DE LA RECHERCHE À L'INDUSTRIE

Nuclear Energy Basics

Joint EPS-SIF International School on Energy

Varenna, 19 July 2023

Sylvie Leray

- **Basics on nuclear fission and fusion**
  - Fission: more details in M. Ripani’s lecture
  - Fusion: more details in A. Spagnuolo and D. Batani’s lectures
- **Nuclear energy in the world: status and perspectives**
  - Some perspectives in R. De Salvo’s lecture
- **Nuclear waste management and environmental impact**
  - more details in V. Montoya and A. Mariani’s lectures
- **Conclusions**

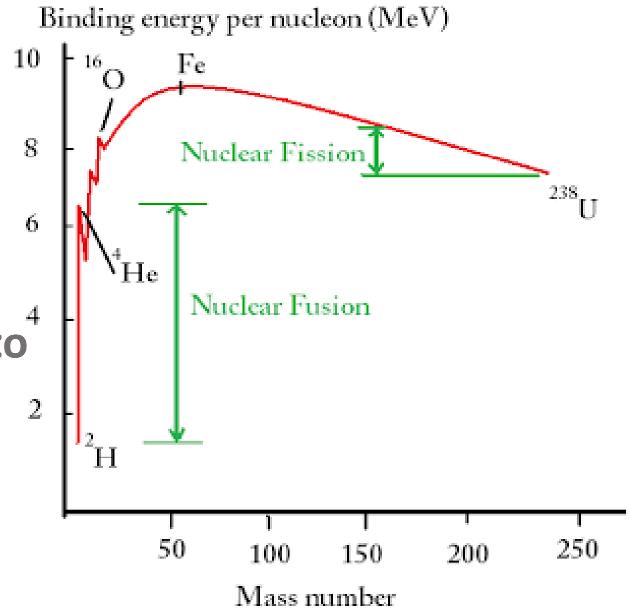
Nuclear energy basics

- **Nuclear energy comes from the binding energy of the atomic nucleus**

  Nuclei are composed of nucleons (neutrons and protons) held together by the strong nuclear force

  $M(A,Z) = Z\, m_p + (A-Z)\, m_n - B(A,Z)$

  B=Binding energy, **B/A maximum around Fe**



- **is released thanks to nuclear reactions in which the constituents of the initial nuclei are redistributed into different final nuclei**

  Target nucleus + projectile → Final nucleus + ejectile + *Q*

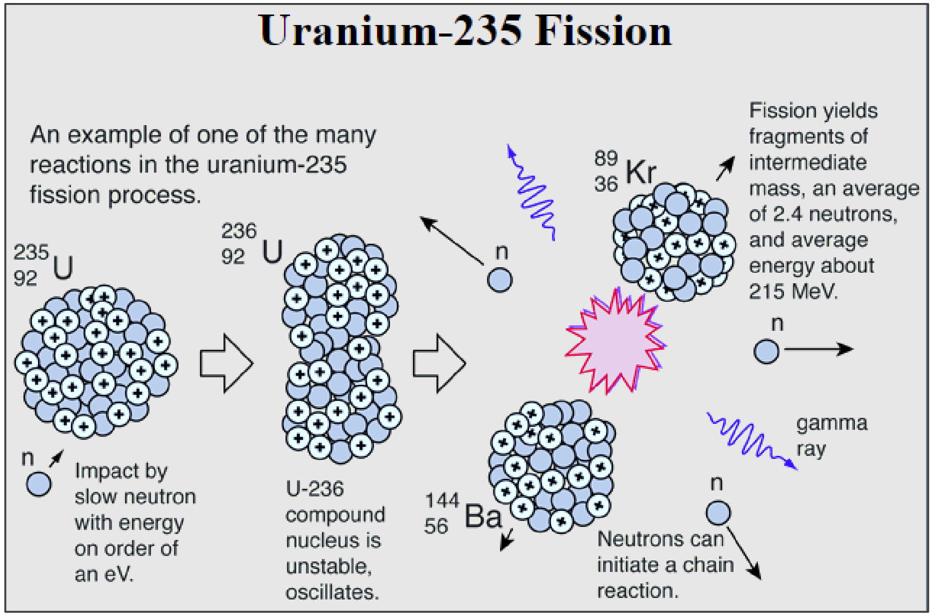
  Q = Energy released

  Q = B(Target) + B(projectile) - B(Final nucleus) – B(ejectile)

  Either

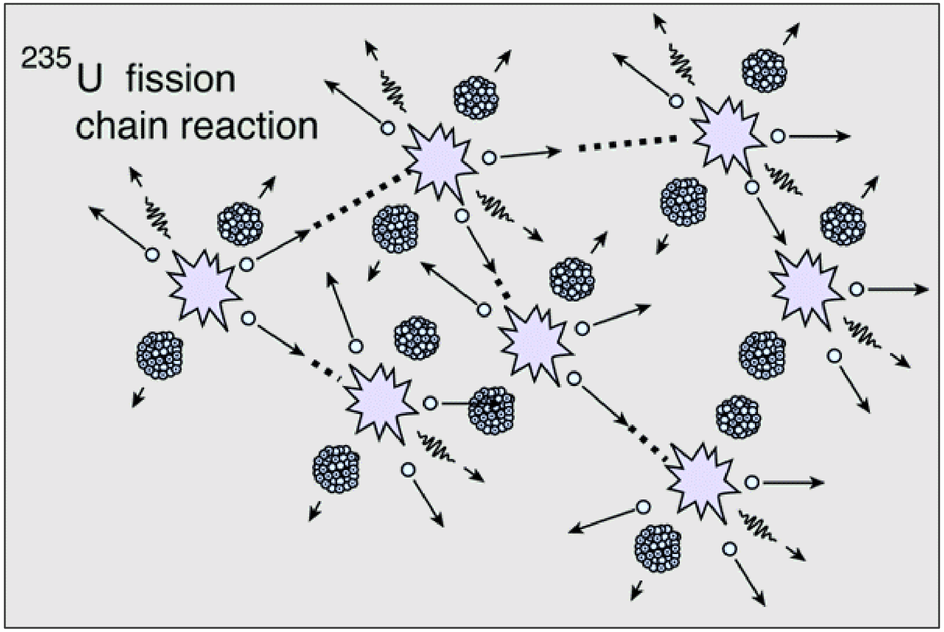
  - by splitting heavy nuclei into smaller ones: **Fission**
  - By merging two light nuclei into a larger one: **Fusion**

- Fission reactions can be induced by slow neutrons on some (fissile) nuclei such as ^{235}U producing 2 fission fragments and 2.4 neutrons in average



Source: http://hyperphysics.phy-astr.gsu.edu/

- Neutrons, after slowing down, can initiate a chain reaction



Fission: nuclear fuels

- **Uranium: Natural uranium is composed of 0.7% ^{235}U, 99,3% ^{238}U**
  - ^{235}U is fissile by neutron capture regardless of the energy of the neutron, but the probability increases with decreasing neutron energy
  - ^{238}U can fission only with high energy neutrons and with a small probability

  ↪ In most of presently operating reactors:
  - ^{235}U enrichment (around 3% in French light-water reactors)
  - Slowing down of neutrons down to thermal energy

↪ **See lecture by Marco Ripani**

- **Plutonium: ^{239}Pu is fissile**
  - ^{239}Pu is produced by neutron capture on ^{238}U in thermal reactors

    ^{238}U (n,γ) ⟶ ^{239}U (23min) ⟶ ^{239}Np (2.3d) ⟶ ^{239}Pu (2.4×10^4y)
  - In light-water reactors up to one third of the fissions come from ^{239}Pu

- **Thorium: ^{232}Th is not itself fissile but is 'fertile'**
  - neutron absorption leads to ^{233}U, which is fissile

    ^{232}Th (n,γ) ⟶ ^{233}Th (22min) ⟶ ^{233}Pa (23d) ⟶ ^{233}U (1.6×10^5y)
  - Thorium reactors require either that ^{232}Th is first irradiated in another reactor to provide ^{233}Pa or plutonium to initiate the process

▶ Fusion reactions can be initiated in a plasma of hydrogen isotopes

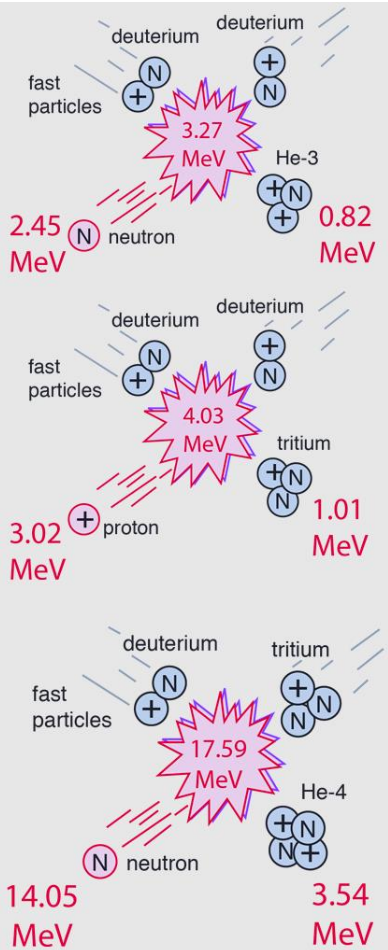
$$ {}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + {}^{1}_{0}n + 3.27\,MeV $$

Deuterium-deuterium Fusion

$$ {}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{1}H + {}^{1}_{1}H + 4.03\,MeV $$

$$ {}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + 17.59\,MeV $$

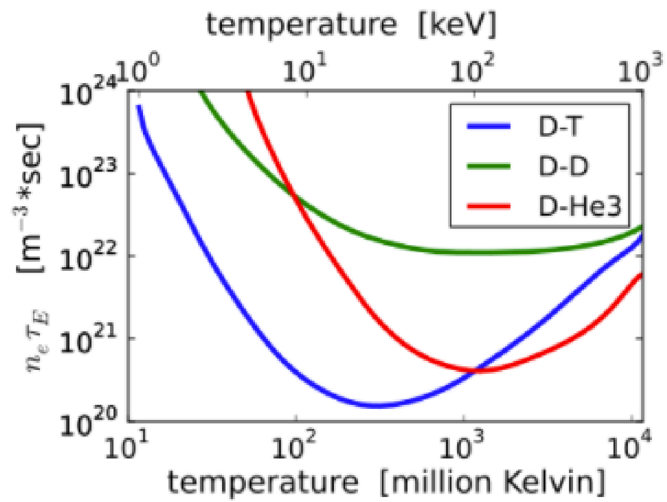
Deuterium-tritium Fusion



Source: http://hyperphysics.phy-astr.gsu.edu/

▶ Lawson's criterion for sustained fusion plasma

- Sufficiently high temperature to enable the particles to overcome the Coulomb barrier,
- Temperature maintained for a sufficient confinement time, τ
- Sufficient ion density, n, to obtain a net yield of energy.



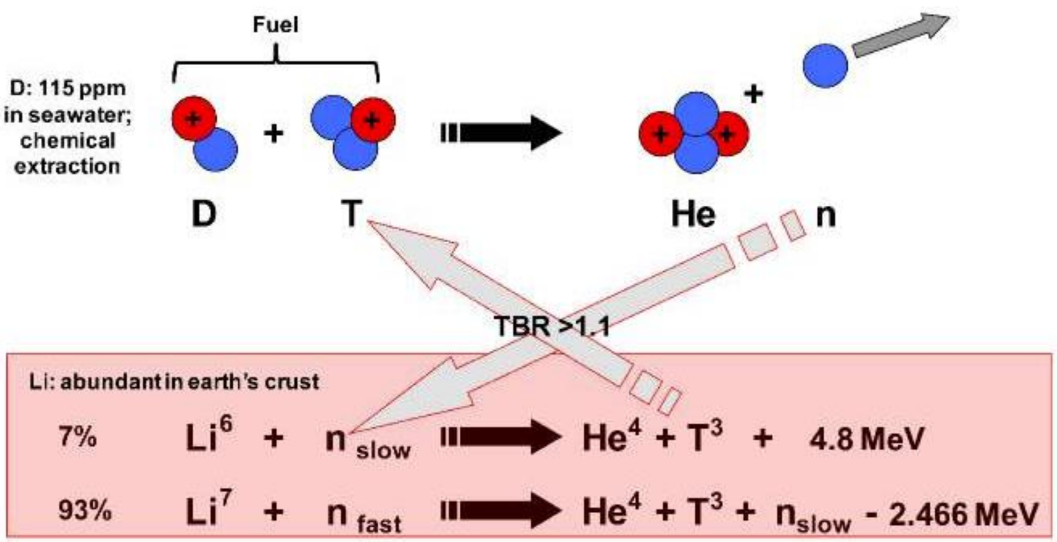
Inertial confinement (by lasers)

- Low volume (compression of a millimetric target)
- High density (10^6 x air density)
- Low characteristic time (10^{-11} s)
- High temperature (100 million K)

Magnetic confinement

- High volume (tokamak)
- Low density (10^{-5} x air density)
- Large characteristic time (10 s)
- High temperature (100 million K)

Tritium breeding needed



➥ **See lectures by Alessandro Spagnuolo and Dimitri Batani**

Fuel energy content

- Coal (C): $C + O_2 \rightarrow CO_2$ + **4 eV**

  1g coal = $4 \times 1.6 \times 10^{-19} \times 6.02 \times 10^{23}/12$ = **32 kJ**

1 eV = 1.6×10^{-19} J
1 mole = 6.02×10^{23} atoms

- Natural Gas (CH_4): $CH_4 + O_2 \rightarrow CO_2 + 2H_2O$ + **8 eV**

  1g gaz = $8 \times 1.6 \times 10^{-19} \times 6.02 \times 10^{23}/16$ = **48 kJ**

- Nuclear fission (U): $^{235}U + n \rightarrow {}^{93}Rb + {}^{141}Cs + 2n$ + **200 MeV**

  1g ^{235}U = $2 \times 10^{8} \times 1.6 \times 10^{-19} \times 6.02 \times 10^{23}/235$ = **8.2×10^{7} kJ**

- Nuclear fusion: $^{2}H + {}^{3}H \rightarrow {}^{4}He + n$ + **17.5 MeV (80% carried by n)**

  1g D-T = $1.75 \times 10^{7} \times 1.6 \times 10^{-19} \times 6.02 \times 10^{23}/5$ = **3.4×10^{8} kJ**

- **Fuel Consumption, 1000 MWe Power Plant (=10^6 homes) per day**
  - Coal (40% efficiency)

    10^9x8.64x10^4 / 0.4x3.2x10^4 ≈ **6750 ton/day**

  - Natural Gas (50% efficiency) : density 0.657 kg·m^{-3} (gas, 25 °C, 1 atm)

    10^9x8.64x10^4 / 0.5x4.8x10^4 ≈ **3600 t/day**

  - Natural uranium (^{235}U = 0.7%, 33% efficiency):

    10^9x$8,64$x10^4 / 0.33x0.7x10^{-2}x8.2x10^{10} ≈ **460 kg/day**

  - D-T in nuclear fusion (assuming 10% efficiency):

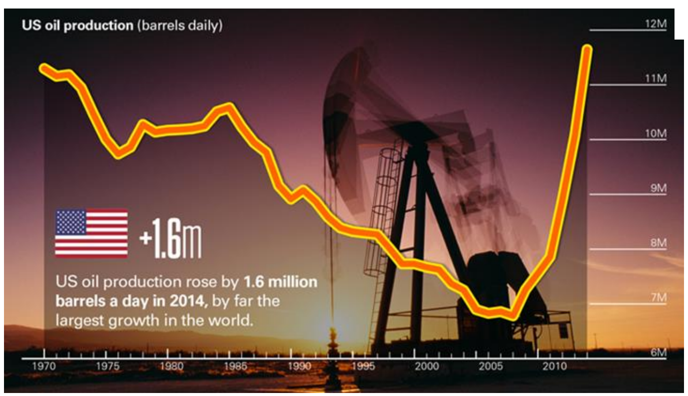
    10^9x$8,64$x10^4 / 0.1x3.4x10^{11} ≈ **2,5 kg/day**

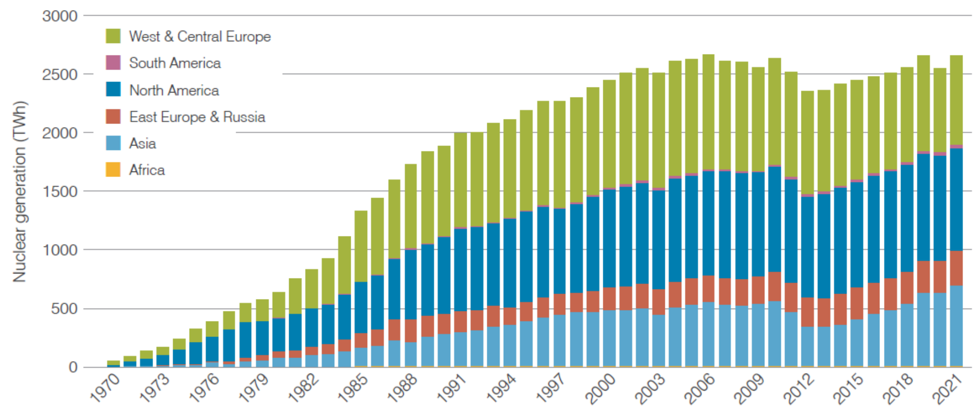
Nuclear energy in the world: status and perspectives

The growth expected twenty five years ago has not happened:

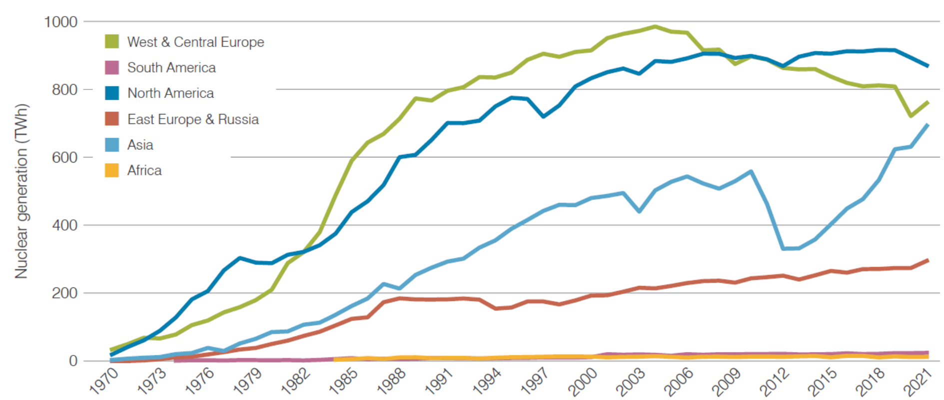
- 2008 economic crisis
- 2011 Fukushima accident
- Shale oil “revolution”

http://www.scottishenergynews.com/





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



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

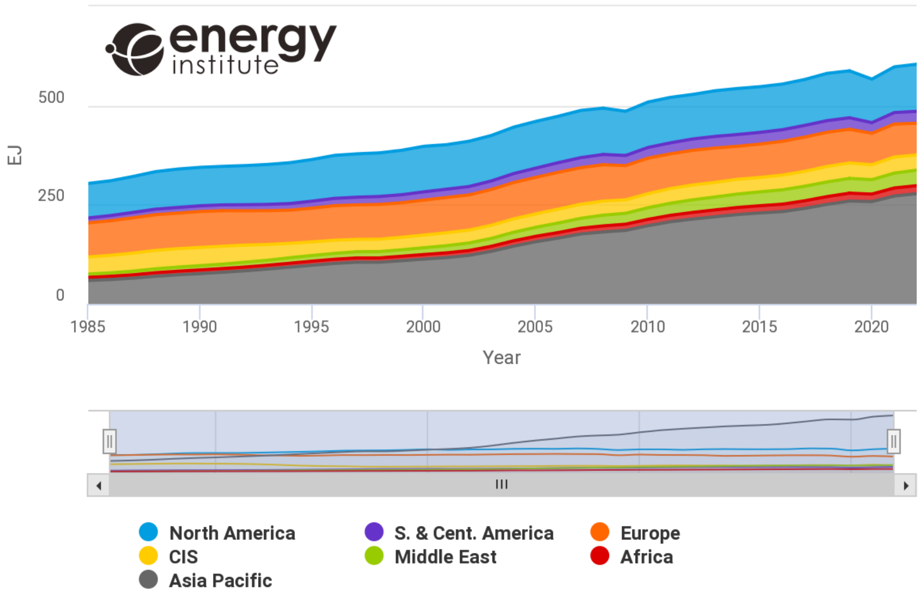
But nuclear energy production had begun increasing slowly again, driven mainly by China and Russia

Energy demand

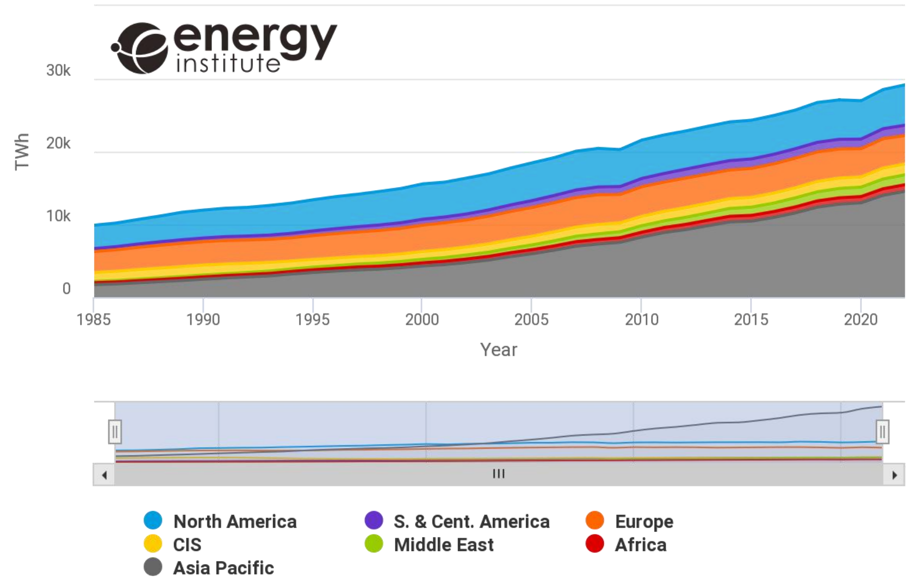
▶ Increase in energy demand due to growth of world population and improving of the standard of living

▶ Demand in electricity increases even faster boosted by the development of smart electronic devices, air-conditioning, electric cars…

Total primary energy



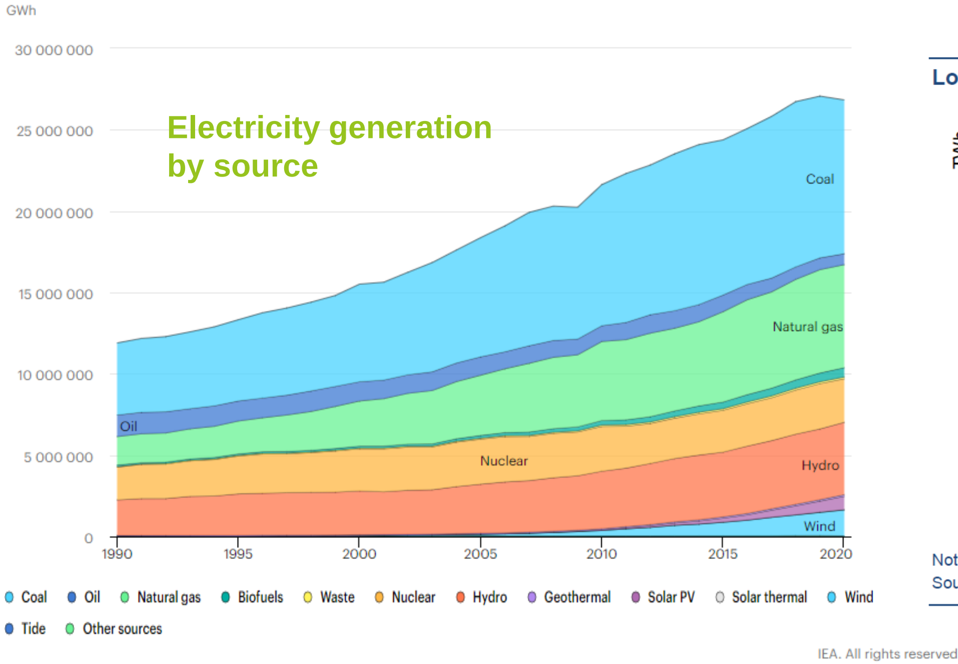
Electricity



Source: BP Statistical Review of World Energy 2022

Nuclear power role in electricity generation

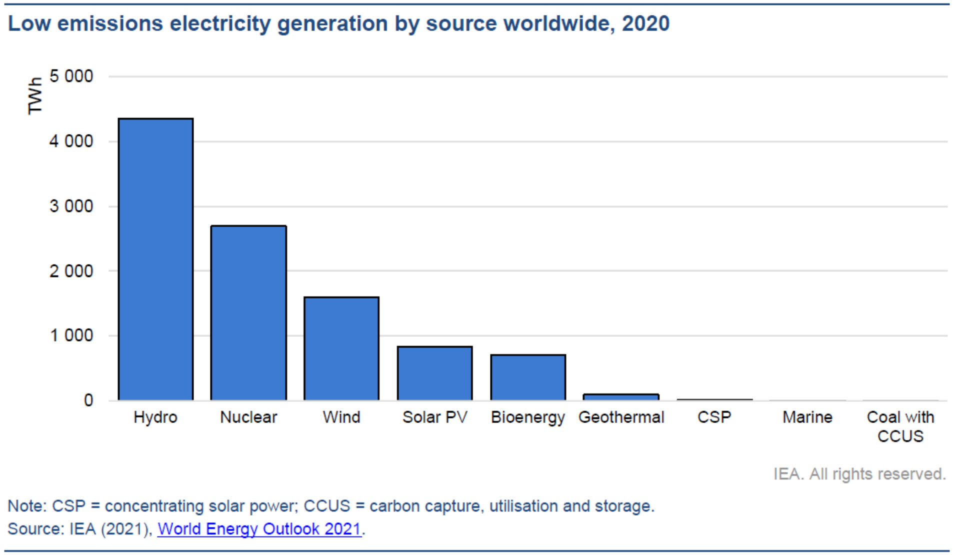
- Share of nuclear energy rather small (~10%) declining from the 90s
- Share of renewables solar and wind increasing significantly



Source: IEA Key world energy statistics 2022

But

- **still exceeding the contribution of combined solar and wind production in the low emissions electricity generation**



Source: IEA Nuclear Power and Secure Energy Transitions 2022

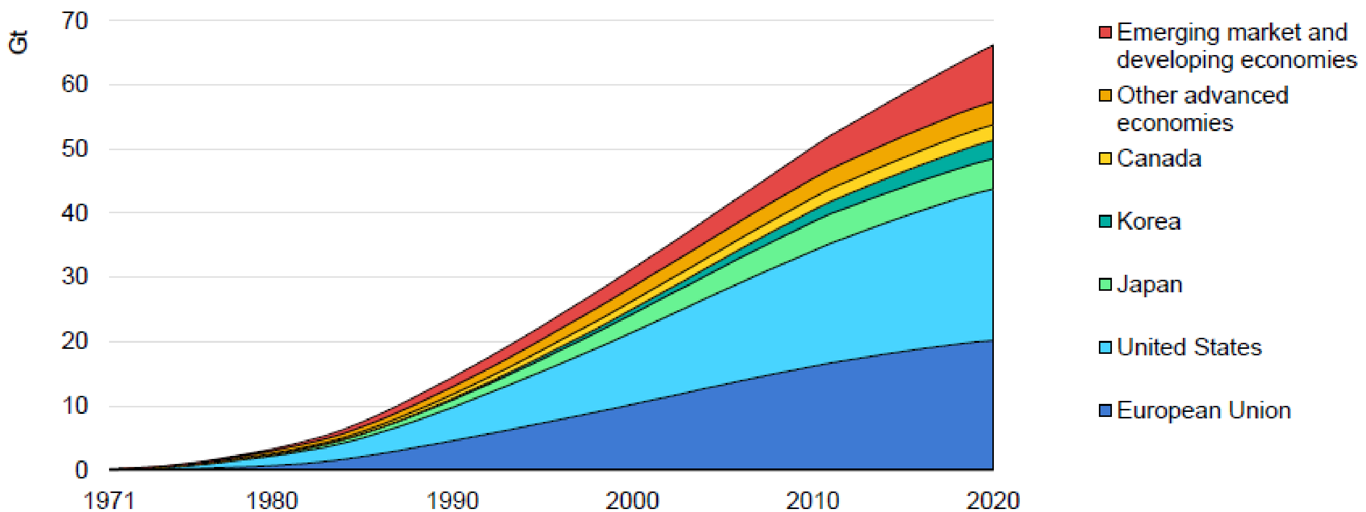
CO_2 emissions

IEA report: Nuclear Power and Secure Energy Transitions, Sept. 2022

- ~66 Gt of CO_2 avoided between 1971 and 2020

- *Without the contribution of nuclear power, total emissions from electricity generation would have been almost 20% higher (40% for Europe) and total energy-related emissions 6% higher over that period.*

Cumulative CO_2 emissions avoided by nuclear power by country/region



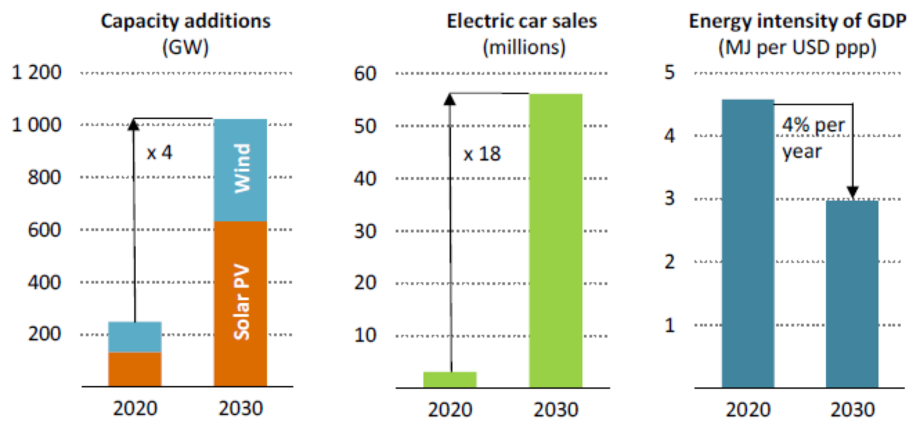
Reducing CO_2 emissions:

- Energy saving and increase of energetic efficiency but limited and counterbalanced by increase in developing countries
- Reducing use of fossil fuels, in particular in electricity production, heating and transportation, but then higher demand for electricity
- Carbon capture and storage, but expensive and profitable only if close to the emission site
- Hydropower but possibilities for new sites limited
- Wind and solar renewable energies but intermittent and variable, and question of critical material supply (lithium, rare earth elements, …)
- Nuclear energy but concerns about safety and waste

➢ **no miracle solution but need for a combination of all possibilities to decrease the share of fossil fuels**

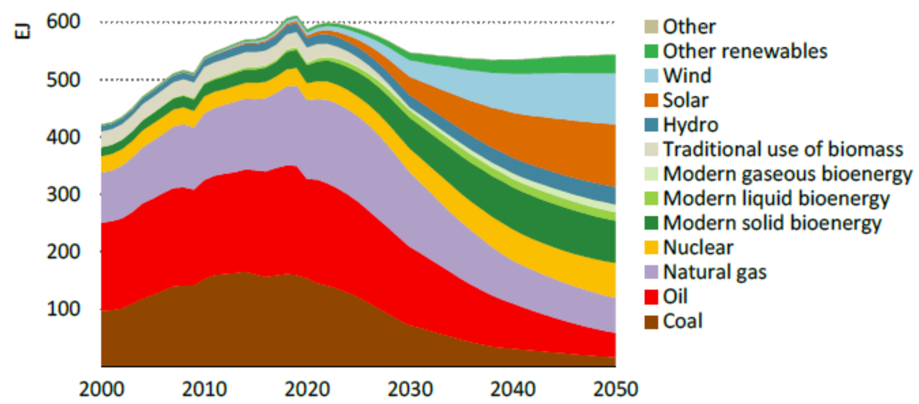
- Reducing CO_2 emissions: IEA net-zero by 2050 proposed scenario
  - Assumes a decrease of the energy demand (decrease of energy intensity of GDP)
  - Combination of all solutions
  - Replacing fossil fuels by electricity in many domains

Key clean technologies ramp up by 2030 in the net zero pathway



Note: MJ = megajoules; GDP = gross domestic product in purchasing power parity.

Figure 2.5 ▷ Total energy supply in the NZE

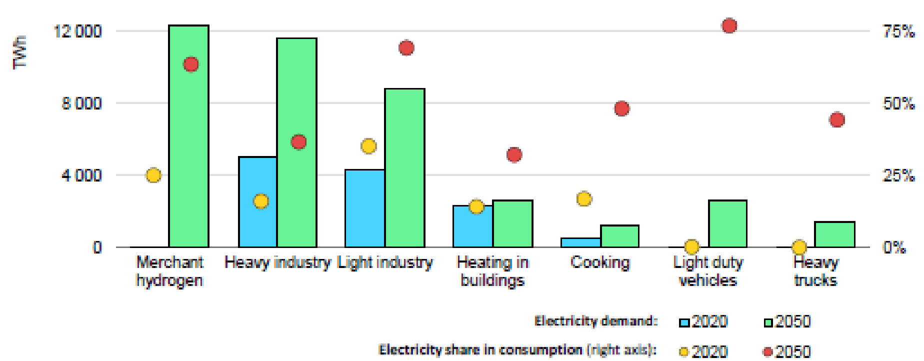


Renewables and nuclear power displace most fossil fuel use in the NZE, and the share of fossil fuels falls from 80% in 2020 to just over 20% in 2050

IEA Net Zero by 2050 report
iea.li/nzeroadmap

▶ Big increase in electricity demand

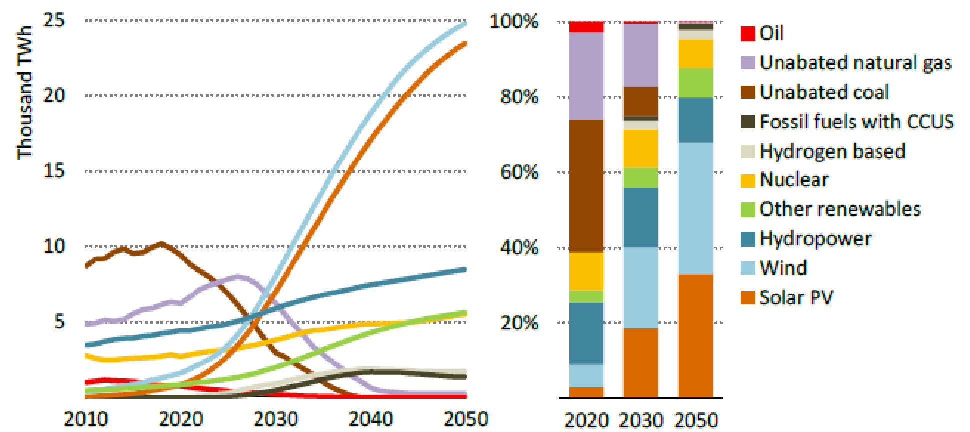
Global electricity demand and share of electricity in total energy consumption in selected applications in the Net Zero Emissions by 2050 Scenario



Source: IEA (2021), Net Zero by 2050: A Roadmap for the Global Energy Sector.

▶ Nuclear power capacity has to be at least doubled

Figure 3.10 ▷ Global electricity generation by source in the NZE



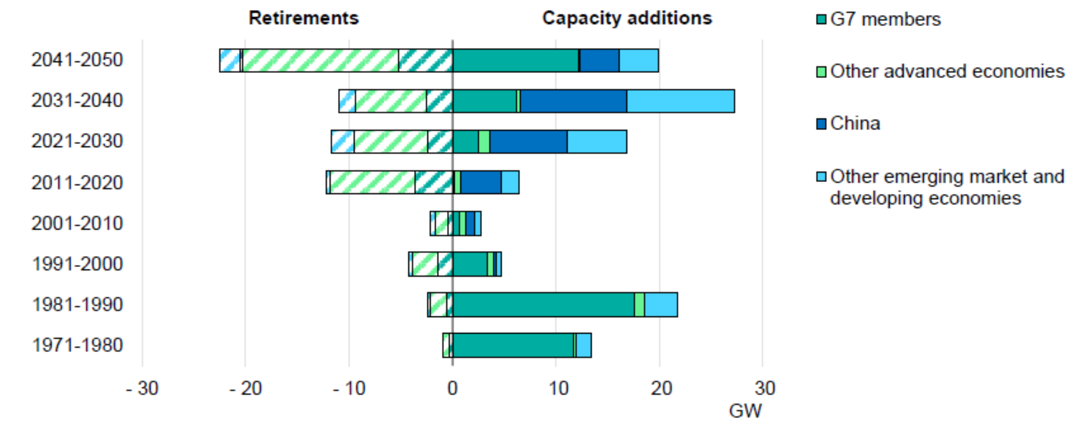
Solar and wind power race ahead, raising the share of renewables in total generation from 29% in 2020 to nearly 90% in 2050, complemented by nuclear, hydrogen and CCUS

IEA net zero by 2050 proposed scenario

▶ Nuclear power capacity has to be at least doubled

- **Advanced economies:**
  - lifetime extensions for existing reactors
  - 4.5 GW / year new construction from 2021 to 2035
  - increasing emphasis on small modular reactors

Nuclear power capacity additions and retirements in the Net Zero Emissions by 2050 Scenario by country/region and decade



Sources: IEA (2021), Net Zero by 2050: A Roadmap for the Global Energy Sector; IEA (2021), Achieving Net Zero Electricity Sectors in G7 Members.

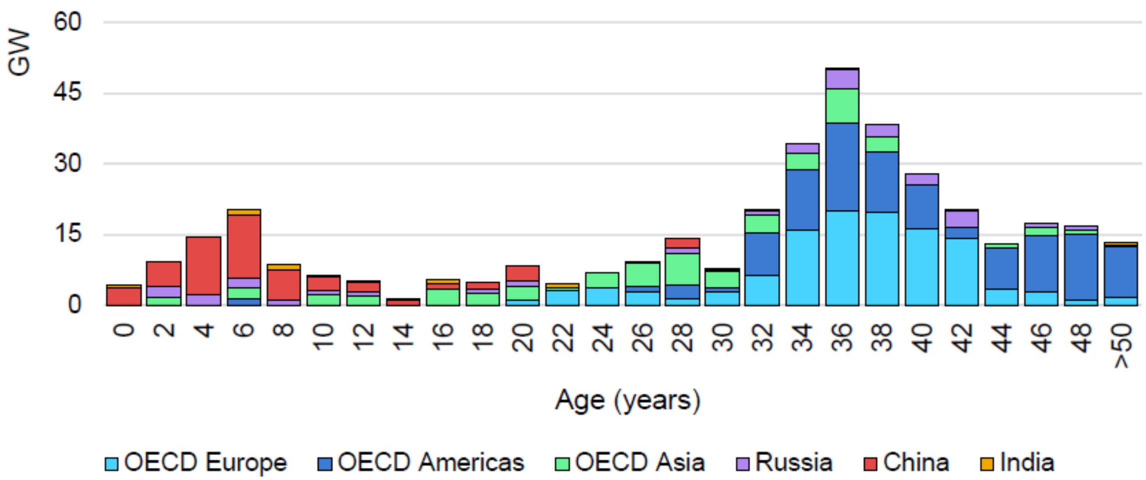
- **Emerging and developing economies**
  - Two-thirds of new nuclear power capacity
  - mainly in the form of large scale reactors,
  - fleet of reactors quadruples to 2050

Life time extension of existing reactors

IEA report: Nuclear Power and Secure Energy Transitions, Sept. 2022

▶ ***Extending nuclear plants' lifetimes is an indispensable part of a cost-effective path to net zero by 2050.***

Age distribution of operational nuclear capacity by region, end of 2021

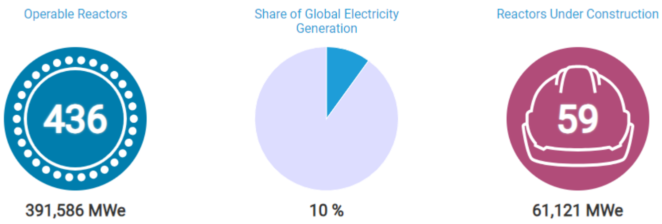


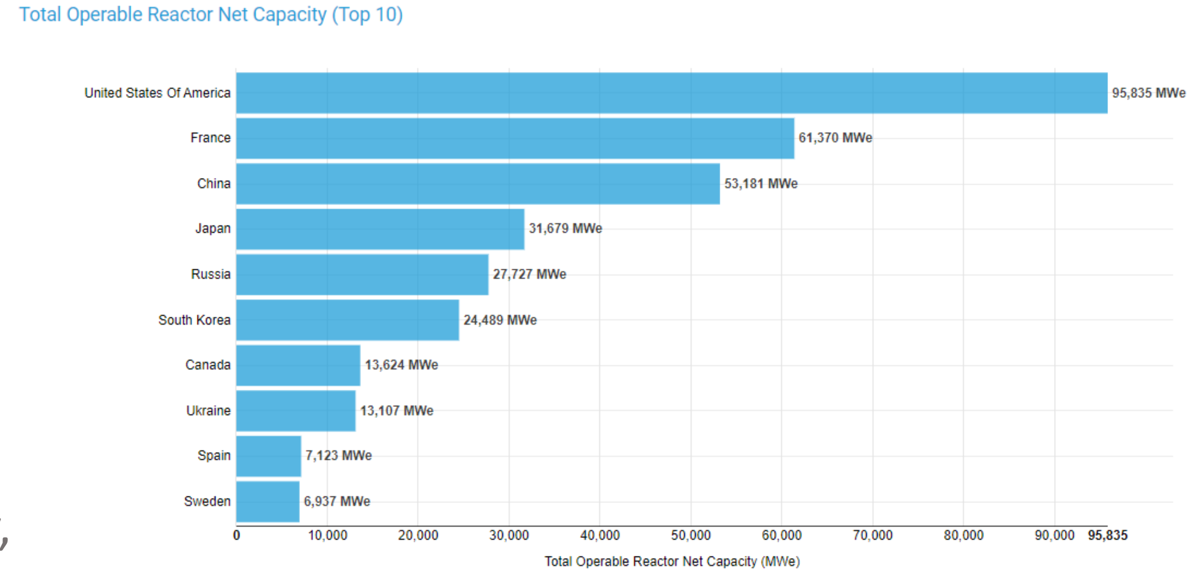
Note: OECD Europe includes Belgium, Czech Republic, Finland, France, Germany, Hungary, Lithuania, Netherlands, Slovakia, Slovenia, Spain, Sweden, Switzerland and the United Kingdom. OECD Americas includes Canada, Mexico and the United States. OECD Asia includes Japan and Korea.
Source: IAEA Power Reactor Information System (PRIS).

- In US, 88 reactors have obtained a 20-year license extension to 60 years and 11 recently applied for a further extension to 80 year
- In UK, Hungary, Finland and the Czech Republic, recent extensions by 20 years
- In France, 10 years extensions possible after check of safety requirement

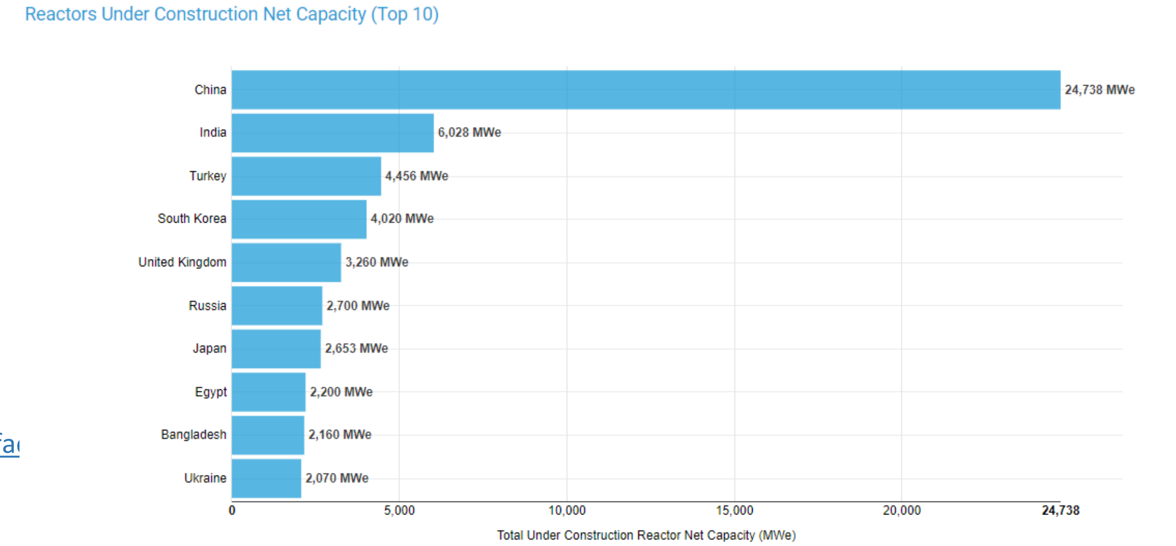
avoiding the closure of nearly 25% of the available capacity

World Nuclear Power Reactors





- 59 reactors under construction, of which 21 in China, 8 in India, 4 in Turkey, 3 in Russia
- 100 reactors planned, of which 45 in China, 25 in Russia, 12 in India



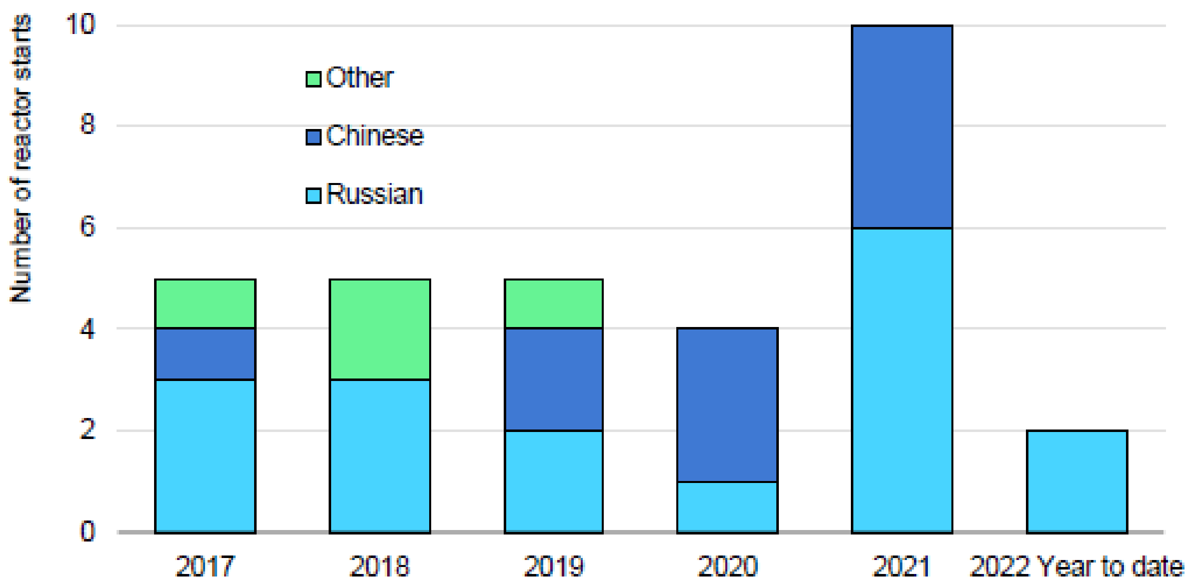
Source: World Nuclear Association, July 2023
https://www.world-nuclear.org/information-library/fa figures/world-nuclear-power-reactors-and-uranium-requireme.aspx

World Nuclear Power Reactors

IEA report: Nuclear Power and Secure Energy Transitions, Sept. 2022

- *Market leadership is shifting away from advanced economies*

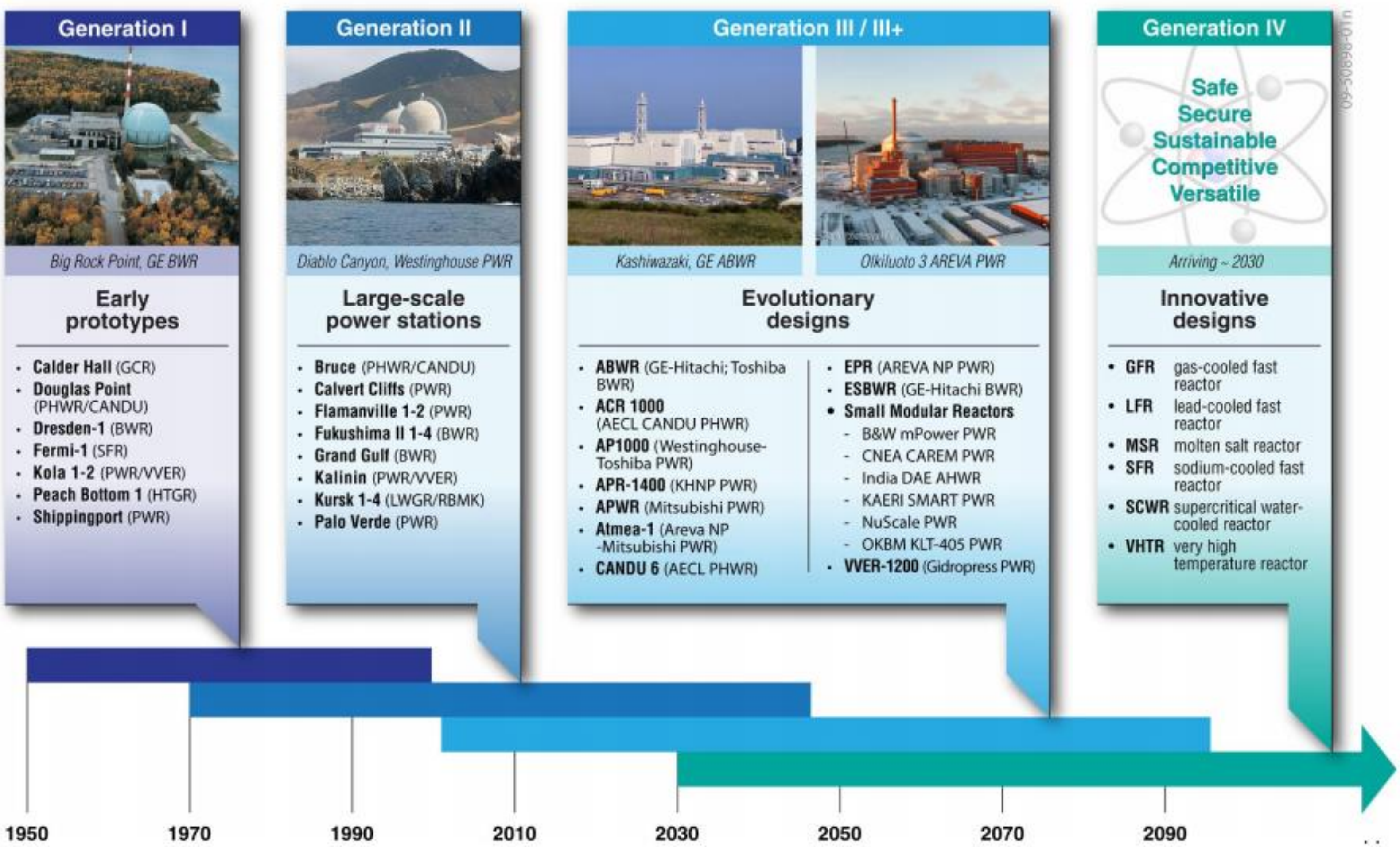
Nuclear power construction starts by national origin of technology, 2017-2022



Source: IAEA Power Reactor Information System (PRIS).

Nuclear energy roadmap

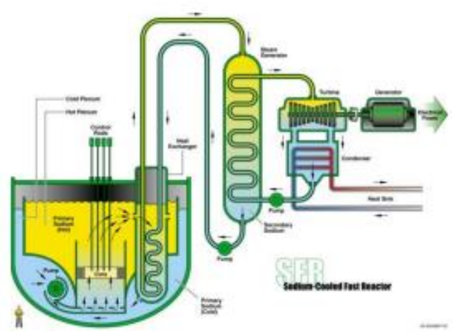
- **Presently, going from Generation II to Generation III**
- **Preparing for Generation IV**



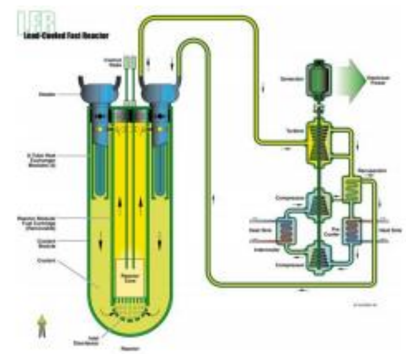
Source: Generation IV International Forum, www.gen-4.org

Generation IV technology goals

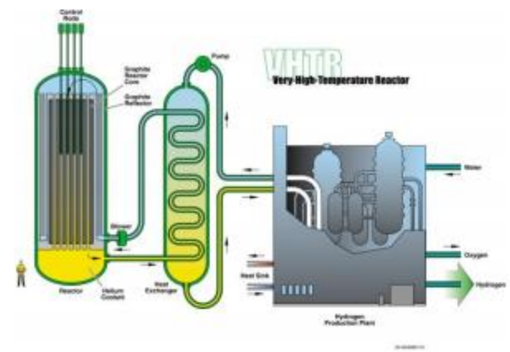
• Sustainable energy generation • Long-term availability • Minimization and management of their nuclear waste • Economical competitiveness • High level of safety and reliability • Proliferation-resistance



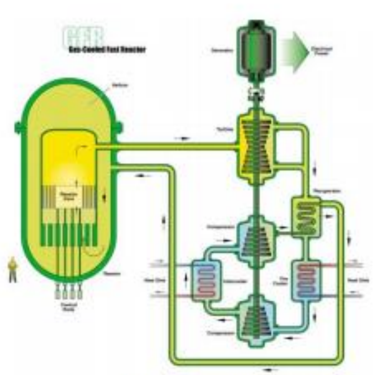
Sodium Fast Reactor



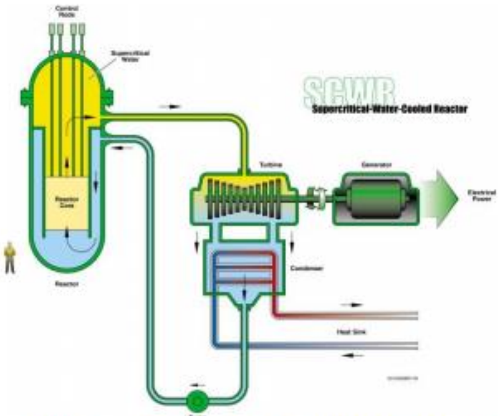
Lead Fast Reactor



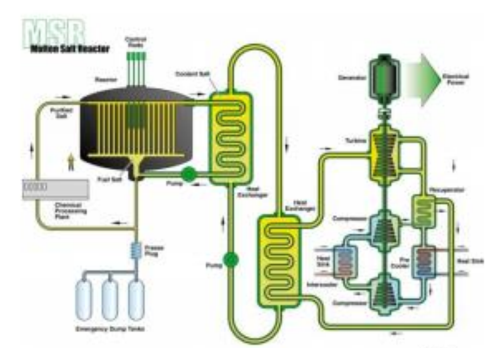
Very High Temperature Reactor



Gas Cooled Fast Reactor



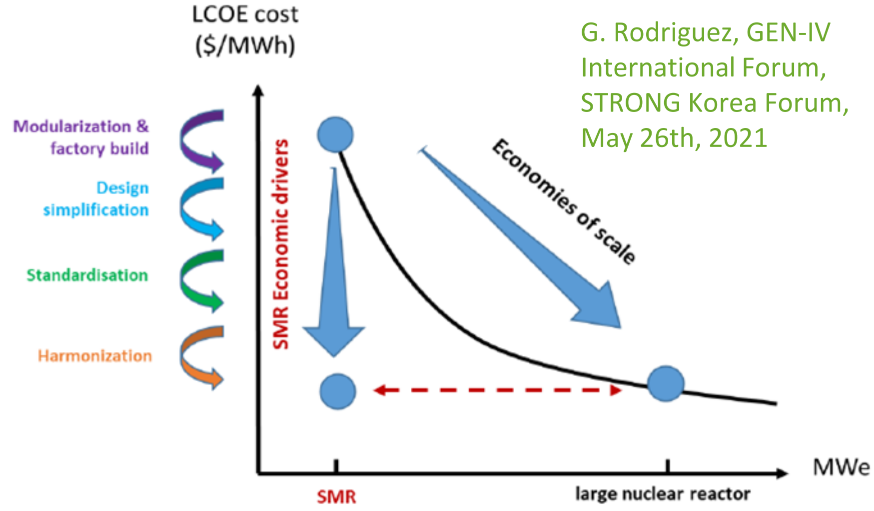
Supercritical Water Cooled Reactor



Molten Salt Cooled Reactor

The emergence of small / micro modular reactors

- **Definitions: SMR / AMR / MMR**
  - **Small Modular Reactor (SMR):** <500 MWe max, usually between 50 and 200 MWe, generally based on GEN-III technology (PWR, BWR, sometimes HTR)
  - **Advanced Modular Reactor (AMR):** SMR type but of GEN-IV type system (Molten salt, Na, Pb, Gas, SuperCritical Water)
  - **Micro Modular Reactor (MMR) or Very Small Modular Reactor (vSMR)** : Electro- and/or calogen nuclear reactor of a range power from 1 to 20 MWe



G. Rodriguez, GEN-IV International Forum, STRONG Korea Forum, May 26th, 2021

- Scale effect => modularization plus off-site fabrication
- Design simplifications allowed by a reduced power => limitation of the Emergency Planning Zones
- Series effect => Reduction of construction time & costs
- Opening towards new specific markets => remote areas, non-electrical applications, electricity/heat cogeneration …

The emergence of small / micro modular reactors

- In 2020, IAEA listed more than 70 projects of SMRs in the world

Advances in Small Modular Reactor Technology Developments
https://aris.iaea.org/Publications/SMR_Book_2020.pdf

- In 2023, OECD/NEA SMR Dashboard to track the progress of 21 SMRs around the world, assessing progress in licensing, siting, financing, supply chain, engagement, and fuel.

https://www.oecd-nea.org/upload/docs/application/pdf/2023-02/7650_smr_dashboard.pdf

- Innovative nuclear reactors call France 2030 investment plan
- UK launching SMR selection competition (Great British Nuclear plan)

Table 2. **SMRs assessed in The NEA SMR Dashboard**

Name	Design organisation	Headquarter (city/region)	Country	Thermal power (MWth)	Outlet temperature (°C)	Spectrum (thermal/fast)	Fuel type
ARC-100	ARC Clean Technology	Saint John, New Brunswick	Canada	286	510	Fast	Metallic U-Zr alloy
CAREM	CNEA[1]	Buenos Aires	Argentina	100	326	Thermal	UO_2 pellets
ACPR50S	CGN[2]	Shenzhen	China	200	321.8	Thermal	UO_2 pellets
ACP100	CNNC[3] and NPIC[4]	Hainan Province	China	385	319.5	Thermal	UO_2 pellets
Nuward	EDF[5]	Paris	France	540	307	Thermal	UO_2 pellets
BWRX-300	GE-Hitachi/ Hitachi-GE	Wilmington, North Carolina	United States	870	287	Thermal	UO_2 pellets
Hermes	Kairos Power	Alameda, California	United States	35	585	Thermal	TRISO pebble
SEALER-55	Leadcold Reactors	Stockholm	Sweden	140	432	Fast	Uranium nitride
Stable Salt Reactor - Wasteburner	Moltex Energy	Saint John, New Brunswick	Canada	750	590	Fast	Molten salt fuel
VOYGR	NuScale Power	Portland, Oregon	United States	250	321	Thermal	UO_2 pellets
Aurora	OKLO	Sunnyvale, California	United States	4	500	Fast	Metallic U-Zr alloy
Rolls-Royce SMR	Rolls-Royce SMR Ltd	Manchester	United Kingdom	1 358	325	Thermal	UO_2 pellets
KLT-40S	Rosatom	Moscow	Russia	150	316	Thermal	UO_2 pellets
RITM-200N	Rosatom	Moscow	Russia	190	321	Thermal	UO_2 pellets
RITM-200S	Rosatom	Moscow	Russia	198	318	Thermal	UO_2 pellets
Natrium	TerraPower	Bellevue, Washington	United States	840	500	Fast	Metallic U-Zr alloy
HTR-PM	INET[6]	Beijing	China	500	750	Thermal	TRISO pebble
MMR	Ultra Safe Nuclear	Seattle, Washington	United States	15	630	Thermal	TRISO prismatic
U-Battery	Urenco	Stoke Poges	United Kingdom	10	710	Thermal	TRISO prismatic
eVinci	Westinghouse Electric Company	Cranberry Township, Pennsylvania	United States	13	750	Thermal	TRISO
XE-100	X-energy	Rockville, Maryland	United States	200	750	Thermal	TRISO-X pebble

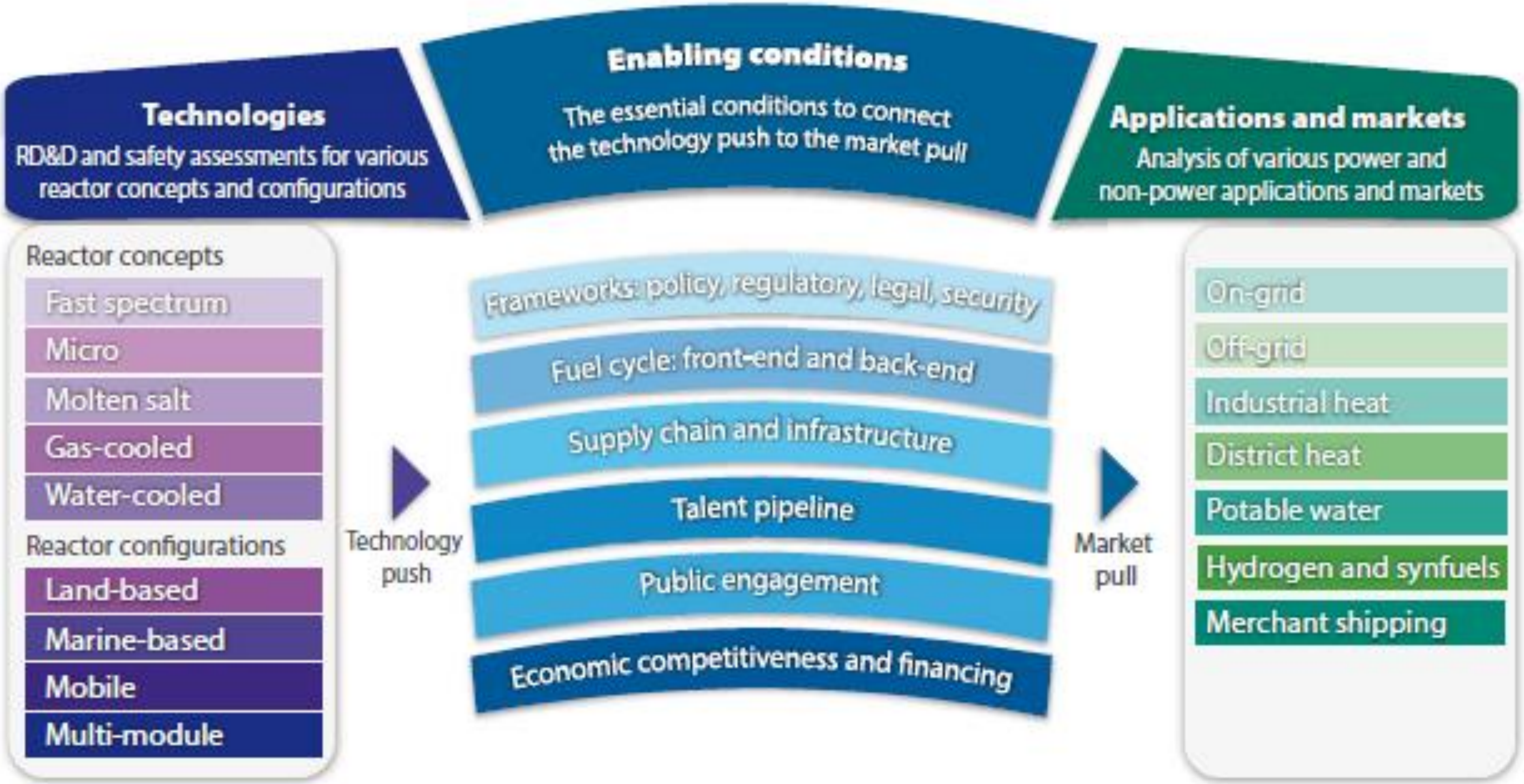
(1) Argentina's National Atomic Energy Commission; (2) China General Nuclear Power Group; (3) China National Nuclear Corporation; (4) Nuclear Power Institute of China; (5) Electricité de France; (6) Tsinghua University Institute of Nuclear and New Energy Technology.

THE NEA SMALL MODULAR REACTOR DASHBOARD, NEA No. 7650, © OECD 2023

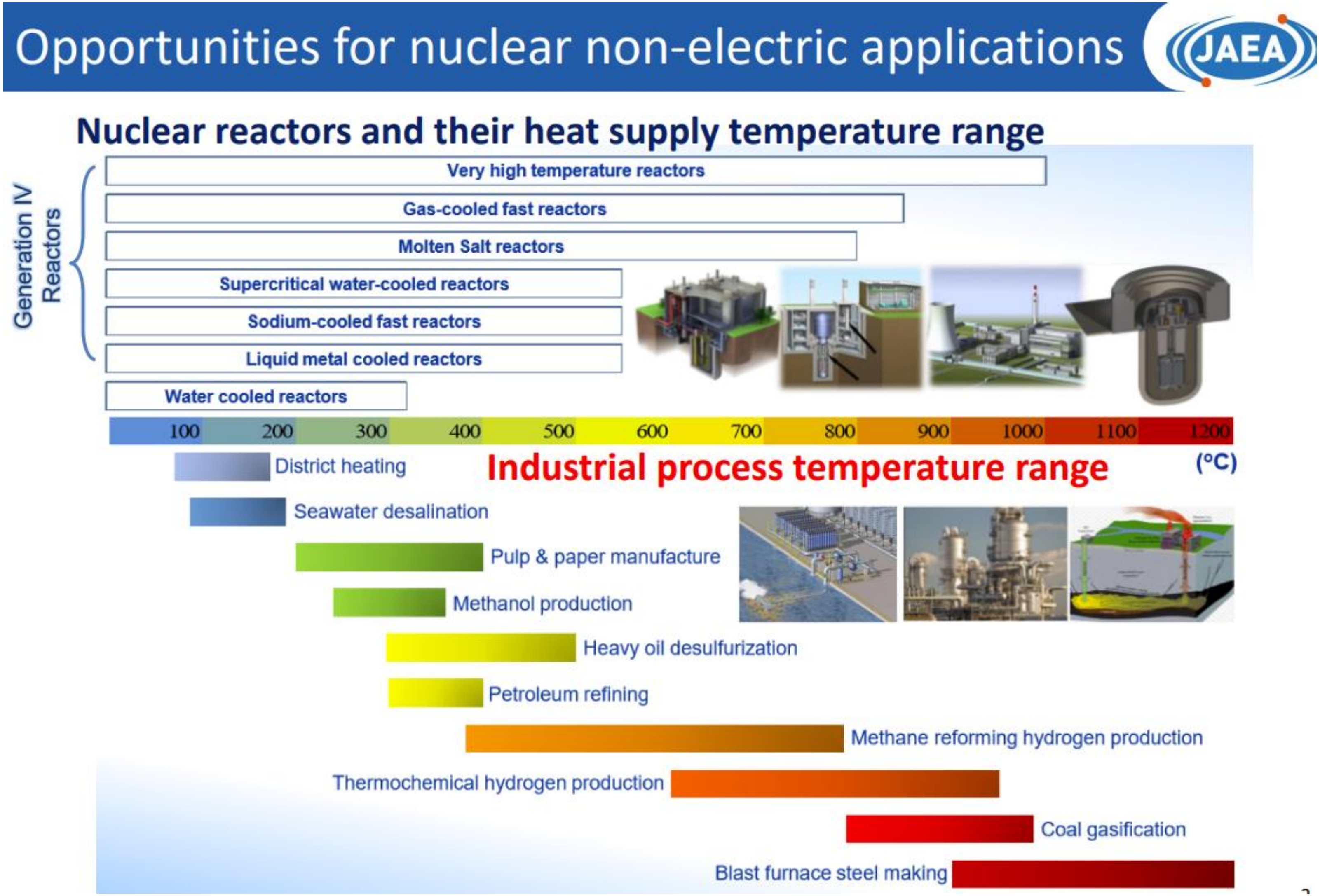
- NEA SMR Strategy

https://www.oecd-nea.org/upload/docs/application/pdf/2023-02/7650_smr_dashboard.pdf

Figure 11. **NEA SMR Strategy**



Non electric applications of reactors



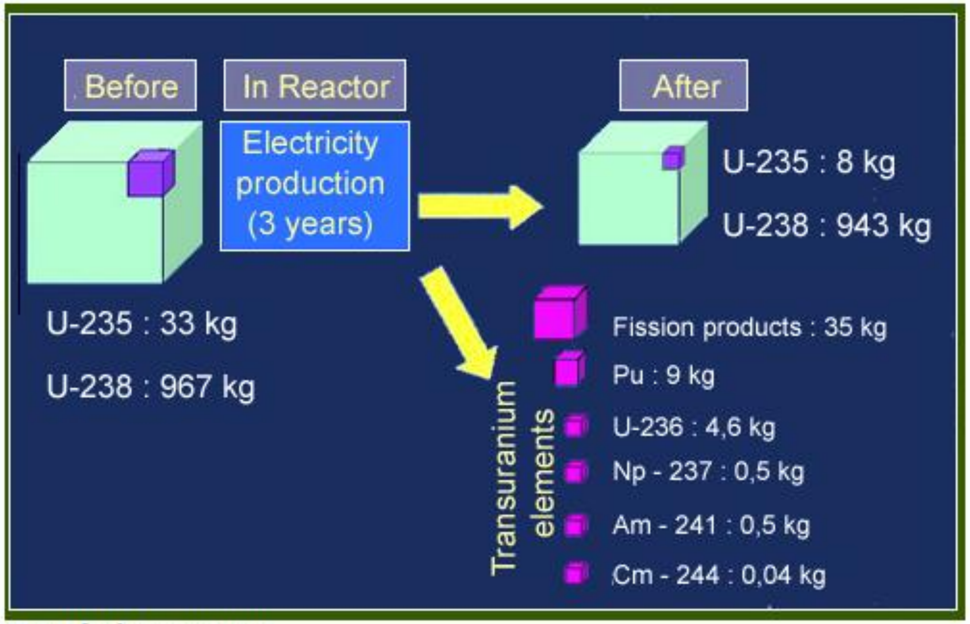
From Xin L. Yang, JAEA, https://nucleus.iaea.org/sites/INPRO/df16/Day-1/Keynote_YAN.pdf

Nuclear waste management and environmental impact

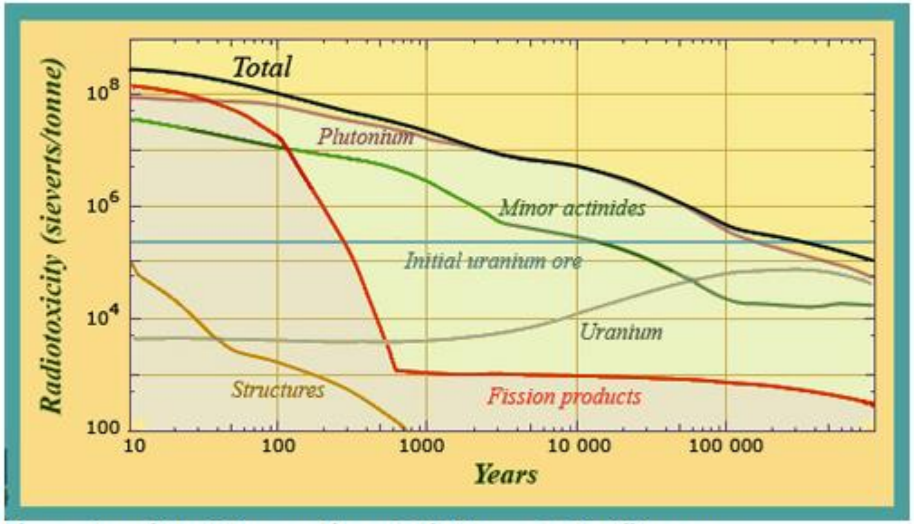
Waste management

- All human activities generate waste
- Only 3 ways to manage waste
  - Dilution
  - Transformation
  - Storage

Spent fuel composition and radiotoxicity



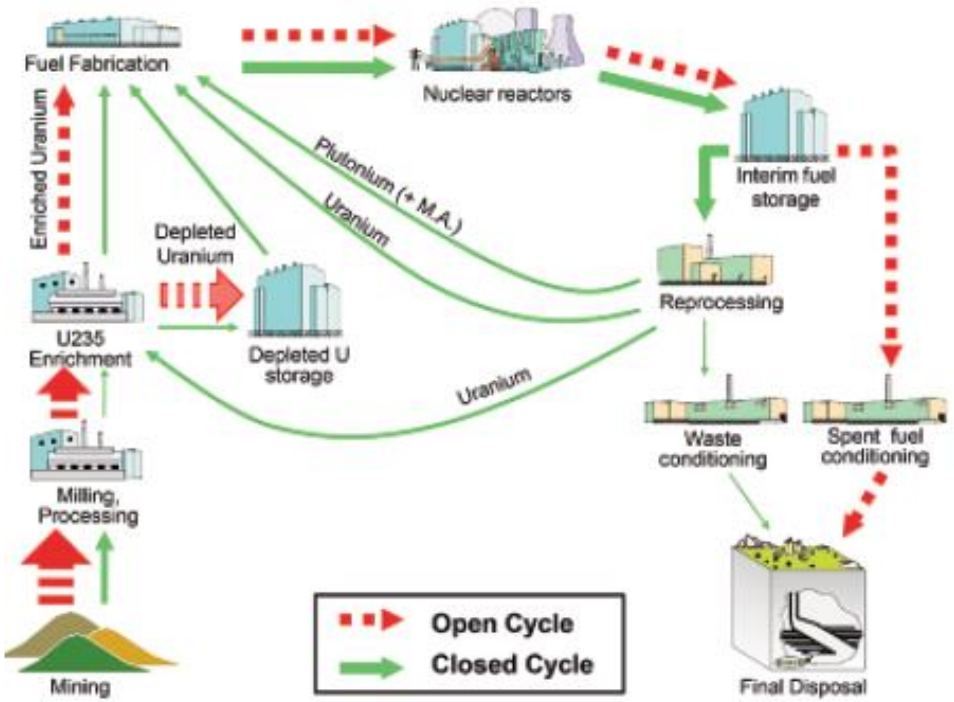
Spent fuel composition
Distribution (in kg per tonne of fuel) and mass produced by the principal radioactive elements present in fuel unloaded from an irradiated pressurised water reactor core.
©IPHC/IN2P3 (Source: Isabelle Billard)



Change in radiotoxicity over the period 10 years to 1 million years
The pattern of change in the radiotoxicity of spent fuel highlights the predominance of plutonium. This element overtakes fission products around 50 years after removal from the reactor.
©Source: CEA

Nuclear fuel cycle

- Two options:
  - Open cycle: direct disposal of spent fuel (US, Sweden, Finland…)
  - Partially closed cycle: reprocessing to extract Pu and make MOX fuels (France, Japan, Russia, China…)

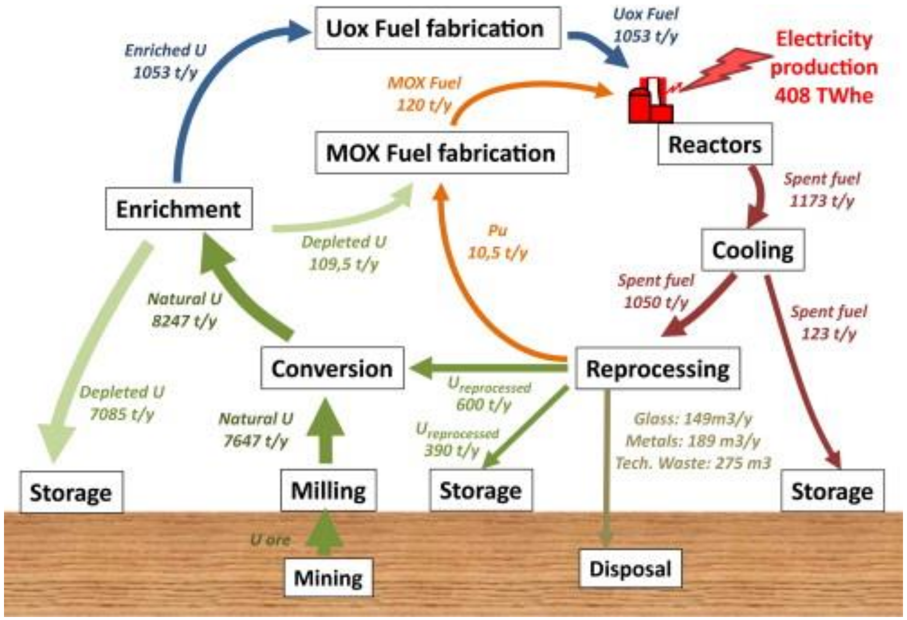


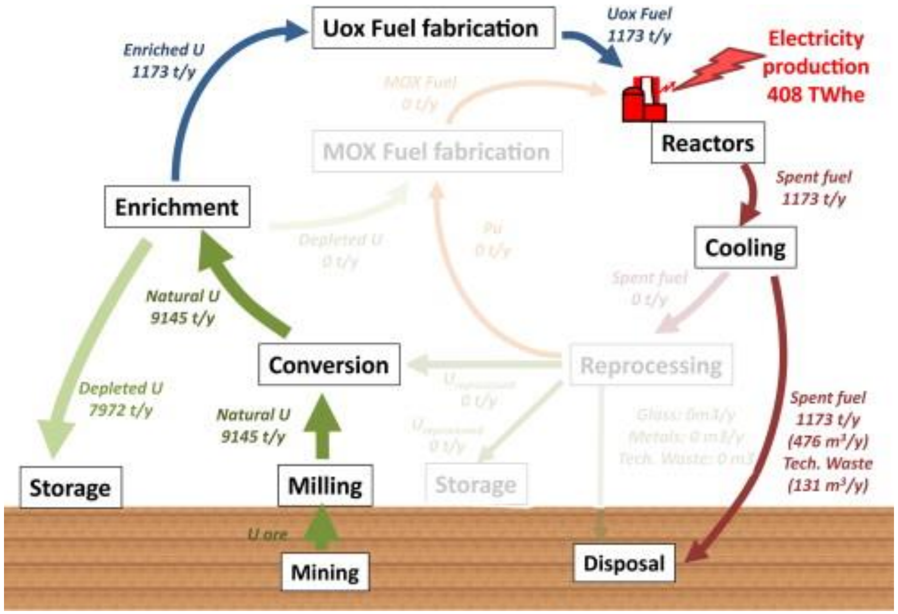
- Reprocessing reduces the amount, volume and radiotoxicity of the high-level waste to be stored, but generates additional volumes of intermediate wastes during the reprocessing and fuel fabrication processes

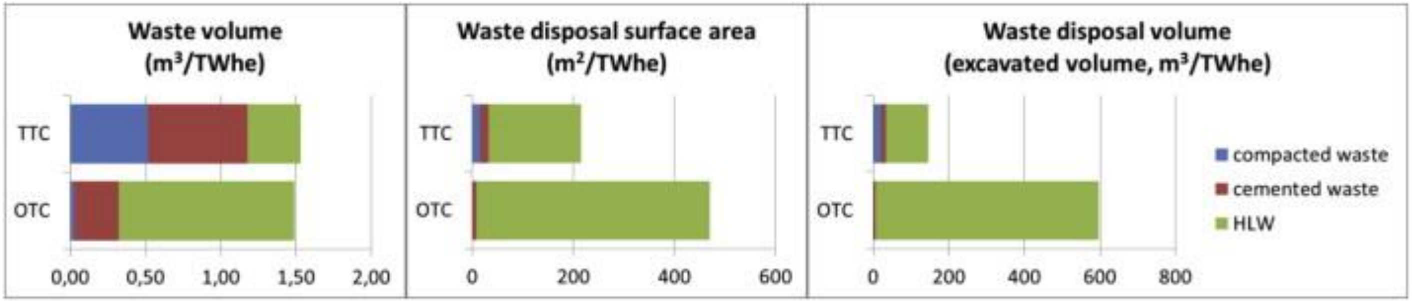
- **In any case a final deep geologic disposal of remaining long-lived high level waste will be necessary**

Nuclear energy: environmental impact

- Comparison between Twice-Through (TTC) and Once-Through Cycle (OTC)





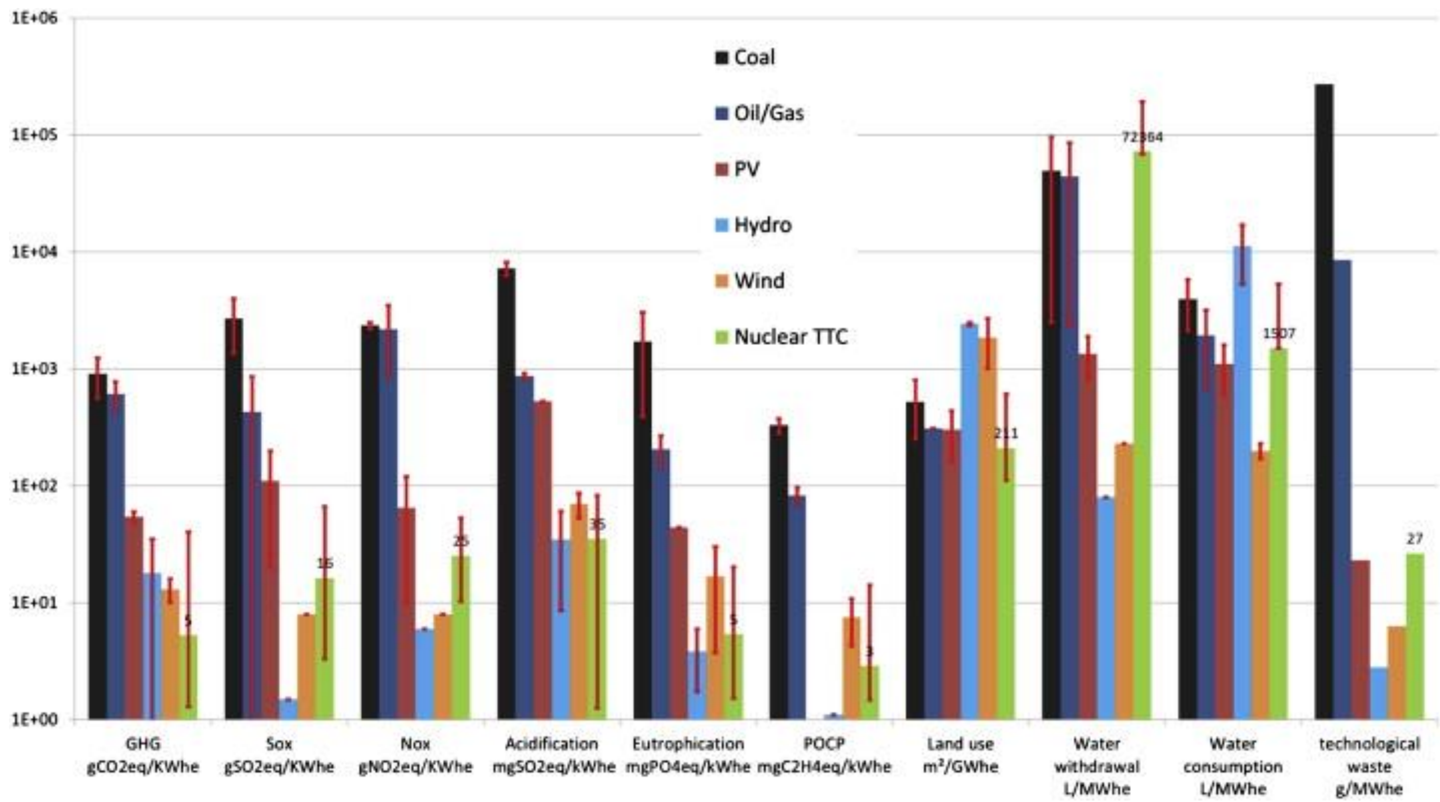


Ch. Poinssot et al. Energy 69 (2014): French case

- Indicators selected to describe the non-radioactive impacts.
- Comparison of the selected indicators between the French Twice-Through Cycle and other energy sources. The error bars represent the gap between the minimum and maximum values found in the literature.

Ch. Poinssot et al. / Energy 69 (2014)

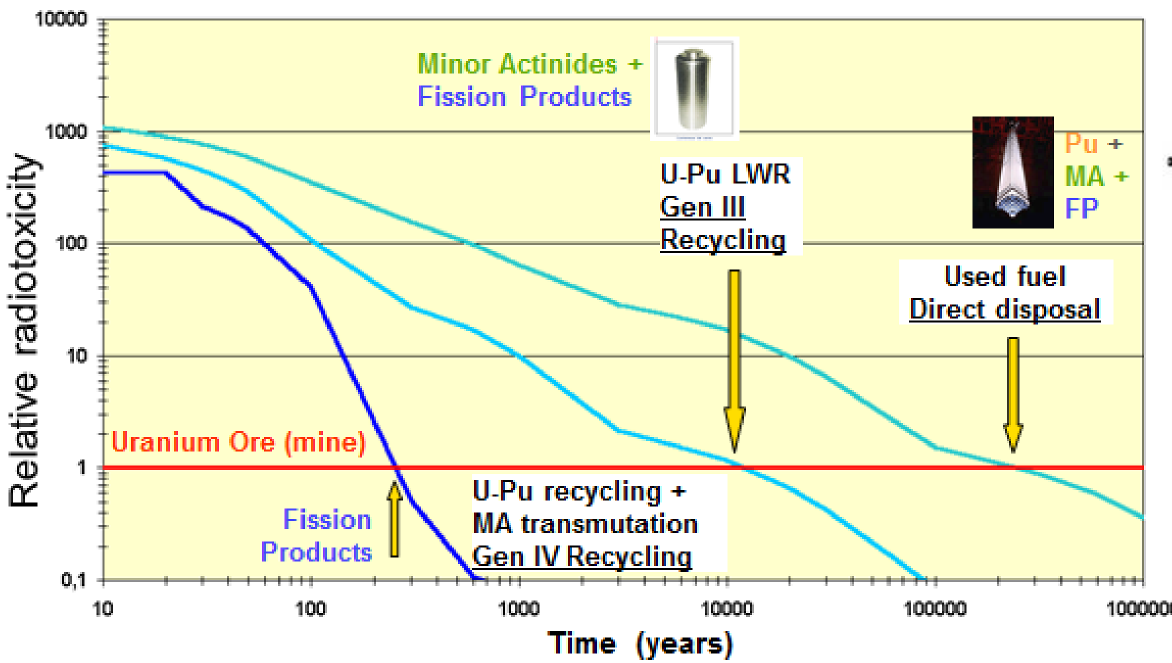
- green-house-gases emissions (GHG, $gCO_2eq/kWhe$),
- atmospheric pollution (mg/kWhe)
  - SOx
  - NOx
- water pollution (mg/kWhe),
  - Acidification
  - Eutrophisation
  - POCP (photochemical ozone creation potential)
- land-use ($m^2/GWhe$)
- water consumption (l/MWhe)
- water withdrawal (l/MWhe)
- production of technological waste (g/MWhe)



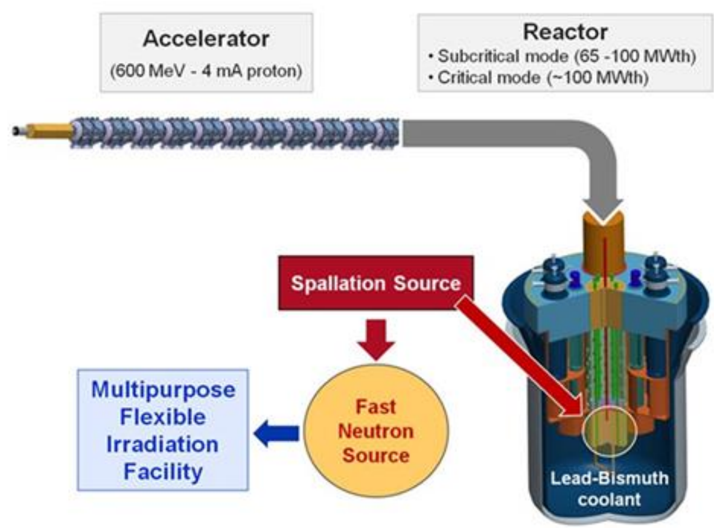
Transmutation of Nuclear Waste

- **Two options:**
  - Small amount of minor actinides in many (fast) reactors
  - Large amount of minor actinides in dedicated systems

Radiotoxicity of UOX spent fuel relative to uranium ore, versus time (years)



H.A. Abderrahim et al., NEA/NSC/R (2015) 2



The MYRRHA PROJECT at SCK•CEN

Conclusions

- Energy demand will likely continue to grow with an increasing importance of electricity
- In a mix of tools to reduce CO_2 emission, nuclear energy has a key role to play
- Most of the new nuclear power reactors are built in emerging countries
- Emergence of Small Modular Reactors with a possible use for non-power applications
- Disposal of long-lived high level waste necessary but global non-radioactive environmental impact lower than for other sources of energy

Thank you for your attention

Commissariat à l'énergie atomique et aux énergies alternatives - www.cea.fr