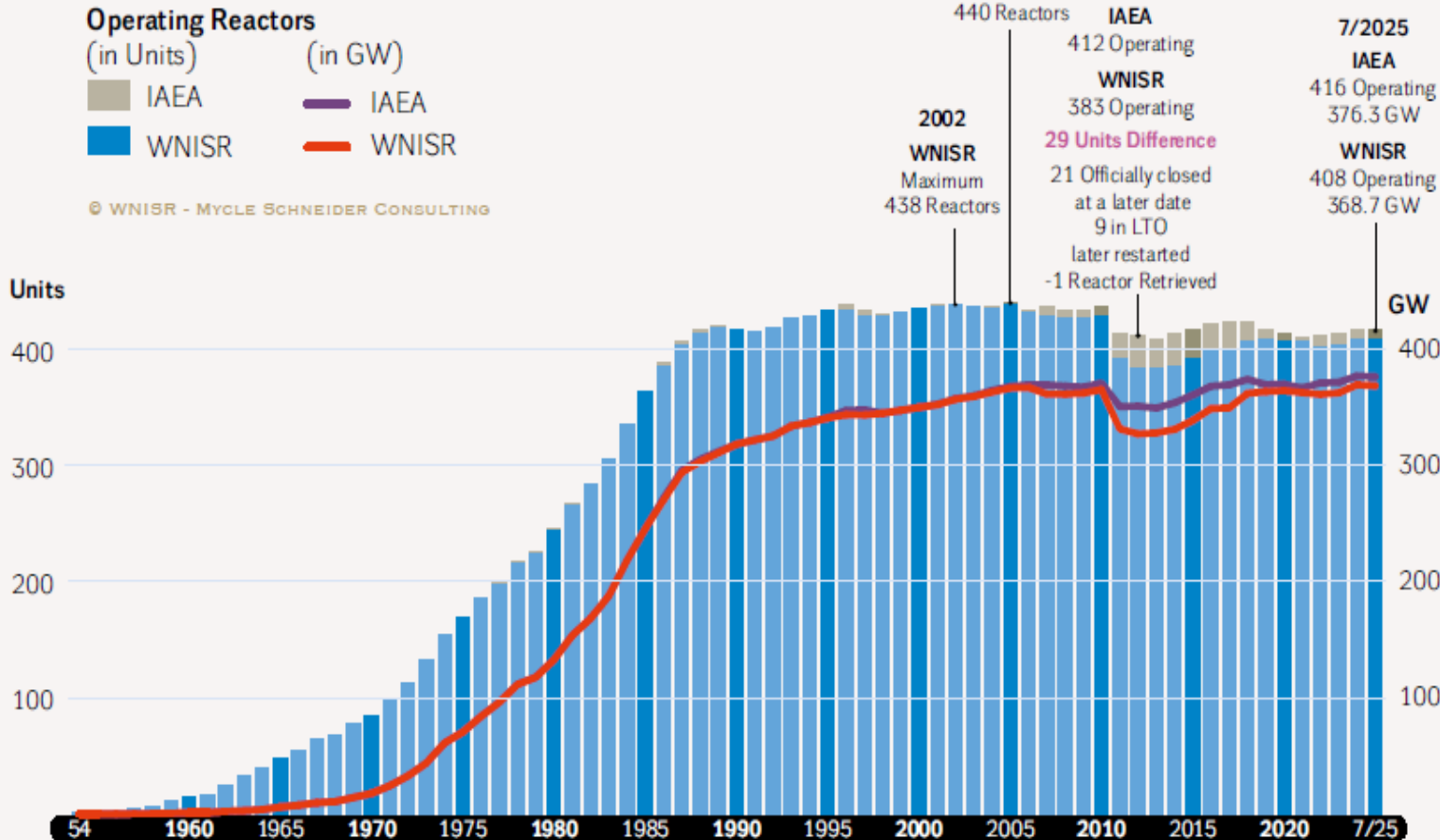
Sources: WNISR with IAEA-PRIS, 2025



Nuclear Generation Capacity (Net) 1954 – July 2025 vs WNISR assessment

Nuclear Reactors in the World Officially Operational vs. WNISR Assessment

in Units and in GW, as of year-end 1954–2024, and mid-2025



Notes:

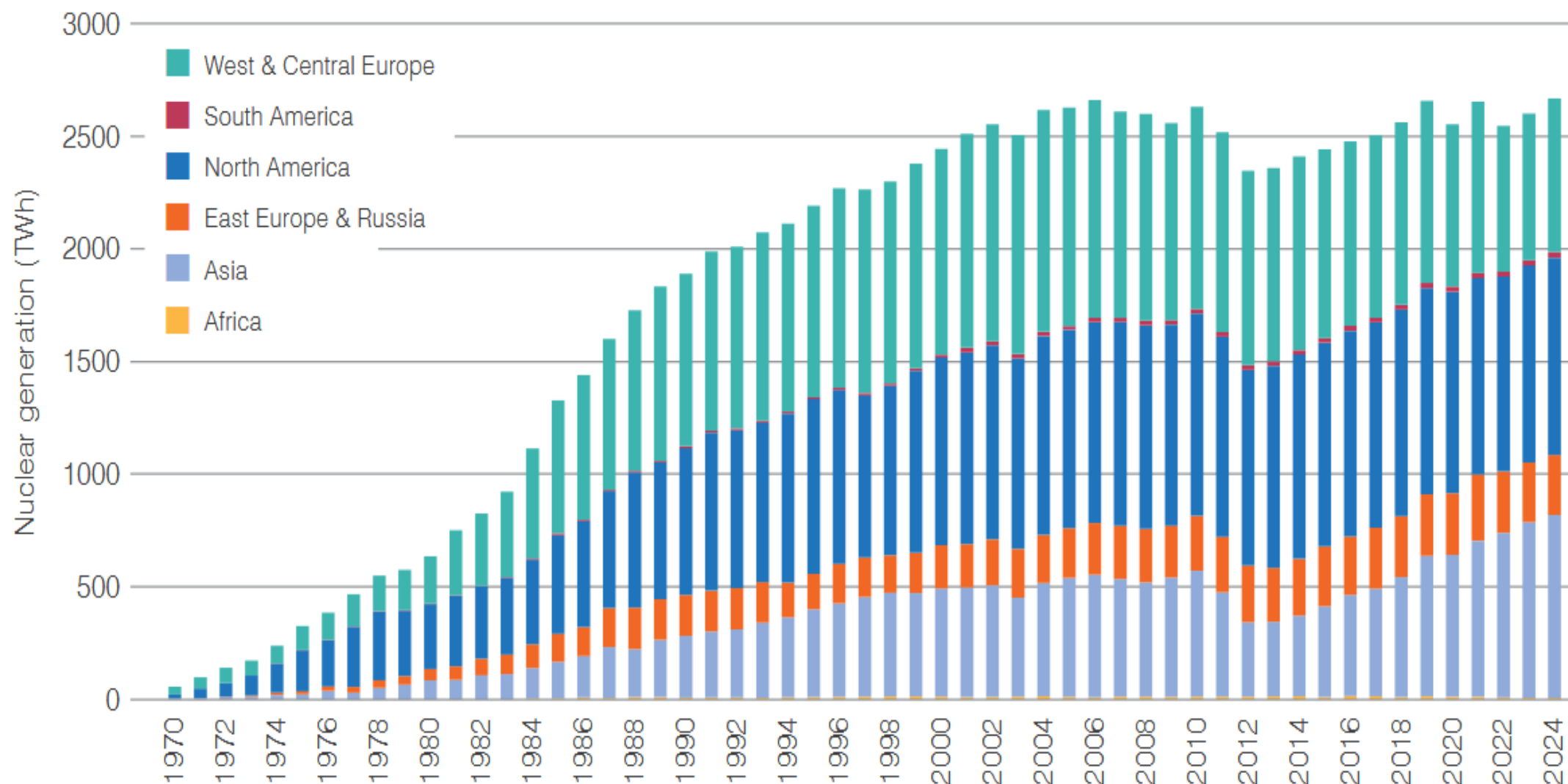
The IAEA data used for this graph includes at least three reactors that have been later withdrawn from the PRIS statistics for operating reactors (Niederaichbach, VAK-Kahl and HDR Großwelzheim, in Germany, now only appearing as “Decommissioning Completed”). On the other hand, the Swiss research reactor in Lucens is not included.

Reactors classified as in “Suspended Operation” by the IAEA are not represented here.

Although the total number of reactors in operation according to WNISR statistics has always remained, albeit slightly, inferior to IAEA-PRIS data, it contains several Chinese reactors not accounted for in PRIS.



Historical evolution of worldwide Electricity Generation

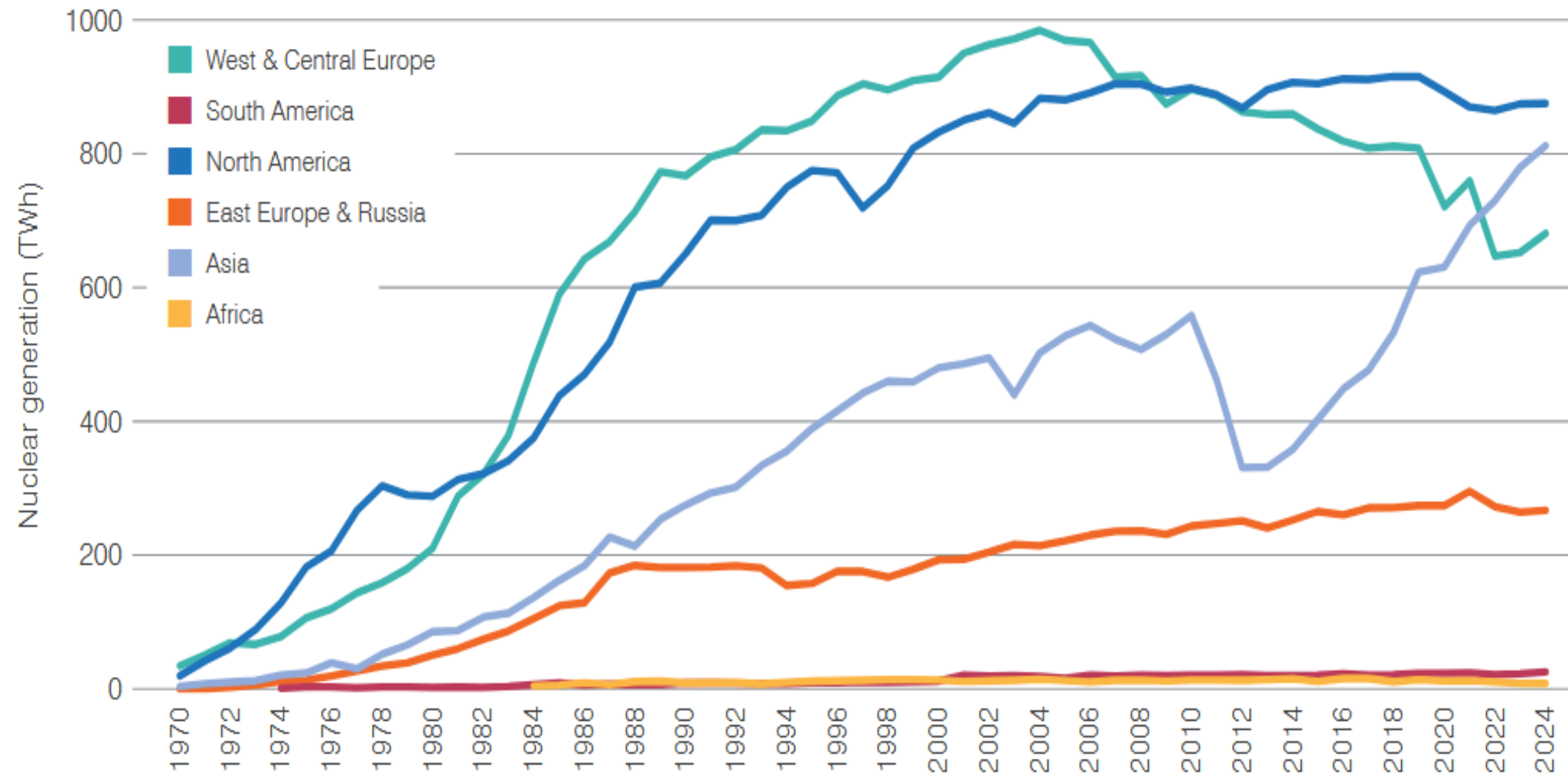


Source: World Nuclear Association and IAEA Power Reactor Information Service (PRIS)

Source: WNA World Nuclear Performance Report 2025



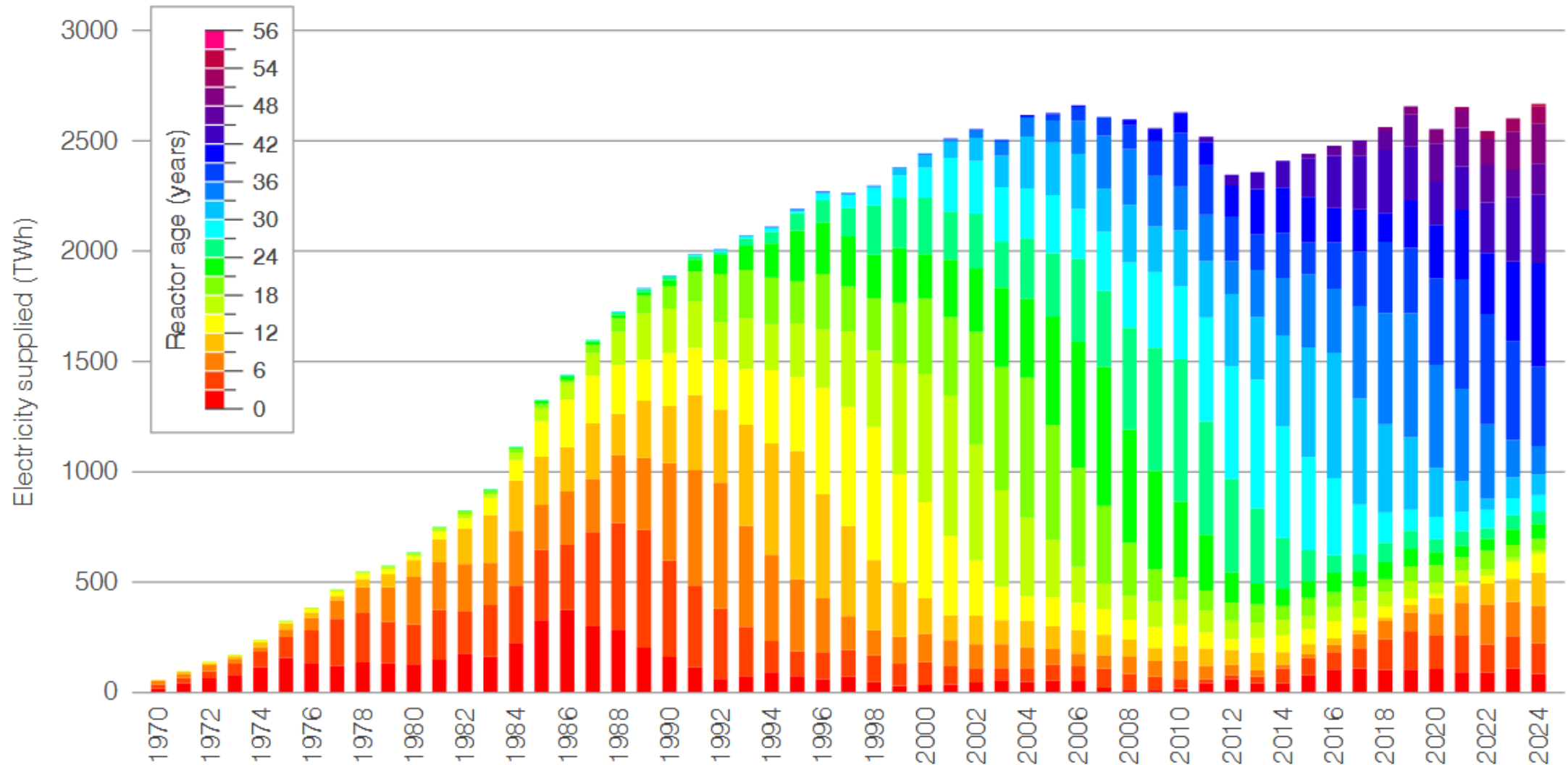
Evolution of worldwide Electricity Generation by Regions



Source: World Nuclear Association, IAEA PRIS



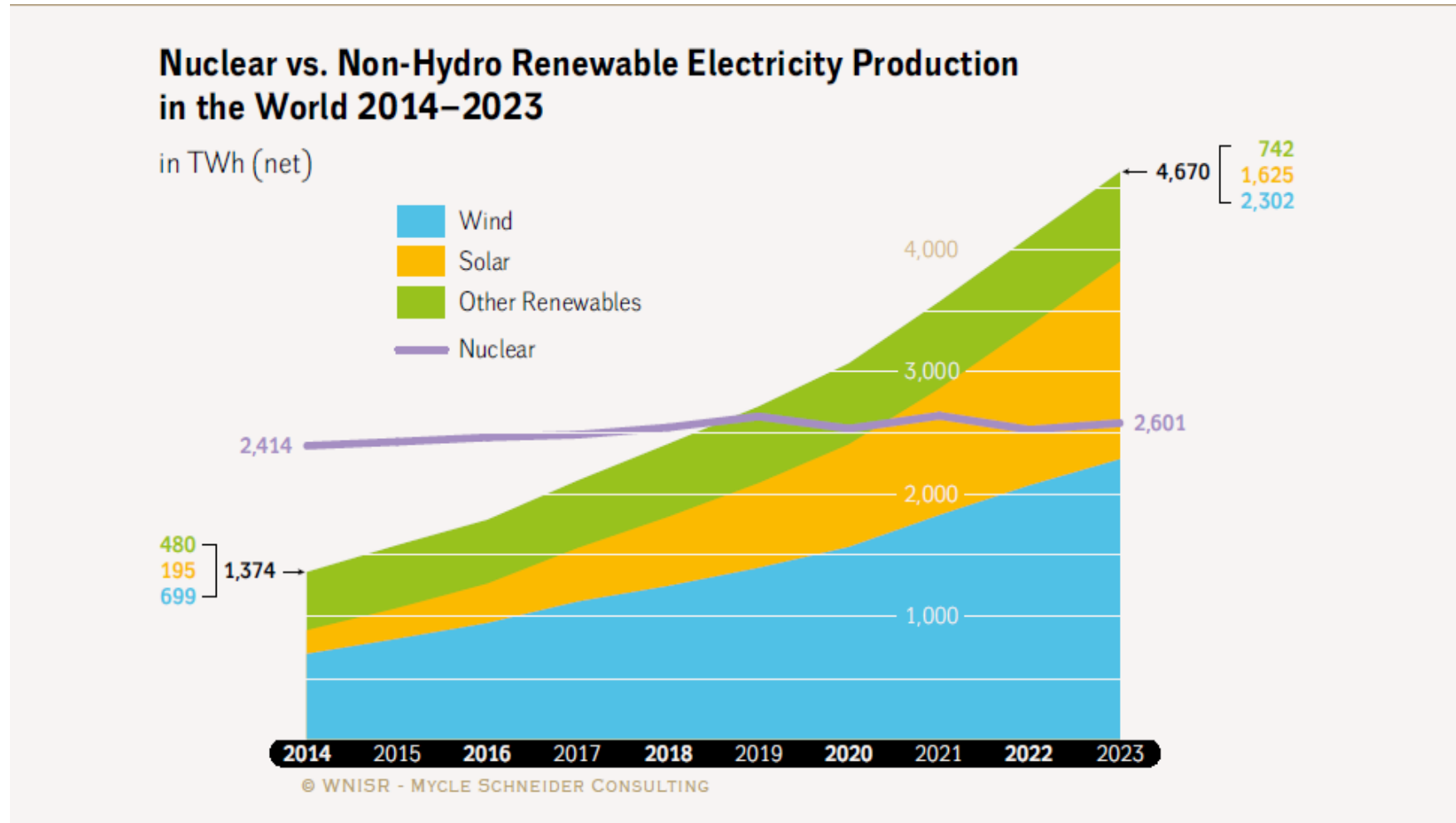
Evolution of worldwide Electricity Generation by age of reactors



Source: World Nuclear Association, IAEA PRIS



Nuclear Electricity vs Non-hydro Electricity Production in the World 2014 – 2023 - # 2600 TWh in 2023 # Stability



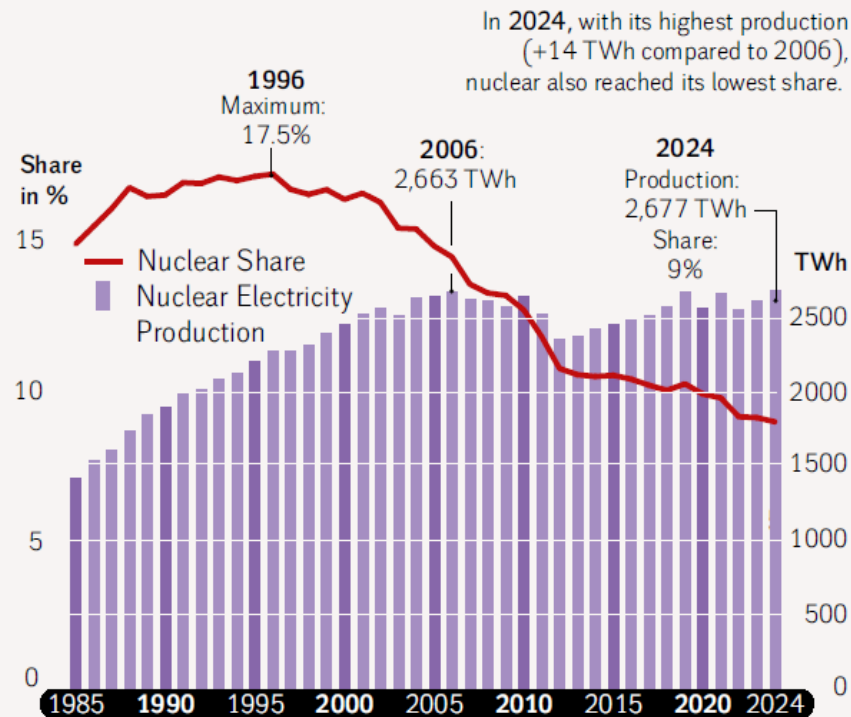
Sources: Energy Institute, 2024



Nuclear Electricity Production in the World 1985 – 2024 - # 2680 TWh in 2024

Nuclear Electricity Production 1985–2024 in the World...

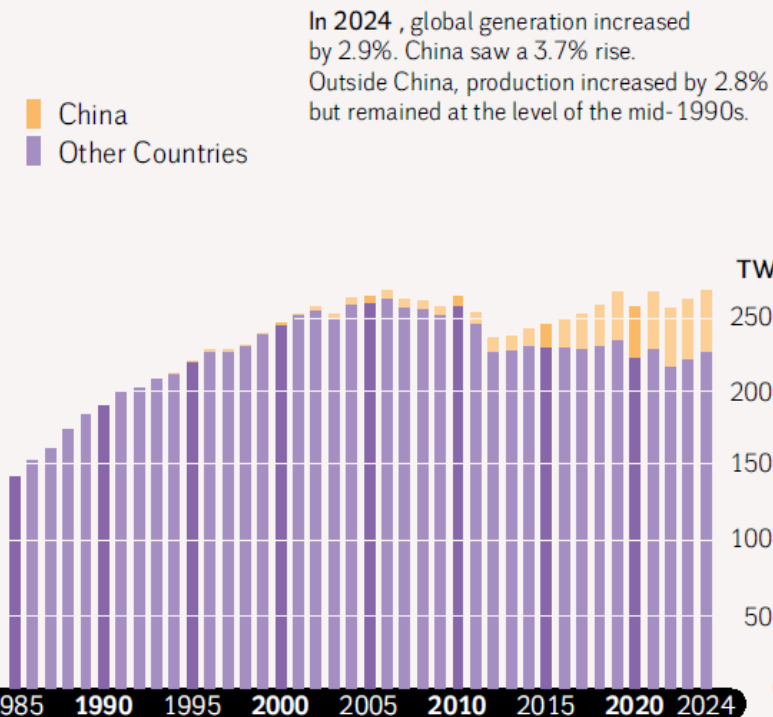
in TWh (net) and Share in Electricity Generation (gross)



© WNISR - MYCLE SCHNEIDER CONSULTING

...and in China and the Rest of the World

in TWh (net)



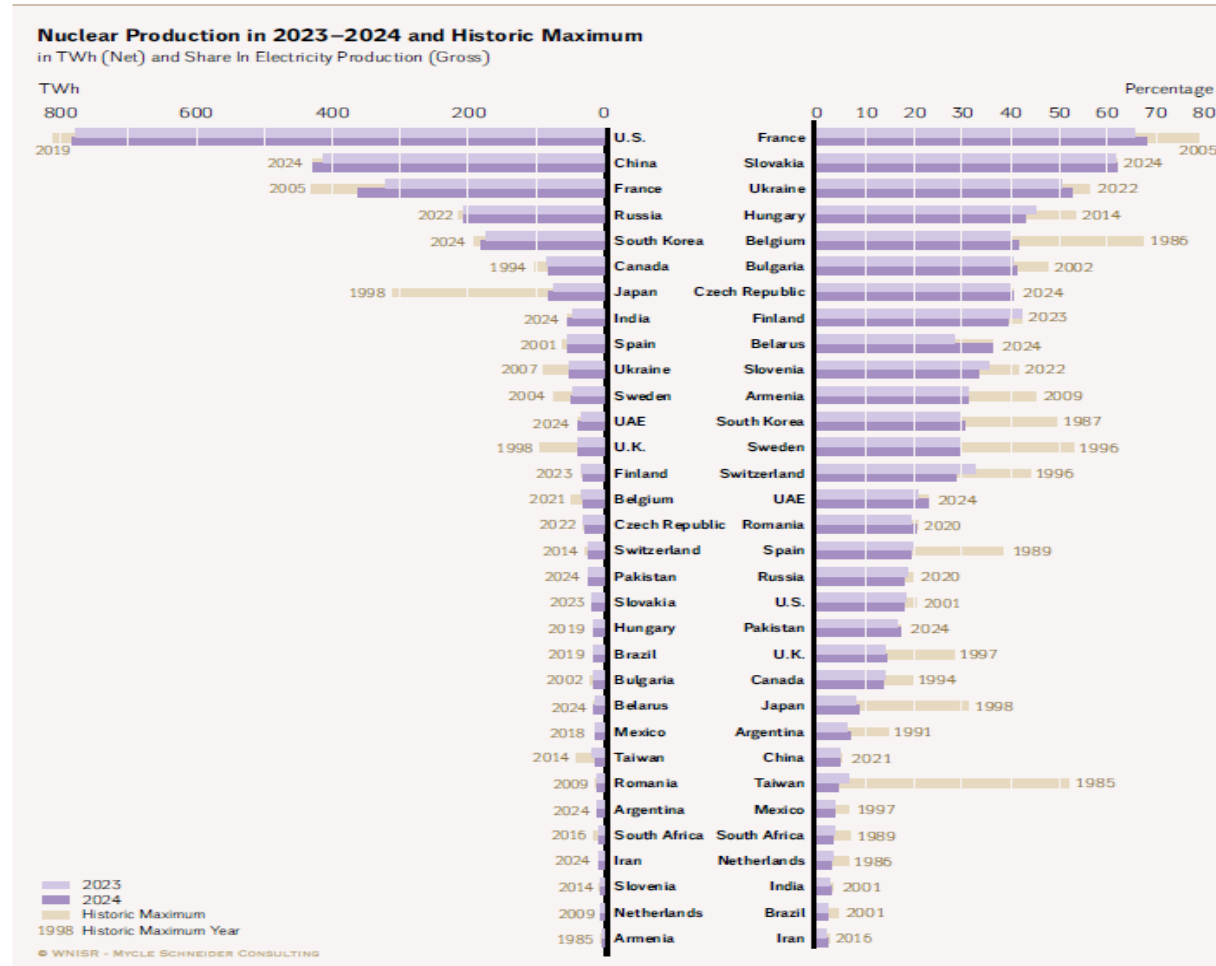
© WNISR - MYCLE SCHNEIDER CONSULTING

Sources: WNISR with Energy Institute, 2025

Source: Mycle Schneider
WNISR, IAEA-PRIS September 2025



Nuclear Electricity Production in the World 2023 – 2024 and historic maximum (TWh)



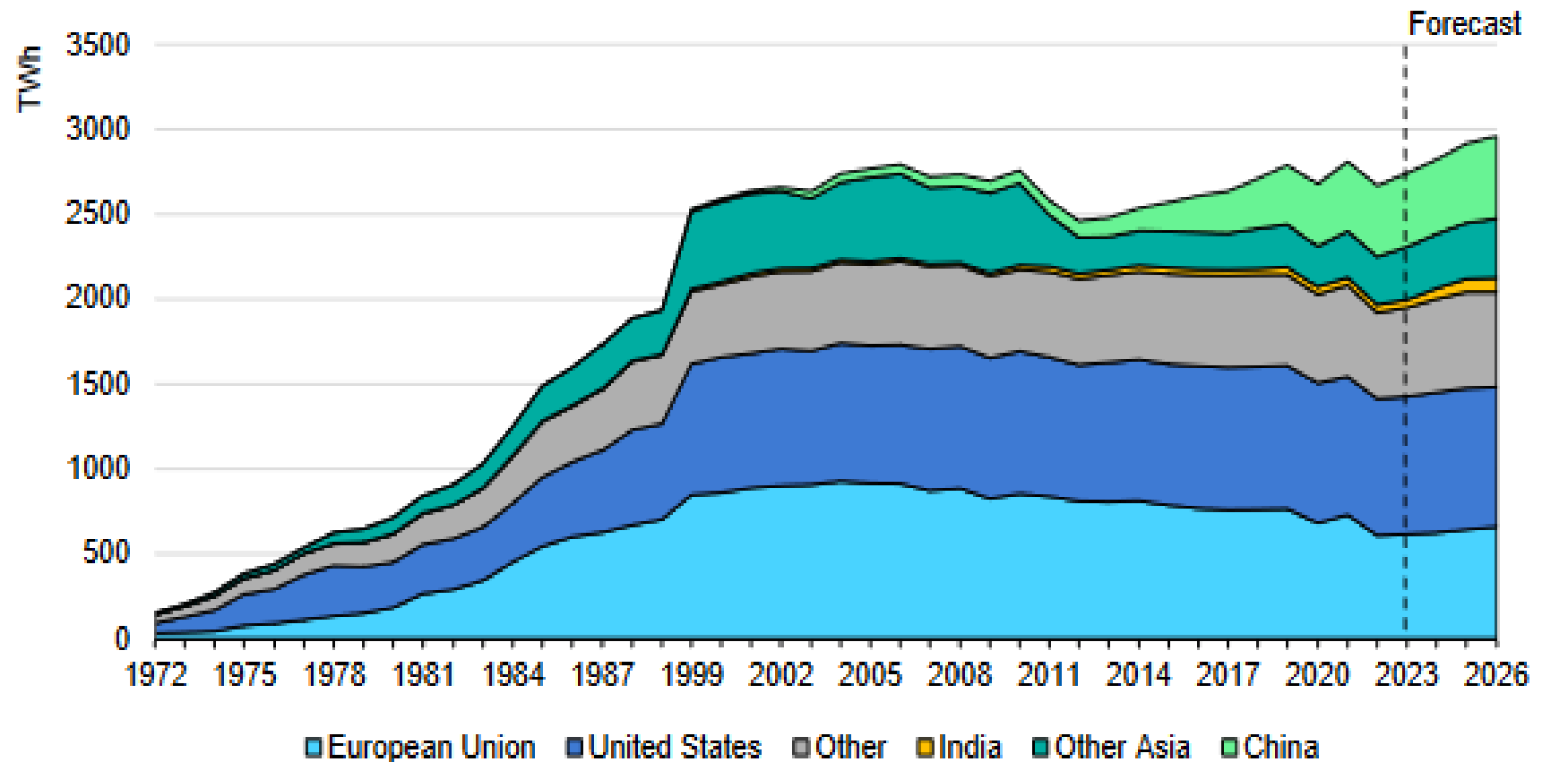
Sources: compiled by WNISR with Energy Institute, 2025

Notes: For comparison reasons, data used in this graphic are Energy Institute data¹, and may differ from data used in the country sections.
 Production: in TWh net; Share: calculated from gross data (nuclear and total generation), except for Armenia (IAEA-PRIS).

Source: Mycle Schneider
 WNISR, IAEA-PRIS September 2025



Nuclear Electricity Generation by Regions in the World 1972 – 2026 - # 3000 TWh in 2026



IEA. CC BY 4.0

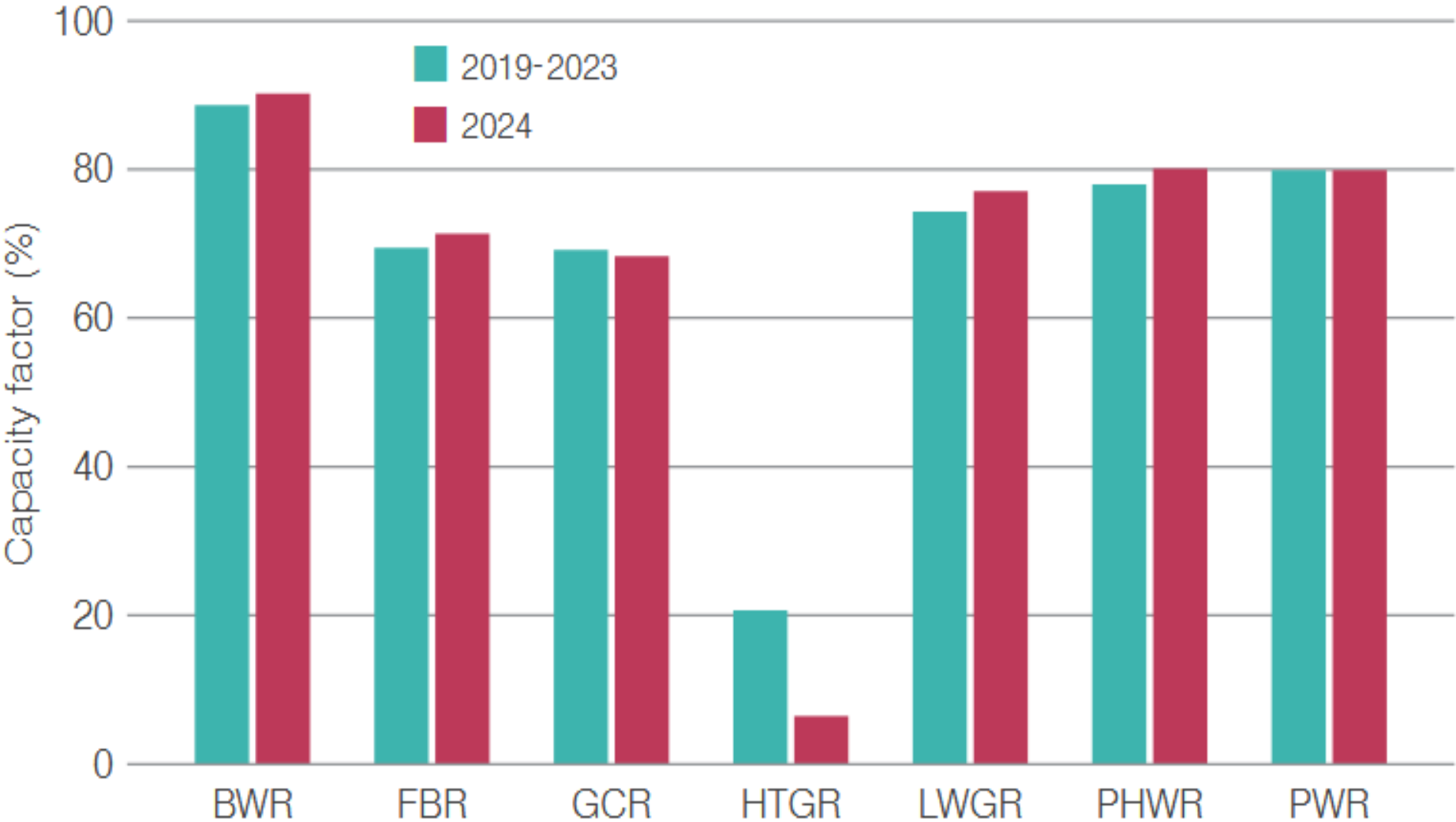
Note: The 2026 forecast is based on projects currently under construction and expected to be operational by the end of the period.



Capacity factors



Capacity Factors by Reactor type - Mean # 80 % in 2024



Source: World Nuclear Association, IAEA PRIS



Capacity Factors by Regions - Mean # 80 % in 2024

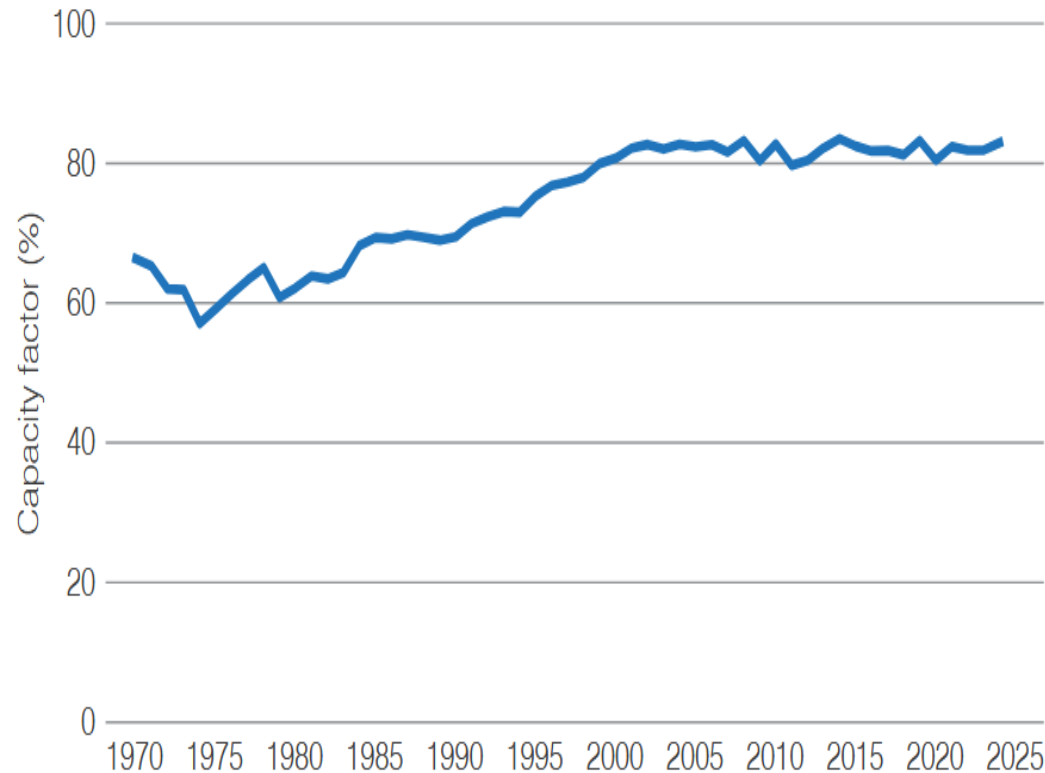


Source: World Nuclear Association, IAEA PRIS



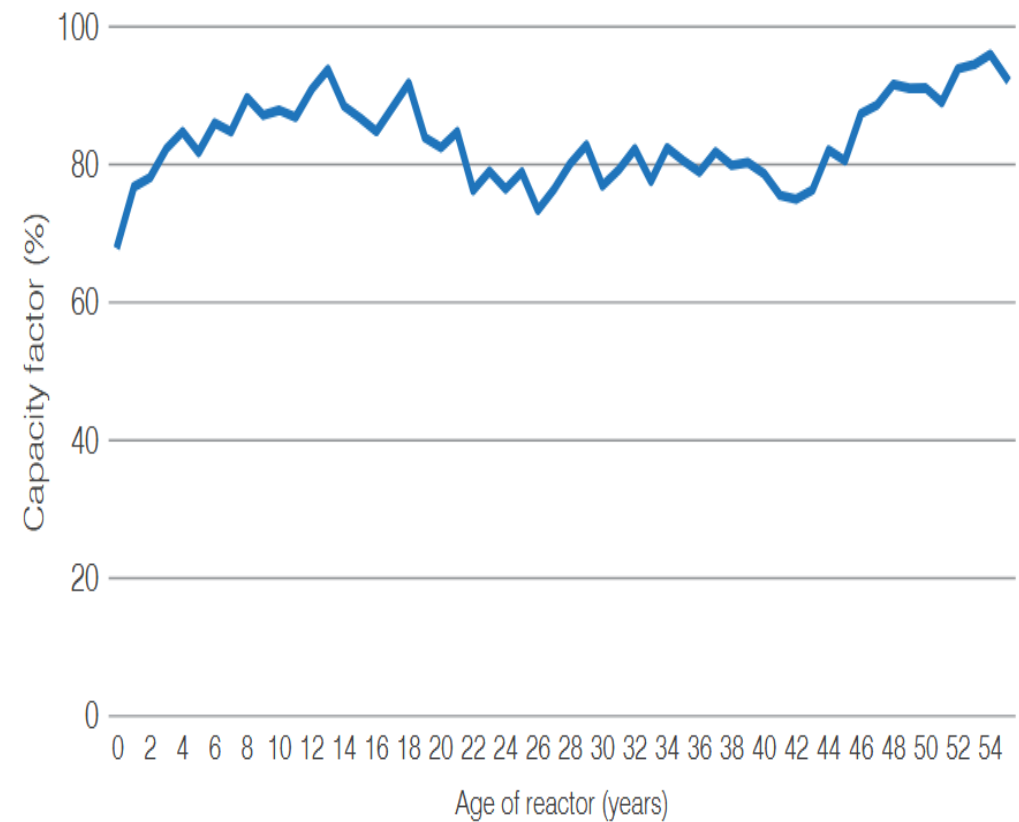
Capacity Factors: > 80%

Evolution 1970 – 2025
80% in 2024



Source: World Nuclear Association, IAEA PRIS

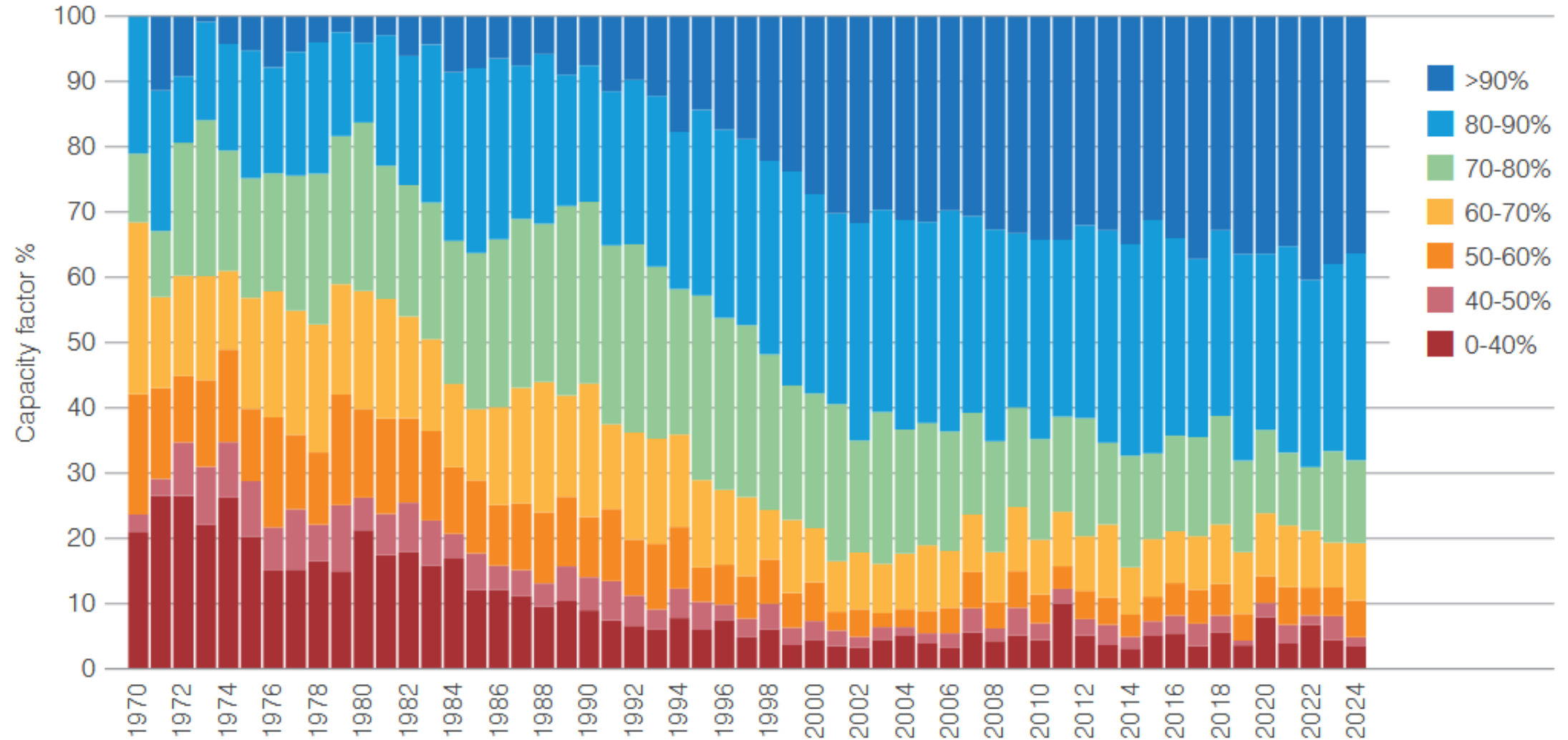
By age of reactors
Mean 2019 - 2024



Source: World Nuclear Association, IAEA PRIS



Long Term Trends in Capacity Factors



Source: World Nuclear Association, IAEA PRIS



Nuclear Industry – Reactors Constructions

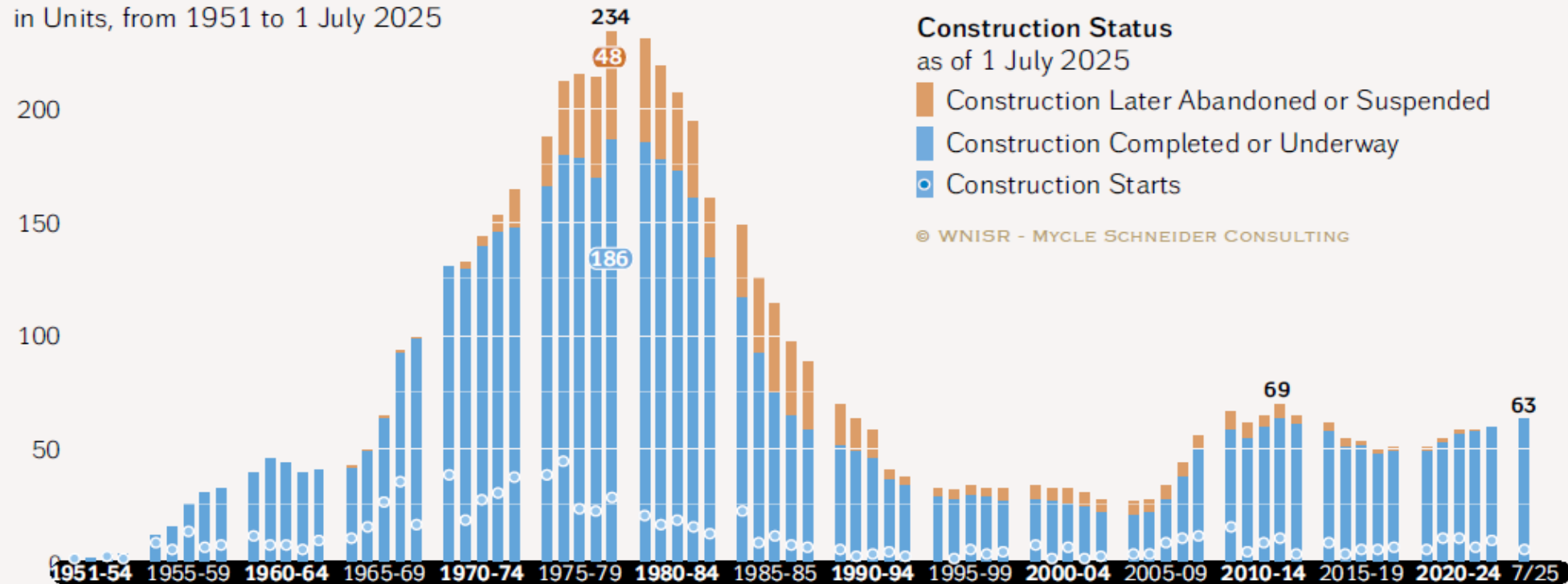


Nuclear Reactors Constructions 1951 – July 2025

Dynamic Activity 1970-1985 - Rebound after 2006

Reactors Under Construction in the World

in Units, from 1951 to 1 July 2025



Sources: WNISR, with IAEA-PRIS, 2025

Notes: This figure includes construction of two CAP1400 reactors at Rongcheng/Shidaowan, although their construction has not been communicated by the IAEA, one of which has been connected to the grid in October 2024 (see [China Focus](#)).

Source: Mycle Schneider
WNISR, IAEA-PRIS September 2025

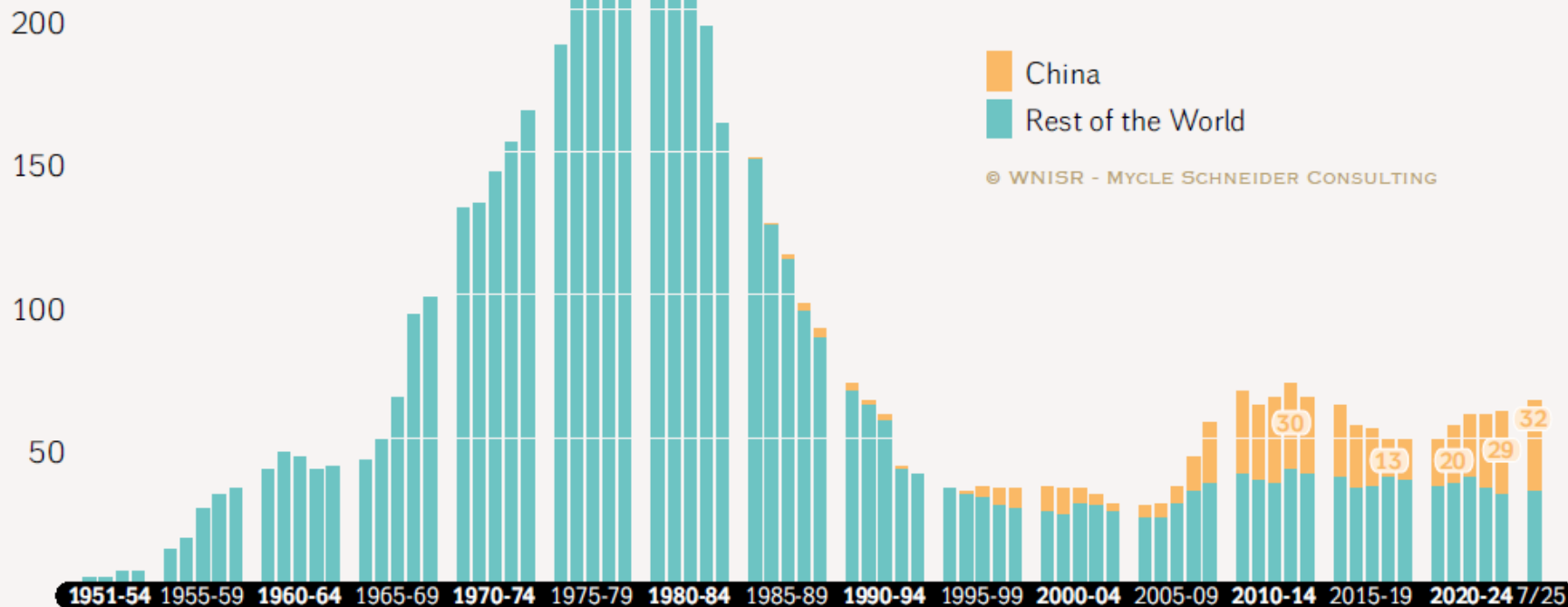


Nuclear Reactors Constructions 1951 – July 2024

The role of China

Reactors Under Construction in the World

in Units, from 1951 to 1 July 2025



Sources: WNISR with IAEA-PRIS, 2025

Source: Mycle Schneider
WNISR, IAEA-PRIS September 2025



Nuclear Reactors under Construction as of July 2025

Country	Units (Domestic Design)	Other Vendor	Capacity (MW net)	Construction Start	Grid Connection	Units Behind Schedule
China	32 (28)	Russia: 4	34 512	2017 – 2025	2025 – 2030	1 (2?)
Russia	7 (7)	–	5 110	2018 – 2025	2025 – 2032	3 (5?)
India	6 (2)	Russia: 4	4 768	2004 – 2021	2026 – 2028	6
Türkiye	4 (–)	Russia: 4	4 456	2018 – 2022	2026 – 2029	4
Egypt	4 (–)	Russia: 4	4 400	2022 – 2024	2028 – 2031	–
South Korea	3 (3)	–	4 020	2017 – 2025	2026 – 2032	2
Bangladesh	2 (–)	Russia: 2	2 160	2017 – 2018	2025 – 2027	2
U.K.	2 (–)	France: 2	3 260	2018 – 2019	2030 – 2031	2
Slovakia	1 (–)	Russia: 1 ^(a)	440	1985	2025	1
Iran	1 (–)	Russia: 1	974	1976	2029	1
Pakistan	1 (–)	China: 1	1 117	2024	2030	
Total	63		65 217	1976 – 2025	2025 – 2032	22 (26?)
Total per Vendor Country: Russia: 27 – China: 29 – South Korea: 3 – France: 2 – India: 2						

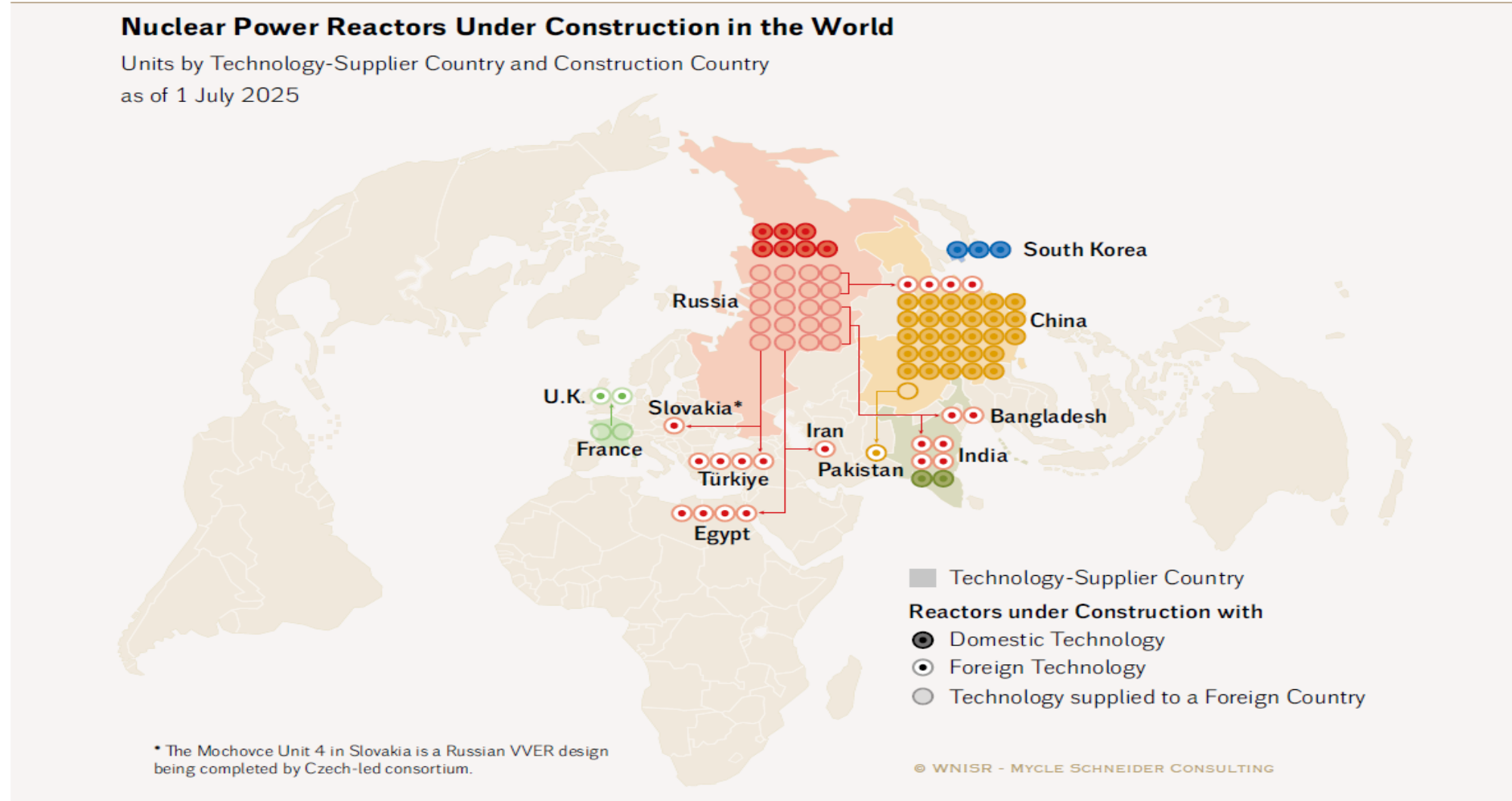
Sources: Various, compiled by WNISR, 2025

(a) - Mochovce -4 is a Russian VVER design being completed by a Czech-led consortium.

This table does not contain suspended or abandoned constructions. It does include construction of one CAP1400 reactor at Rongcheng/Shidaowan, although that has not been communicated by the IAEA (see [China Focus](#)) as well as two floating reactors of Russian design to be deployed in Russia—thus counted under Country-Russia, but with the barges built in China, which are likely also delayed.



Nuclear Reactors under Construction by Technology – Supplier Country



Sources: WNISR with IAEA-PRIS, 2025

Source: Mycle Schneider
WNISR with IAEA-PRIS September 2025



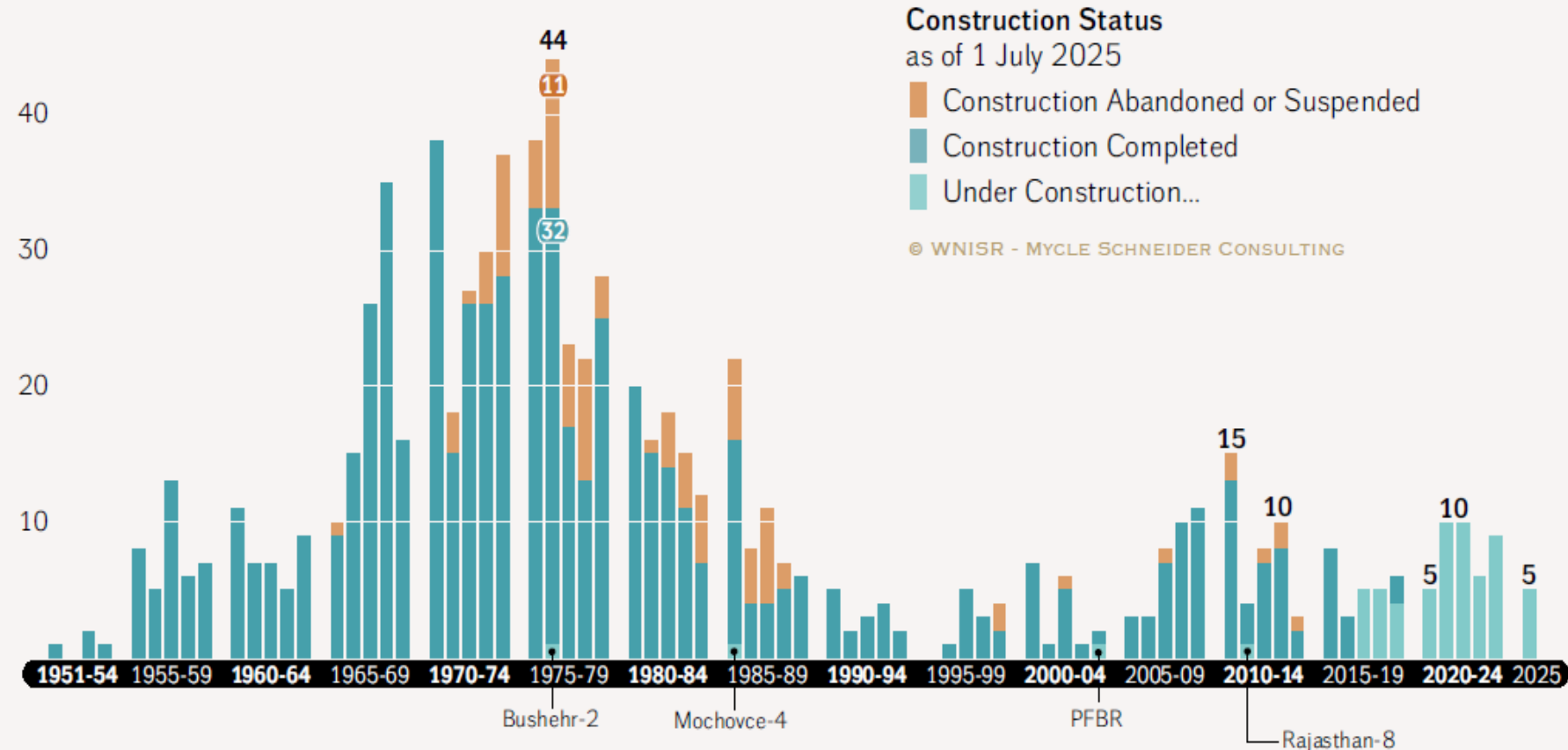
Nuclear Industry – Starts-up & Closures



Nuclear Reactors Construction Starts

Construction Starts of Nuclear Reactors in the World

in Units, from 1951 to 1 July 2025



Sources: WNISR with IAEA-PRIS, 2025

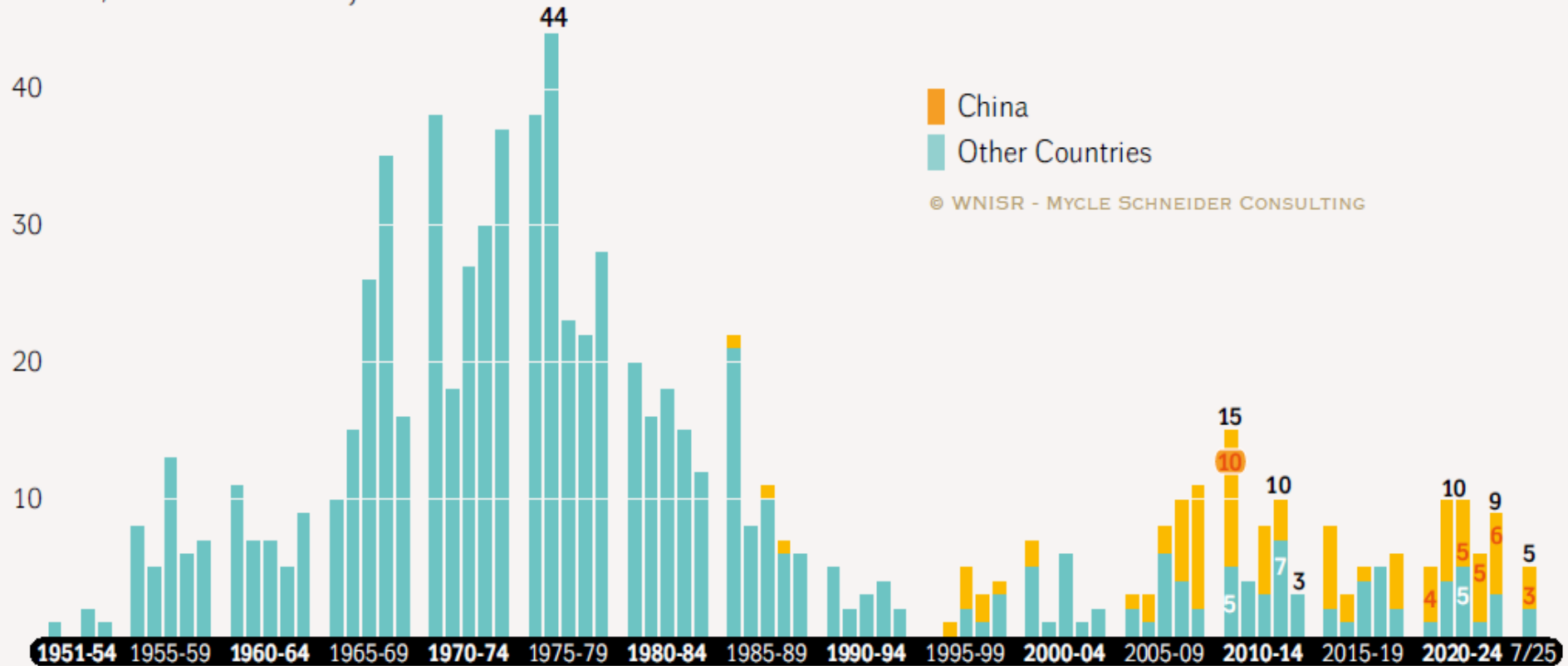
Source: Mycle Schneider
WNISR with IAEA-PRIS September 2025



Nuclear Reactors Construction Starts – The role of China

Construction Starts of Nuclear Reactors in the World

in Units, from 1951 to 1 July 2025

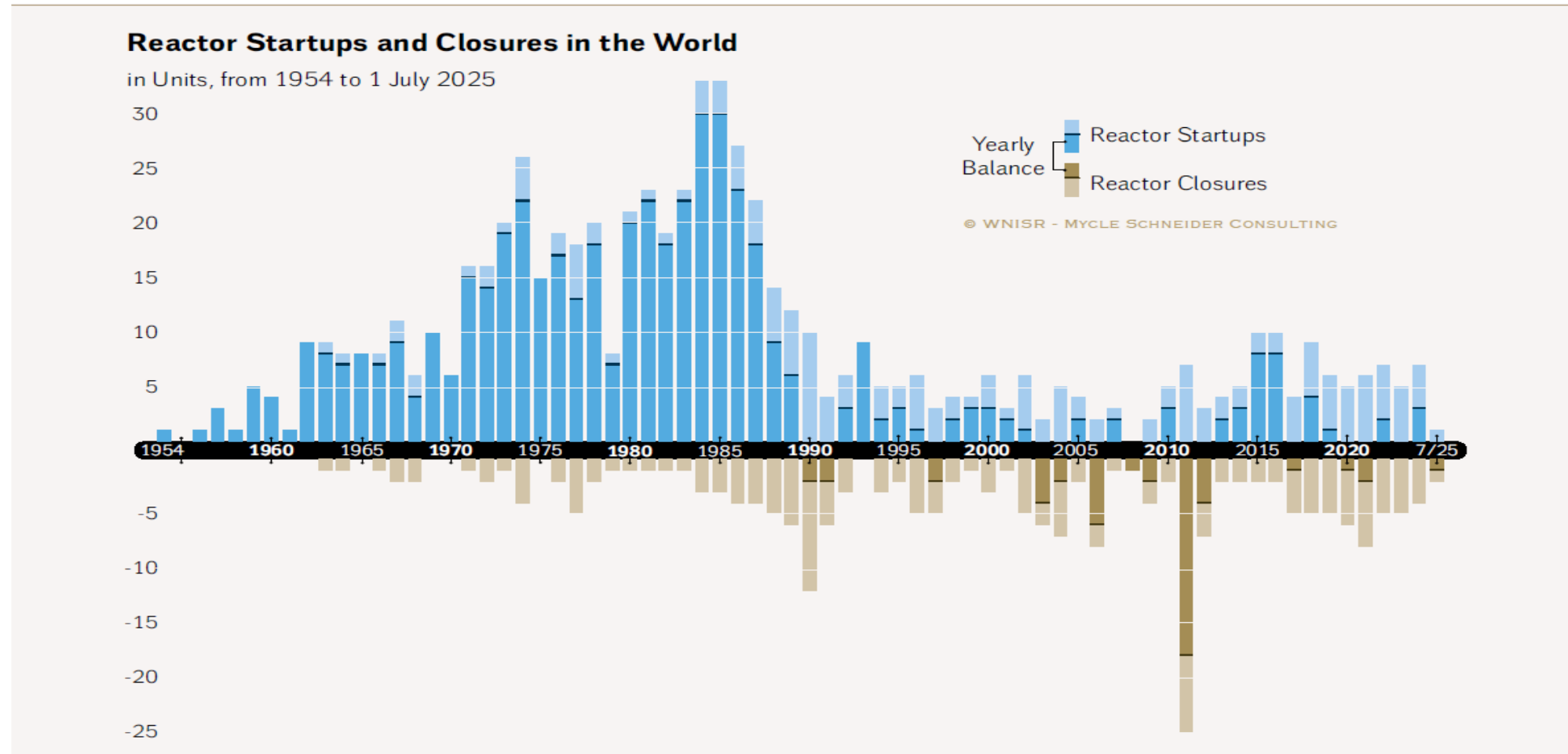


Sources: WNISR with IAEA-PRIS, 2025

Source: Mycle Schneider
WNISR with IAEA-PRIS September 2025



Nuclear Reactors Start-ups & Closures - 2011: Fukushima (1)



Sources: WNISR with IAEA-PRIS, 2025

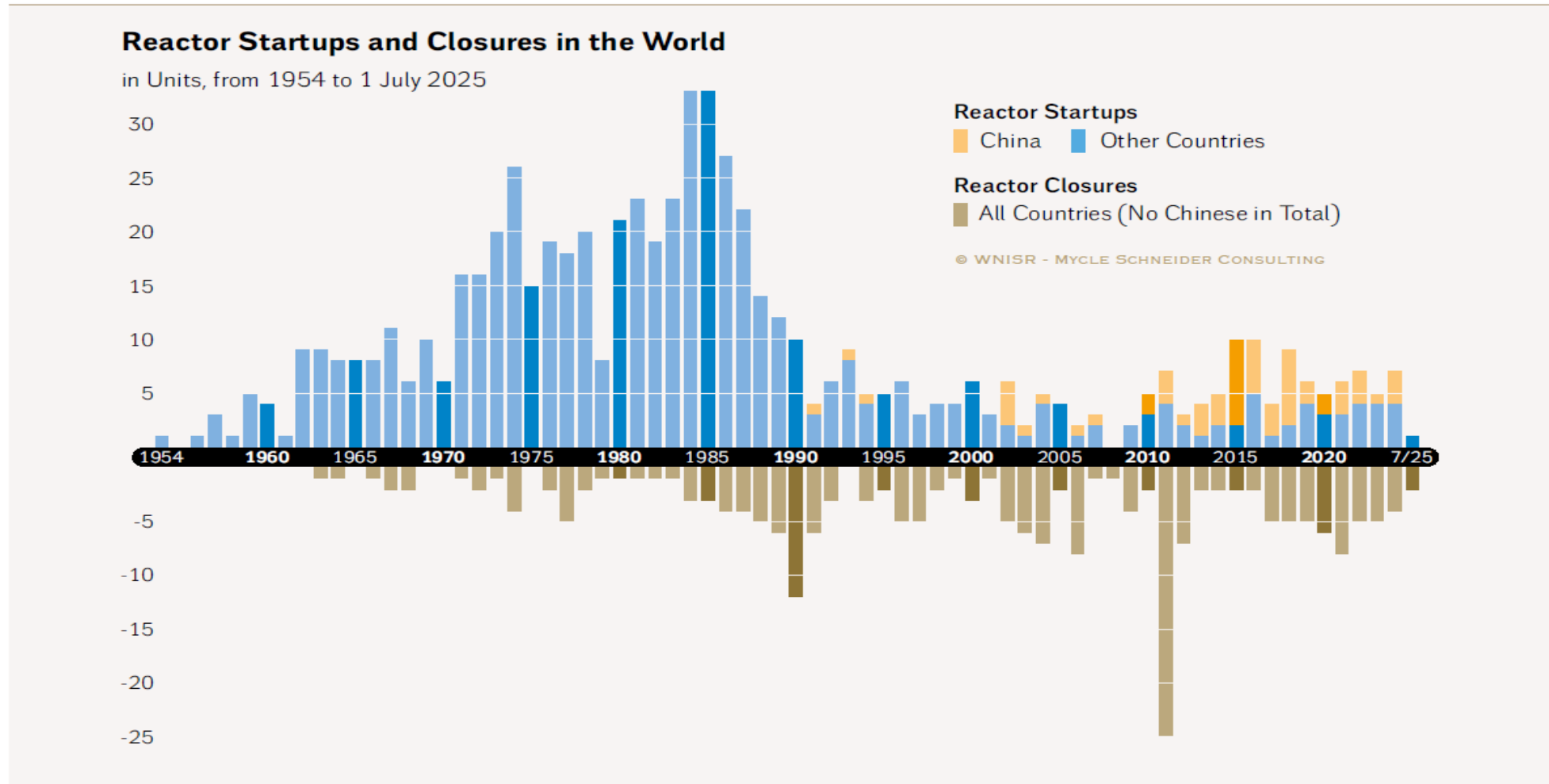
Note: WNISR considers reactors closed as of the date of their last electricity production, and not as of their closure announcement (which can be made years after the reactor ceased production).

Source: Mycle Schneider
WNISR with IAEA-PRIS September 2025



Nuclear Reactors Start-ups & Closures - 2011: Fukushima (2)

The role of China

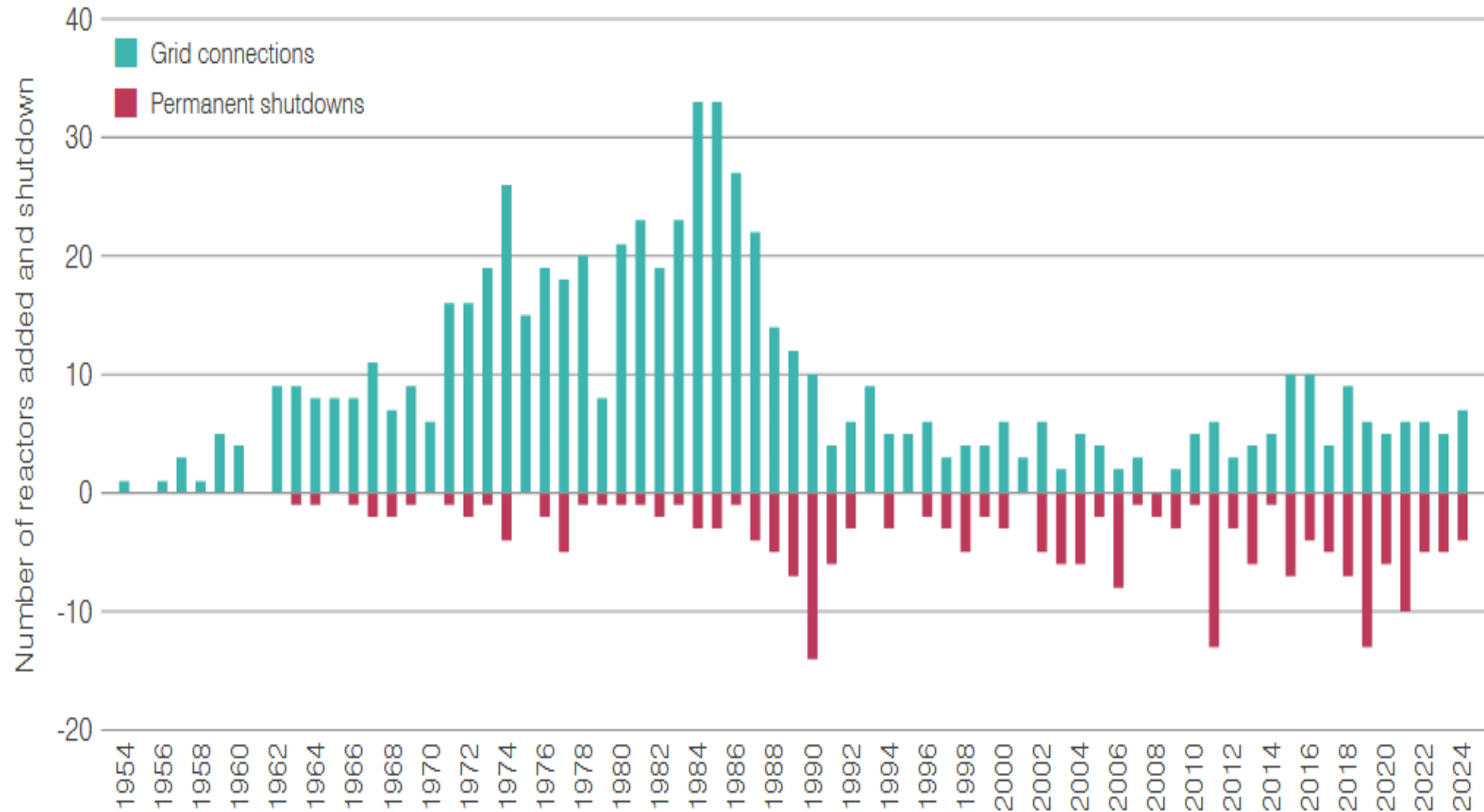


Sources: WNISR, with IAEA-PRIS, 2025

Source: Mycle Schneider
WNISR with IAEA-PRIS September 2025



Reactors Grid connections & permanent Shut-downs



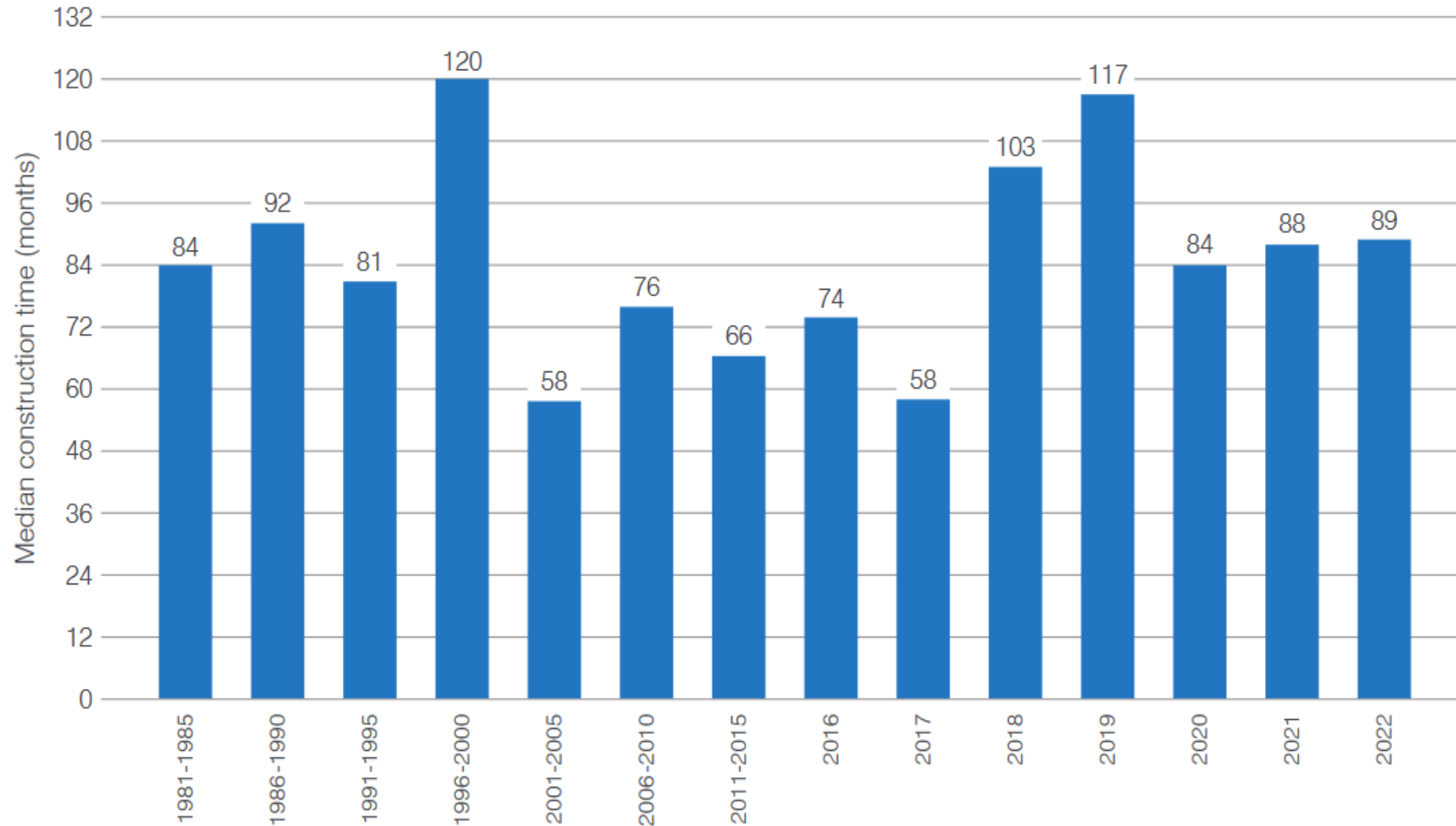
Source: World Nuclear Association, IAEA PRIS



Nuclear Industry – Construction Times



Nuclear Reactors median Construction Times 1981 - 2022

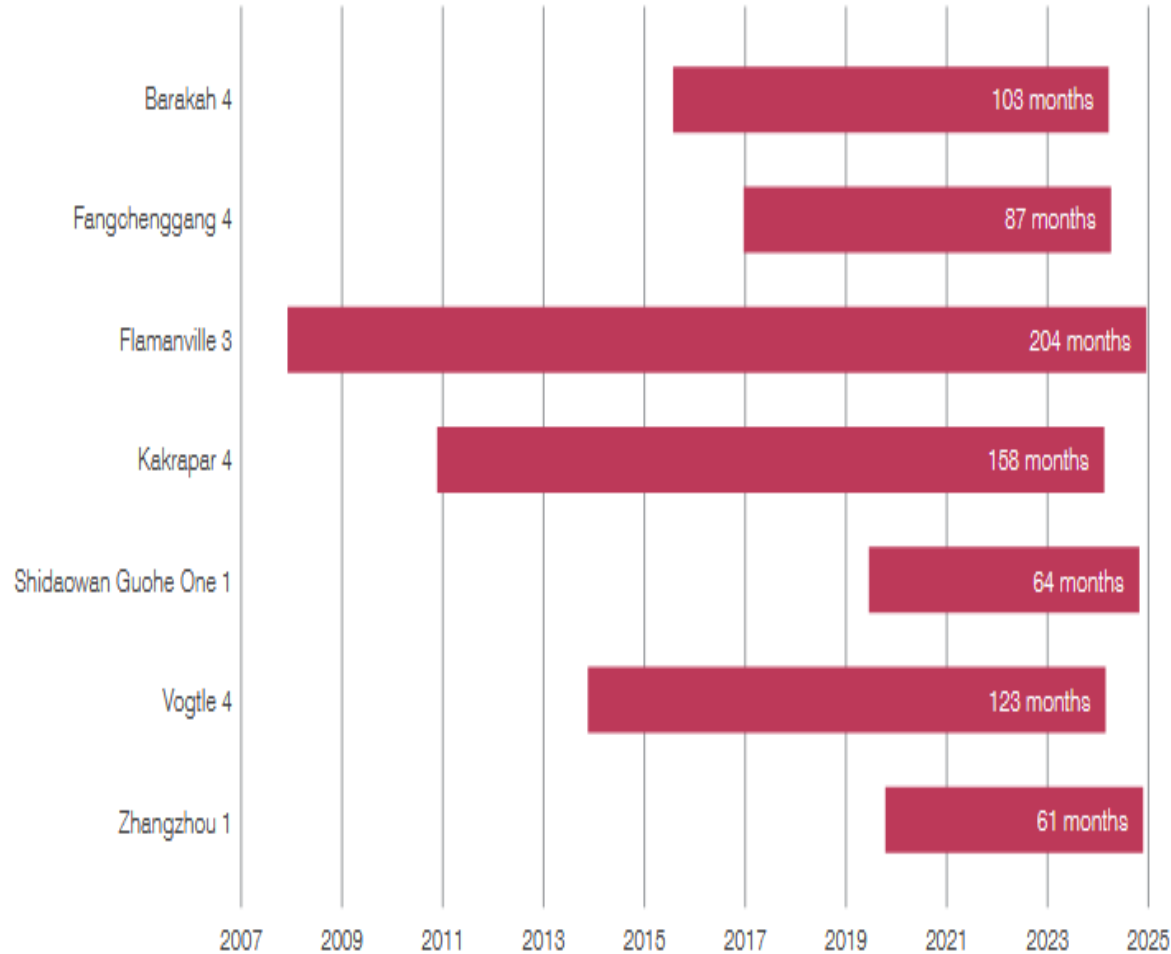


Source: World Nuclear Association, IAEA PRIS

Source: WNA 2023



Nuclear Reactors Construction Times of New Units grid connected in 2024 Between 5 & 17 years



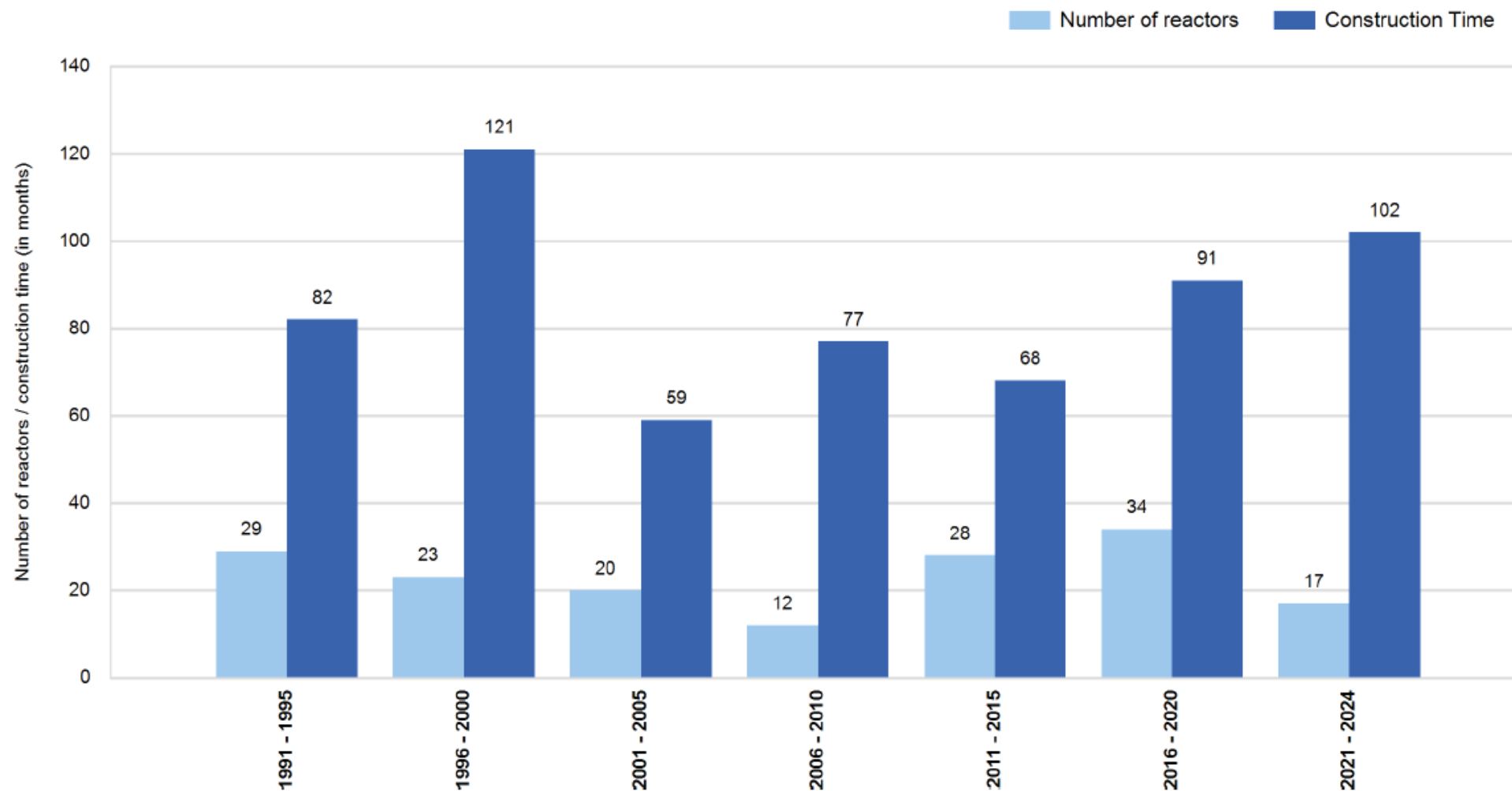
Source: World Nuclear Association, IAEA PRIS

	Model	Process	Net capacity (MWe)	Construction start	Grid connection	Construction time (months)
Zhangzhou 1	Hualong One	PWR	1126	16 October 2019	28 November 2024	61
Vogtle 4	AP1000	PWR	1117	19 November 2013	1 March 2024	123
Shidaowan Guohe One 1	CAP1400	PWR	1400	19 June 2019 (estimate)	31 October 2024	64
Kakrapar 4	PHWR-700	PHWR	630	22 November 2010	20 February 2024	158
Flamanville 3	EPR	PWR	1630	3 December 2007	21 December 2024	204
Fangchenggang 4	HPR1000	PWR	1105	23 December 2016	9 April 2024	87
Barakah 4	APR-1400	PWR	1337	30 July 2015	23 March 2024	103

Source: World Nuclear Association, IAEA PRIS



Median construction time in months by 5 years period

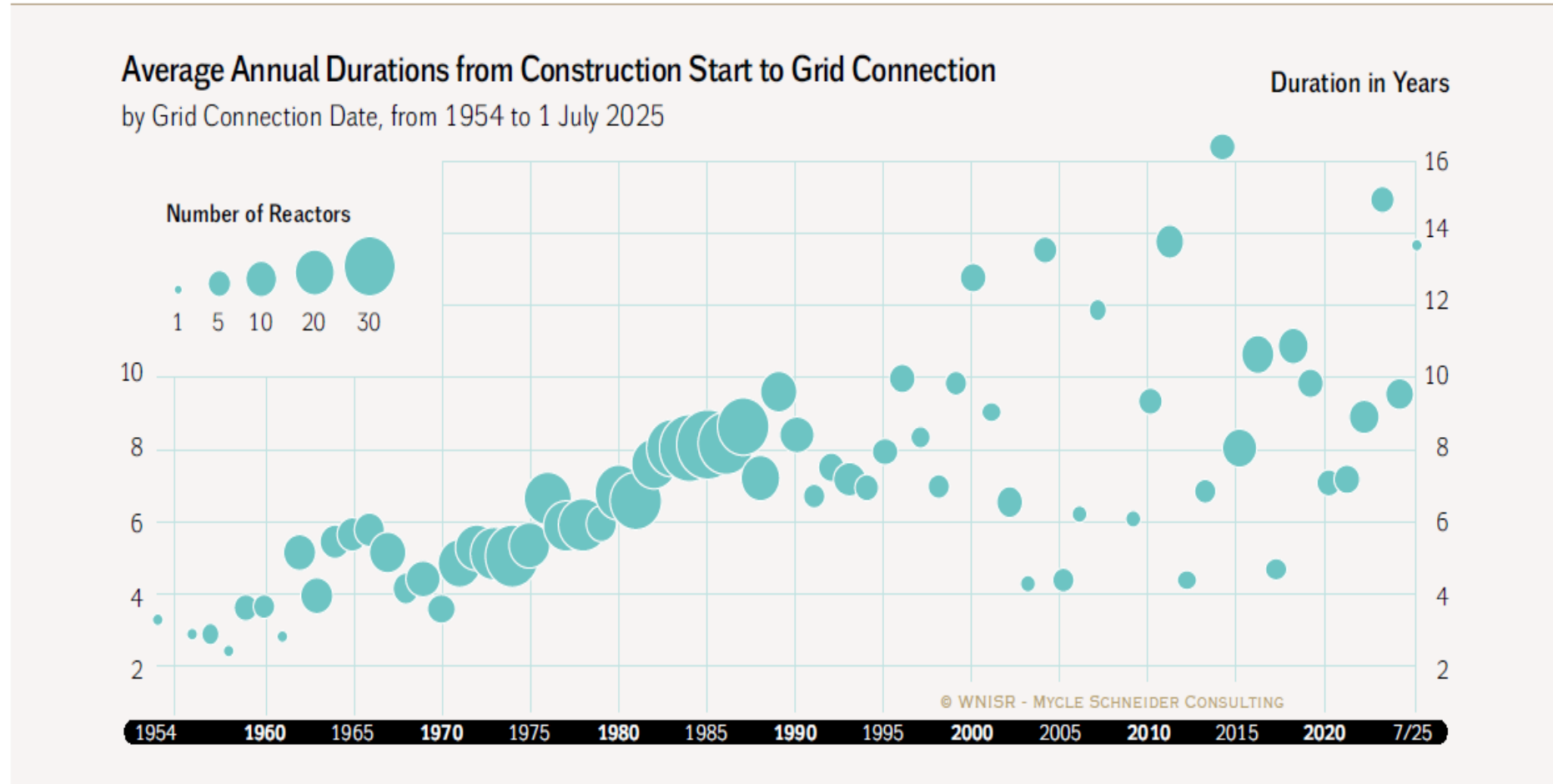


Source: IAEA PRIS: International Atomic Energy Agency/Power Reactors Information System
2025 Edition – Nuclear Power Reactors in the World



Nuclear Reactors Construction Times 1954 – 2025

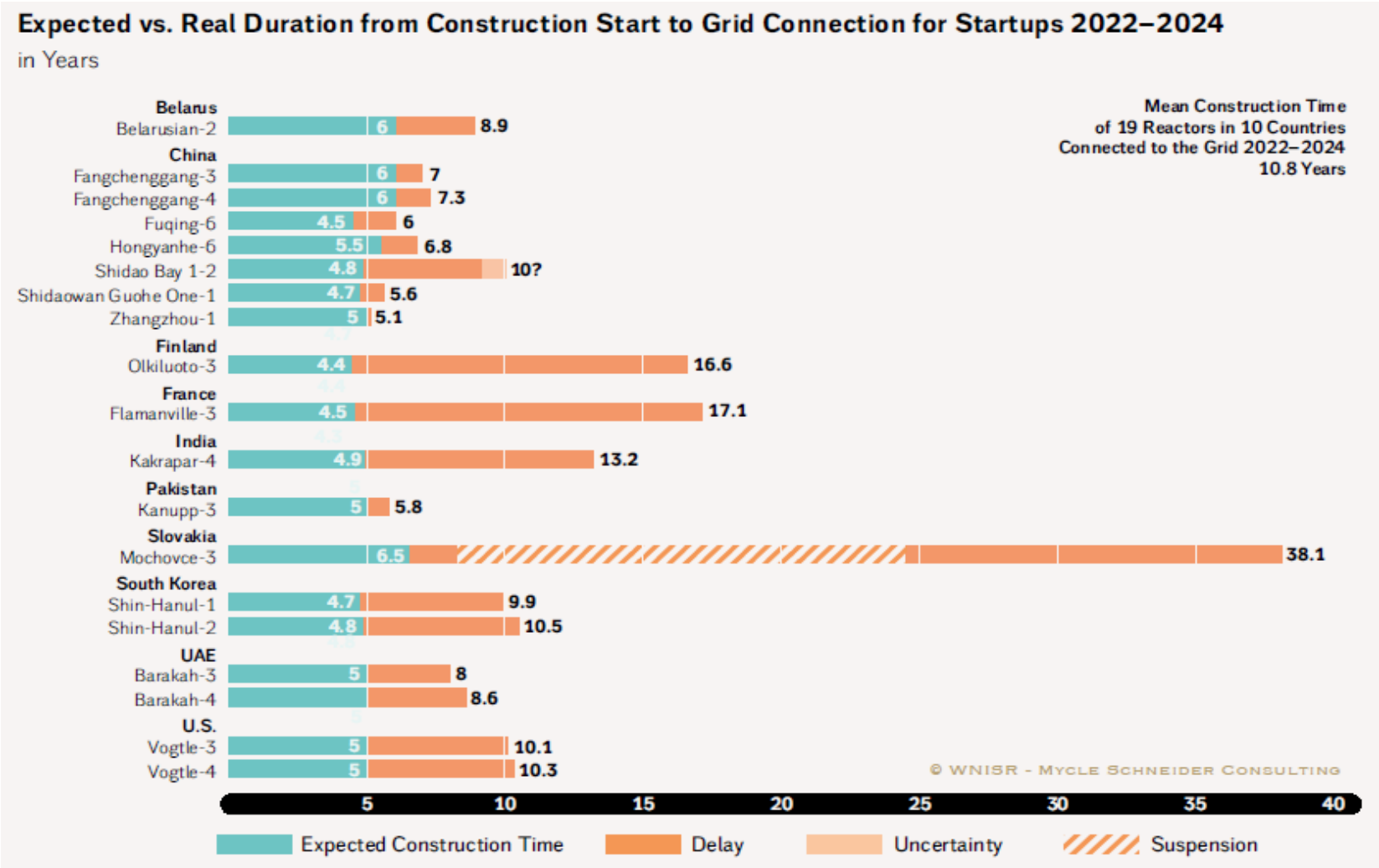
Large scale – From 4 to 16 years



Sources: WNISR with IAEA-PRIS, 2025

Source: Mycle Schneider
WNISR with IAEA-PRIS September 2025

Nuclear Reactors Expected Construction Time vs Real Construction Time Period 2021/2024 - Mean Construction Time: 9 years



Notes:

Expected construction time is based on grid connection data provided at construction start when available; alternatively, best estimates are used, based on commercial operation, completion, or commissioning targets.

At Shidao Bay, the HTR plant, where construction started in 2012, has two reactor modules onsite and is therefore counted as two units as of WNISR2020. Grid connection of the first unit of the twin reactors officially took place on 20 December 2021. No date was provided for startup of the second reactor, which WNISR considers operating by the of end-2022 with total construction time set at 10 years.

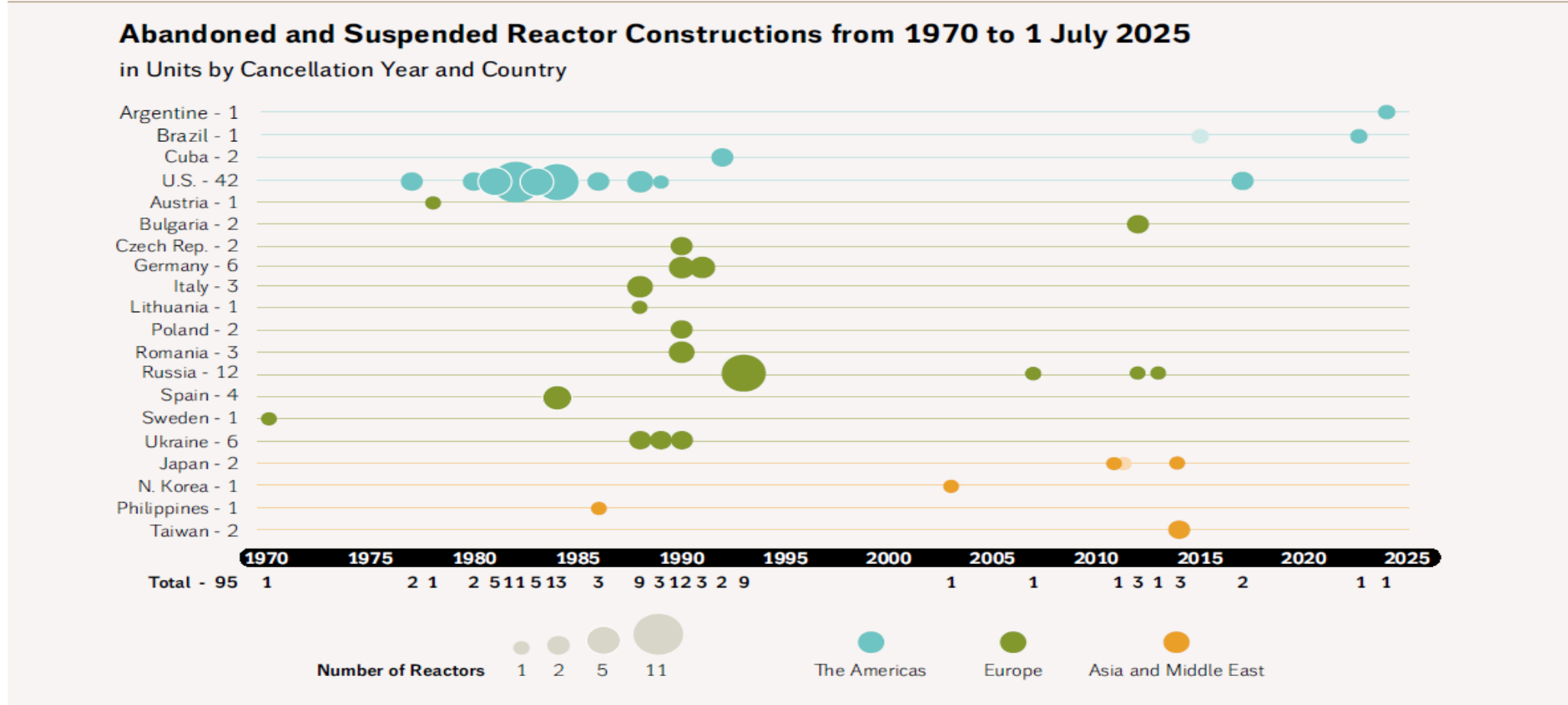
Source: Mycle Schneider
WNISR with IAEA-PRIS September 2025



Nuclear Industry – Abandoned/suspended Constructions



Abandoned/Suspended Constructions 1970 – 2025



Sources: Various, compiled by WNISR, 2025

Notes: The shaded colors indicate the first suspension in the case of reactors where construction was suspended several times (Brazil and Japan).

This figure only includes constructions that had officially started with the concreting of the base slab of the reactor building. Many more projects have been cancelled at earlier stages of construction/site preparation and equipment manufacturing.

Source: Mycle Schneider
WNISR with IAEA-PRIS September 2025



Shut-downs Scenarios

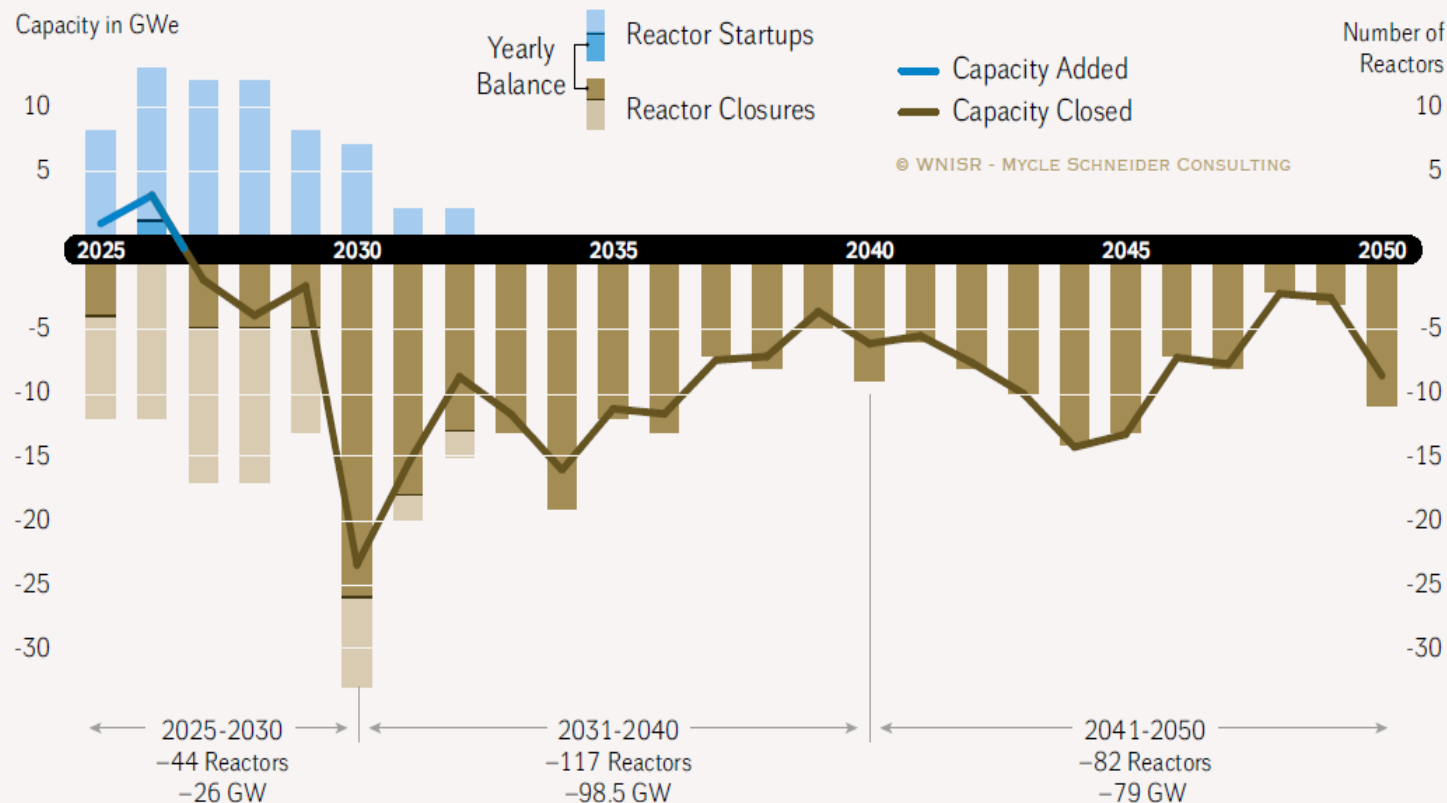


Shut-Downs scenario for the next 30 years for the world nuclear park

Projection 2025–2050 of Nuclear Reactors/Capacity in the World

General assumption of 40-year mean lifetime + Authorized Lifetime Extensions

Operating and Under Construction as of 1 July 2025, in GWe and Units



Sources: Various sources, compiled by WNISR, 2025

Notes:

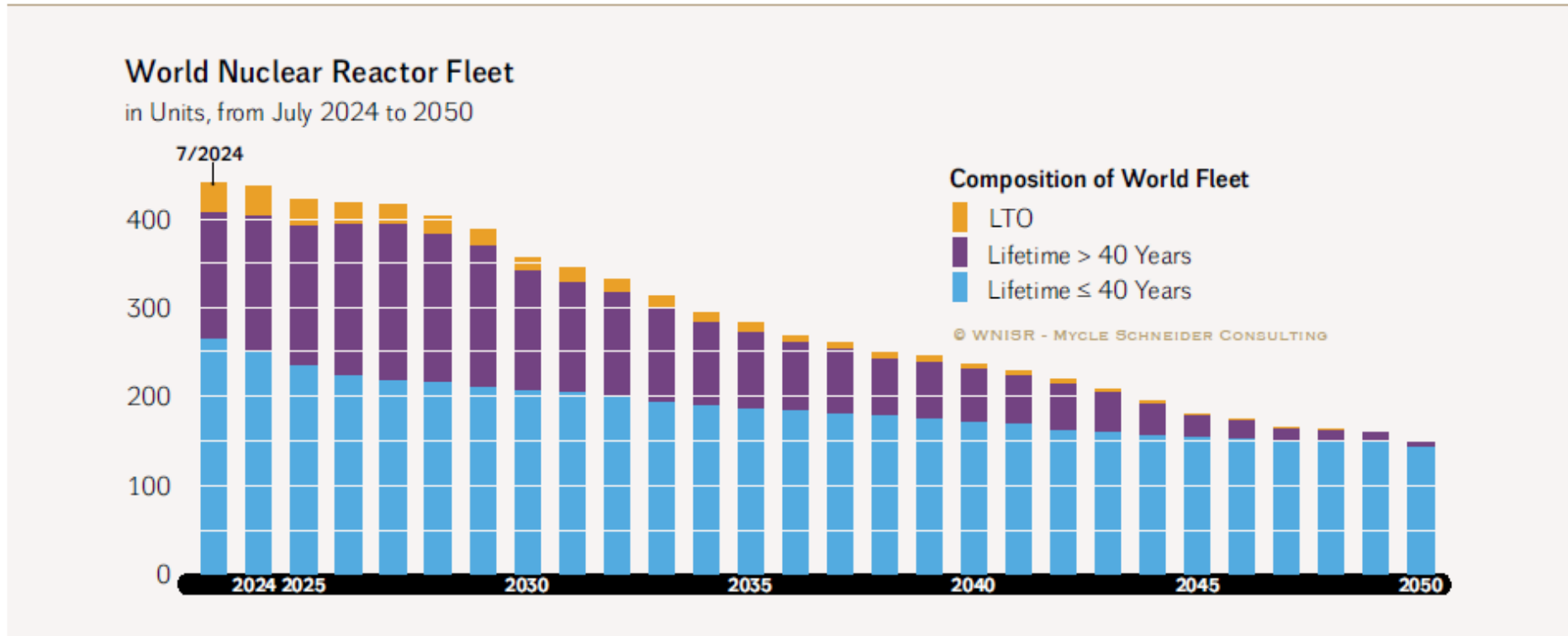
Restarts or closures amongst the 33 reactors in LTO as of 1 July 2025 are not represented; however, at least some are expected to be restarted (and later closed, after 2050 in some cases).

In the case of reactors that have reached 40 years of operation prior to 2025, the projection uses the end of their licensed lifetime, including 80 years for 13 reactors in the U.S, where the Subsequent License Renewal Applications have been approved for a further 20 years of operation.

In the case of the French 900 MW-fleet the projection uses the scheduled date of their 4th periodic safety review. In case this deadline is or will be passed by the end of 2025, we apply a “de facto” 10-year extension (operation to 50 years) or the deadline for the fifth review when available.



Reminder: Mycle Schneider Scenarios for the next 30 years: Decline of the World Nuclear Fleet



Sources: Various, compiled by WNISR, 2024

Note: This figure illustrates the trends, and the projected composition of the current world nuclear fleet, taking into account existing reactors (operating and in LTO) and their closure dates (40-years Lifetime vs authorized Lifetime Extension) as well as the 59 reactors under construction as of 1 July 2024. The graph does *not* represent a forecasting of the world nuclear fleet over the next three decades as it does not speculate about future constructions.

This figure takes into account the restarts of Rajasthan-3 during the second half-year of 2024, as well as Darlington-1 expected in 2025.

Source: Mycle Schneider WNISR September 2024
LTO: Long Term Outage



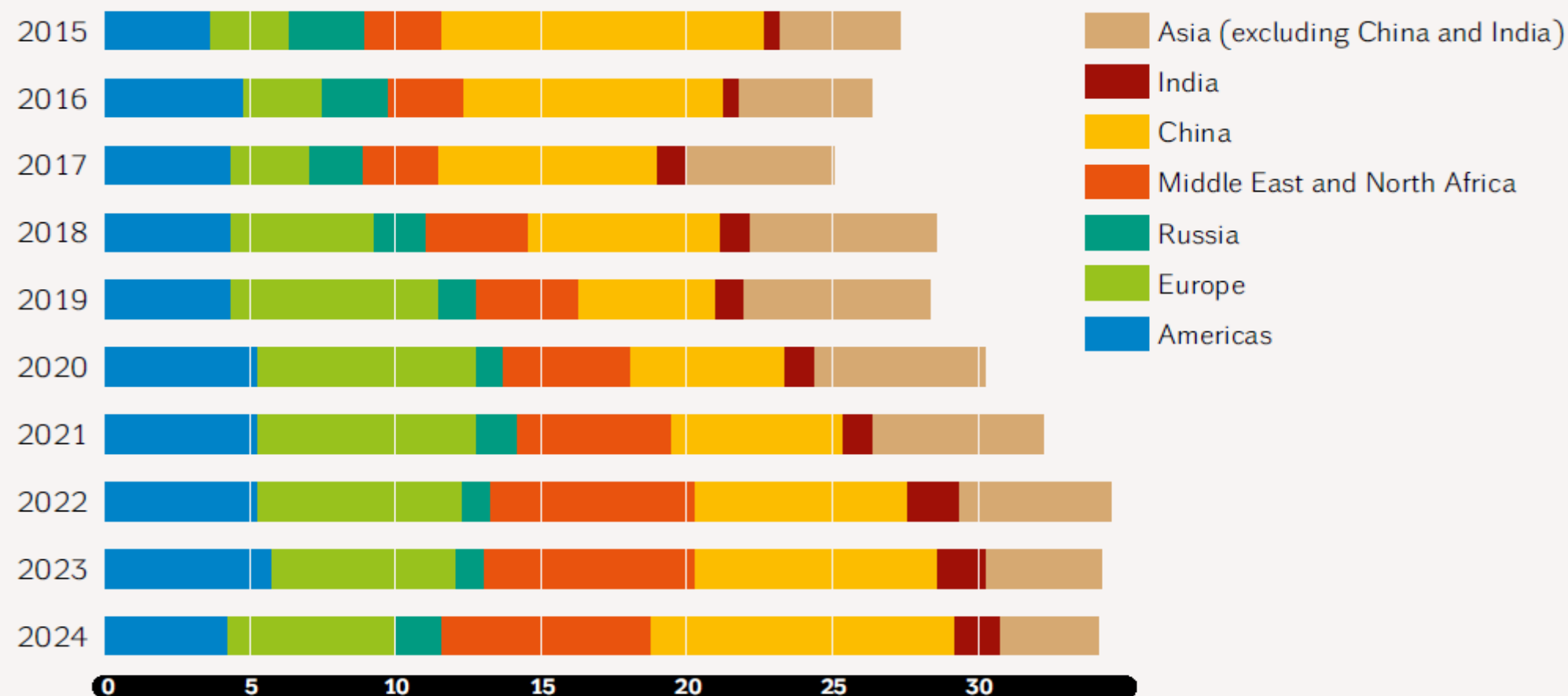
Nuclear Industry – Costs & Investments



Regional Breakdown of Nuclear Plants Investments

Regional Breakdown of Nuclear Power Plant Investments

in US\$ billion, 2015–2024



© WNISR - MYCLE SCHNEIDER CONSULTING

Source: Mycle Schneider
WNISR IAEA-PRIS September 2025



3-4

The Competition



The Competition – Situation 2015

Vendor	Country	Design	Type	Net capacity (MW)	In operation*	Under construction*
AREVA	France	EPR	PWR	1 600	0	4 (Finland, France, China)
AREVA/MHI	France/ Japan	ATMEA	PWR	1 100	0	0
CANDU Energy	Canada	EC6	PHWR	700	0	0
CNNC-CGN	China	Hualong-1	PWR	1 100	0	0
GE Hitachi – Toshiba	United States/ Japan	ABWR	BWR	1 400-1 700	4 (Japan)	4 (Japan, Chinese Taipei)
		ESBWR	BWR	1 600	0	0
KEPCO/KHNP	Korea	APR1400	PWR	1 400	0	7 (Republic of Korea, United Arab Emirates)
Mitsubishi	Japan	APWR	PWR	1 700	0	0
ROSATOM	Russia	AES-92, AES-2006	PWR	1 000-1 200	1	10 (Russia, Belarus, China, India)
SNPTC	China	CAP1000, CAP1400	PWR	1 200-1 400	0	0
Westinghouse/ Toshiba	United States/ Japan	AP1000	PWR	1 200	0	8 (China, United States)

*: As of 31 December 2014.

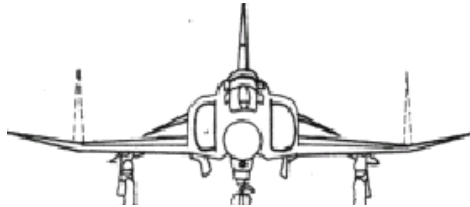
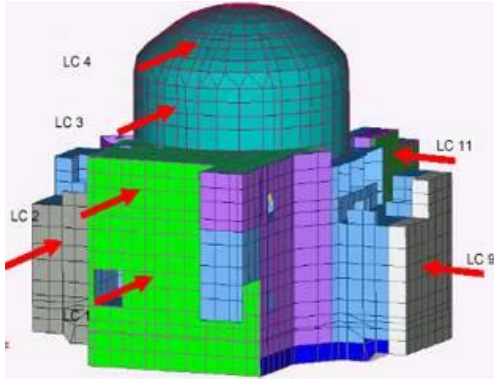
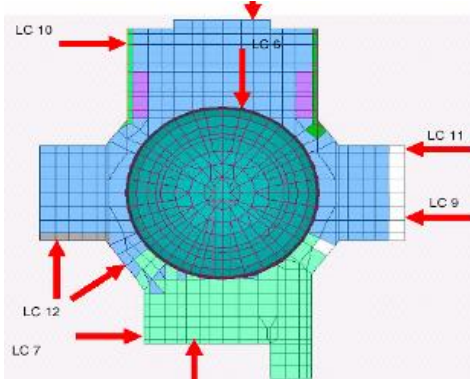
AREVA France: Olkiluoto 3-Finland, Flamanville 3-France, Taishan 1 & 2-China

China develops its own 3rd generation reactor 1100 MW: Hualong 1



EPR aircraft hazard protection in the post 9-11 World

◆ EPR Designed to withstand impact of:

<i>Large Commercial Jet</i> & <i>Military Aircraft</i>	
	
<i>At various Elevations</i> & <i>From different Sides</i>	
	

The EPR resists to commercial and military aircraft crashes

EPR
Redundancy # 4
**(The safer nuclear power plant is the one which
is not going to be built.....)**



Olkiluoto EPR (Connected to network beginnig 2022?)

Olkiluoto 2007



Olkiluoto 2013



Flamanville EPR 2020 (1650 MW)



Source: eDF
Updated Capex by french Cour des Comptes



Taishan (2 EPR) 2013



Taishan (2 EPR 1750 MW)

Taishan 1: Start-up on 14 december 2018



Taishan 1 :start-up 14 december 2018
Taishan 2: start-up september 2019
Total cost : 12,2 G€

Image CGN – China General Nuclear Power Corp.



EPR in the world: status July 2023

◆ Operational : 3

- Olkiluoto (Finland) : connected to network march 2023 at full power
- Taishan (China) : two started in 2018 and 2019. problems of fuel assembly, one stopped in march 2023, one operational

◆ Under construction : 3

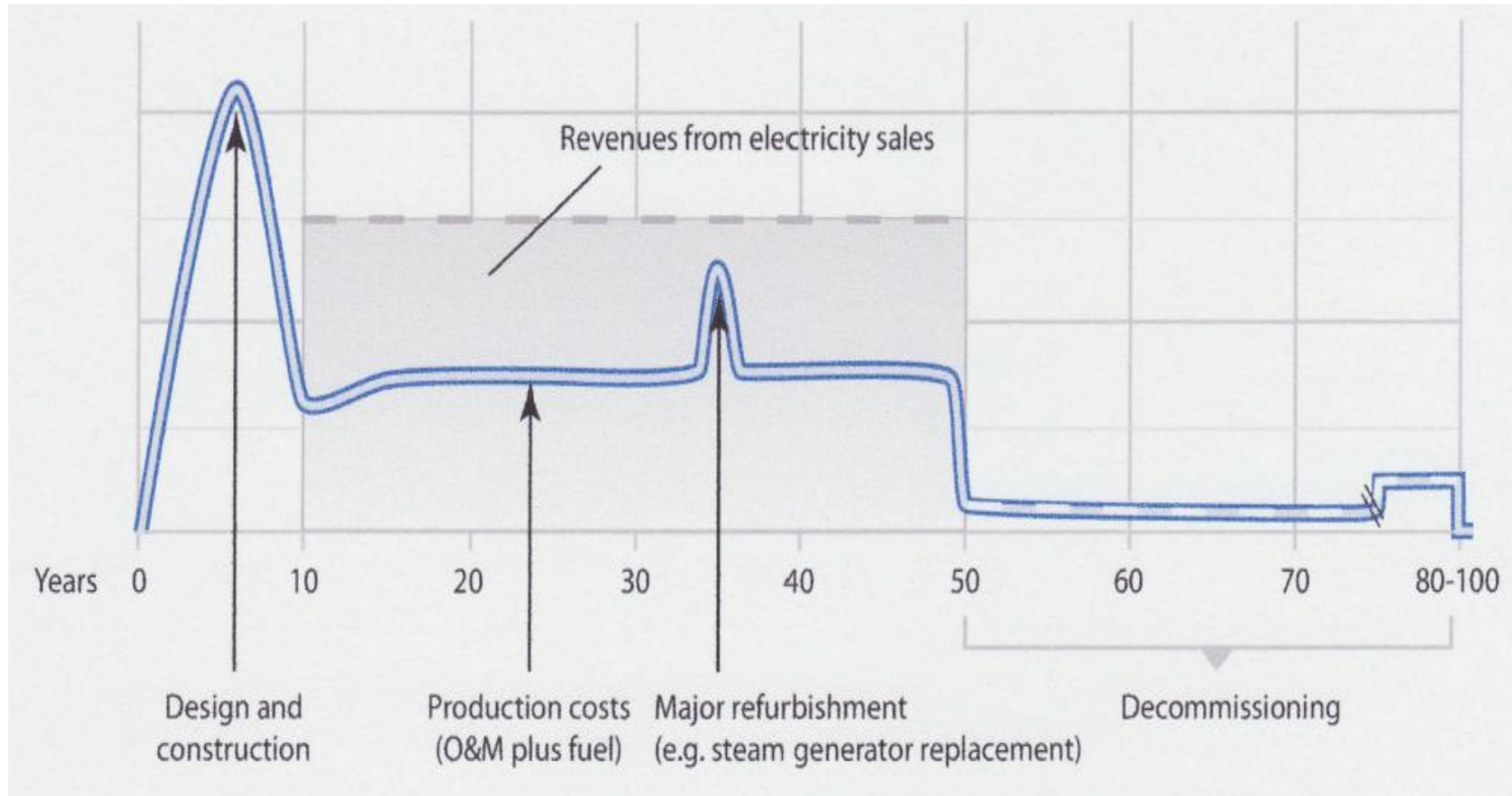
- Flamanville (France) : after long delays, it is expected to start in 2024
- Hinkley Point (UK) : two under construction

◆ Planned : 6

- 6 EPR 2 (an updated version) planned in France on three different sites. Planned start up 2035

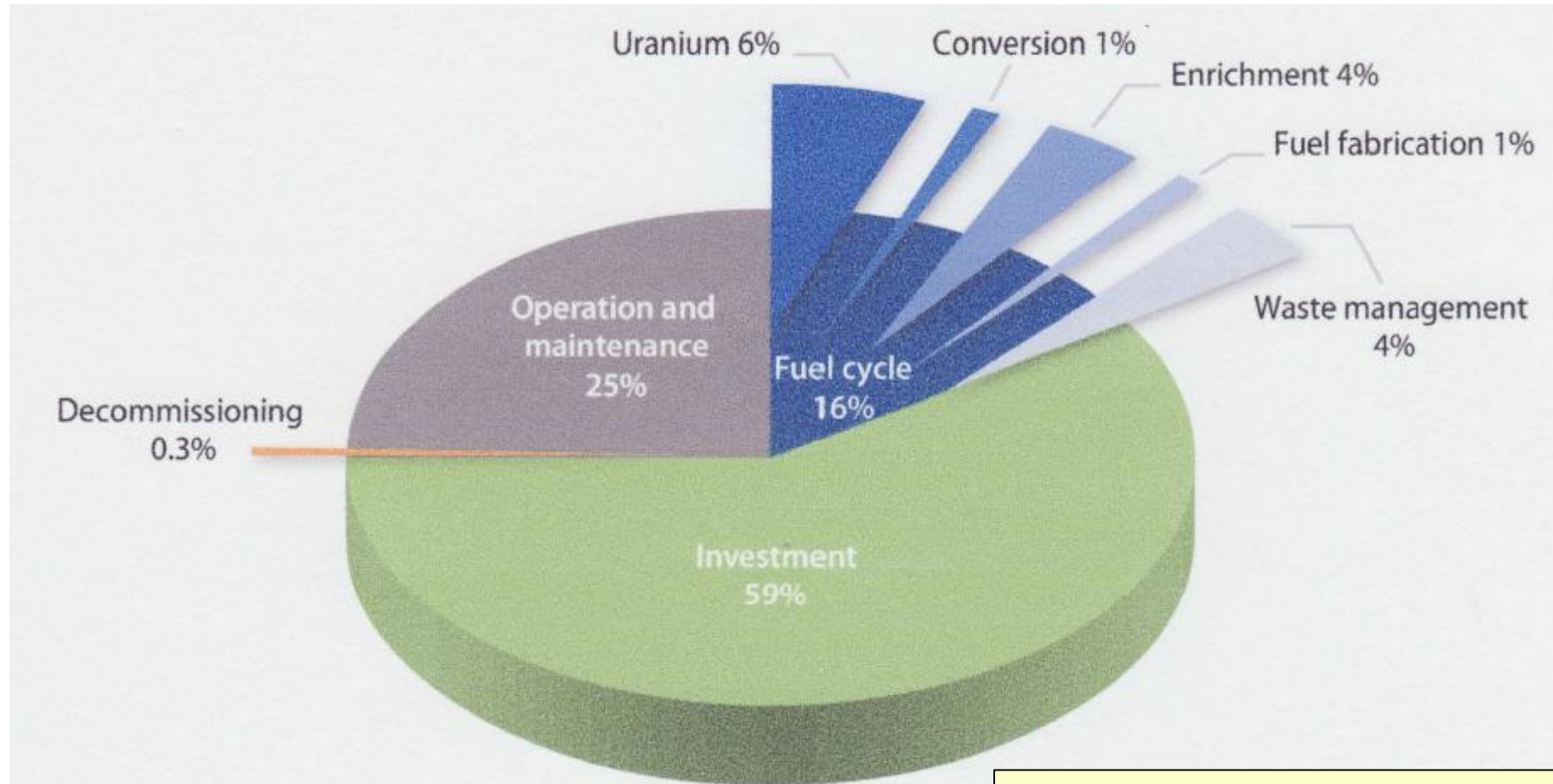


Economic Cycle of a Nuclear Plant



Typical Nuclear Plant Cost Breakdown:

Capital Expenditures represent # 60%, Fuel Cost # 15% including Waste management



Source: IEA/NEA, *Projected Costs of Generating Electricity*, 2010.

Cost of Fuel cycle # 3xCost of Uranium



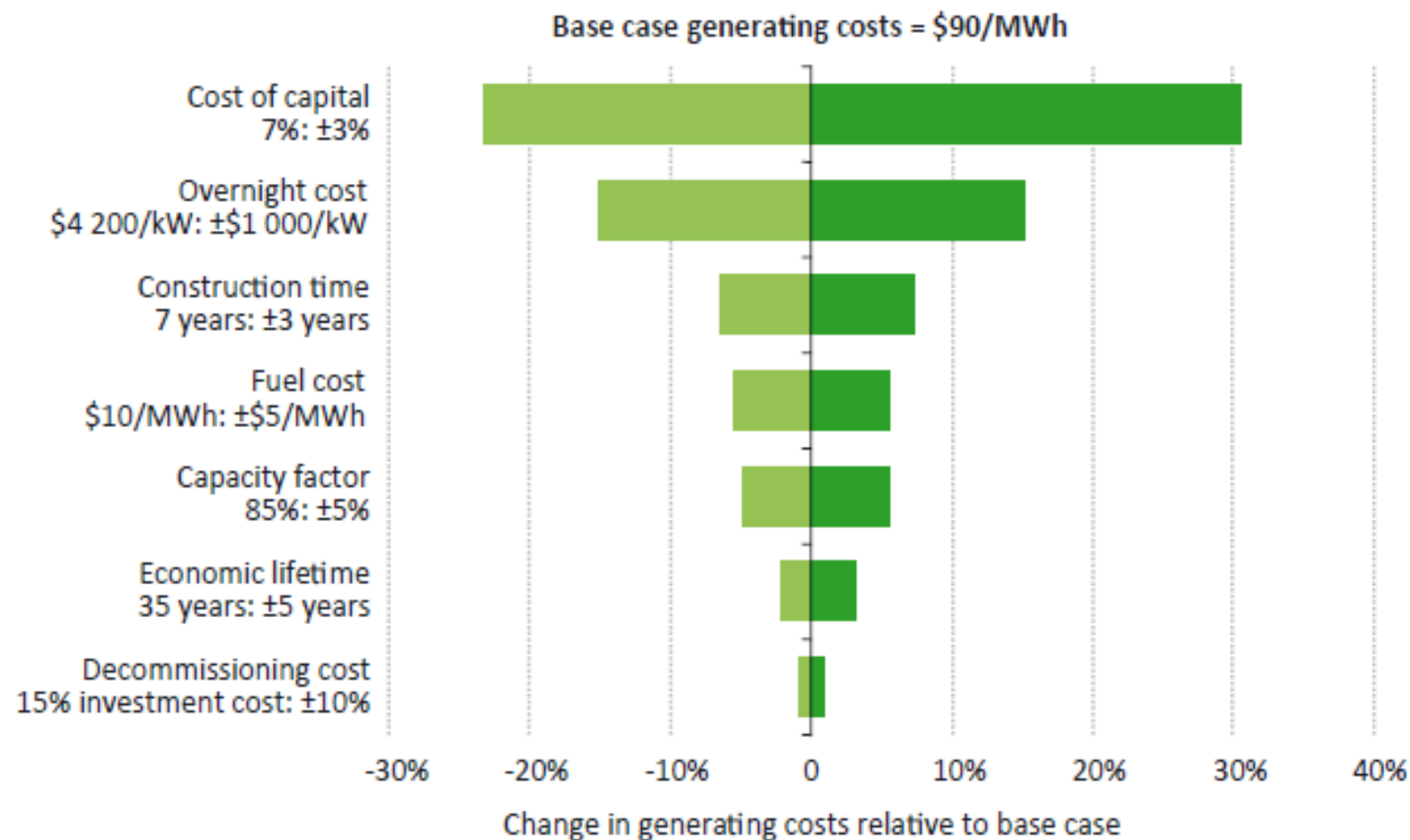
Split of Fuel cycle costs excluding Waste management

Front end fuel cycle costs of 1 kg of uranium as UO₂ fuel

Process	Amount required x price*	Cost	Proportion of total
Uranium	8.9 kg U ₃ O ₈ x \$94.6/kg	\$842	51%
Conversion	7.5 kg U x \$16	\$120	7%
Enrichment	7.3 SWU x \$55	\$401	24%
Fuel fabrication	per kg	\$300	18%
Total		\$1663	

The Cost/MWh: Sensivity to variations of parameters

An illustrative case for an old generation Nuclear plant



Note: The non-fuel O&M cost is assumed to be \$170/kW.



3-5

The Dismantlement



Twice more time to dismantle than to produce electricity – Three examples

- **In certain cases, 100 years will be necessary to dismantle nuclear plants of 1st generation.**
- **Garigliano plant in Italy: Start-up in 1964. Idle since 1978. Decree to dismantle in 2012. 60 years will be necessary to complete the dismantlement project.**
- **Greifswald plant in Germany: 5 reactors supplied by ex-USSR. 15000 personnes worked on the site during the exploitation till the end of the 80's. Dismantlement started thereafter, deconstruction of equipments, storage and management of waste, completion scheduled for 2029. Germany must select a dedicated site to store HLW in a deep geological storage. 40 years of dismantlement operations.**
- **Chooz reactor in France: Start-up in 1967, idle since 1991. Decree to dismantle in 2007. Works completion scheduled for 2022. Additional works to restore the site till 2047.**



Dismantlement costs are taken into account in the LCOE – But estimates vary

- **EDF estimate of the french nuclear park dismantlement (58 reactors) = 27 G€, 61 G€ if waste management and ultimate waste treatment are included.**
- **EDF estimate for the dismantlement of one typical nuclear reactor = 350 to 500 M€.
EON estimate = 1 000 M€.**
- **Underestimate of the corresponding provisions in the Company's account?**
- **Dismantlement taking place very late in time, its discounted cost remains very limited in the LCOE.**

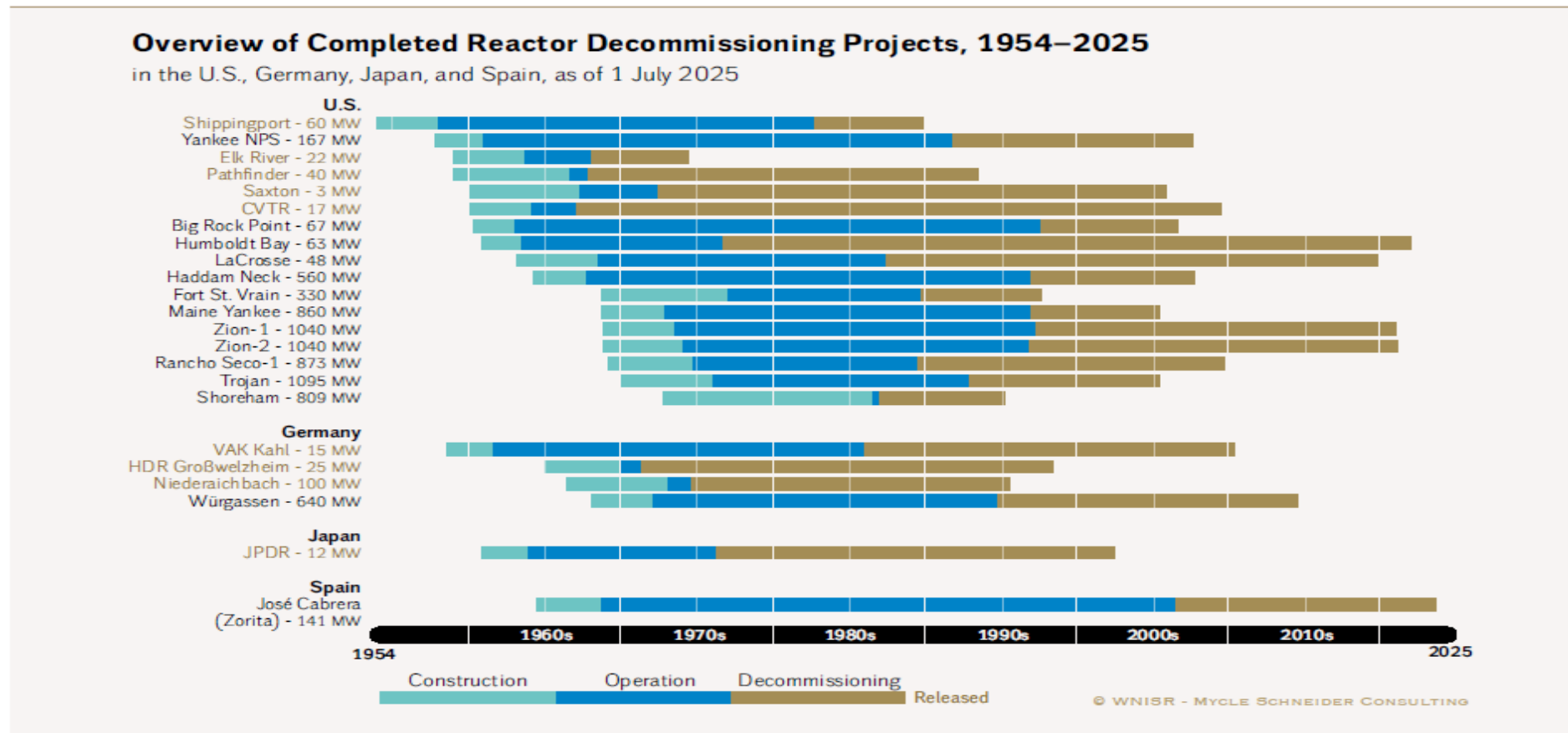


Some definitions

- The **warm-up stage** comprises the post-operational stage and the dismantling of systems that are not needed for the decommissioning process. In addition, the dismantling of system parts with higher contamination begins, including the defueling of the reactor, which is crucial for any further undertakings and means removing the spent fuel from the reactor core and the spent-fuel pools.
- The **hot-zone stage** comprises the dismantling activities in the hot zone, i.e., the dismantling of highly contaminated or activated parts, e.g., the reactor pressure vessel (RPV) and its internals (RVI) and the biological shield.
- The **ease-off stage** comprises the removal of operating systems as well as the decontamination of the buildings. This stage concludes with the end of physical demolition work.



Completed Reactor Decommissioning 1954 – 2024 US, Germany, Japan, Spain at 1s July 2025



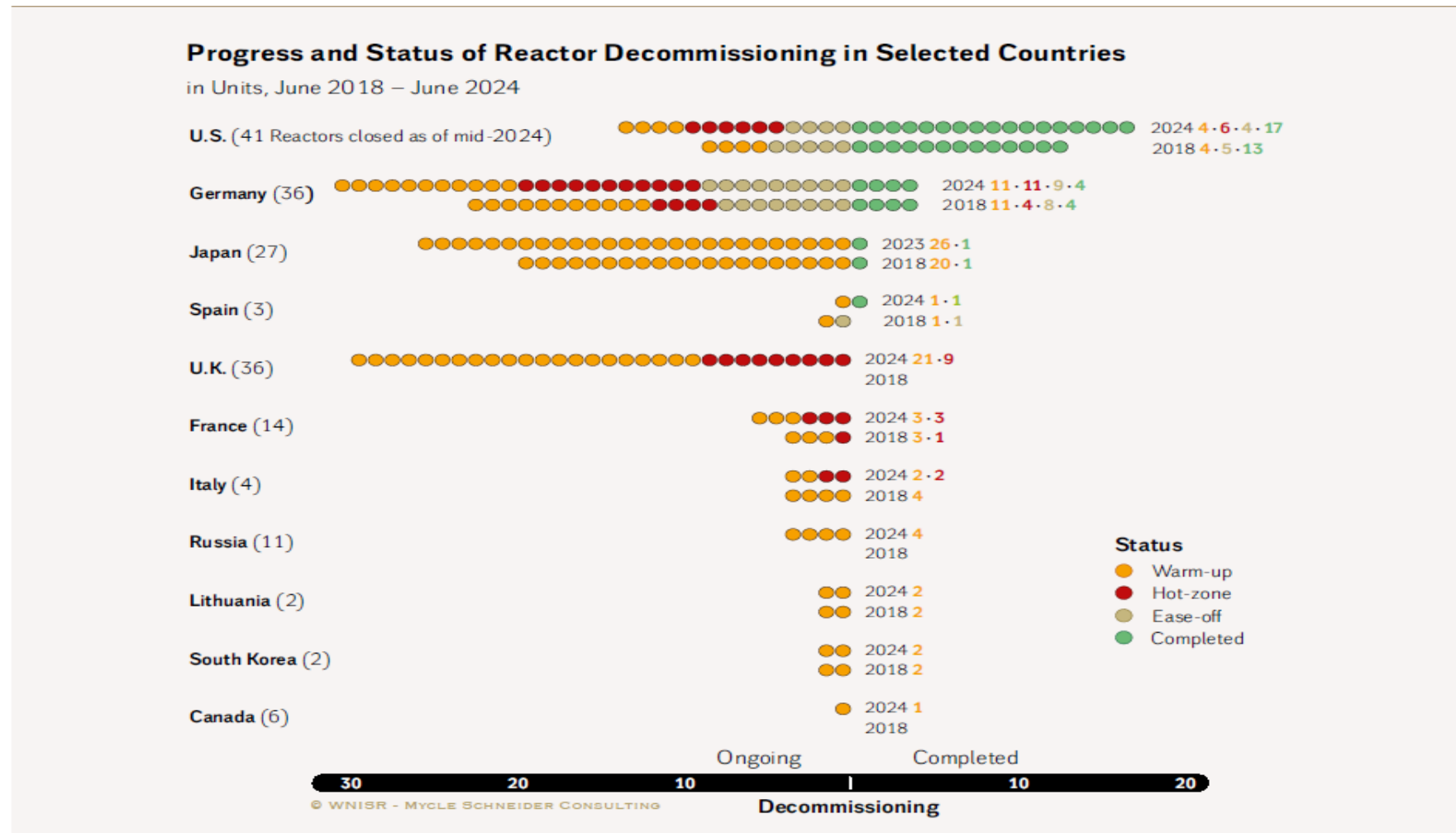
Sources: Various, compiled by WNISR, 2025

Note: As of WNISR2024, the “released” category only mentions “greenfield released” reactors, whereas it also contained “brownfield released” reactors in previous editions (see definitions in the introduction of the chapter). The LaCrosse and Shoreham reactors had in previous WNISR editions been classified as “greenfield released”. However, the site at LaCrosse still contains an interim spent-fuel storage facility and is thus reclassified as a brownfield site, and while the Shoreham reactor was released from regulatory oversight, it was never entirely dismantled, and most buildings have remained intact.

Source: Mycle Schneider
WNISR IAEA-PRIS September 2025



Progress of Reactor Decommissioning in Selected Countries



Sources: Various, compiled by WNISR, 2024

Note: After a decommissioning strategy change, the U.K. has begun to move reactors from LTE to various stages of decommissioning.

Source: Mycle Schneider
WNISR IAEA-PRIS September 2024



Progress of Reactor Decommissioning in Selected Countries

Country	Closed Reactor	Decommissioning Status						
		Warm-up (of which defueled)		Hot Zone	Ease-off	LTE	Completed (of which released as greenfield sites ^(a))	Completed Share of Total Closed (share of total closed released as greenfield sites ^(a))
U.S.	41	4	(4) ^(b)	6	5	9	17 (5)	41% (12%)
Germany	36	10	(4)	10	11	1	4 (3)	11% (8%)
U.K.	36	19	(12)	11	0	6	0	0%
Japan	27	25	(4)	1	0	0	1 (1)	4% (4%)
France	14	3	(2)	3	0	8	0	0%
Russia	11	6	(5)	0	0	5	0	0%
Canada	8	3	(1)	0	0	5	0	0%
Sweden	7	2	(2)	0	5	0	0	0%
Taiwan	6	6	(0)	0	0	0	0	0%
Bulgaria	4	4	(4)	0	0	0	0	0%
Italy	4	3	(3)	1	0	0	0	0%
Belgium	4	3	(0)	0	1	0	0	0%
Ukraine	4	0	(0)	0	0	4	0	0%
Spain	3	1	(0)	0	0	1	1 (0)	33%
Slovakia	3	1	(1)	0	2	0	0	0%
Lithuania	2	2	(2)	0	0	0	0	0%
South Korea	2	2	(0)	0	0	0	0	0%
Armenia	1	0	(0)	0	0	1	0	0%
Kazakhstan	1	0	(0)	0	0	1	0	0%
Netherlands	1	0	(0)	0	0	1	0	0%
Switzerland	1	0	(0)	1	0	0	0	0%
India	1	1	(1)	0	0	0	0	0%
Pakistan	1	1	(0)	0	0	0	0	0%
Total	218	96	(45)	33	24	42	23 (9)	11% (4%)

Sources: Various, compiled by WNISR, 2025

Notes:

LTE: Long-Term Enclosure.

(a) As of WNISR2024, the “released” category only contains “greenfield released” reactors, whereas it also contained “brownfield released” reactors in previous editions (see **definitions** in the introduction of the chapter).

(b) Three reactors in the U.S. are currently undergoing preparations or are being considered for a restart. These are Palisades, Three Mile Island-1 (now called Christopher M. Crane Clean Energy Center or CCEC), and Duane-Arnold-1. Until the reactors are restarted and this is officially confirmed, WNISR classifies them in their respective last known decommissioning phases (warm-up for Palisades and LTE for the others).

(c) In WNISR2024, the Trino reactor in Italy was erroneously placed into the hot-zone stage and is therefore listed in the warm-up stage in this edition.



3-6

Risk Management



The International Nuclear Event Scale (INES)



Nuclear Reactor Safety



Source IAEA

Chernobyl and Fukushima Daichi



Chernobyl unit 4
after the accident.

Source: De Cort et al., 1998.



Tsunami wave
overrunning the sea
walls and flooding
the Fukushima Daiichi
nuclear power plant
on 11 March 2011
(photo taken from
unit 5).

Source: TEPCO.

The major accidents



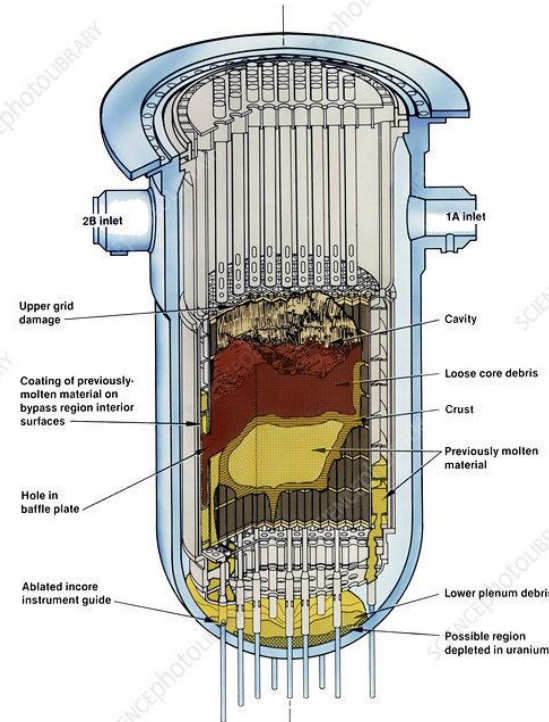
Major Accident : Three Mile Island US (*level 5*)



Source: Britannica

09/24 : To restart TMI unit #1 (835 MWe – stopped in 2019) to power Microsoft data center (~100 \$/MWh)

TMI-2 Core End-State Configuration



Source: Science photo library

PWR

March 28, 1979 (TMI #2, Pennsylvania)

- ◆ **Malfunction of the cooling system (pressurizer valve failure)**
- ◆ **Wrong reaction from the personnel in charge (not aware that the valve remains open)**
- ◆ **The water leaves the reactor, the temperature increases**
- ◆ **Partial meltdown of the reactor core.**
- ◆ **Release of radioactive water in auxiliary building → Release of a significant amount of radioactivity in the air.**
- ◆ **Release of hydrogen (explosion contained inside)**

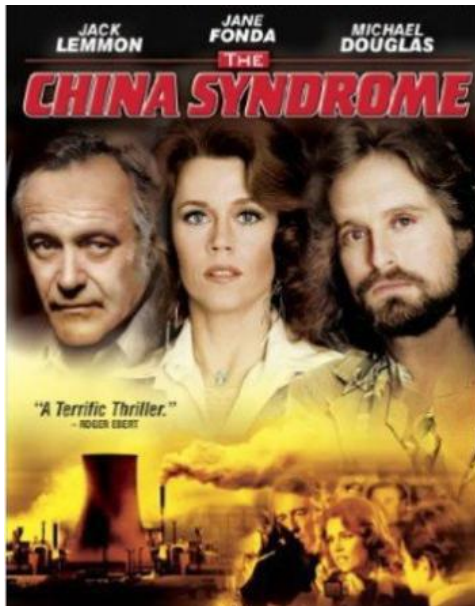
Main causes :

- ◆ **Lack of training of operators**
- ◆ **Poor operating instructions**



Impact of Three Mile Island Accident

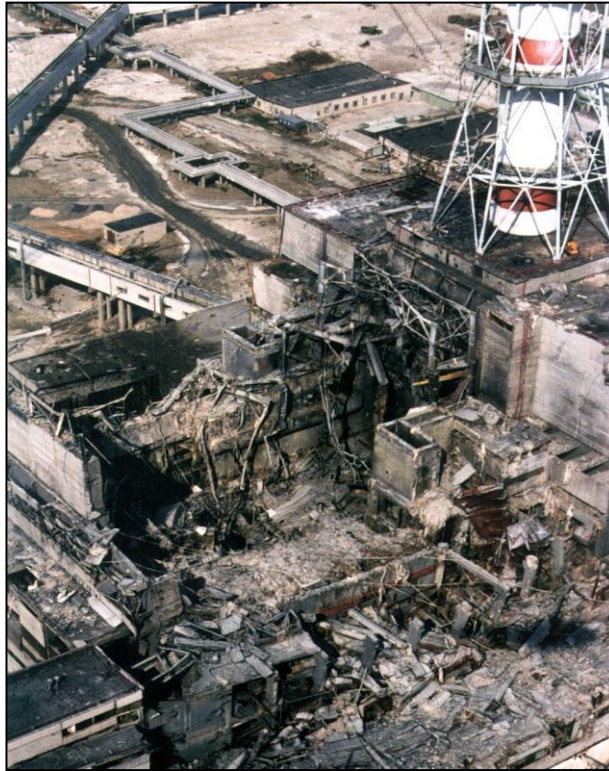
- ◆ No death
- ◆ No radioactive sickness
- ◆ Limited release of radioactive elements in the air (low level)
- ◆ Unjustified evacuation of people
- ◆ Mental stress!



Source: Stanford University



Major Accident : Chernobyl Ukraine *(level 7)*



April 26, 1986 – 1:24 a.m.: Reactor No. 4 explodes in Chernobyl ...

RBMK

April 26, 1986

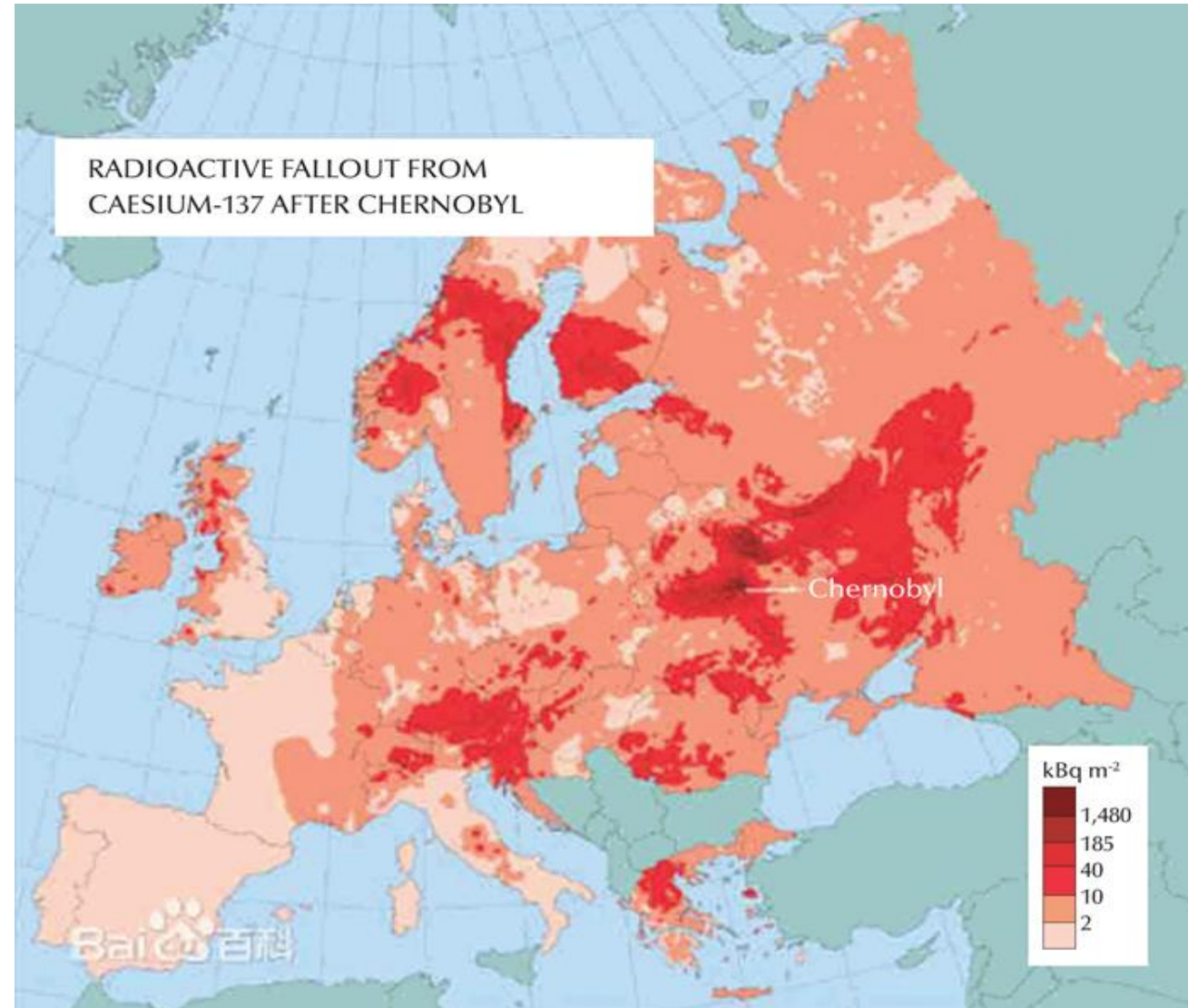
- Redundancy test :
 - Reduce power to 1/3
 - Emergency Core Cooling System Disconnected
 - Instruction : do not “operate” the core
 - Shortage of power in the region → request to operate the plant at 50% without further decrease of power (duration of test extended → nuclear core impacted)
 - New (night) shift: not prepared for the test
 - Operators’ wrong decisions and mistakes
- Melting of the reactor core
- Pressure build-up → ‘Steam’ explosion (not a ‘nuclear’ explosion)
- Several other explosions
- Fire of the building
- Release of radioactive contaminants

Main cause : several violations of the procedures



Impact of Chernobyl Accident : Geographical

- Burning of the graphite tips of the rods
- Radioactive ashes in the air
- All over Europe...



Source: JLE



Impact of Chernobyl Accident : Short Term

- 31 rescue team members died within days of the accident.
- 200,000 workers ("liquidators") irradiated in the following months.
- 350,000 people evacuated from contaminated areas
- 200,000 km² contaminated in Europe.
- 784,320 ha of agricultural land and 694,200 ha of no-production forests.



Source: Actu.fr



Source: Science et Avenir



Impact of Chernobyl Accident : Long Term

Mid-term effects → 2005 (OMS)

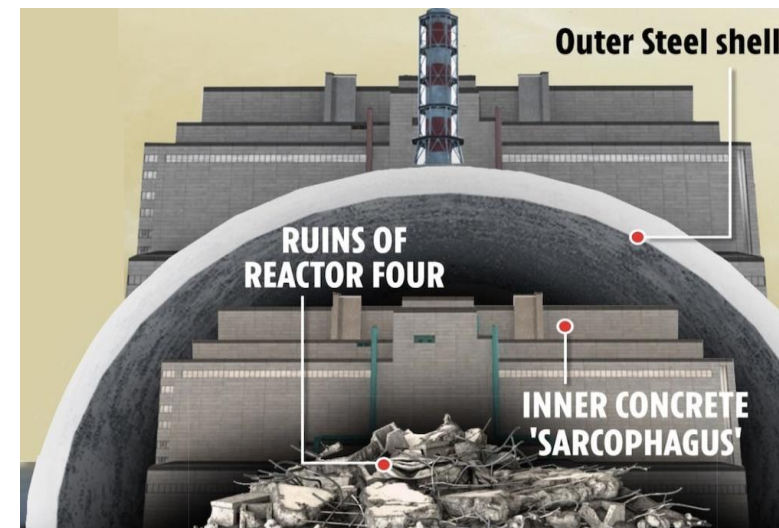
- Less than 50 deaths in total.
- 4000 cases of thyroid cancer (children irradiated at the time of the accident)
- Nine young people died.
- No indication of increased birth defects, leukemia or other cancer.

Long term consequences

- 4000 people *could* die of cancer ...
- of which 2200 among the 200,000 liquidators.



Source: UN News



Source: Trust my science

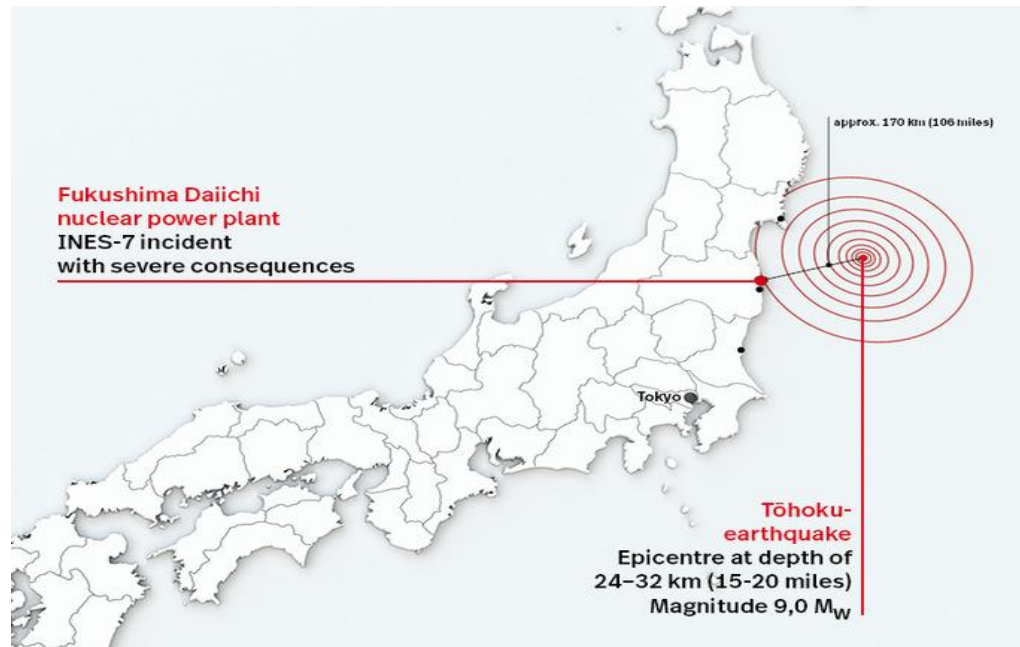


Major Accident : Fukushima Daiichi Japan *(level 7)*



Source: CNET

BWR



Friday March 11, 2011

- ◆ **Earthquake** : reactors 1, 2 & 3 automatically shut down (others not in operations)
- ◆ **Tsunami** (40 min later): 2 waves (~10 m & ~14 m high)
- ◆ **Flooding** : cooling systems & backup systems (diesel generators & some DC batteries) damaged (flooding).
- ◆ Residual heat → vaporization of water in the reactor vessel
- ◆ Decrease in the water level until part of the fuel is uncovered.
- ◆ Fusion of the cores (melted) & release of hydrogen.
- ◆ Explosion of hydrogen

Main cause : underestimation of the wave high during a tsunami (human error at the design phase)



Impact of Fukushima Accident

- ◆ No death
- ◆ No radioactive sickness
- ◆ 160 000 people evacuated
- ◆ Volatile fission products released in the air (due to explosions)
- ◆ Water contaminated : removal of radioactive elements & progressive release into the sea

(The earthquake and the tsunami caused directly the death of more than 15 000 people!)



Source:
Washington post



Source:
Financial Times

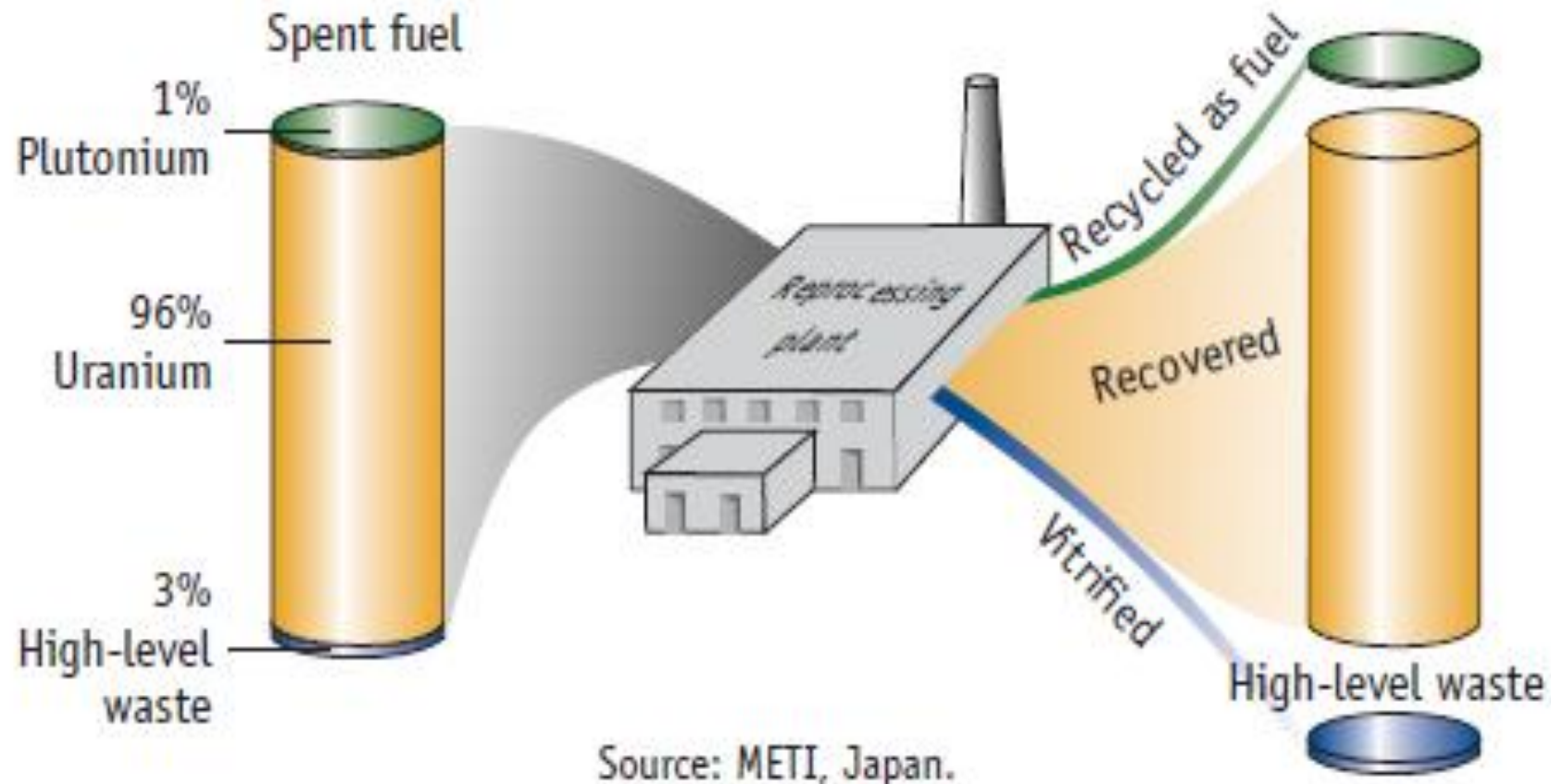


3-7

Waste Management



Composition and Reprocessing of Spent Fuel



HLW Half-life

Isotope	Approximate half-life
Strontium-90	29 years
Caesium-137	30 years
Americium-241	430 years
Americium-243	7 400 years
Plutonium-239	24 000 years
Technetium-99	213 000 years

Pure Uranium is weakly radioactive. It decays slowly by emitting an alpha particle.

Uranium ₂₃₈	4,47 billion years
Uranium ₂₃₅	704 million years

HLW: High Level Waste



Volumes (m3) of Radioactive Waste Produced Annually by a Typical 1 000 MW Plant

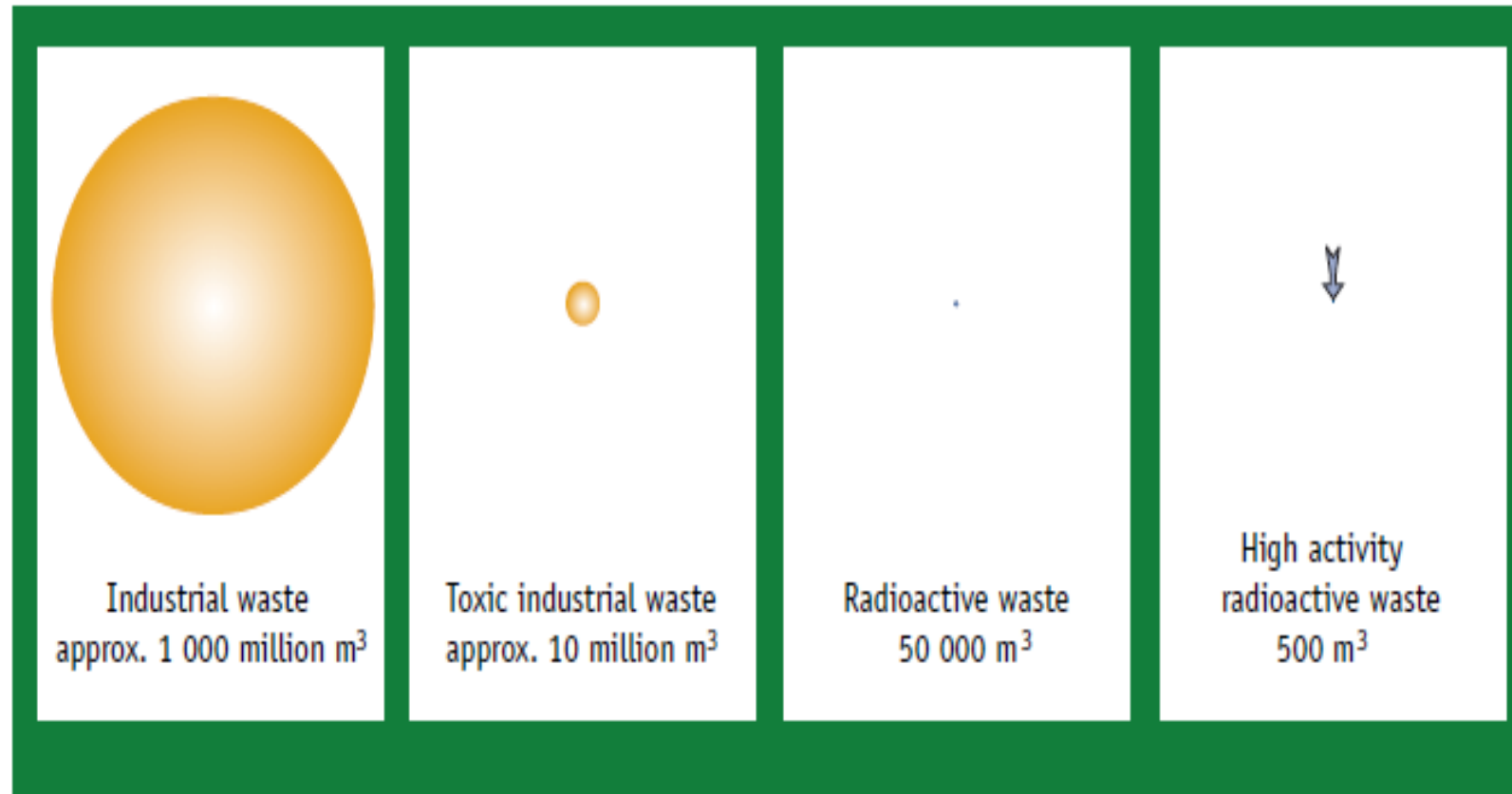
LLW: Low Level Waste ILW: Intermediate Level Waste HLW: High Level Waste SNF: Spent Nuclear Fuel	Waste type	Once-through fuel cycle	Recycling fuel cycle
	LLW/ILW	50 - 100	70 – 190
	HLW	0	15 – 35
	SNF	45 - 55	0

Source: European Commission , Radioactive Waste Management in the European Union (1998)

Source: OECD NEA 2012



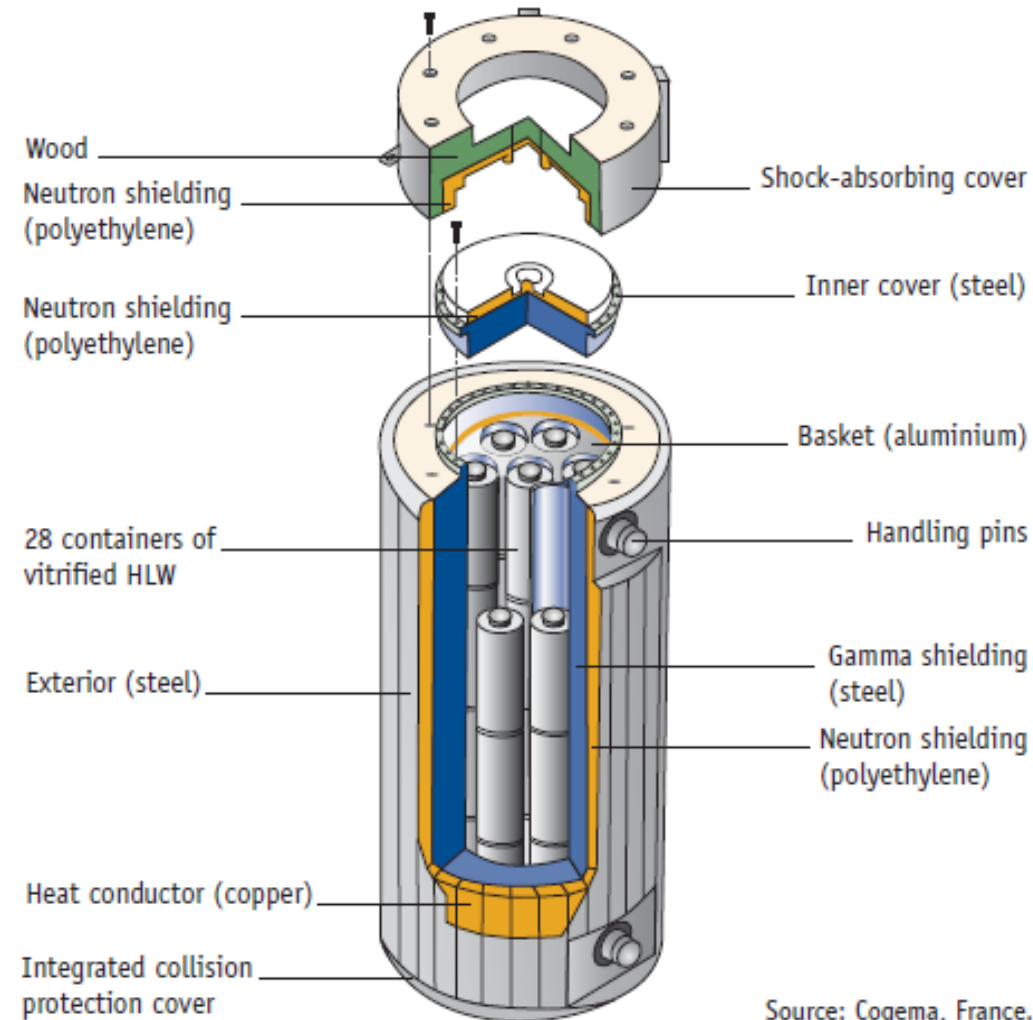
Yearly Waste Production in EU



Source: *Nuclear and Renewable Energies* (Rome: Accademia Nazionale dei Lincei, 2000), updated with data from the European Commission, *Radioactive Waste Management in the European Union* (Brussels: EC, 1998).



A Typical HLW Transport Cask



Source: Cogema, France.



Nuclear Waste Repository planning and countries

Country	Share of Global Once Operating Nuclear Capacity*	Disposal Site Location	Status	Commissioning date as of 2023	Repository Ownership as of 2023
United States	23.32%	None selected to replace Yucca Mountain	Project proposed	Suspended	State
France	13.48%	Cigéo	Site selected	2035 (10-year slippage from 2015 estimate)	State
China	10.71%	None selected	Project proposed	2050+	State
Japan	9.83%	None selected	Project proposed	2035	Utility
Russia	6.38%	Krasnoyarsk	Site selected	To be confirmed	State
Germany	5.31%	None selected	Site search	2046–2068+ for site selection (several decades slippage from 2015 estimate)	State
South Korea	5.18%		Under study	Construction of underground facilities from 2043-2060	State
Canada	3.17%	None selected	Project proposed	2040+ (5-year slippage from 2015 estimate)	Mixed; NWMO set up by utilities (some state-owned) and Atomic Energy Canada LTD.; not clear on ownership of the repository site.
United Kingdom	2.75%	None selected	Project proposed	2040 (was no target date in 2015)	State
Sweden	2.21%	Forsmark	Site selected	2030-2032 (2-4-year slippage from 2015 estimate)	Mixed; utility responsibility, though most of the reactors are owned by Vattenfall AB which is wholly owned by the Swedish state.
Spain	1.65%				State
India	1.39%	None selected	Project proposed	To be confirmed	State
Belgium	1.2%				State
Finland	0.88%	Onkalo	Construction underway	2024	Mixed; Posiva owned by Fortum (majority state-owned) and TVO (private, but partially owned by Fortum)
Czech Republic	0.79%	None selected	Project proposed	2065	State
Switzerland	0.67%	Nördlich Lägern	Site selected	2060 (was no target date in 2015)	State
Slovakia	0.65%	None selected	Project proposed	To be confirmed	
Hungary	0.39%	None selected	Project proposed	2030	State

Sources: compiled by WNISR, based on NEA, 2020; WNA, 2023; IAEA/PRIS, 2023; repository owner websites, 2023; Pulse, 2022⁶⁶³

Note: * Share of global capacity based on Operating, LTO and Closed reactors as of 1 July 2023.

Source: Mycle Schneider WNISR December 2023

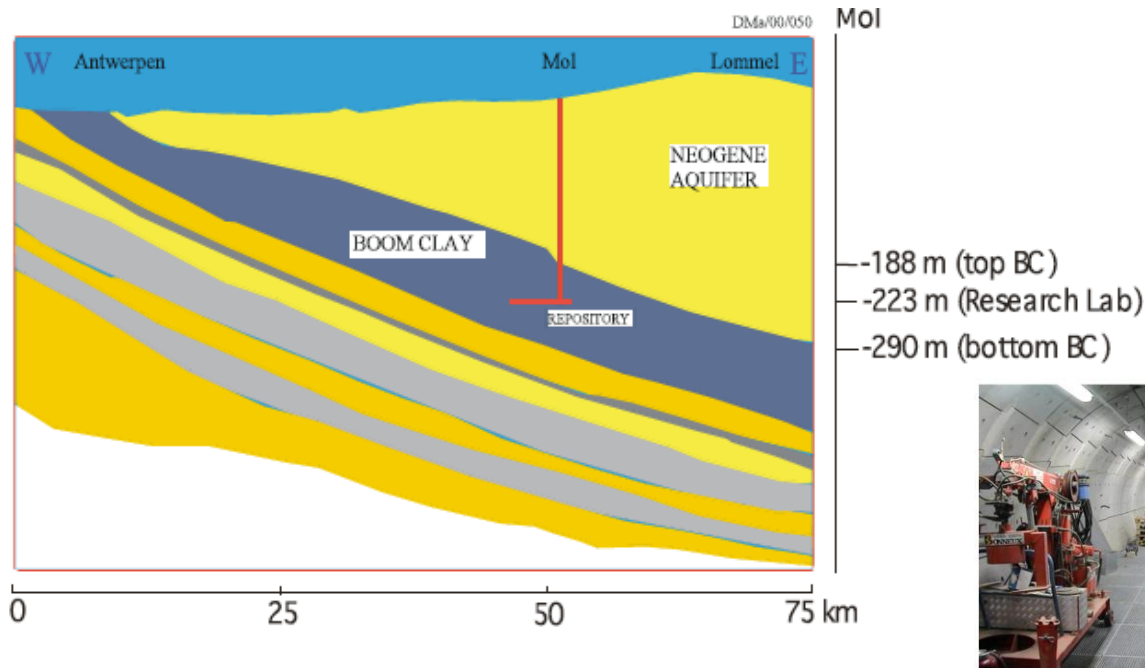


LLW and ILW Management

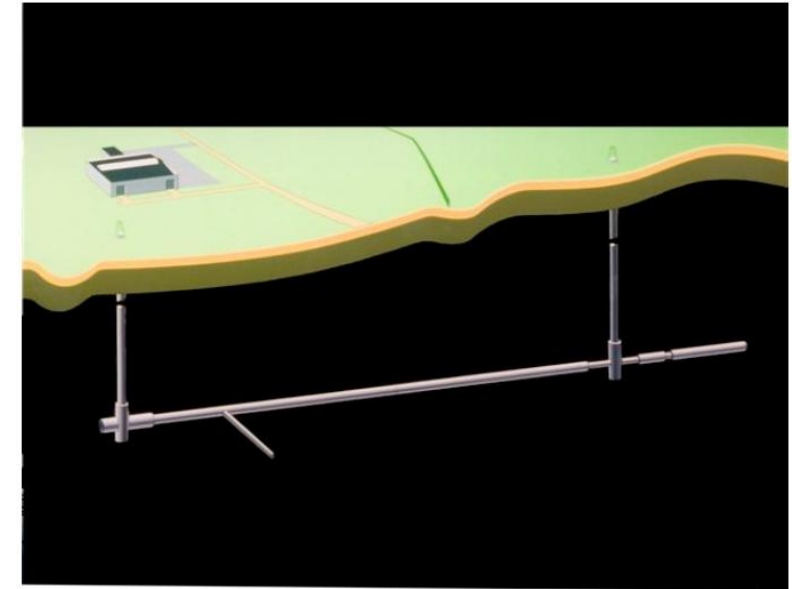
Repository for LLW and ILW in Sweden.



Geological Disposal



Argillaceous formation: Boom Clay (Mol, Belgium)



Hades Underground Laboratory



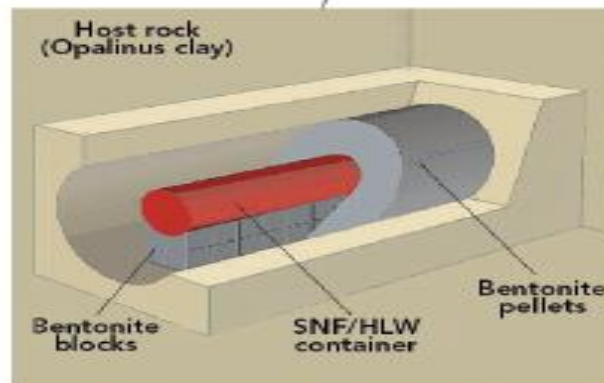
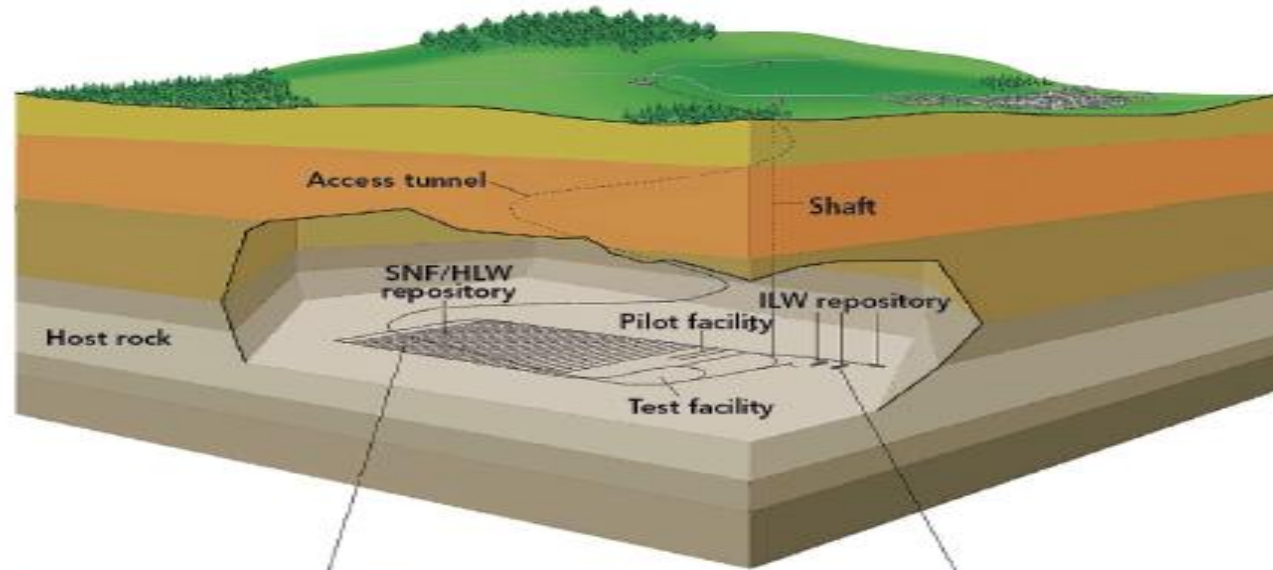
The HADES underground research laboratory :

The name “EURIDICE” stands for “European Underground Research Infrastructure for Disposal of nuclear waste in a Clay Environment”.

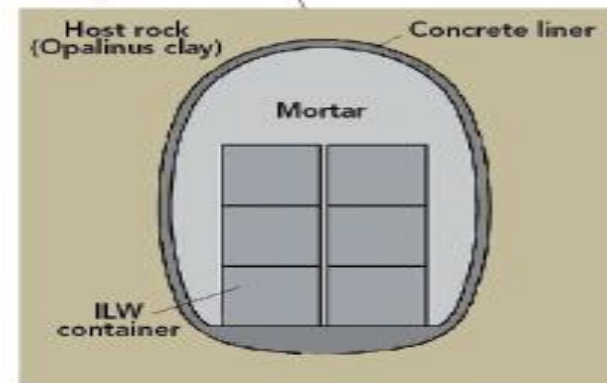
EURIDICE manages and operates the underground research laboratory known as HADES (High Activity Disposal Experimental Site), where experts develop and test industrial technologies for building, operating and sealing a waste repository in deep clay.



Multiple-Barrier System for Geological Disposal



Emplacement drift for SNF/HLW



Emplacement tunnel for ILW

Note: Based on the Swiss concept.
Source: Nagra.

Note: One project in France:
CIGEO/Bure



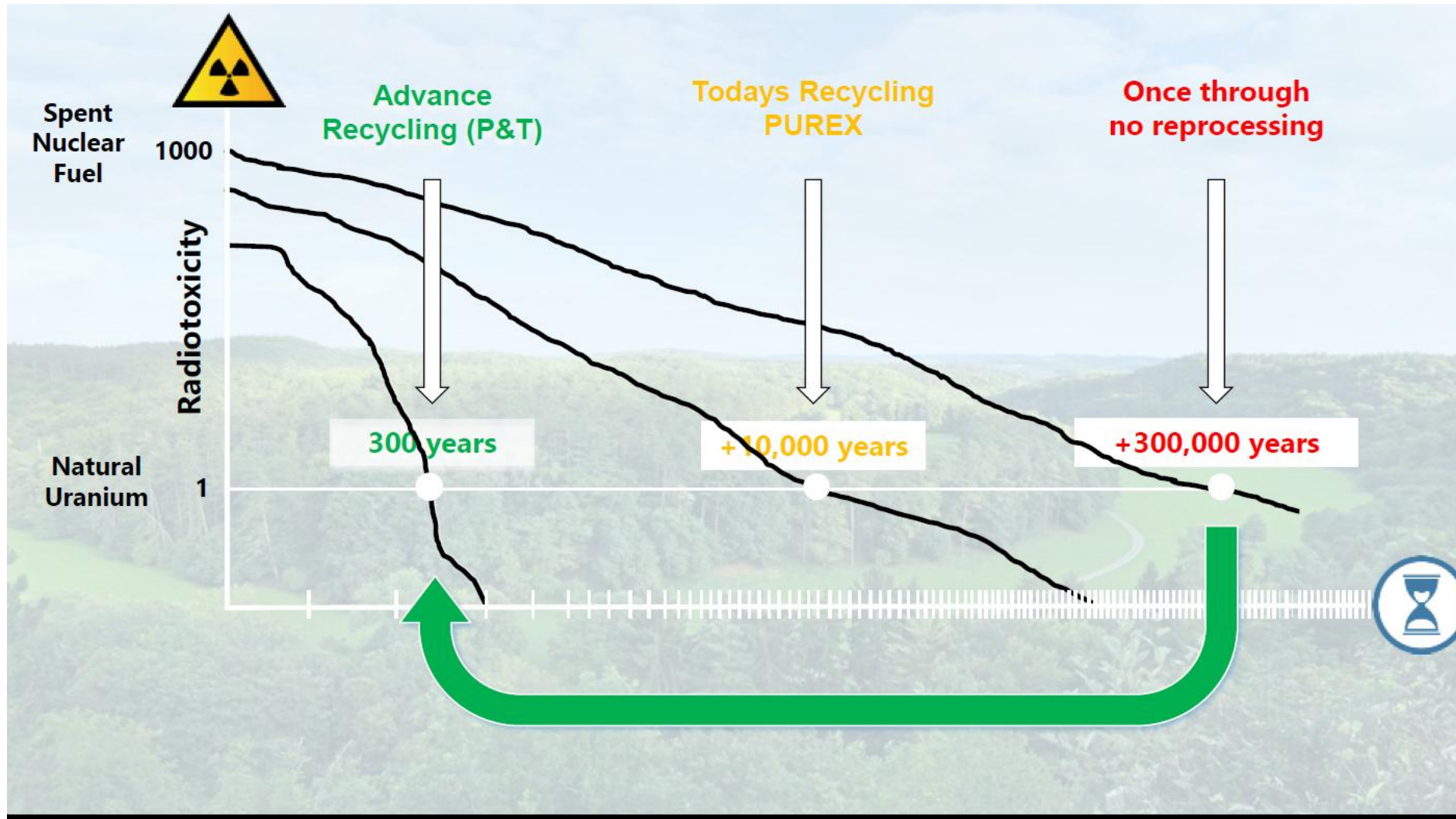
Funding mechanisms for Decommissioning and Waste Management

	Funding Management of Spent Fuel and High-level Radioactive Waste		Funding of Decommissioning	
Countries with Activities to be Funded	Number of Countries 47	Share of Countries	Number of Countries 49	Share of Countries
Funding Mechanisms				
Government Funding	10	21.3%	12	24.5%
Government Funding b/c State Owned Enterprise	4	8.5%	2	4.1%
Some Government Funding by Design or Shortfall	6	12.8%	5	10.2%
User Funding Only	27	57.4%	30	61.2%
All countries rely on governments to make up any shortfalls				

Sources: IAEA, 2023¹⁰⁶



Advance Recycling of Nuclear Waste



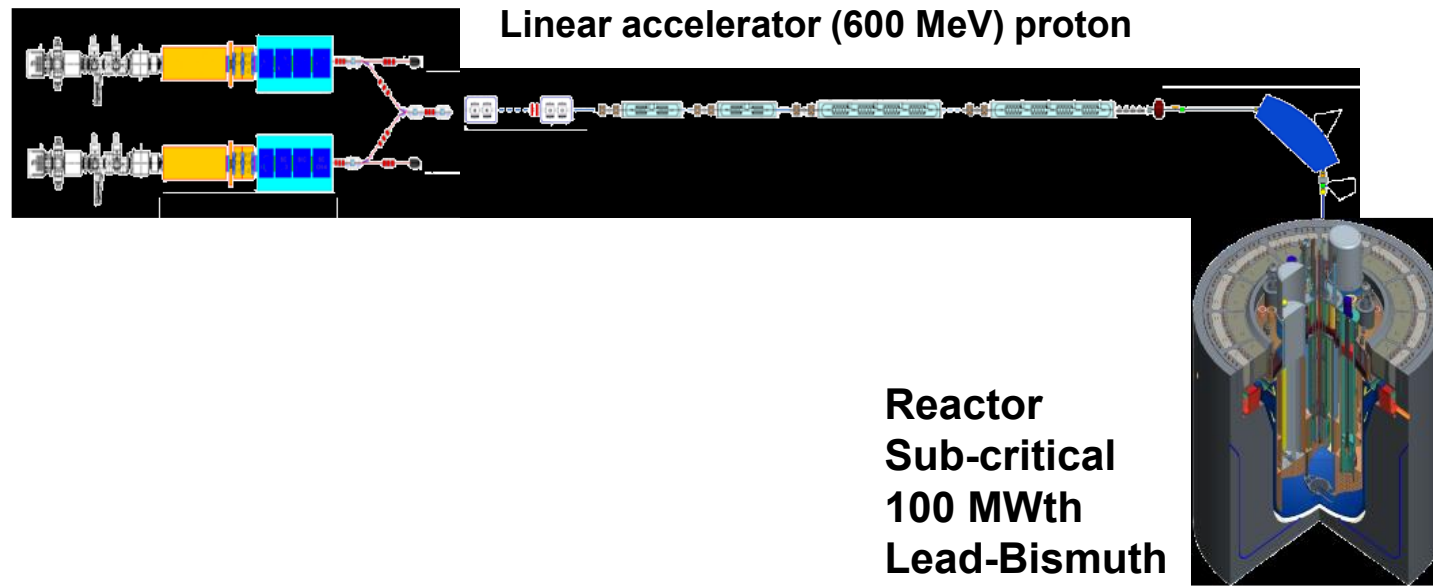
P&T : partitioning
& transmutation



Reducing the duration of radiotoxicity of minor actinides?

◆ Radiotoxicity of minor actinides (half-life)

- Once through / no reprocessing : 300 000 yr
- Today's Recycling Purex 10 000 yr
- Advance recycling (partitioning & transmutation) 300 yr



First phase of demonstration
project under construction
(*Multi-purpose hYbrid Research
Reactor for High-tech
Applications*)

Source : SCK CEN



4

Future evolution



TABLE OF CONTENTS

1. What is nuclear energy ?
2. What are uranium resources ?
3. The world nuclear industry: past and present
4. Future evolution
5. The world nuclear industry and the energy and oil & gas industry: interest from stakeholders ?



4-1

Past Evolution and Perspectives



The situation **post-Fukushima** (11 March 2011)

- EU announced plans to « stress test » all nuclear plants in its 27 countries
- France continues to support nuclear power. Safety as priority. Fessenheim closed in 2020.
- USA continues to support nuclear power. Safety as priority.
- Japan announced a review of the existing plans, massive investments in gas supply.
- Russia continues to support nuclear power. Comprehensive safety review
- **Germany decided to close nuclear reactors by 2022**
- **Belgium (7 nuclear reactors) decided to phase out nuclear energy by 2025.**
- **Switzerland plans to close its 5 reactors by 2034.**
- **Italy, Austria, Spain: ban on the reintroduction of a nuclear programme.**
- **The new president in South Korea put on hold some nuclear plants projects.**
- China had new construction going on for an additional 40 GW (closed to shore, 3rd generat.) but recently, there has been a slowdown in the construction program.
- UK has plans to build 8 new reactors by 2025
- India plans to boost nuclear capacity to 63 GW by 2032.
- Turkey started construction of Akkuyu nuclear plant in 2018. Other projects are under study.
- Belarus, Bangladesh, Poland, Saudi Arabia (17 projects announced, 18 GW, 80 G\$ investments), UAE, Iran, Egypt, Jordan, Brazil, South Africa, Netherlands, Sweden, Chile, consider to pursue nuclear power plants programme (Plans, Commitments, Call for tenders, Constructions)



In OECD, Nuclear Industry is facing difficulties

- Nuclear industry remains important for decarbonized electricity generation.
- 62 reactors (78 GWe) under construction
 - 28 in China, 42 in all Asia,

BUT

- 2007 : 439 operable reactors → 2024 : 440 operable reactors
 - Fukushima accident in 2011
 - German decision - Energiewende
- The industry suffered **suspensions of projects, construction delays & costs overruns**:
 - Flamanville 3 : 12 years delay, 23,7 G€ final vs 3,3 G€ initial estimate
 - Olkiluoto : 13 years delay, 8,8 G€ = 3x initial budget
- The sector suffered from **bankruptcy** & bailout affecting some historical actors of the nuclear industry:
 - Toshiba/Westinghouse,
 - Areva (Now Orano),
 - Debt of EdF (64 G€ end 2022),



In France, Nuclear Industry is facing difficulties

- **Huge projects** : Flamanville EPR (1650 MW):
 - 120 000t of steel, 70 000t of framework, 400 kms of pipes, 1 850 kms of cables, 460 000m³ of concrete, double containment enclosure
 - Will supply 2 million people in electricity.
- **Huge problems: Delays, Costs overruns.**
- **Why?**
 - Multiple changes of regulations,
 - Loss of technical competence for all stakeholders...
 - Inconsistency of political decisions by successive governments,
 - Lack of new investments in the sector,
 - Emphasis given to a program of existing nuclear reactors closure ,.....
- **Three conditions:**
 - Best Available Technologies,
 - Skilled Staff,
 - Independent Control Authority (ASN – Autorité de Sûreté Nucléaire)



The situation in 2025

- Energy Independency remains vital (Russia-Ukraine war!).
- The Energy Mix needs to be decarbonated.
 - **Nuclear Energy remains part of the solution**
- In **France**, decision in 2023 to
 - Construct 6 to 14 EPR2 (new generation). Production start-up in 2035. Cost for 6 EPR2 # 67 G€, current estimate.
 - Develop Small Modular Reactors (SMR)
 - Extend existing reactors duration life (50 G€ available by EdF)
 - Foresee 30/40 EPR new generation for 2050.
- In **Sweden**, on November 2023, decisions to :
 - re-activate the nuclear industry in the country.
 - remove the limit of 10 reactors maximum in the country
 - built 10 new reactors by 2045.
 - promote the construction of Small Modular Reactors (SMR)
- In **Belgium**, between 2023 and 2025, decision to
 - Extend the life of 2 reactors by 10 yrs
 - Remove the lawful obligation to close all reactors
 - Promote the construction of new reactors and/or SMRs
- In **Japan**, re-launch of some reactors stopped after Fukushima
- In a number of countries, new nuclear plants are under construction and/or are planned.
- Growing Electricity needs for AI & Data centers. Involvement of Big Tech companies: Meta, Microsoft, Amazon,....
- Large investments anticipated in US (New AP1000, reopening of Three Mile Island?) & elsewhere.

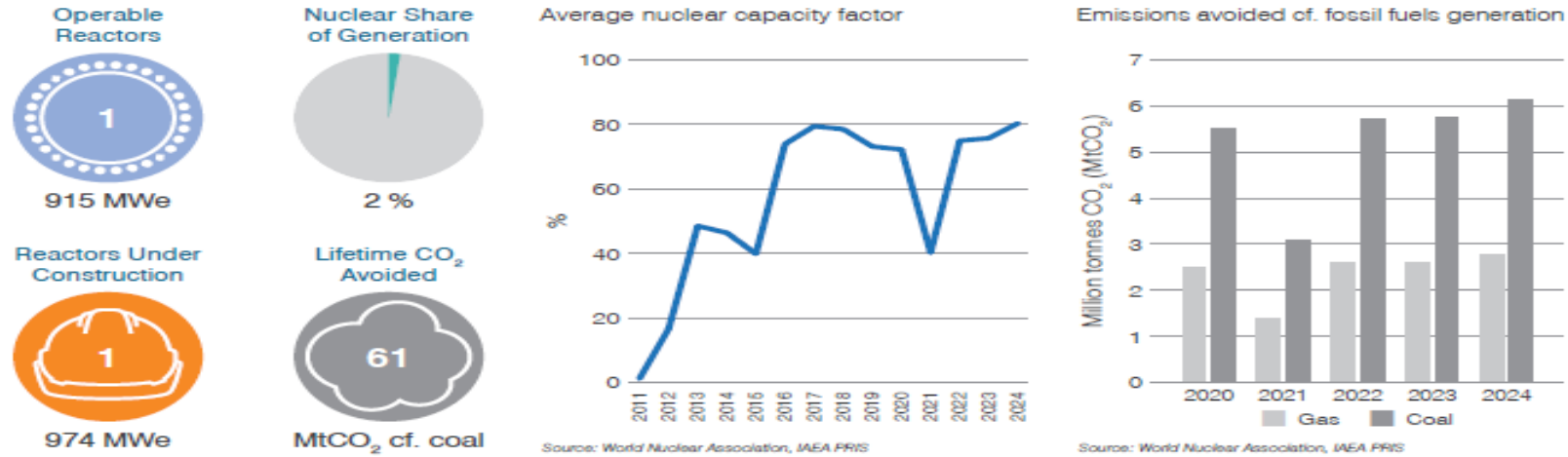


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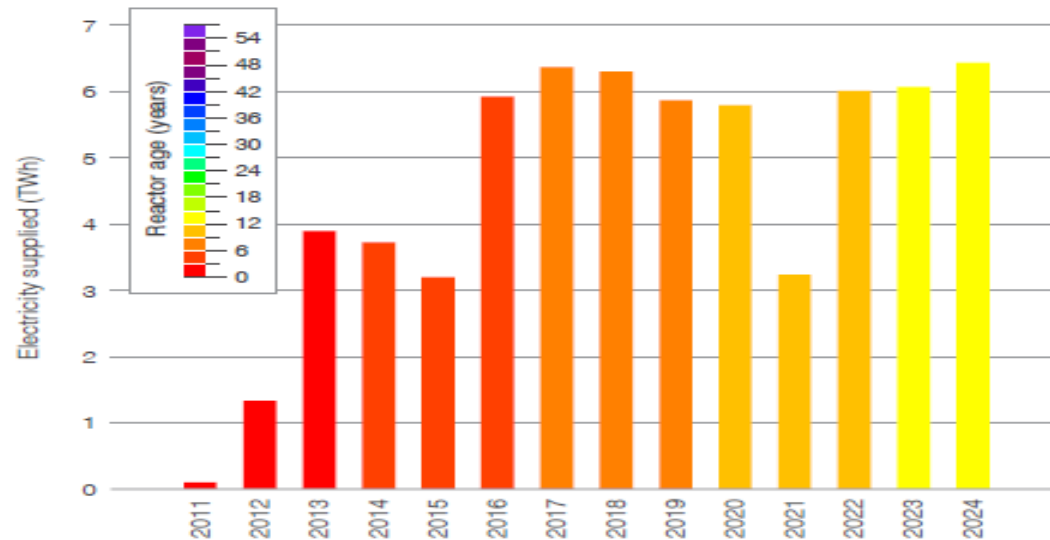
A Zoom on the Middle East



Nuclear Energy in Iran



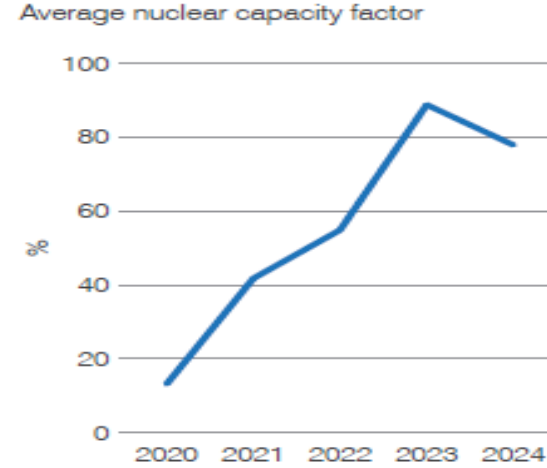
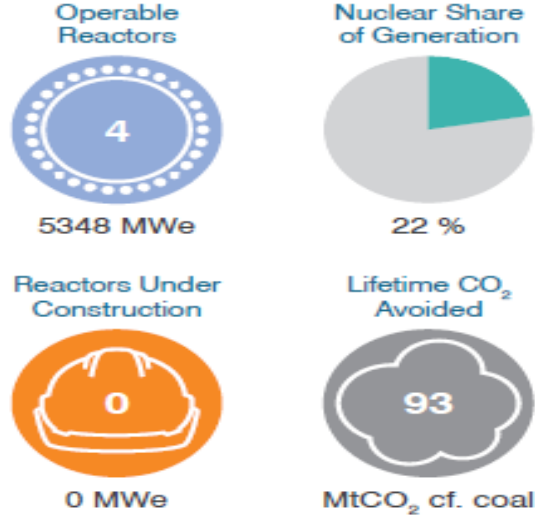
Nuclear electricity production



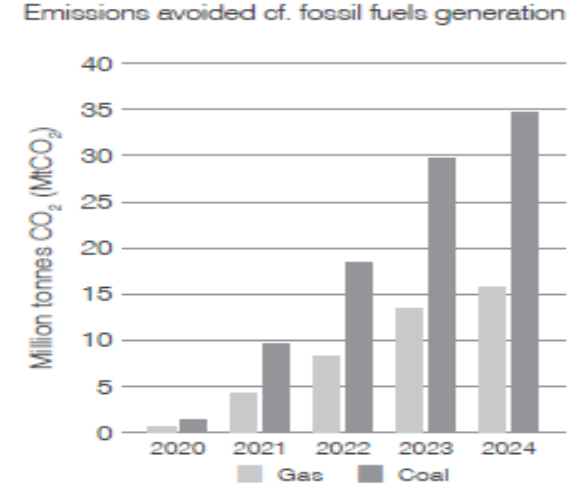
Source: World Nuclear Association, IAEA PRIS



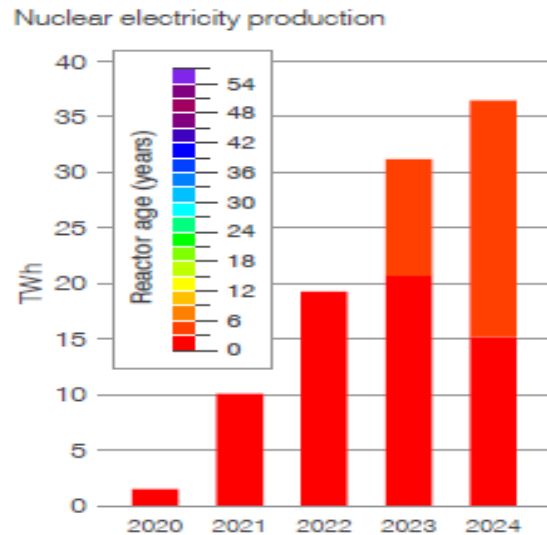
Nuclear Energy in UAE



Source: World Nuclear Association, IAEA PRIS



Source: World Nuclear Association, IAEA PRIS



Source: World Nuclear Association, IAEA PRIS

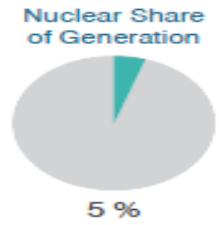
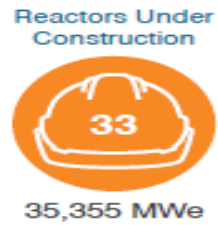
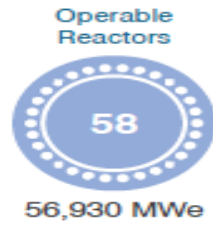


4-3

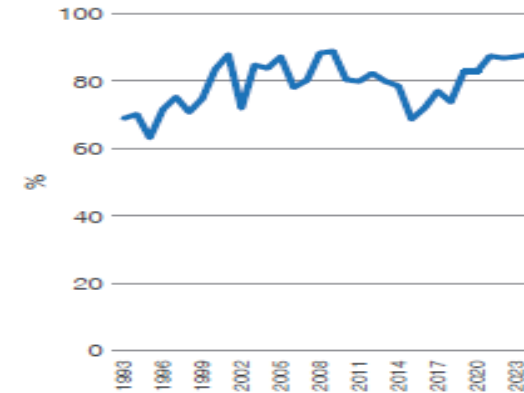
A Zoom on China



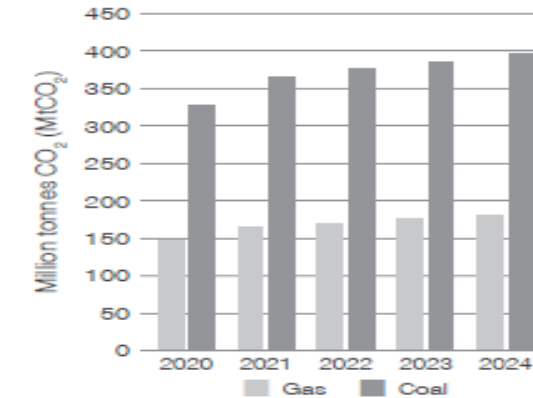
Nuclear Energy in China



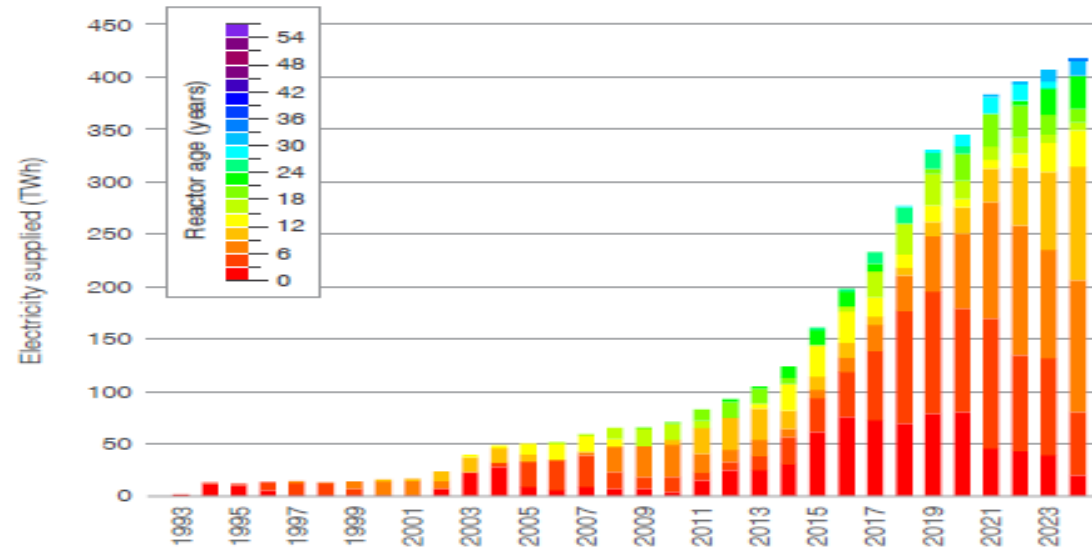
Average nuclear capacity factor



Emissions avoided of fossil fuels generation



Nuclear electricity production

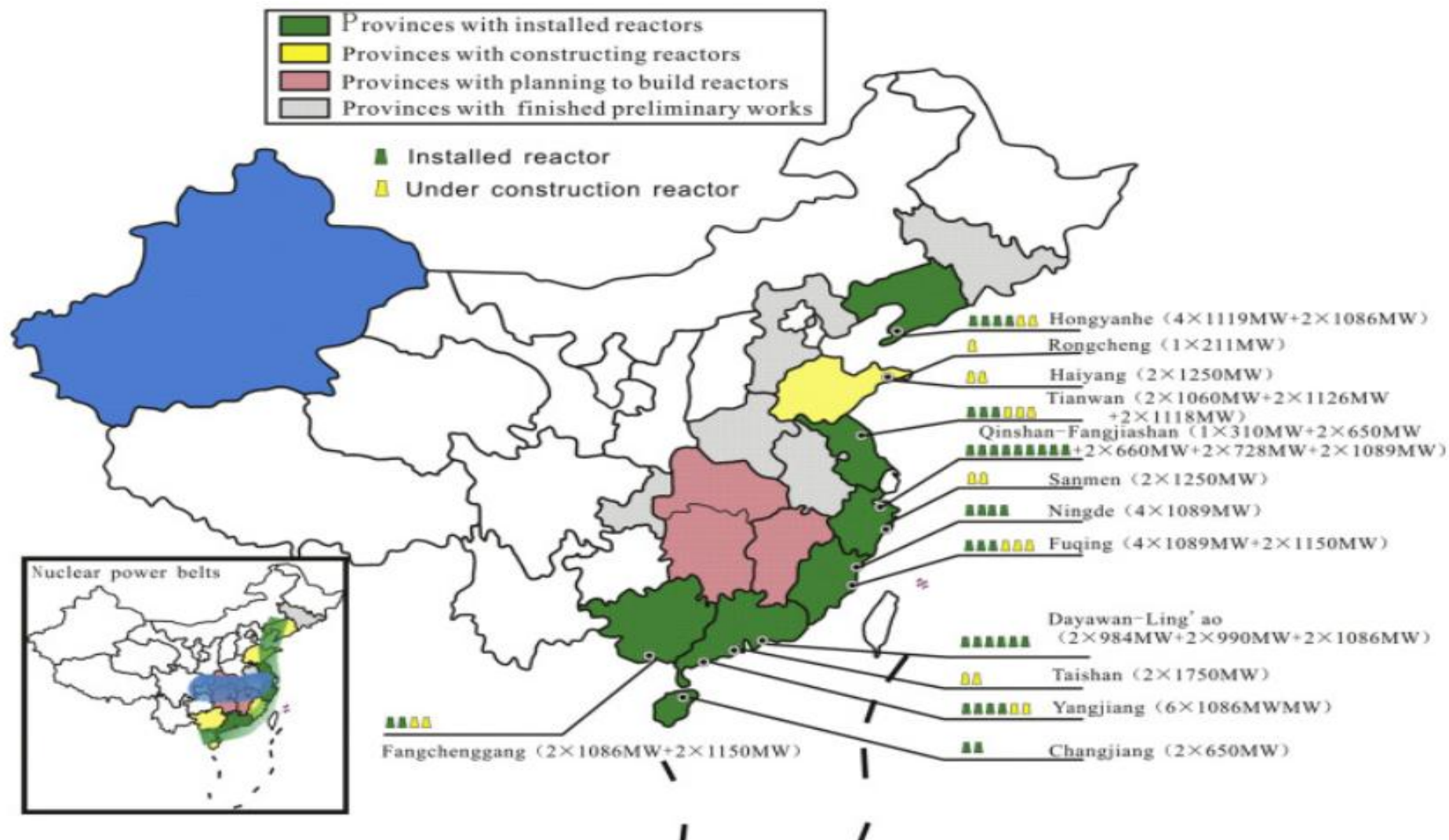


A boom forecasted in China for Nuclear Energy

- **February 2018: merger between CNNC (China National Nuclear Corporation) and CNEC (China Nuclear Engineering and Construction)**
- **China's objective: to replace coal-fired plant by decarbonized sources of energy.**
- **As of end 2024, 58 operable reactors with 57 GWe generating capacity , 33 under construction for a capacity of # 35 GWe. A program to build additional reactors is ongoing.**
- **Third generation reactor Hualong One (made in China) is exportable.**
- **10/12 new reactors per year over 10 years in China in the near future?**
- **But, more recently, uncertainty on the program.**
- **New Areva/CNNC contract for nuclear waste treatment plant – 10 G€.**



Locations of Nuclear Plants Projects in China

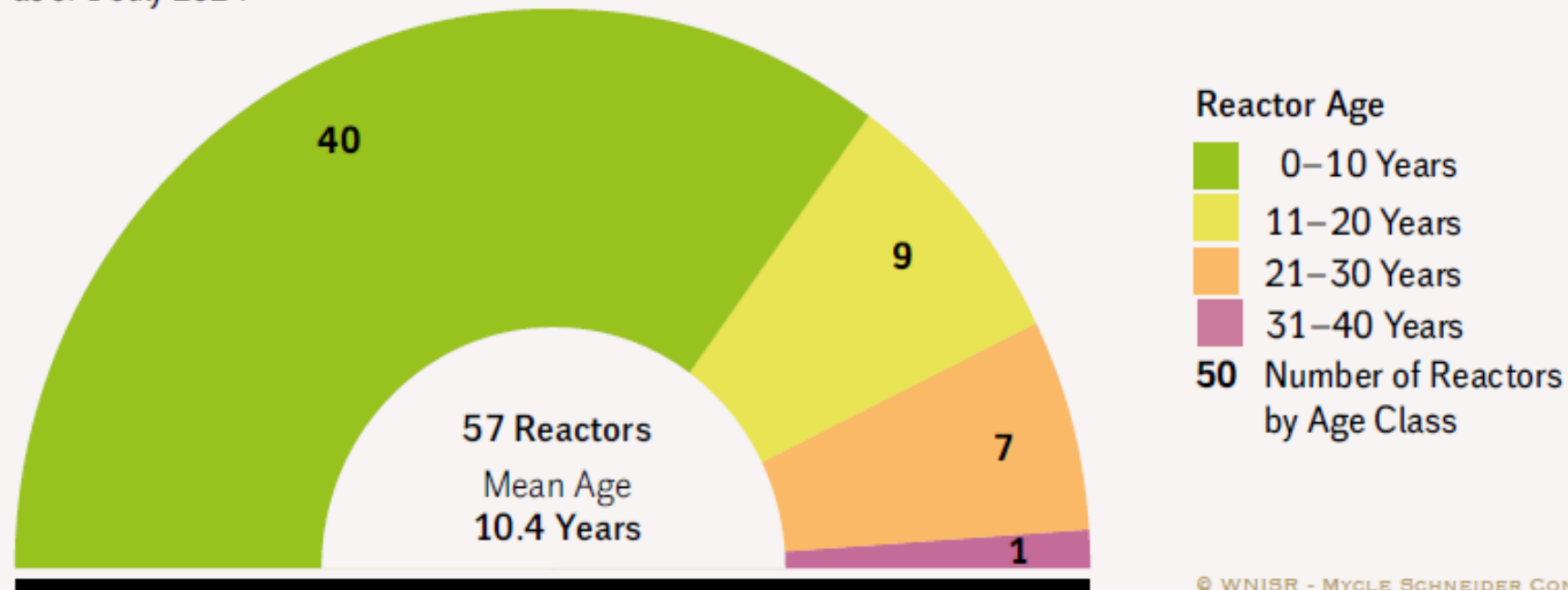


A boom forecasted in China for Nuclear Energy

A young nuclear Fleet today – Mean age: 11 years in 2025

Age of Chinese Nuclear Fleet

as of 1 July 2024



Sources: WNISR with IAEA-PRIS, 2024

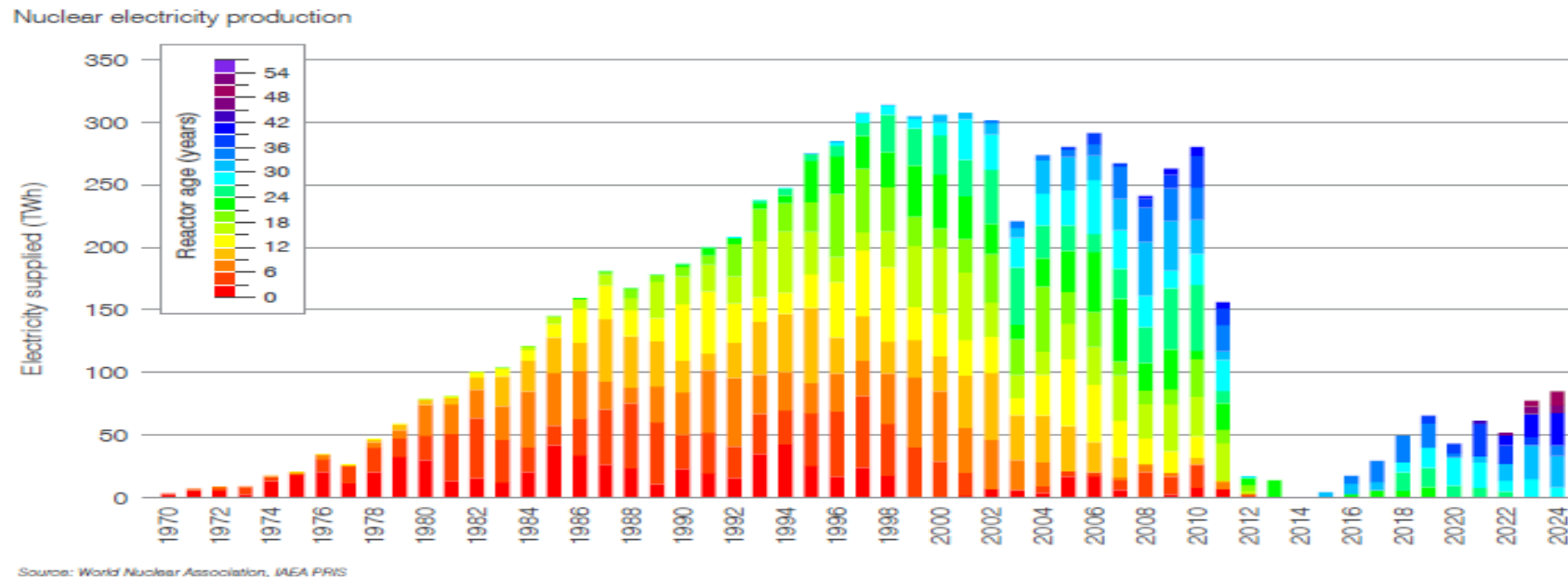
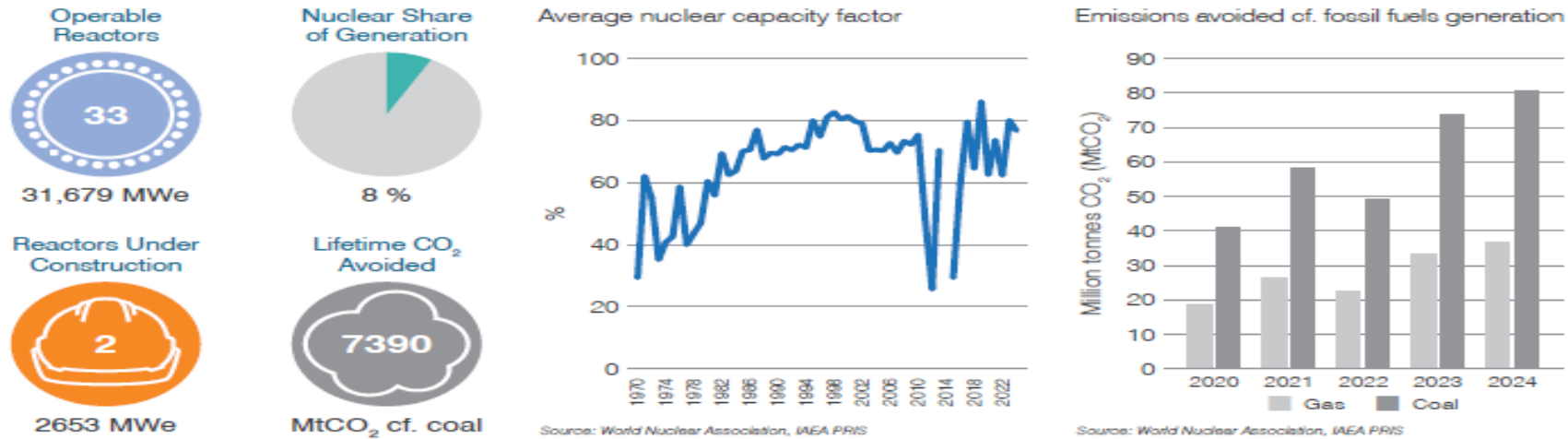
Source: Mycle Schneider
WNISR IAEA-PRIS September 2024

4-4

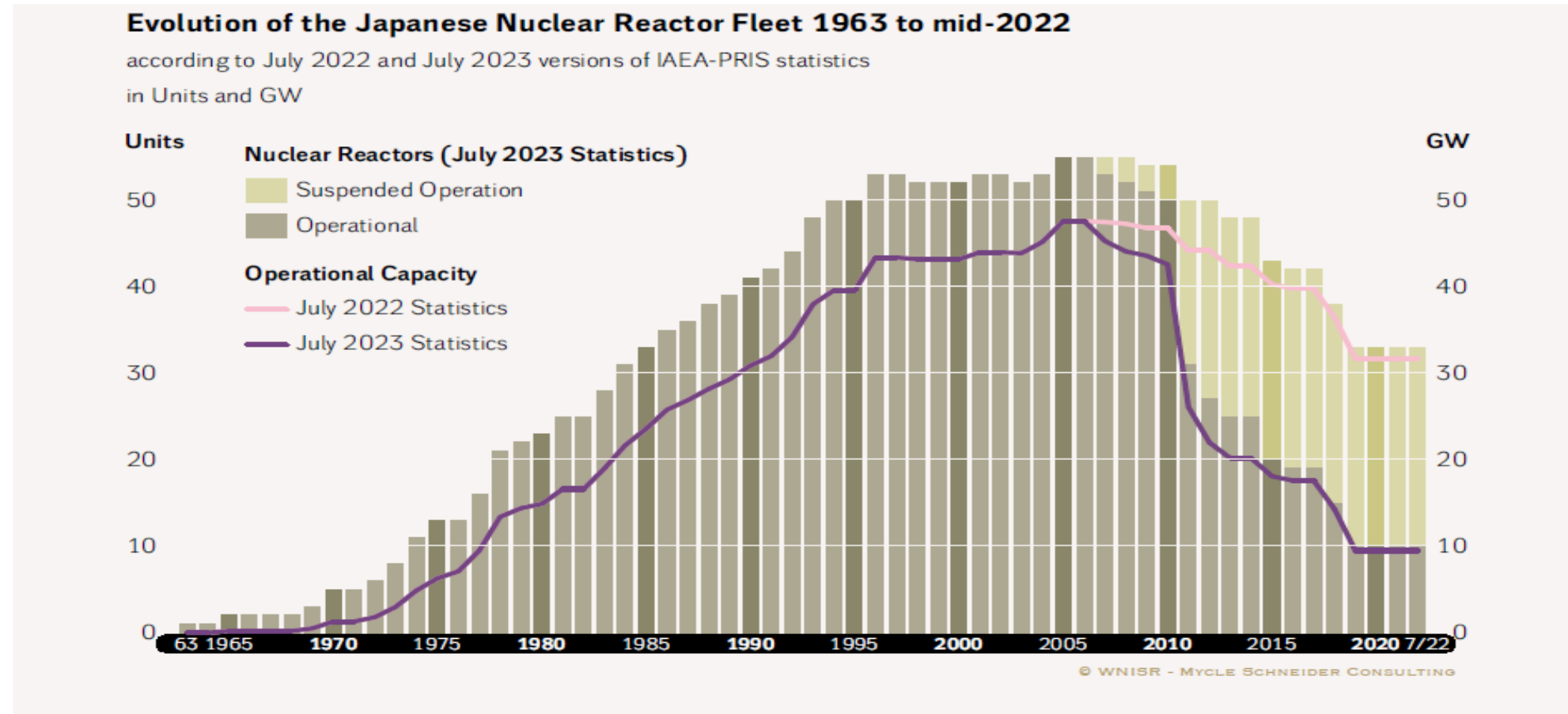
A Zoom on Japan



Nuclear Energy in Japan



Japanese Nuclear Reactors 1963 - 2022



Sources: IAEA-PRIS, July 2022 and July 2023

Note: All reactors listed in the “Suspended Operation” category as of July 2023, were considered Operational in July 2022 statistics.

Source: Mycle Schneider
WNISR with IAEA-PRIS December 2023



Fukushima Situation from March 2011 to 2019



11 March 2011: Explosion/fusion of the core of Fukushima nuclear reactors



24 March 2011: Shock wave in one control room. No corporal victims due to the accident, contrary to the consequences of the tsunami.



2019: Zone with prohibited access in Fukushima prefecture. 165000 persons evacuated, 36000 are still homeless.

Source: Challenges 11 mars 2021



Fukushima Situation at beginning 2021 and further steps

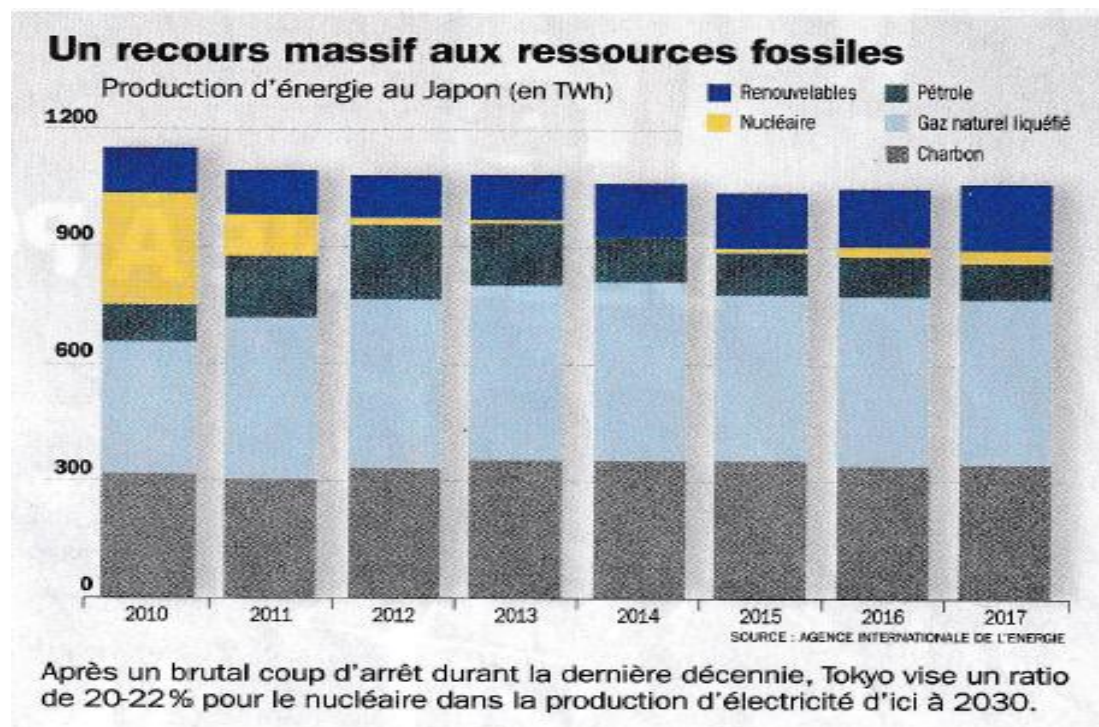
- **Works are going on onsite and offsite**
- **7 000 workers are mobilized for decommissioning work onsite.**
- **Onsite: Spent Fuel Removal and Fuel Debris Removal are continuing together with Contaminated Water Management.**
- **900 t of melted fuel has to be extracted.**
- **965 tanks of contaminated water (tritium) are being used, but with limited level of Bq. Maximum capacity will be reached in 2022.**
- **Infrastructures devastated by the tsunami have been rebuilt.**
- **During the five past years, no traces of cesium in agricultural production.**
- **Other offsite issues are being followed-up: future of evacuees from affected municipalities, health consequences of the disaster, decontamination wastes management, and costs involved (# 170 G€ estimated today)**
- **A recent decision has been taken to evacuate low contaminated water in the sea**
- **At least 3 decades will be necessary to restore the site.**



Fukushima Situation at beginning 2021

Le Japon réactive l'atome

Consommateur d'énergie atomique et acteur engagé dans la filière, l'Archipel a soutenu l'essor des renouvelables après Fukushima. Mais il a besoin du nucléaire pour l'objectif «zéro carbone» d'ici à 2050.



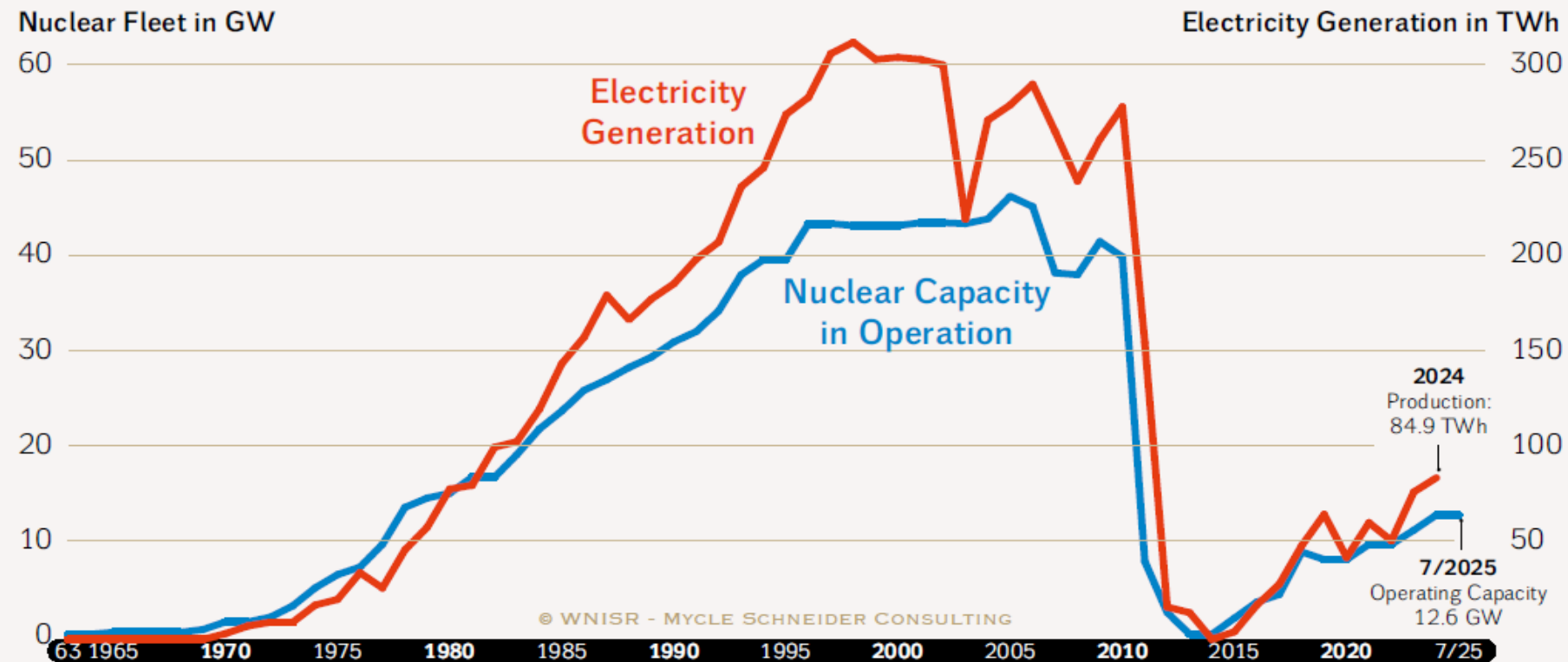
Source: Challenges 11 mars 2021

Japanese Nuclear Program 1963-2025

Consequence of Fukushima

Rise and Fall, and Slow Restart of the Japanese Nuclear Program - 1963 to July 2025

Operating Fleet (in GW) and Electricity Generation (gross in TWh)



Sources: WNISR with Energy Institute and IAEA-PRIS, 2025

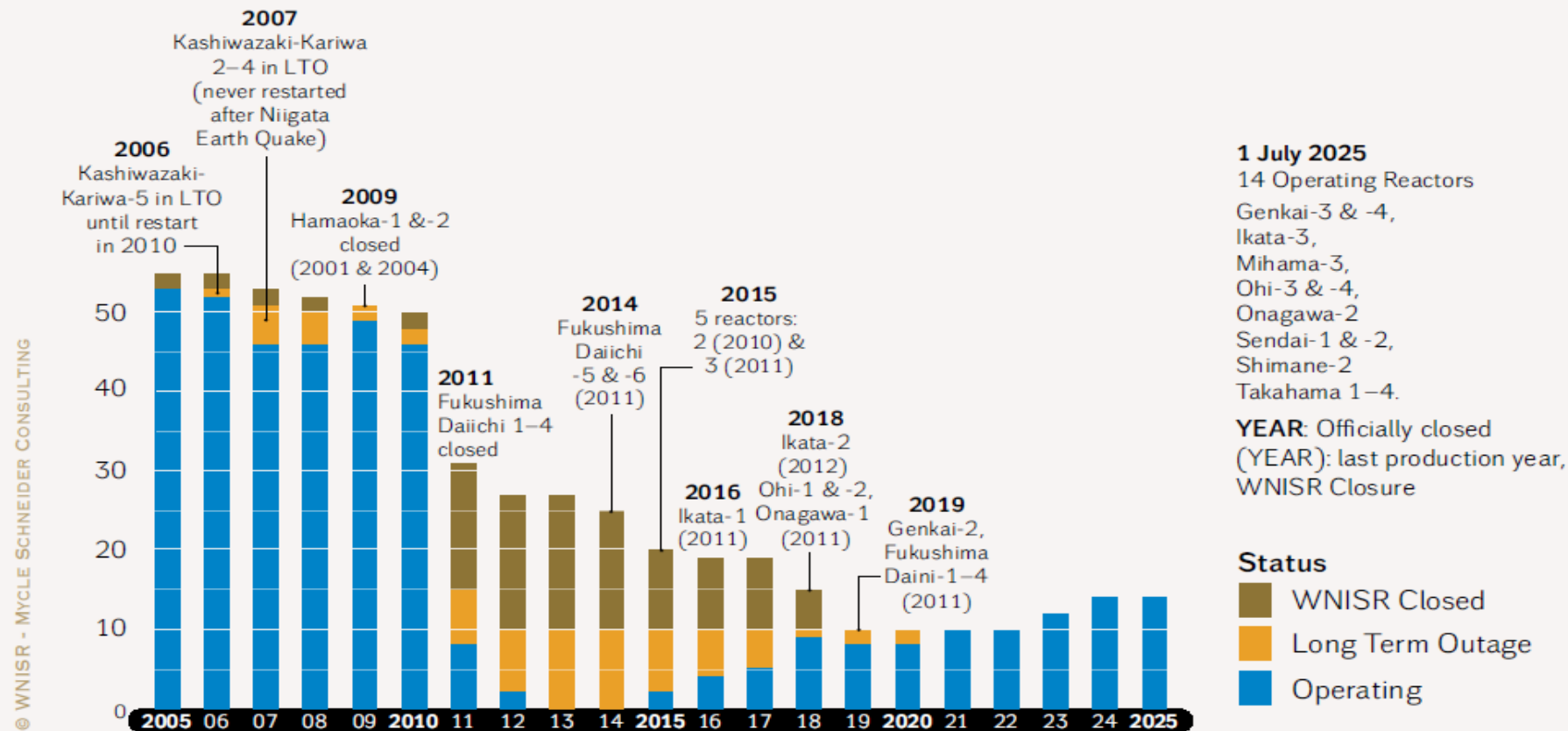
Source: Mycle Schneider
WNISR IAEA-PRIS September 2025



Japanese Nuclear Program 2005-2025

Consequence of Fukushima

Status of Reactors Officially Operational in Japan vs. WNISR Assessment
in Units, as of year-end 2005–2024, and mid-2025



Sources: Various, compiled by WNISR, 2025

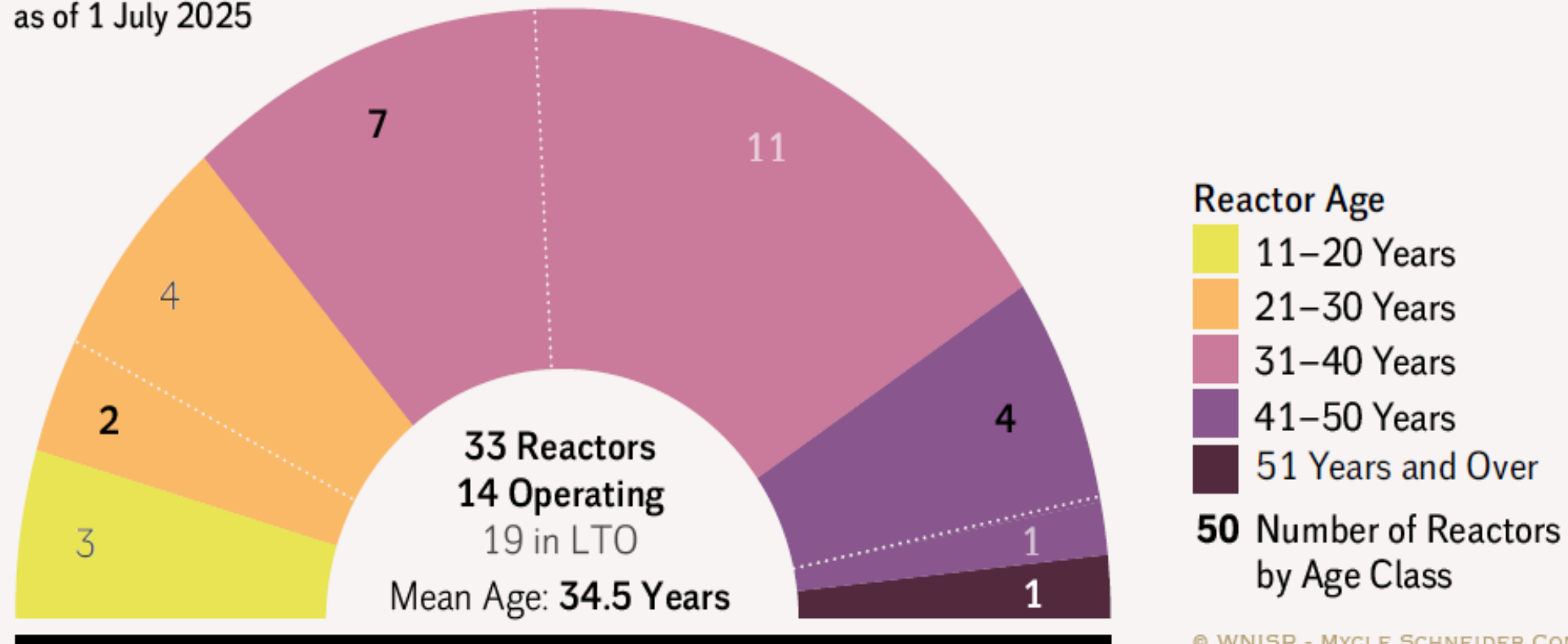


Age of Japanese Nuclear Reactors

Mean Age: 34 years

Age of Japan Nuclear Fleet

as of 1 July 2025



© WNISR - MYCLE SCHNEIDER CONSULTING

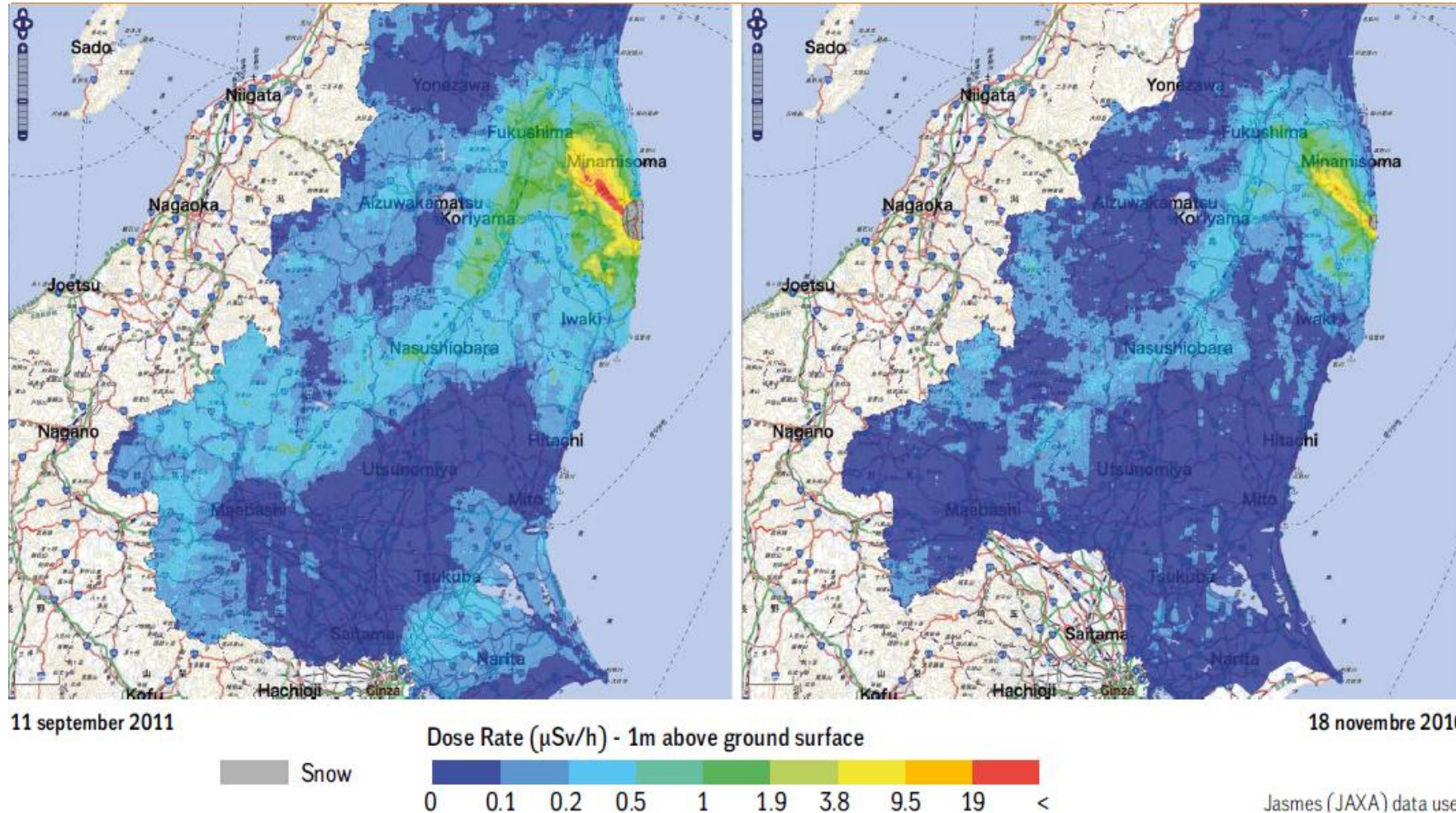
Sources: WNISR with IAEA-PRIS, 2025

Source: Mycle Schneider
WNISR IAEA-PRIS September 2025



Japan around Fukushima

Distribution of Radioactive Doses ($\mu\text{Sv/h}$)

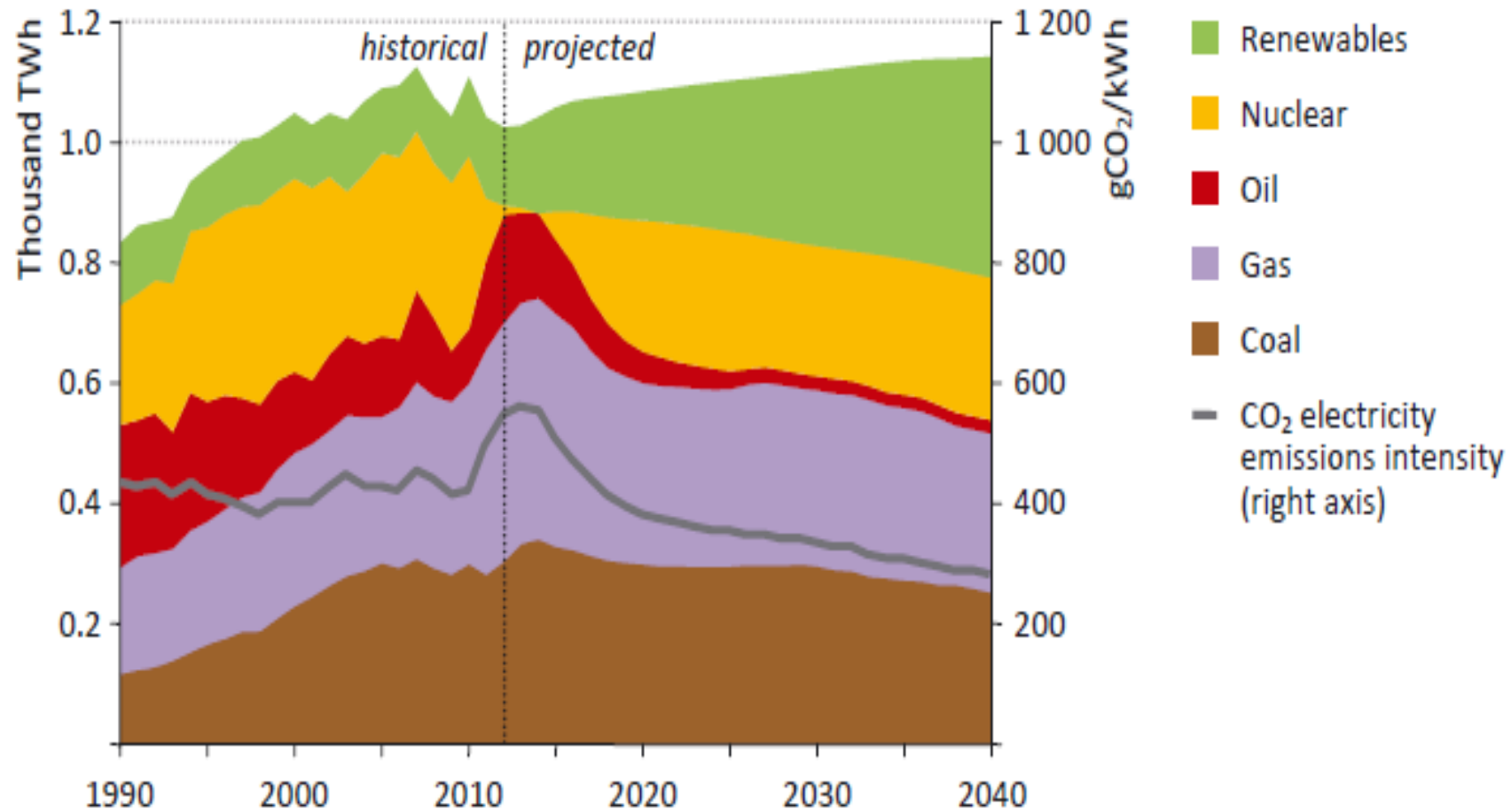


Source: Mycle Schneider Consulting
Status Report September 2017

Nota:
1 $\mu\text{Sv/h}$ # 9 mSv/year
Natural Radiation = 3 mSv/year

olbox Energy Book 10 – Nuclear

Reminder: Japan Electricity Generation by Source and CO2 intensity (p.m: IEA 2014 Central Scenario)



Source: IEA WEO 2014

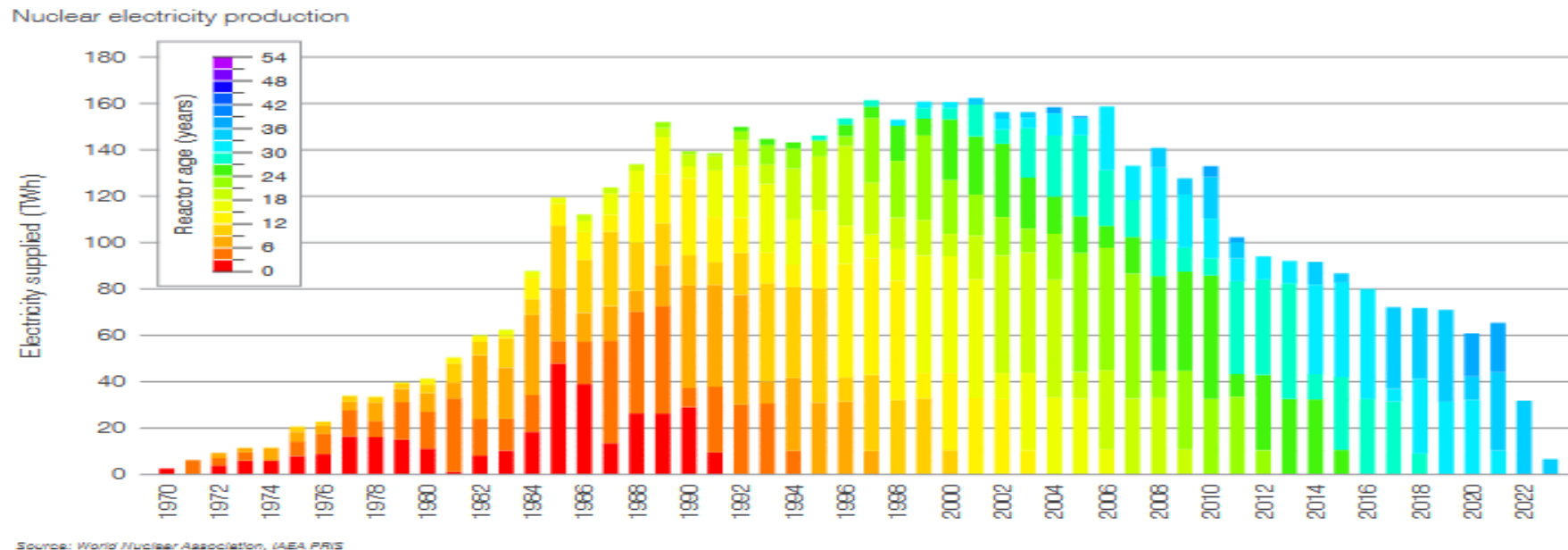
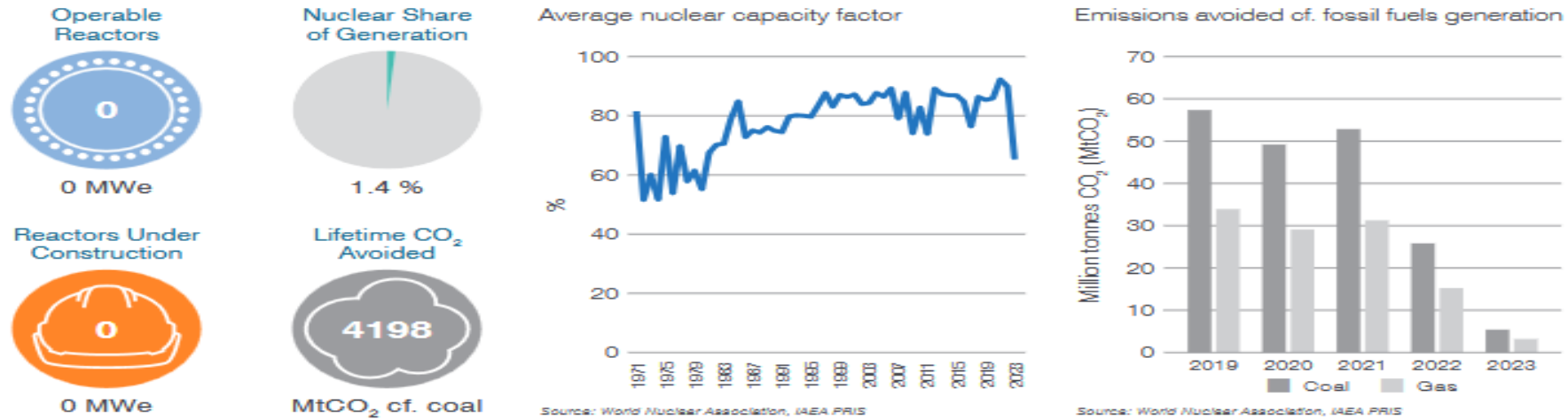


4-5

A Zoom on Germany

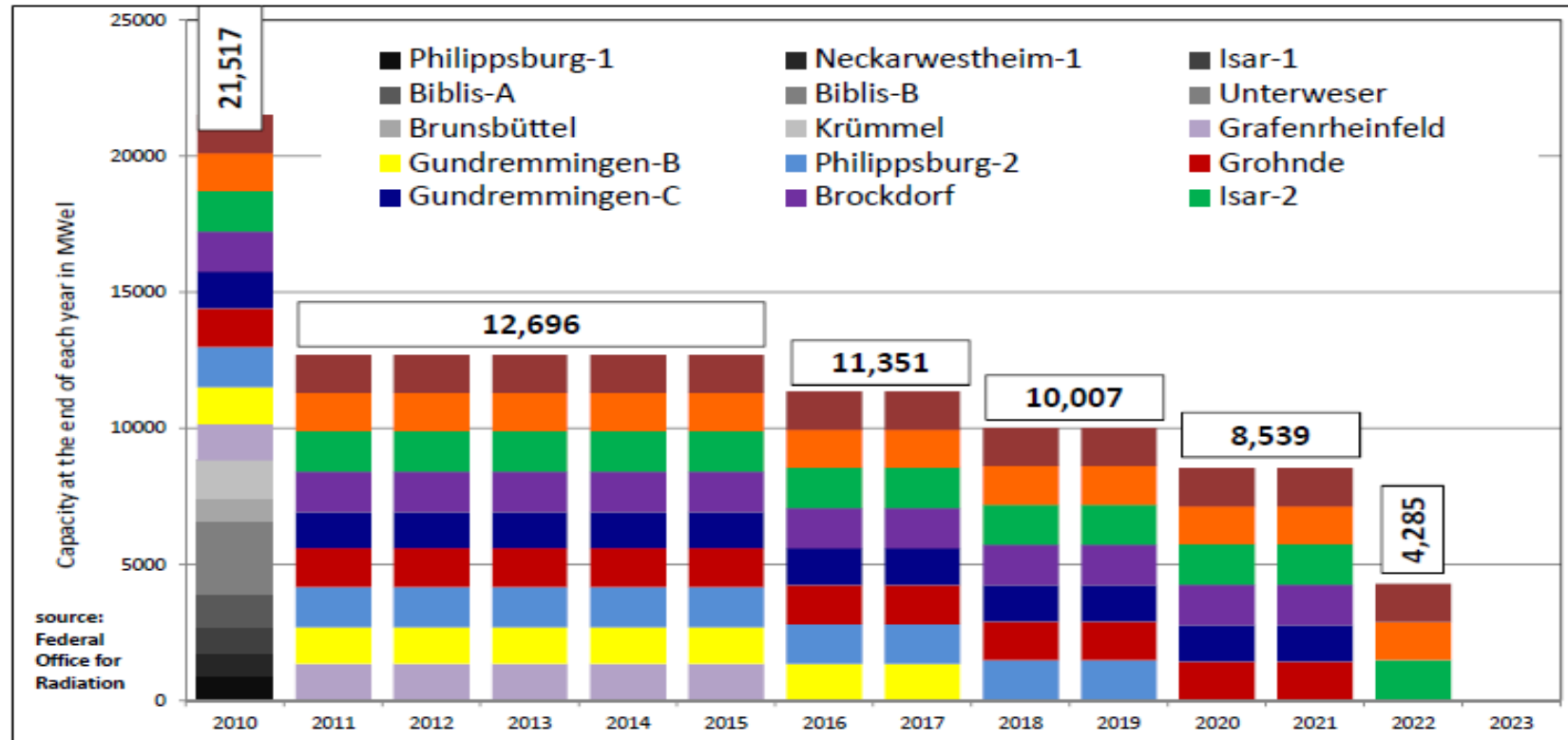


Nuclear Energy in Germany



Reminder - Nuclear Phase-out: The German Schedule

The phase-out pathway of nuclear energy in Germany:
the last reactors will be shut down at the end of 2022



Dr. Hans-Joachim Ziesing
The German « Energiewende



Reminder - The German « Energiewende »

**The German « Energiewende » will cost 400/1000 G€.
The cost of Renewables (subsidies) is huge**

As a consequence, Germany is obliged to re-open and build coal (lignite) power plants, generating additional CO2 emissions in the atmosphere (Klimakiller....) Two coal-fired power plants (1,6 and 0,9 GW) were recently put into operation.

Reminder: Electricity price for households in 2016 (All taxes incl.):

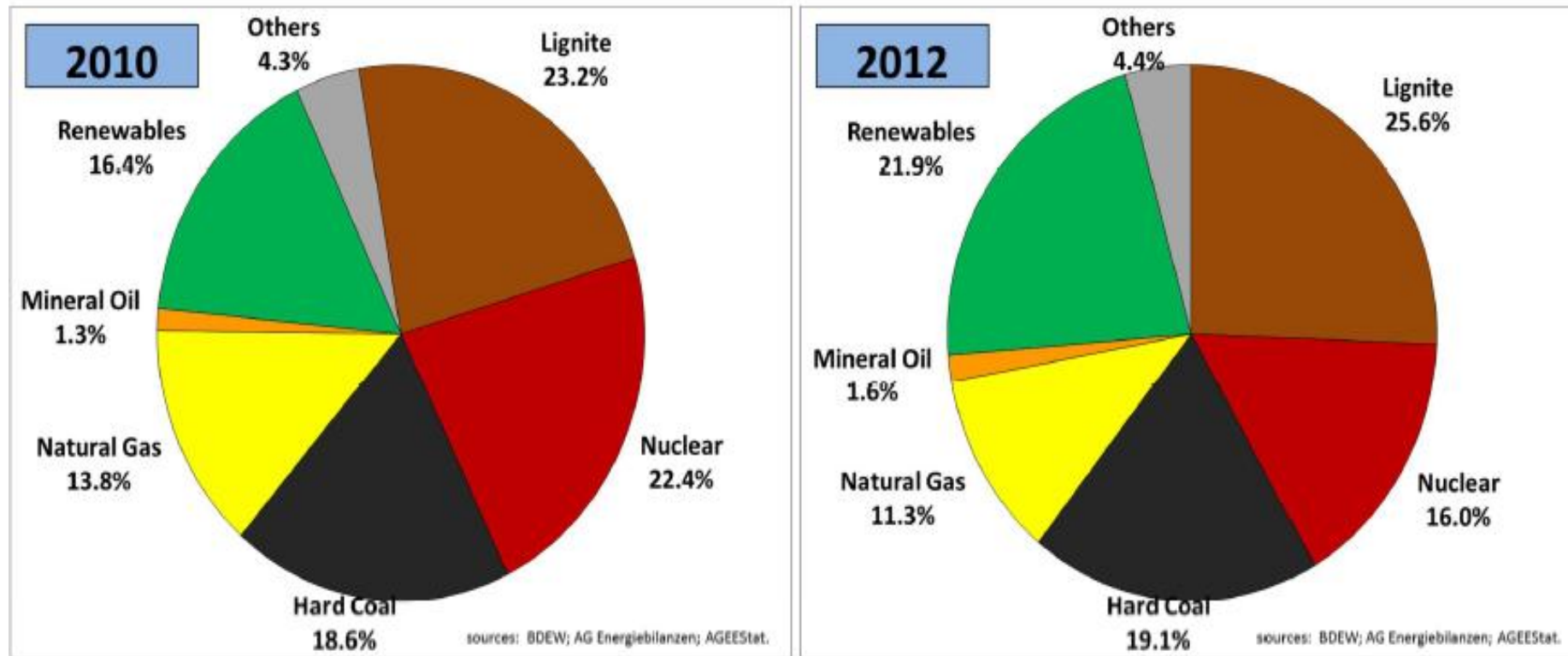
Germany: 290 €/MWh

France: 150 €/MWh

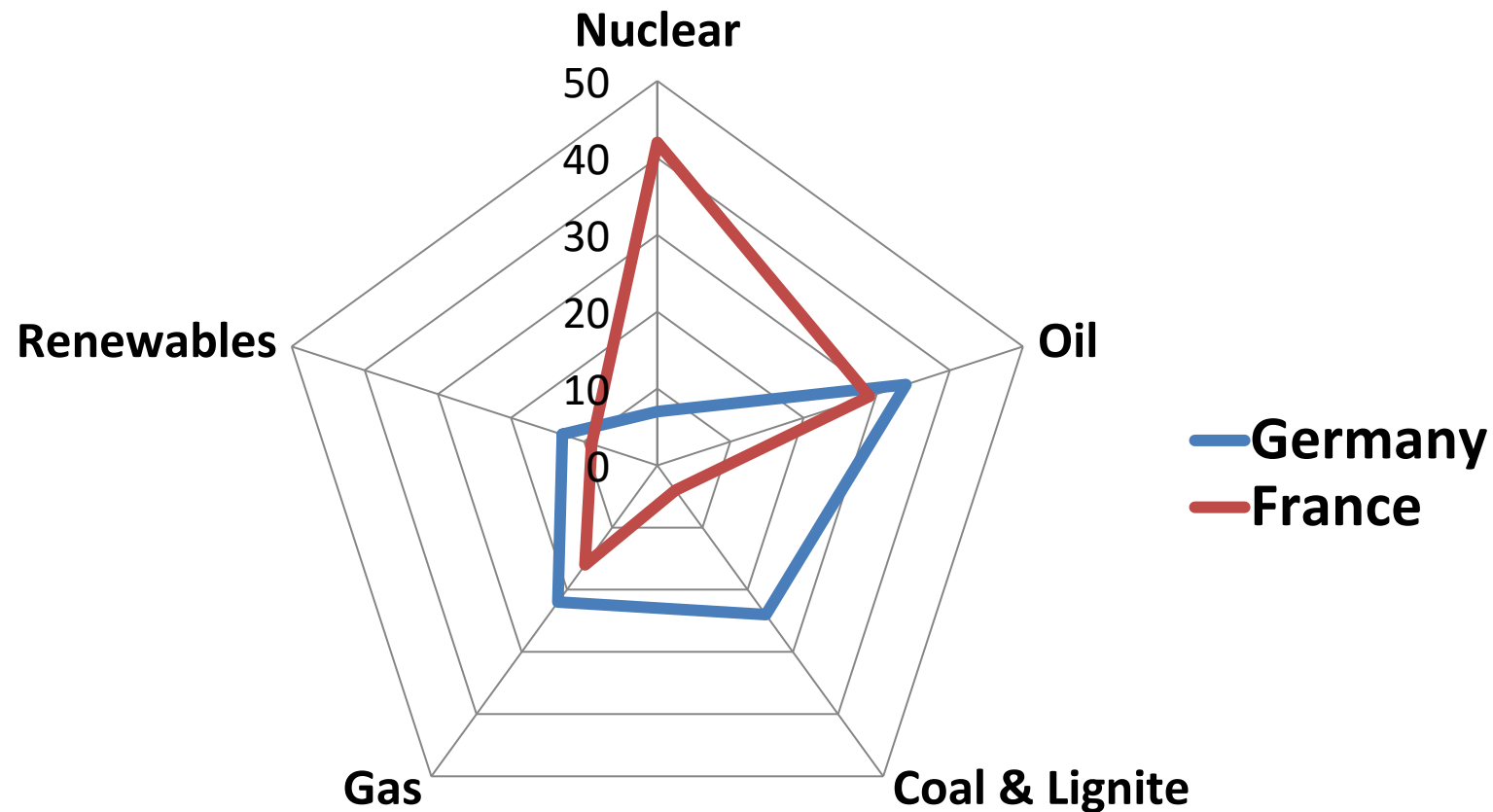
Extensive political debate in Germany on the issue.



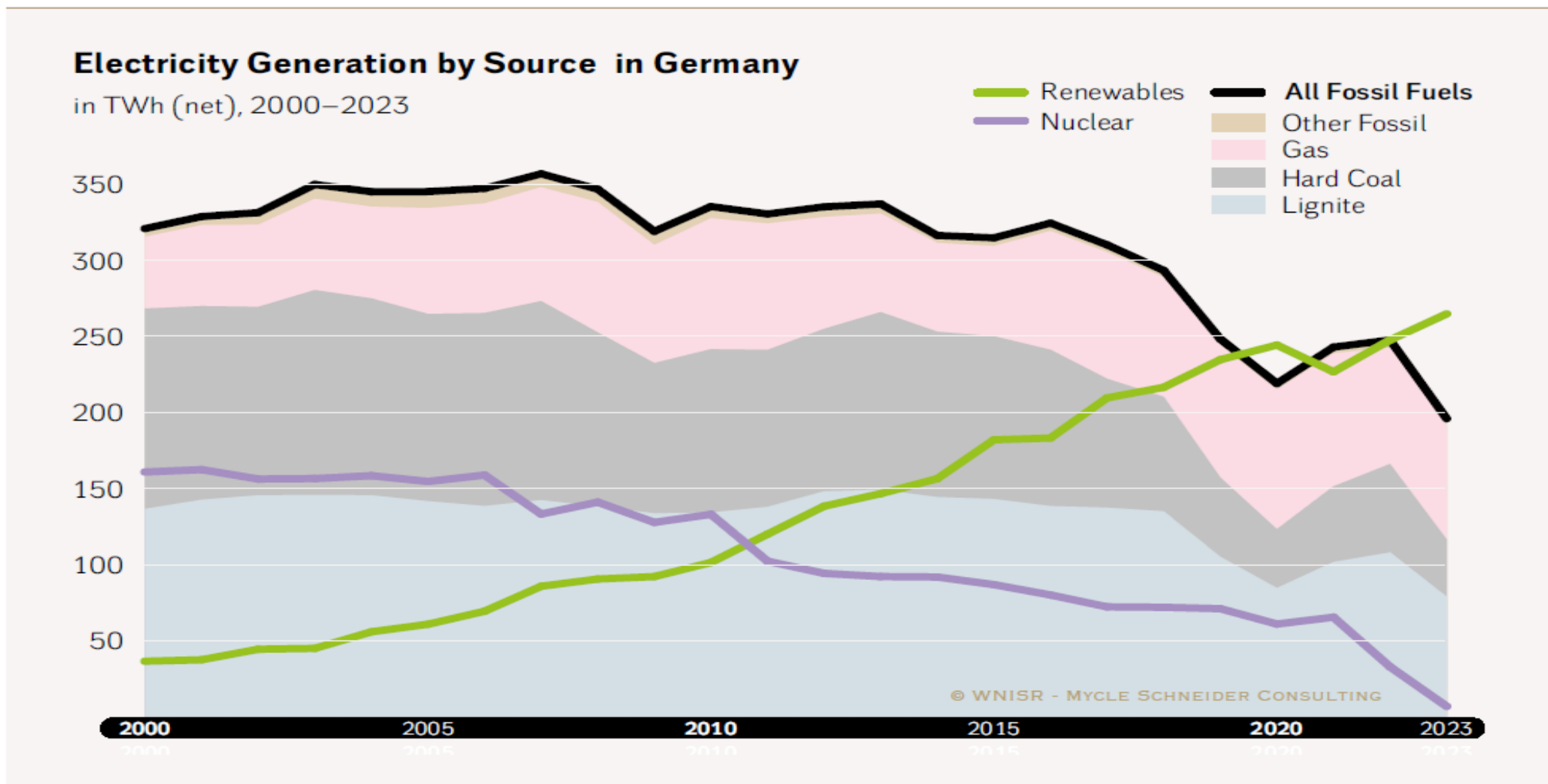
Reminder - Electricity Generation in Germany



Reminder - Primary Energy Mix in Germany and France are quite different – Year 2016



Electricity Generation in Germany



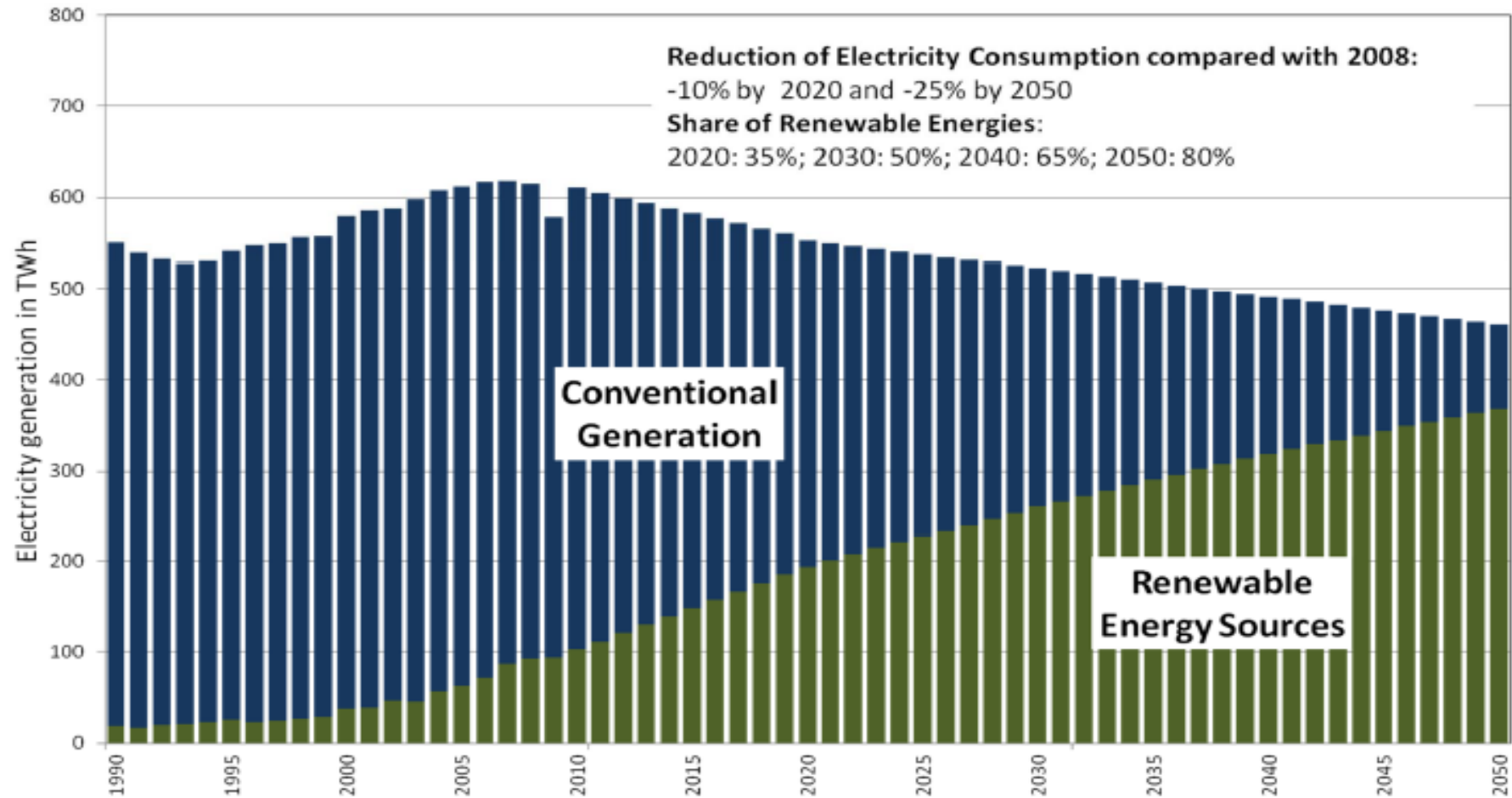
Source: AGEb, 2024

Source: Mycle Schneider
WNISR IAEA-PRIS September 2024

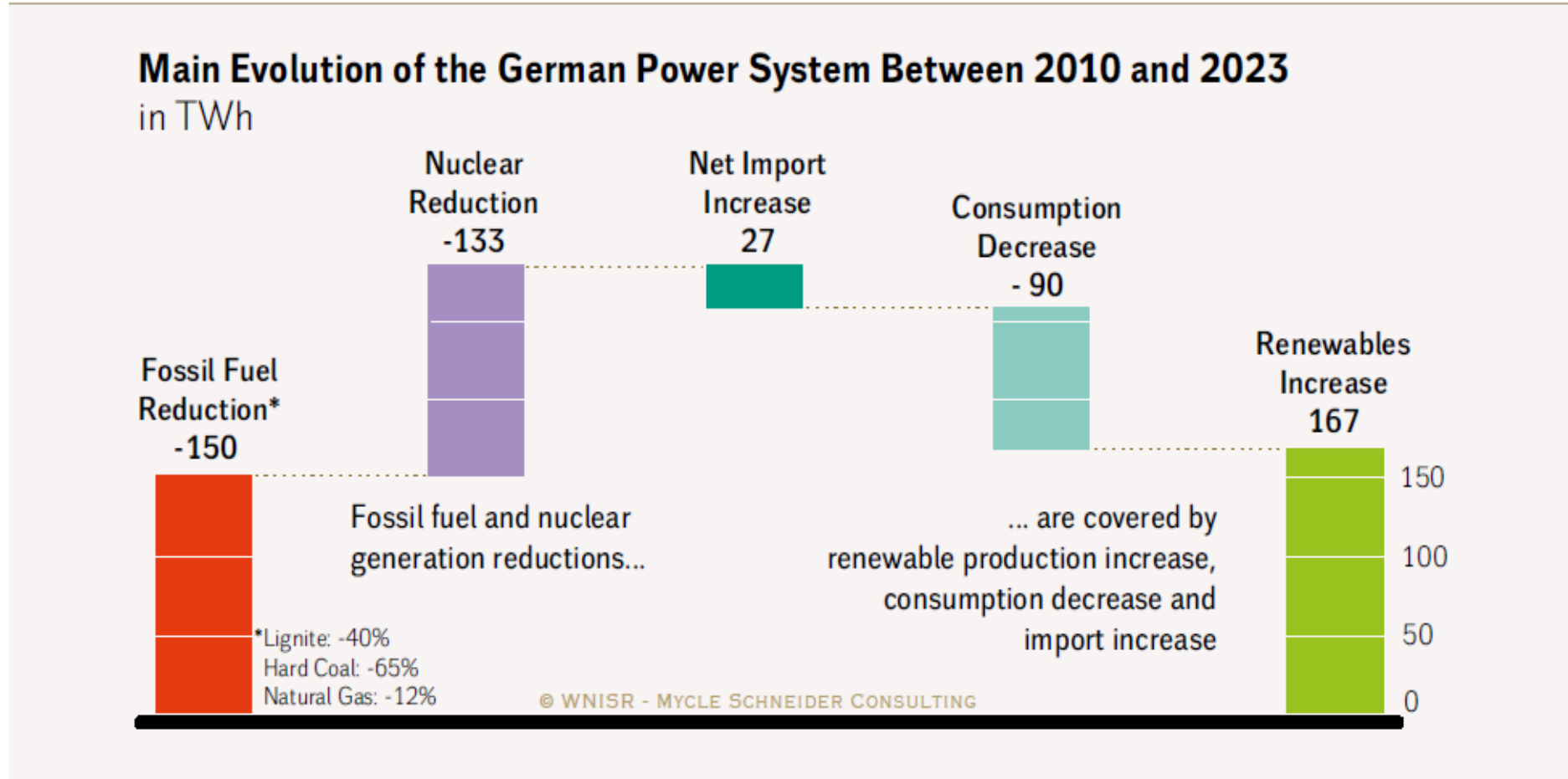


Electricity Generation in Germany

Dreams or achievable perspectives?



In Germany, the programme to reduce nuclear capacity must be compensated by other means



Sources: WNISR, based on AGEb, 2024

Source: Mycle Schneider
WNISR IAEA-PRIS September 2024

Legal closure dates for Germany Nuclear Reactors

Reactor Name (Type, Net Capacity)	Owner/Operator	First Grid Connection	End of License (latest closure date)
Biblis-A (PWR, 1167 MW)	RWE	1974	6 August 2011
Biblis-B (PWR, 1240 MW)	RWE	1976	
Brunsbüttel (BWR, 771 MW)	KKW Brunsbüttel ^(a)	1976	
Isar-1 (BWR, 878 MW)	PreussenElektra	1977	
Krümmel (BWR, 1346 MW)	KKW Krümmel ^(b)	1983	
Neckarwestheim-1 (PWR, 785 MW)	EnBW	1976	
Philippsburg-1 (BWR, 890 MW)	EnBW	1979	
Unterweser (BWR, 1345 MW)	PreussenElektra	1978	
Grafenrheinfeld (PWR, 1275 MW)	PreussenElektra	1981	31 December 2015 (closed 27 June 2015)
Gundremmingen-B (BWR, 1284 MW)	KKW Gundremmingen ^(c)	1984	31 December 2017
Philippsburg-2 (PWR, 1402 MW)	EnBW	1984	31 December 2019
Brokdorf (PWR, 1410 MW)	PreussenElektra/Vattenfall ^(d)	1986	31 December 2021
Grohnde (PWR, 1360 MW)	PreussenElektra	1984	
Gundremmingen-C (BWR, 1288 MW)	KKW Gundremmingen	1984	
Isar-2 (PWR, 1410 MW)	PreussenElektra	1988	31 December 2022
Emsland (PWR, 1329 MW)	KKW Lippe-Ems ^(e)	1988	
Neckarwestheim-2 (PWR, 1310 MW)	EnBW	1989	

Sources: German Atomic Energy Act/Atomgesetz, 31 July 2011; Atomforum Kernenergie, May 2011; WNISR with IAEA-PRIS, 2022¹⁸¹

Source: Mycle Schneider
WNISR IAEA-PRIS October 2022

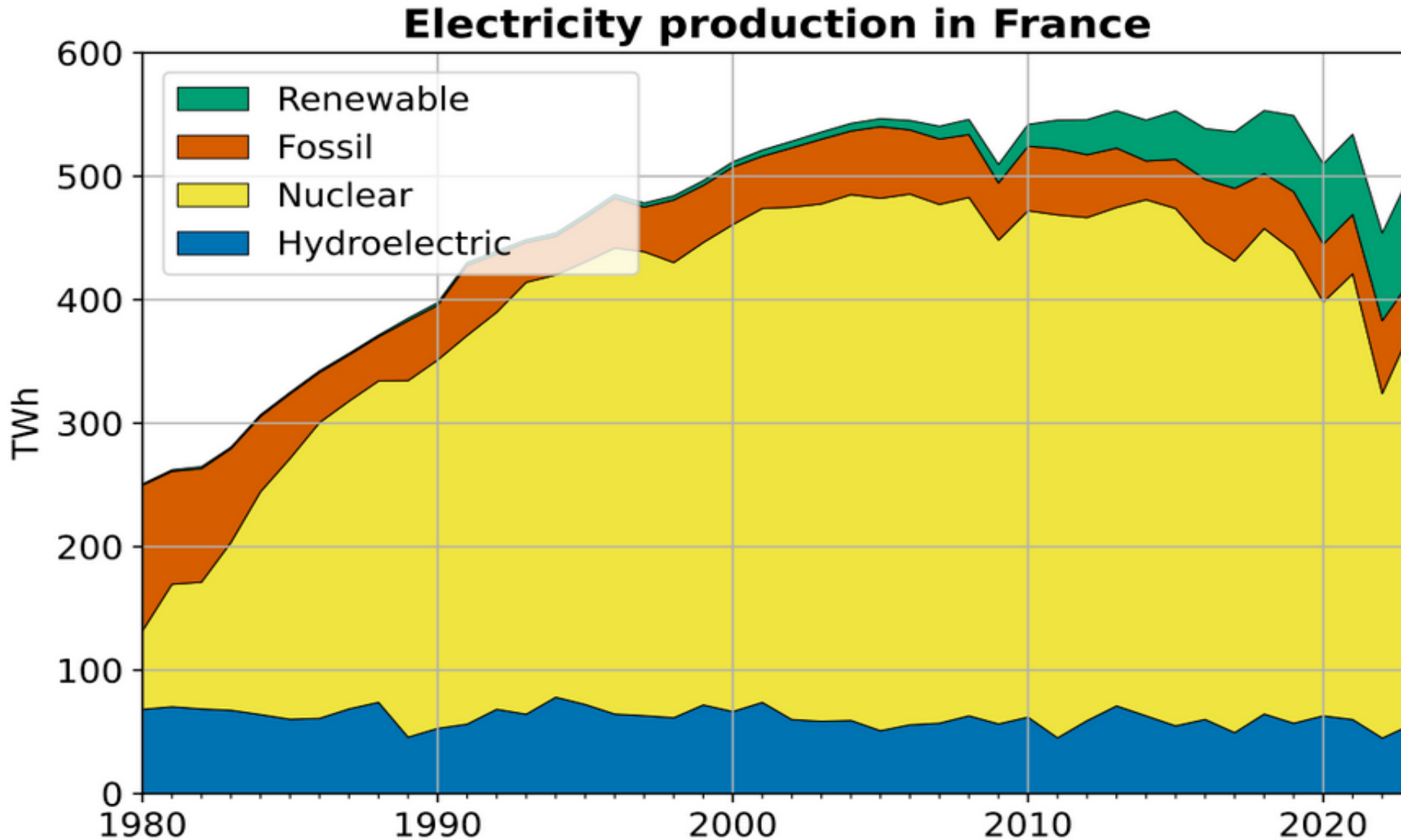


4-6

A Zoom on France



Nuclear Energy in France



Nuclear Energy in France

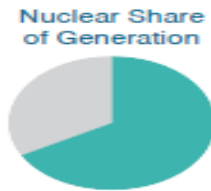


63,000 MWe

Reactors Under Construction



0 MWe



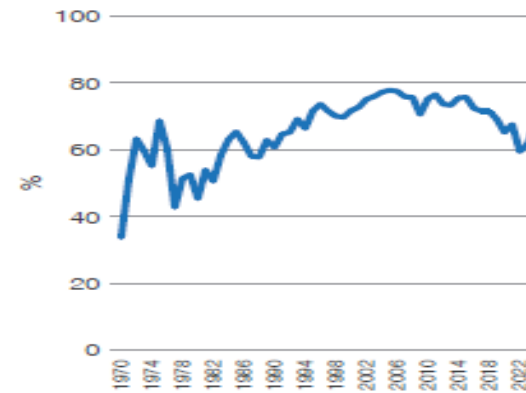
67 %

Lifetime CO₂ Avoided



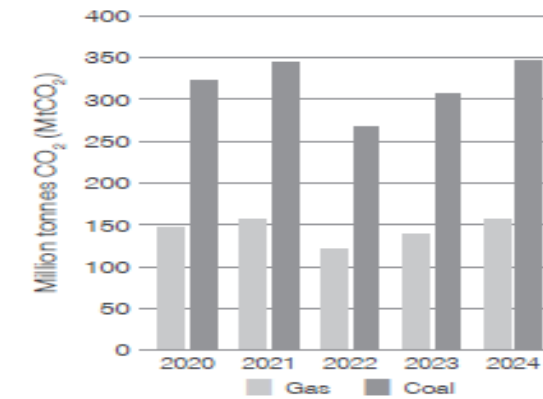
MtCO₂ cf. coal

Average nuclear capacity factor



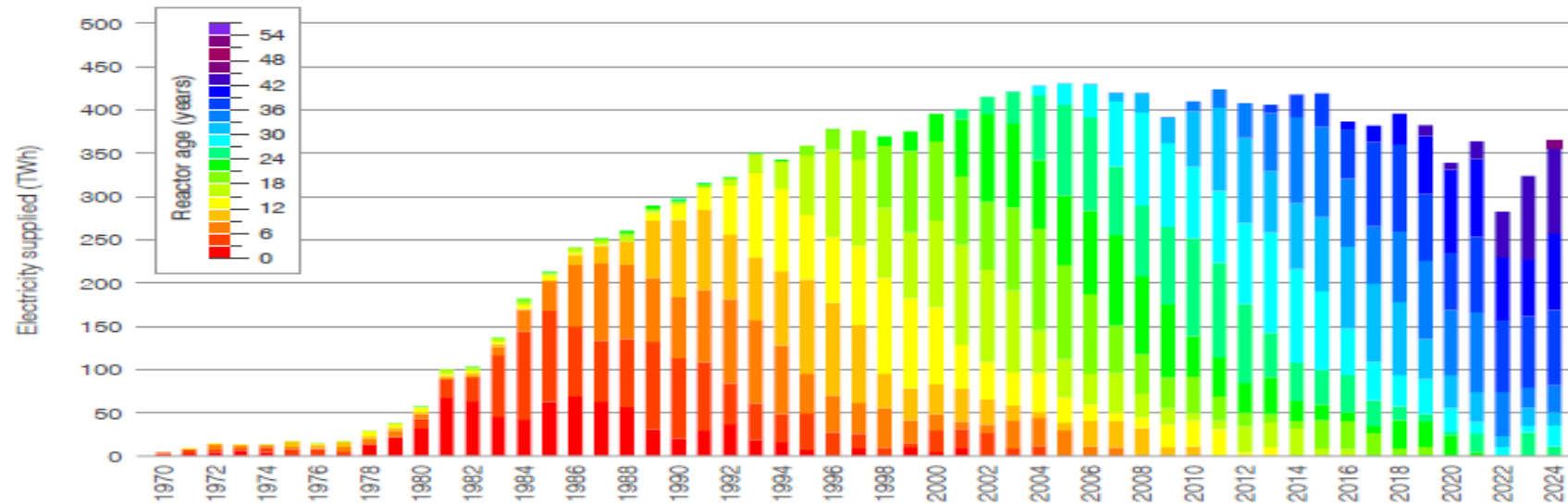
Source: World Nuclear Association, IAEA PRIS

Emissions avoided cf. fossil fuels generation



Source: World Nuclear Association, IAEA PRIS

Nuclear electricity production



Source: World Nuclear Association, IAEA PRIS



A Zoom on France

 **En couverture**

1958 Un plan national stratégique. En 1958, le général de Gaulle visite le réacteur 92 à Marcoule, dans le Gard. Il a placé le nucléaire au cœur de sa politique de souveraineté militaire et énergétique.

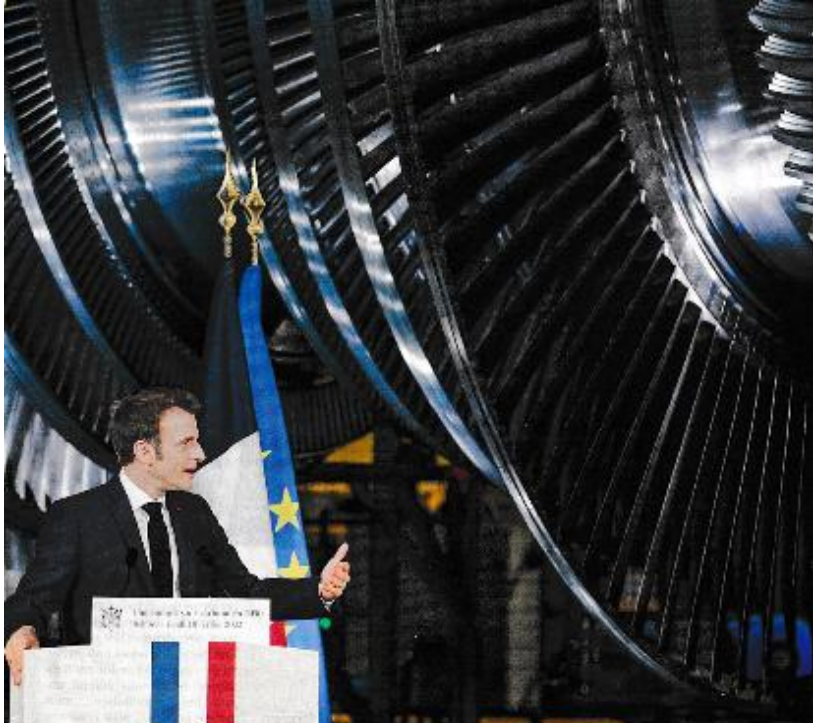




NUCLÉAIRE
LE GRAND GÂCHIS

L'atome faisait la fierté de l'industrie française mais, depuis un quart de siècle, la filière n'a cessé d'être fragilisée. Histoire d'une décadence... et d'une promesse de relance.

54 • CHALLENGES N° 775 • 2 MARS 2023



2022 Seconde chance? En février, Emmanuel Macron choisit de se rendre à l'usine de turbines nucléaires Ansaldo de Balloir pour annoncer un vaste plan de relance du nucléaire français, avec la construction de six nouveaux réacteurs.

Fini, la sinistre rose. Depuis que, le 10 février 2022 à Balloir, Emmanuel Macron a annoncé un vaste plan de relance du nucléaire, avec la construction de six nouveaux réacteurs de dernière génération (EPR2) d'ici à 2050, la filière (5 200 entreprises, 180 000 salariés) est aux anges. « C'est l'été nucléaire qui a débuté pas en un an mais maintenant », se réjouit Stéphane Aubertin, directeur délégué du groupe d'ingénierie nucléaire Assystem. Il faut dire que les deux dernières crises ont peiné à Perly (Seine-Maritime) sont supposées durer jusqu'en 2025. Et plus des années pour minimiser de plus en plus fréquents de ses réacteurs vieillissants, l'industrie a senti de nouveaux problèmes de corrosion sur ses centrales les plus récentes (voir page 67). Au total, presque la moitié de ses 55 réacteurs ont été immobilisés à un moment de l'année et « la durée moyenne des arrêts s'est élevée à 142 jours », a calculé Mylène Schneider, consultant indépendant, auteur du « World Nuclear Industry Status Report ». Des données qui ont contribué à la perte record d'EDF de ▶▶▶

2 MARS 2023 • CHALLENGES N° 775 • 55



History of Nuclear Industry in France

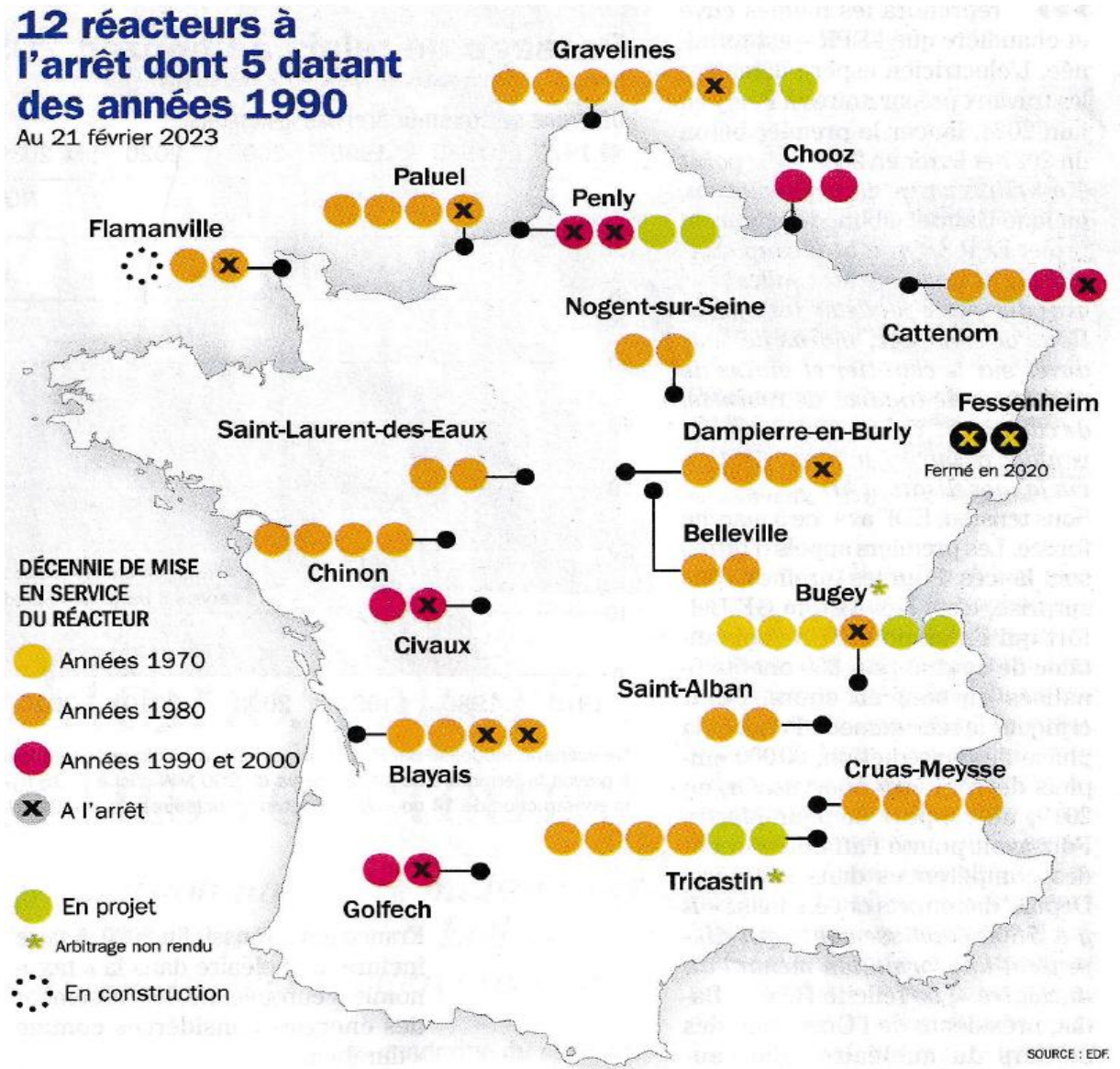
- **1958:** General de Gaulle has placed the nuclear industry development in the heart of France energy sovereignty.
- **1950:** Under the supervision of CEA (Commissariat à l'Energie atomique), 6 reactors are built using the UNGG (Uranium Naturel Graphite Gaz) technology.
- **1973:** After the 1st oil shock, massive investment programme for the construction of 58 reactors (PWR – Pressurized Water Reactor) during 20 years, for a cost of 93 G€ (2012 – Cour des Comptes)
- **1997:** Decision to close Superphénix, Fast Breeder Reactor (FBR) developed by CEA.
- **2006:** New research programme to build a FBR new generation: Astrid (Advanced Sodium Technological Reactor for Industrial Demonstration).
- **2010:** Under the pressure of Bruxelles (and notably of Germany), EDF (Electricité de France) is obliged to sell 25% of its production to third parties at a price of 42 €/MWh) – Arenh mechanism (Accès régulé à l'électricité nucléaire historique)
- **2015:** F.Hollande, french president, decides that the share of nuclear in the electricity mix should be downgraded from 70% to 50% in 2025 and to close 2 reactors at Fessenheim.
- **2018:** E.Macron, french president: Nuclear in the electricity mix from 70% to 50% delayed to 2035.
- **2019:** Closure of Astrid project.
- **2022/2024:** E.Macron, French president, launches a vast programme to reactivate the nuclear industry in France and promotes the development of SMR (Small Modular Reactors)



History of Nuclear Industry in France – Situation 2023

12 réacteurs à l'arrêt dont 5 datant des années 1990

Au 21 février 2023

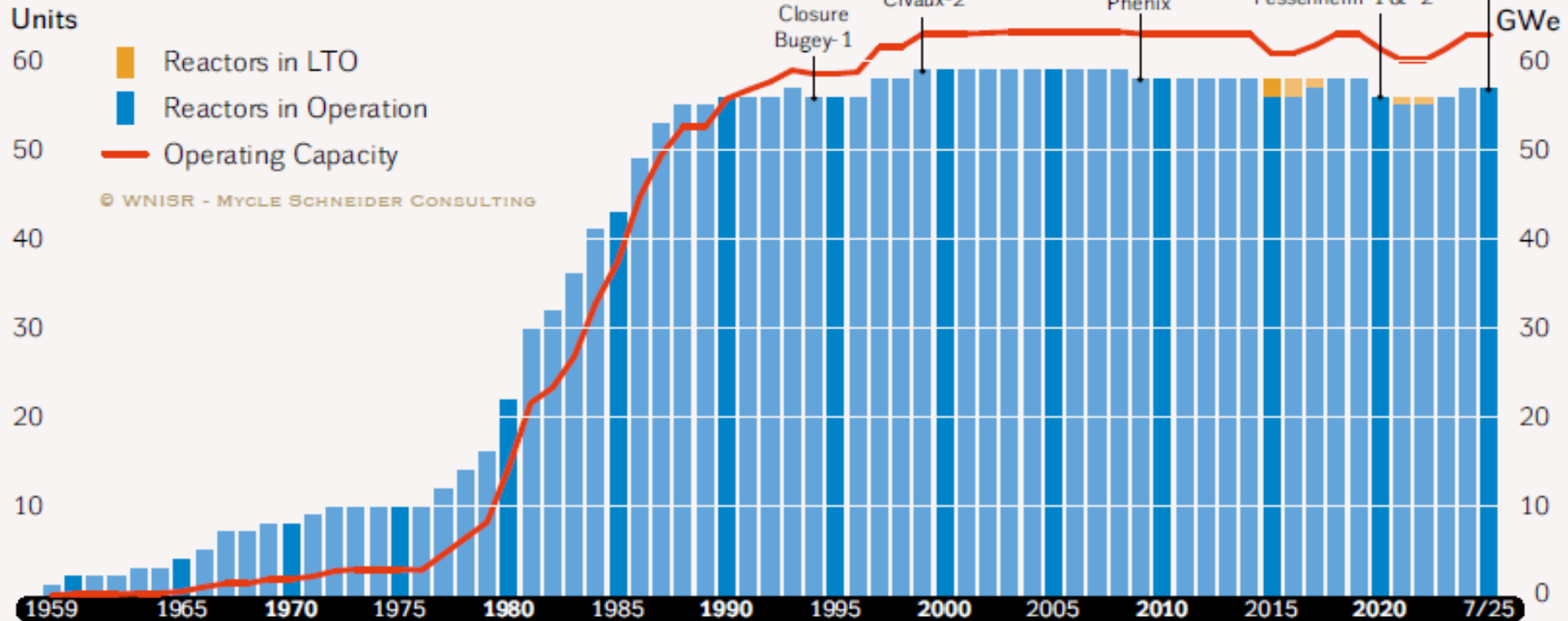


SOURCE : EDF.

Nuclear Power Plants in France

Nuclear Reactors and Net Operating Capacity in France

in Units and GWe, from 1959 to 1 July 2025

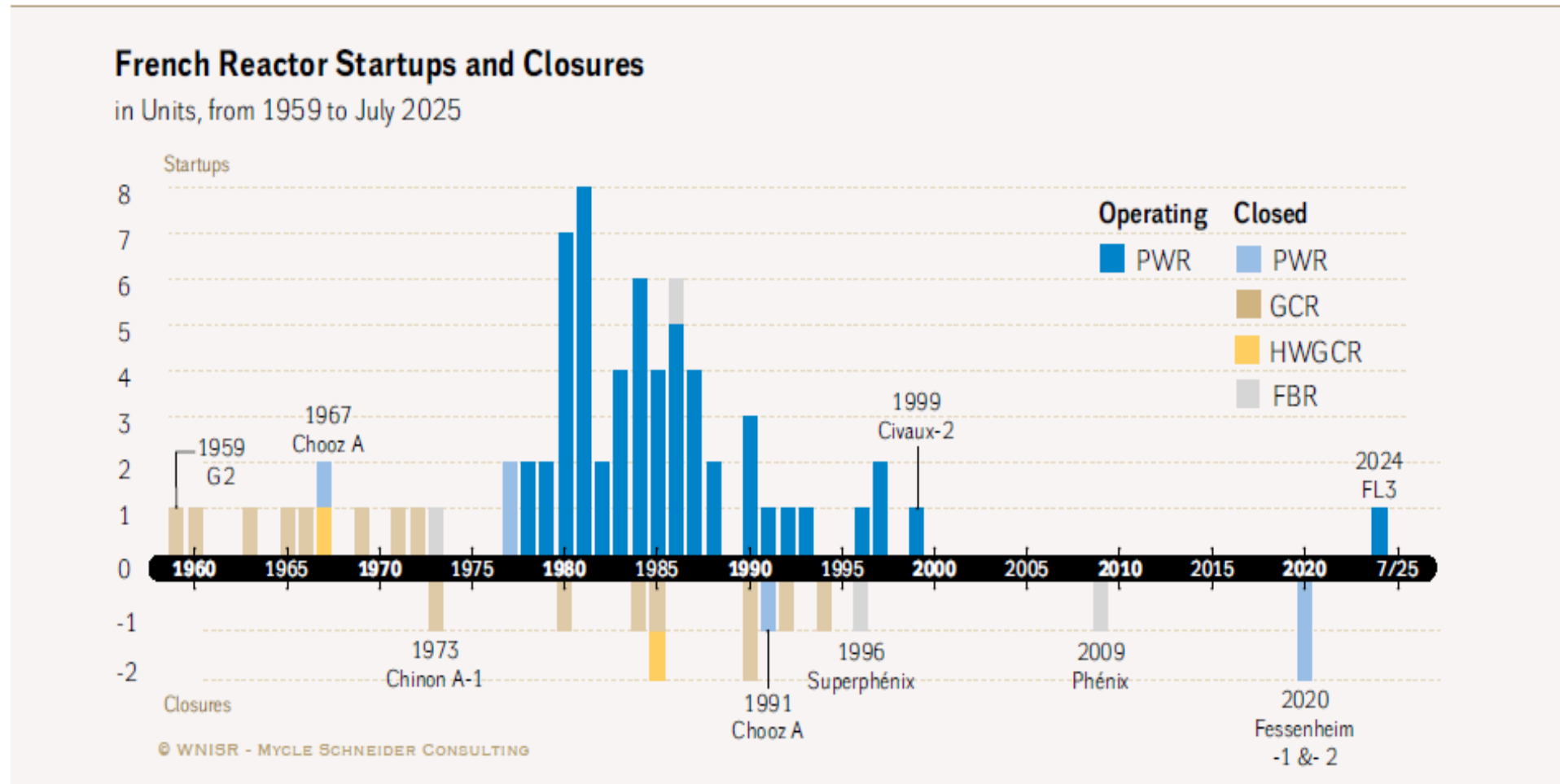


Sources: WNISR with IAEA-PRIS, 2025

Source: Mycle Schneider
WNISR IAEA-PRIS September 2025



Nuclear Power Plants in France



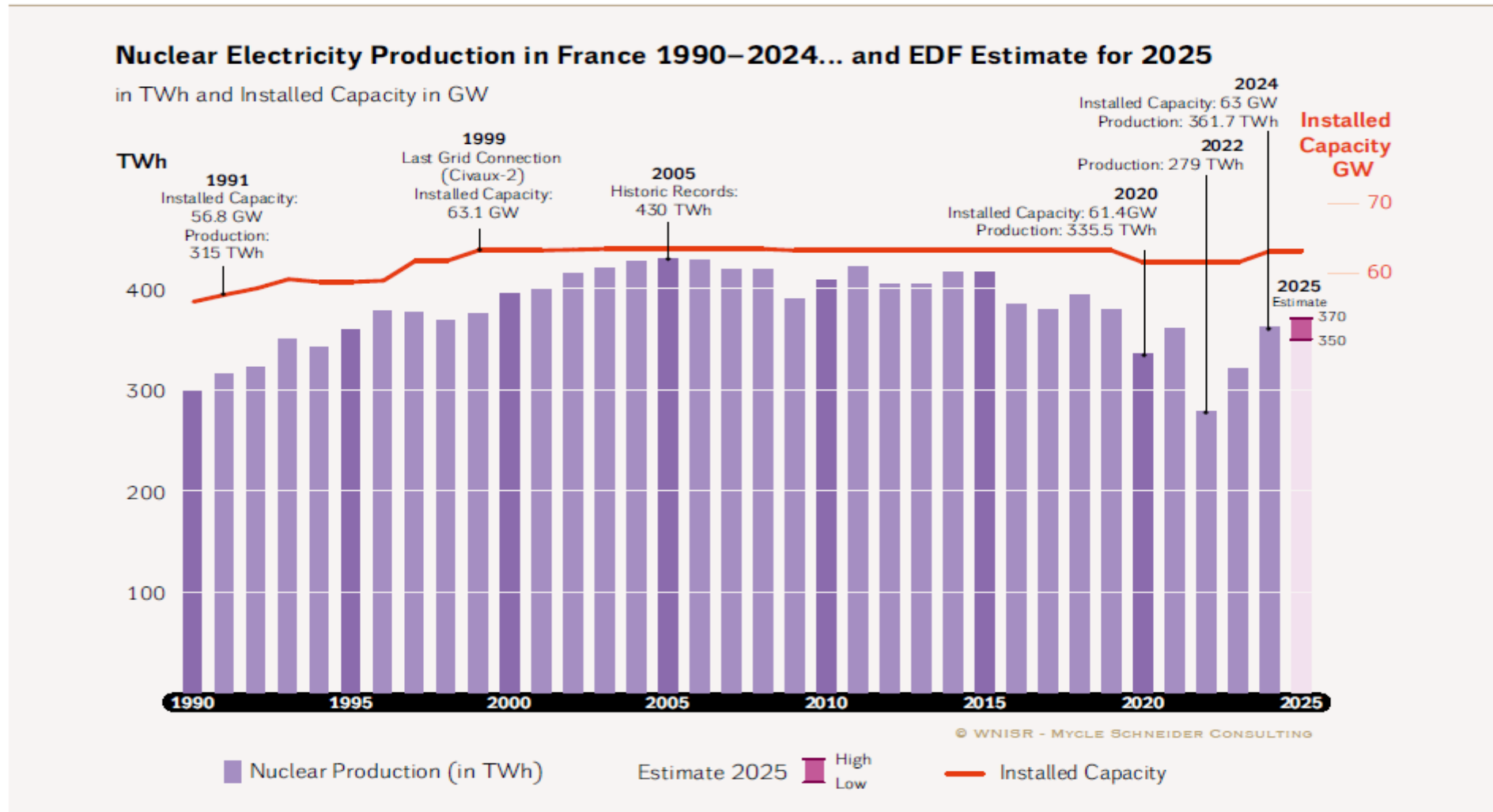
Sources: WNISR with IAEA-PRIS, 2025

Notes: **PWR**: Pressurized Water Reactor; **GCR**: Gas-Cooled Reactor; **HWGCR**: Heavy Water Gas Cooled Reactor; **FBR**: Fast Breeder Reactor.

Source: Mycle Schneider
WNISR IAEA-PRIS September 2025



Nuclear Power Plants in France & Installed Capacity (1)



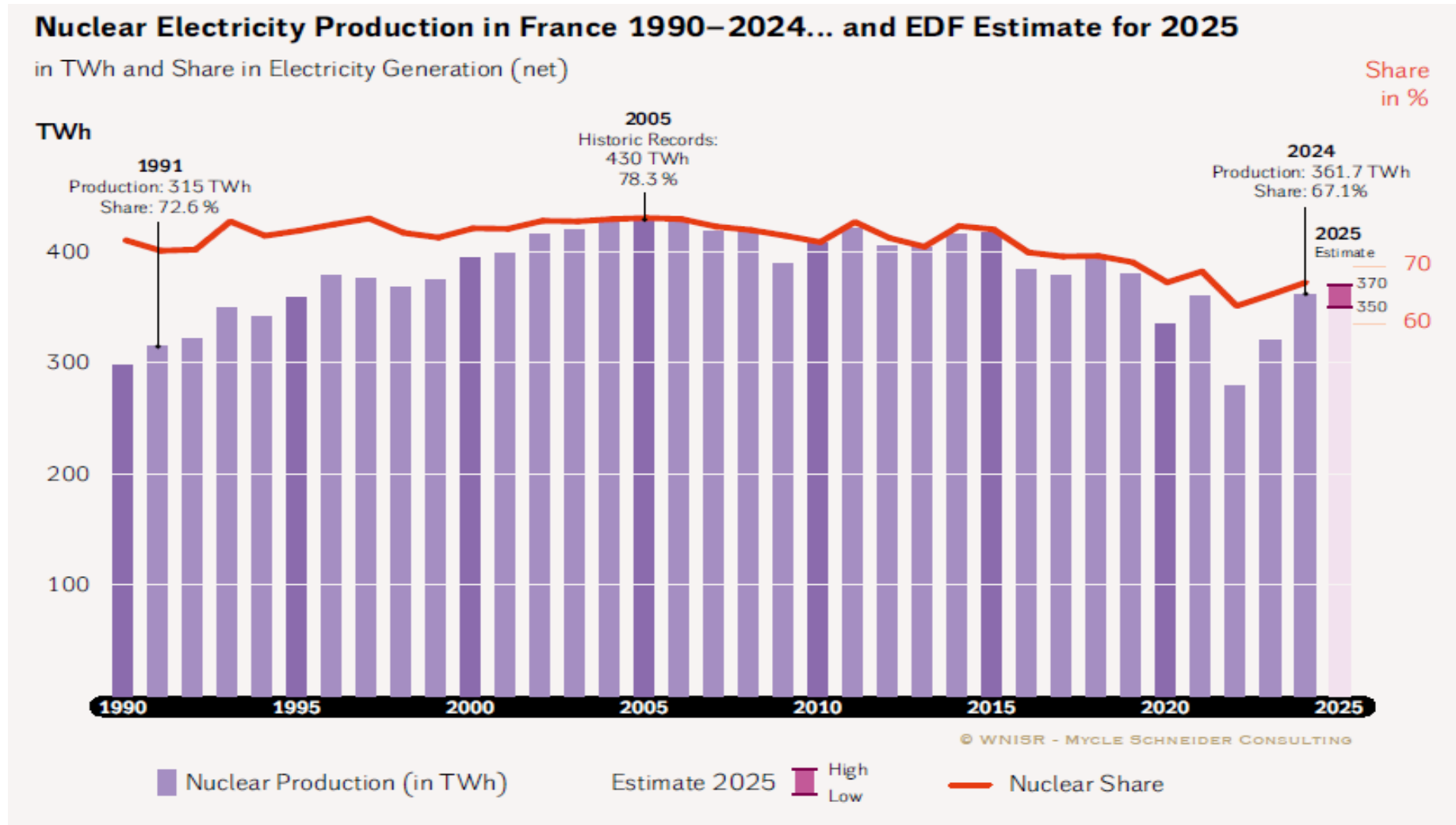
Sources: RTE, 2000–2025; and EDF, 2025

Note: In Figure 27, reactors in LTO are counted in the “installed capacity”.

Source: Mycle Schneider
WNISR IAEA-PRIS September 2025



Nuclear Power Plants in France & Nuclear Share(2)



Sources: RTE, 2000–2025; and EDF, 2025

Source: Mycle Schneider
WNISR IAEA-PRIS September 2025

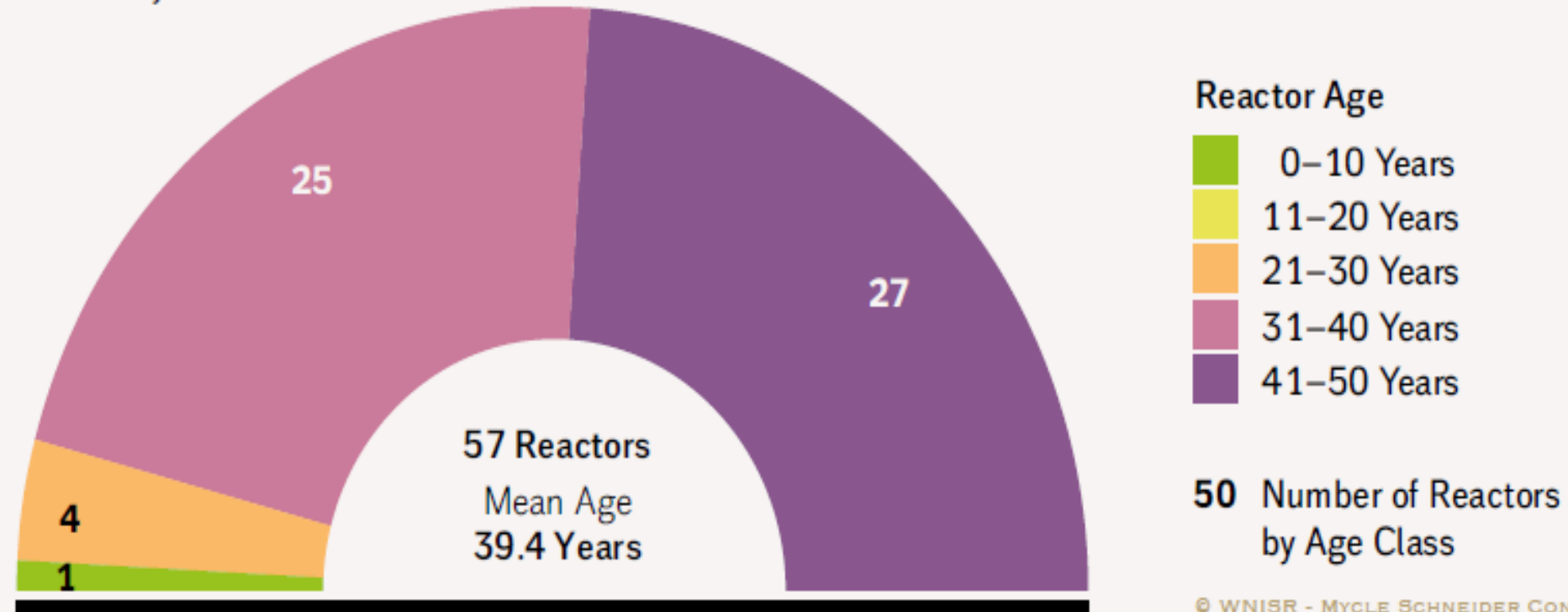


The Age of French Reactors

Mean Age: 39 years

Age of French Nuclear Fleet

as of 1 July 2025



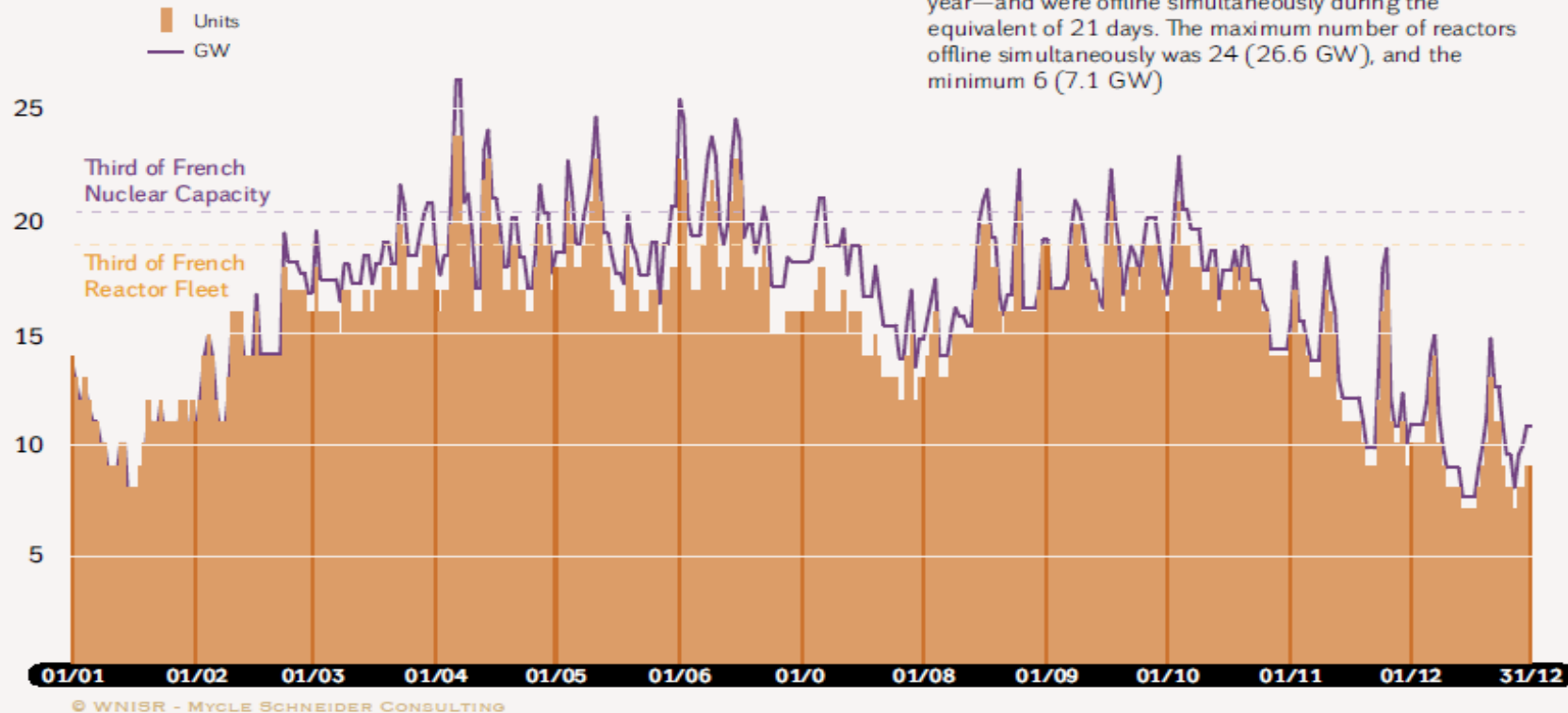
Sources: WNISR with IAEA-PRIS, 2025

Source: Mycle Schneider
WNISR IAEA-PRIS September 2025

France – Reactors Offline 2024

Unavailability of French Nuclear Reactors in 2024 Reactors Offline the Same Day (Zero Output)

in Units and Capacity



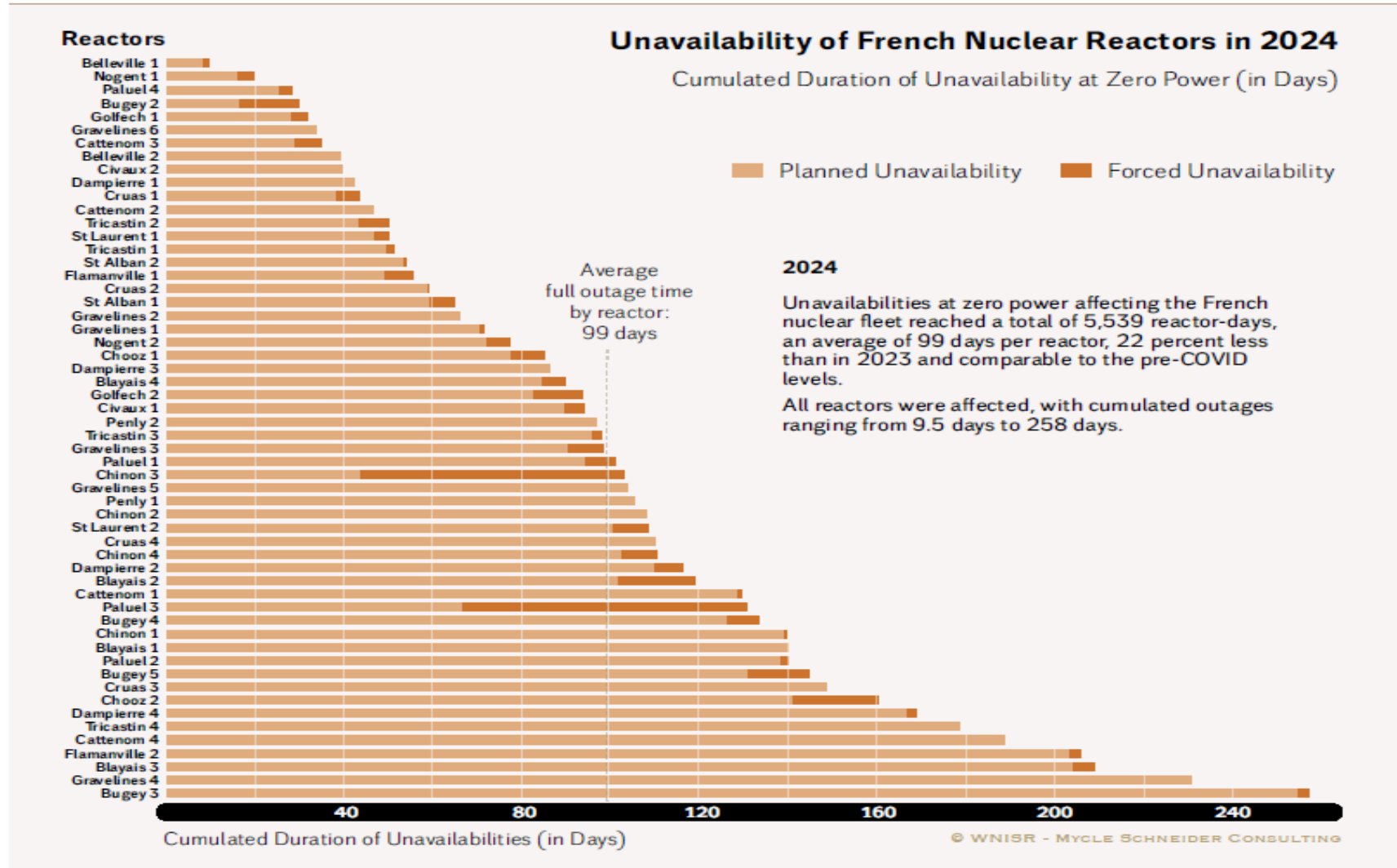
In 2024, six reactors or more were offline at any time of the year. 20 or more reactors did not produce any power at least part of the day on 32 days—less than 10% of the year—and were offline simultaneously during the equivalent of 21 days. The maximum number of reactors offline simultaneously was 24 (26.6 GW), and the minimum 6 (7.1 GW)

Sources: compiled by WNISR with RTE and EDF REMIT Data, 2021–2025

Notes: For each day in the year, this graph shows the total number of reactors offline, not necessarily simultaneously, as all unavailabilities do not overlap, but on the same day. This figure does not take into account Flamanville-3 that was briefly connected to the grid in December 2024.

Source: Mycle Schneider
WNISR IAEA-PRIS September 2025

France – Reactors Offline 2024



Notes:

This graph only compiles outages at zero power, thus excluding all other operational periods with reduced capacity >0 MW. Impact of unavailabilities on power production is therefore significantly larger. Flamanville-3, briefly connected to the grid in December 2024, is not considered here. “Planned” and “Forced” unavailabilities as declared by EDF.

Sources: compiled by WNISR with RTE and EDF REMIT Data, 2021–2025

Source: Mycle Schneider
WNISR IAEA-PRIS September 2025



The Cost of Nuclear in France

- 57 reactors on operations as of July 2025, 9 reactors are being deconstructed: 1 PWR (Chooz), 6 UNGG (Uranium Naturel Graphite Gaz, Bugey, Chinon, St-Laurent), 1 HWR (Brennilis), 1 Fast Breeder Reactor (Creys-Malville) Dismantlement takes time.
- Depending upon various assumptions, Costs vary from 33 to 50 €/MWh.
- In the framework of the liberalization process, the Cost defined by Arenh (Accès réglementé à l'énergie nucléaire historique) is 42 €/MWh (Price at which potential competitors may purchase electricity to EDF, up to 25% of the production)
- This price will probably increase in the years to come.
- Production and Maintenance Costs have increased. Maintenance is essential to preserve safety. Lessons learned from Three Mile Island, Tchernobyl, Fukushima.
- Maintenance costs for EDF were 800 M€/year between 2003 and 2008, will increase up to 3 500 M€/year between 2011 and 2025. One year delay # 500 – 800 M€, i.e. 2/3 M€/day.
- The disponibility rate is 82% (utilisation in semi-base) vs 90% for US nuclear park (utilisation in base)
- New EPR: Flamanville cost # 23,9 G€ (Cour des comptes) vs 3,3 G€ initially expected (2006). 12 years delay. Less difficulties for the 2 Taishan (China) EPR now operational. (More problems for the Olkiluoto project in Finland)
- Ultimate cost for the EPR (industrial maturity) could range from 70 to 90 €/MWh?
- Closure of Fessenheim.
- Current debate on increasing the exploitation life of reactors from 40 to 60 years.



**Reminder - French nuclear programme within the
« Programmation Pluriannuelle de l'Energie – PPE »
November/December 2018**



France

Reminder - Programmation Pluriannuelle de l'Energie 2023 – 2028

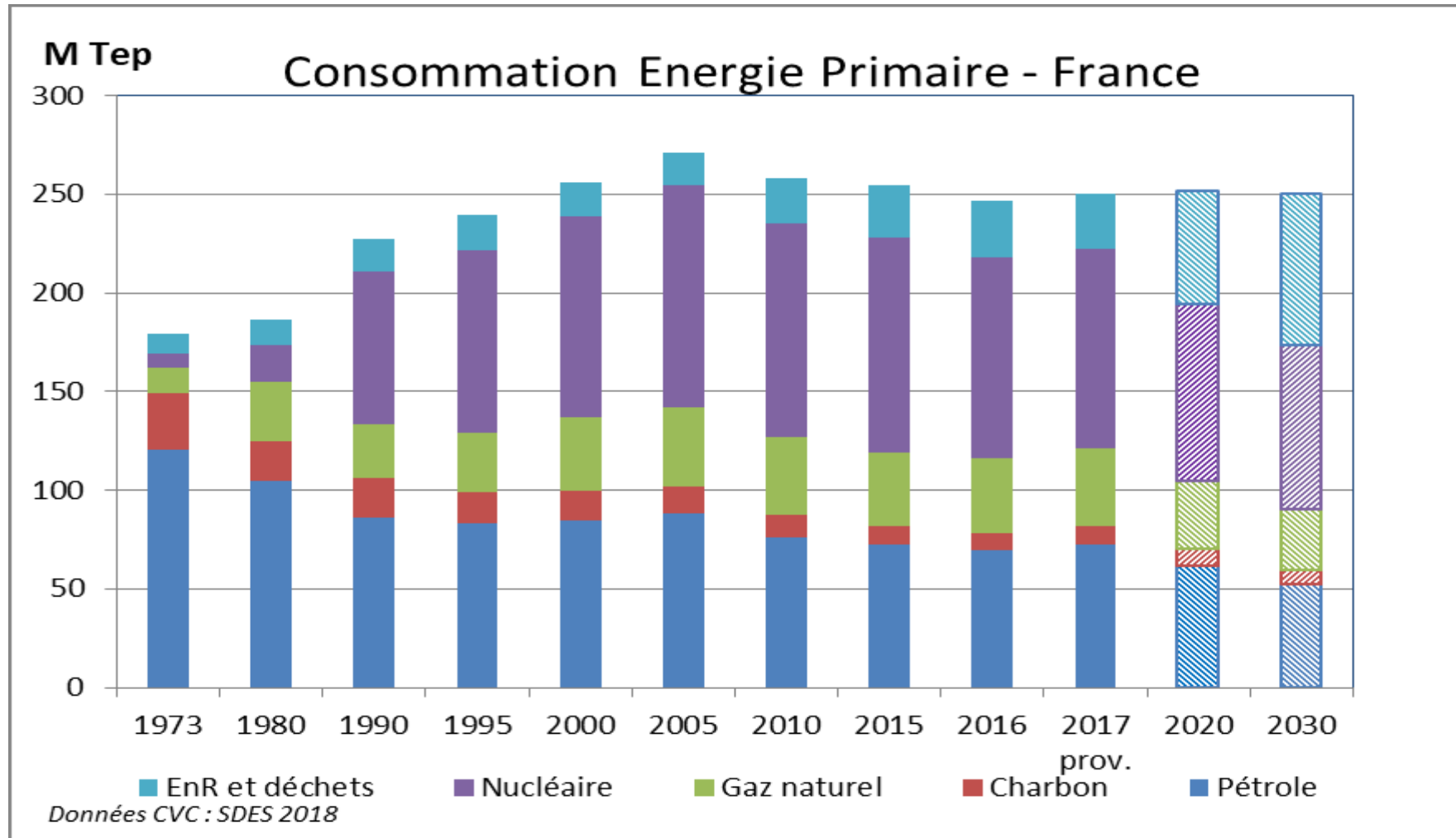
Nuclear: 50% of the Electricity Mix in 2035

Principales mesures :

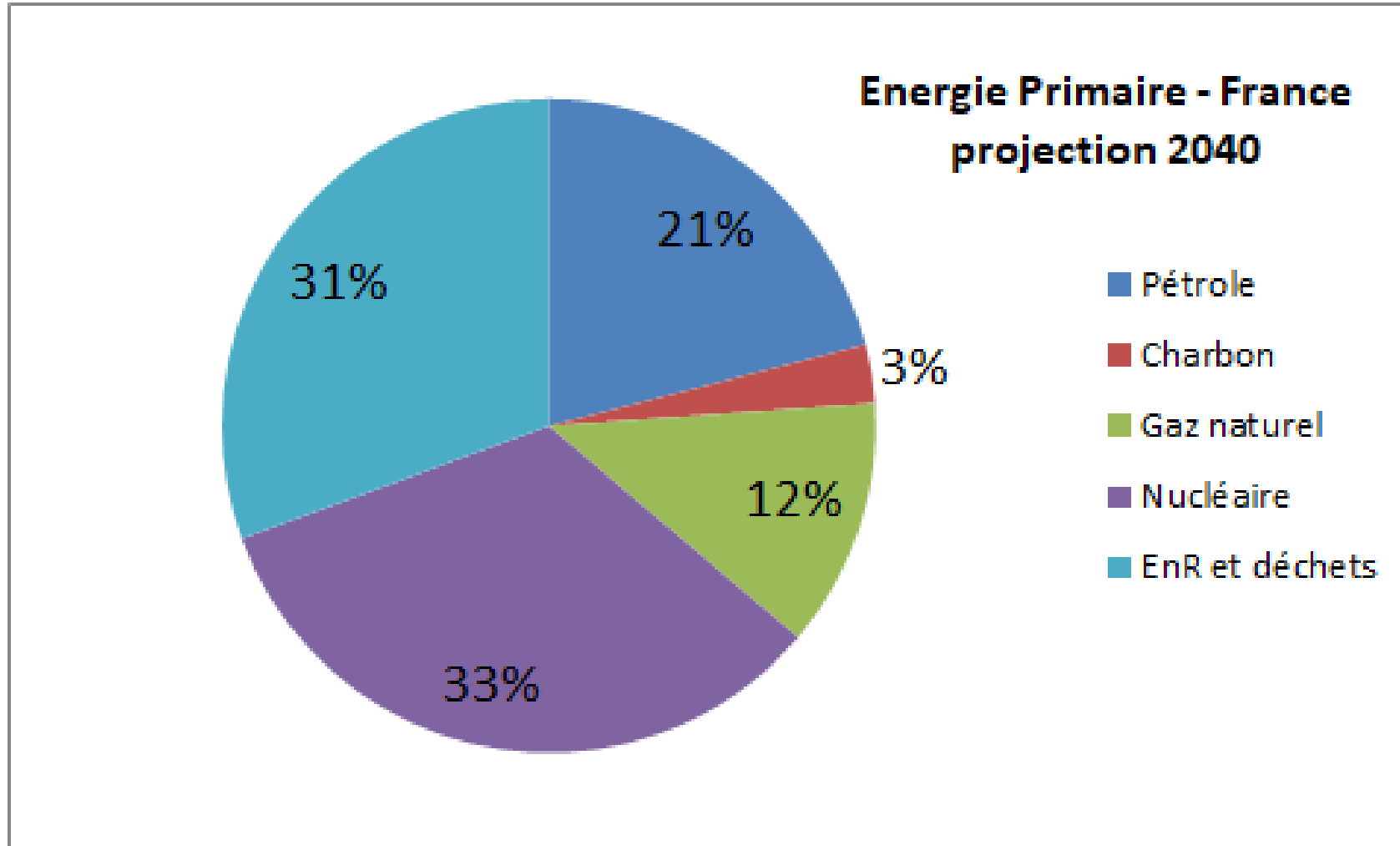
- Le Gouvernement se fixe l'objectif d'atteindre une part du nucléaire au sein du mix électrique de 50 % à l'horizon 2035. L'objectif inscrit dans le Code de l'énergie sera modifié en conséquence.
- L'atteinte de cet objectif impliquera la fermeture de 14 réacteurs nucléaires de 900MW, dont les deux réacteurs de Fessenheim.
- Le calendrier de fermeture des centrales respectera les échéances de 5e visite décennale des réacteurs concernés, à l'exception de 2 réacteurs qui fermeront dans la deuxième période de la PPE en 2027 et en 2028, sous réserve du respect du critère de sécurité d'approvisionnement.
- Si certaines conditions relatives au prix de l'électricité et à l'évolution du marché de l'électricité à l'échelle européenne sont remplies, la fermeture de deux réacteurs additionnels pourra intervenir à l'horizon 2025-2026, sur la base d'une décision à prendre en 2023
- Le Gouvernement identifiera les sites faisant prioritairement l'objet de fermetures, sur la base de la programmation transmise par EDF. Sauf exceptions, la décroissance du parc nucléaire ne devra conduire à l'arrêt complet d'aucun site nucléaire.
- La stratégie de traitement-recyclage du combustible nucléaire sera préservée sur la période de la PPE et au-delà, jusqu'à l'horizon des années 2040. A cette fin, le moxage d'un certain nombre de réacteurs 1300 MW sera entrepris et des études seront menées en vue du déploiement du multirecyclage des combustibles dans les réacteurs du parc actuel.



Reminder - France – Plan Pluriannuel de l'Energie (PPE) November/December 2018



Reminder - France – Plan Pluriannuel de l'Energie (PPE) November/December 2018

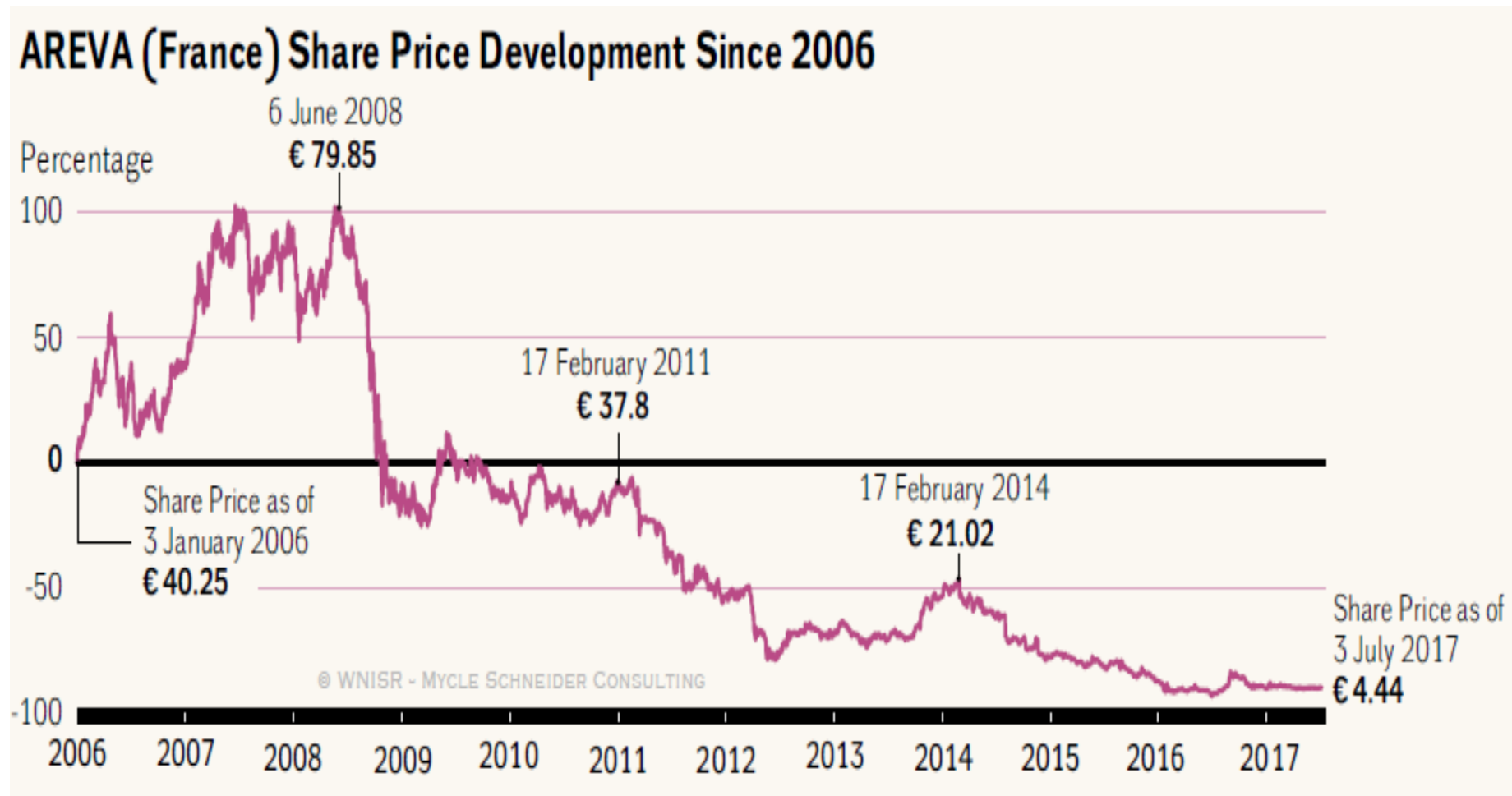


The Dilemma of Nuclear in France

- ◆ **Energy transition Law in France: Nuclear contribution for Electricity generation from 75% to 50% in 2035.**
- ◆ **IMPOSSIBLE and IRRELEVANT! The 2018 PPE is no longer valid!**
- ◆ **Production cost of existing nuclear in France = 32 €/Mwh (Not LCOE) Generation 2 power plants, including actual depreciation of assets, ie. opex & maintenance for 22 €/Mwh including fuel cost at 5 €/Mwh + 10 €/Mwh for plant life extension) vs 130 €/MWh for wind offshore.**
- ◆ **2029: anticipated date when the first 900 MW reactors will reach 50 years of operational exploitation.**
- ◆ **Alternative option: to prolong reactors life time by 10 years. EDF forecasts 48 G€ investments for maintenance and revamping.**
- ◆ **In the meantime, development of new generation of EPR, more standard and less expensive.**
- ◆ **Fessenheim will be closed when Flamanville EPR will be connected to the network (2020?) Flamanville not yet operational in 2023!**



Reminder - AREVA (Now ORANO): Business Difficulties



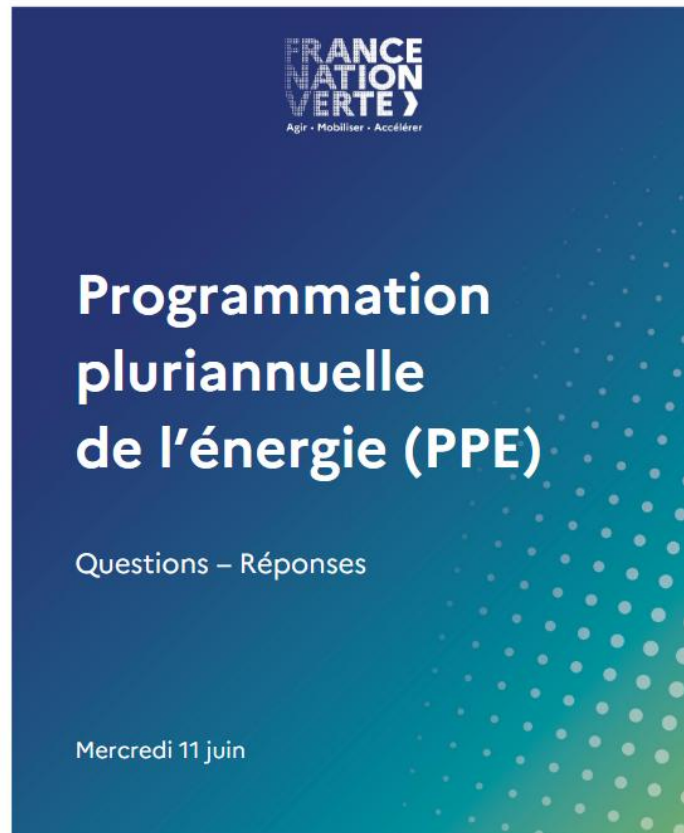
Source: Mycle Schneider Consulting
Status Report September 2017



France – PPE 2025 (Not yet promulgated in June 2025)

PPE 3 : à quand le décret de la feuille de route énergétique ?


MINISTÈRE
CHARGÉ DE L'INDUSTRIE
ET DE L'ÉNERGIE
*Liberté
Égalité
Fraternité*



La PPE mise en consultation introduit les objectifs suivants :

	2022	2030	2035
Nucléaire	56 réacteurs 279 TWh	57 réacteurs 360 TWh	en service
Photovoltaïque	16 GW	54-60 GW	65 - 90 GW
Eolien terrestre	21 GW	33-35 GW	40 - 45 GW
Eolien en mer	0,6 GW	4 GW	18 GW
Hydroélectricité	25,9 GW	26,3 GW	28,7 GW
Chaleur renouvelable	172 TWh	276-326 TWh	330-419 TWh
Biogaz	17,7 TWh dont 7 TWh injectés	50 TWh dont 44 TWh injectés	50-85 TWh
Biocarburants	38,5 TWh	50-55 TWh	70-90 TWh
Hydrogène	0 GW	Jusqu'à 4,5 GW	Jusqu'à 8 GW



France – Programmation Pluriannuelle de l'Énergie Published in February 2026



Stratégie française
pour l'énergie
et le climat

Dossier de presse
Février 2026



France – Programmation Pluriannuelle de l'Énergie

Published in February 2026 – PPE3

La programmation pluriannuelle de l'énergie, une stratégie pour la souveraineté énergétique de la France

Le Gouvernement déploie, à travers la 3^e Programmation Pluriannuelle de l'Énergie (PPE3), un plan ambitieux visant à accroître la production d'énergie décarbonée, souveraine et à prix compétitif en France. Ce plan fixe les orientations énergétiques pour les dix prochaines années et trace la voie vers la neutralité carbone à horizon 2050.

Face à l'urgence climatique et la nécessité d'indépendance géostratégique : la PPE3 projette la France vers une production énergétique indépendante et performante. Elle répond ainsi à 3 objectifs : souveraineté énergétique, neutralité carbone et compétitivité des prix.

La PPE3 fixe un cap clair : accroître la production énergétique décarbonée notamment électrique (entre 650 et 693 TWh en 2035, contre 544 TWh en 2025) et réduire la consommation d'énergies fossiles (environ 330 TWh en 2035 contre 900 TWh en 2023). Cette augmentation permettra d'inverser la tendance actuelle, passant de 60 % d'énergies fossiles dans la consommation à 60 % d'énergie décarbonée d'ici 2030, et 70 % en 2035.

La PPE3 dessine une trajectoire fondée sur un bouquet énergétique diversifié, combinant production électrique de différentes sources (nucléaire, hydroélectricité, éolien en mer et terrestre, photovoltaïque), électrification des usages et développement de substituts bas carbone aux énergies fossiles (réseaux de chaleur, biométhane, biocarburants, hydrogène), afin de réduire la dépendance aux énergies fossiles (pétrole, gaz).

Main trends:

- To pursue nuclear production with prolongation of reactors operational life to 50/60 years
- To develop 6 EPR2
- To promote SMR (Small Modular Reactors)
- To develop Hydroelectricity by increasing pumping stations (STEP) and dam's capacities
- To slow down Wind onshore, optimize existing sites
- To develop Wind offshore farms
- To pursue development of solar Energy

France – Programmation Pluriannuelle de l'Énergie: PPE 3

Published in in February 2026

Chiffres clés

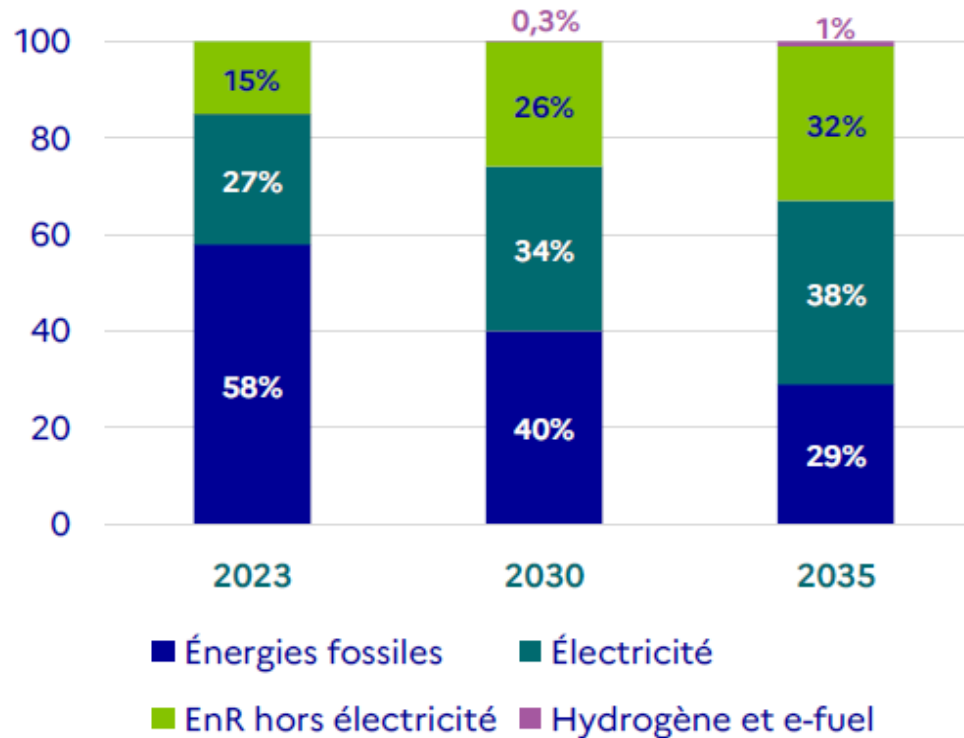
Les objectifs par filière à horizon 2035

		2023	2030	2035
Filières électriques	PRODUCTION D'ÉLECTRICITÉ DÉCARBONÉE ¹	458 TWh	585 TWh	Entre 650 et 693 TWh
	PRODUCTION NUCLÉAIRE	56 réacteurs 320,4 TWh	57 réacteurs en service 380 TWh (Cible haute à 420 TWh)	
	PHOTOVOLTAÏQUE	19,3 GW ² 22,7 TWh	48 GW ~59 TWh	55 – 80 GW ~67 – 98 TWh
	ÉOLIEN TERRESTRE	21,9 GW ³ 48,7 TWh	31 GW ~68 TWh	35 – 40 GW ~80 – 91 TWh
	ÉOLIEN EN MER	0,84 GW ⁴ 1,9 TWh	3,6 GW ~14 TWh	15 GW ⁵ ~59 TWh
	HYDRO-ÉLECTRICITÉ	25,9 GW (avec STEP) ⁶ 54,2 TWh ⁷	26,3 GW (avec STEP) ~54 TWh	28,7 GW (avec STEP) ⁸ ~54TWh
Filières non électriques	CHALEUR ET FROID RENOUVELABLES ET DE RÉCUPÉRATION	172 TWh chaleur ⁹ 1 TWh froid livré par les réseaux	297 TWh chaleur 2 TWh froid livré par les réseaux	328-421 TWh chaleur 2,5 – 3 TWh froid livré par les réseaux
	BIOMÉTHANE injecté dans les réseaux de gaz naturel (objectifs en TWh PCS)	9 TWh	44 TWh*	47 – 82 TWh
	BIOCARBURANTS dans le transport	38 TWh dans le transport	55 TWh dans le transport	70 – 90 TWh (transport et hors transport)
	HYDROGÈNE (capacité d'électrolyse installée)	0 GW	Jusqu'à 4,5 GW (9-19 TWh pci)	Jusqu'à 8 GW (16-40 TWh pci)

France – Programmation Pluriannuelle de l'Énergie Published in February 2026

La décarbonation de l'économie française dans la PPE

Accroître les énergies décarbonées et diminuer la part des énergies fossiles, fortement émettrices de carbone



Il est essentiel de réduire le poids des énergies fossiles dans notre bouquet énergétique.

En 2023, nous consommons près de

60% d'énergie finale fossile

Notre objectif est de n'en consommer

plus que **40 % en 2030**



France – Programmation Pluriannuelle de l'Énergie

Published in February 2026

Relance du nucléaire : une rupture avec la précédente programmation pluriannuelle de l'énergie

La PPE3 marque une rupture : alors que la PPE précédente prévoyait la fermeture de 14 réacteurs, la PPE3 acte la relance du nucléaire et garantit les investissements sur le long terme.

Conformément aux orientations définies par le président de la République lors du discours de Belfort du 10 février 2022, elle établit de nouveaux objectifs afin de donner un coup d'accélérateur à la filière.

- Sur le parc existant, elle vise à prolonger la durée de vie des réacteurs à 50 ou 60 ans, en respectant l'ensemble des exigences de sûreté, et à augmenter la puissance disponible des réacteurs existants.
- Dans le prolongement du discours de Belfort, elle confirme le lancement de la construction de six réacteurs EPR2 et fixe pour objectif d'être en mesure de décider en 2026 du lancement de la construction de huit réacteurs supplémentaires.

Elle propose de soutenir les petits réacteurs modulaires (« SMR ») et des petits réacteurs innovants avec l'objectif d'un premier réacteur au début de la décennie 2030.

Elle transcrit l'objectif de renouvellement des usines de l'aval du cycle, à travers le programme « Aval du futur ».

Elle comprend la poursuite des travaux sur la fermeture du cycle (usines de fabrication de combustible, réacteurs à neutrons rapides, usine de retraitement des combustibles), avec l'objectif de définir une feuille de route stratégique en vue d'une décision en 2026.

Elle vise la poursuite de la recherche dans le secteur du nucléaire.



Source: GOUVERNEMENT

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France – Programmation Pluriannuelle de l'Énergie Published in February 2026

Énergies renouvelables : un développement ambitieux et réaliste

La PPE3 poursuit le développement des énergies renouvelables en privilégiant les technologies le plus compétitives.

Les objectifs ont été définis en prenant en compte des critères de coûts, de disponibilité, d'acceptabilité locale et sociale et de souveraineté.

1. La réforme de l'hydroélectricité : redémarrage d'une filière souveraine

L'hydraulique occupe une place importante dans le bouquet énergétique de la France. Ce procédé représente en 2024 près de 15 % de la production d'électricité en France, se plaçant ainsi deuxième filière de production électrique après le nucléaire, et la première parmi les filières renouvelables.

La PPE3 et les nouveaux investissements permettront de développer le parc de stations de transfert d'énergie par pompage (STEP). Les sites existent déjà, ce qui rend cette solution à la fois pérenne et largement acceptée par l'écosystème, sans nécessiter la création de nouveaux sites.

La PPE3 fixe ainsi un objectif de développement ambitieux :

- Augmenter à hauteur de 1,7 GW les capacités de STEP
- Augmenter de 1,1 GW la puissance installée des ouvrages existants, notamment par l'optimisation et le suréquipement d'aménagements.

Une étape importante a été franchie dans la résolution des précontentieux avec la Commission européenne sur l'hydroélectricité à l'été 2025.

La Commission européenne a donné son accord de principe sur les modalités permettant une relance massive des investissements dans les barrages et les vallées au bénéfice de la transition énergétique et de la gestion de l'eau. Le régime juridique des concessions hydroélectrique va ainsi évoluer en faveur de la modernisation et l'extension d'installations essentielles au système énergétique.

La proposition de loi Battistel-Bolo visant à relancer les investissements dans le secteur de l'hydroélectricité pour contribuer à la transition énergétique a été adoptée par l'Assemblée nationale le 5 février 2026. Elle doit permettre la mise en œuvre de cette réforme.

2. Accélération sur l'éolien en mer : la montée en puissance d'une aventure industrielle

La PPE poursuit le développement de l'éolien en mer en prenant en compte les réalités industrielles de la filière et les besoins d'infrastructures. Avec 5 000 emplois industriels et 3 des 11 sites européens de fabrication des grands composants de turbines, la France est leader européen dans la fabrication des équipements de l'éolien en mer.

Le Gouvernement réitère son engagement pour développer avec ambition une filière industrielle complète dans le domaine de l'éolien en mer et de son raccordement :

- Une cible de 15 GW de puissance installée d'ici 2035 ;
- Un ajustement du calendrier pour l'objectif de 18 GW, désormais fixé à 2037, afin de mieux intégrer les réalités industrielles, notamment celles liées au raccordement des parcs au réseau électrique ;
- Des appels d'offres supplémentaires pour initier de nouveaux projets sur l'ensemble des façades maritimes.

La PPE permet la publication des prochains appels d'offres. L'introduction de critères de résilience issus du règlement « Industrie zéro net » (Net Zero Industry Act) européen dans les appels d'offres pour l'éolien en mer permettra de maximiser les retombées industrielles du développement de l'éolien en mer sur le territoire européen.

Concernant les autres énergies renouvelables marines, un tournant décisif sera pris pour la filière hydrolienne avec un premier appel d'offre de 250 MW au raz Blanchard ; l'usine marémotrice de la Rance de 240 MW continuera sa production.

3. Poursuite raisonnée du développement des énergies renouvelables électriques terrestres

Les objectifs d'installations des énergies renouvelables électriques ont été ajustés pour tenir compte de l'évolution de la consommation électrique sur les dernières années.

Depuis la version mise à la consultation du public, les cibles en 2030 et 2035 ont été adaptées pour tenir compte du rythme réel d'électrification du pays. Dans l'attente d'une accélération sur l'électrification des usages, le Gouvernement a décidé de maintenir stable les objectifs d'octroi de soutien public par appel d'offres inscrits dans la PPE 2 pour les énergies renouvelables terrestres jusqu'en 2028. En gardant le rythme établi par la PPE précédente, elle maintient le niveau de déploiement propice à l'émergence de projets industriels souverains, notamment dans l'industrie photovoltaïque.

Pour l'éolien terrestre, l'ambition est claire : privilégier les projets visant à l'augmentation de la puissance des parcs existants, avec une cible de 31 GW en 2030, 35-40 GW en 2035, contre environ 24 GW en 2025.

En ce qui concerne la trajectoire photovoltaïque, le Gouvernement maintient une trajectoire ambitieuse avec une cible de 48 GW en 2030 et 55-80 GW en 2035, contre un peu plus de 31 GW en 2025.

4. Poursuite du développement des énergies bas carbone non-électriques

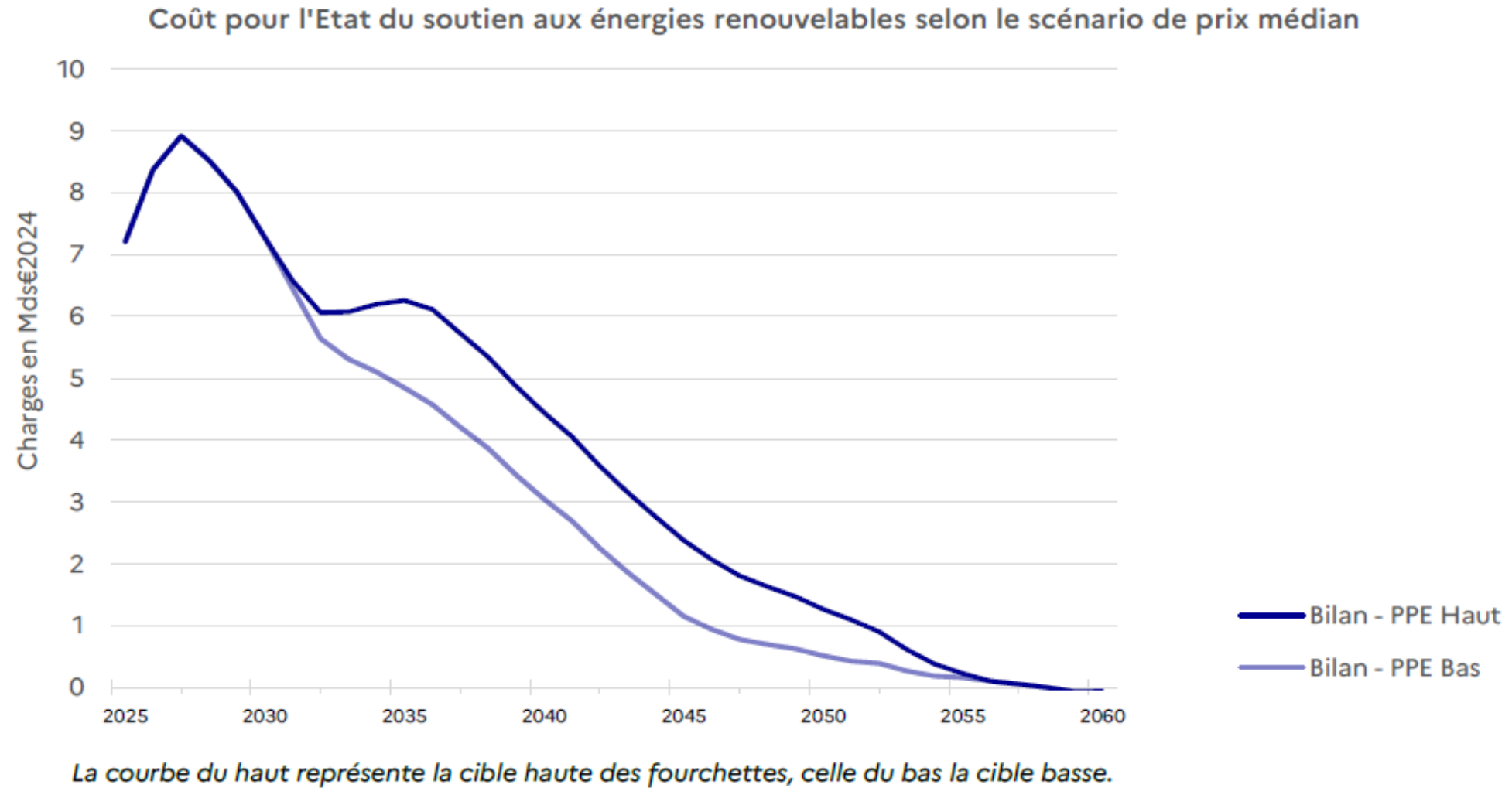
Grâce à l'électrification, la France pourra considérablement réduire son recours aux énergies carbonées : il s'agit d'inverser la part des énergies fossiles dans la consommation du pays qui s'élève aujourd'hui 60 % pour passer à 60 % d'énergie décarbonée en 2030.

L'électricité nucléaire et renouvelable et l'électrification massive des usages permettront d'accomplir près de 70 % de la réduction d'énergies fossiles prévue par la PPE en 2035. Toutefois, certains usages nécessitent des combustibles aujourd'hui assurés par des énergies fossiles, principalement le pétrole et le gaz.

À travers cette PPE, pour les usages de l'énergie que l'on peut difficilement électrifier, le Gouvernement promeut le recours à des substituts décarbonés tels que le biométhane, l'hydrogène décarboné, la chaleur renouvelable et les biocarburants.

Compte tenu du coût de ces substituts relativement plus élevés que les hydrocarbures, afin de répondre à une ambition forte de déploiement des énergies bas carbone, l'État a mis en place plusieurs dispositifs incitatifs et de soutien.

France – Programmation Pluriannuelle de l'Énergie Published in February 2026



France – Programmation Pluriannuelle de l'Énergie Published in February 2026

Plus de 100 000 nouveaux emplois dans la transition énergétique

Les cibles d'énergies décarbonées de la PPE impliqueront des besoins importants en emplois, notamment dans le nucléaire, le photovoltaïque et l'éolien en mer. Le tableau ci-dessous fournit des estimations par filière des besoins en emploi à l'horizon 2030¹⁰.

Emplois par filières	Emplois en 2022 ¹¹	Trajectoire 2030 ¹²
Réseaux de chaleur	3 740	8 690
Réseaux de froid	210	420
Hydroélectricité	14 720	14 720
Éolien terrestre	14 670	21 656
Éolien en mer	5 080 ¹³	33 867 ¹⁴
Solaire thermique	2 830	11 320
Solaire photovoltaïque	18 920	56 760
Géothermie	2 780	8 237
Biogaz	5 290	14 944
Filière nucléaire	125 000 ¹⁵	156 000 ¹⁶
Total énergies (hors biocarburant, hydrogène et dérivés, énergie fossile et filière réseaux) ¹⁷	~ 193 200	~326 600

France – Programmation Pluriannuelle de l'Énergie Published in February 2026

Comparaison avec les cibles du Bilan prévisionnel de RTE

Le scénario de la PPE a été préparé par le Gouvernement sur le fondement d'une grande consultation et dans une logique de minimisation des coûts, d'acceptabilité sociale et de souveraineté industrielle.

Il ne se positionne pas exactement sur l'un des scénarios du bilan prévisionnel de RTE publié en décembre 2025, mais s'inspire du scénario R3, en y intégrant des contraintes industrielles et d'acceptabilité.

	R1	R2	R3	R4	PPE 3	Scénario RTE correspondant
Eolien en mer						
Objectif 2035	7 GW	10 GW	13 GW	15 GW	15 GW	R4 (objectif industriel)
Eolien terrestre						
Objectif 2030	27 GW	27 GW	32 GW	35 GW	31 GW	R3 (cohérence avec la proposition de loi Gremillet)
Objectif 2035	30 GW	30 GW	40 GW	45 GW	35-40 GW	R2 – R3
Photovoltaïque						
Objectif 2030	35 GW	42 GW	47 GW	54 GW	48 GW	R3 (cohérence avec la proposition de loi Gremillet)
Objectif 2035	40 GW	55 GW	65 GW	90 GW	55 - 80 GW	R2 – R« 3,5 » (objectif industriel)



Source: GOUVERNEMENT

Liberté
Égalité
Fraternité



Reminder - France PPE March 2025 - Renewables Incentive Costs Additional Commitments 2025-2035 to fulfill PPE3 objectives

Estimation des coûts de soutien entre 2025 et 2060 (Md€ ₂₀₂₄)	Scénario de prix bas	Scénario de prix médian	Scénario de prix haut
Photovoltaïque	30,1 à 55,3	20,8 à 38,4	9,4 à 17,6
Éolien terrestre	21,6 à 27,6	6,1 à 7,6	-16,0 à -11,9
Éolien en mer	36,3	4,5	-35,2
Hydraulique	4,2	2,2	-0,2
Hydrolien	1	0,8	0,5
Biométhane	5,0 à 10,9	4,4 à 9,4	3,7 à 7,8
Total PPE 3	98,2 à 135,2	38,7 à 62,9	-33,7 à -25,5
Déjà engagé avant la PPE 3	114,3	90,1	60,1
Total	212,5 à 249,6	128,8 à 152,9	26,4 à 34,6



Zoom sur le PP3/Éolien Offshore – Qu'en penser?

Projets PPE3	AO10 – 10 ^{ème} Appel d'offres pour le soutien de l'éolien en mer	Nucléaire - Programme pour les EPR2
Date de lancement	12 Juin 2026	9 Novembre 2021
Programme	Construction de 10 GW 5 GW éolien en mer + 5 GW éolien terrestre	Construction de 6 EPR2, 1750 GW par unité 3 paires de 2 réacteurs
Sites	Ensemble des façades maritimes	3 sites: Penly, Gravelines, Bugey
Attribution des contrats	Février 2027	Plusieurs contrats attribués
Démarrage travaux	?	Entre été 2024 et Avril 2028 selon les sites
Mise en service prévue	?	Entre 2037 et 2042 selon les sites
Durée	25 ans, à démanteler et renouveler tous les 25 ans	60 ans+
Production attendue	Intermittente – # 30 TWh/an pendant 25 ans Tenant compte du facteur de charge	# 70 TWh/an pendant 60 ans+
Coût	Prix d'achat moyen pondéré = 100 €/MWh (p.m. Parc Yeu/Noirmoutier: 61 éoliennes x 8MW = 488 MW - Invest. 2,5 G€ - 167 €/MWh)	73 G€ (Source EdF)

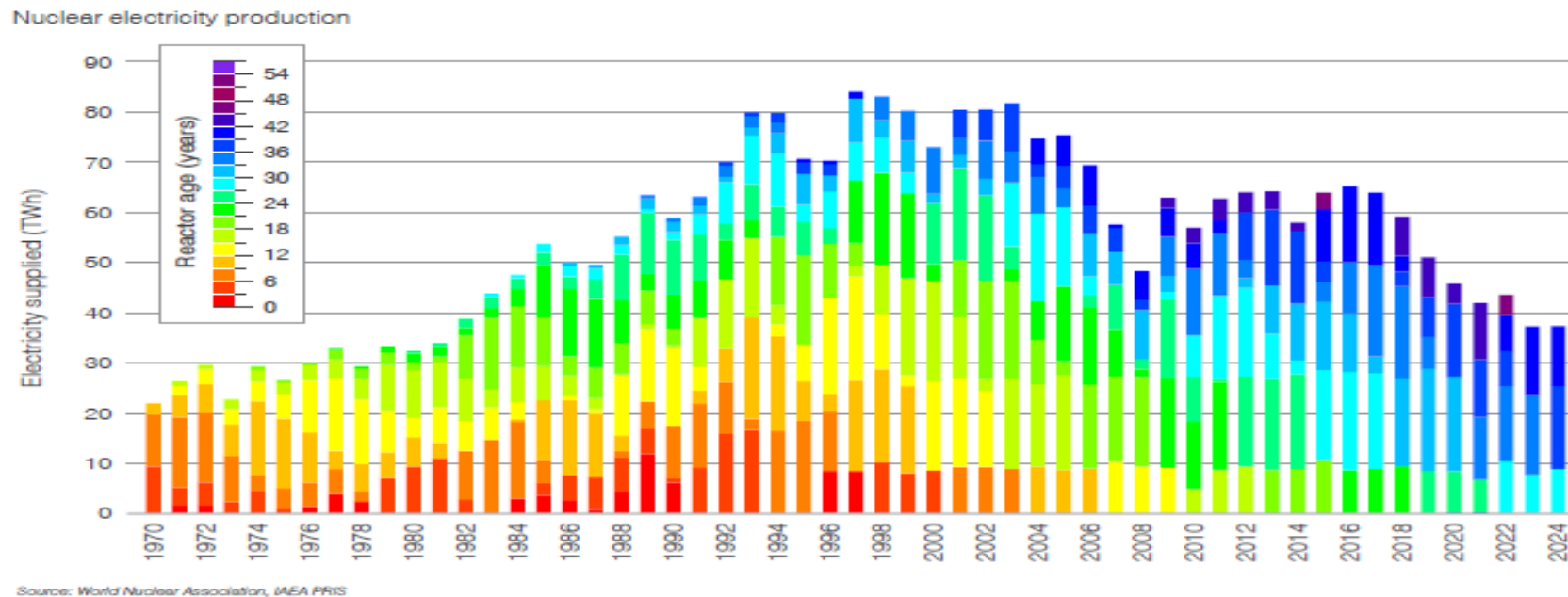
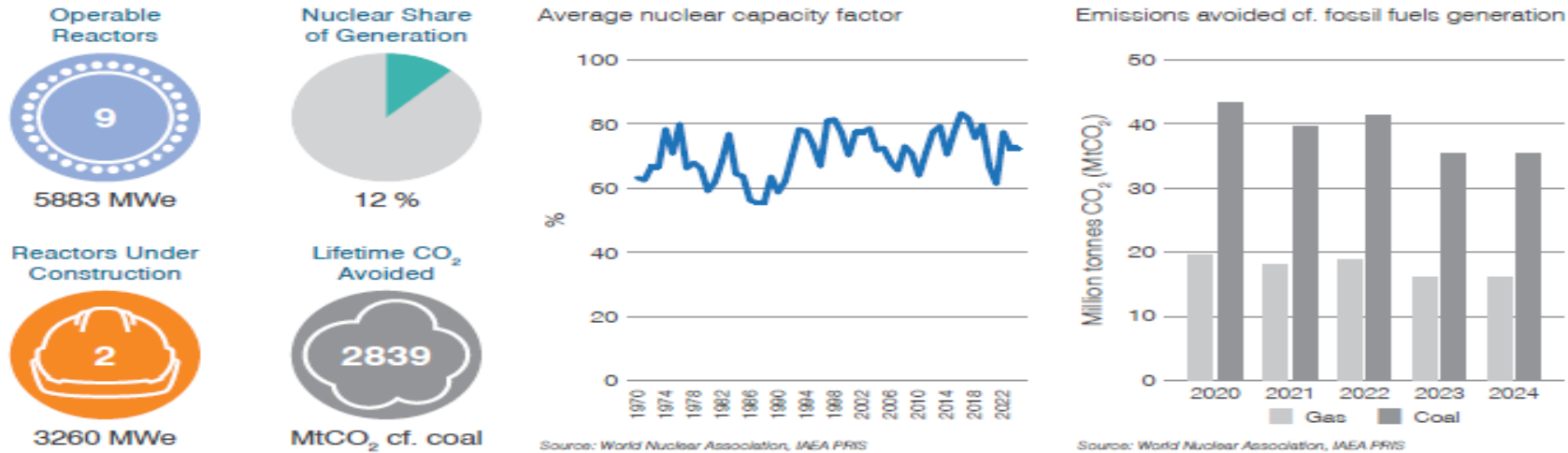


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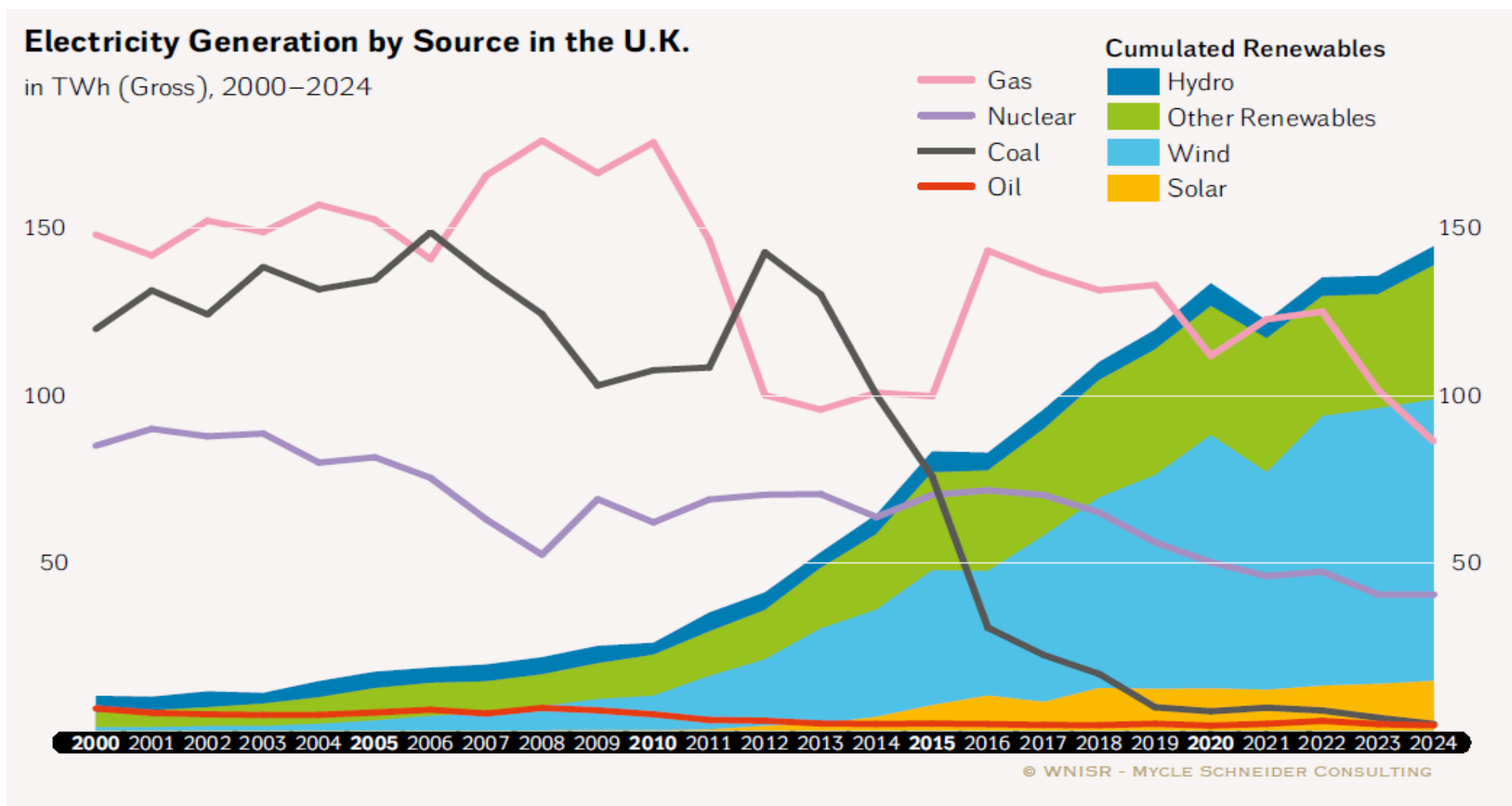
A Zoom on UK



Nuclear Energy in UK



Electricity by Source in the UK 2000 - 2024



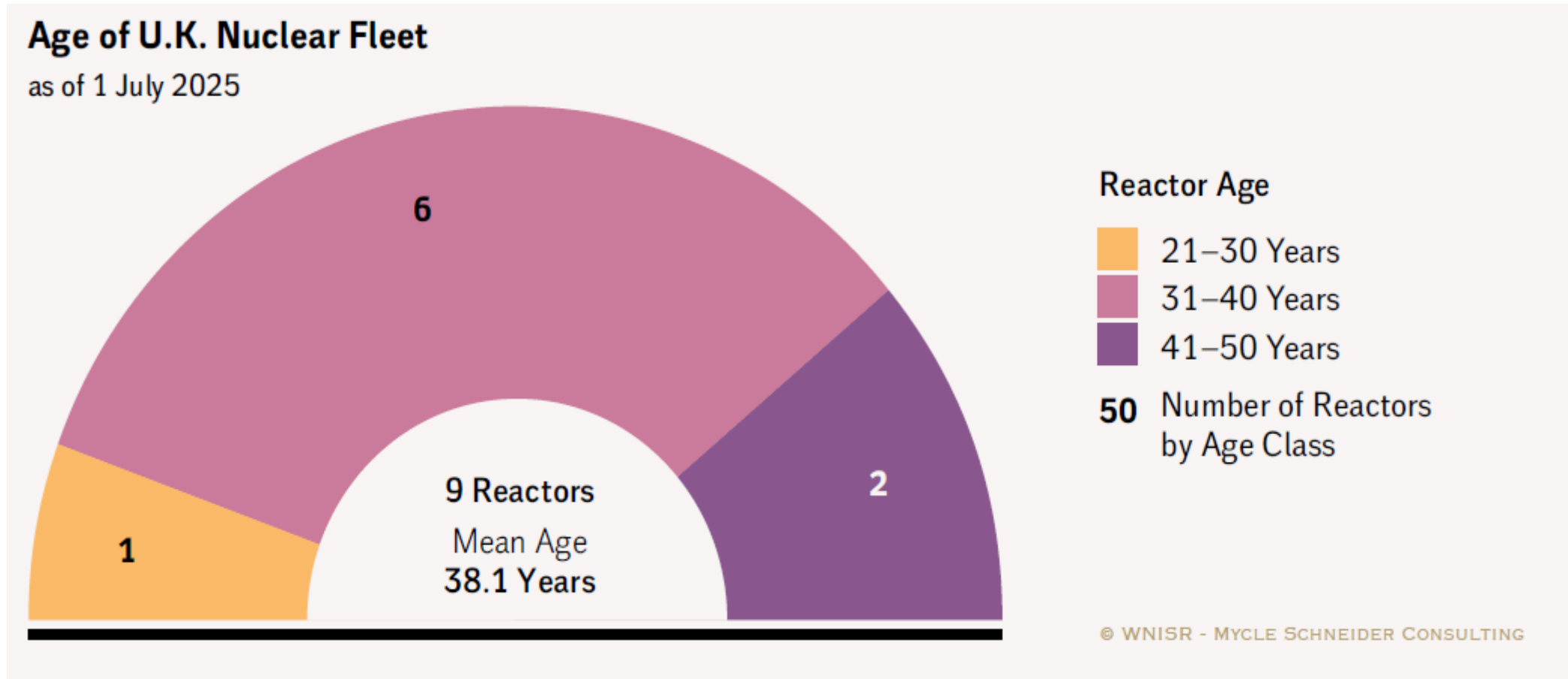
Source: U.K. Government, 2025^{SS1}

Source: Mycle Schneider
WNISR IAEA-PRIS September 2025



The Age of UK Reactors

Mean Age: 38 years



Sources: WNISR with IAEA-PRIS, 2025

Source: Mycle Schneider
WNISR IAEA-PRIS September 2025

New EPR's in the UK – The History & present situation

- ◆ Agreement between EdF Energy and DECC on 21 October 2013 (Contract for Difference related to the price of electricity purchased)
- ◆ Electricity price: 92,5 £/MWh, 2012 money (109 €/MWh*), down to 89,5£/MWh (105 €/MWh*) if Sizewell decision is confirmed.
- ◆ Consortium initially composed of EdF Energy/Areva/CGN (China General Nuclear Power Corporation)/CNNC (China National Nuclear Corporation). Areva participation questioned & left. Present participation end 2025: EdF Group (73%), CGN (27%)
- ◆ Construction of 2 EPR at Hinkley Point C (2x1600 MW)
- ◆ Supply of electricity to 6 million households. Start-up now scheduled between 2029 & 2031.
- ◆ Approbation by European Commission in October 2014. UK government approval on 15 september 2016, contract signed on 29 september 2016. by EdF, CGN, UK gvnt. EdF confirms FID. Operational start-up: initially scheduled for 2026.  Technical difficulties, capex overruns, additional delays.
- ◆ Capex: initial budget = 16 G£ (present final estimate : 35 G£ # 40 G€*)
- ◆ Study of two additional units at Sizewell C.
- ◆ EdF new design studies for a « EPR New Model » to replace existing reactors.

Note: 9 reactors in operation in UK mid 2023 – 48 TWh in 2022.

Costs of EPR are expected to decrease down to 70/90 €/MWh when more units are built and sold.

*Depends upon the exchange rate



New EPR's in UK



Illustration of Hinkley Point C – Photo EdF Energy



New EPR's in UK



Illustration of Hinkley Point C – Photo EdF Energy

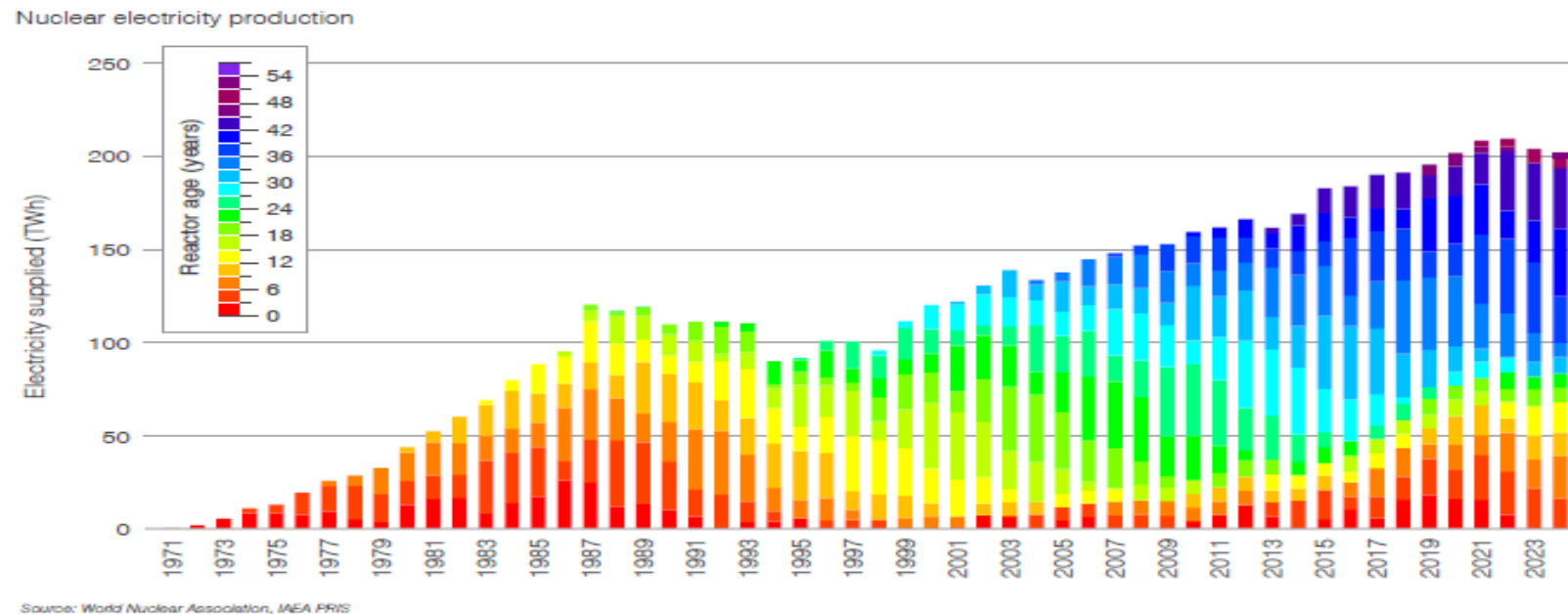
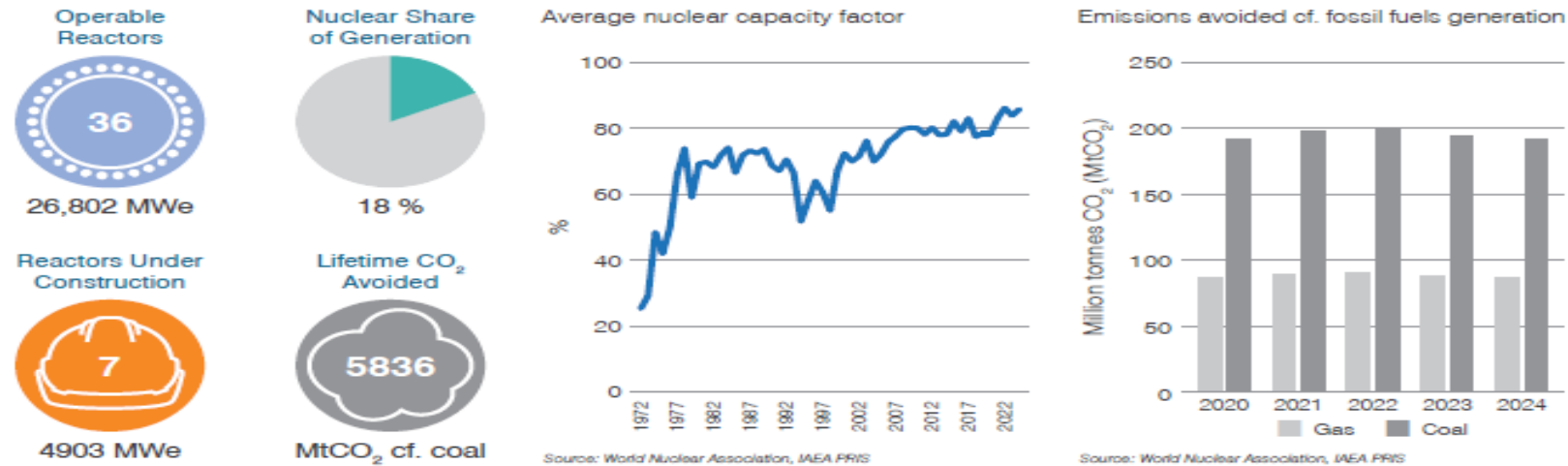


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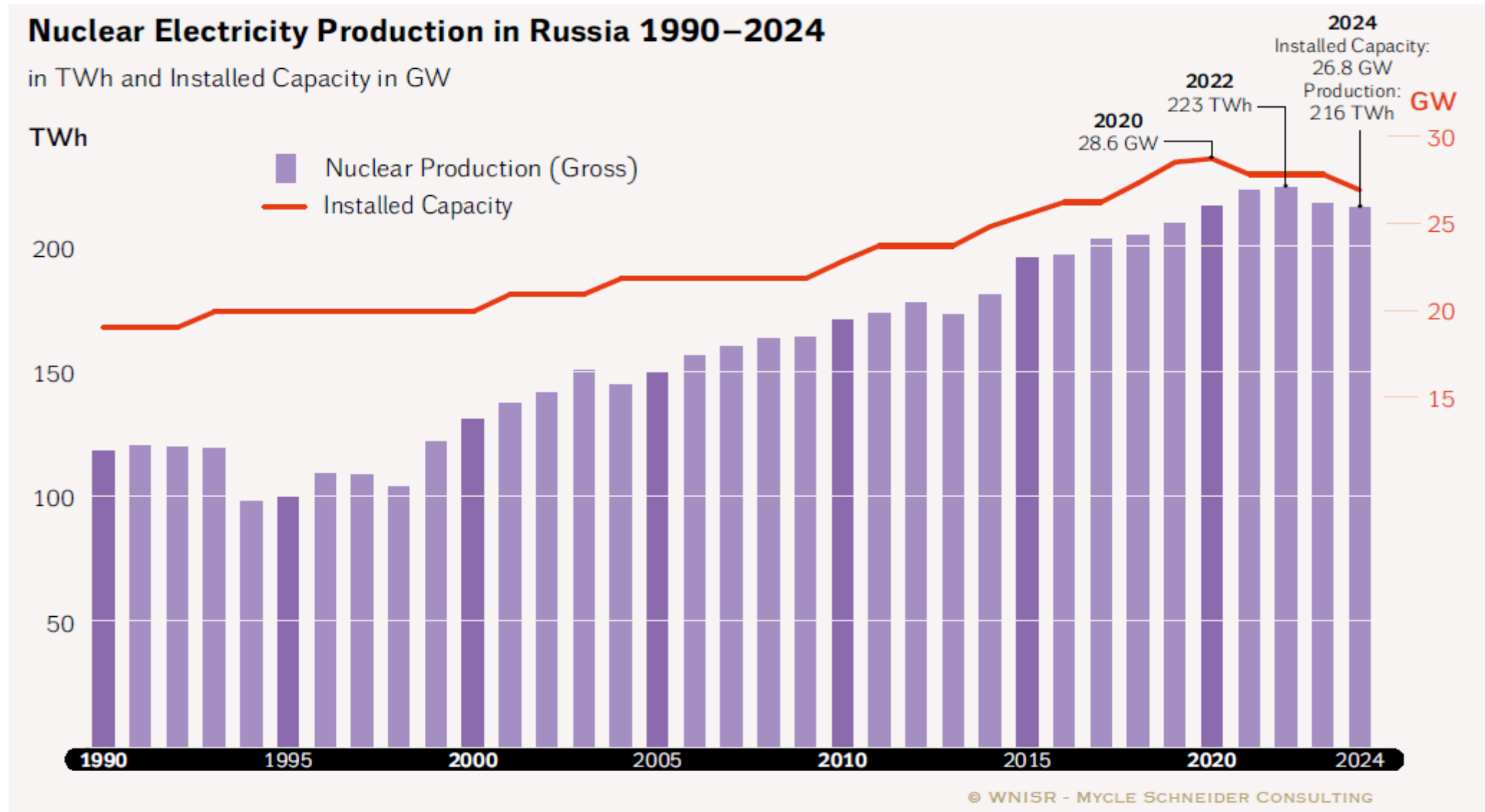
A Zoom on Russia



Nuclear Energy in Russia



Nuclear Energy in Russia

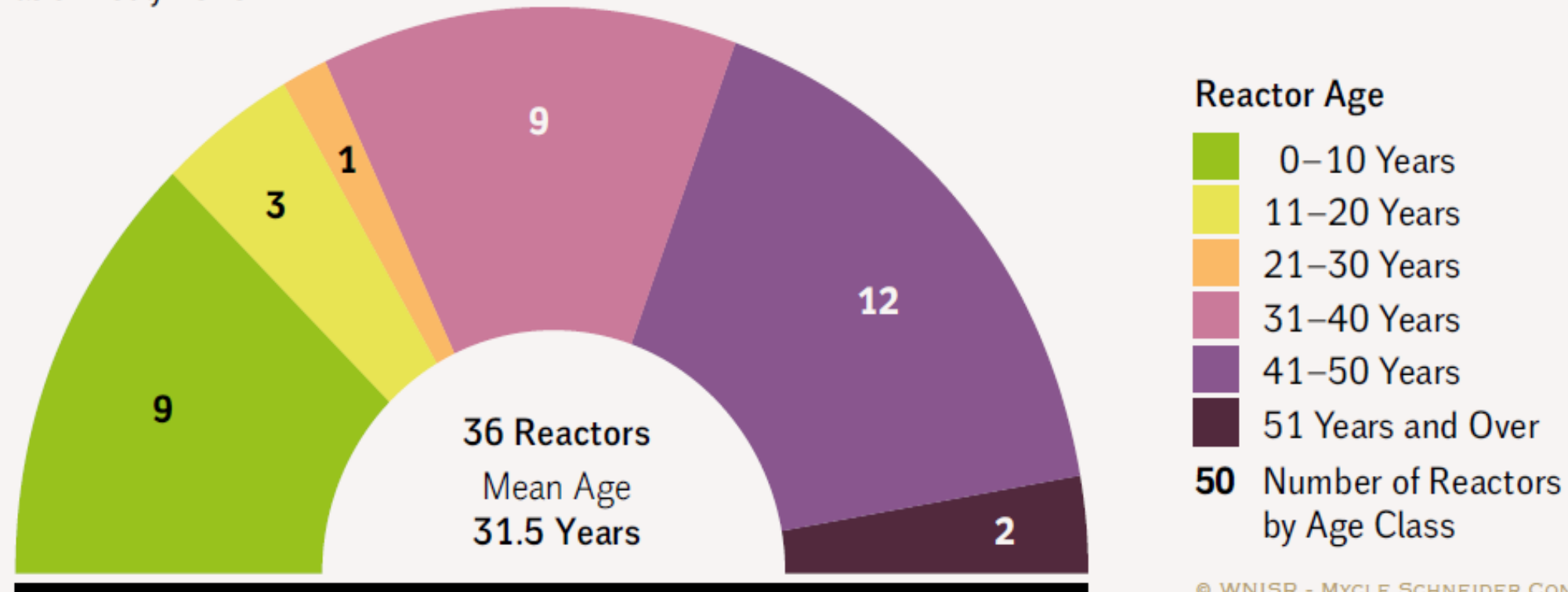


The Age of Russian Reactors

Mean Age: 31 years in 2025

Age of Russian Nuclear Fleet

as of 1 July 2025



© WNISR - MYCLE SCHNEIDER CONSULTING

Sources: WNISR with IAEA-PRIS, 2025

Source: Mycle Schneider
WNISR IAEA-PRIS September 2025



The first floating nuclear plant

Pevek Harbor/Tchoukotka peninsula - Russia

Floating nuclear power plant

Akademik Lomonosov

Length 110m
Width 30m

Storage of spent fuel and radioactive waste

Hydrotechnical structures

Heat distribution centre



Two KLT-40S nuclear reactors (35MW each)

Steam turbines

Electric transmission unit

Hot water tanks



**Academic Lomonossov: 144 m length, 30 m width. Displacement: 21500 t.
2 PWR reactors, 35 MW each. Will feed a 200 000 inhabitants city. Operator Rosatom.
Destination 2019: Tchoukotka peninsula eastern Siberia.**



Land-based SMR in Russia – 55 MW

Nuclear regulator Rostekhnadzor has granted a licence to build the country's first land-based small modular reactor (SMR), in the Republic of Sakha (also known as Yakutia) in Russia's Arctic north.



April 2023 - Rosatom and the Corporation for the Development of the Far East and the Arctic signed a cooperation agreement relating to the construction of the plant, saying "the project will provide a clean, cost-effective and stable source of energy to the remote Arctic territories of Yakutia with a decentralised energy supply. The electric power of the station will be at least 55 MW, the service life of non-replaceable equipment will be up to 60 years".

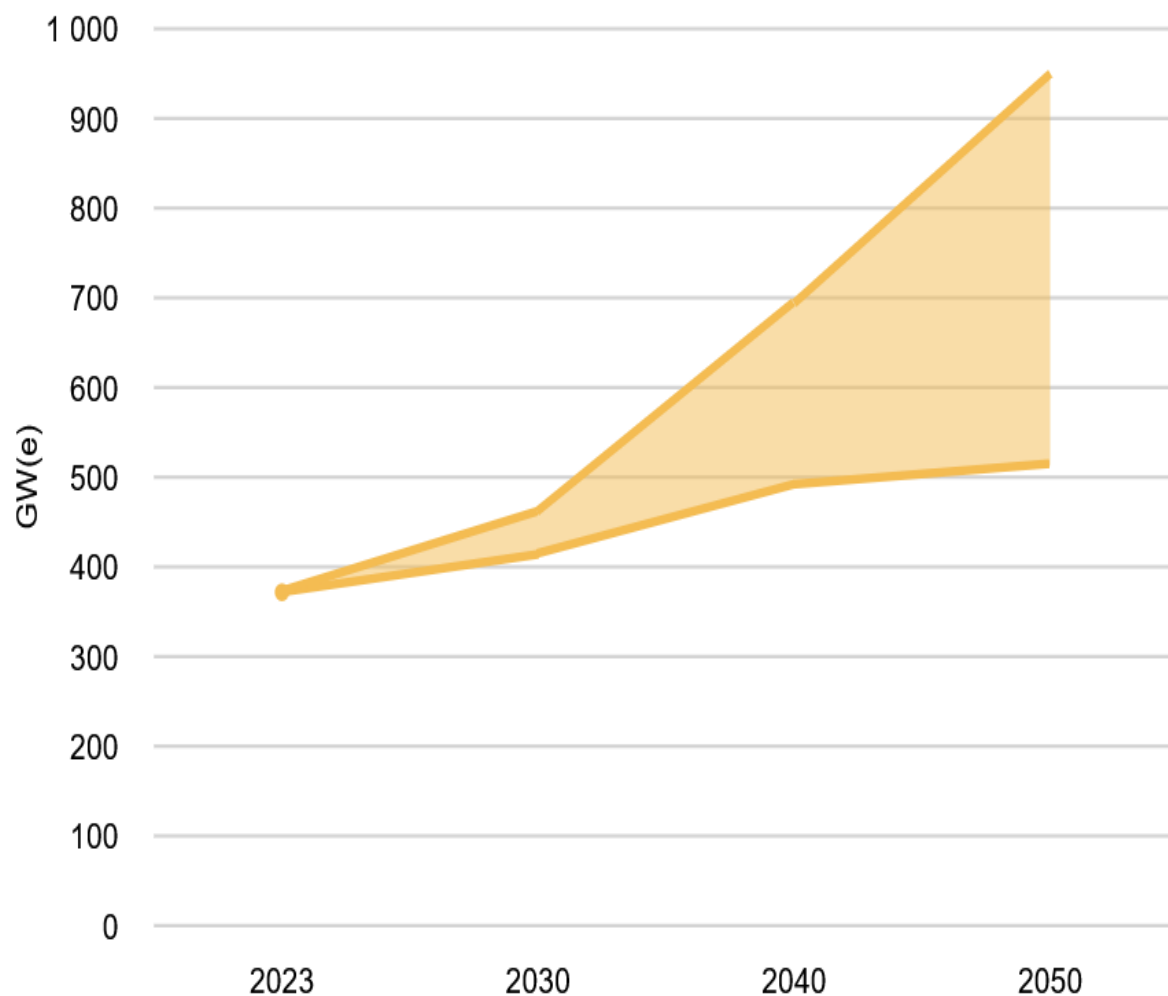


4-9

Some Scenarios



IAEA Scenarios – Low case & High case



Electrical Capacity	2023	2030		2040		2050	
		Low	High	Low	High	Low	High
Total	8 992	10 042	10 042	13 747	13 747	20 329	20 329
Nuclear	372	414	461	491	694	514	950
<i>Nuclear as % of Electrical Capacity</i>	4.1%	4.1%	4.6%	3.6%	5.0%	2.5%	4.7%

Source: IAEA Energy, Electricity & Nuclear Power Estimates Edition 2024



4-10

**Competitiveness of Nuclear Energy
The LCOE
See also Book 2 Energy, Chapter 17**



Levelized Cost of Electricity production (LCOE) = Discounted Costs/Discounted Production

$$LCOE = \sum_{k=0}^{k=n} \frac{C_k + O_k + F_k}{(1+i)^k} / \sum_{k=0}^{k=n} \frac{Q_k}{(1+i)^k}$$

- *Q : Production of Electricity*
- *C : Capital Expenditures*
- *O : Operating Expenses*
- *F : Fuel Expenses*
- *n : Economic Plant Life*
- *i : Discount Rate*
- *Due to discounting, decommissioning costs have a negligible effect (included in Capex)*
- *For Renewables, Intermittency Costs are not included*

Nota: In the following, raw data from IEA, US DOE, UK DBEIS, IRENA, Lazard, Fraunhofer ISE, WNA,.....



LCOE is very dependant upon changes of the environment (Inflation, prices of fuels, cost of new nuclear, production costs of solar energy, access to mineral materials in particular)

For wind energy and solar energy, cost of intermittency has to be added.

LCOE is also very dependant upon the selected **Discount Rate**

The following graphs have been established taking into account the most recent data of the various components of the LCOE (Capex, Opex, Cost of Fuels) deriving from external pertinent sources. For reason of simplicity, they are illustrating the mean values for LCOE of all technologies generating Electricity. They refer to European/OECD sites, knowing that there exist large disparities according to the various sites and locations in the World



Levelized Cost of Electricity production - LCOE Assumptions (2023/2024 Environment)

- Crude oil price : 75 \$/b (Brent price 2024)
- Gas price : 14 \$/Mbtu (German Import price 2024)
- Coal price : 140 \$/t (NW Europe price 2024)
- Uranium price : 80 \$/lbU₃O₈ (Spot price 2024)
- Exchange rate : 1€ = 1,07 \$
- **Discount rate : 5%**
- Standard power ranges
- **Reference : European/OECD sites**
- Mean values, ranges differ depending upon technologies
- For Renewables, costs of intermittency are not included and have to be added.

Nota: A large range of LCOE can be observed depending upon the publications and the location of the projects
Data below from IEA, NREL, EIA, Lazard, Fraunhofer, DBEIS UK.....



Levelized cost of Electricity production

Assumptions: 2023/2024 Environment

		Nuclear Gener. 2	Nuclear EPR	Gas CCGT	Gas CCGT&CCS	Heavy Fuel	Coal Sup. crit.	Coal IGCC	Coal IGCC&CCS	Wind Onshore	Wind Offshore	Solar PV Utility	Solar PV Rooftop	Solar CSP	Hydro Large	Biomass	Geother.
Power reference	Mwe	1000	1650	600	600	600	700	700	700	120	250	100	0	150	1000	50	50
Construction lead	Years	7,0	8,0	3,0	3,0	3,0	5,0	5,0	5,0	1,5	2,5	2,0	0,3	2,0	6,0	3,0	3,0
Duration life	Years	60	60	30	30	30	40	40	40	25	25	25	25	25	80	25	80
Availability	%	90%	90%	80%	80%	80%	80%	80%	80%	33%	45%	17%	17%	45%	35%	80%	85%
Thermal Energy Efficiency	%	33%	37%	60%	60%	42%	40%	40%	40%								
Capex	€/kW	6000	10000	1000	2700	1200	4000	5000	7000	1500	3400	1000	2000	7000	2300	4400	5000
Opex (incl. Maintenance)	€/MWh	21	35	8	14	6	13	29	36	11	20	12	20	20	16	25	18

CCGT: Combined-Cycle Gas Turbine

IGCC: Integrated Gasification Combined-Cycle

CCS: Carbon Capture & Storage

Note: Gas CCGT & CCS and Coal IGCC & CCS includes 10€/MWh for CO2 transport & storage



Cost price of Electricity produced by the various types of Power Plants @ 5% excluding CO₂ price (**2023/2024** Environm., European/OECD sites, **Mean values**)

(€/MWh)

160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0

Nuclear Gen. 2
Nuclear New EPR
Gas CCGT
Gas CCGT with CCS
Heavy fuel
Coal Super Critical
Coal IGCC
Coal IGCC with CCS
Wind onshore
Wind Offshore
Solar PV Utility
Solar PV Rooftop
Solar CSP
Hydro Large
Biomasse
Geothermal

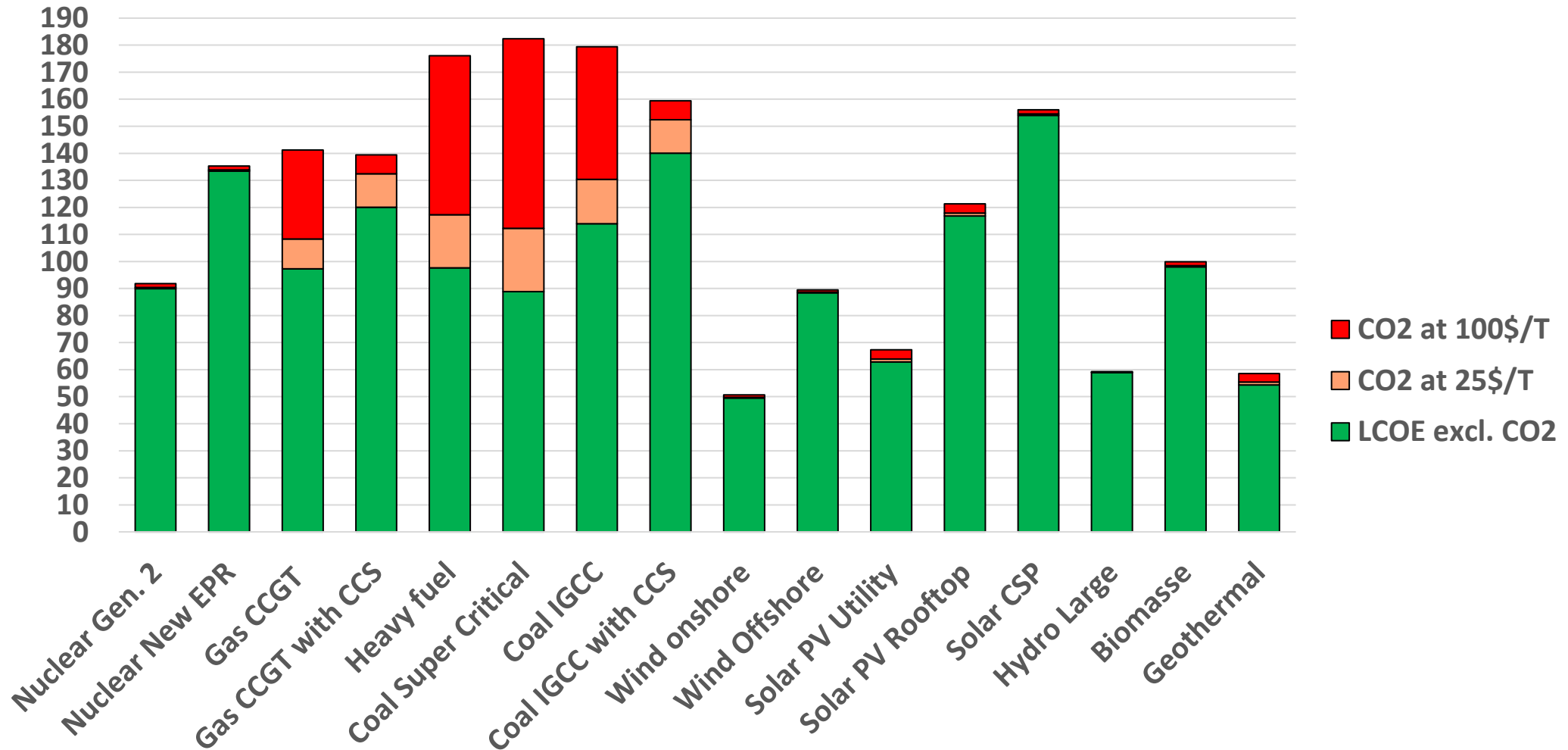
Variability of LCOE, according to sites, estimates 2023
Solar CSP : 100-250 €/MWh
Large Hydro : 40-120 €/MWh
Geothermal : 40-150 €/MWh
Biomasse : 50-240 €/MWh
Marine : > 350 €/MWh

Fuel Costs
Opex
Capex

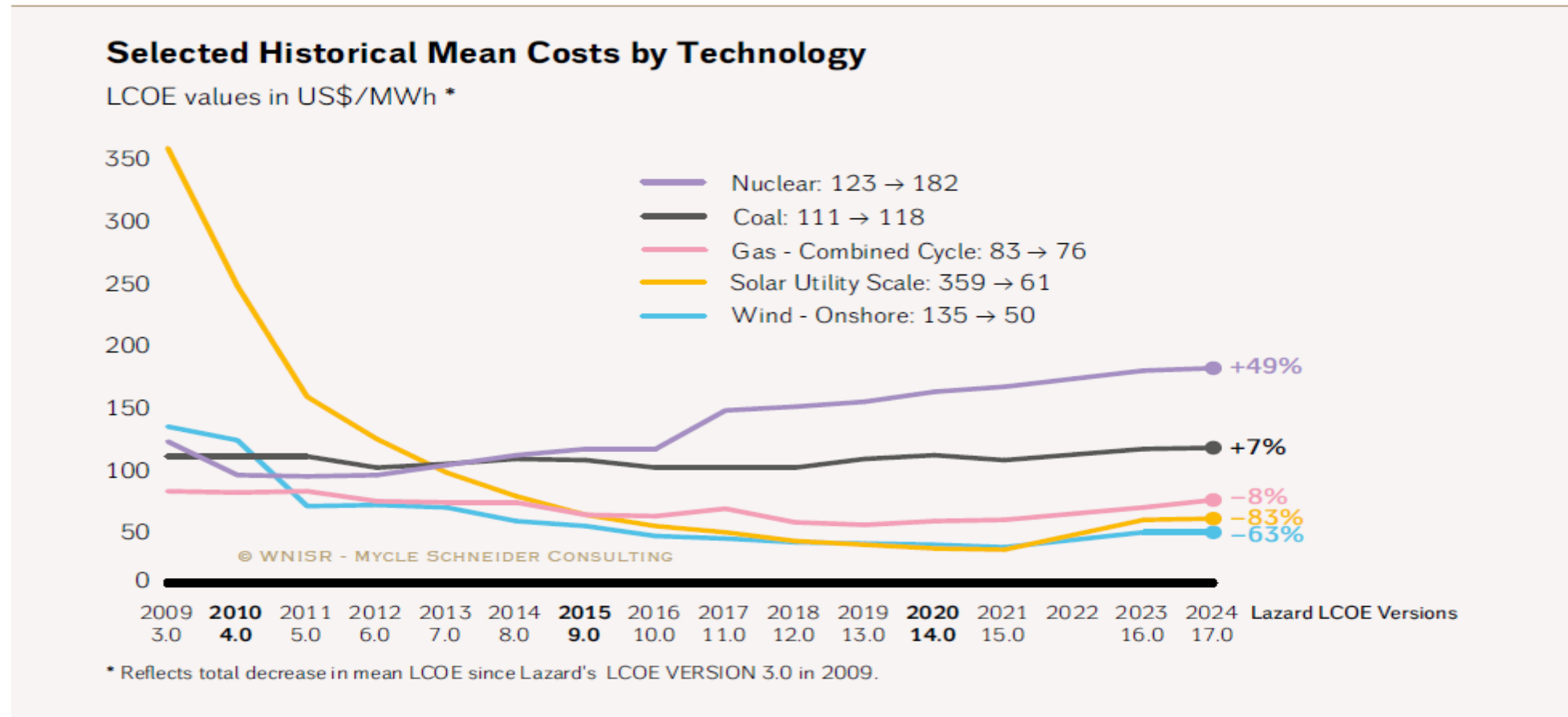


Cost price of Electricity produced by the various types of Power Plants @ 5%
including CO₂ price (**2023/2024** Environm., European/OECD sites, **Mean values**)

(€/MWh)



Nuclear LCOE estimates



Source: Lazard Estimates, 2024

Notes: **LCOE**: Levelized Cost of Energy

*This graph reflects the average unsubsidized LCOE values for a given version of LCOE study. It primarily relates to the North American energy landscape but reflects broader/global cost developments. See also Figure 69.

Source: Mycle Schneider & Lazard estimates 2024 (Specific assumptions)
WNISR IAEA-PRIS September 2024

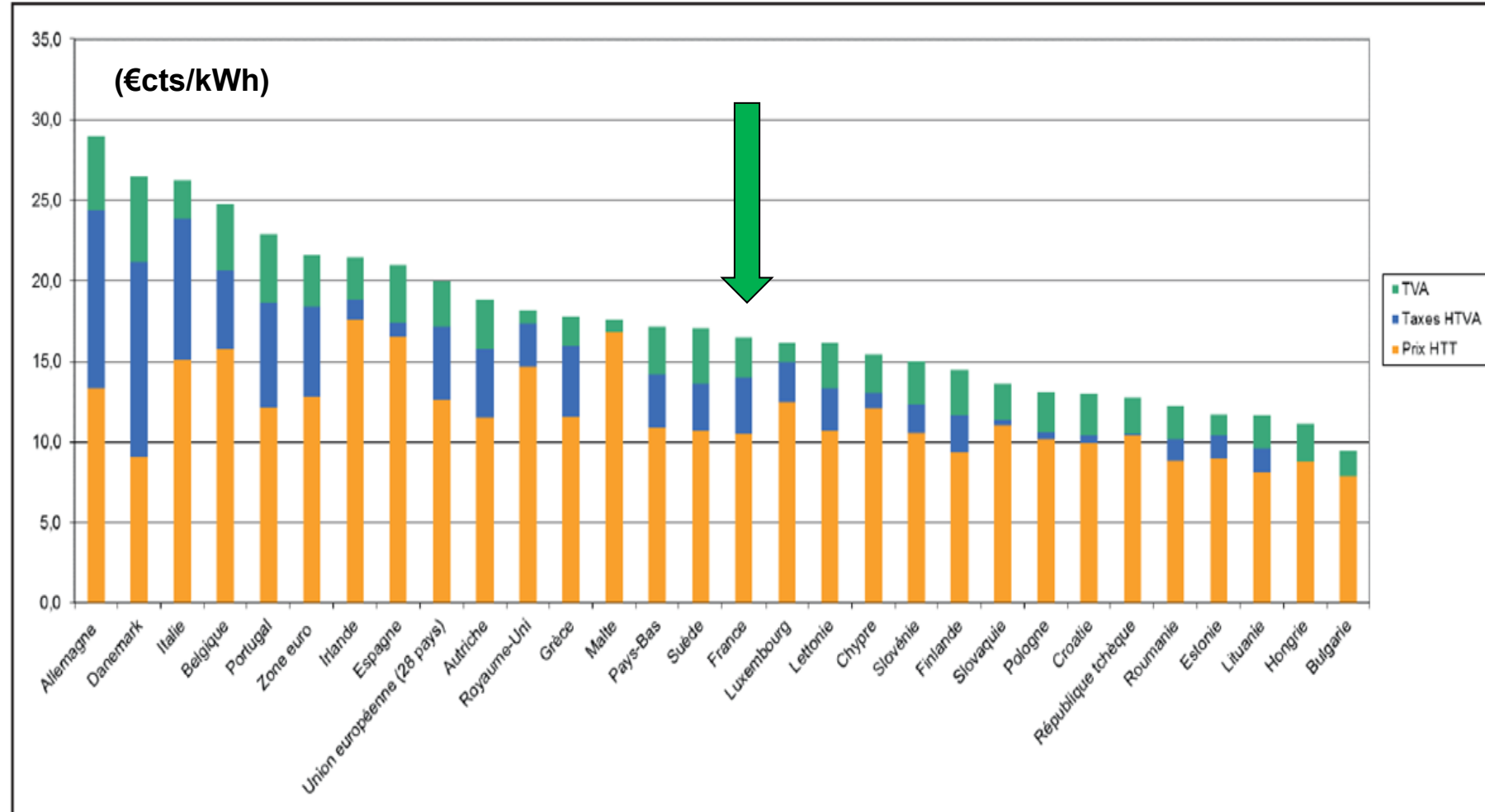


From 2013 to 2024, LCOE have evolved very much, in particular in relation with the costs savings attached to Renewable Energy, the costs increases of the new Nuclear, following the changes of the technical and economical environment. The geopolitical turmoils have also consequences on the Energy economics



Reminder - Final Cost of Electricity in France (72% generated by nuclear plants) - 2018

*Comparaison des prix de l'électricité à la consommation dans les pays européens – Source SDES**



*SDES: Service de la Donnée et des Etudes Statistiques
Ministère du Développement Durable

362

TPA Toolbox Energy Book 10 – Nuclear



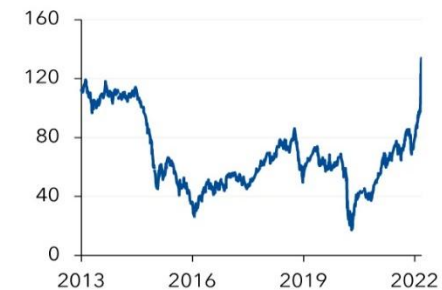
Russia – Ukraine War - 2022

Major Impact on World Economy and Energy Markets

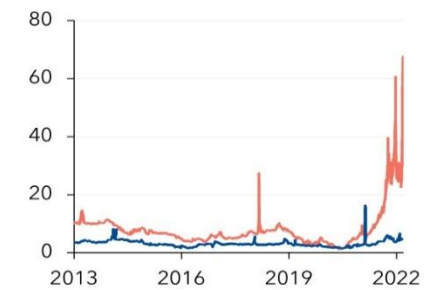
Growing pressures

Prices for energy, grains, and metals soared since the invasion of Ukraine, signaling that inflation rates are poised to accelerate.

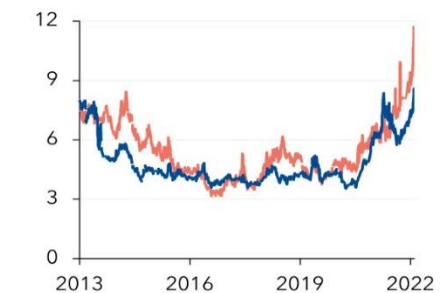
Brent Crude Oil
(\$US/barrel)



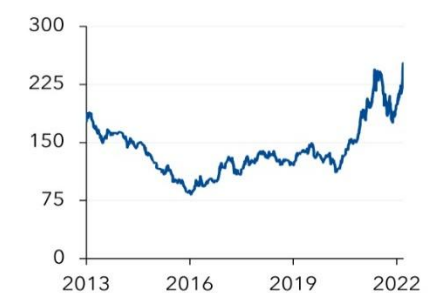
European & US Natural Gas*
(\$US/MMBtu)



Corn, Wheat
(\$US/bushel)



Metals Index**
(2016=100)



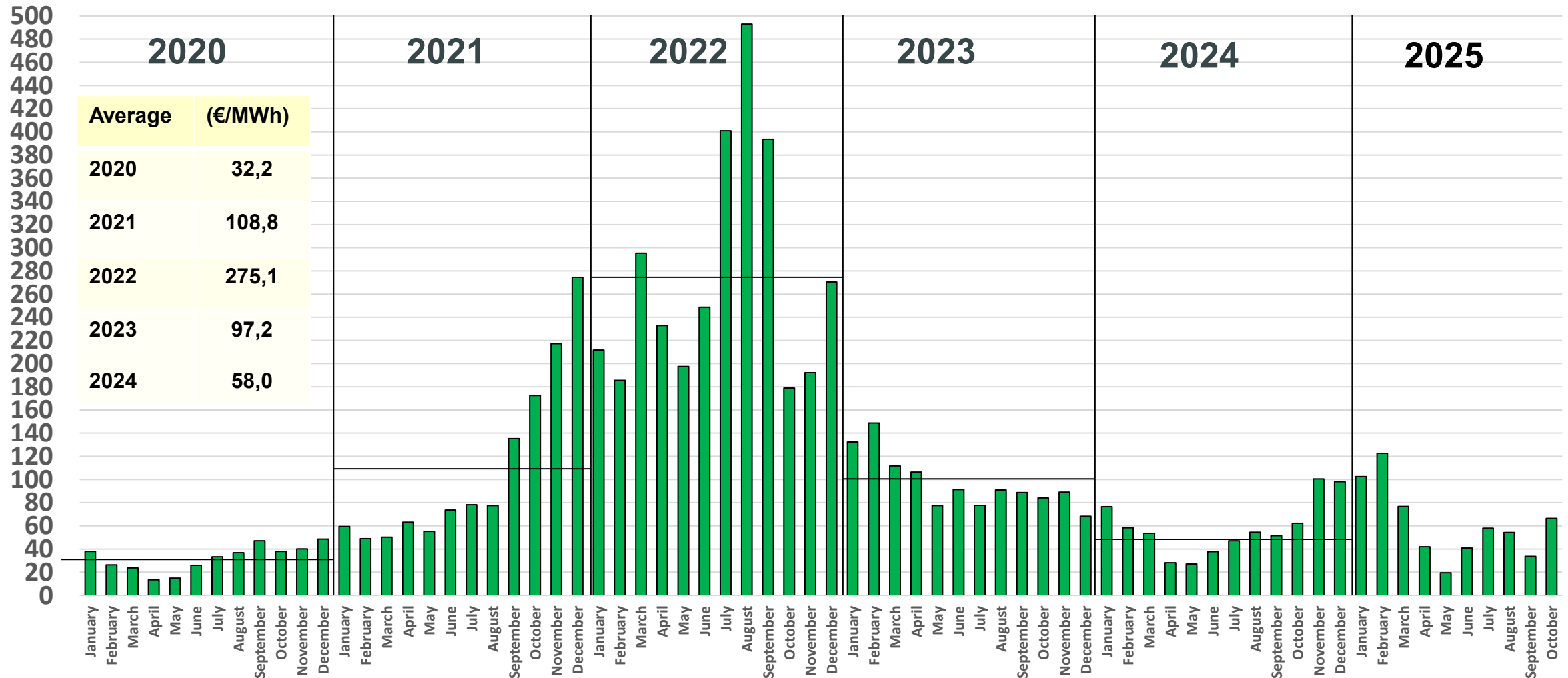
Source: Bloomberg, USDA, Datastream, and IMF staff calculations.
Note: *European & US natural gas prices use the Dutch TTF and Henry Hub as proxies, respectively. **Base Metals Price Index includes aluminum, cobalt, copper, iron ore, lead, molybdenum, nickel, tin, uranium, and zinc.

IMF

Source: Harvard University – International Monetary Fund

Monthly Wholesale Electricity Prices France 2020 – 2025 (€/MWh)

The impacts of economic & geopolitical turmoils are great

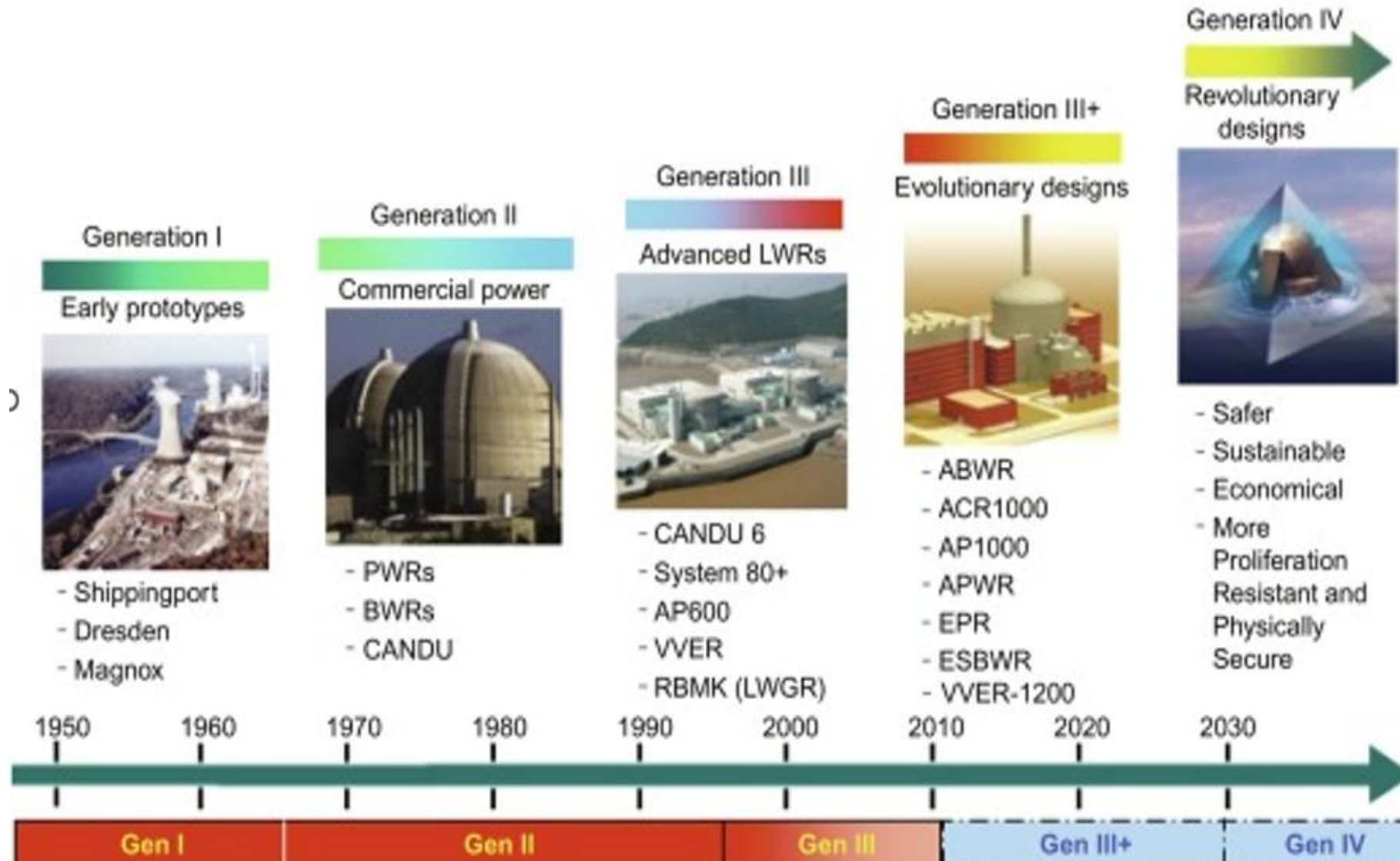


4-11

Generation IV International Forum (GIF)



Evolution of Nuclear Power



New energy systems for the future

GIF: Generation IV International Forum

GENERATION IV : To coordinate Research & Development of new generation nuclear energy systems

- ◆ Deployable by 2030/2040 (?)
- ◆ With significant advances in:
 - Sustainability
 - Enhanced Safety and reliability
 - Minimisation of waste
 - Proliferation and physical protection
 - Economics
- ◆ Competitive in various markets
- ◆ Designed for different applications:
 - Electricity, Hydrogen, Clean water, Heat



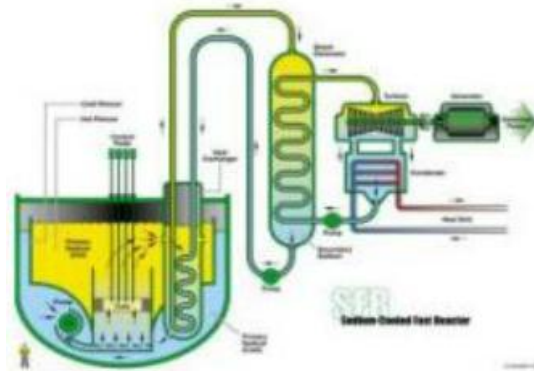
Framework Agreement signed Feb. 2005. 2006: + Russia, China 10 years extension signed in 2015 & 2016. Australia & EU joined. 13 entities today: Argentina, Australia, Brazil, Canada, China, France, Japan, Korea, Russia, South Africa, Switzerland, UK and USA, as well as Euratom.



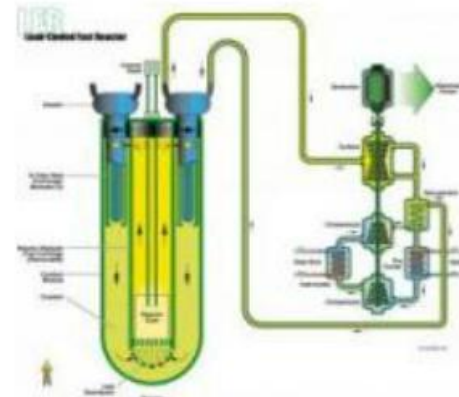
Generation IV Reactors

Most 'nuclear' countries are working together to develop Gen IV reactors:

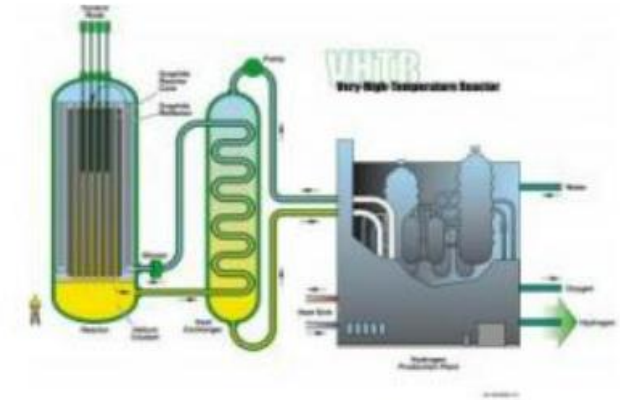
- GIF : Generation IV International Forum
- Selection of 6 promising technologies
- Pilots under development



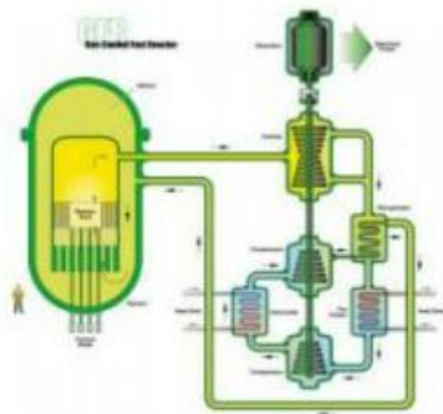
Sodium Fast Reactor



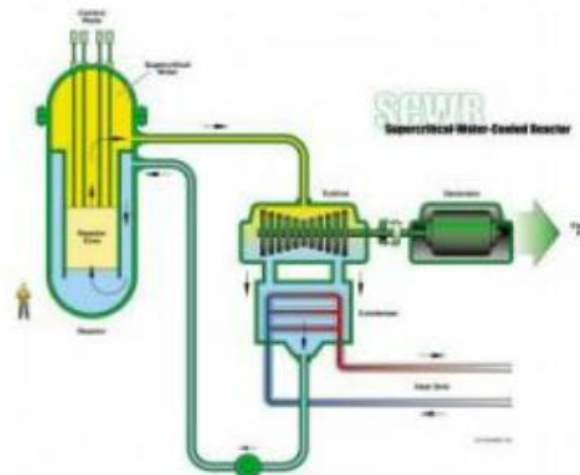
Lead Fast Reactor



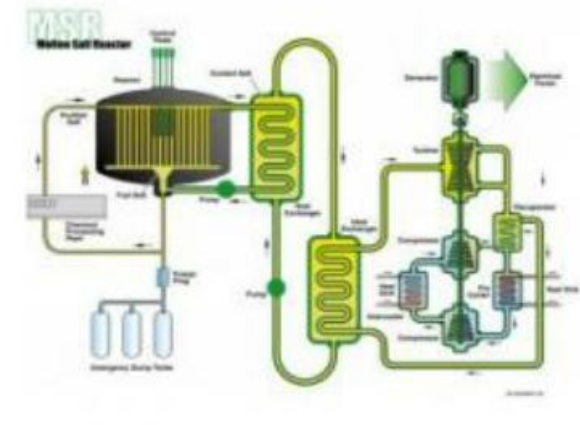
Very High Temperature Reactor



Gas Cooled Fast Reactor



Supercritical Water Cooled Reactor



Molten Salt Cooled Reactor



Generation IV Reactors : Operations?

#	Name	Abbrev.	Status
1	Sodium Fast Reactor	SFR	Units (600 MWe) in operations in Russia and China
2	Lead Fast Reactor	LFR	Unit (300 MWe) soon (2026?) in operations in Russia
3	Very High Temperature Reactor	VHTR	SMR (210 MWe) in operations in China
4	Gas Cooled Fast Reactor	GFR	Conceptual Design
5	Supercritical Water-Cooled Reactor	SWCR	Conceptual Design
6	Molten Salt Reactor	MSR	Demo unit (2 MWe – Thorium) in China

- **3 types of fast reactors**
- **2 types of high temperature reactors**

Selection criteria:

- Intrinsic safety
- Sustainable (feedstock)
- Sustainable (waste)
- Economical
- Proliferation resistant
- Physically secure



Thorium Reactor : demonstration unit

◆ September 2022 : China :

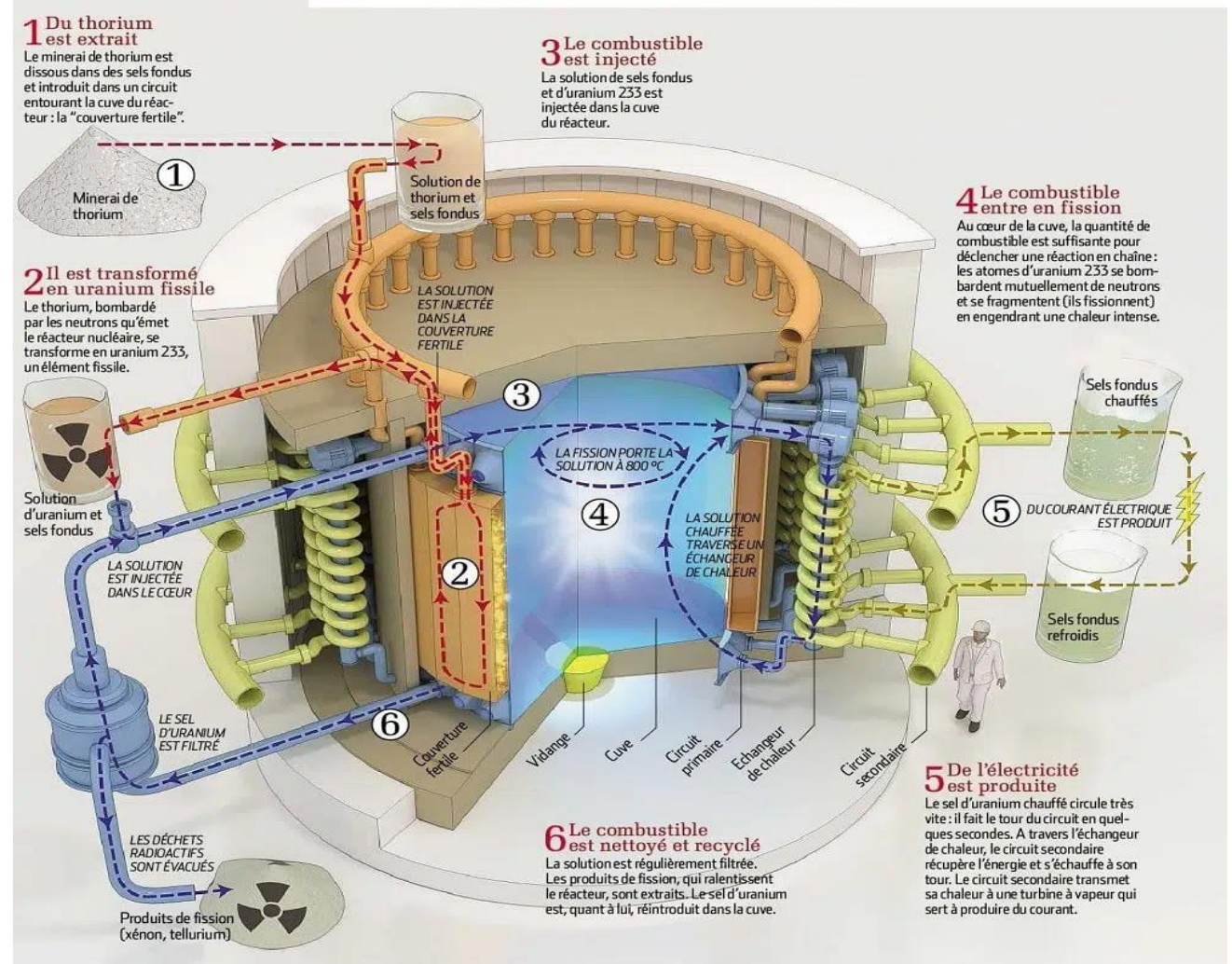
- 2 MW
- Liquid Thorium (and U₂₃₆)
- Molten Salt

◆ Benefits:

- Reduced waste toxicity
- Improved safety (impact of leaks)
- No water required for cooling

◆ Next step:

- 2030
- 100 MWe



The world Nuclear industry and the energy and oil & gas industry : interest from stakeholders ?



TABLE OF CONTENTS

1. What is nuclear energy ?
2. What are uranium resources ?
3. The world nuclear industry: past and present
4. Future evolution
5. The world nuclear industry and the energy and oil & gas industry: interest from stakeholders ?



The world nuclear industry and the energy and oil & gas industry: interest from stakeholders ?

- **International oil companies and nuclear**
- **Oil producing countries and nuclear**



International Oil Companies and Nuclear Energy in the past

IN THE 50's AND 60's

◆ Strong involvement of the oil industry in nuclear :

- EXXON → invested in the full cycle
 - Mining
 - Fuel Fabrication
 - Enrichment
 - Reprocessing
- SHELL → invested also in the cycle (at a lower level)
- AGIP → built the first nuclear plant in Italy

IN THE 70's AND 80's

- After the 1973 and 1979 oil shocks some 20 oil companies invested in nuclear :
- SHELL → HTGR reactor with GULF General Atomic (8 letters of intent + 10 letters of interest)
- EXXON, OCCIDENTAL, ELF, TOTAL (until 1995), etc → in uranium exploration and mining.

IN THE LAST 20 YEARS : 2005-2025

- TOTAL announced in 2006 and 2007 their intention to "look at nuclear". In 2009, submitted, with AREVA and GDF SUEZ, a proposal following a call for tender in Abu Dhabi, which was not selected.
- Other IOC's keep silent up to now.
- Today, all the Majors are concentrating on their core business with a large diversification towards renewable energy. TotalEnergies decided not to be involved in Nuclear Energy business.



Oil producing countries and nuclear – the case of Iran (1)

- Up to recently most of oil producing countries looked at nuclear energy as a competitor or a threat.
- The specific case of Iran
 - In July 1968, Iran signed the Nuclear Non-Proliferation Treaty as a non-nuclear weapons state.
 - Under the Shah regime, Iran launched a comprehensive nuclear program from uranium exploration to enrichment (via Eurodif), and electricity generation (2 major plants contracted with European vendors, including Bushehr). The contracts were cancelled after the revolution (1979). A new contract was signed in 1995 with Rosatom (Russia). One VVER 1000 is currently in operation. Bushehr-1 generates < 1% of electricity in the country.
 - Non proliferation concerns about enrichment facilities (Natanz) and heavy water production (Arak), underground nuclear facilities, have been under discussions with IAEA/UN Security Council. First sanctions against Iran in 2006. UN inspections.....
 - April 2015: Lausanne agreement (1st step): Reduction of Iranian centrifuge units from 19000 to 6000, uranium enrichment rate limited at 3,67%, reduction of uranium stock from 10000 to 300 kg during 15 years.....
 - January 2016: announcement by Barack Obama that sanctions against Iran are lifted after compliance of nuclear deal (mothballing most of the centrifuges, disabling Arak reactor,....)



Oil producing countries and nuclear – the case of Iran (2)

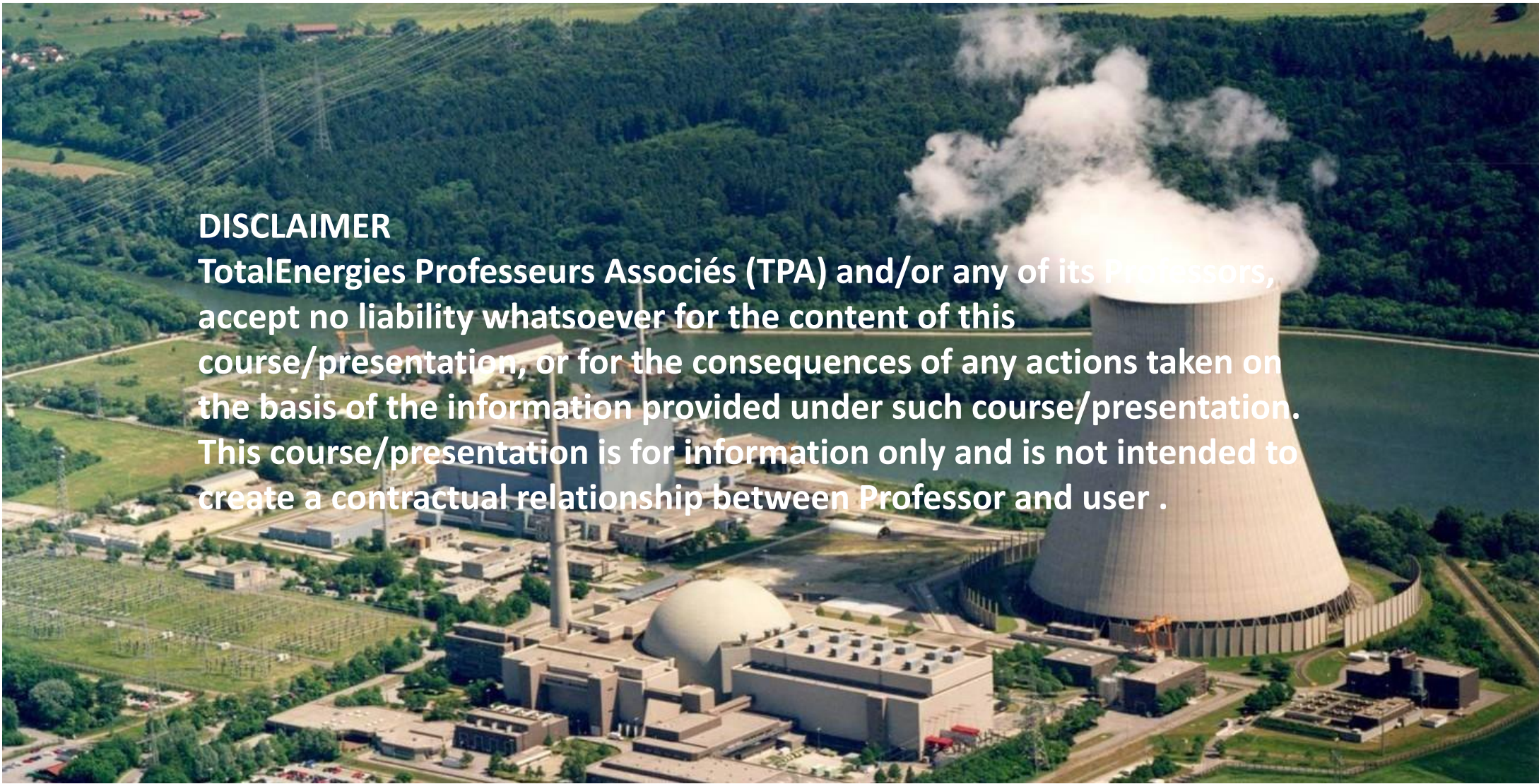
- **2018: Denunciation by Donald Trump of the Iranian nuclear deal with Iran.....New sanctions.**
- **2019: Iran announced its intention to increase enrichment rate above 3,67% and to develop Arak reactor....**
- **2020: Assassination of Iran top nuclear scientist.**
- **New US president in January 2021, Joe Biden. Geopolitical tensions continue between Iran and US, besides the pursuit of potential negotiations.**
- **In 2022, Iran announced that they have been successful in increasing the enrichment rate up to 60%, increasing the threat from the country to fabricate a nuclear bomb.**
- **In 2023/2024, in the framework of increasing geopolitical tensions, Iran continues to work on uranium enrichment.**
- **After Israel's intervention and US strikes in Iran 1st half 2025, there is a great uncertainty on the development of the situation. In June 25, the Iranian parliament passed legislation suspending Iran's cooperation with the IAEA/International Atomic Energy Agency.**
- **Beginning 2026, new massive strikes from US and Israel on Iranian facilities. At end May 2026, great uncertainties on the development of the situation. According to IAEA, Iran would possess 441 kg uranium enriched at 60% enough to fabricate 10 atomic bombs if enriched at 90%.**



Oil producing countries and nuclear

- A number of oil producing countries have expressed interest in "looking" at nuclear: Algeria, Arabic peninsula States, Libya, Indonesia...
- In 2009, Abu Dhabi launched a call for tender for 4 nuclear reactors (20 G\$). A consortium Edf/Areva/GdFSuez/Total/Vinci/Alstom submitted a proposal based on EPR technology. Kepco (South Korea) won the contract with a traditional and less expensive technology (APR 1400) These nuclear power plants are now operational. Delays in the programme have been experienced. Barakah-1 began feeding power into UEA's grid in August 2020.
- This interest is focused on two objectives: electricity generation and sea water desalination (Libya, Emirates).
- With the Climate Change and Energy Transition challenges, Oil producing countries have also to think about decarbonized sources of Energy.



An aerial photograph of a nuclear power plant. A large, white, conical cooling tower is the central feature, with thick white steam rising from its top. To the left of the tower is a large, white, dome-shaped containment building. Various other industrial buildings and structures are scattered around the site. The plant is situated in a green, wooded area with a body of water visible in the background. High-voltage power lines are visible in the upper left corner.

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