Nuclear Energy Basics

Joint EPS-SIF International School on Energy

Varenna, 22 July 2021

DE LA RECHERCHE À L'INDUSTRIE

Sylvie Leray

- **Basics on nuclear fission and fusion**
  - Fission: more details in M. Ripani's lecture
  - Fusion: more details in J. Ongena's and F. Romanelli's lectures
- **Nuclear energy in the world: status and perspectives**
- **Nuclear waste management and environmental impact**
- **Conclusions**

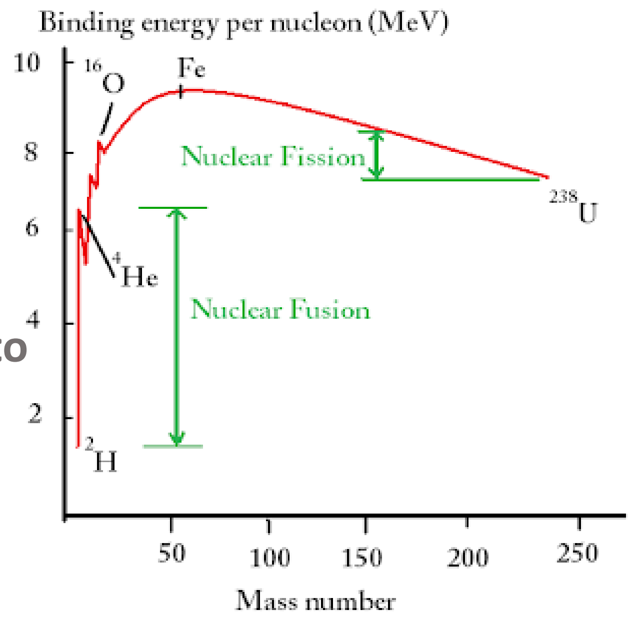
Nuclear energy basics

- **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

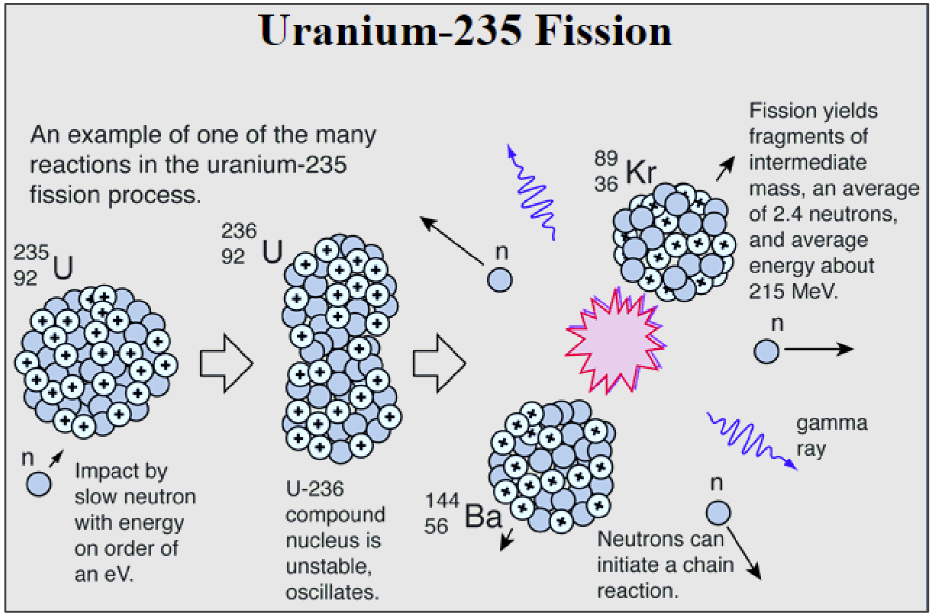
  Q = B(Target) + B(projectile) - B(Final nucleus) – B(ejectile)

  Either

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

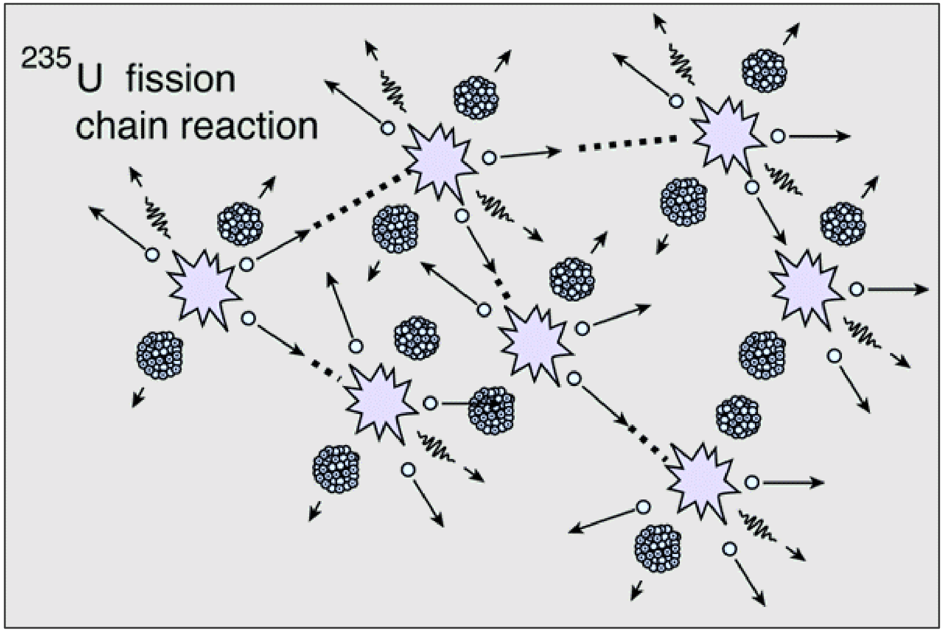
Fission

- 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: fissile
  - ^{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

- **Plutonium: ^{239}Pu is fissile**

  ➥ **See lecture by Marco Ripani**

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

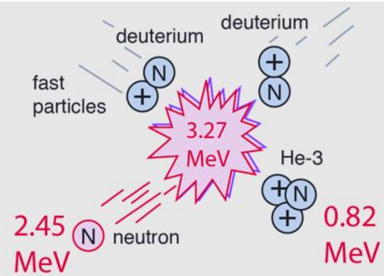
    ^{238}U (n,γ) ⟶ ^{239}U (23min) ⟶ ^{239}Np (2.3d) ⟶ ^{239}Pu (2.4x10^{4}y)
  - In light-water reactors up to one third of the fissions come from ^{239}Pu

- **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 (1.6x10^{5}y)
  - Thorium reactors require either that ^{232}Th is first irradiated in another reactor to provide ^{233}Pa or plutonium to initiate the process

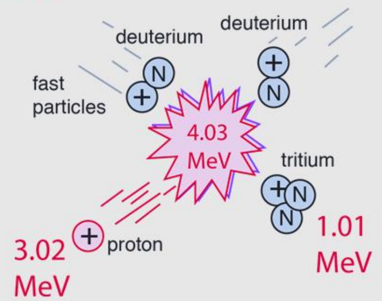
Fusion reactions can be initiated in a plasma of hydrogen isotopes

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



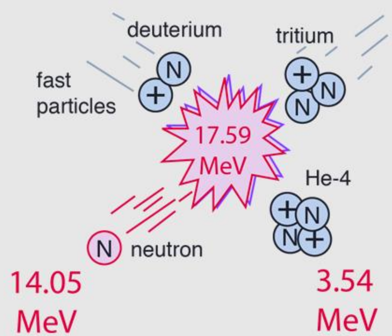
Deuterium-deuterium Fusion

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



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

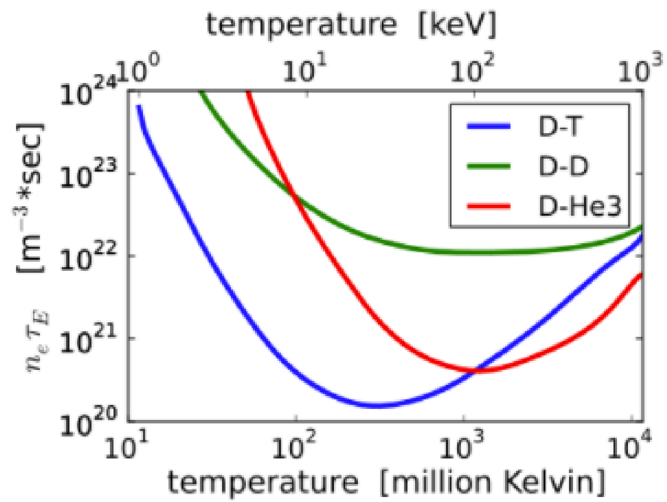
Deuterium-tritium Fusion



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.



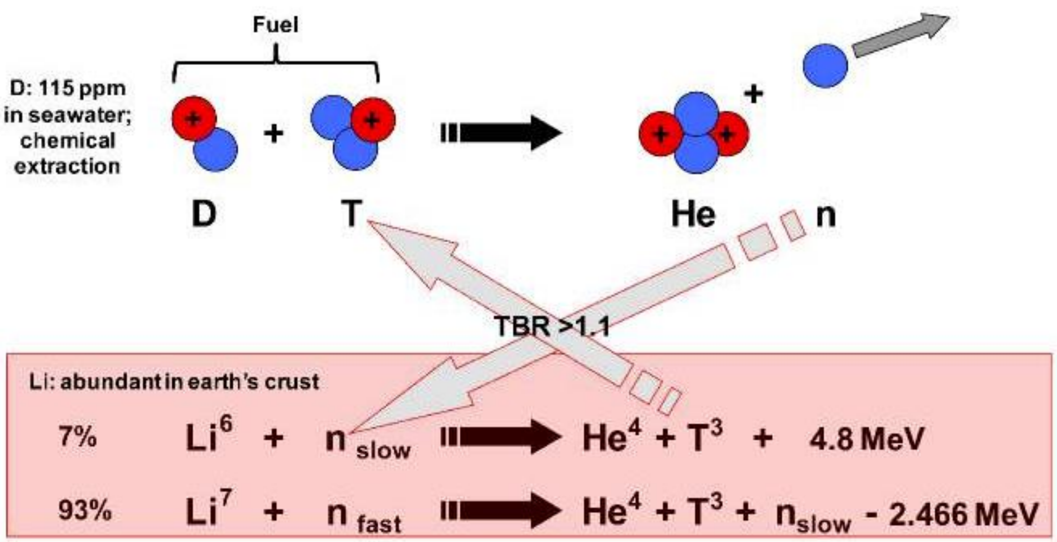
Inertial confinement (by lasers)

- 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 Jef Ongena and Francesco Romanelli**

Fuel energy content

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

  1g coal = $4 \times 1.6 \times 10^{-19} \times 6.02 \times 10^{23}/12$ = **3.2×10^4 J**

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 = $8 \times 1.6 \times 10^{-19} \times 6.02 \times 10^{23}/16$ = **4.8×10^4 J**

- 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^{10} J**

- Nuclear fusion: $^2H + {}^3H \rightarrow {}^4He + n$ + **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^{11} J**

Nuclear compared to fossil fuels

- **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 (**/657 = **5.50x10^6 m^3/day)**

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

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

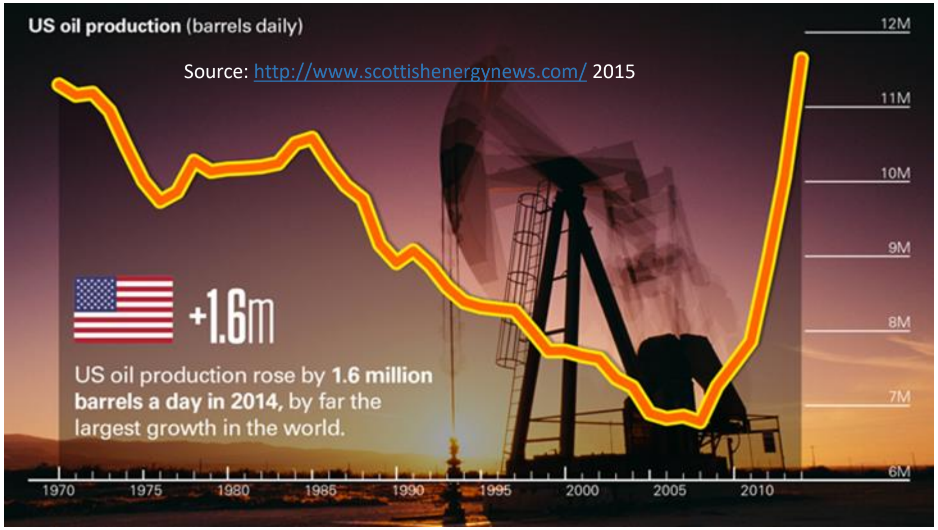
  - D-T in nuclear fusion (assuming 10% efficiency):

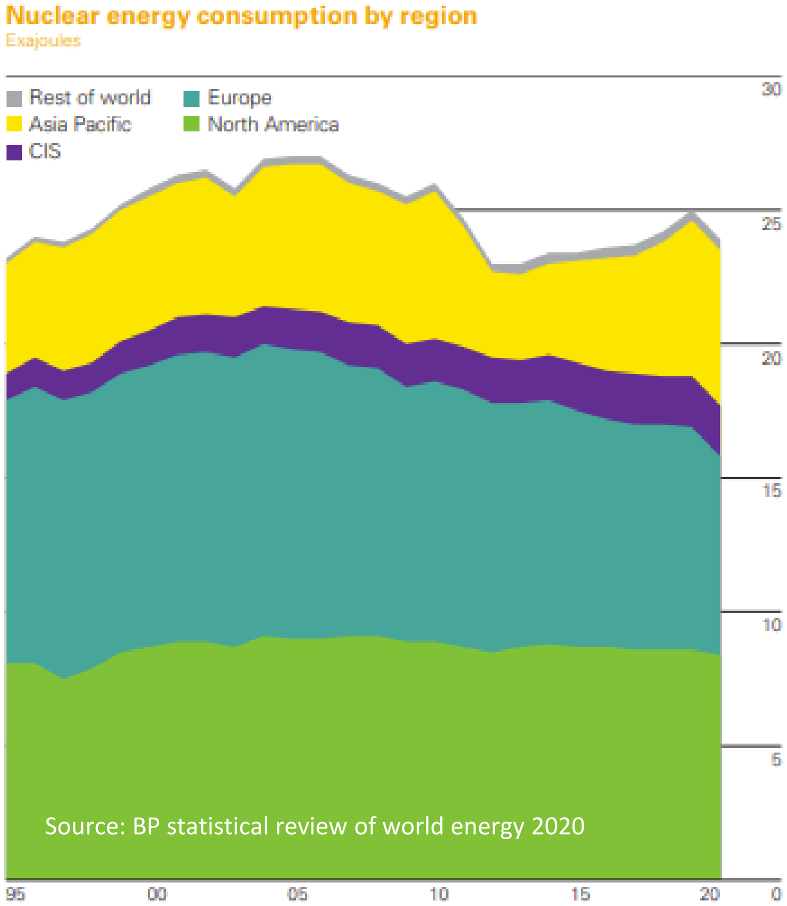
    10^9x8,64x10^4 / 0.1x3.4x10^{11} ≈ **250 kg/day**

Nuclear energy in the world: status and perspectives

The growth expected twenty years ago has not happened:

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





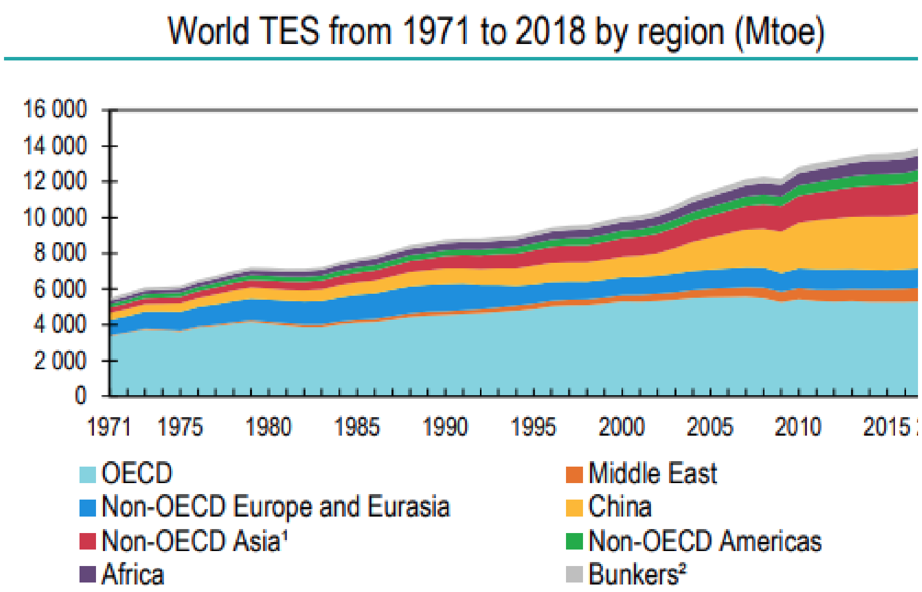
But nuclear energy production had begun increasing again, …before COVID-19

Energy demand

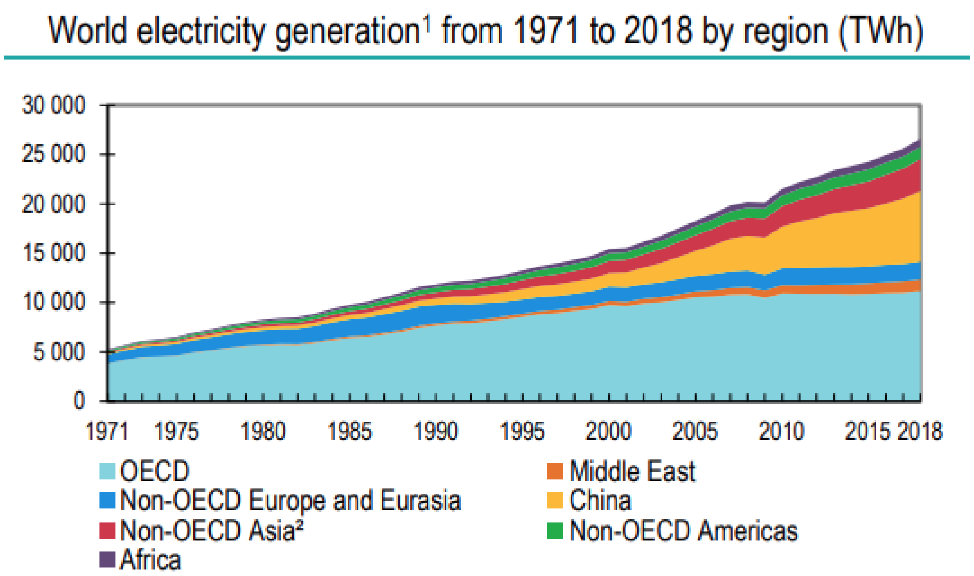
▶ Increase in energy demand due to growth of world population and improving of the standard of living

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

Total primary energy



Electricity

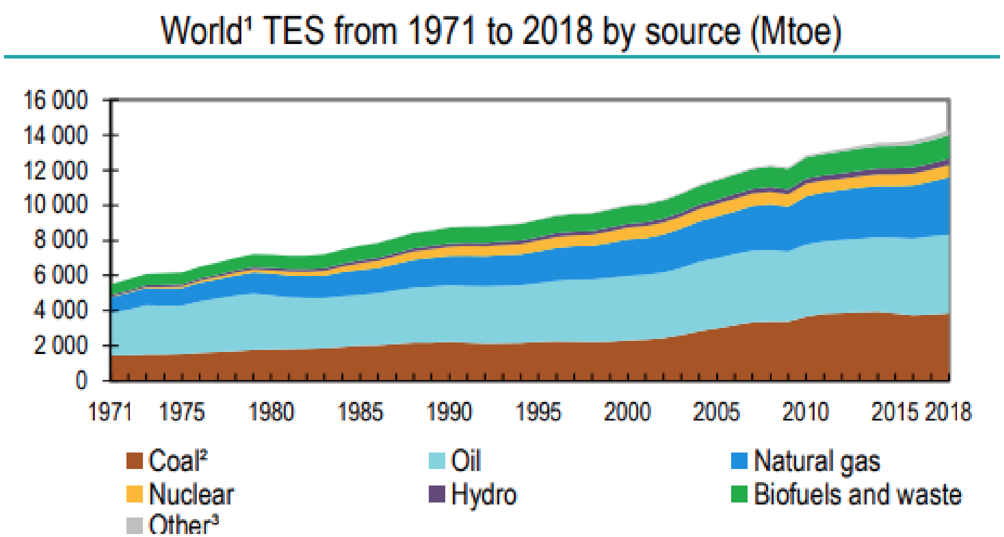


Source: IEA Key world energy statistics 2020

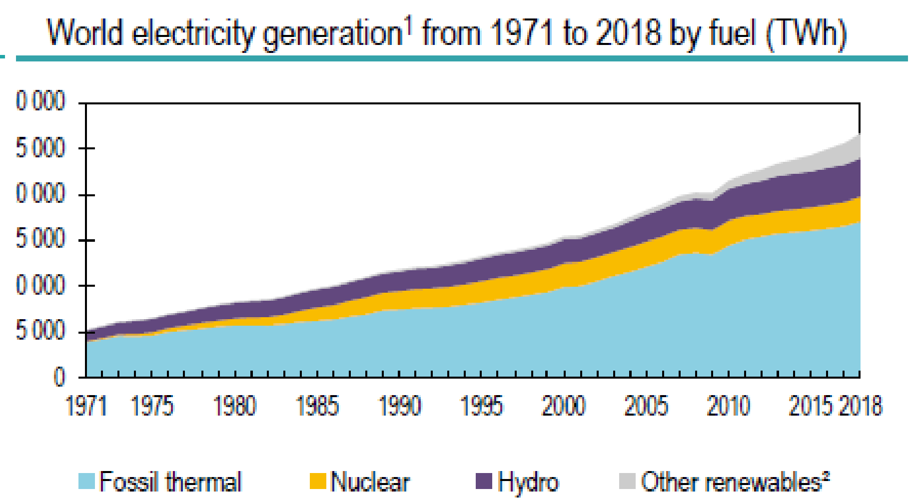
Energy demand

- Total primary energy still produced mostly by fossil fuels
- Share of nuclear energy (~10%) no longer increasing in recent years
- Share of renewables increasing significantly

Total primary energy



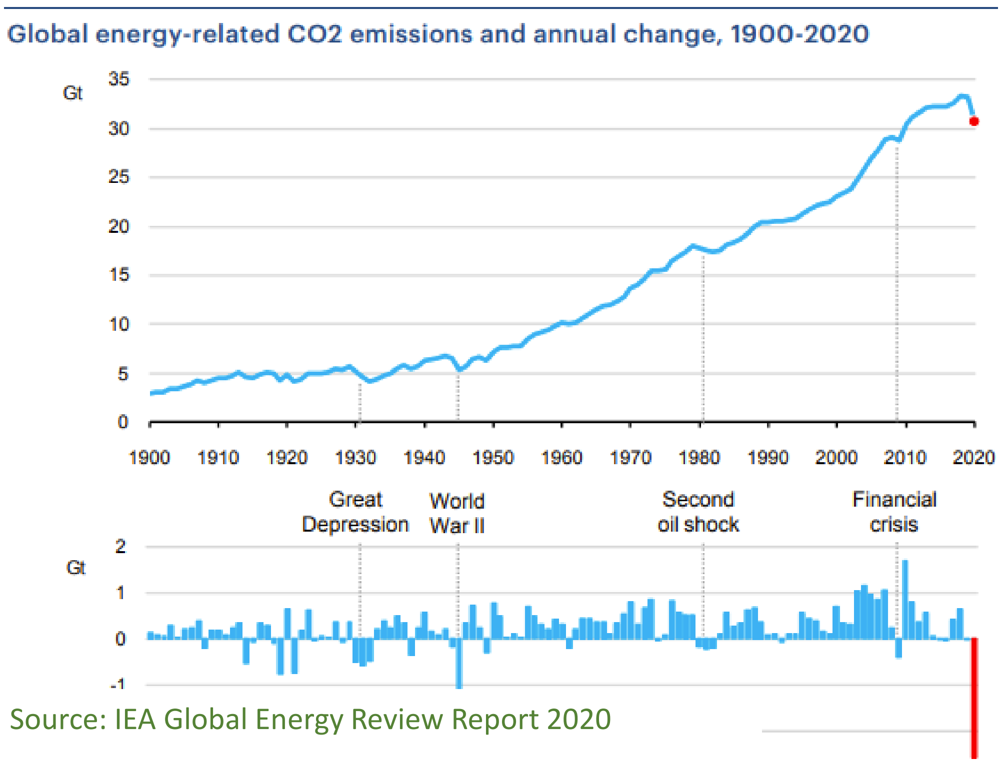
Electricity



Source: IEA Key world energy statistics 2020

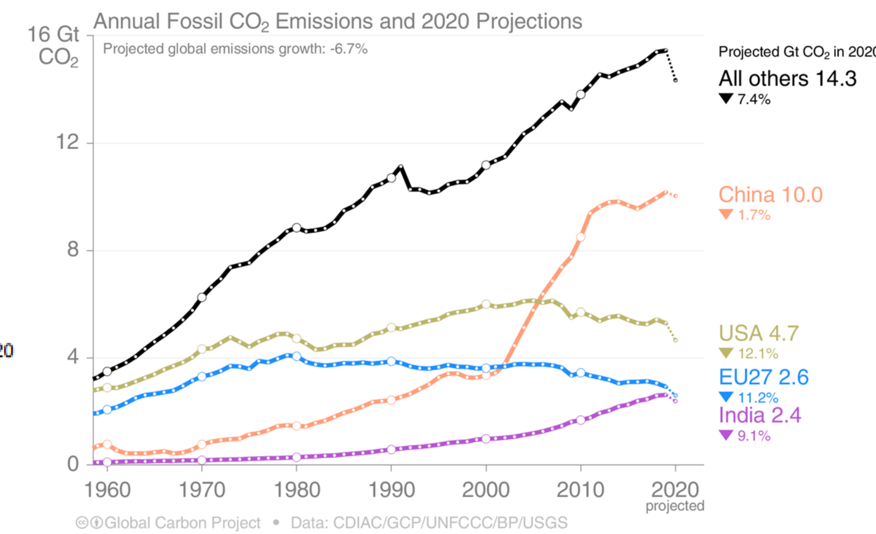
CO_2 emissions

- CO_2 emissions should decrease to mitigate global warming
- new increase since 2017 after 2 years of stagnation
- Impact of COVID19 in 2020



Source: IEA Global Energy Review Report 2020

CO_2 emissions of the top 4 emitters

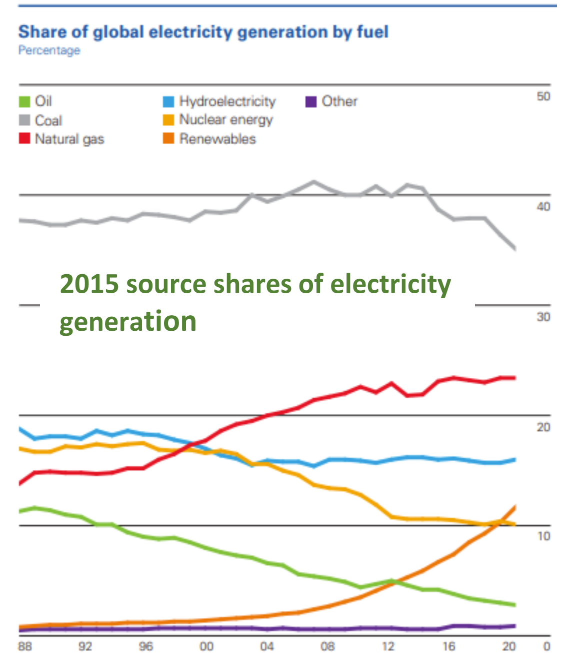


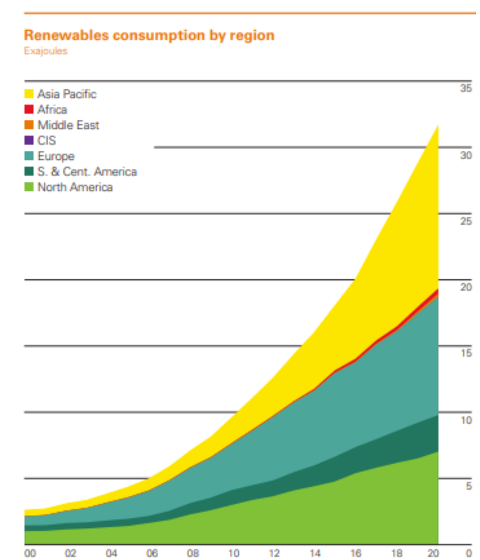
Source: Global Carbon Project, Dec. 2020

▶ 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 and transportation
- Carbon capture and storage, but expensive and profitable only if close to the emission site
- Renewable energies but intermittent and expensive, rare earth element supply
- Nuclear energy but fear of accident and question of waste

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





BP statistical review of world energy 2021

Reducing CO_2 emissions: IEA net-zero by 2050 proposed scenario

- Combination of all solutions
- Share of electricity in total energy supply has to increase
- Nuclear energy has to be at least doubled

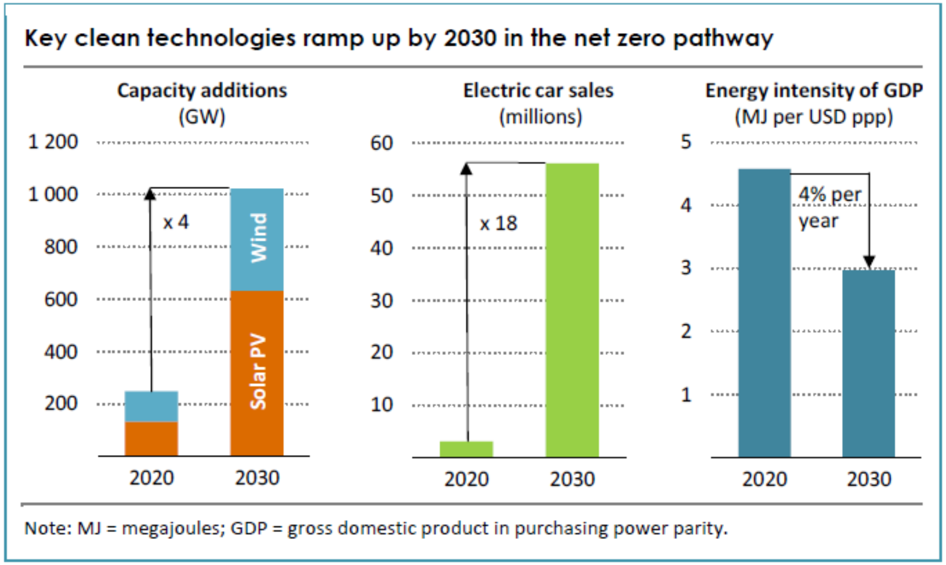
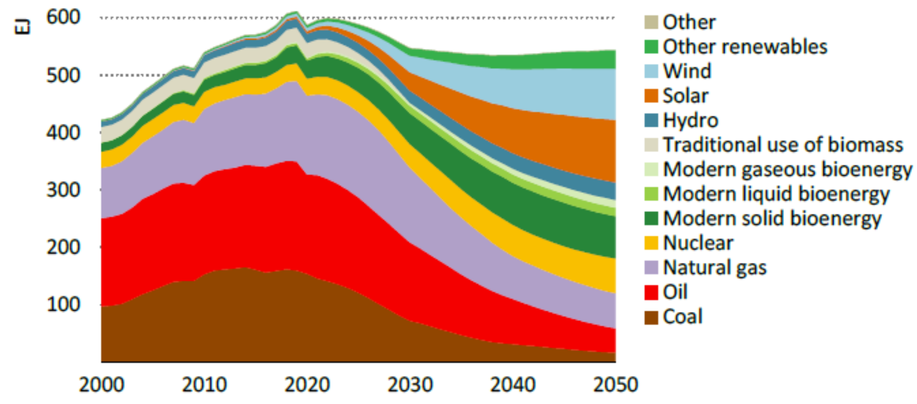


Figure 2.5 ▷ Total energy supply in the NZE



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

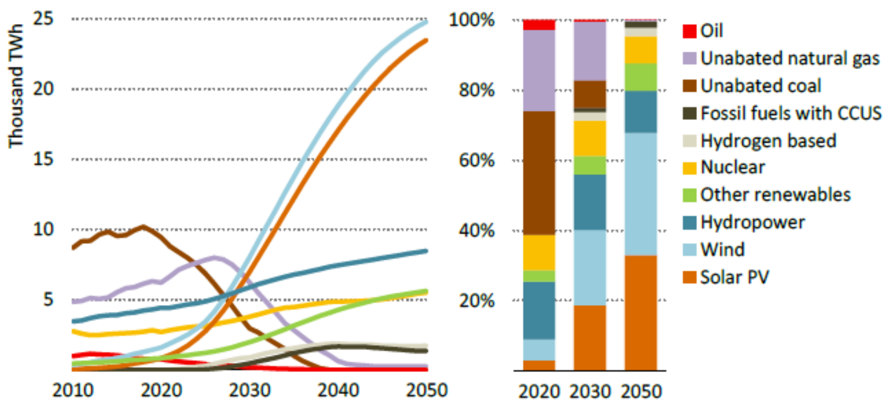
IEA Net Zero by 2050 report
iea.li/nzeroadmap

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
- **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

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

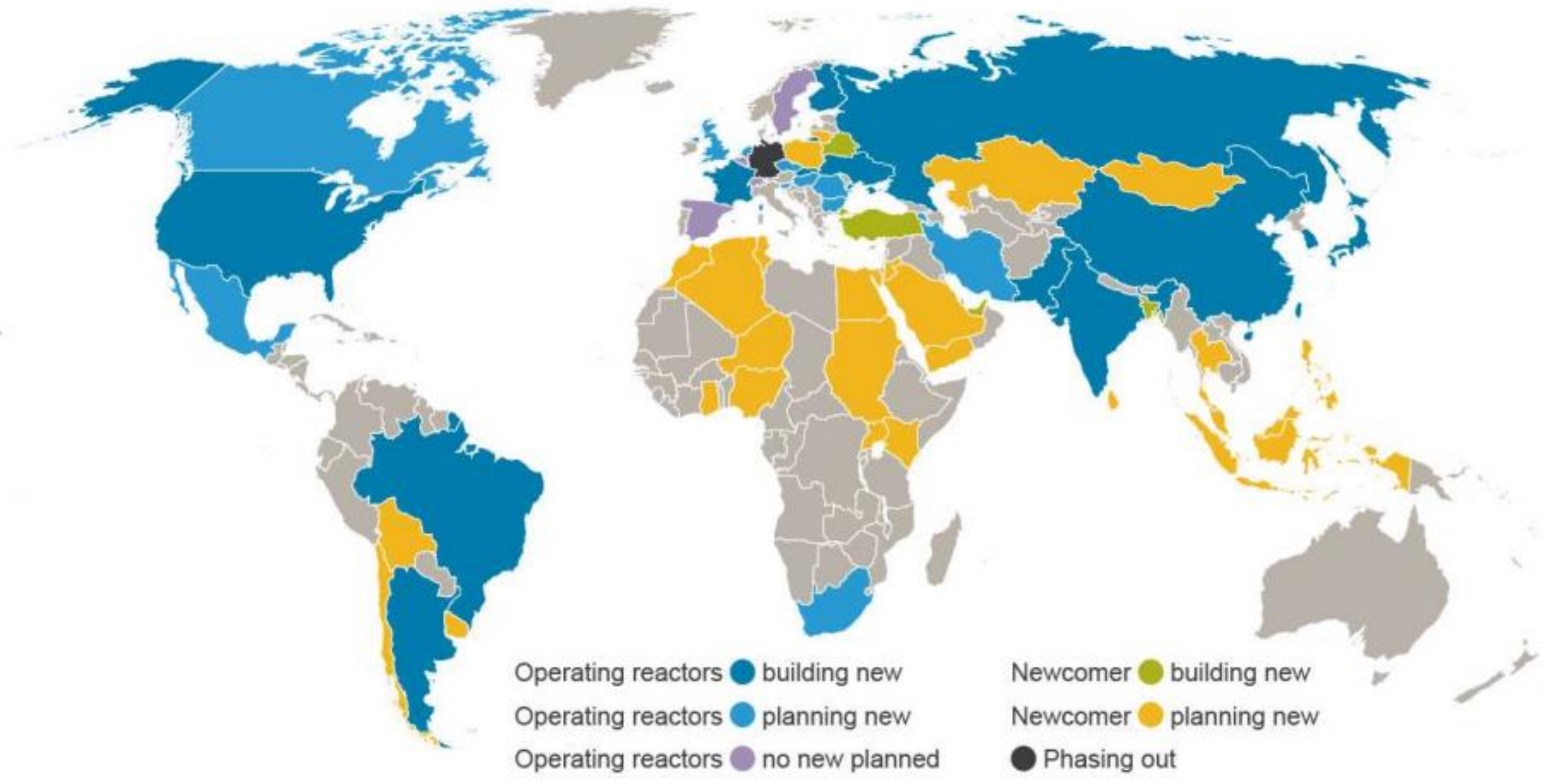
IEA Net Zero by 2050 report
iea.li/nzeroadmap

Nuclear energy

WORLD NUCLEAR ASSOCIATION

New build and new countries

Agneta Rising, World Nuclear Association, March 2018



- **56 reactors under construction, of which 16 in China, 6 in Russia, 7 in India**
- **152 reactors planned, of which 43 in China, 25 in Russia, 14 in India**

World Nuclear Power Reactors

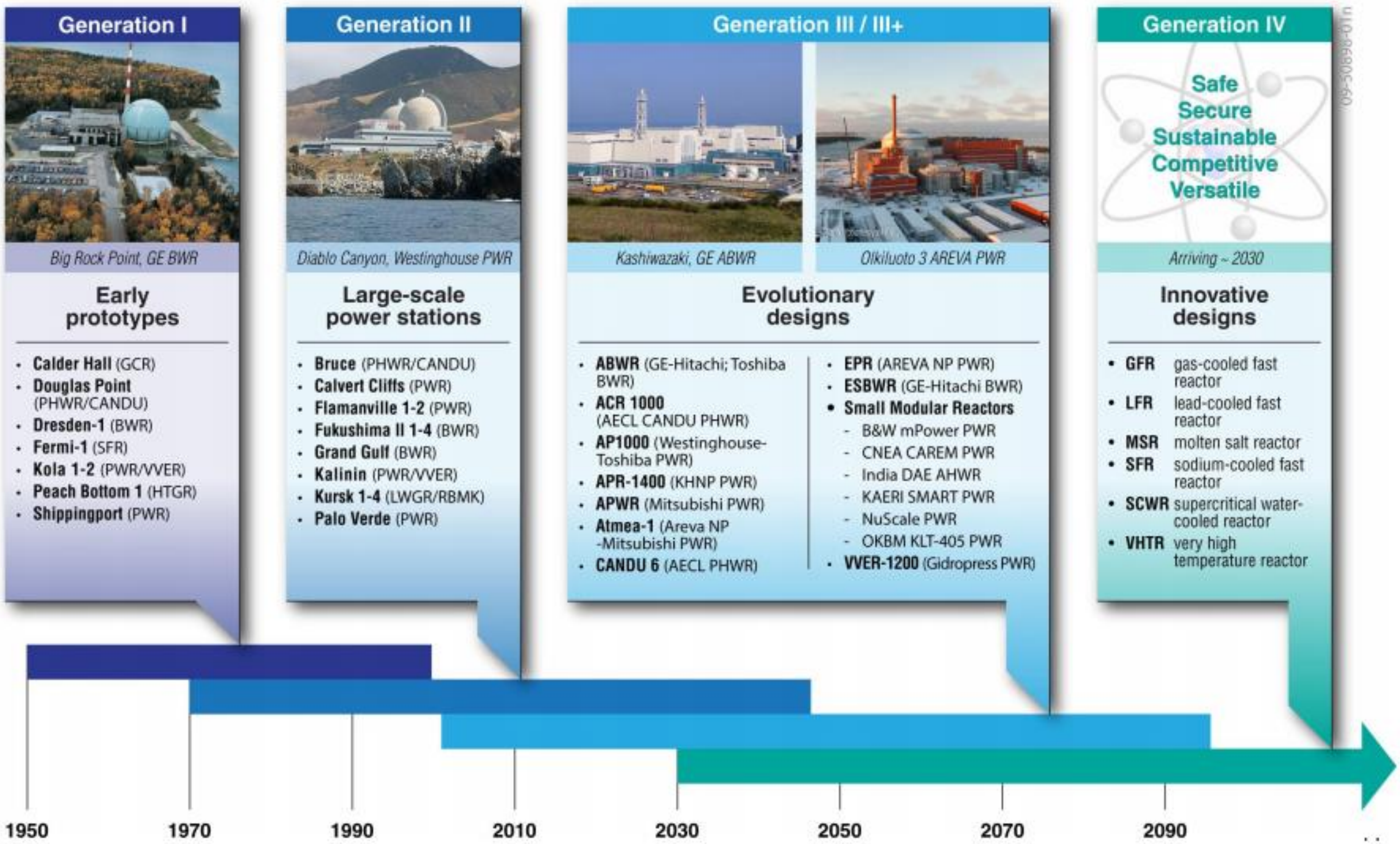
Source: The World Nuclear Association
https://www.world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme.aspx

COUNTRY	NUCLEAR ELECTRICITY GENERATION 2020		REACTORS OPERABLE June 2021		REACTORS UNDER CONSTRUCTION June 2021		REACTORS PLANNED June 2021		REACTORS PROPOSED June 2021	
	TWh	% e	No.	MWe net	No.	MWe gross	No.	MWe gross	No.	MWe gross
Argentina	10.0	7.5	3	1641	1	29	1	1150	2	1350
Armenia	2.6	34.5	1	415	0	0	0	0	1	1060
Bangladesh	0	0	0	0	2	2400	0	0	2	2400
Belarus	0.3	1.0	1	1110	1	1194	0	0	2	2400
Belgium	32.8	39.1	7	5942	0	0	0	0	0	0
Brazil †	13.2	2.1	2	1884	1	1405	0	0	4	4000
Bulgaria	15.9	40.8	2	2006	0	0	1	1000	2	2000
Canada	92.2	14.6	19	13,624	0	0	0	0	2	1500
China	344.7	4.9	51	49,569	17	18,616	38	41,785	168	196,86
Czech Republic	28.4	37.3	6	3934	0	0	1	1200	3	3600
Egypt	0	0	0	0	0	0	4	4800	0	0
Finland	22.4	33.9	4	2794	1	1720	1	1170	0	0
France	338.7	70.6	56	61,37	1	1650	0	0	0	0
Germany	60.9	11.3	6	8113	0	0	0	0	0	0
Hungary	15.2	48.0	4	1902	0	0	2	2400	0	0
India	40.4	3.3	23	6885	6	4600	14	10,5	28	32
Iran	5.8	1.7	1	915	1	1057	1	1057	5	2760
Japan †	43.0	5.1	33	31,679	2	2756	1	1385	8	11,562
Jordan	0	0	0	0	0	0	0	0	1	1000
Kazakhstan	0	0	0	0	0	0	0	0	2	600
Korea RO (South)	152.6	29.6	24	23,15	4	5600	0	0	2	2800
Lithuania	0	0	0	0	0	0	0	0	2	2700
Mexico	10.9	4.9	2	1552	0	0	0	0	3	3000
Netherlands	3.3	3.9	1	482	0	0	0	0	0	0
Pakistan	9.6	7.1	6	2332	1	1100	1	1170	0	0
Poland	0	0	0	0	0	0	0	0	6	6000
Romania	10.6	19.9	2	1300	0	0	2	1440	1	720
Russia ‡	201.8	20.6	38	28,578	2	2510	25	23,89	21	20,1
Saudi Arabia	0	0	0	0	0	0	0	0	16	17
Slovakia	14.4	53.1	4	1837	2	942	0	0	1	1200
Slovenia	6.0	37.8	1	688	0	0	0	0	1	1000
South Africa	11.6	5.9	2	1860	0	0	0	0	8	9600
Spain	55.8	22.2	7	7121	0	0	0	0	0	0
Sweden	47.4	29.8	6	6882	0	0	0	0	0	0
Switzerland	23.0	32.9	4	2960	0	0	0	0	0	0
Thailand	0	0	0	0	0	0	0	0	2	2000
Turkey	0	0	0	0	3	3600	1	1200	8	9500
Ukraine †	71.5	51.2	15	13,107	2	1900	0	0	2	2,4
UAE	0	0	1	1345	3	4200	0	0	0	0
United Kingdom	45.9	14.5	15	8923	2	3440	2	3340	2	2300
USA	789.9	19.7	93	95,523	2	2500	3	2550	18	8000
Uzbekistan	0	0	0	0	0	0	2	2400	2	2400
WORLD*	**2553**	**c 10.1****	**444**	**395,267**	**54**	**61,219**	100	**102,437**	**325**	**353,812**
	TWh	**% e**	**No.**	**MWe**	**No.**	**MWe**	**No.**	**MWe**	**No.**	**MWe**
	NUCLEAR ELECTRICITY GENERATION		OPERABLE		UNDER CONSTRUCTION		PLANNED		PROPOSED	

Nuclear Power Reactors : China

Source: Mark Hibbs, The future of nuclear power in China, Carnegie Endowment for International Peace, 2018.

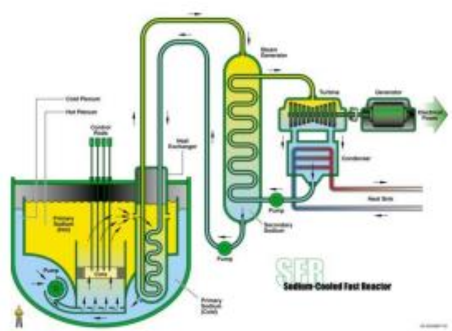
- **Presently, going from Generation II to Generation III**
- **Preparing for Generation IV**



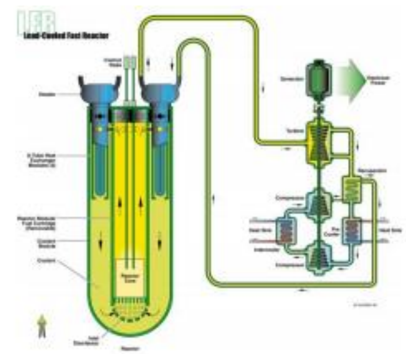
Source: Generation IV International Forum, www.gen-4.org

Generation IV technology goals

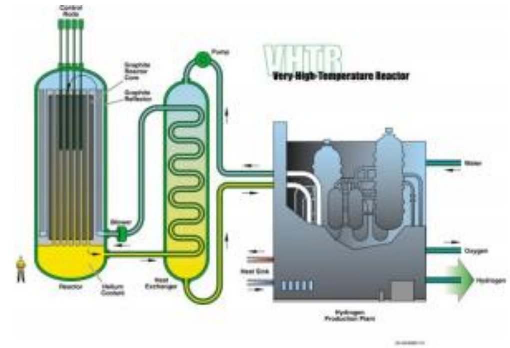
• Sustainable energy generation • Long-term availability • Minimization and management of their nuclear waste • Economical competitiveness • High level of safety and reliability • Proliferation-resistance



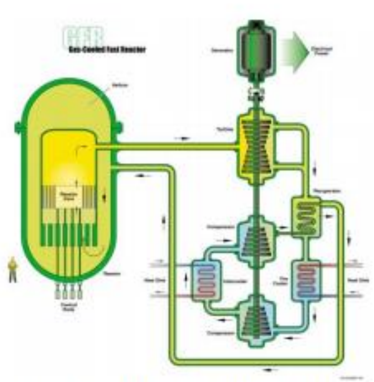
Sodium Fast Reactor



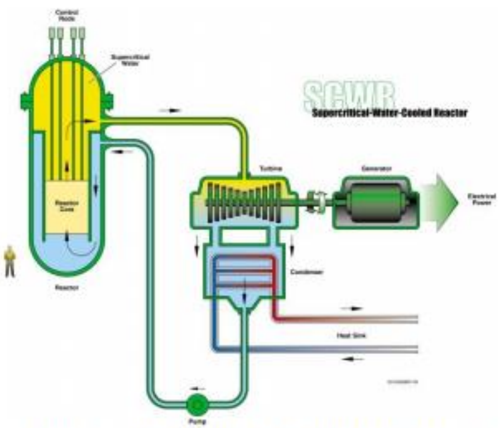
Lead Fast Reactor



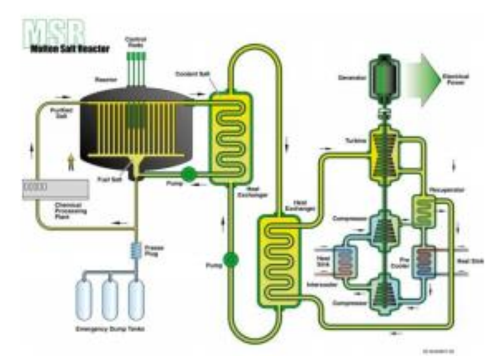
Very High Temperature Reactor



Gas Cooled Fast Reactor



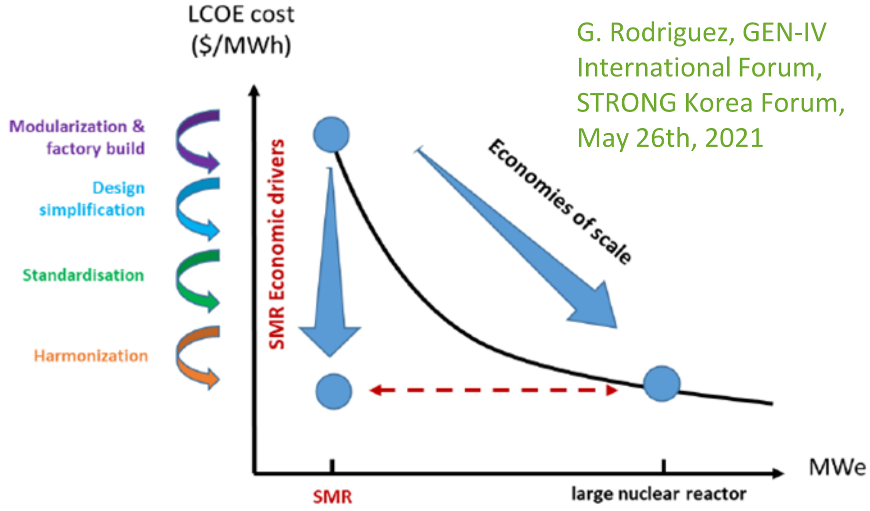
Supercritical Water Cooled Reactor



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-3 technology (PWR, BWR, sometimes HTR)
  - **Advanced Modular Reactor (AMR):** SMR type but of GEN-4 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, mix between electricity/heat…

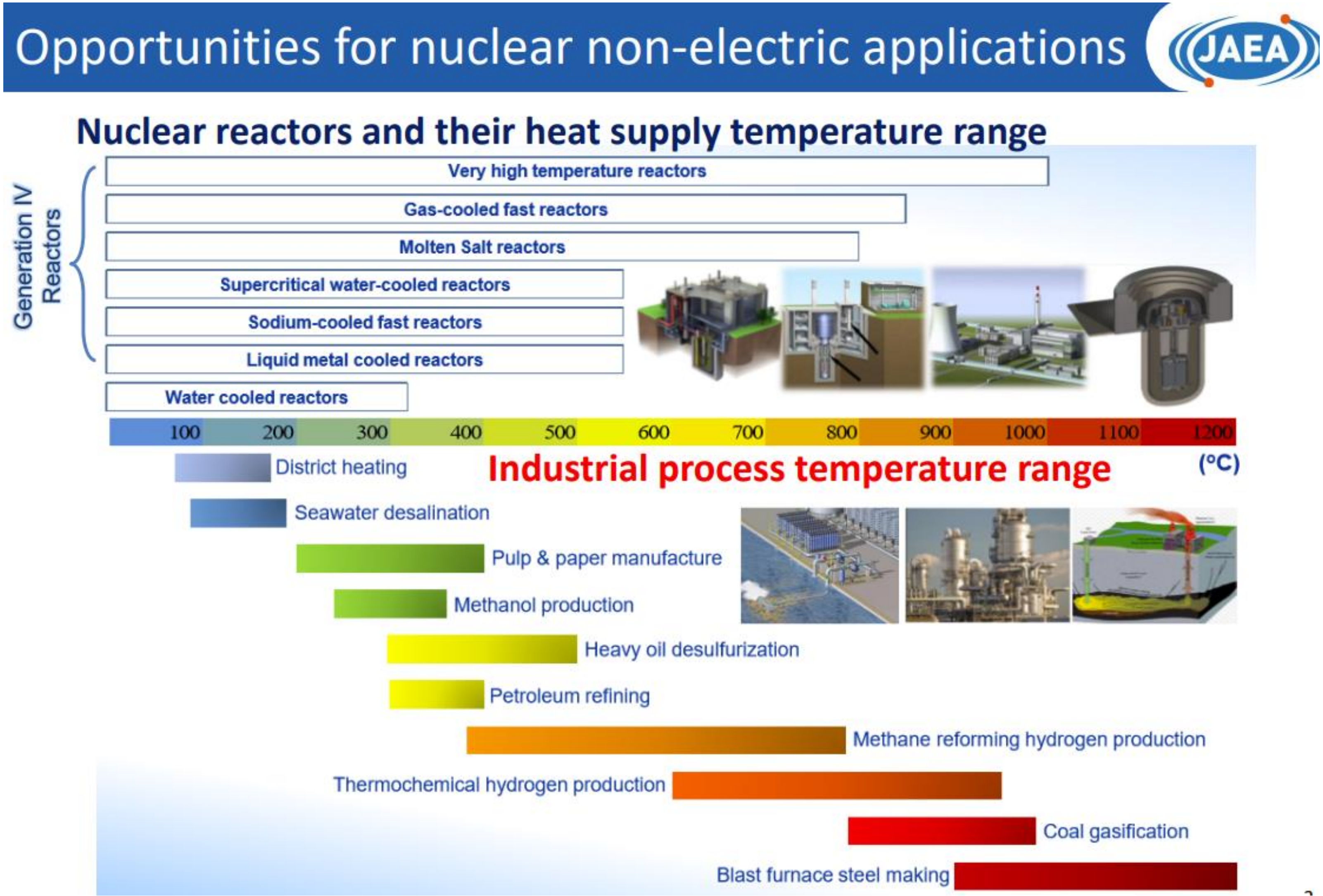
The emergence of small / micro modular reactors

Design	Output MW(e)	Type	Designers	Country	Status
PART 1: WATER COOLED SMALL MODULAR REACTORS (LAND BASED)					
CAREM	30	PWR	CNEA	Argentina	Under construction
ACP100	100	PWR	CNNC	China	Detailed Design
CANDU SMR	300	PHWR	Candu Energy Inc (SNC-Lavalin Group)	Canada	Conceptual Design
CAP200	200	PWR	SNERDI/SPIC	China	Conceptual Design
DHR400	400 MW(t)	LWR (pool type)	CNNC	China	Basic Design
HAPPY200	200 MW(t)	PWR	SPIC	China	Detailed Design
TEPLATOR™	50 MW(t)	HWR	UWB Pilsen & CIIRC CTU	Czech Republic	Conceptual Design
NUWARD	2 × 170	PWR	EDF, CEA, TA, Naval Group	France	Conceptual Design
IRIS	335	PWR	IRIS Consortium	Multiple Countries	Basic Design
DMS	300	BWR	Hitachi-GE Nuclear Energy	Japan	Basic Design
IMR	350	PWR	MHI	Japan	Conceptual Design
SMART	107	PWR	KAERI and K.A.CARE	Republic of Korea, and Saudi Arabia	Certified Design
RITM-200	2 × 53	PWR	JSC "Afrikantov OKBM"	Russian Federation	Under Development
UNITHERM	6.6	PWR	NIKIET	Russian Federation	Conceptual Design
VK-300	250	BWR	NIKIET	Russian Federation	Detailed Design
KARAT-45	45 - 50	BWR	NIKIET	Russian Federation	Conceptual Design
KARAT-100	100	BWR	NIKIET	Russian Federation	Conceptual Design
RUTA-70	70 MW(t)	PWR	NIKIET	Russian Federation	Conceptual Design
ELENA	68 kW(e)	PWR	National Research Centre "Kurchatov Institute"	Russian Federation	Conceptual Design
UK SMR	443	PWR	Rolls-Royce and Partners	United Kingdom	Conceptual Design
NuScale	12 × 60	PWR	NuScale Power Inc.	United States of America	Under Regulatory Review
BWRX-300	270 - 290	BWR	GE-Hitachi Nuclear Energy and Hitachi GE Nuclear Energy	United States of America, Japan	Pre-licensing
SMR-160	160	PWR	Holtec International	United States of America	Preliminary Design
W-SMR	225	PWR	Westinghouse Electric Company, LLC	United States of America	Conceptual Design
mPower	2 × 195	PWR	BWX Technologies, Inc	United States of America	Conceptual Design
PART 2: WATER COOLED SMALL MODULAR REACTORS (MARINE BASED)					
KLT-40S	2 × 35	PWR in Floating NPP	JSC Afrikantov OKBM	Russian Federation	In Operation
RITM-200M	2 × 50	PWR in FNPP	JSC Afrikantov OKBM	Russian Federation	Under Development
ACPR50S	50	PWR in FNPP	CGNPC	China	Conceptual Design
ABV-6E	6-9	PWR in FNPP	JSC Afrikantov OKBM	Russian Federation	Final design
VBER-300	325	PWR in FNPP	JSC Afrikantov OKBM	Russian Federation	Licensing Stage
PART 6: MICRO MODULAR REACTORS					
Energy Well	8	FHTR	Centrum výzkumu Řež	Czech Republic	Pre-Conceptual Design
MoveluX	3~4	Heat Pipe	Toshiba Corporation	Japan	Conceptual Design
U-Battery	4	HTGR	Urenco	United Kingdom	Conceptual Design
Aurora	1.5	FR	OKLO, Inc.	United States of America	Conceptual Design
Westinghouse eVinci	2 -3.5	Heat Pipe	Westinghouse Electric Company, LLC.	United States of America	Under Development
MMR	5-10	HTGR	Ultra Safe Nuclear Corporation	United States of America	Preliminary Design

Design	Output MW(e)	Type	Designers	Country	Status
SHELF	6.6	PWR in Immersed NPP	NIKIET	Russian Federation	Detailed Design
PART 3: HIGH TEMPERATURE GAS COOLED SMALL MODULAR REACTORS					
HTR-PM	210	HTGR	INET, Tsinghua University	China	Under Construction
StarCore	14/20/60	HTGR	StarCore Nuclear	Canada/UK/US	Pre-Conceptual Design
GTHTR300	100 - 300	HTGR	JAEA	Japan	Pre-licensing
GT-MHR	288	HTGR	JSC Afrikantov OKBM	Russian Federation	Preliminary Design
MHR-T	4 × 205.5	HTGR	JSC Afrikantov OKBM	Russian Federation	Conceptual Design
MHR-100	25 – 87	HTGR	JSC Afrikantov OKBM	Russian Federation	Conceptual Design
PBMR-400	165	HTGR	PBMR SOC Ltd	South Africa	Preliminary Design
A-HTR-100	50	HTGR	Eskom Holdings SOC Ltd.	South Africa	Conceptual Design
HTMR-100	35	HTGR	Steenkampskraal Thorium Limited	South Africa	Conceptual Design
Xe-100	82.5	HTGR	X-Energy LLC	United States of America	Basic Design
SC-HTGR	272	HTGR	Framatome, Inc.	United States of America	Conceptual Design
HTR-10	2.5	HTGR	INET, Tsinghua University	China	Operational
HTTR-30	30 (t)	HTGR	JAEA	Japan	Operational
RDE	3	HTGR	BATAN	Indonesia	Conceptual Design
PART 4: FAST NEUTRON SPECTRUM SMALL MODULAR REACTORS					
BREST-OD-300	300	LMFR	NIKIET	Russian Federation	Detailed Design
ARC-100	100	Liquid Sodium	ARC Nuclear Canada, Inc.	Canada	Conceptual Design
4S	10	LMFR	Toshiba Corporation	Japan	Detailed Design
microURANUS	20	LBR	UNIST	Korea, Republic of	Pre-Conceptual Design
LFR-AS-200	200	LMFR	Hydromine Nuclear Energy	Luxembourg	Preliminary Design
LFR-TL-X	5~20	LMFR	Hydromine Nuclear Energy	Luxembourg	Conceptual Design
SVBR	100	LMFR	JSC AKME Engineering	Russian Federation	Detailed Design
SEALER	3	LMFR	LeadCold	Sweden	Conceptual Design
EM²	265	GMFR	General Atomics	United States of America	Conceptual Design
Westinghouse LFR	450	LMFR	Westinghouse Electric Company, LLC.	United States of America	Conceptual Design
SUPERSTAR	120	LMFR	Argonne National Laboratory	United States of America	Conceptual Design
PART 5: MOLTEN SALT SMALL MODULAR REACTORS					
Integral MSR	195	MSR	Terrestrial Energy Inc.	Canada	Conceptual Design
smTMSR-400	168	MSR	SINAP, CAS	China	Pre-Conceptual Design
CA Waste Burner 0.2.5	20 MW(t)	MSR	Copenhagen Atomics	Denmark	Conceptual Design
ThorCon	250	MSR	ThorCon International	International Consortium	Basic Design
FUJI	200	MSR	International Thorium Molten-Salt Forum: ITMSF	Japan	Experimental Phase
Stable Salt Reactor - Wasteburner	300	MSR	Moltex Energy	United Kingdom / Canada	Conceptual Design
LFTR	250	MSR	Flibe Energy, Inc.	United States of America	Conceptual Design
KP-FHR	140	Pebble-bed salt cooled Reactor	KAIROS Power, LLC.	United States of America	Conceptual Design
Mk1 PB-FHR	100	FHR	University of California at Berkeley	United States of America	Pre-Conceptual Design
MCSFR	50 - 1200	MSR	Elysium Industries	USA and Canada	Conceptual Design

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

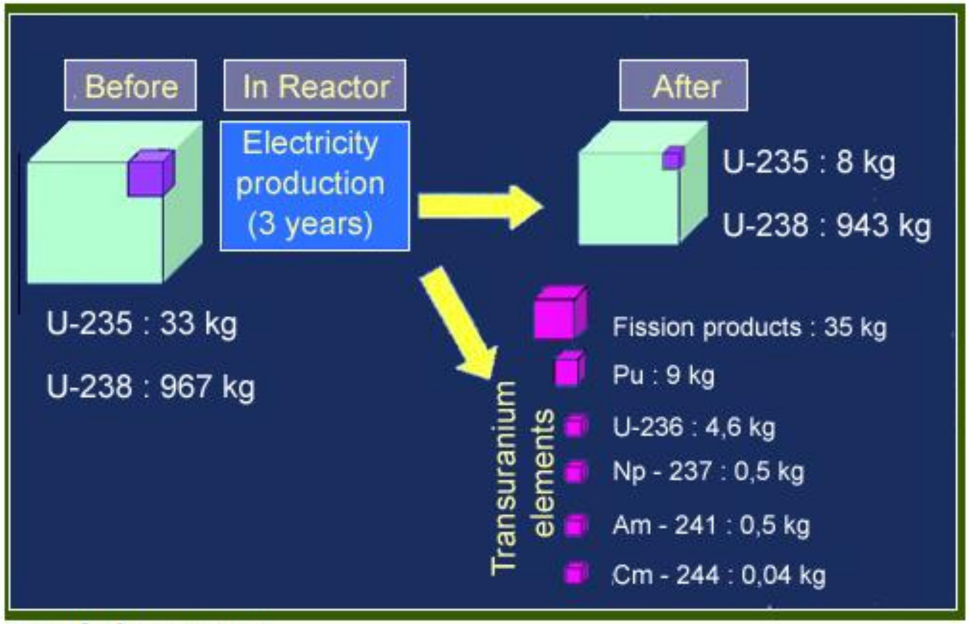
Non electric applications of reactors



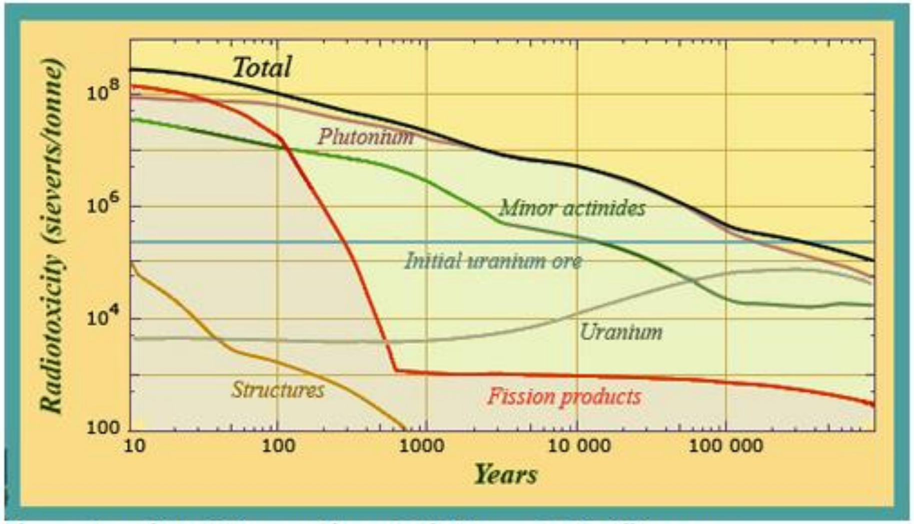
From Xin L. Yang, JAEA, https://nucleus.iaea.org/sites/INPRO/df16/Day-1/Keynote_YAN.pdf

Nuclear waste management and environmental impact

Spent fuel composition and radiotoxicity



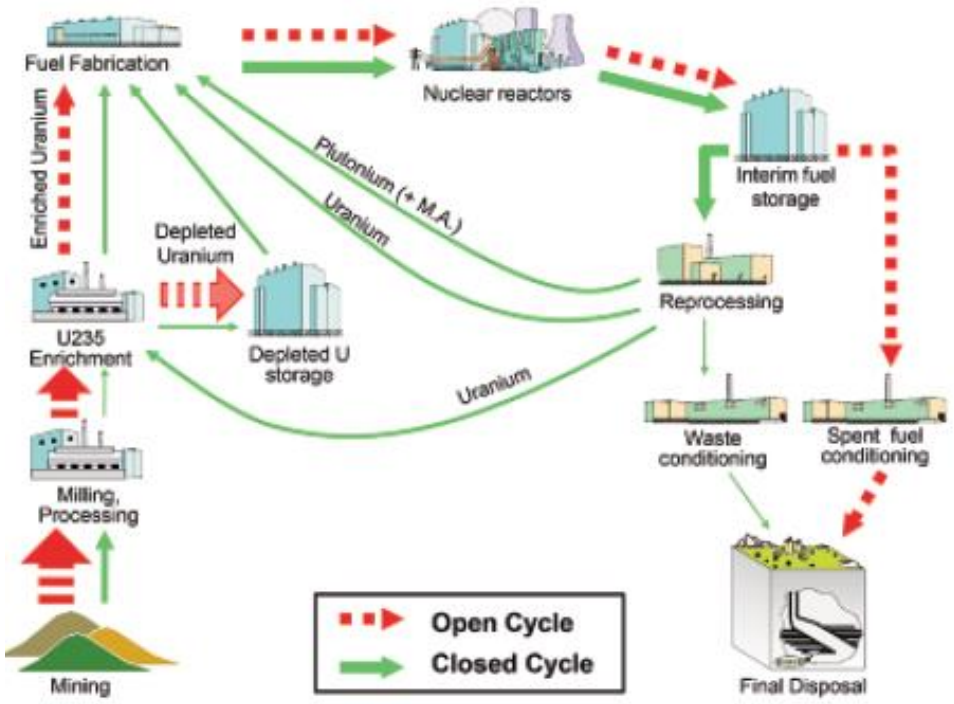
Spent fuel composition
Distribution (in kg per tonne of fuel) and mass produced by the principal radioactive elements present in fuel unloaded from an irradiated pressurised water reactor core.
©IPHC/IN2P3 (Source: Isabelle Billard)



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

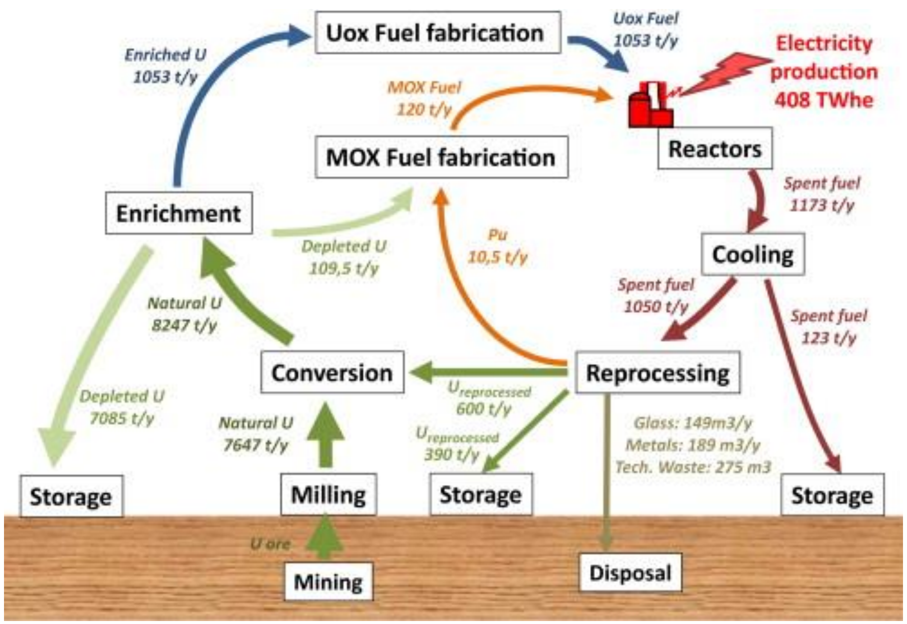
Nuclear fuel cycle

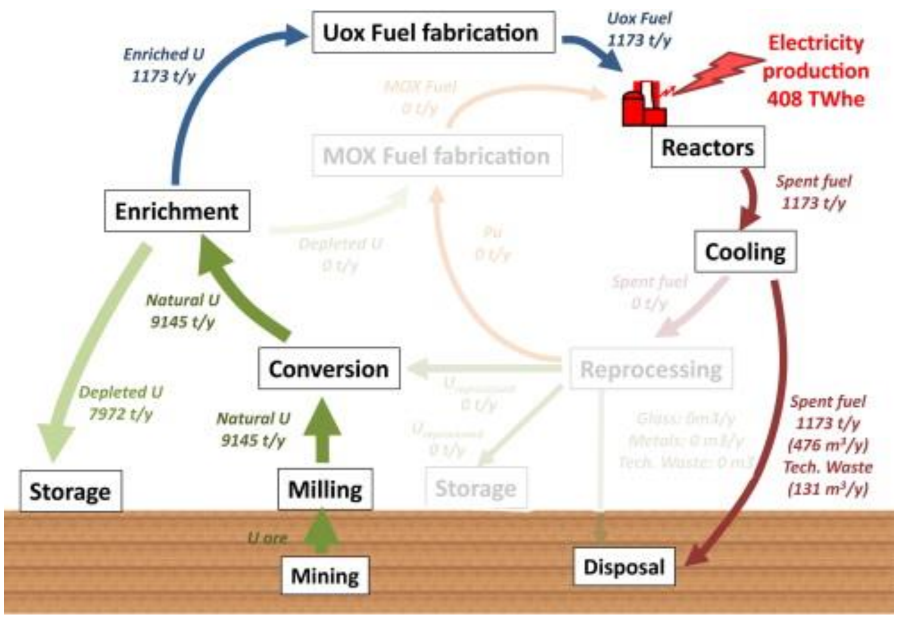
- **Two options:**
  - Open cycle: direct disposal of spent fuel (US, Sweden, Finland…)
  - Partially closed cycle: reprocessing to extract Pu and make MOX fuels (France, Japan, Russia, China…)

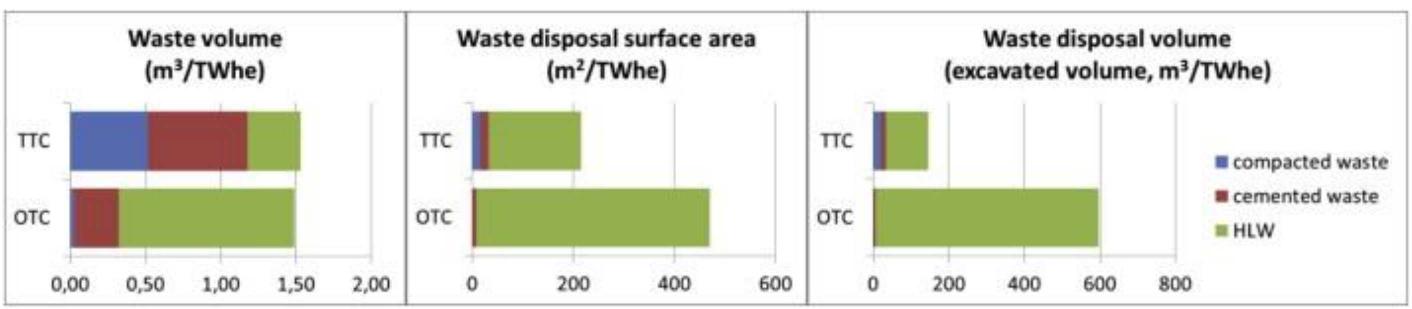


- Reprocessing reduces the amount, volume and radiotoxicity of the high-level waste to be stored, but generates additional volumes of intermediate wastes during the reprocessing and fuel fabrication processes
- **In any case a final deep geologic disposal of remaining long-lived high level wastes will be necessary**

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





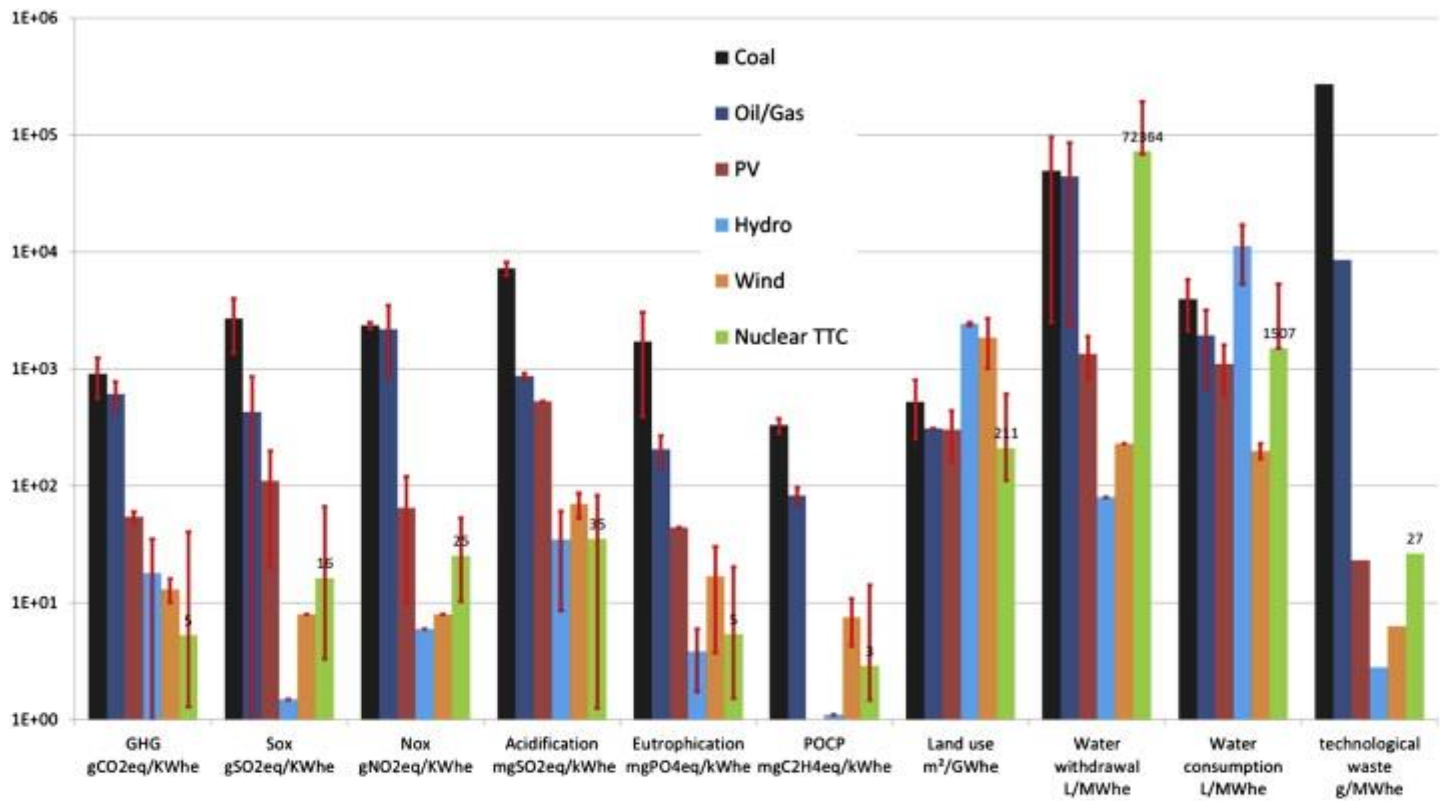


Ch. Poinssot et al. Energy 69 (2014): French case

- 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)

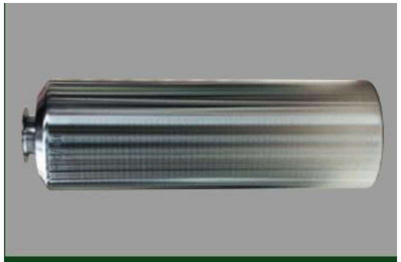
- green-house-gases emissions (GHG, $gCO_2eq/kWhe$),
- atmospheric pollution (mg/kWhe)
  - SOx
  - NOx
- water pollution (mg/kWhe),
  - Acidification
  - Eutrophisation
  - POCP (photochemical ozone creation potential)
- land-use ($m^2/GWhe$)
- water consumption (l/MWhe)
- water withdrawal (l/MWhe)
-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



Nuclear Waste types

High-level waste (HLW) :

- Used fuel or separated waste from reprocessing of used fuel.
- Decay heat (>2kW/m^3) leading to temperature increase
- **3% of the volume, but 95% of the total radioactivity of produced waste**
- Have long-lived and short-lived components



Colis de déchets HA

Intermediate-level waste (ILW) :

- comprises resins, chemical sludges, and metal fuel cladding, as well as contaminated materials from reactor decommissioning
- Highly radioactive but decay heat < 2kW/m^3
- **7% of the volume, 4% of total radioactivity**

Hulls from the zirconium alloy cladding that covers fuel pellets

Low-level waste (LLW) :

- radioactive content not exceeding 4 GBq/t of alpha activity or 12 GBq/t beta-gamma activity
- comprises paper, rags, tools, clothing, filters, etc., which contain small amounts of mostly short-lived radioactivity
- **90% of the volume, 1% of total radioactivity**

Déchets issus de l'utilisation de produits radioactifs dans un laboratoire

Very low-level waste (VLLW) :

- radioactive materials at a level not considered harmful to people or the surrounding environment
- demolished material (concrete, plaster, bricks, metal, valves, piping, etc.) produced during rehabilitation or dismantling operations

VLLW

Photos from ANDRA Synthesis report 2021

▶ Management solutions for each type of waste

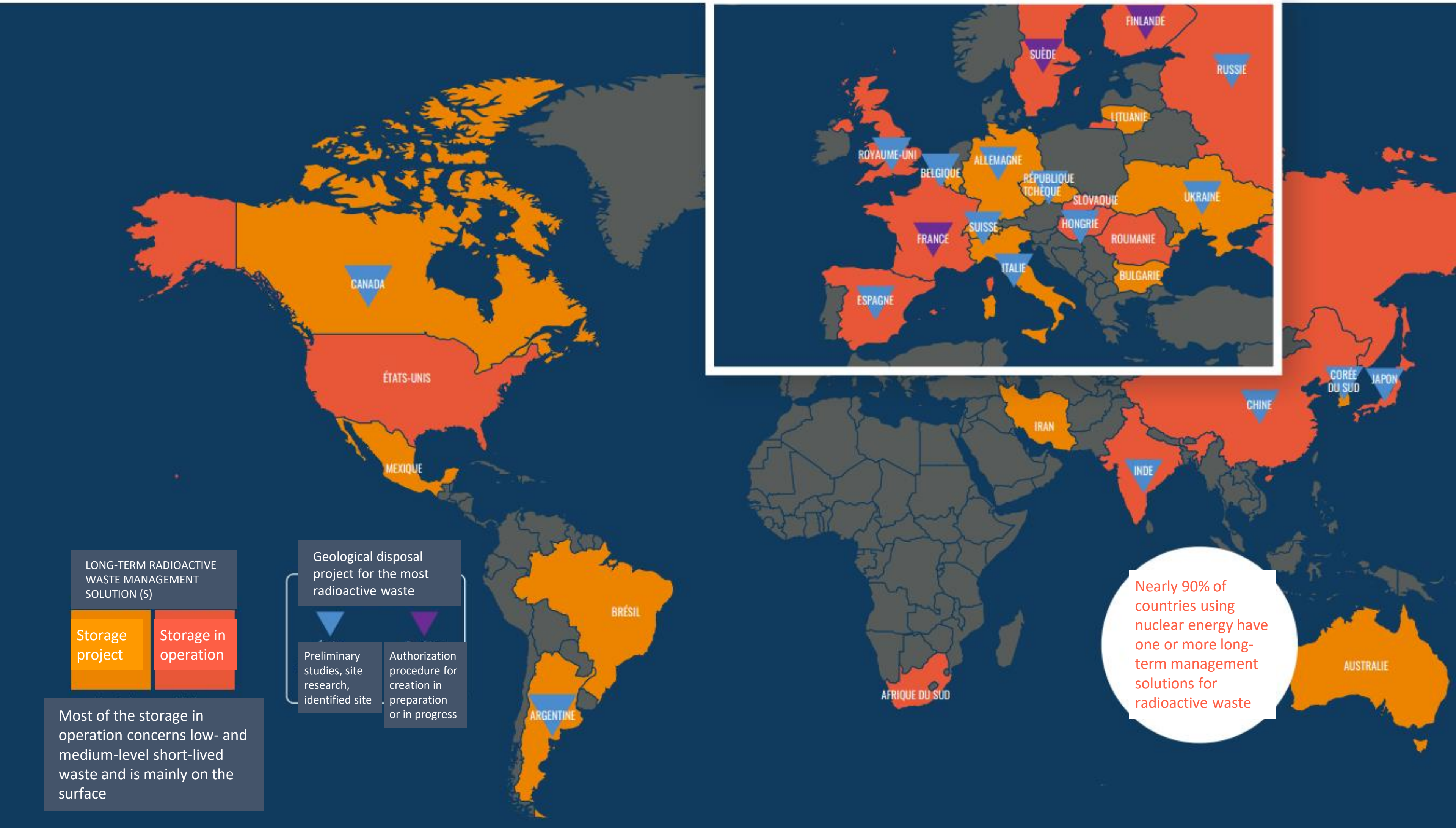
CATEGORIES OF RADIOACTIVE WASTE AND ASSOCIATED MANAGEMENT SOLUTIONS

Radioactive half-life* / Activity level**	Very short-lived (VSL) (Half-life < 100 days)	Mainly short-lived (SL) (Half-life ≤ 31 years)	Mainly long-lived (LL) (Half-life > 31 years)
Very low-level (VLLW) < 100 Bq/g	VSLW Management through radioactive decay	VLLW Surface disposal (Industrial facility for grouping, storage and disposal)	
Low-level waste (LLW-LL) several hundred Bq/g to one million Bq/g		LILW-SL Surface disposal (Aube and Manche disposal facilities)	LLW-LL Near-surface disposal under development
Intermediate-level waste (ILW) around 1 million to 1 billion Bq/g			ILW-LL Deep geological disposal under development (Cigeo project)
High-level waste (HLW) around several billion Bq/g	Not applicable		HLW

*Half-life of the radioactive elements (radionuclides) contained in the waste
**Activity level of the radioactive waste

From ANDRA Synthesis report 2021

Nuclear Waste management

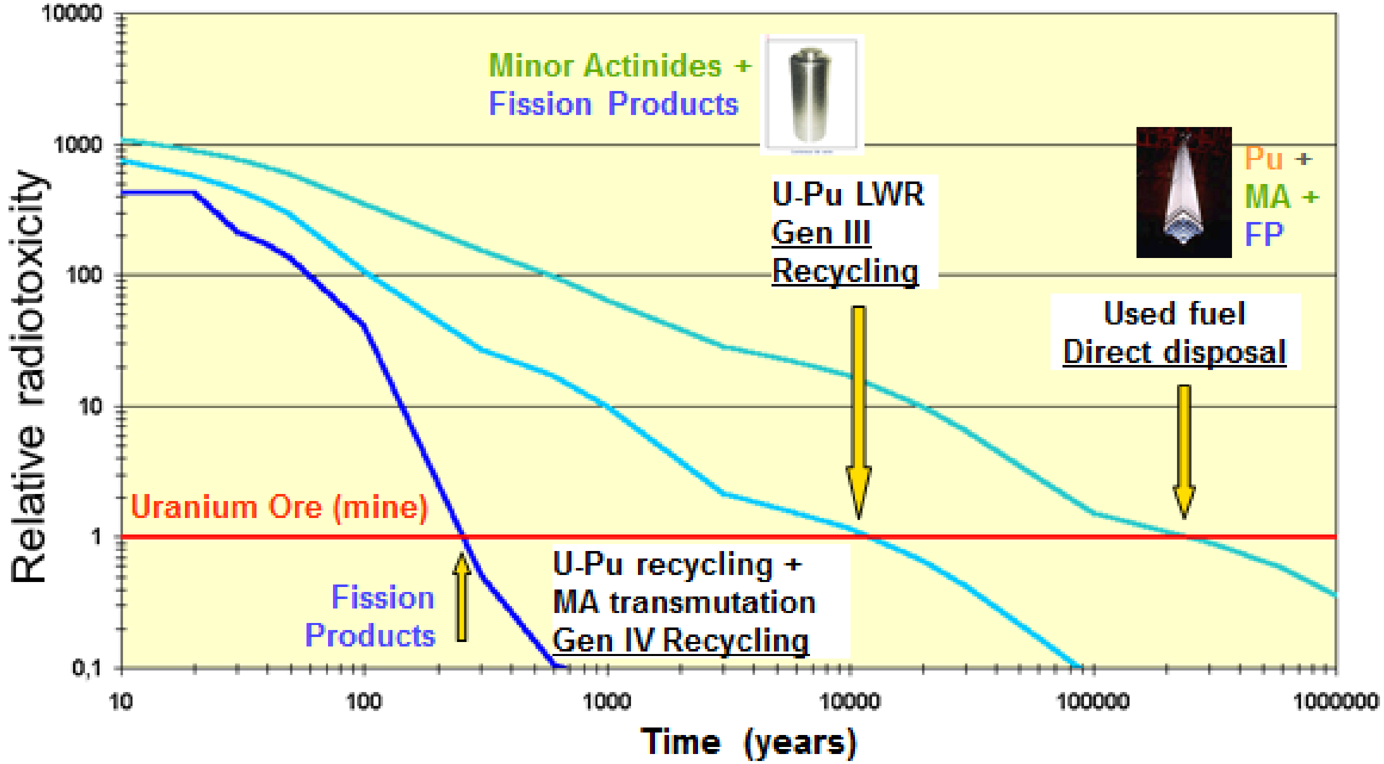


From ANDRA: https://www.andra.fr/panorama-mondial-ou-en-sont-les-autres-pays

Transmutation of Nuclear Waste

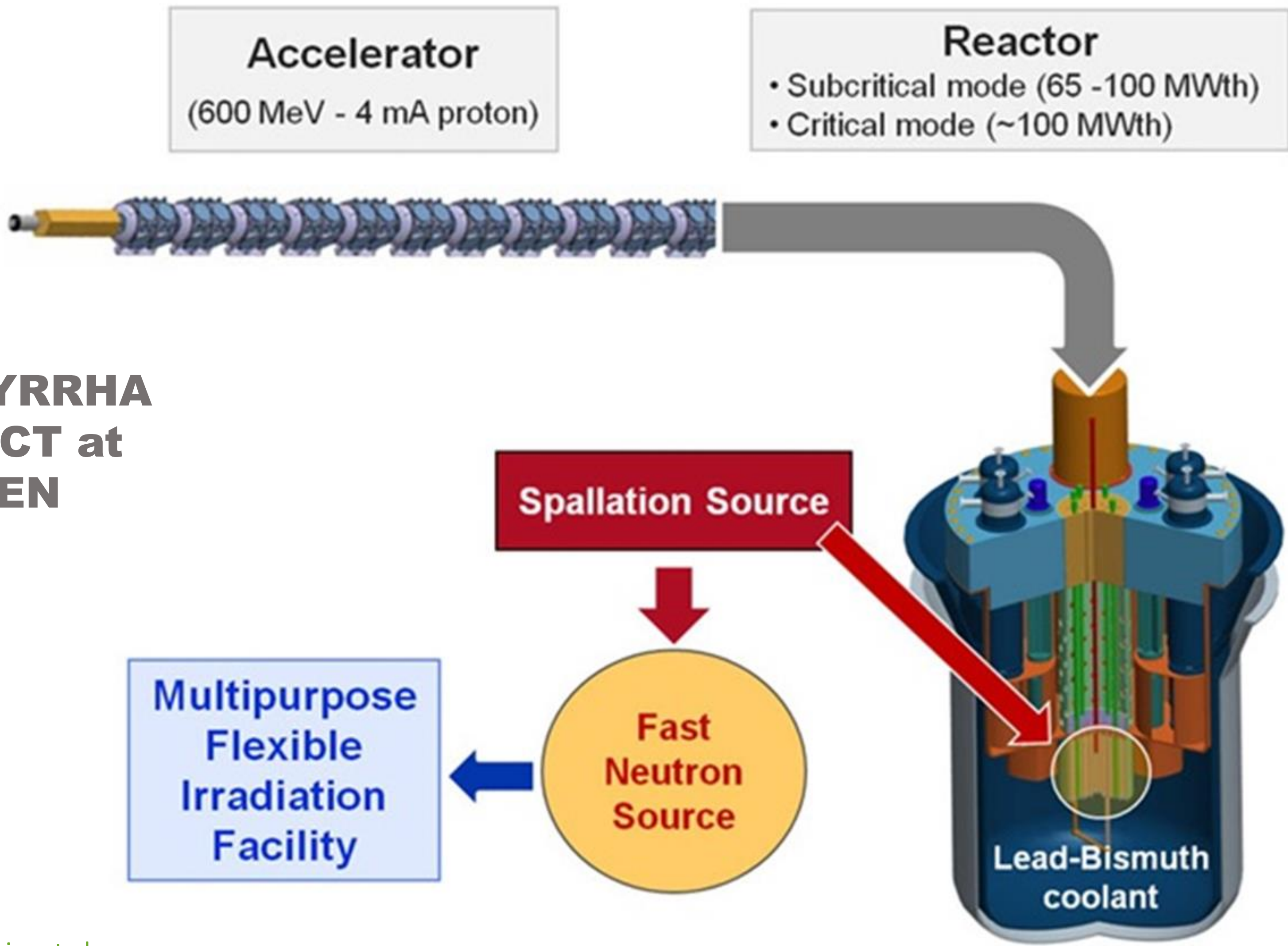
- Two options:
  - Small amount of minor actinides in many (fast) reactors
  - Large amount of minor actinides in dedicated systems

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



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

ADS as a possible contributor to waste minimization



The MYRRHA PROJECT at SCK•CEN

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

Conclusion

- Nuclear energy must be part of the tools to fight climate change
- Most of the new nuclear power reactors are built in emerging countries
- Small Modular Reactors to play an increasing role
- Global non-radioactive environmental impact lower than for other sources of energy
- Nearly 90% of countries using nuclear energy have one or more long-term management solutions for radioactive waste

Thank you for your attention