FUSION
FOR
ENERGY

BRINGING
THE POWER
OF THE SUN
TO EARTH

PROSPECTS FOR A NEW NUCLEAR ERA

Alfredo Portone

Fusion For Energy, Barcelona

alfredo.portone@f4e.europa.eu

Special thanks:

Sylvie Leray, CEA (F)

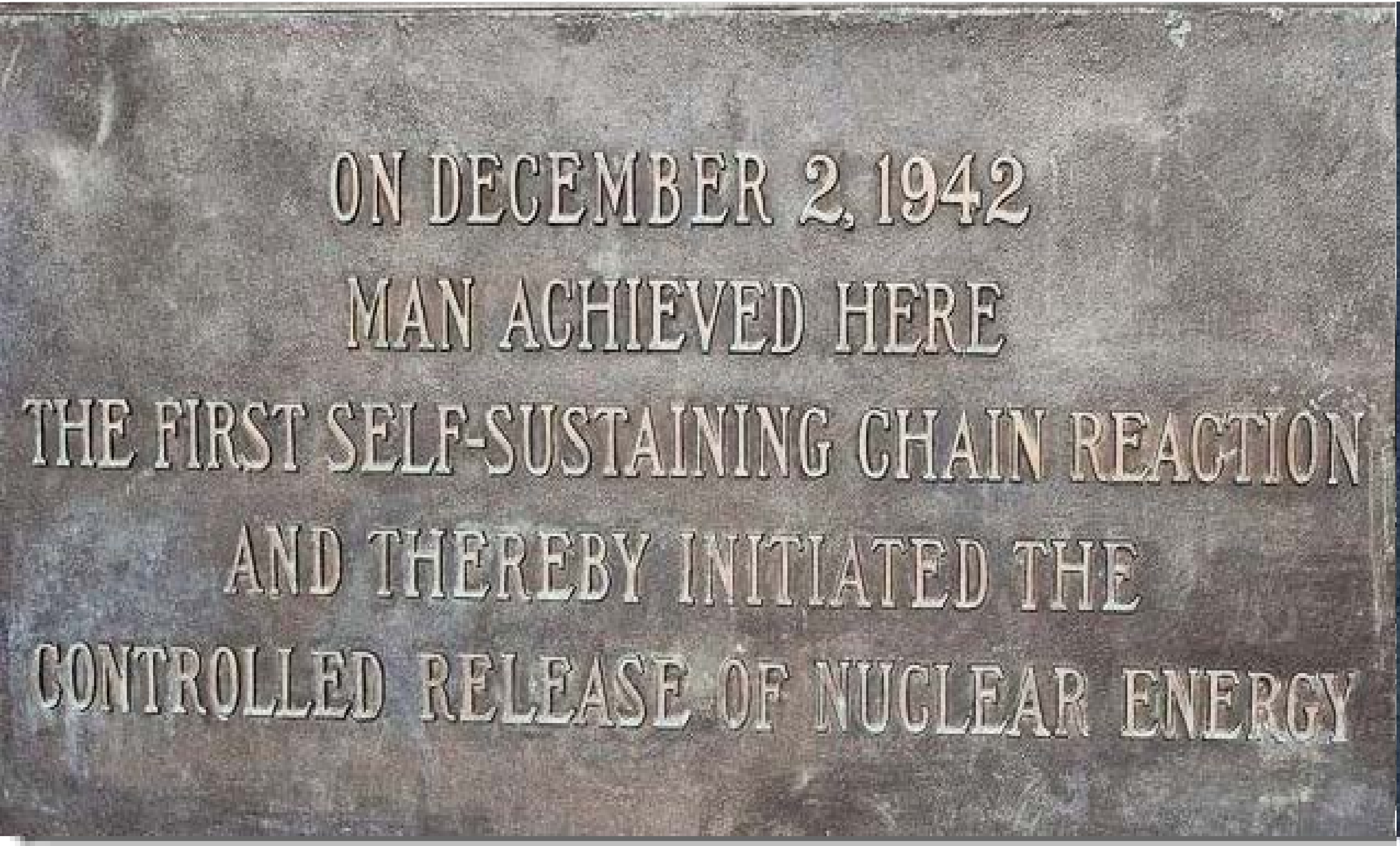
Raul Pampin, F4E (E)

Marco Ripani, INFN (I)

CHICAGO, DECEMBER 2ND 1942, 3:25 PM

“The Italian navigator has just landed in the new world”

(Call by Arthur Compton to James Conant in Washington)



ON DECEMBER 2, 1942
MAN ACHIEVED HERE
THE FIRST SELF-SUSTAINING CHAIN REACTION
AND THEREBY INITIATED THE
CONTROLLED RELEASE OF NUCLEAR ENERGY

ALAMOGORDO, JULY 16TH 1945, 5:29 AM

"Now I am become death, the destroyer of worlds"

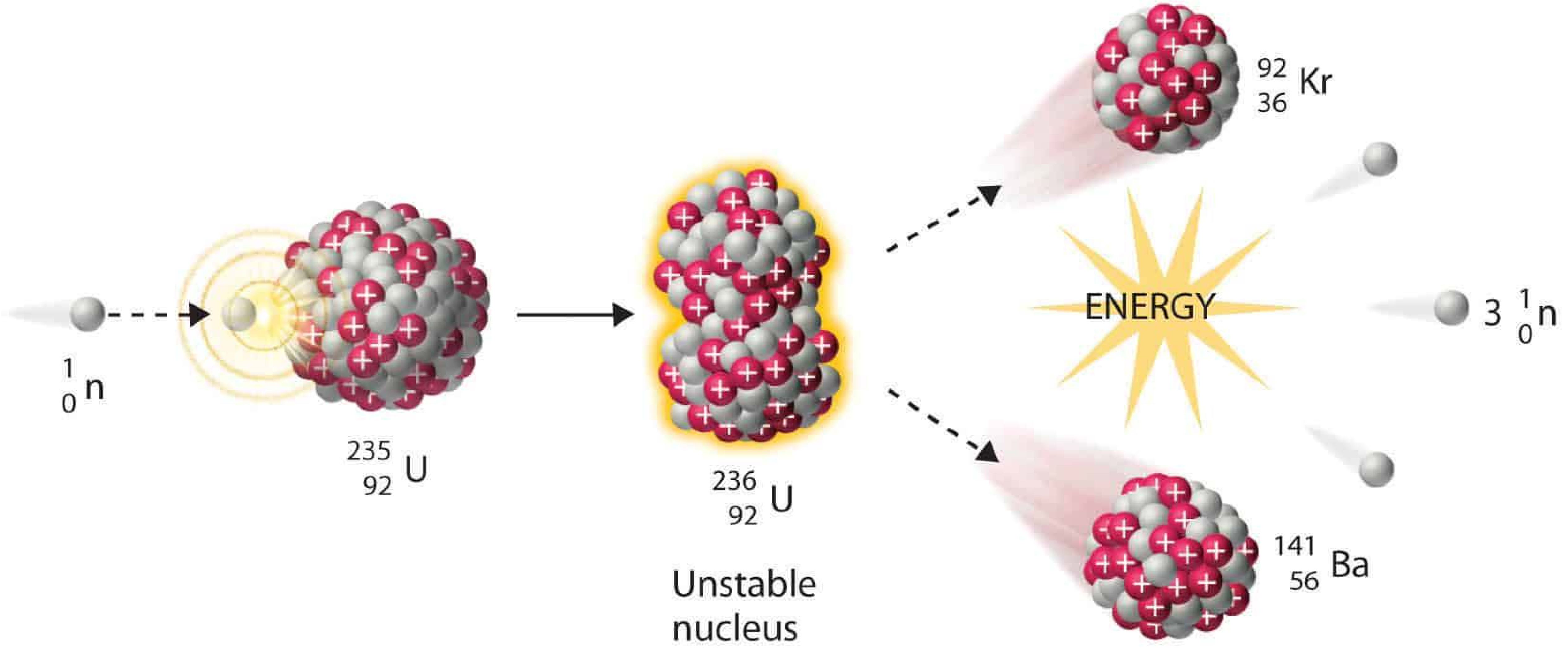
(Robert Oppenheimer after witnessing the Trinity test quoting Bhagavadgita)

OUTLINE

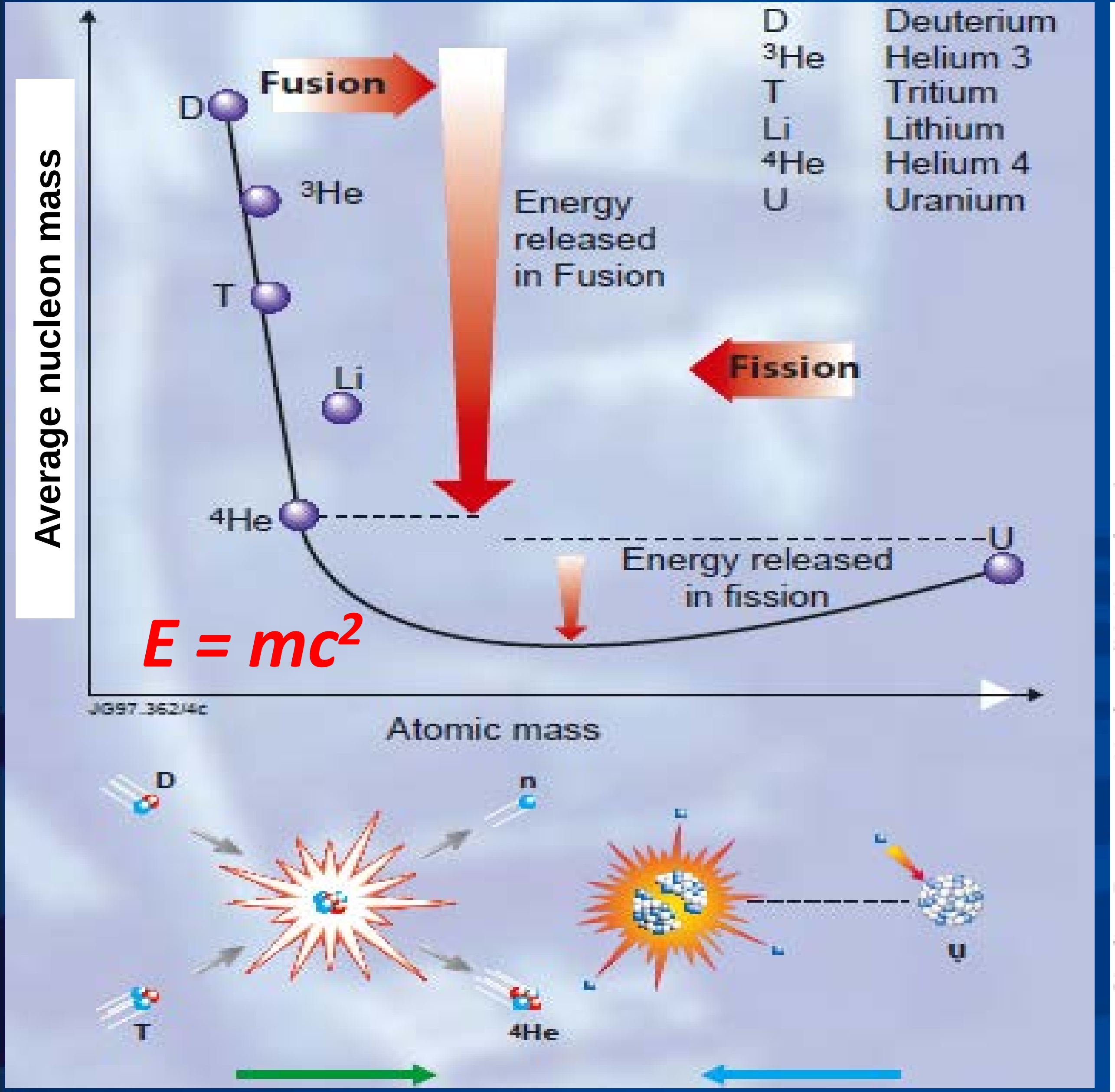
1. Nuclear reactors basics
2. Fuel cycle and radioactive waste
3. Reactors generations and types
4. Nuclear energy production in the world
5. Economics
6. Safety
7. Conclusions

NUCLEAR FISSION

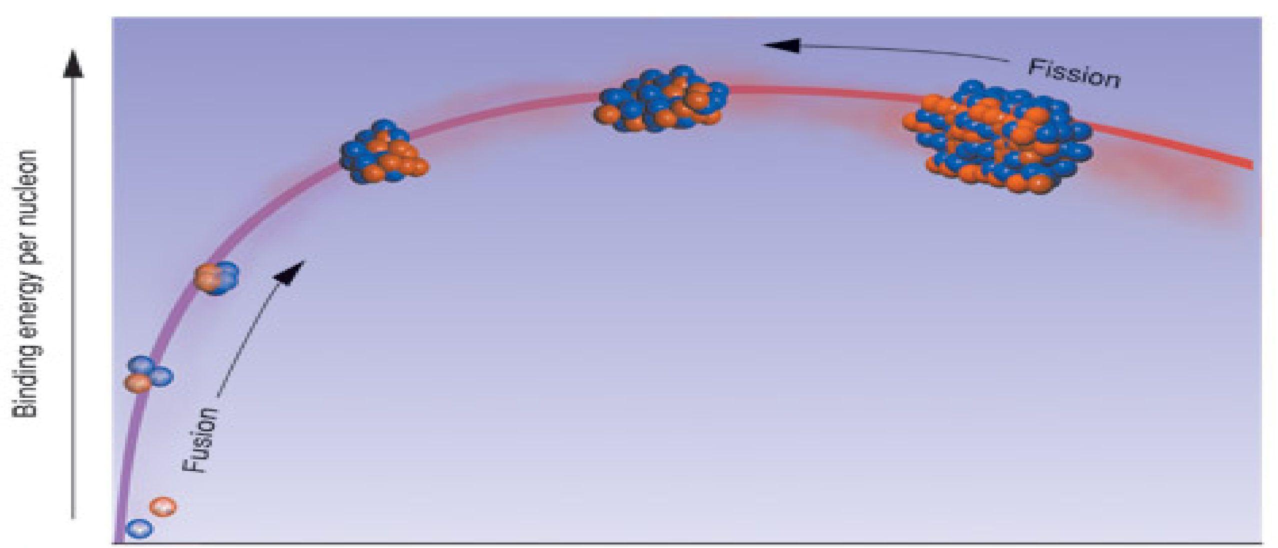
(HAHN-STRASSMANN, MEITNER-FRISCH, DECEMBER 1938)

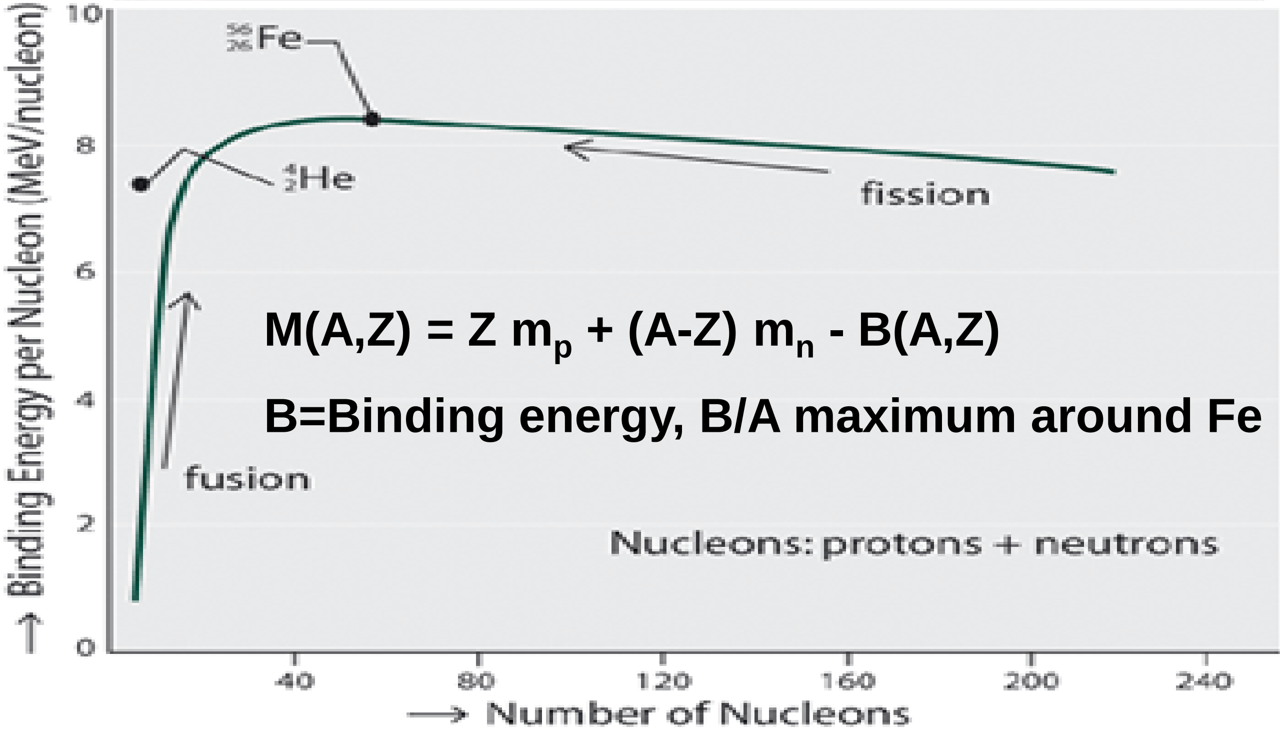


NUCLEAR BINDING ENERGY



$E = mc^2$

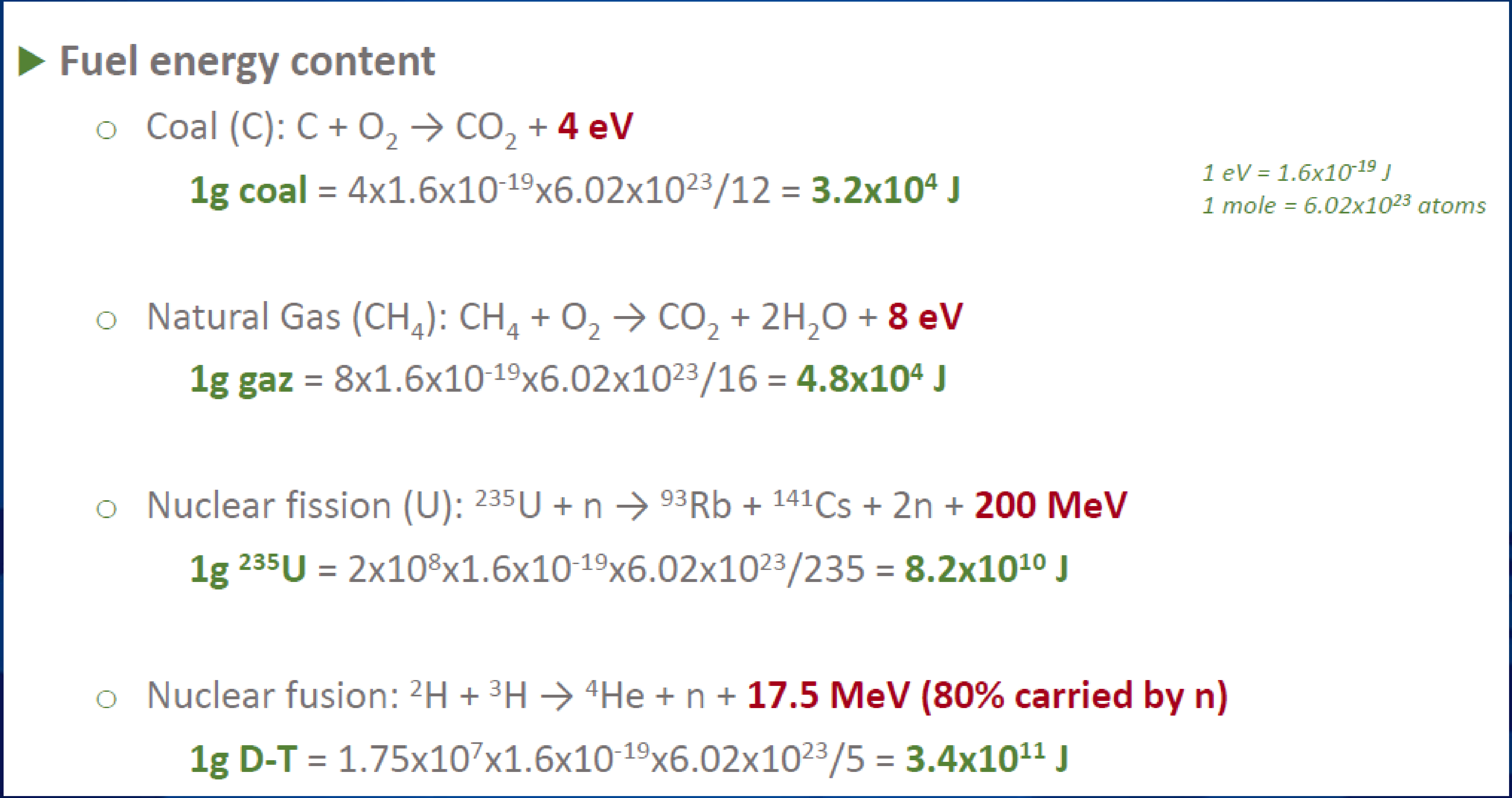




$M(A,Z) = Z\,m_p + (A-Z)\,m_n - B(A,Z)$

B=Binding energy, B/A maximum around Fe

CHEMICAL VS NUCLEAR ENERGY DENSITY



- **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**

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

1 eV = 1.6×10^{-19} J

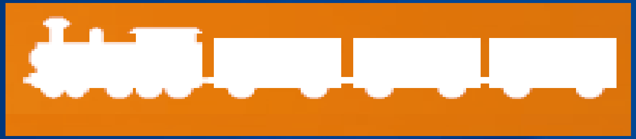
1 mole = 6.02×10^{23} atoms

CHEMICAL VS NUCLEAR ENERGY DENSITY

Primary energy consumption of Italy for 1 day

1 x

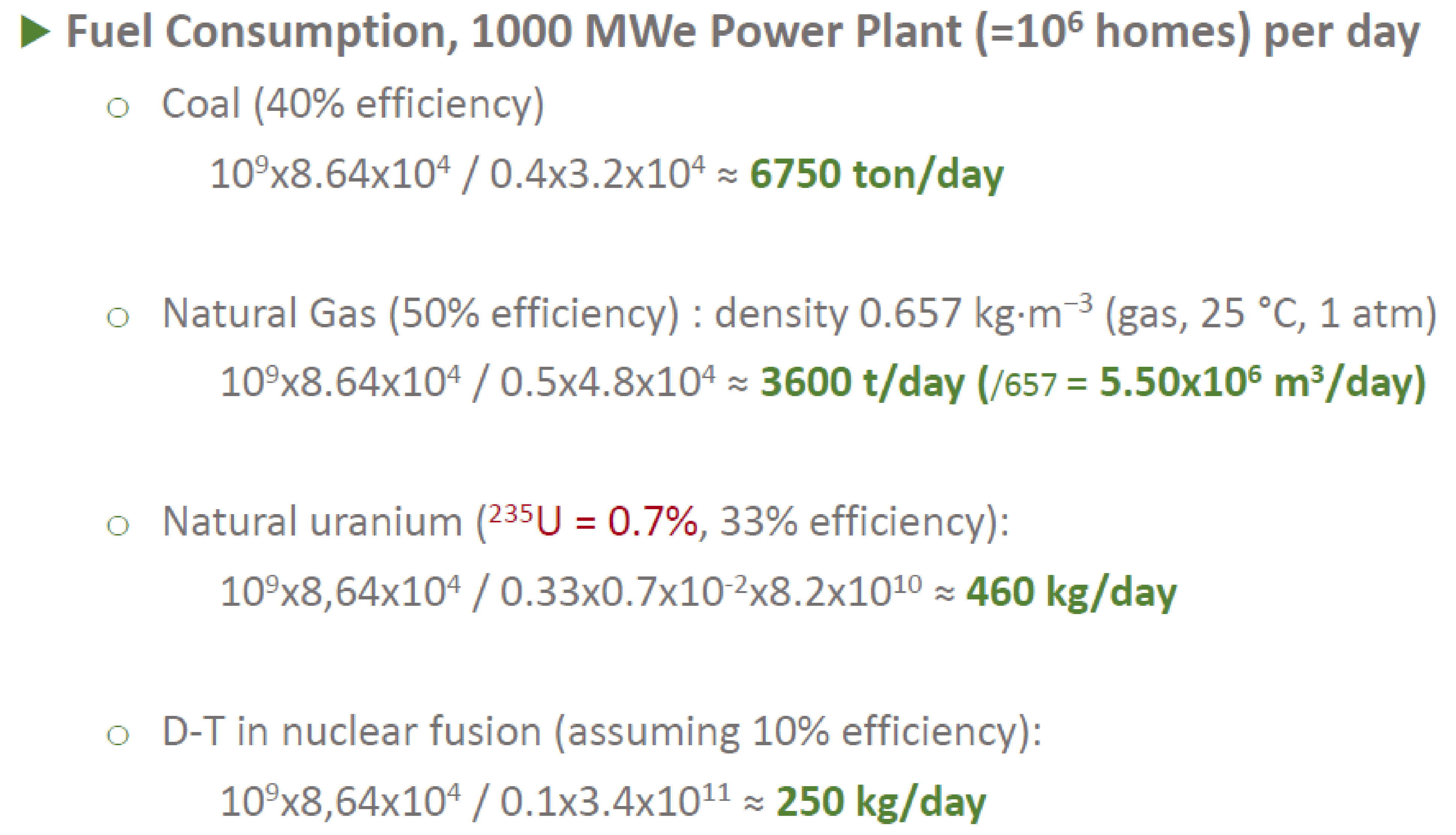
= 400,000 tons of oil

40 x

= 560,000 tons of coal
(40 trains, 120-car each, 120 ton/car net weight)

12 x

= 220 kg U235 (=12 litres)

FUEL CONSUMPTION & ELECTRICAL POWER GENERATION



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

    $10^9 x 8.64 x 10^4$ / $0.4 x 3.2 x 10^4$ ≈ **6750 ton/day**

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

    $10^9 x 8.64 x 10^4$ / $0.5 x 4.8 x 10^4$ ≈ **3600 t/day (/657 = $5.50 x 10^6$ m^3/day)**

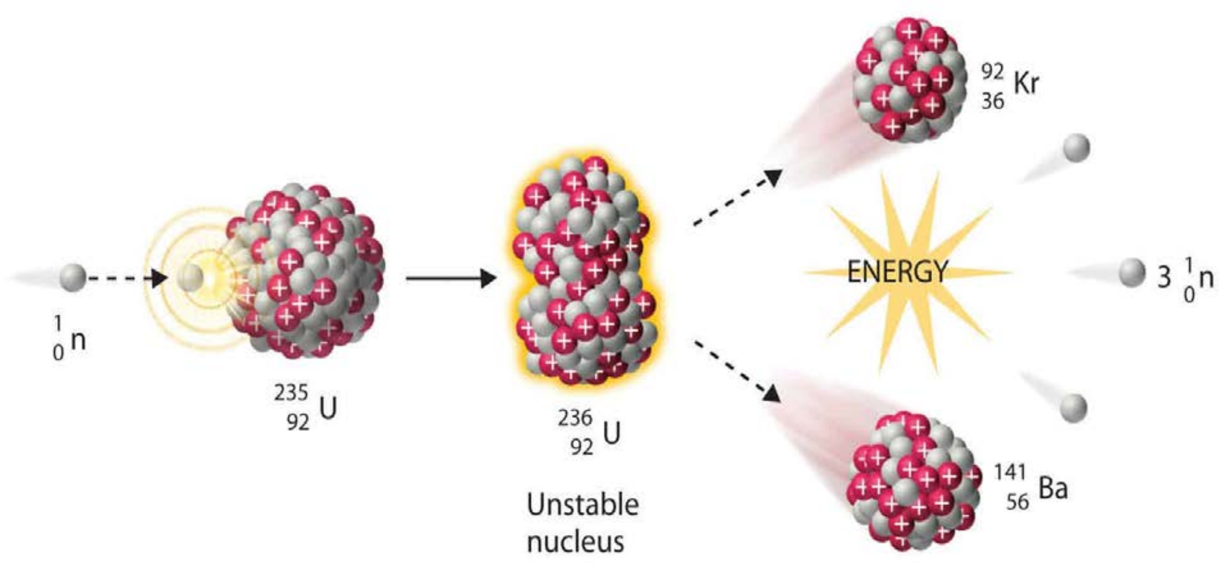
  - Natural uranium (^{235}U = 0.7%, 33% efficiency):

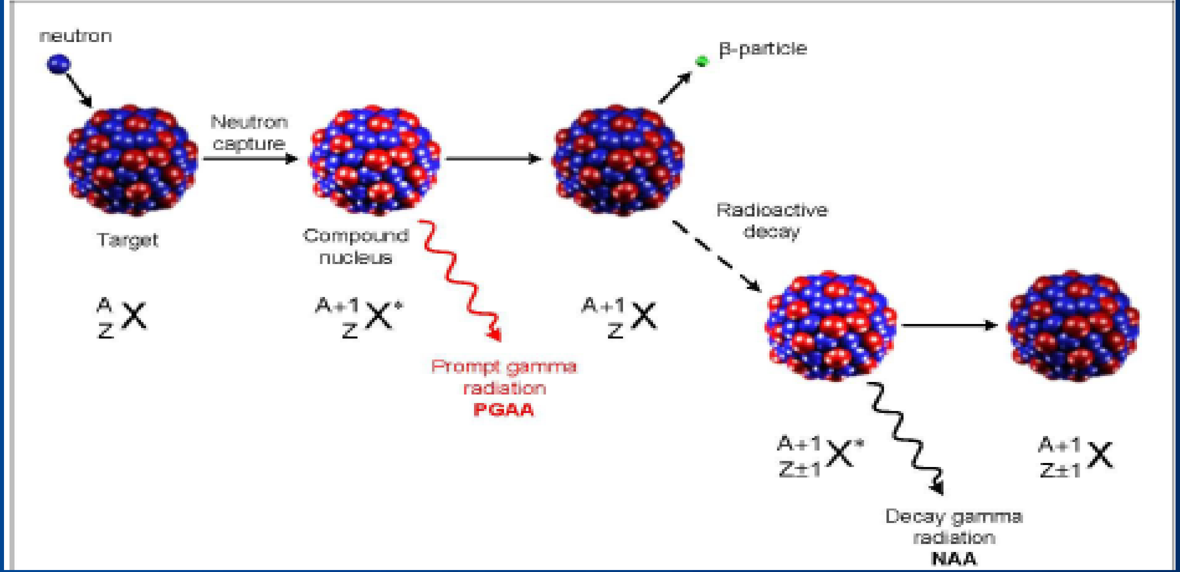
    $10^9 x 8,64 x 10^4$ / $0.33 x 0.7 x 10^{-2} x 8.2 x 10^{10}$ ≈ **460 kg/day**

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

    $10^9 x 8,64 x 10^4$ / $0.1 x 3.4 x 10^{11}$ ≈ **250 kg/day**

NUCLEAR FISSION VS TRANSMUTATION





- For other materials (e.g. steel), RNC can lead to the formation of radioactive nuclei → this process is called activation
- γ radiation can also occur due to neutron scattering
- Activation can also occur due e.g. due to (n, 2n) reactions

Example: Plutonium production from Uranium

$n + {}^{238}U \rightarrow {}^{239}U + \gamma \rightarrow {}^{239}Np + \beta + \text{anti-}\nu \rightarrow {}^{239}\mathbf{Pu} + \beta + \text{anti-}\nu$

Example: ^{60}Co production in steel

$n + {}^{59}Co \rightarrow {}^{60}\mathbf{Co} + \gamma \rightarrow {}^{60}Ni + \beta + \text{anti-}\nu$

Fissile, fissionable, fertile isotopes

- Heavy nuclei with a high fission cross section at low (thermal) neutron energies are called **fissile** (e.g. ^{233}U, ^{235}U, ^{239}Pu,…)

- Those with a non-zero fission cross section only at higher neutron energies are called **fissionable** (e.g. ^{238}U,…)

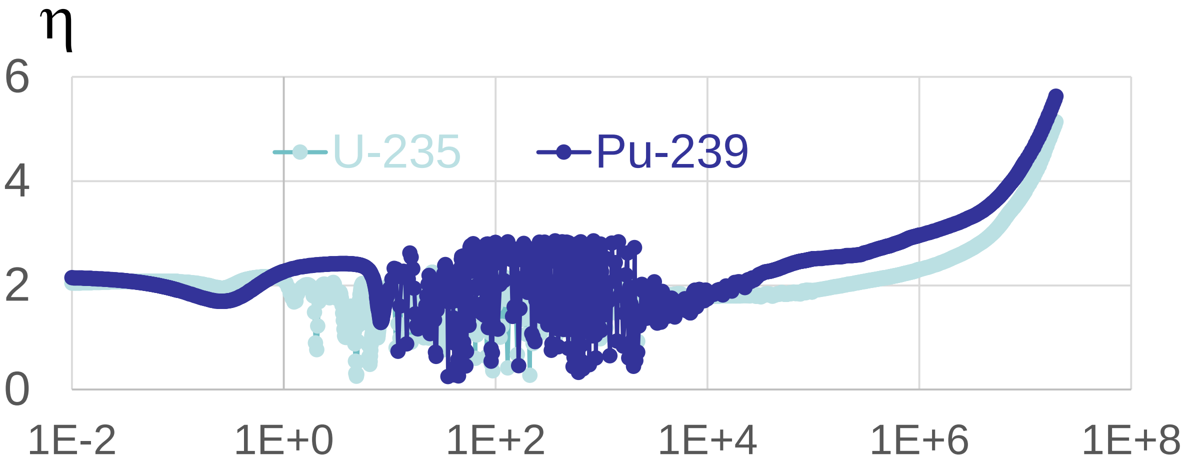
- Those that can produce a fissile isotope via neutron radiative capture and β decay are called **fertile**, i.e. they can be used to **produce fuel** (e.g. ^{238}U,…)

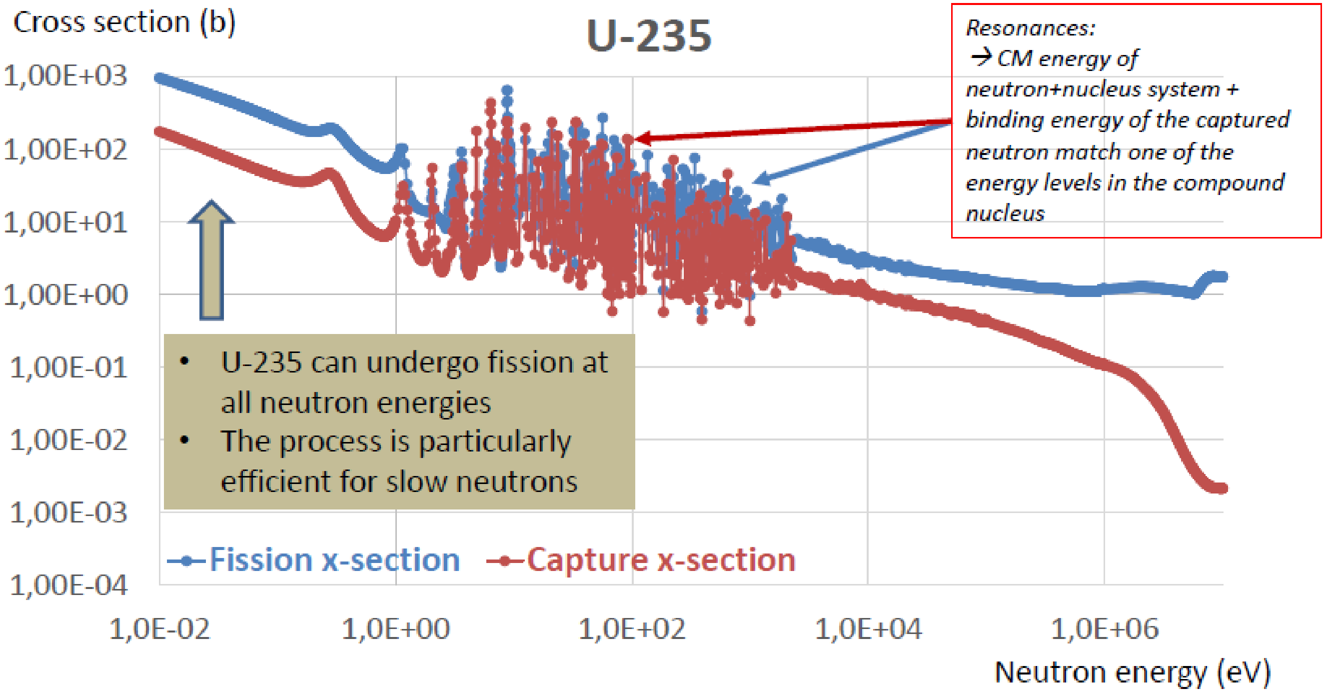
- n+^{238}U → ^{239}U + γ → ^{239}Np + β + anti-ν → $\boxed{^{239}\text{Pu}}$ + β + anti-ν

- n+^{232}Th → ^{233}Th + γ → ^{233}Pa + β + anti-ν → $\boxed{^{233}\text{U}}$ + β + anti-ν

fissile

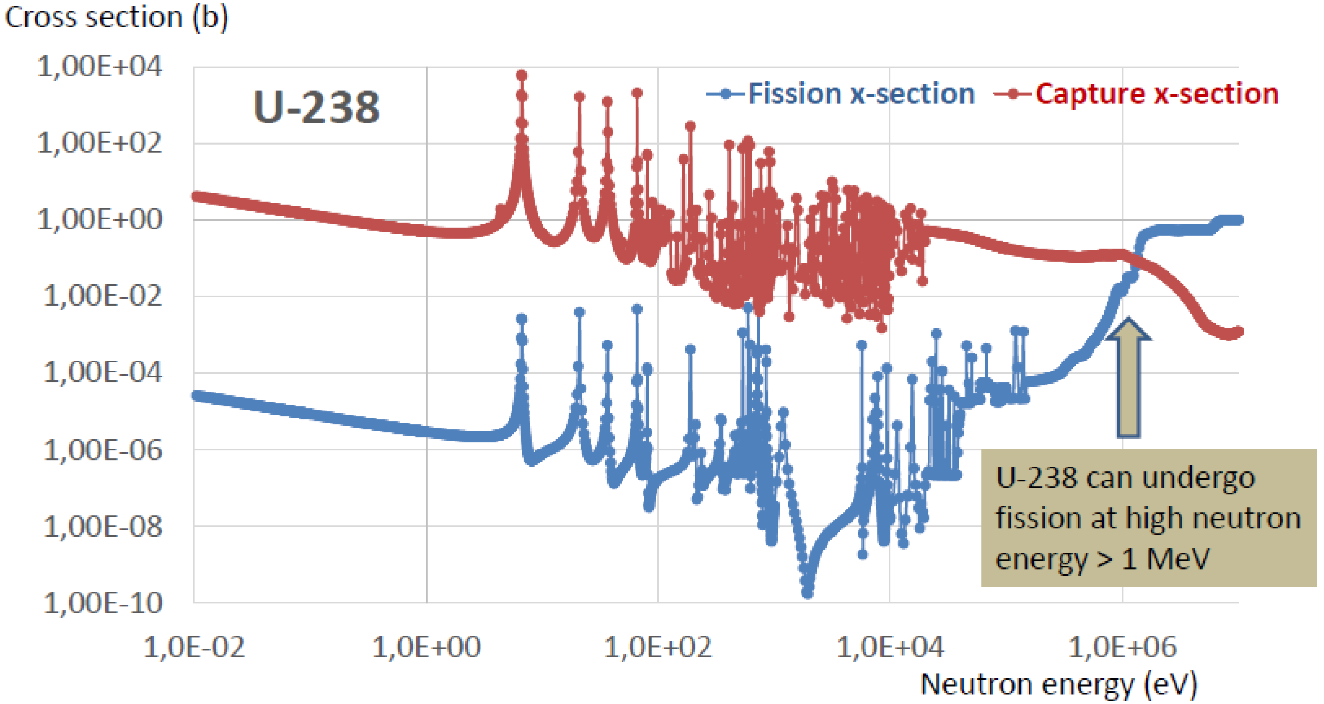
- ✓ Natural Uranium → 0.7 % ^{235}U + 99.3 % ^{238}U → **most reactors need 3-5 % ^{235}U → “enrichment” process**
- ✓ Plutonium production is also called “breeding”
- ✓ Under certain conditions, a reactor can produce more Pu than it consumes → it is called “breeder”





Resonances:
→ CM energy of neutron+nucleus system + binding energy of the captured neutron match one of the energy levels in the compound nucleus

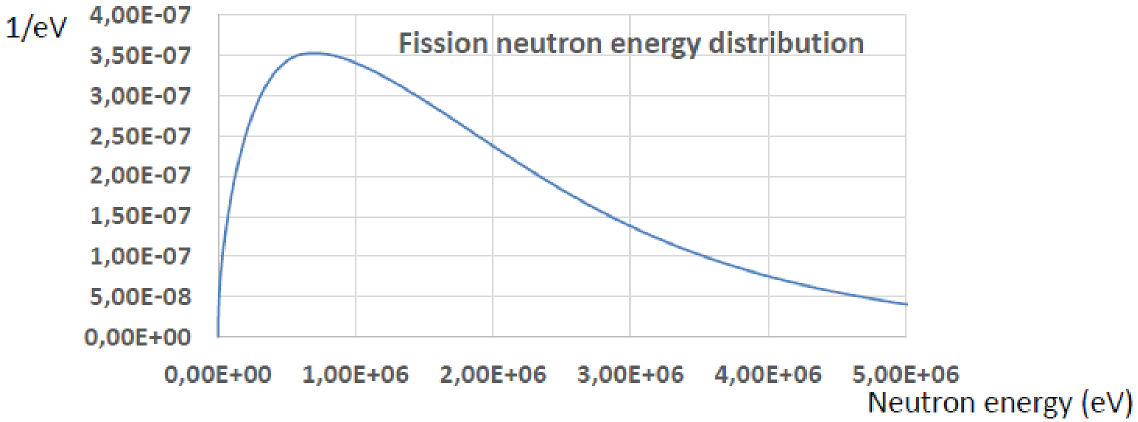
- U-235 can undergo fission at all neutron energies
- The process is particularly efficient for slow neutrons



U-238 can undergo fission at high neutron energy > 1 MeV

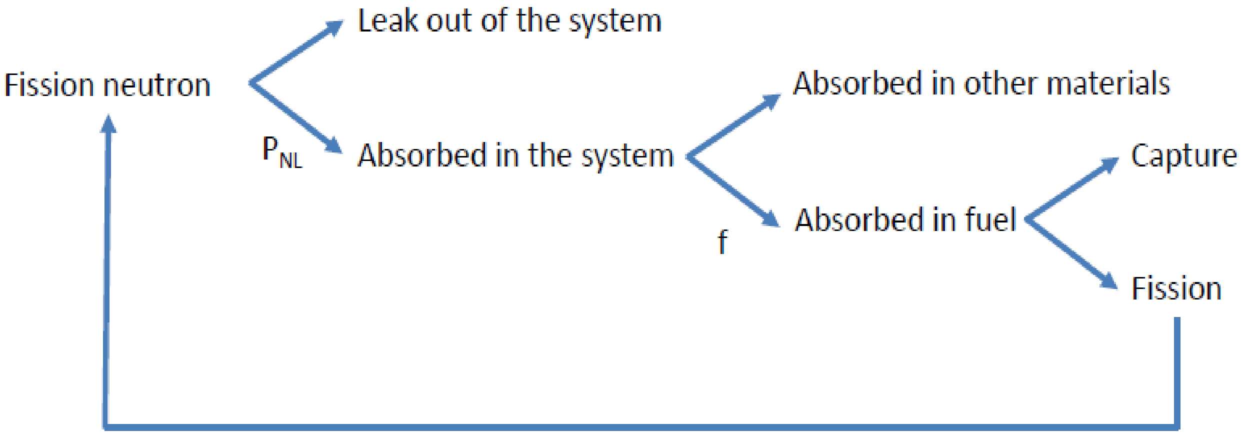
NEUTRON 'THERMALIZATION'

Fission spectrum, fast and slow neutrons



It is customary to adopt the following classification:

- **slow neutrons**: those with kinetic energy $T_n < 1$ eV
- in particular **thermal neutrons** have T_n around 0.025 eV or 25 meV (the value of kT, where k is the Boltzmann constant and T is the temperature
- **epithermal neutrons**: 1 eV < T_n < 100 keV (0.1 MeV)
- **fast neutrons**: 0.1 MeV < T_n < 20 MeV



Slowing down neutrons (moderation)

It is easy to show in non-relativistic kinematics that **after a scattering off a nucleus with mass number A**, the kinetic energy of the neutron changes according to the ratio

$$\frac{T'_n}{T_n} = \frac{m_n^2 + m_A^2 + 2m_n m_A cos\theta_{CM}}{(m_n + m_A)^2}$$

Assuming an isotropic CM cross section that does not depend on $\cos\theta_{CM}$, the corresponding term averages out to zero, so that we can write on average

$$\frac{T'_n}{T_n} = \frac{m_n^2 + m_A^2}{(m_n + m_A)^2}$$

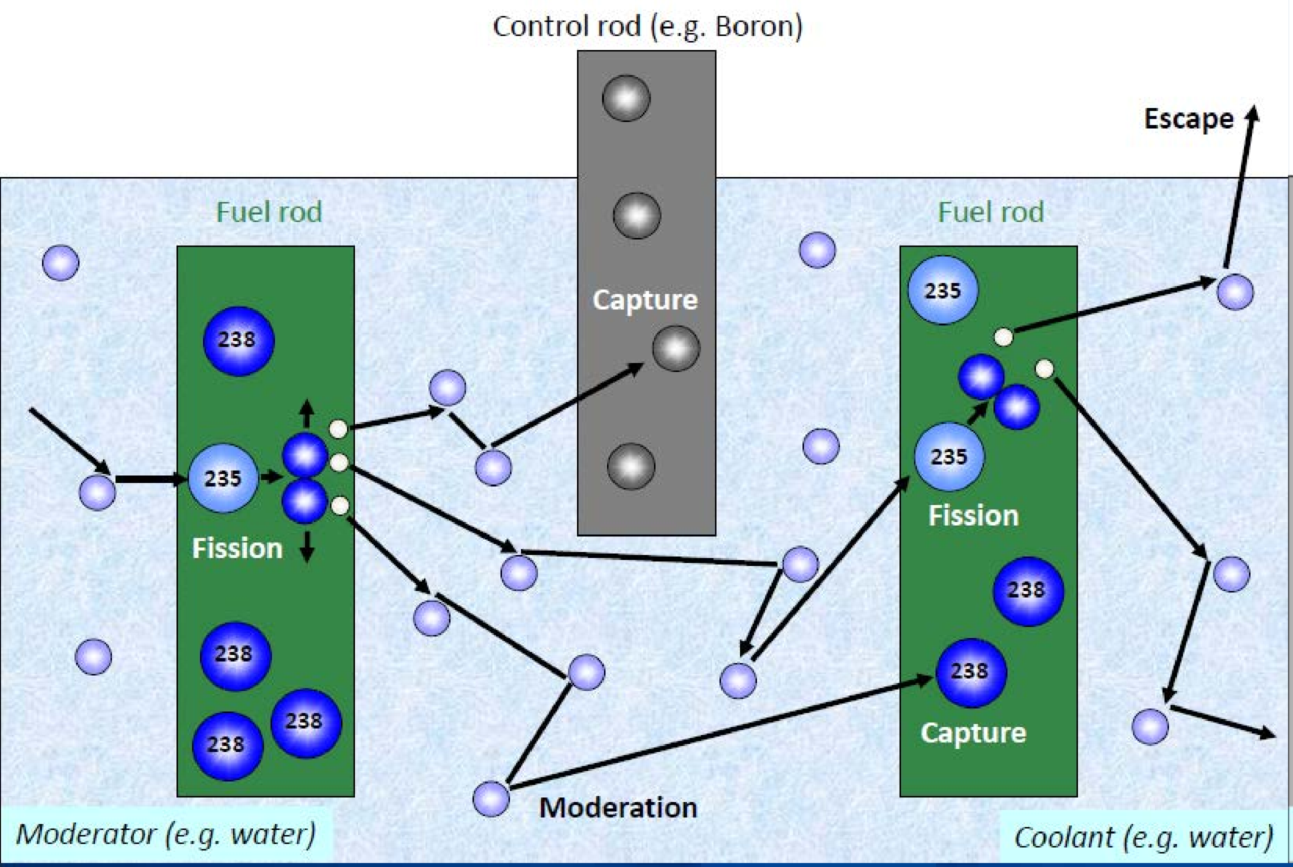
➔ Assuming $M_A \cong Am_n$ ➔

$$\frac{T'_n}{T_n} = \frac{1 + A^2}{(1 + A)^2}$$

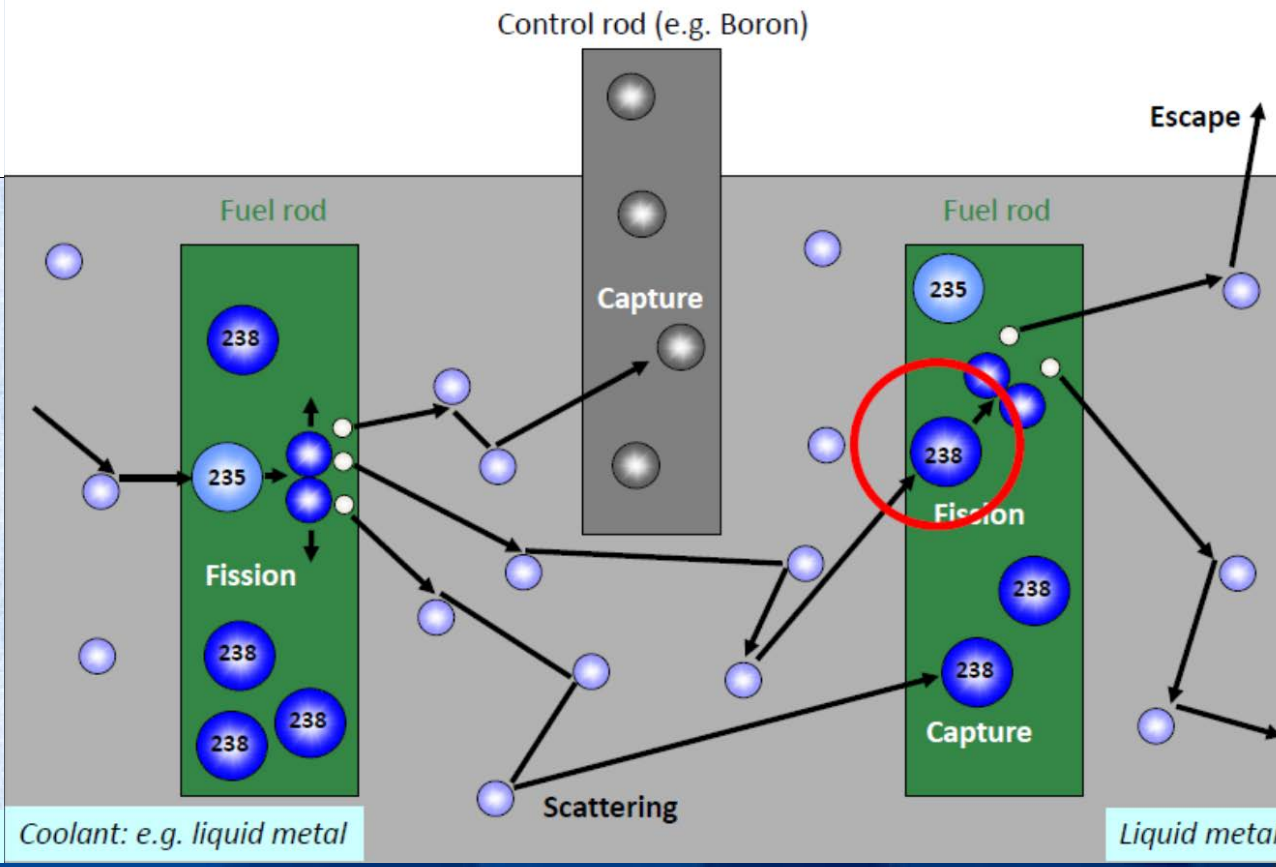
For a **heavy nucleus A>>1** → $T_n' \cong T_n$ or in other words, the neutron has to undergo many collisions in order to significantly lose energy.
Consider instead the case **A=1** → (target containing hydrogen, i.e. protons as nuclei) $T_n' = T_n/2$ i.e. on average a neutron will lose half of its energy at each collision and therefore few collisions are sufficient to rapidly decrease its energy

➔ **Moderators = light materials containing hydrogen = water, paraffin or graphite**

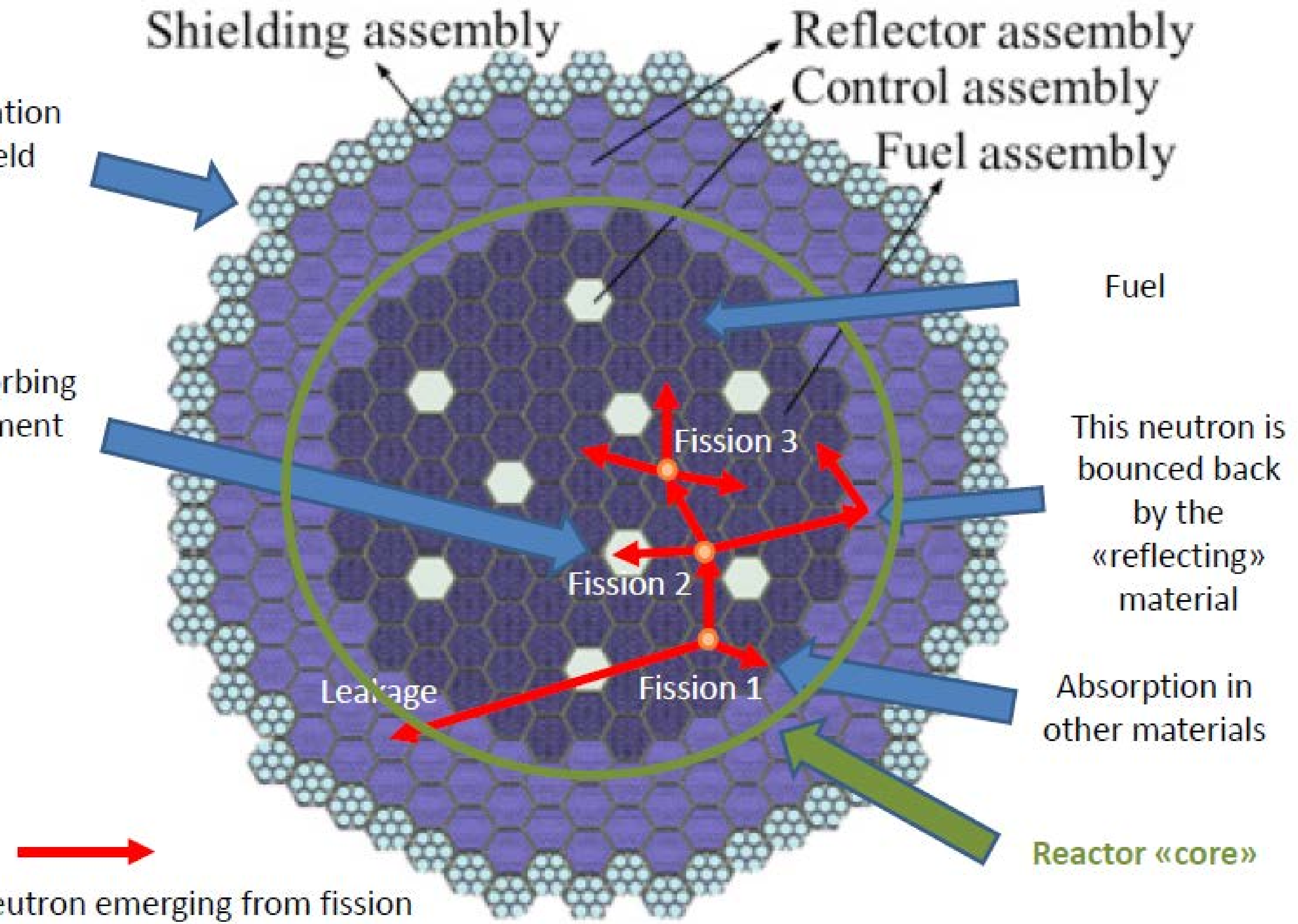
THERMAL REACTOR



FAST REACTOR



Physics of multiplication: visual representation



Radiation shield

Absorbing element

Fuel

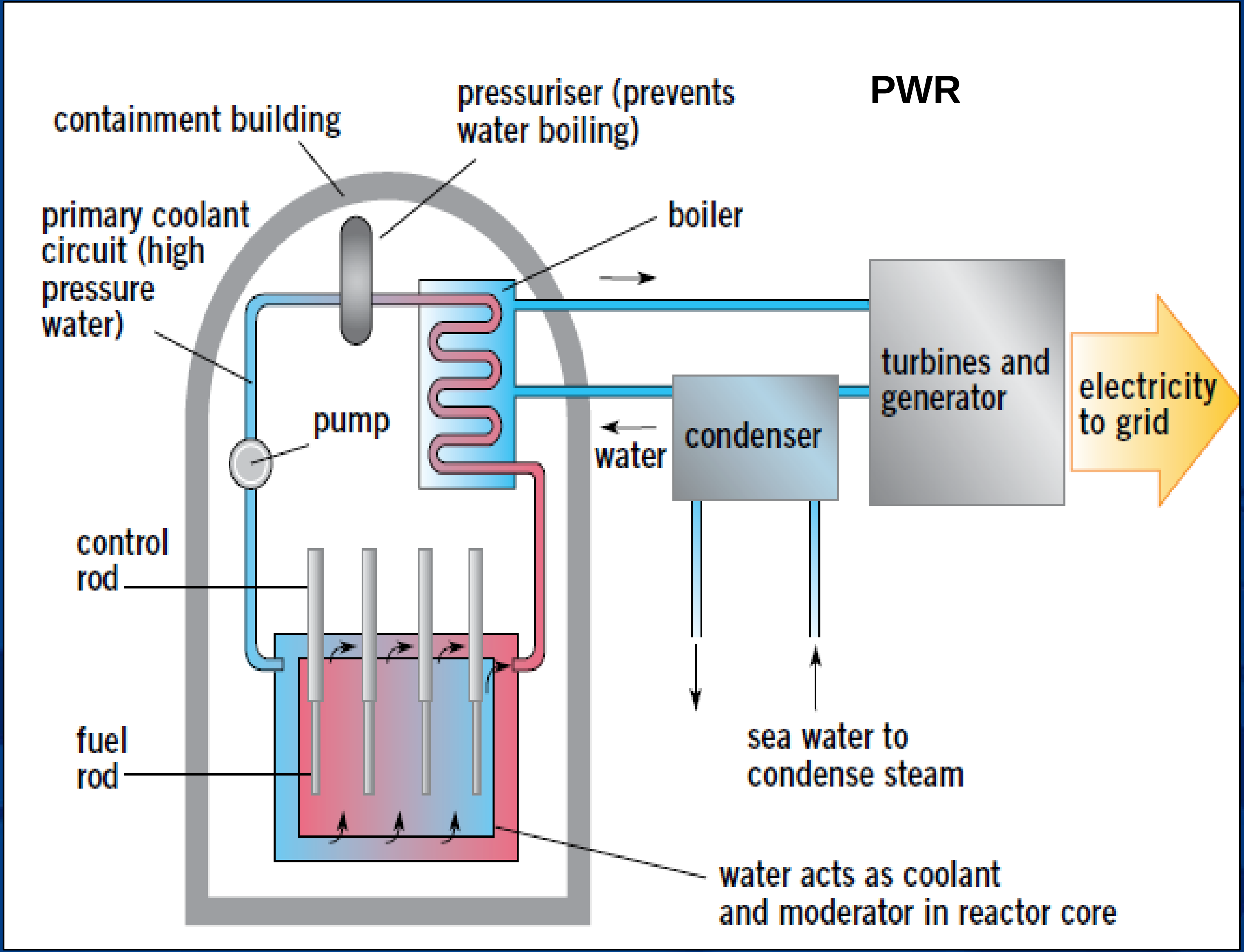
This neutron is bounced back by the «reflecting» material

Absorption in other materials

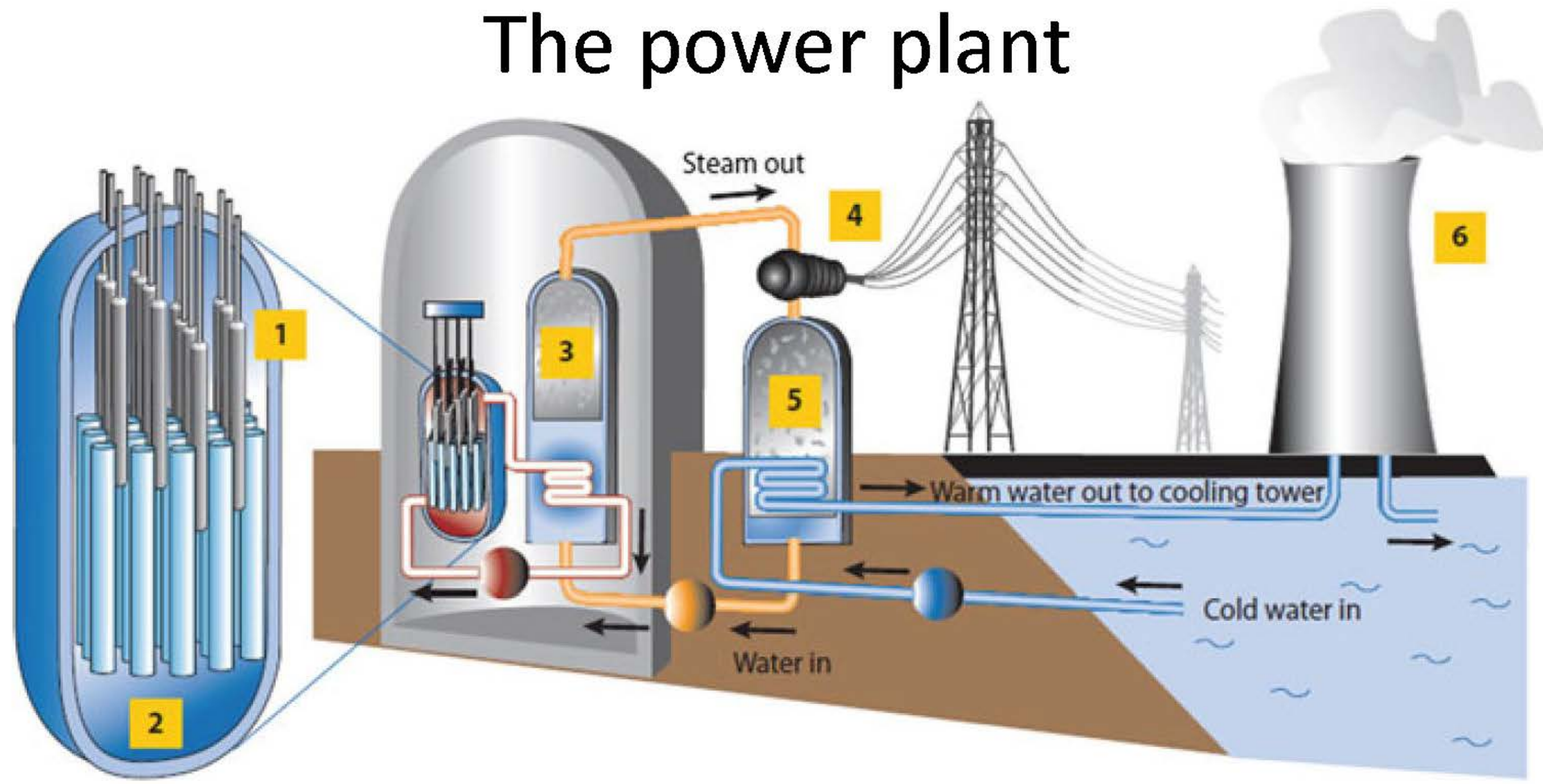
Reactor «core»

Neutron emerging from fission

FISSION REACTOR WORKING PRINCIPLES



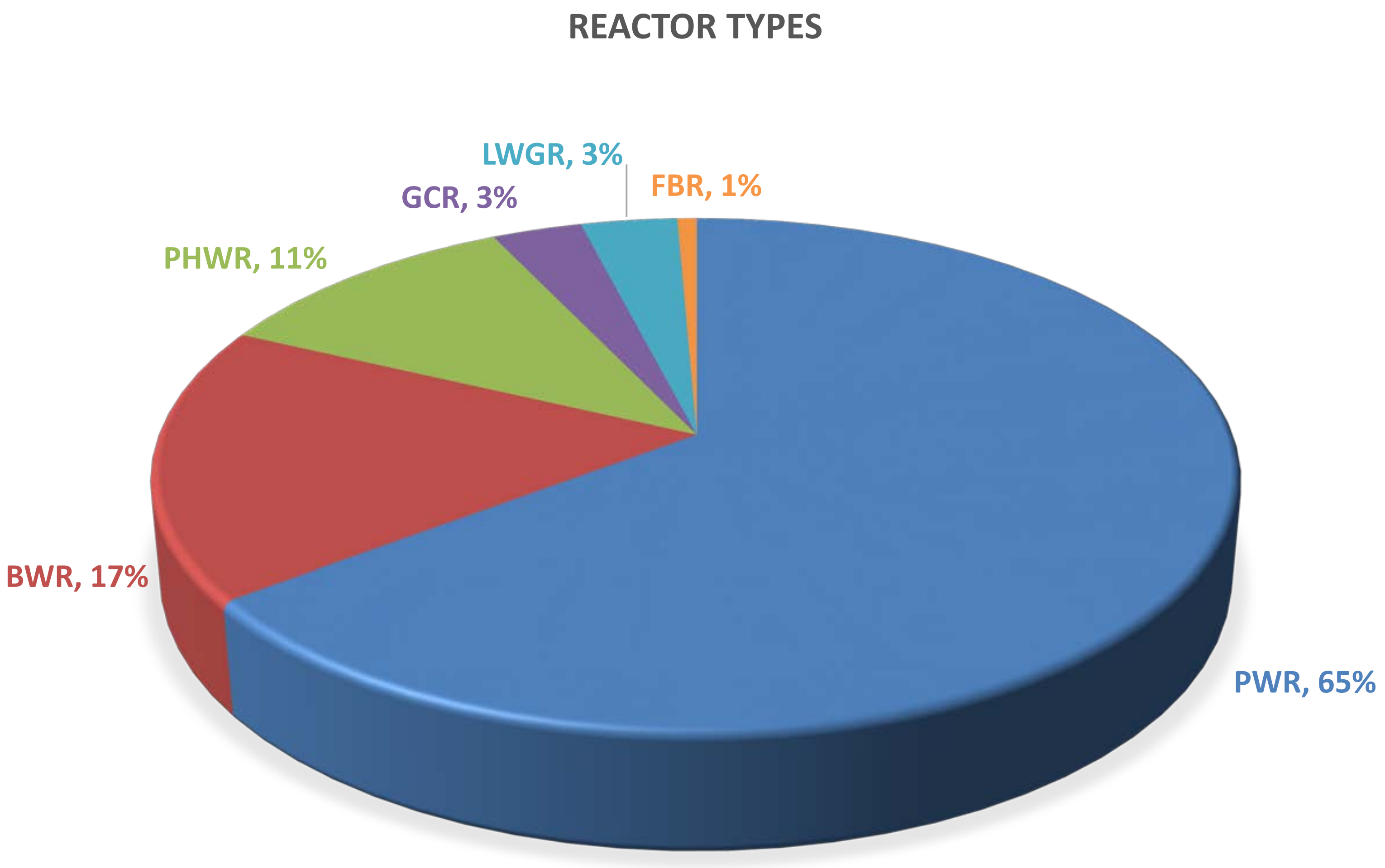
FISSION REACTOR WORKING PRINCIPLES



Basic components of a thermal nuclear power reactor (pressurised water reactor):
1-Reactor: fuel rods (light blue) heats up pressurised water. Control rods (grey) absorb neutrons to control or halt the fission process
2-Coolant and moderator: fuel and control rods are surrounded by water (primary circuit) that serves as coolant and moderator
3-Steam generator: water heated by the nuclear reactor transfers thermal energy through thousands of pipes to a secondary circuit of water to create high-pressure steam
4-Turbo-generator set: steam drives the turbine, which spins the generator to produce electricity just like in a fossil-fuel plant
5-Condenser: removes heat to convert steam back to water, which is pumped back to the steam generator
6-Cooling tower: removes heat from the cooling water that circulates through the condenser, before returning it to the source at near-ambient temperature

Source: OECD-NEA Nuclear Energy Today, 2nd edn. (2012), ISBN 978-92-64-99204-7. NEA Report No. 6885

REACTOR TYPES IN USE WORLDWIDE (END OF 2016)



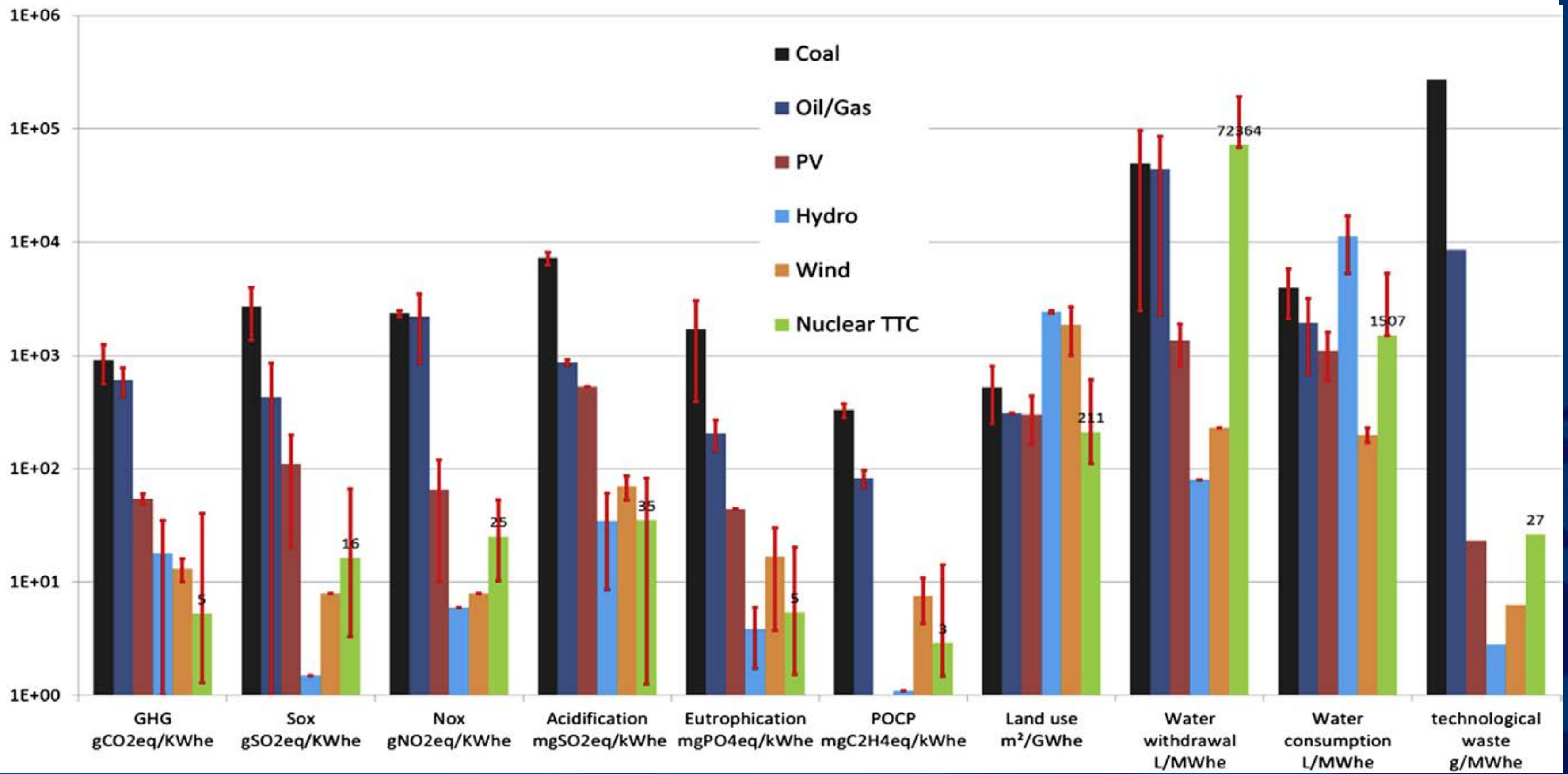
PWR = Pressurized Water Reactor
BWR = Boiling Water Reactor
PHWR = Pressurized Heavy Water Reactor
GCR = Gas-Cooled Reactor
LWGR = Light Water cooled, Graphite moderated Reactor

Source: [European Nuclear Society]

NON-RADIOACTIVE ENVIRONMENTAL IMPACT

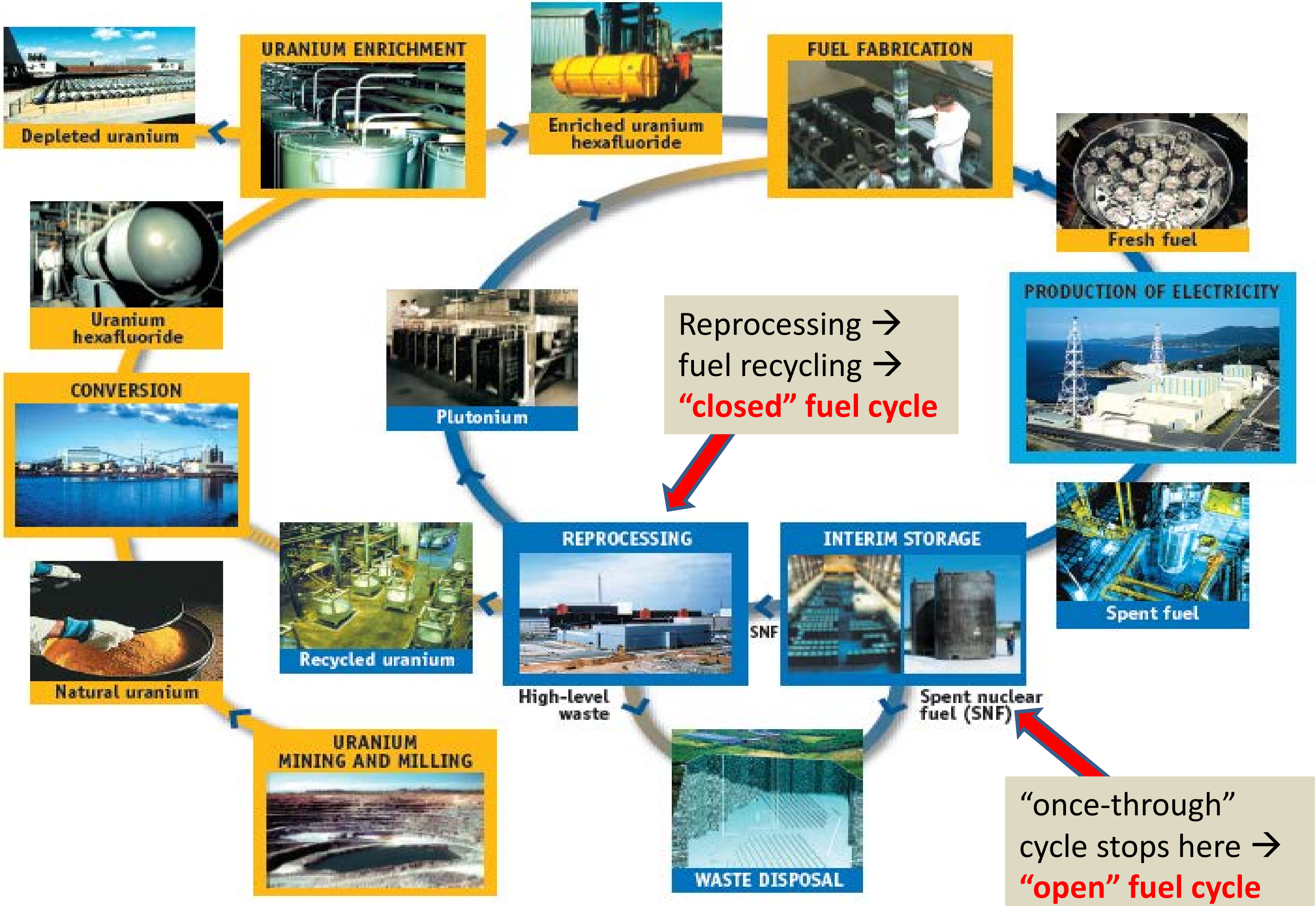
- Indicators selected to describe the non-radioactive impacts.
- Comparison of the selected indicators between the French Twice-Through Cycle and other energy sources. The error bars represent the gap between the minimum and maximum values found in the literature.

- 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)



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

The nuclear fuel cycle

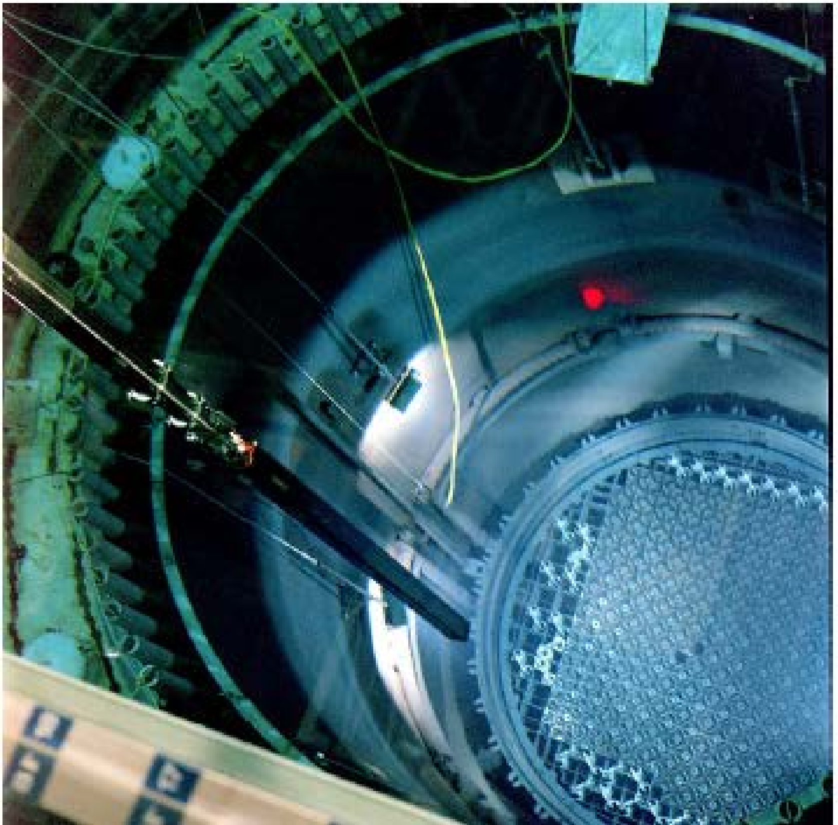


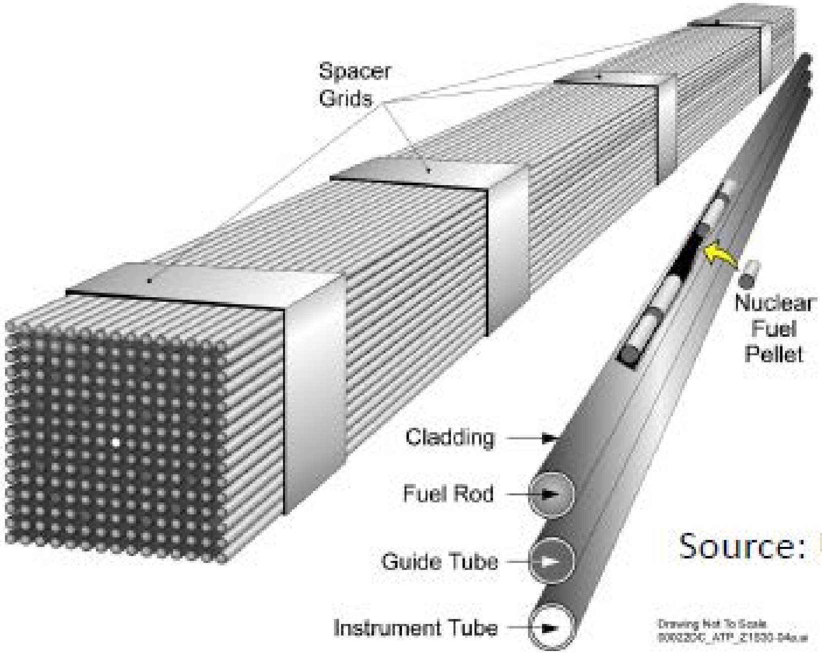
Reprocessing →
fuel recycling →
"closed" fuel cycle

"once-through"
cycle stops here →
"open" fuel cycle

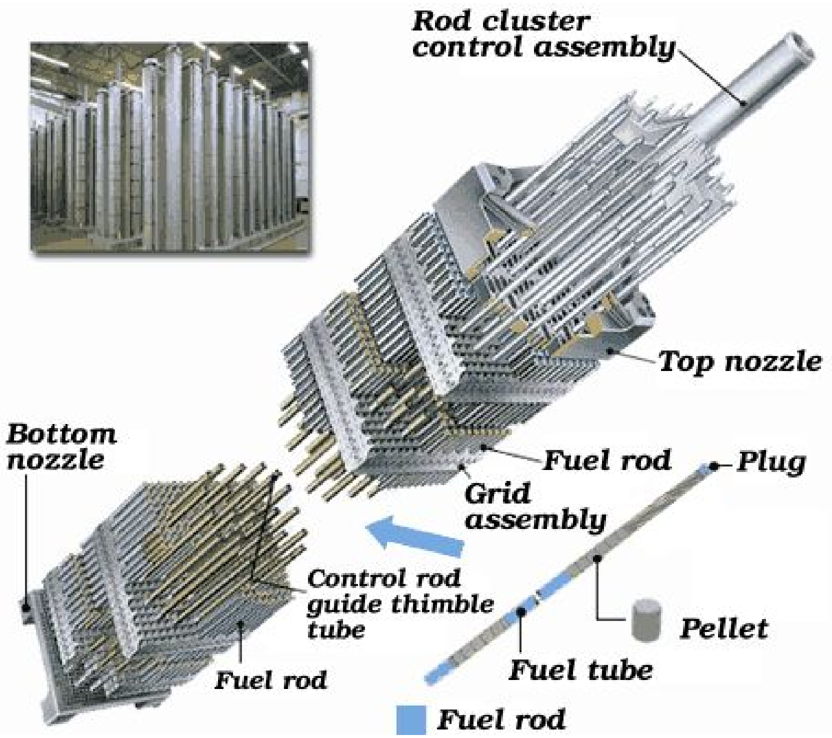
Nuclear fuel element

Fuel pellets. Photo: Areva/US NRC





Source: US DOE



Long lifetime radioactive waste production (1 GW$_e$ LWR)

$^{244, 245}$Cm
1.5 Kg/yr

^{241}Am:11.6 Kg/yr
^{243}Am: 4.8 Kg/yr

^{237}Np: 16 Kg/yr

Minor actinides

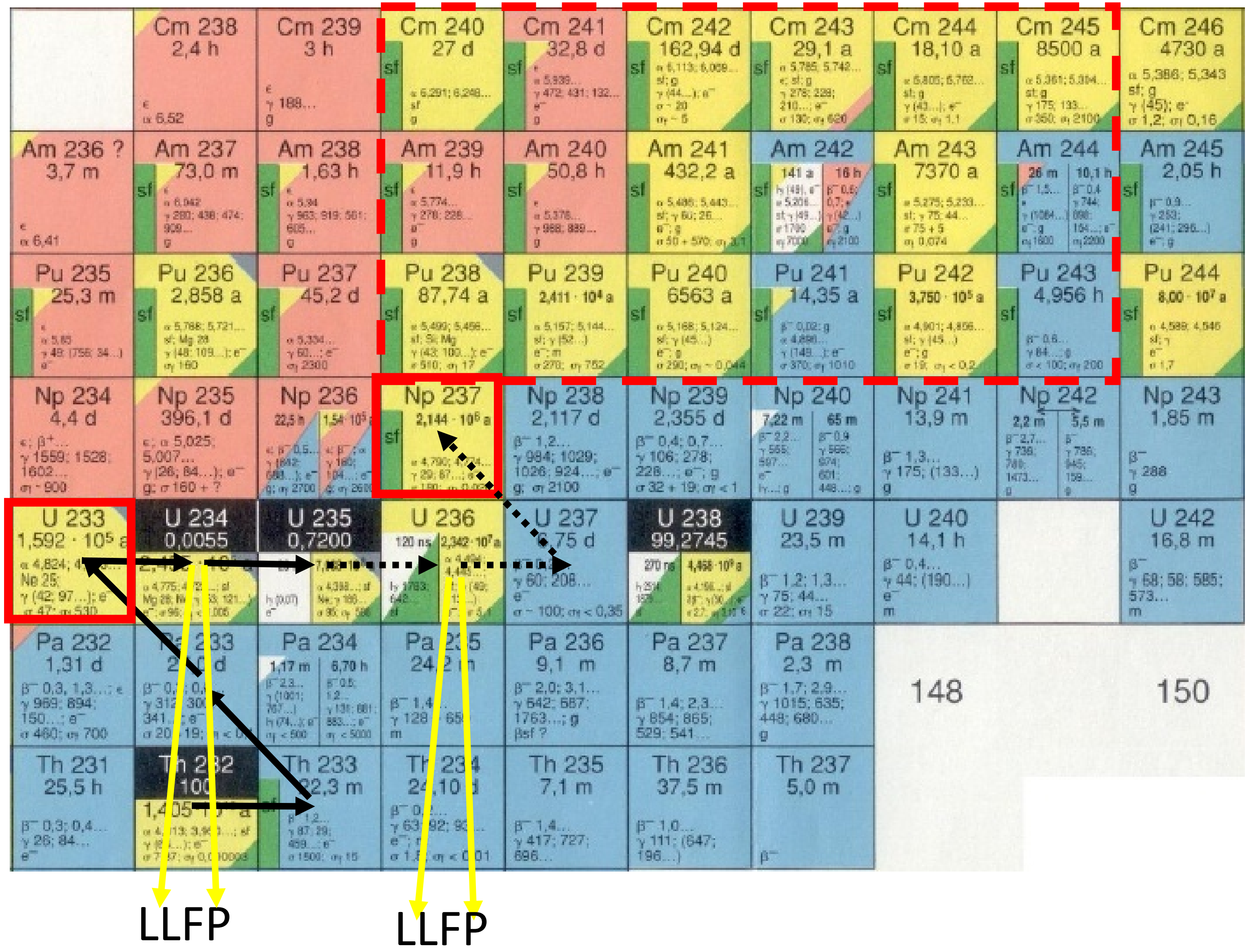
^{239}Pu: 125 Kg/yr

LLFP
76.2 Kg/yr

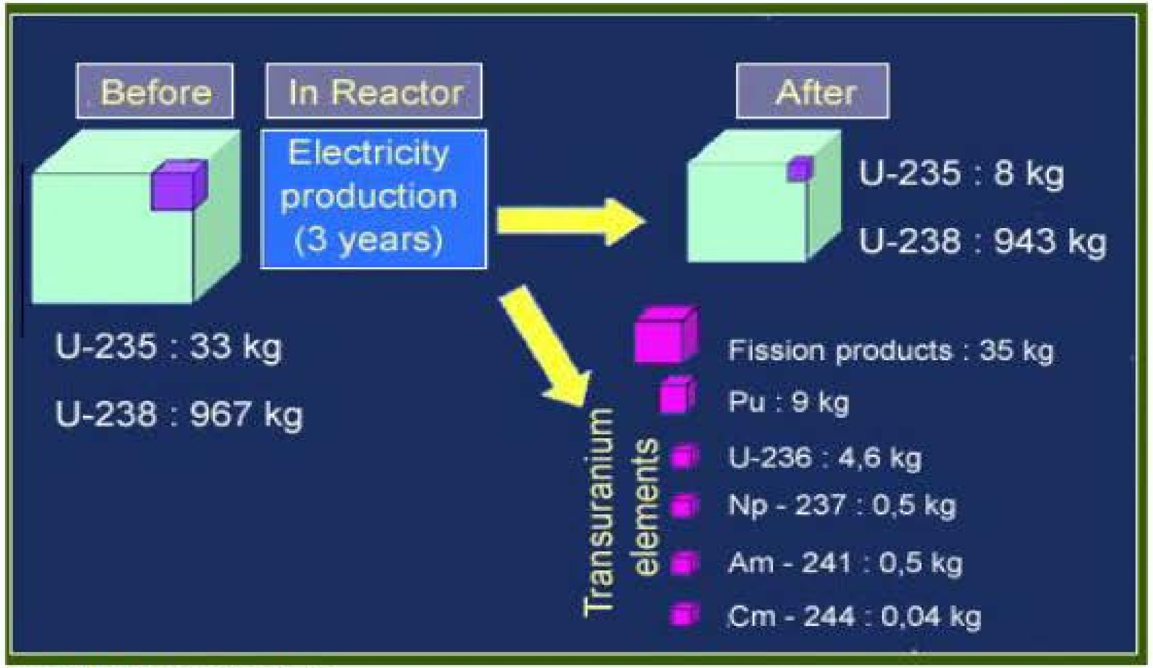
LLFP=Long Life Fission Products

🟥 Transuranics = Minor Actinides + Pu

The thorium cycle



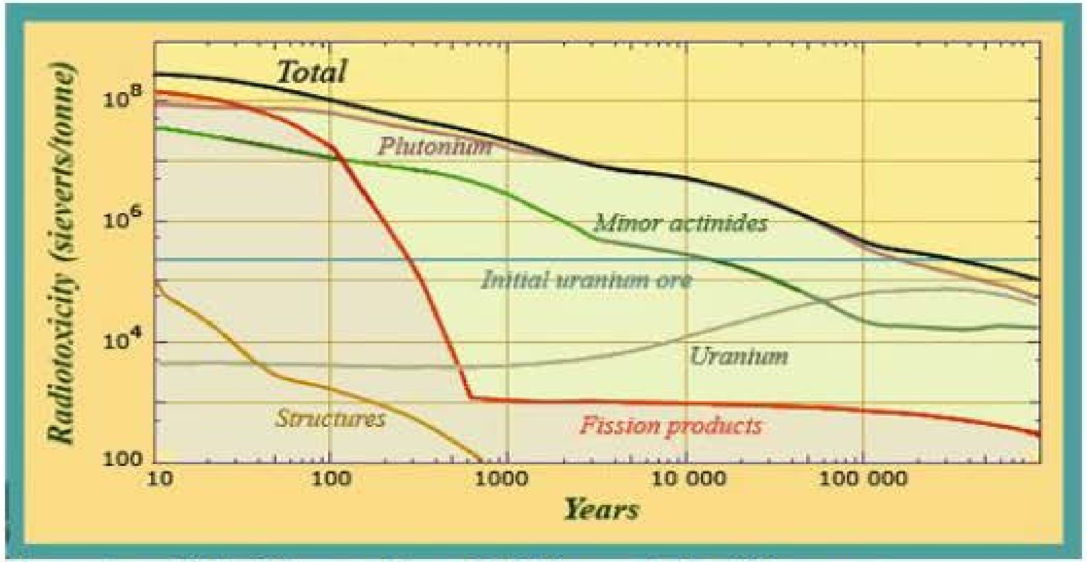
SPENT FUEL COMPOSITION AND RADIO-TOXICITY



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)

Radiotoxicity (Sievert Sv):
Activity (how much radioactivity from the material, measured e.g. in Becquerel=decays/sec) x Dose per Bq (equivalent dose per activity, measures the biological damage, measure in Sievert)

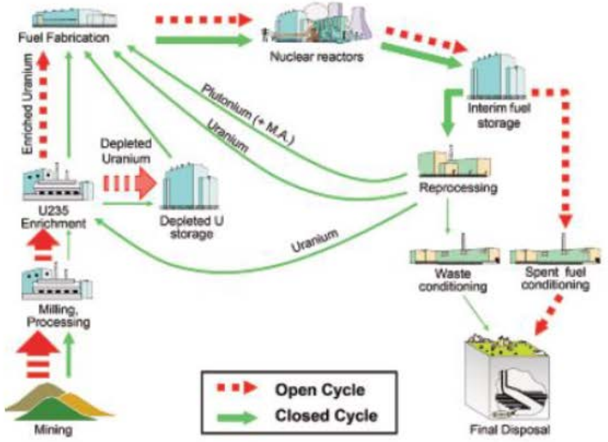
1 Sievert = 1 Joule/Kg (after correction depending on radiation type)



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

OPEN (OTC) VS CLOSED (TTC) FUEL CYCLE

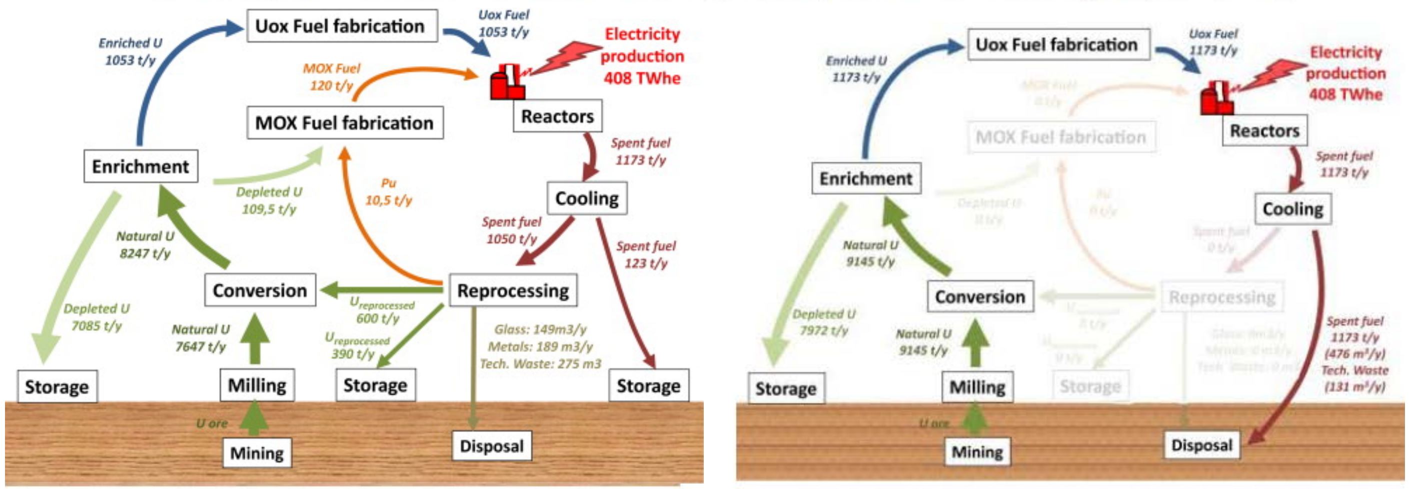
- Two options:
  - Open cycle: direct disposal of spent fuel (US, Sweden, Finland…)
  - Partially closed cycle: reprocessing to extract Pu and make MOX fuels (France, Japan, Russia, China…)

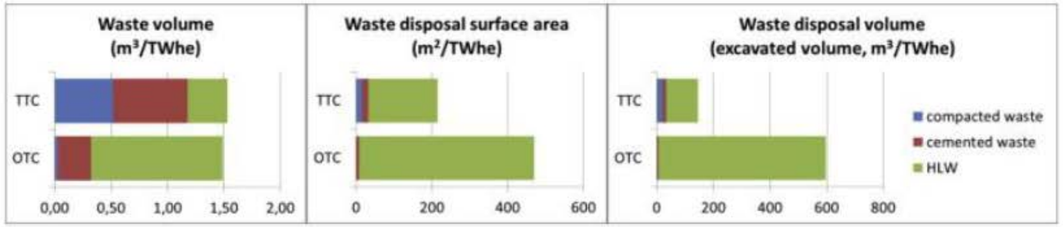


Pu recovery and MOX fabrication

- 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

NUCLEAR WASTE TRANSMUTATION/INCINERATION

Transmutation (or nuclear incineration)
of radioactive waste

⇩

Neutron induced reactions that transform **long-lived** radioactive isotopes into **stable** or **short-lived** isotopes.

Transmutation reactions

Long-Lived Fission Fragments (LLFF)

^{151}Sm, ^{99}Tc, ^{121}I, ^{79}Se …

⇩

neutron **capture** (n,γ)

n + ^{99}Tc (2.1x10^{5} y) → ^{100}Tc (16 s) → ^{100}Ru

Pu and Minor Actinides

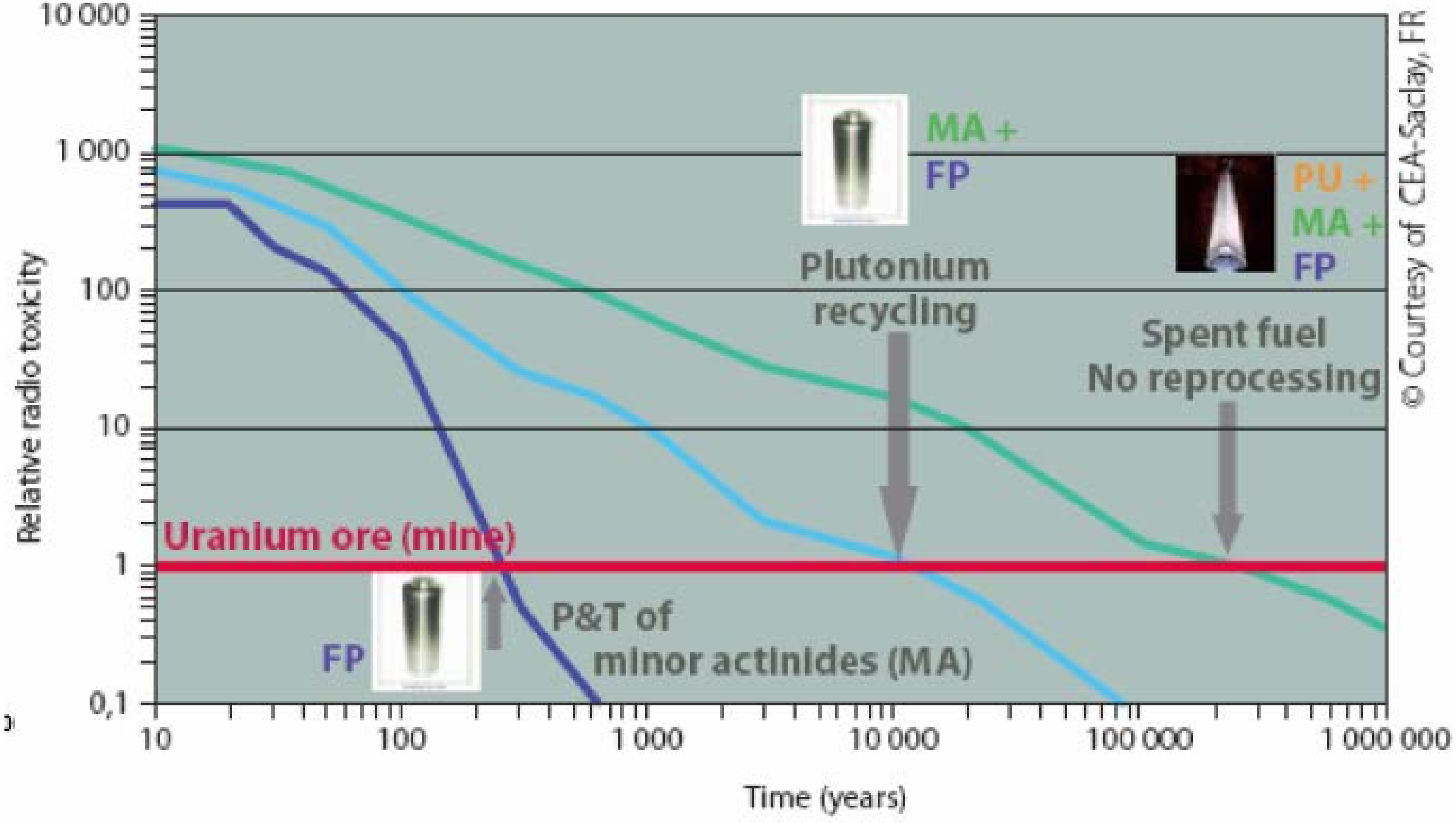
^{240}Pu, ^{237}Np, ^{241,243}Am, ^{244,245}Cm, …

⇩

neutron-induced **fission** (n,f)

neutron **capture** (n, γ)

NUCLEAR WASTE TRANSMUTATION/INCINERATION



Moreover, since in the new reactors the fuel may include non-separated actinides, the *proliferation* issue (use of Pu to make weapons) would be mitigated

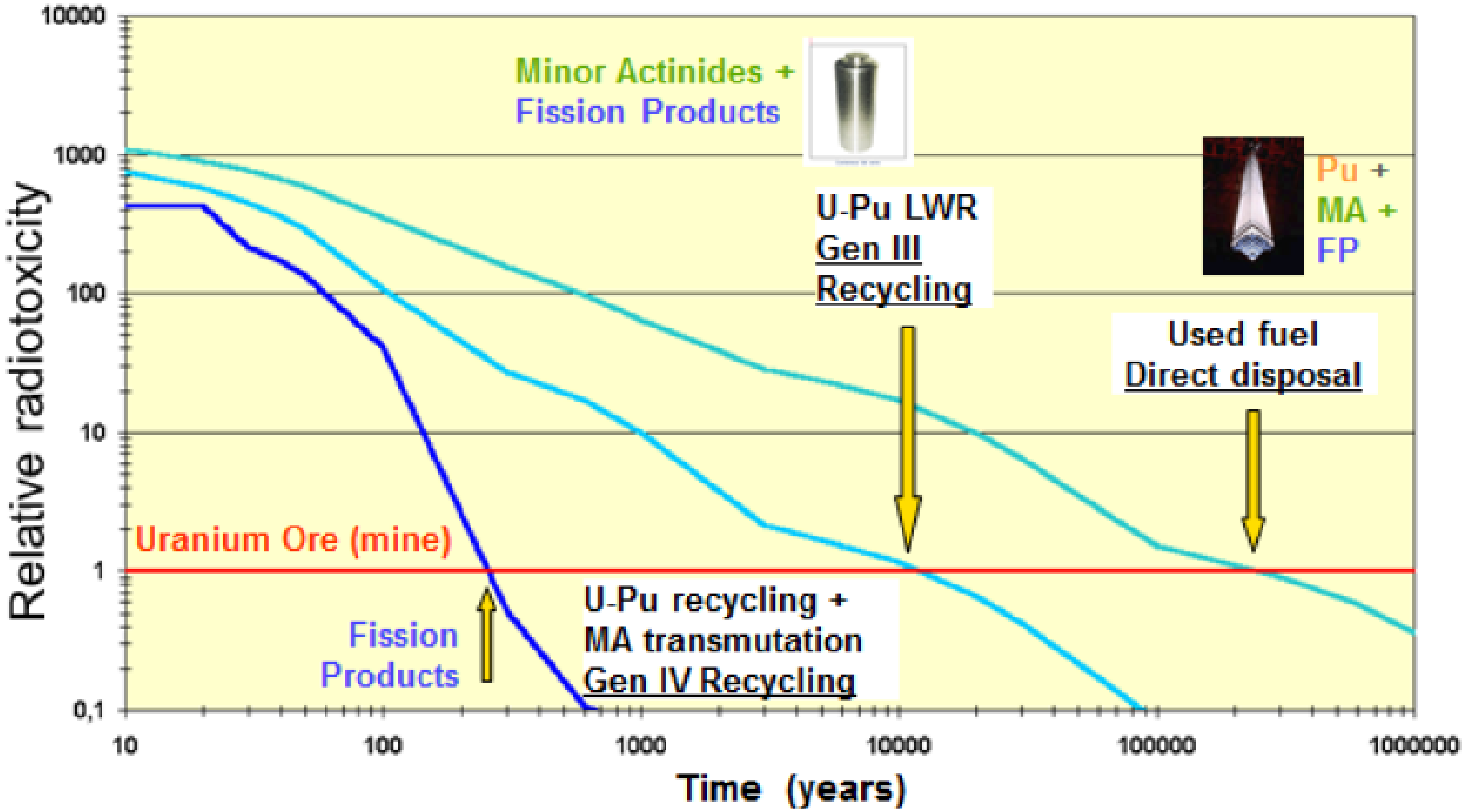
Radiotoxicity= Activity (how much radioactivity from the material, measured e.g. in Becquerel=decays/sec) x Dose per Bq (equivalent dose per activity, measures the biological damage, measure in Sievert)

1 Sievert = 1 Joule/Kg (after correction depending on radiation type)

NUCLEAR WASTE TRANSMUTATION/INCINERATION

- 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)



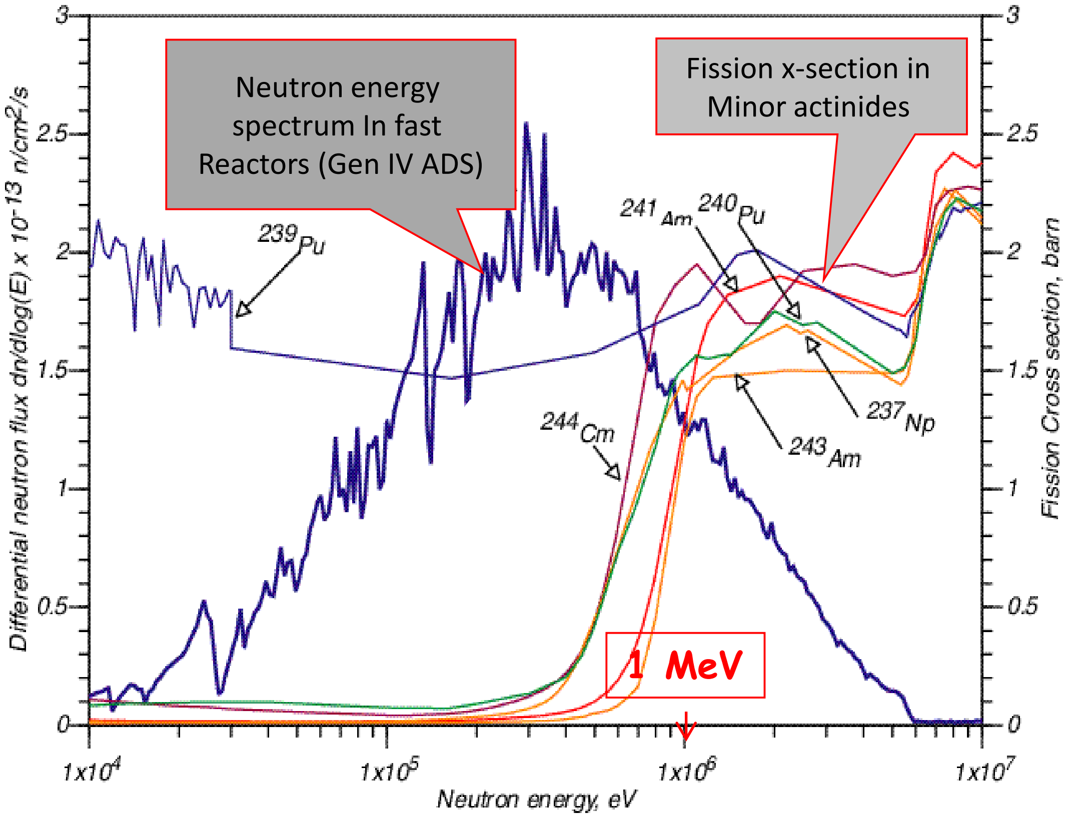
H.A. Abderrahim et al.,
NEA/NSC/R (2015) 2

FAST SPECTRUM SYSTEMS

Apart for ^{245}Cm, minor actinides are characterized by a **fission threshold** around the **MeV**.

In order to transmute actinides, need **fast neutrons** → **minimal moderation** in intermediate medium → (cooling) medium must be **gas, sodium, lead**, etc.

➔ Such isotopes can be burnt in **fast reactors or in fast Accelerator Driven Systems (ADS)** (neutron spectrum from 10 keV to 10 MeV)


Neutron energy spectrum In fast Reactors (Gen IV ADS)

Fission x-section in Minor actinides

1 MeV

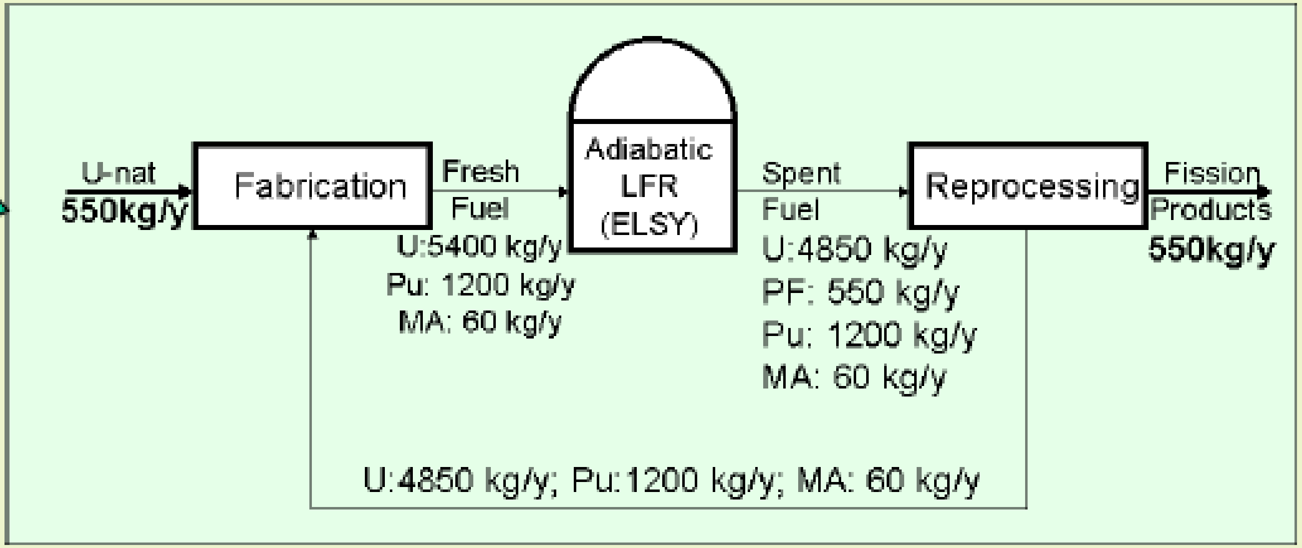
Delayed neutron fraction from FF, e.g.: ^{235}U = 0.65 % ^{241}Am = 0.113 %

In **ADS delayed neutrons** emitted by FF are **less important** for the reactor control: **fast ADS** can therefore be fueled with almost any Transuranic element and burn them

Fast ADS → good candidates as transmuters of high activity and long lifetime (thousands of years) Generation III reactor waste into much shorter lifetime fragments (few hundred years), to be stored in temporary surface storage. But further R&D is still needed

FAST REACTOR FUEL CYCLE: AN EXAMPLE

Theoretical equilibrium fuel cycle
for 1500 MW_{th} LFR (ELSY-type)



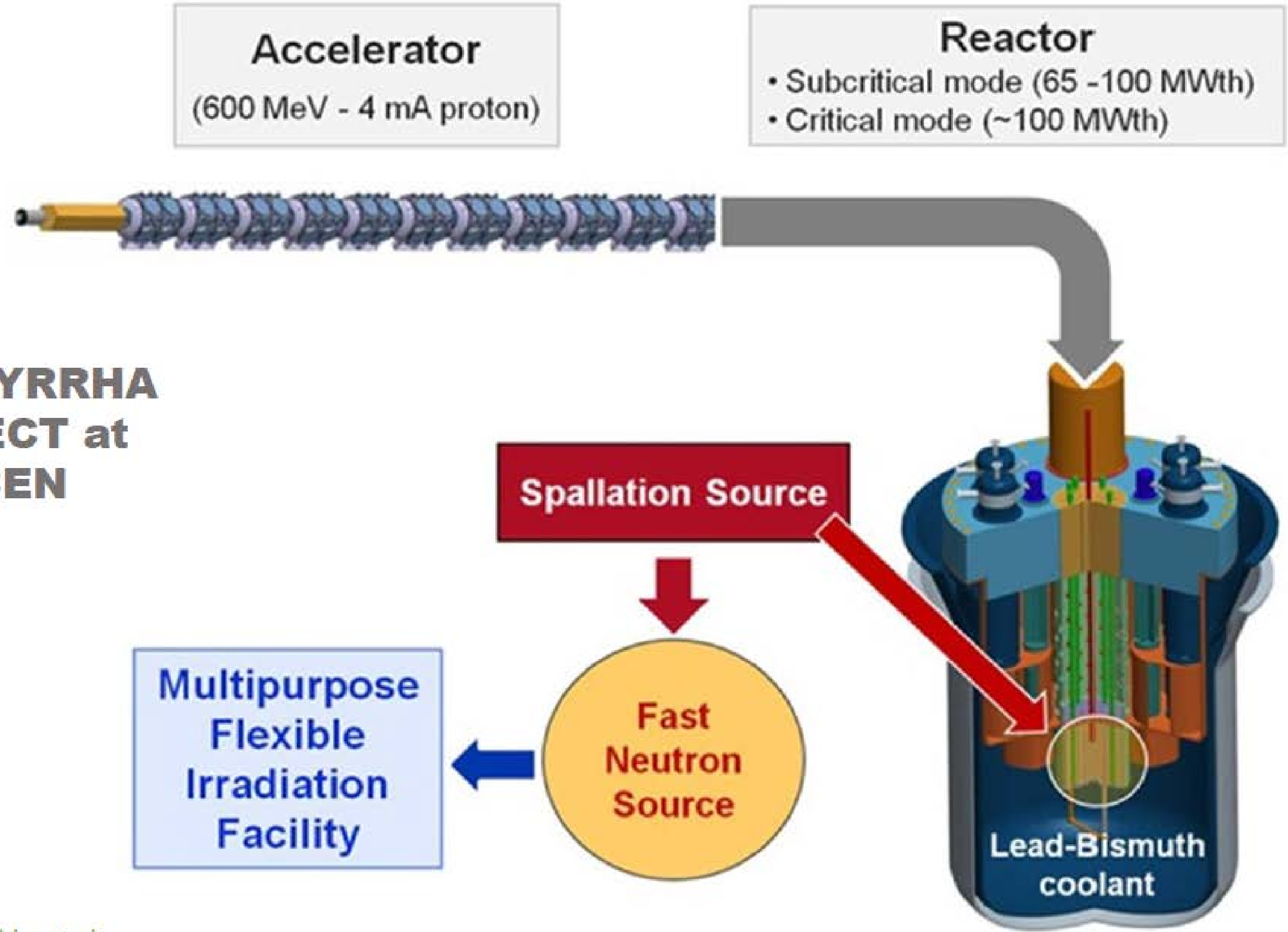
Considering 0.5% losses in the reprocessing:

- in the waste there are also: 25 kg/y U, 6 kg/y Pu , 0.3 kg/ MA;

fed U must be 580 kg/y

ACCELERATOR DRIVEN SYSTEMS (ADS)

The MYRRHA PROJECT at SCK•CEN



Accelerator

(600 MeV - 4 mA proton)

Reactor

- Subcritical mode (65 -100 MWth)
- Critical mode (~100 MWth)

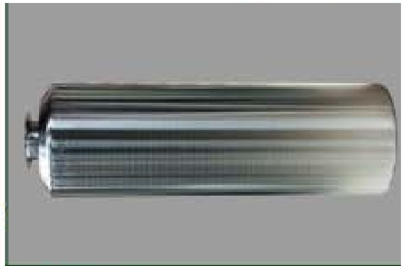
H.A. Abderrahim et al.,
NEA/NSC/R (2015) 2

https://myrrha.be/about-myrrha

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

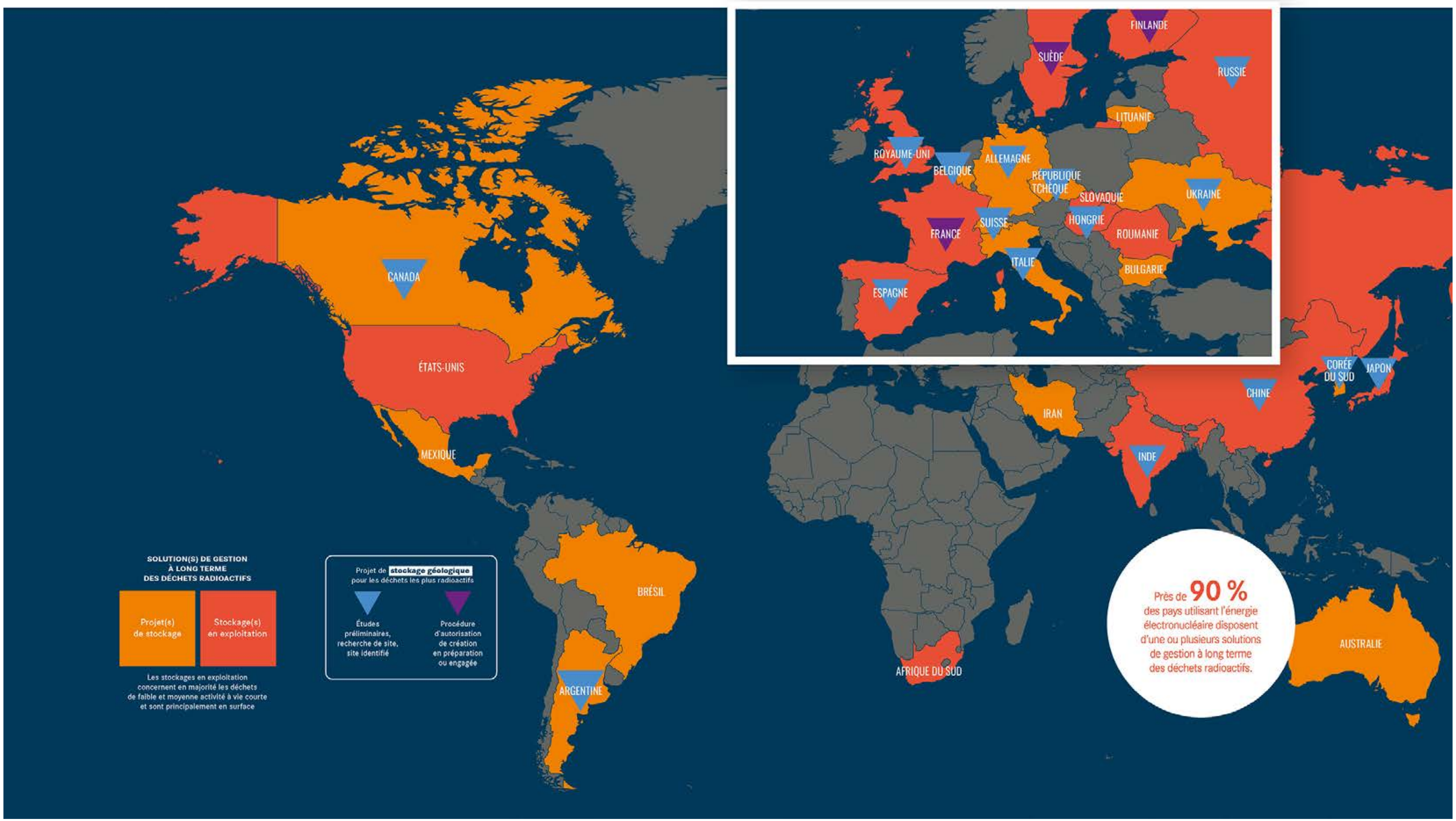
Photos from ANDRA Synthesis report 2021

IAEA SCHEME FOR CLASSIFICATION OF RADIOACTIVE WASTE (2009)

1. **Exempt waste (EW)** – such a low radioactivity content, which no longer requires controlling
2. **Very short-lived waste (VSLW)** – can be stored for a limited period of up to a few years to allow its radioactivity content to reduce by radioactive decay. It includes waste containing radio-nuclides with very short half-lives often used for research and medical purposes
3. **Very low level waste(VLLW)** – usually has a higher radioactivity content than EW but may, nonetheless, not need a high level of containment and isolation. Typical waste in this class includes soil and rubble with low levels of radioactivity which originate from sites formerly contaminated by radioactivity
4. **Low level waste (LLW)** – it has a high radioactivity content but contains limited amounts of long-lived radio-nuclides. ***It requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near-surface facilities***. It covers a very broad range of waste and may include short-lived radionuclides at higher levels of activity concentration, and also long-lived radionuclides, but only at relatively low levels of activity concentration
5. **Intermediate level waste (ILW)** – because of its radioactivity content, particularly of long-lived radionuclides, it requires a greater degree of containment and isolation than that provided by near surface disposal. ***It requires disposal at greater depths, of the order of tens of metres to a few hundred metres***
6. **High level waste (HLW)** – this is waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long-lived radionuclides that need to be considered in the design of a disposal facility for such waste. ***Disposal in deep, stable geological formations usually several hundred metres or more below the surface is the generally recognized option for disposal***

NOTE: Often surface & deep repository are designed together and comprise additional infrastructures (High-Tech Campus)

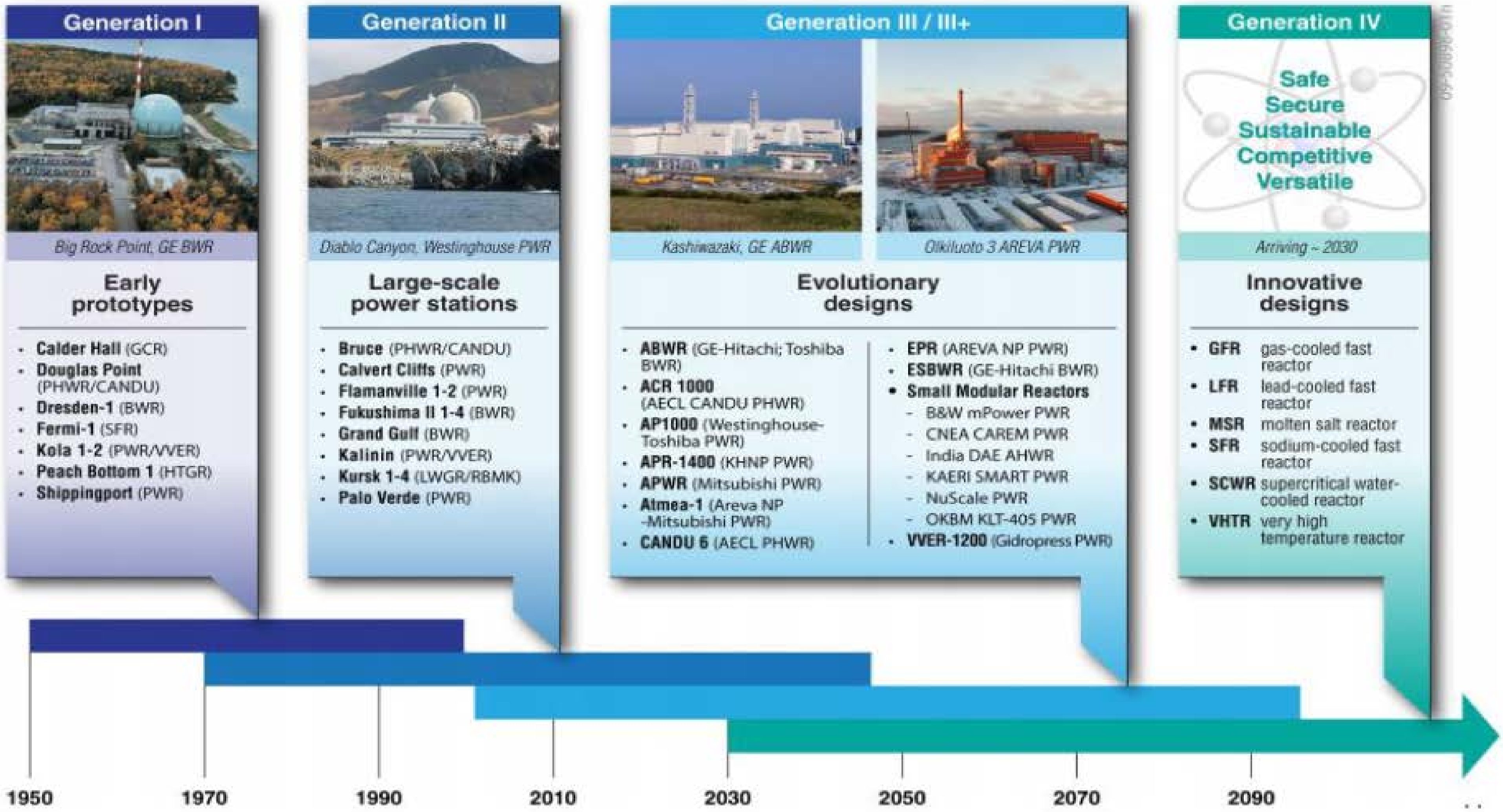
NUCLEAR WASTE MANAGEMENT



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

NUCLEAR REACTORS GENERATIONS

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



Generation I

Big Rock Point, GE BWR

Early prototypes

- **Calder Hall** (GCR)
- **Douglas Point** (PHWR/CANDU)
- **Dresden-1** (BWR)
- **Fermi-1** (SFR)
- **Kola 1-2** (PWR/VVER)
- **Peach Bottom 1** (HTGR)
- **Shippingport** (PWR)

Generation II

Diablo Canyon, Westinghouse PWR

Large-scale power stations

- **Bruce** (PHWR/CANDU)
- **Calvert Cliffs** (PWR)
- **Flamanville 1-2** (PWR)
- **Fukushima II 1-4** (BWR)
- **Grand Gulf** (BWR)
- **Kalinin** (PWR/VVER)
- **Kursk 1-4** (LWGR/RBMK)
- **Palo Verde** (PWR)

Generation III / III+

Kashiwazaki, GE ABWR

Olkiluoto 3 AREVA PWR

Evolutionary designs

- **ABWR** (GE-Hitachi; Toshiba BWR)
- **ACR 1000** (AECL CANDU PHWR)
- **AP1000** (Westinghouse-Toshiba PWR)
- **APR-1400** (KHNP PWR)
- **APWR** (Mitsubishi PWR)
- **Atmea-1** (Areva NP -Mitsubishi PWR)
- **CANDU 6** (AECL PHWR)
- **EPR** (AREVA NP PWR)
- **ESBWR** (GE-Hitachi BWR)
- **Small Modular Reactors**
  - B&W mPower PWR
  - CNEA CAREM PWR
  - India DAE AHWR
  - KAERI SMART PWR
  - NuScale PWR
  - OKBM KLT-405 PWR
- **VVER-1200** (Gidropress PWR)

Generation IV

Safe
Secure
Sustainable
Competitive
Versatile

Arriving ~ 2030

Innovative designs

GFR	gas-cooled fast reactor
LFR	lead-cooled fast reactor
MSR	molten salt reactor
SFR	sodium-cooled fast reactor
SCWR	supercritical water-cooled reactor
VHTR	very high temperature reactor

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

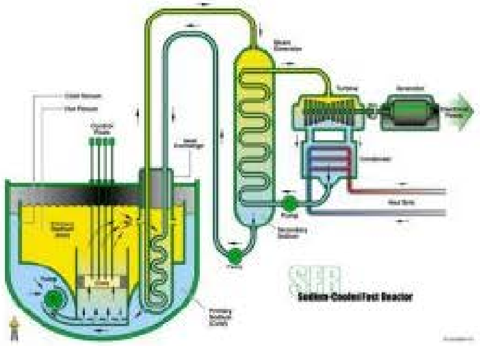
Generation IV: the future of nuclear power from fission

Six conceptual nuclear energy systems selected by Gen. IV International Forum (GIF)
https://www.gen-4.org/gif/

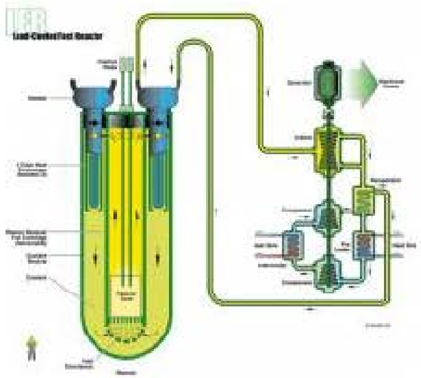
	neutron spectrum (fast/ thermal)	*coolant*	*temperature (^{o}C)*	*pressure*	*fuel*	*fuel cycle*	*size(s) (MWe)*	*uses*
Gas-cooled fast reactors	*fast*	*helium*	*850*	*high*	*U-238 +*	*closed, on site*	*1200*	*electricity & hydrogen*
Lead-cooled fast reactors	*fast*	*lead or Pb-Bi*	*480-570*	*low*	*U-238 +*	*closed, regional*	*20-180* *300-1200* *600-1000*	*electricity & hydrogen*
Molten salt fast reactors	*fast*	*fluoride salts*	*700-800*	*low*	*UF in salt*	*closed*	*1000*	*electricity & hydrogen*
Molten salt reactor - ***Advanced High-temperature reactors***	*thermal*	*fluoride salts*	*750-1000*		*UO_2 particles in prism*	*open*	*1000-1500*	*hydrogen*
Sodium-cooled fast reactors	*fast*	*sodium*	*500-550*	*low*	*U-238 & MOX*	*closed*	*50-150* *600-1500*	*electricity*
Supercritical water-cooled reactors	*thermal or fast*	*water*	*510-625*	*very high*	*UO_2*	*open (thermal)* *closed (fast)*	*300-700* *1000-1500*	*electricity*
Very high temperature gas reactors	*thermal*	*helium*	*900-1000*	*high*	*UO_2 prism or pebbles*	*open*	*250-300*	*hydrogen & electricity*

Generation IV: the future of nuclear power from fission

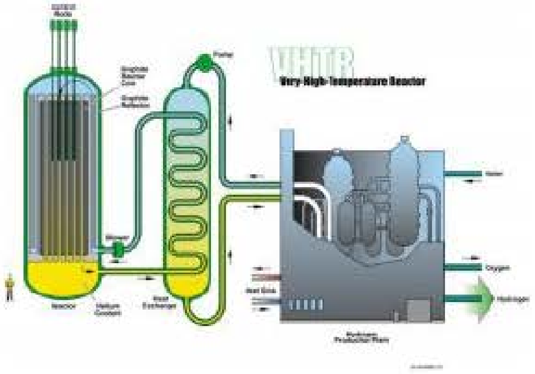
• Sustainable energy generation • Long-term availability • Minimization and management of their nuclear waste • Economical competitiveness • High level of safety and reliability • Proliferation-resistance



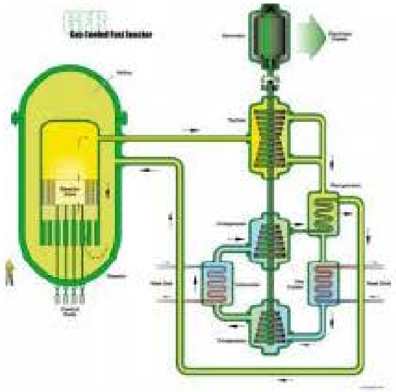
Sodium Fast Reactor



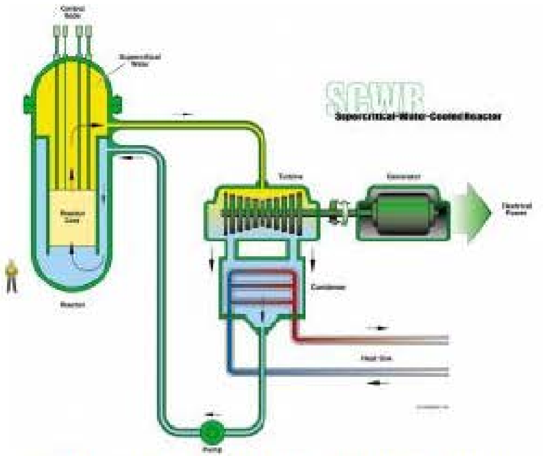
Lead Fast Reactor



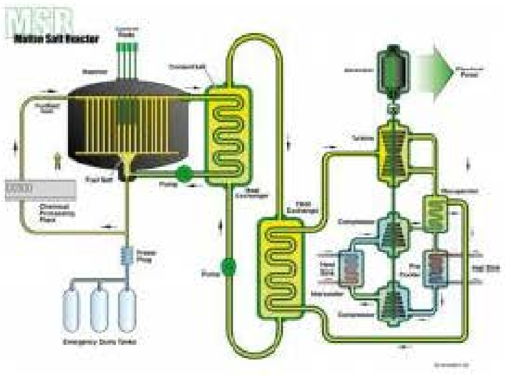
Very High Temperature Reactor



Gas Cooled Fast Reactor



Supercritical Water Cooled Reactor

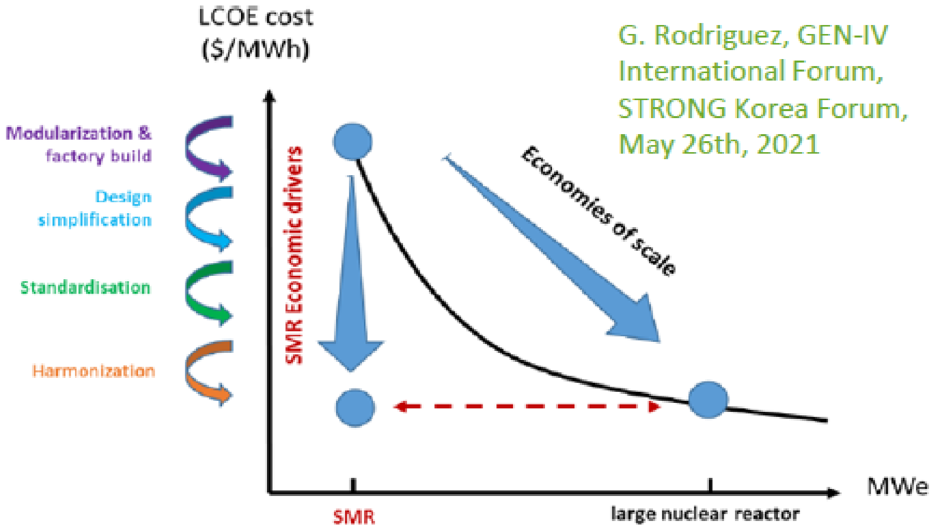


Molten Salt Cooled Reactor

Small and 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

https://aris.iaea.org/Publications/SMR_Book_2020.pdf



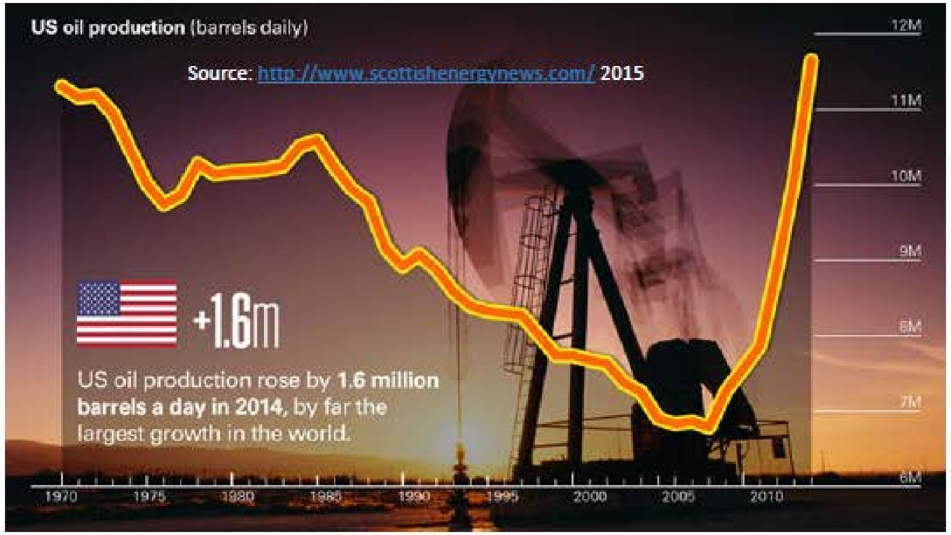
G. Rodriguez, GEN-IV International Forum, STRONG Korea Forum, May 26th, 2021

- 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…

Nuclear Energy World Outlook

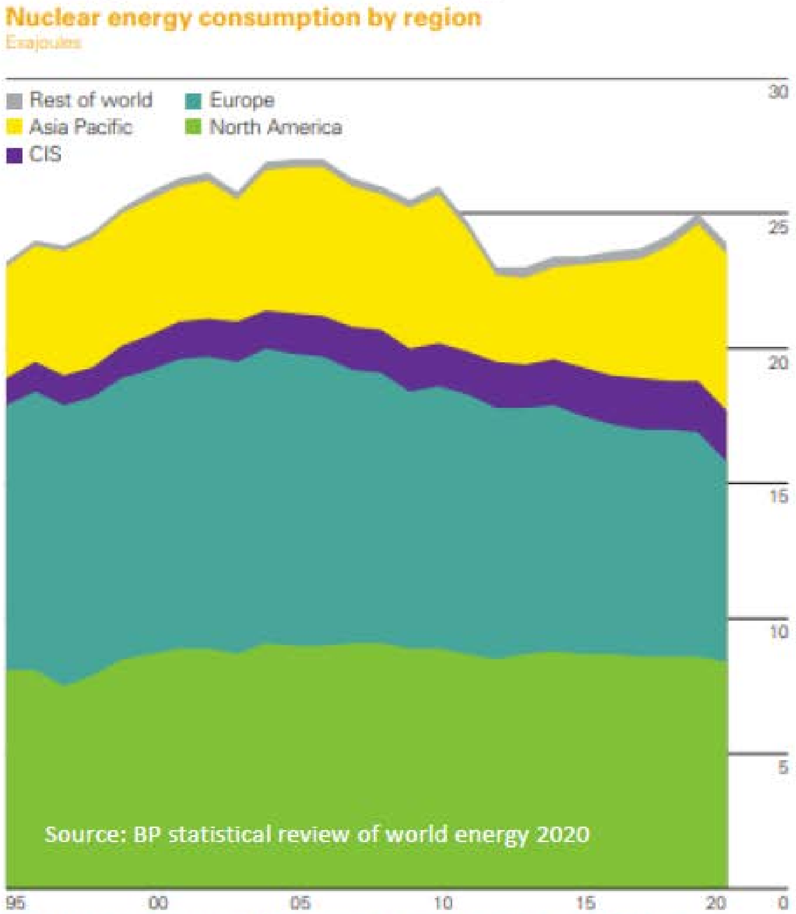
The growth expected twenty years ago has not happened:

- 2008 economic crisis
- 2011 Fukushima accident
- Shale oil "revolution"



US oil production (barrels daily)

Source: http://www.scottishenergynews.com/ 2015



Nuclear energy consumption by region

Exajoules

Source: BP statistical review of world energy 2020

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

Total primary energy

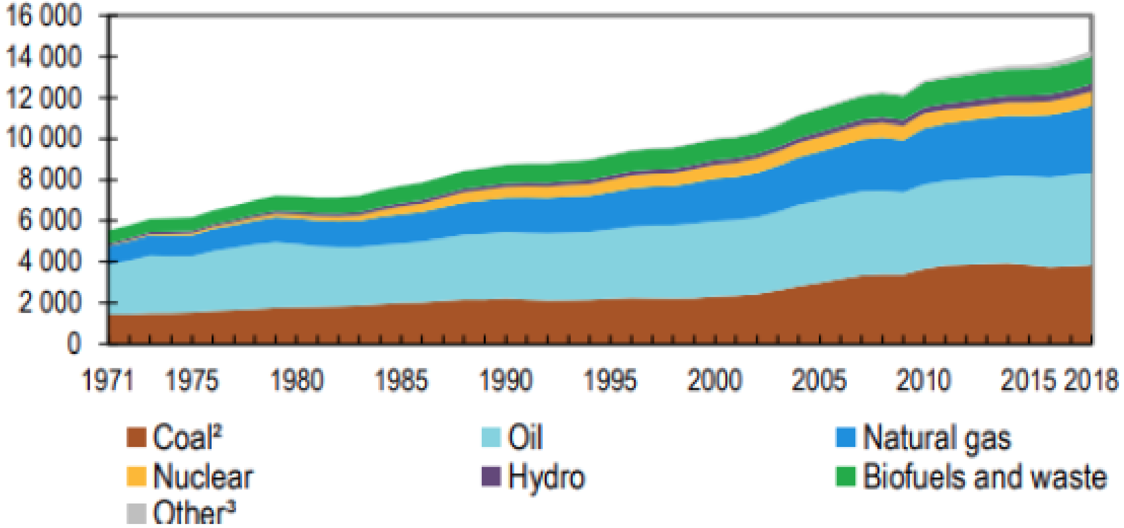
World TES from 1971 to 2018 by region (Mtoe)

Electricity

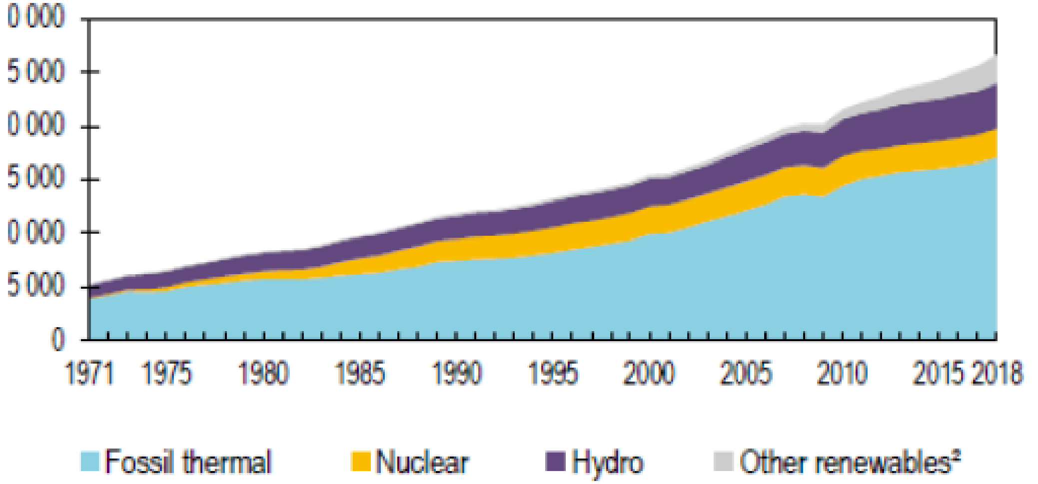
World electricity generation[1] from 1971 to 2018 by region (TWh)

- **Global energy demand increases due to world population growth and improving standard of living**
- **Electricity demand increases <u>even faster</u> boosted by developments in smart electronics, A/C, electric cars..**
- **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**

World[1] TES from 1971 to 2018 by source (Mtoe)

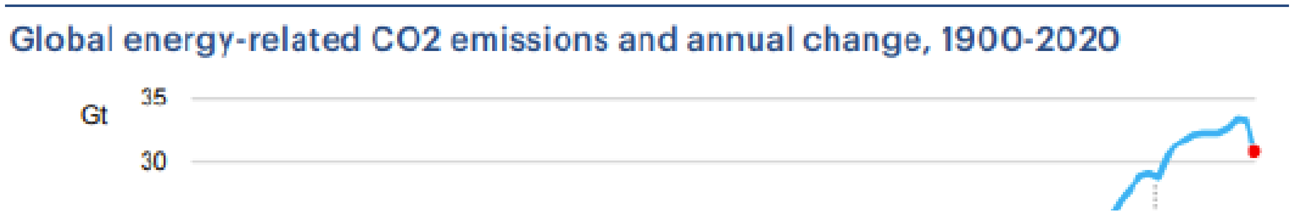


World electricity generation[1] from 1971 to 2018 by fuel (TWh)



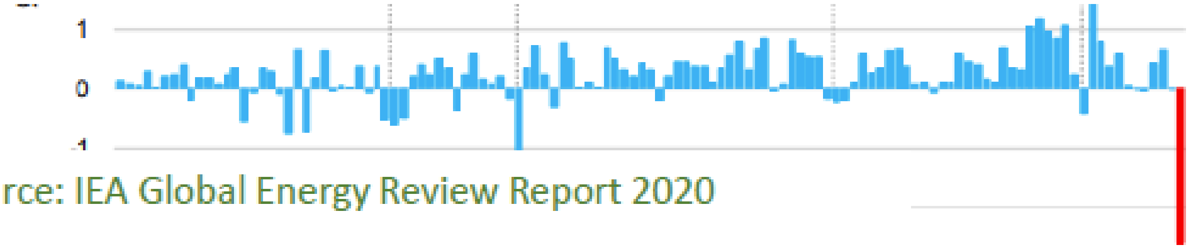
Source: IEA Key world energy statistics 2020

NUCLEAR ENERGY WORLD OUTLOOK



CO_2 emissions of the top 4 emitters

- Reducing CO2 emissions:
  - Energy saving & increase of 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 share of fossil fuels!**



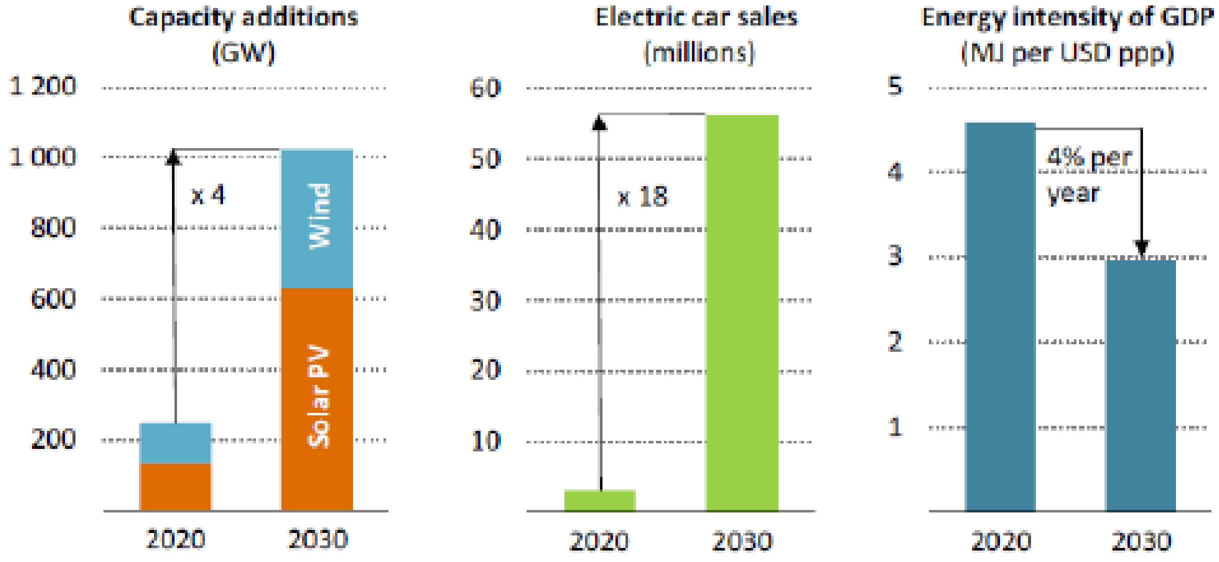
Source: IEA Global Energy Review Report 2020

Source: Global Carbon Project, Dec. 2020

IEA NET-ZERO 2050 PROPOSED SCENARIO

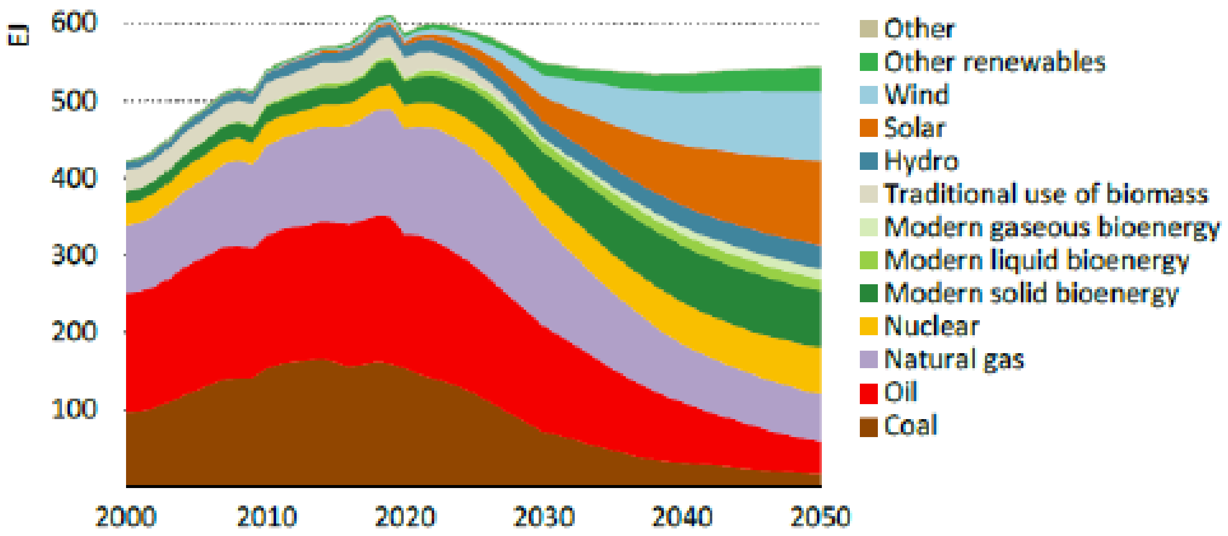
- Combination of all solutions
- Share of electricity in total energy supply has to increase
- Nuclear energy has to be at least doubled

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



IEA. All rights reserved.

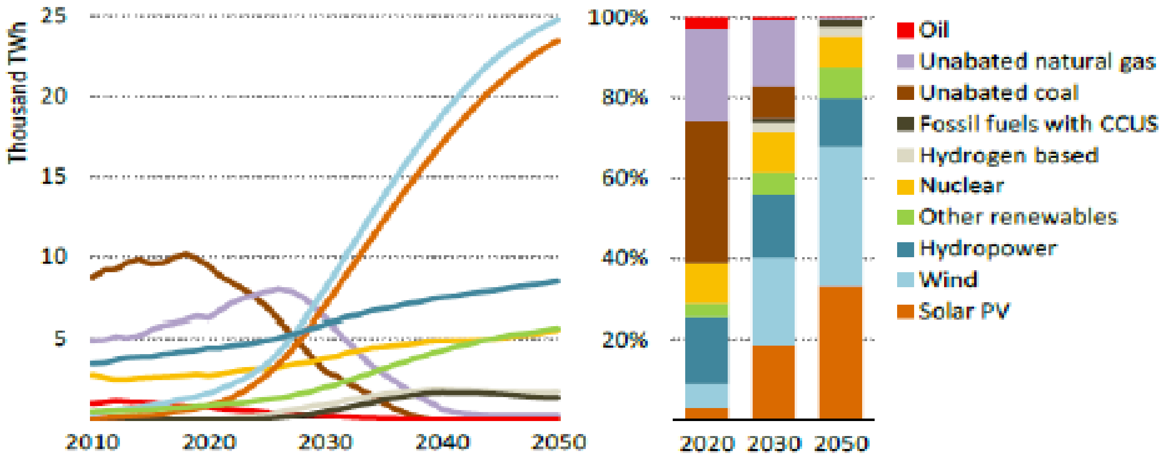
Renewables and nuclear power displace most fossil fuel use in the NZE, and the share of fossil fuels falls from 80% in 2020 to just over 20% in 2050

IEA Net Zero by 2050 report
iea.li/nzeroadmap

IEA NET-ZERO 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



IEA. All rights reserved.

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

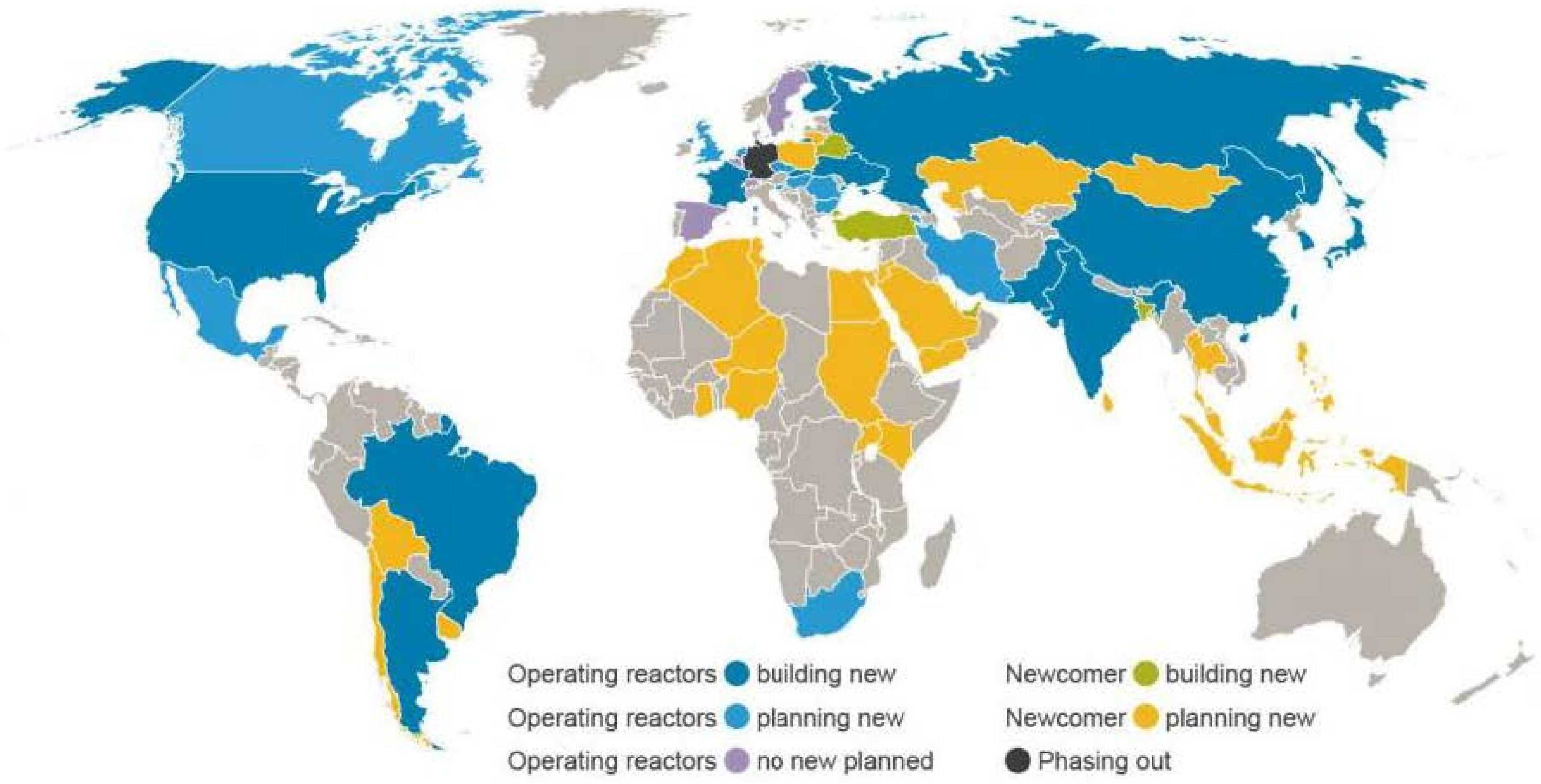
IEA Net Zero by 2050 report
iea.li/nzeroadmap

NUCLEAR ENERGY WORLD OUTLOOK

WORLD NUCLEAR ASSOCIATION

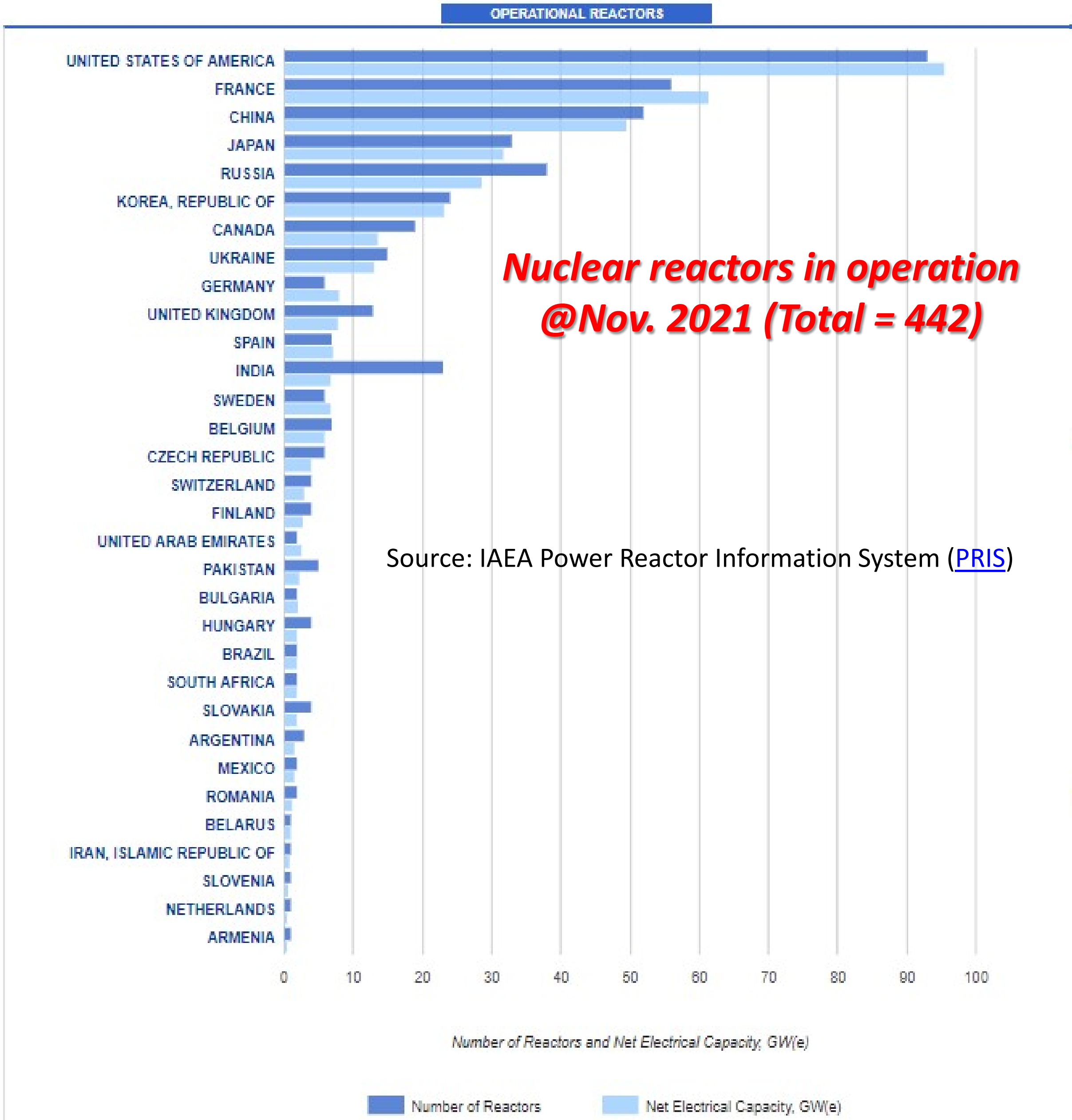
New build and new countries

Agneta Rising, World Nuclear Association, March 2018



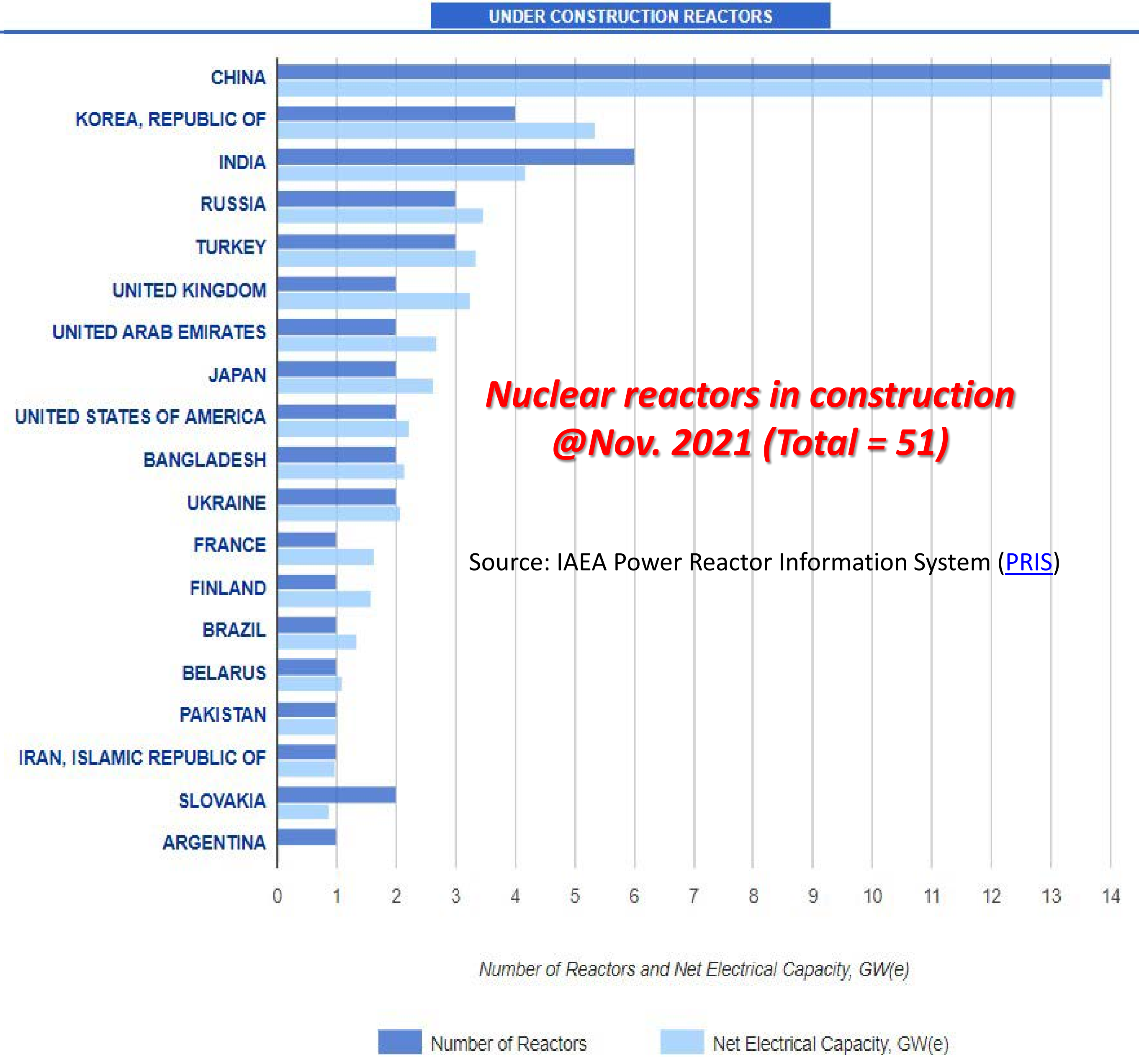
- 56 reactors under construction, of which 16 in China, 6 in Russia, 7 in India
- 152 reactors planned, of which 43 in China, 25 in Russia, 14 in India

NUCLEAR ENERGY TODAY IN THE WORLD



Nuclear reactors in operation @Nov. 2021 (Total = 442)

Source: IAEA Power Reactor Information System (PRIS)



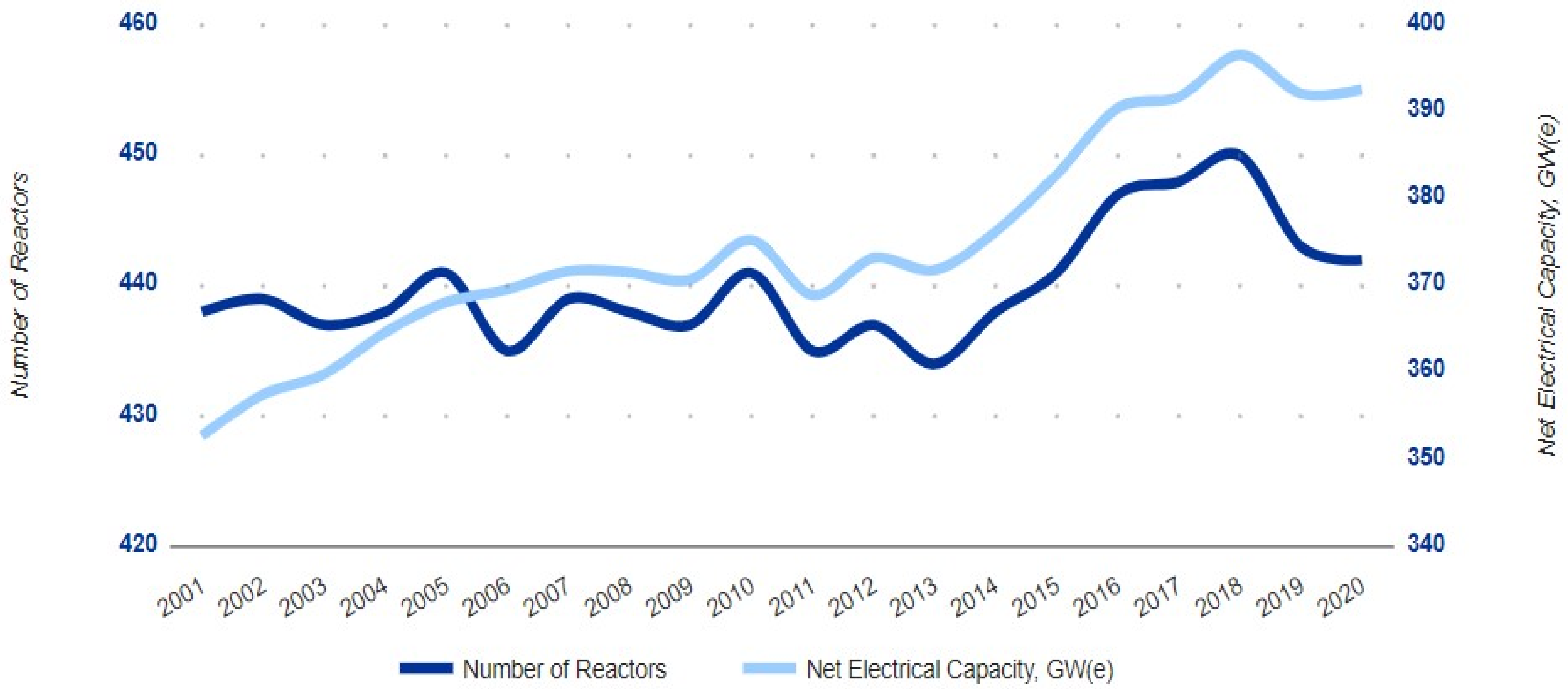
Nuclear reactors in construction @Nov. 2021 (Total = 51)

Source: IAEA Power Reactor Information System (PRIS)

NUCLEAR ENERGY TODAY IN THE WORLD

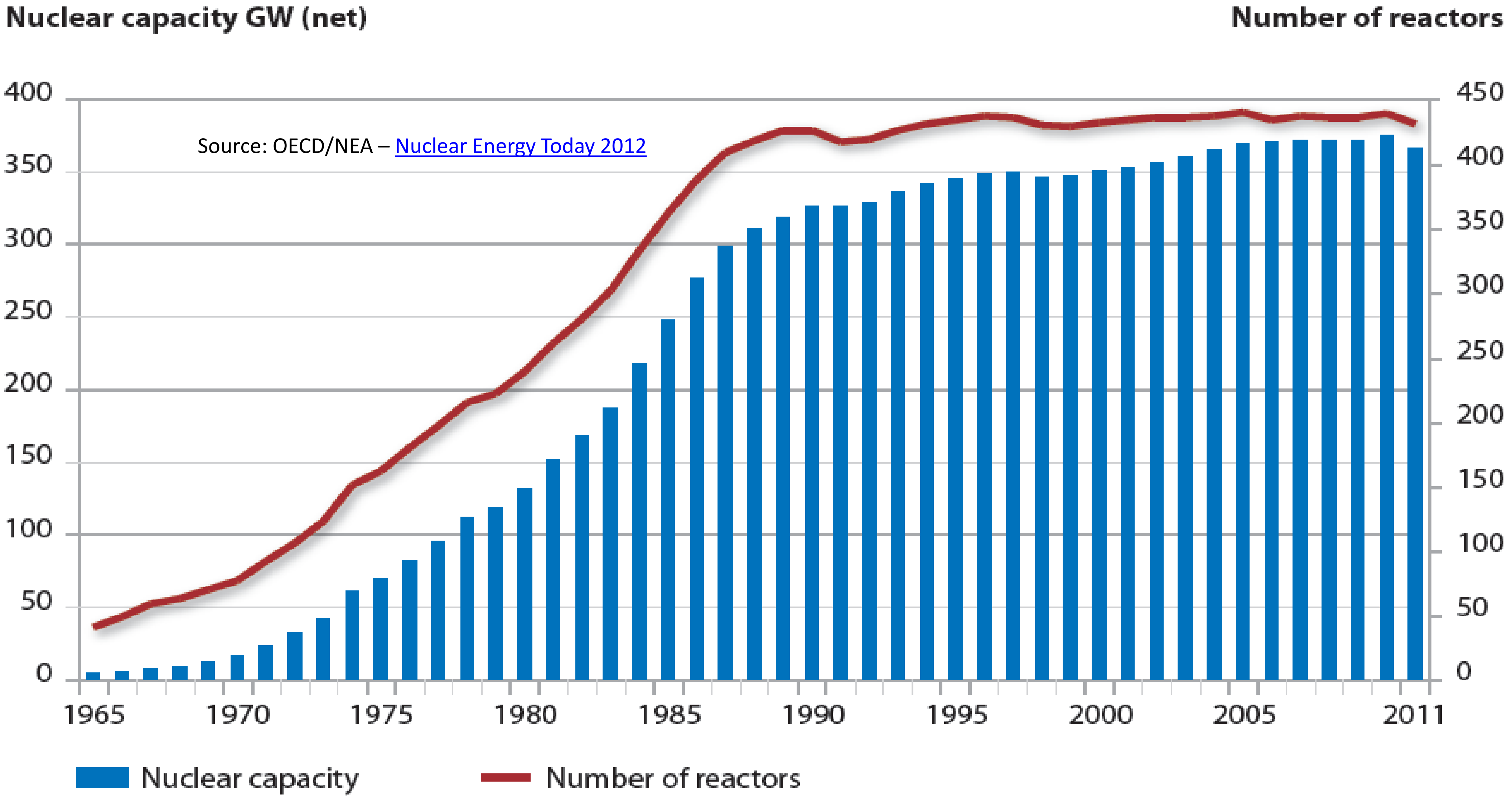
NUCLEAR POWER CAPACITY TREND

Source: IAEA Power Reactor Information System (PRIS)



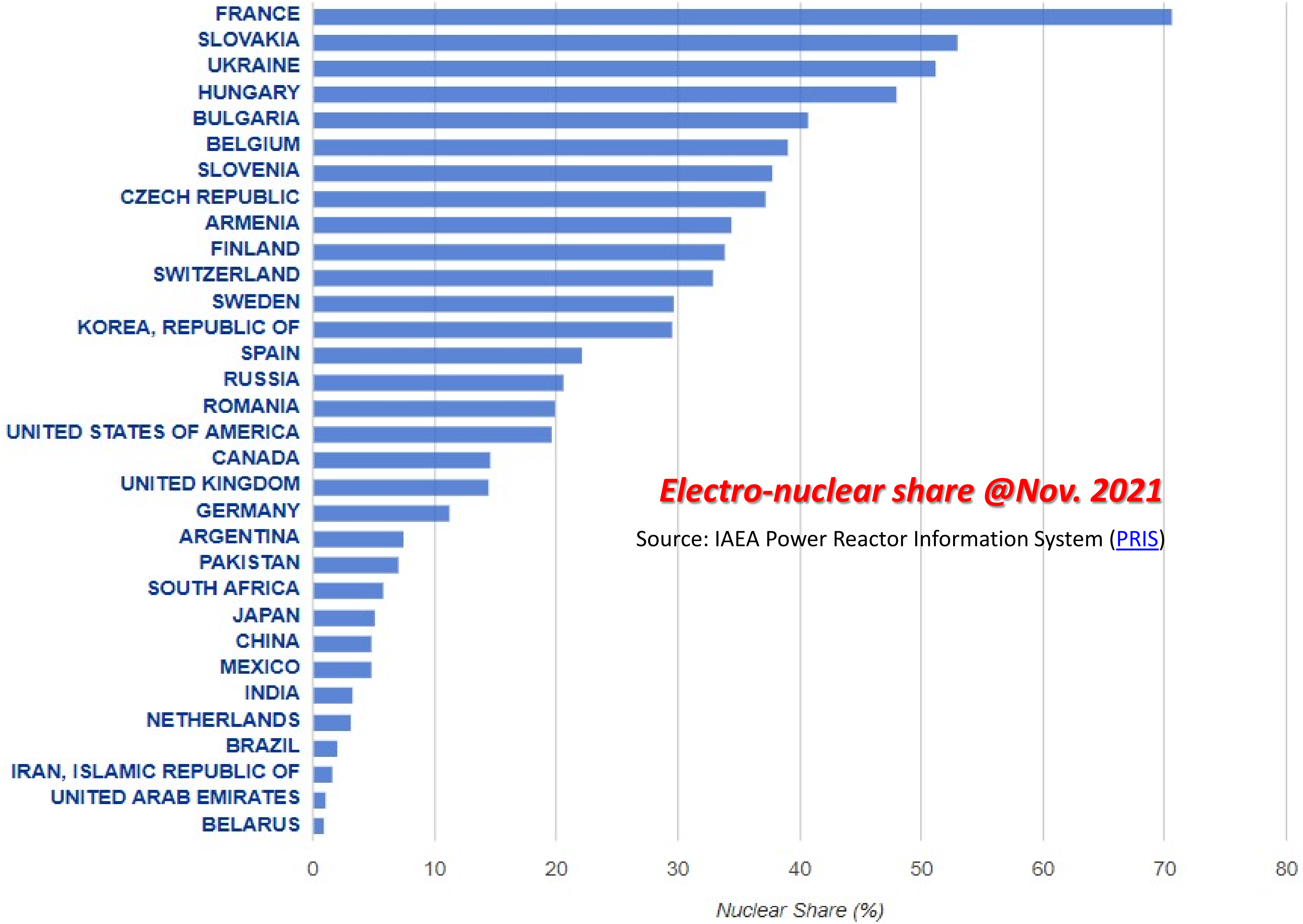
NUCLEAR ENERGY TODAY IN THE WORLD

Worldwide historical nuclear generating capacity and number of operating reactors (1965-2011)



Source: OECD/NEA – [Nuclear Energy Today 2012]

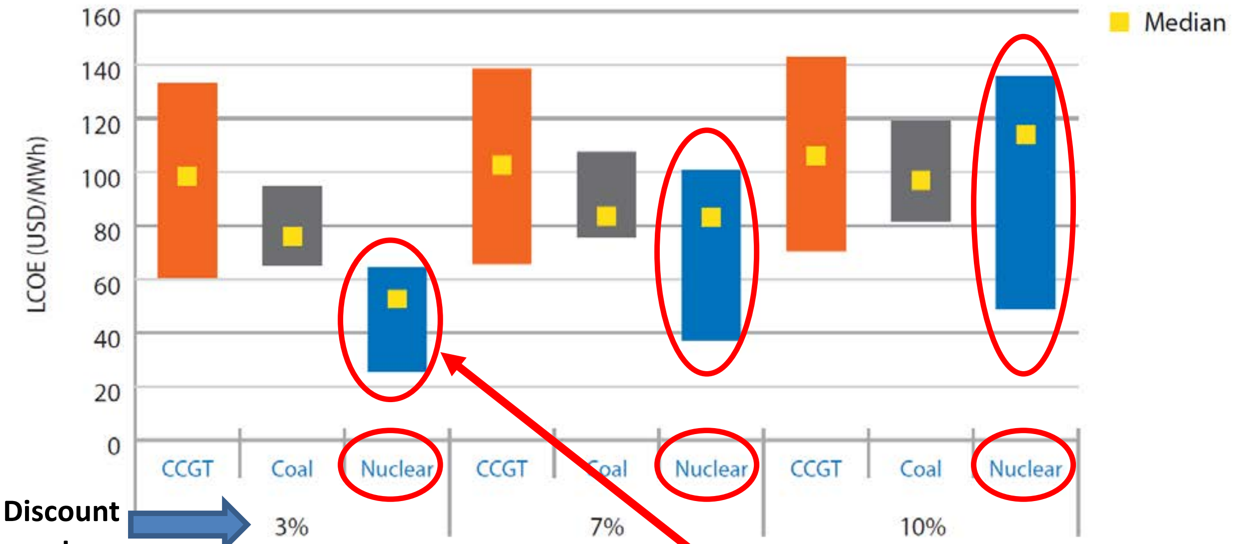
SHARE OF ELECTRICITY



Electro-nuclear share @Nov. 2021

Source: IAEA Power Reactor Information System (PRIS)

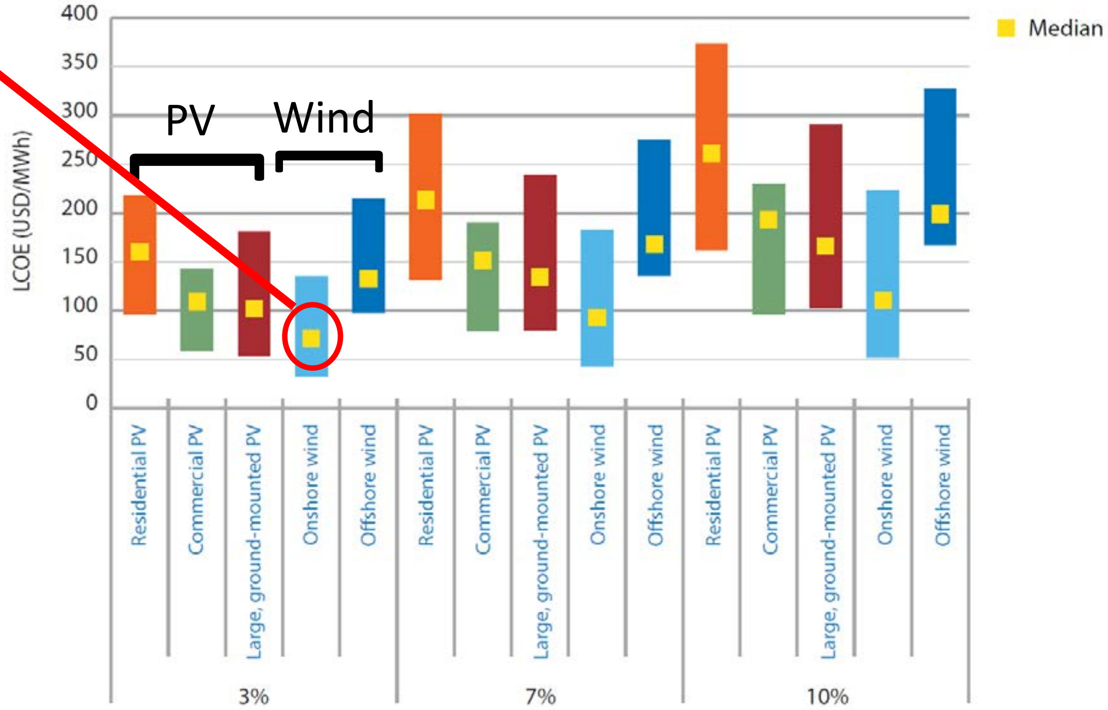
Cost of electricity



Discount rate

LCOE represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generating plant during an assumed financial life and duty cycle

CCGT=combined cycle gas turbine



LCOE (Levelized Cost Of Electricity) for various technologies (USD/MWh)

- ✓ **Measures lifetime costs divided by energy production**
- ✓ **Calculates present value of the total cost of building and operating a power plant over an assumed lifetime**
- ✓ **Allows comparison of different technologies with unequal life spans, project size, different capital cost, risk, return, and capacities**

Source: IEA/NEA, Projected Costs of Generating Electricity, 2015

Energy subsidies

Source: ENERGY SUBSIDIES, International Renewable Energy Agency (IRENA), https://www.irena.org/publications/2020/Apr/Energy-Subsidies-2020

Figure S-1: Total energy sector subsidies by fuel/source and the climate and health costs, 2017

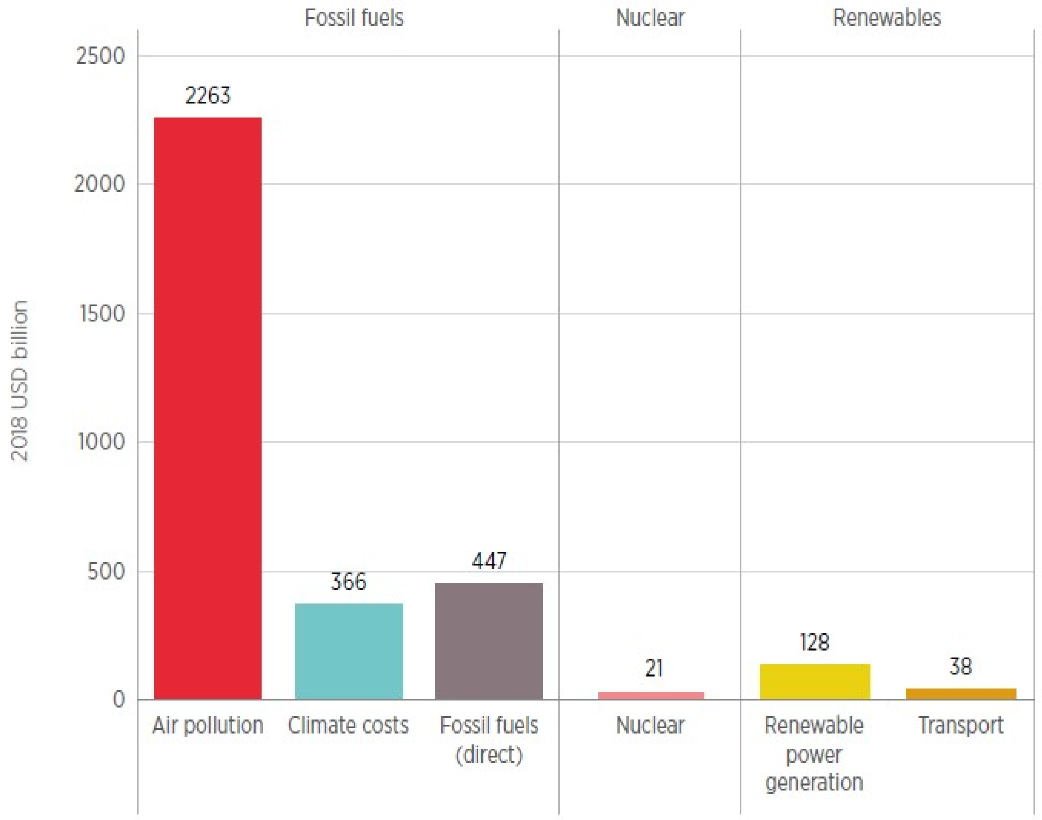
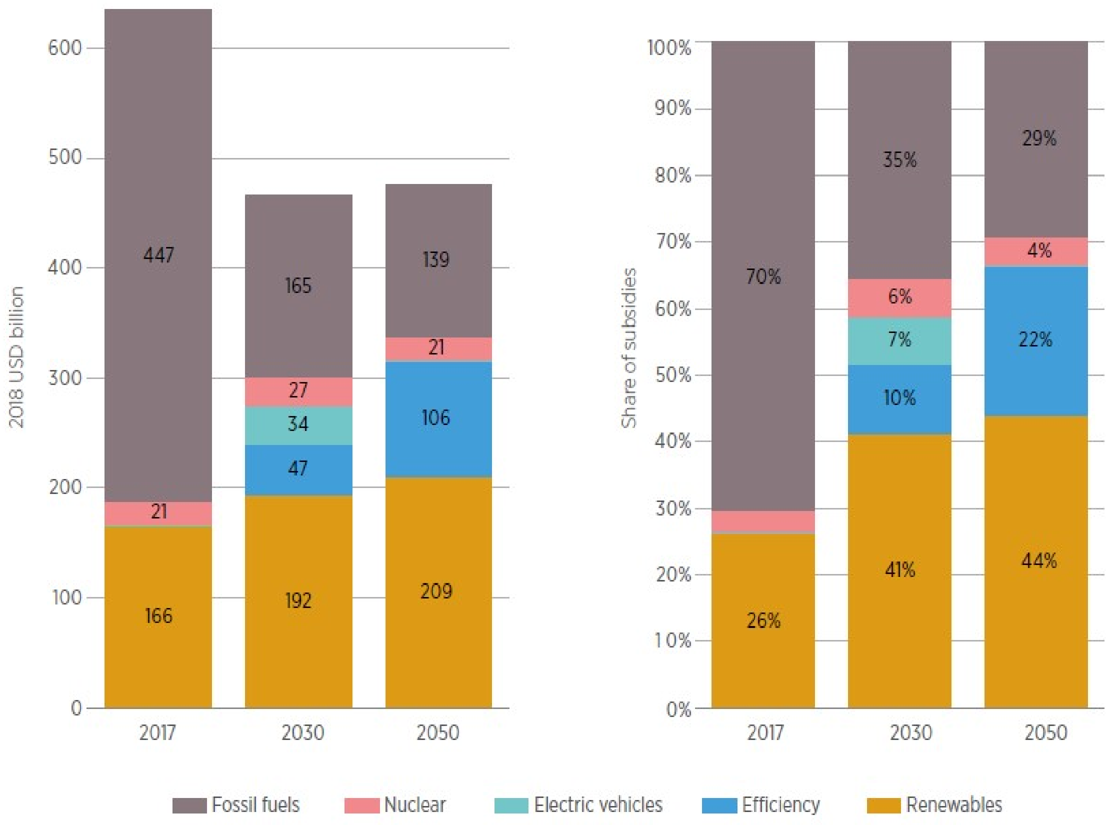


Figure S-2: Energy sector subsidies by source excluding climate and health costs in the REmap Case, 2017, 2030 and 2050

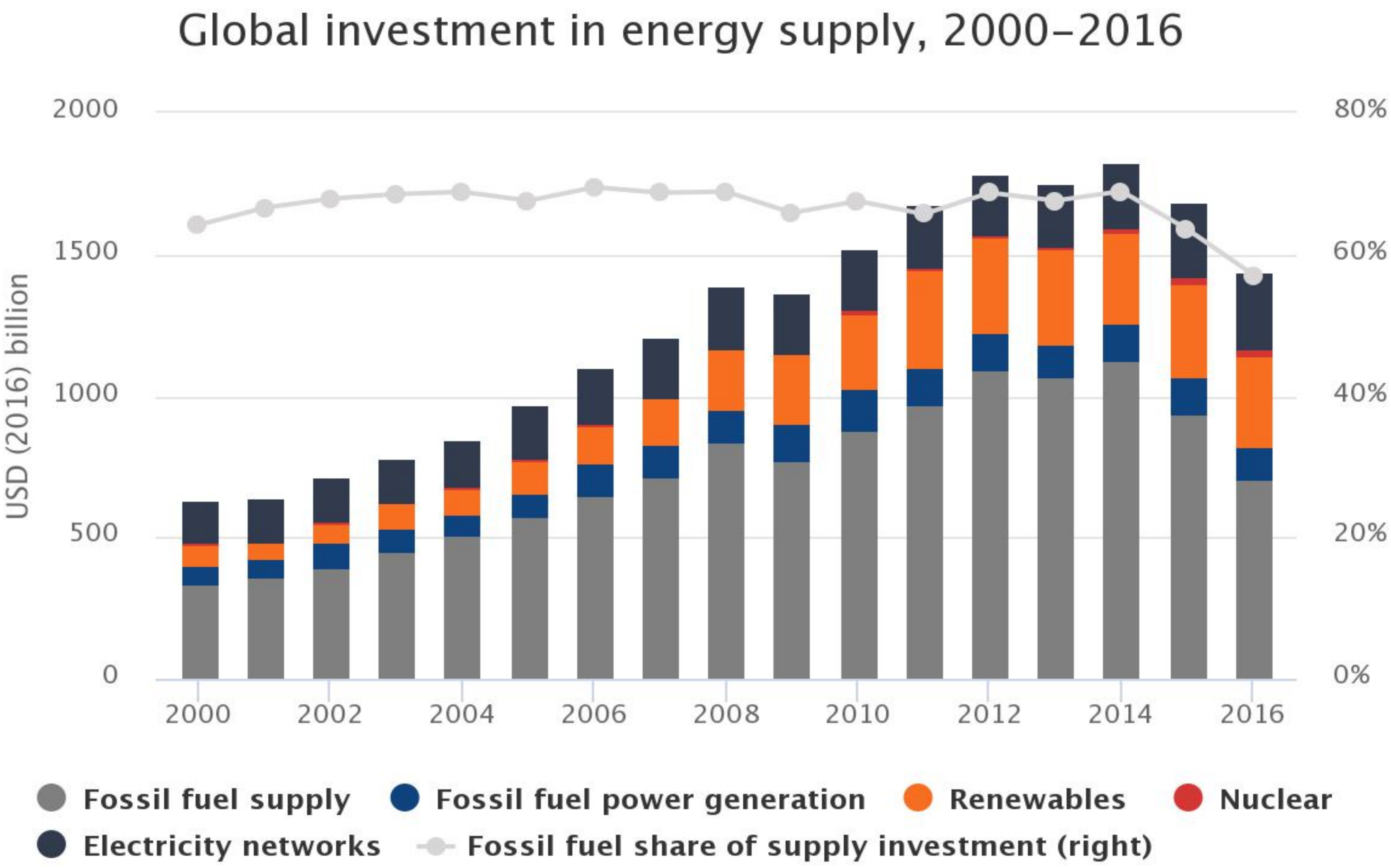


***Energy subsidies** are measures that keep prices for customers below market levels, or for suppliers above market levels, or reduce costs for customers and suppliers. Energy subsidies may be direct cash transfers to suppliers, customers, or related bodies, as well as indirect support mechanisms, such as tax exemptions and rebates, price controls, trade restrictions, and limits on market access.*

Investments

- *Although carbon dioxide emissions stagnated in 2016 for the third consecutive year due to protracted investment in energy efficiency, coal-to-gas switching and the cumulative impact of new low carbon generation,* ***the sanctioning of new low-carbon generation has stalled****.*
- ***Even though the contribution of new wind and solar PV to meeting demand has grown by around three-quarters over the past five years, the expected generation from this growth in wind and solar capacity is almost entirely offset by the slowdown in nuclear and hydropower investment decisions, which declined by over half over the same time frame****.*
- *Investment in new low-carbon generation needs to increase just to keep pace with growth in electricity demand growth, and there is considerable scope for more clean energy innovation spending by governments and, in particular, by the private sector.*

From:
[IEA - World Energy Investment 2017 - Executive Summary]()

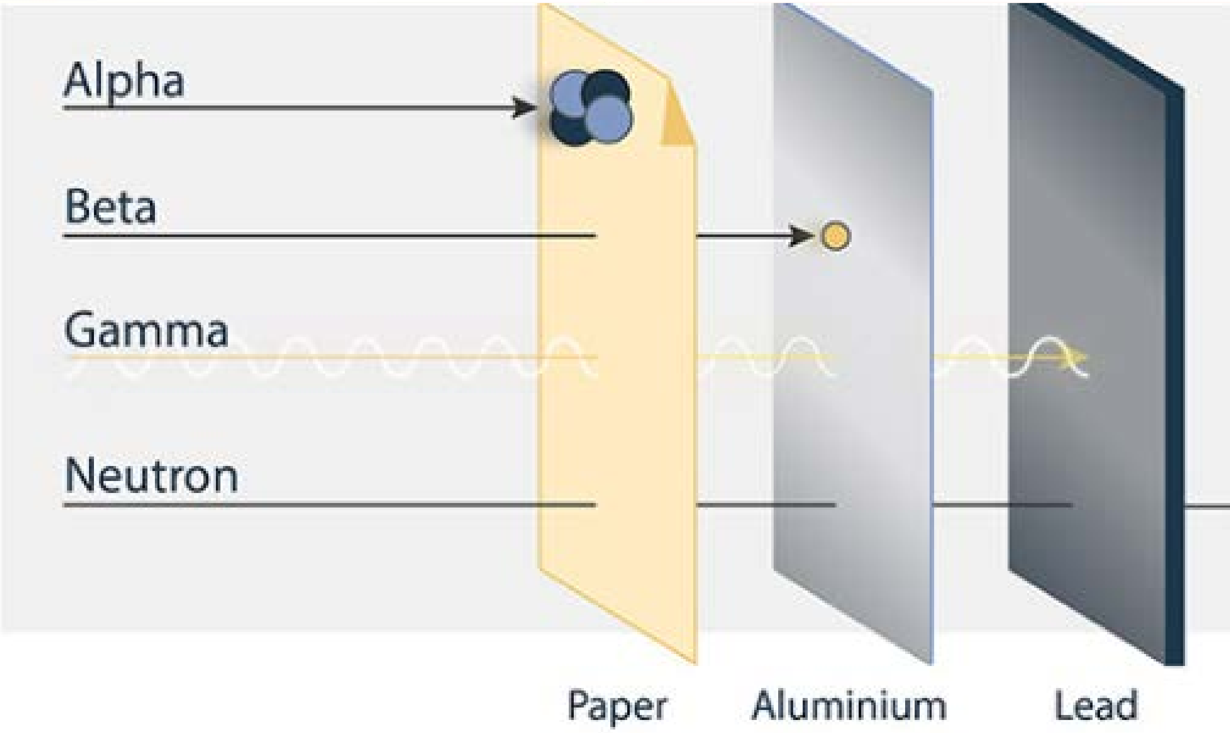

Global investment in energy supply, 2000–2016

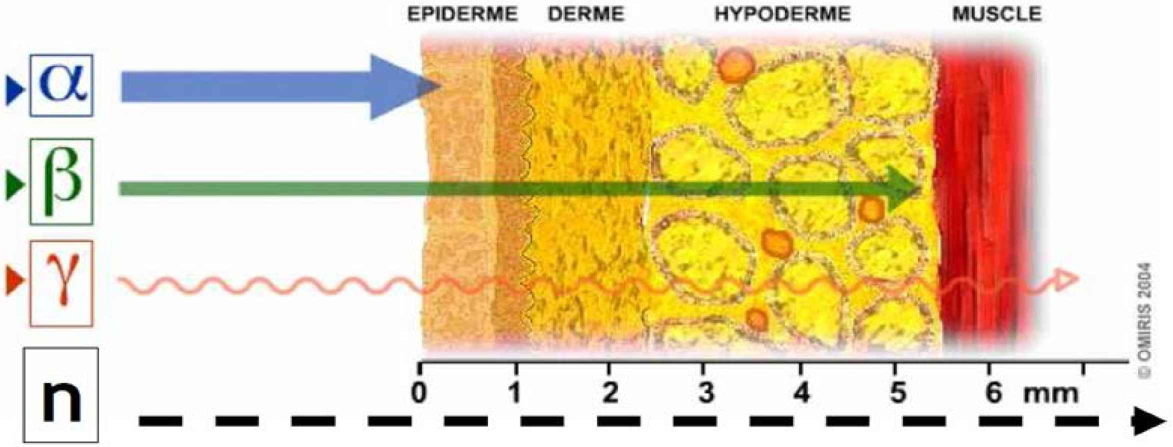
© OECD/IEA

Source:
[IEA - World Energy Investment 2017]()

Types of radiation

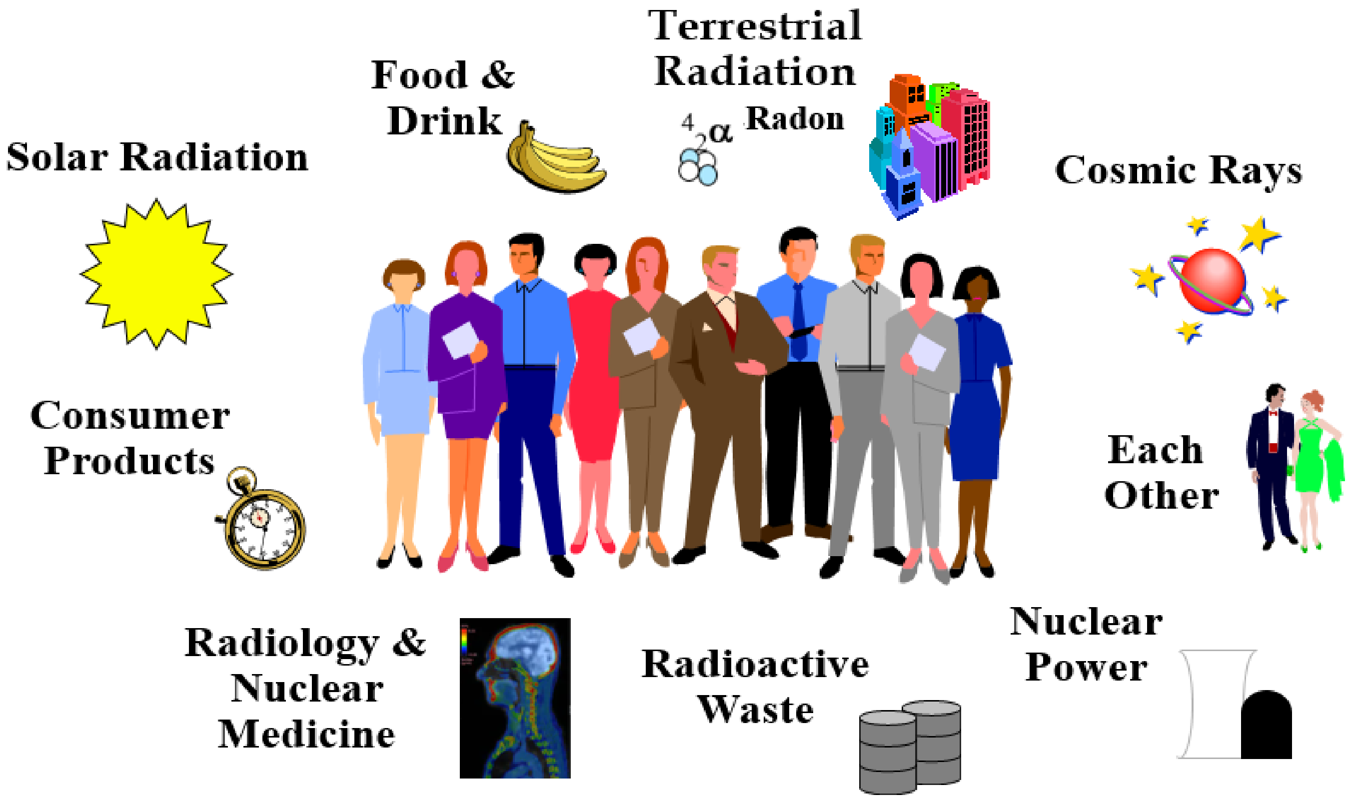
- *α–*particles are helium nuclei (2 protons + 2 neutrons); they are produced in radioactive decay and as a result of some nuclear interactions.
- *β–* particles are either electrons or positrons (antiparticle); they are produced in radioactive decay (e.g. of ***tritium***).
- ***Both α and β radiation are charged*** and therefore easily stopped in a very short range by interactions with the electrons of atoms. In radiation protection, they are not of concern with regards to ***external exposure***, but they are for contamination and ***internal exposure***
- ***Neutrons*** are produced as result of some nuclear reactions such as fission & fusion.
- ***γ-rays*** are photons produced as a result of neutron interactions and also from radioactive decay.
- ***X-rays*** are also photons but produced by electrons in the atoms instead: they are not nuclear radiation but they are ionizing radiation, and therefore of equal concern.
- ***X-rays, γ-rays and neutrons have no charge*** and can penetrate deeply into matter (specially neutrons). They are of concern with regards to external exposure.

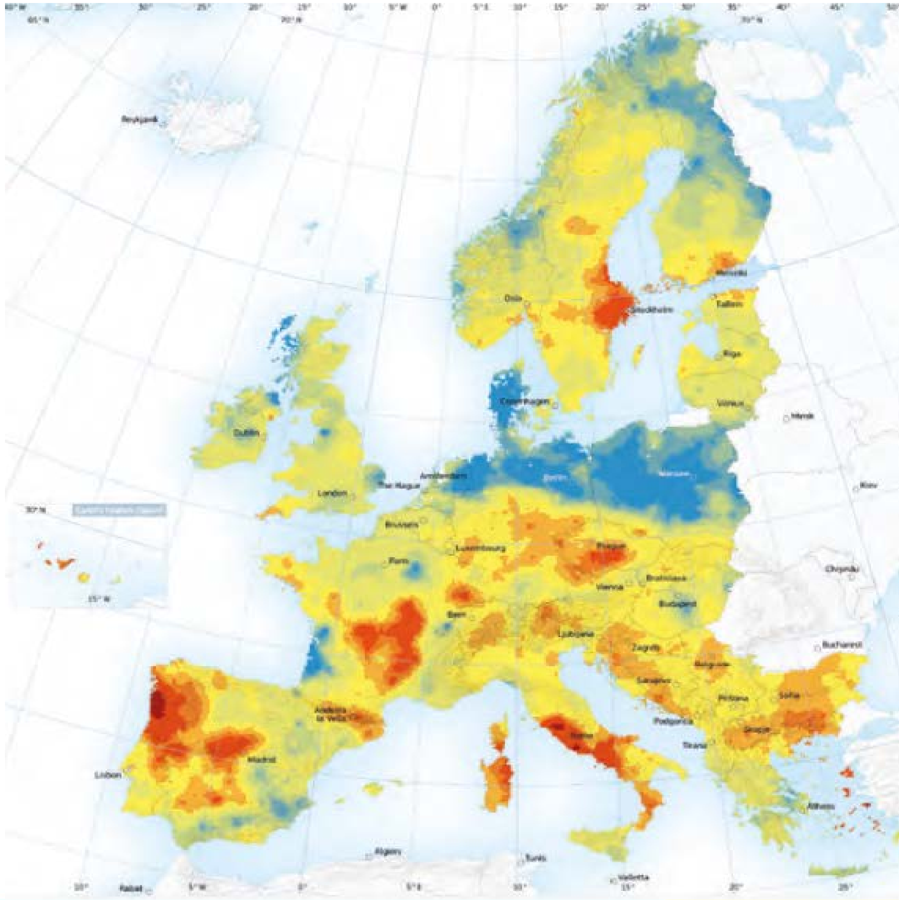




Radiation protection & shielding: health effects

- ***Ionising radiation*** can produce ***damage at biological level*** (→***radiation protection*** discipline primary concern).
- Ionising radiation occurs naturally on Earth. It is one of the mechanisms responsible for genetic mutations and thus natural ***evolution of species***. It also occurs as a result of some human activities.
- ***Background of natural radiation*** varies from tenths to tens of mSv/yr depending on altitude, geological terrain, housing type, diet, lifestyle…





Radiation protection & shielding: health effects

- ***Absorbed dose rate***, ***D_{abs}***, is the energy deposited by an ionising radiation *R* per unit time and per mass of a material *M*
- ***Dose is the time integral of a dose rate***. Absorbed dose is measured in ***gray*** (1 Gy = 1 J/kg), and absorbed dose rate in Gy/h.
- ***Biological dose*** to humans is derived from the dose (Gy) with weights for tissues and type of radiation (***Sievert*** 1 Sv = 1 J/kg), and biological dose rate in Sv/h.

Dose (Sv)	Deterministic effect
<0.1	No clinical symptoms observed
0.5-1	Nausea, decreased white blood cell count
1-4	Some bleeding, conjunctivitis, partial loss of hair, reduced sperm count
4-7	Within weeks: skin reddening, hemorrhages, widespread loss of hair, erythema, cataracts, permanent infertility, some intestinal symptoms (50% mortality)
7-12	Within days: severe gastrointestinal syndrome and hemorrhages (100% mortality)
>12	Within hours: very severe gastrointestinal syndrome and hemorrhages, radiation burns, skin ulceration
>100	Immediate disorientation, loss of consciousness

Risk	Annual occurrence
Radiation worker (20 mSv/yr)	**1 / 1,000**
Air crew worker	1 / 10,000
Construction worker	1 / 10,200
Road accidents	1 / 10,300
Public radiation exposure (1 mSv/yr)	**1 / 20,000**

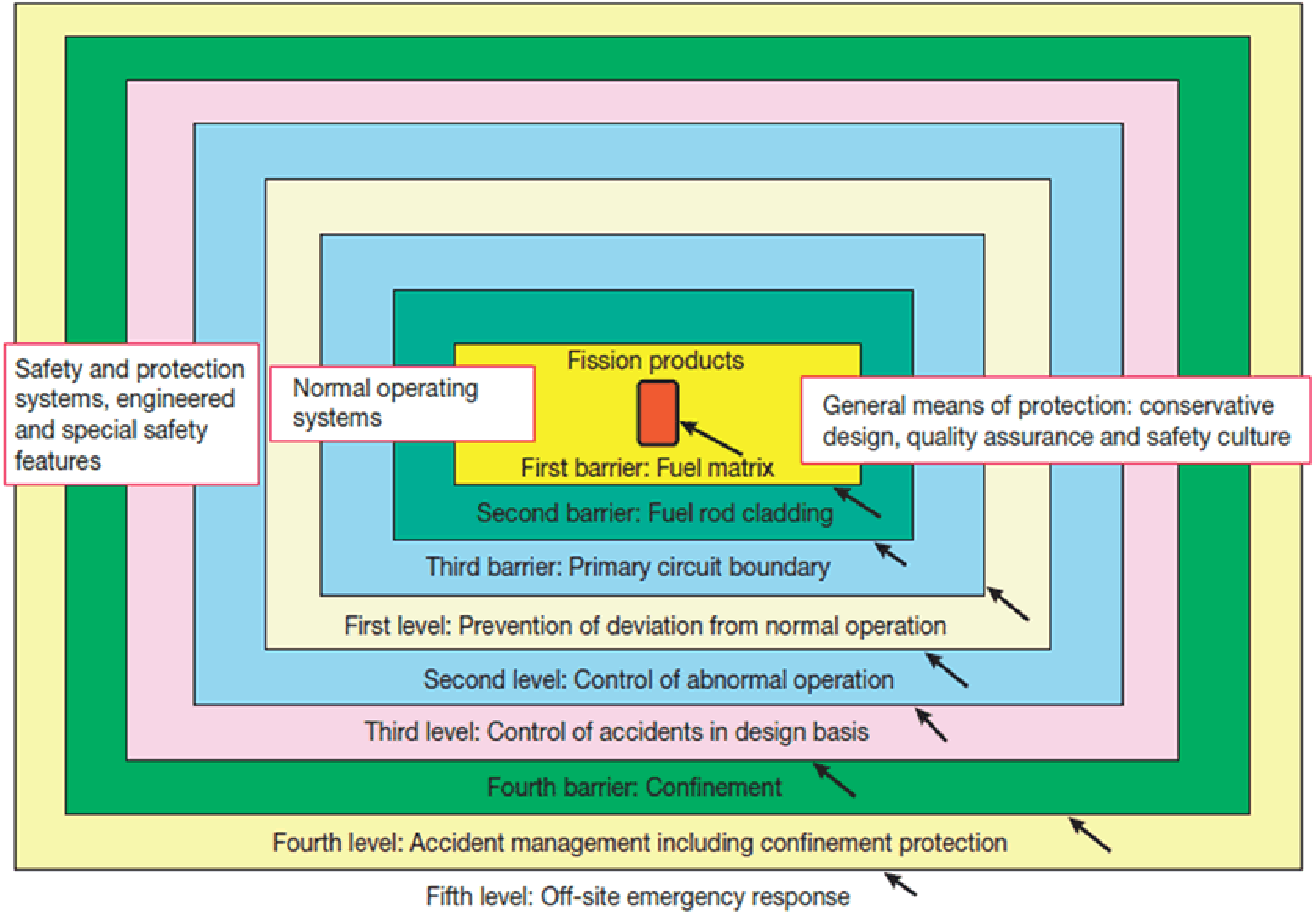
Safety Principles

The fundamental safety objective is to protect people and the environment from harmful effects of ionizing radiation

- **Principle 1: Responsibility for safety**. The prime responsibility for safety must rest with the person or organization responsible for facilities and activities that give rise to radiation risks
- **Principle 2: Role of government**. An effective legal and governmental framework for safety, including an independent regulatory body, must be established and sustained
- **Principle 3: Leadership and management for safety**. Effective leadership and management for safety must be established and sustained in organizations concerned with, and facilities and activities that give rise to, radiation risks
- **Principle 4: Justification of facilities & activities**. Facilities & activities giving rise to radiation risks must yield an overall benefit
- **Principle 5: Optimization of protection**. Protection must be optimized to provide the highest level of safety that can reasonably be achieved
- **Principle 6: Limitation of risks to individuals**. Measures for controlling radiation risks must ensure that no individual bears an unacceptable risk of harm
- **Principle 7: Protection of present and future generations**. People and the environment, present and future, must be protected against radiation risks.
- **Principle 8: Prevention of accidents.** All practical efforts must be made to prevent and mitigate nuclear or radiation accidents.
- **Principle 9: Emergency preparedness and response**. Arrangements must be made for emergency preparedness and response for nuclear or radiation incidents.
- **Principle 10: Protective actions to reduce existing or unregulated radiation risks**. Protective actions to reduce existing or unregulated radiation risks must be justified and optimized.

Source: IAEA – Fundamental Safety Principles – N. SF-1

Safety at work: defence in depth



Safety and protection systems, engineered and special safety features

Normal operating systems

Fission products

First barrier: Fuel matrix

General means of protection: conservative design, quality assurance and safety culture

Second barrier: Fuel rod cladding

Third barrier: Primary circuit boundary

First level: Prevention of deviation from normal operation

Second level: Control of abnormal operation

Third level: Control of accidents in design basis

Fourth barrier: Confinement

Fourth level: Accident management including confinement protection

Fifth level: Off-site emergency response

Control of abnormal operation should include some (negative) feedback mechanisms: e.g. if temperature (power) goes up, reaction cross section goes down

Courtesy of IAEA

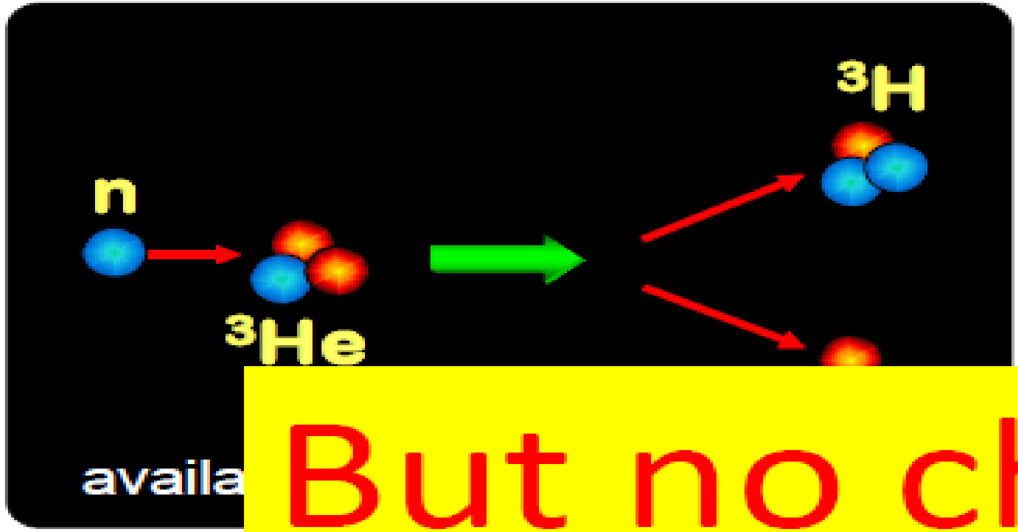
…? WHERE DO WE GO FROM HERE ? …

CONCLUSIONS AND OUTLOOK

- Nuclear fission is a mature technology that offer several outstanding advantages over other energy sources but also drawbacks that still hinder its broad public acceptance
- Among the main issues, in particular in the eyes of public, are those of ***safety, waste disposal and proliferation***
- To address such issues *evolutionary* (Gen III+) **AND** *revolutionary* design concepts (Gen IV, SMRs) are being pursued by the international community
- Once such issues and related technical challenges (e.g. waste incineration) will be solved nuclear fission shall enter a new NUCLEAR ERA for future generations fruition
- ***In view of mitigating CO2 emission and reduce our overall energy production environmental footprint it is ludicrous to restrict our options to any specific source (they all have issues!). <u>We need to aim for a optimal energy mix by deploying at best all (no fossil fuels) resources !</u>***

THANK YOU FOR YOUR ATTENTION

Other neutron absorption processes yielding energy



σ(thermal neutrons) ≈ 5330 b (barn, 1 b=10^{-24} cm^2, σ is proportional to the reaction probability, see later)

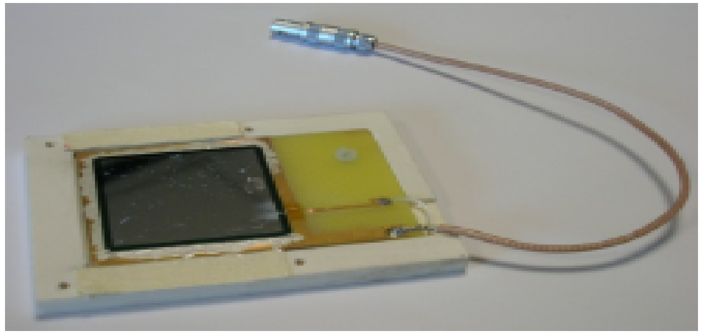
1 MeV= 1 MegaelectronVolt =
10^6 electronVolt = $10^6 \times 1.6 \times 10^{-19}$ Coulomb Volt =

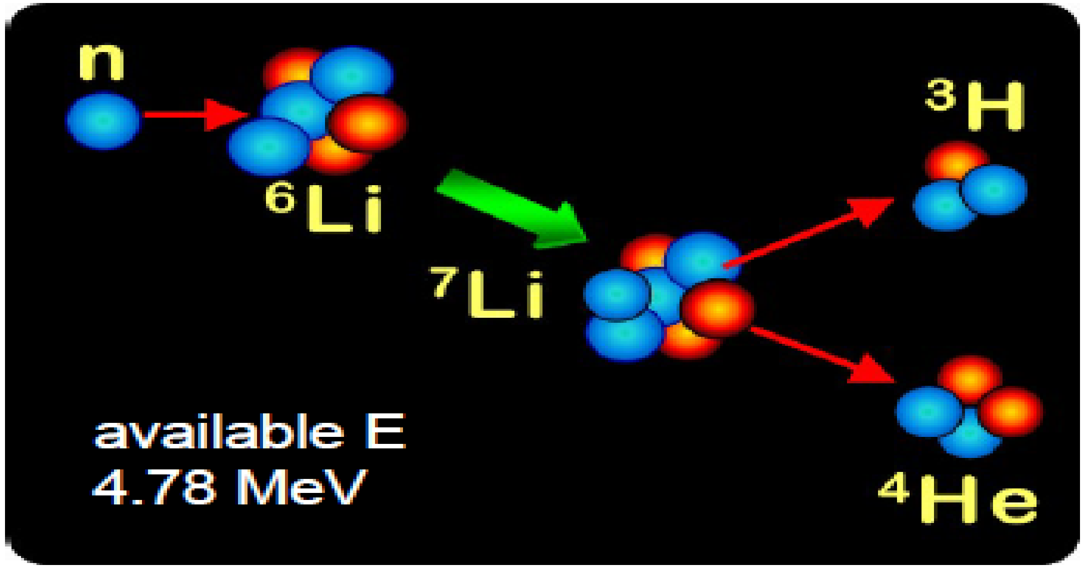
But no chain reaction

≈ 940 b

^{3}He neutron detector

neutron
detector
based on
a LiF film





How long will U resources last ?

As an example, fuel fabrication for a big nuclear power plant with 1000 MWe production, requires about 160.000 Kg natural U per year

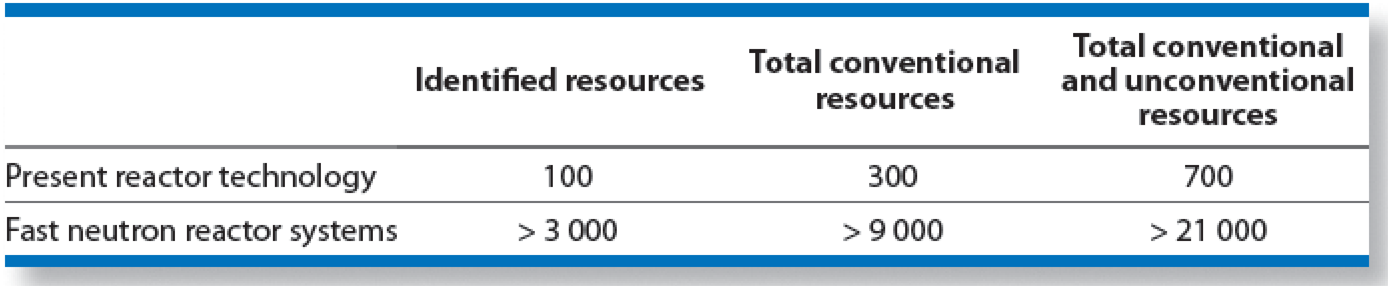
→ In the current scheme with about 450 reactors and 369.000 MWe capacity, “conventional” (cheap) reserves would last for another 80 years (maybe less if average reactor power will increase)

→ Should nuclear power increase as in some of the above scenarios, we should think about (more expensive) resources like phosphates (doable) or U from sea water (still under study)

→ Switching to fast reactors/Thorium cycle would increase availability to a few 100/few 1000 years

	million tons uranium
Australia	1.14
Kazakhstan	0.82
Canada	0.44
USA	0.34
South Africa	0.34
Namibia	0.28
Brazil	0.28
Russian Federation	0.17
Uzbekistan	0.12
World total (conventional reserves in the ground)	4.7
Phosphate deposits	22
Seawater	4 500

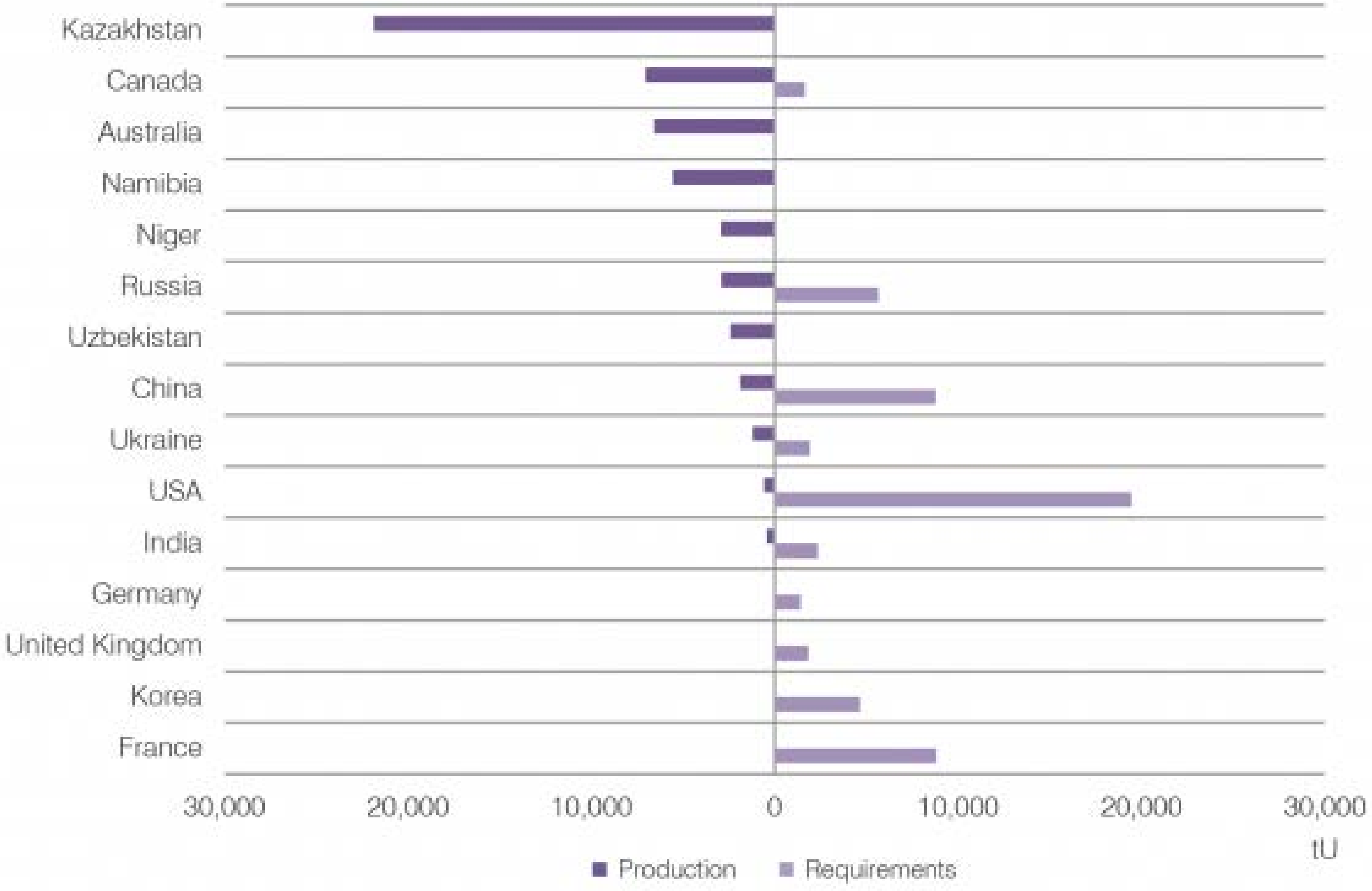
Lifetime of uranium resources (in years) for current reactor technology and future fast neutron systems (based on 2006 uranium reserves and nuclear electricity generation rate)



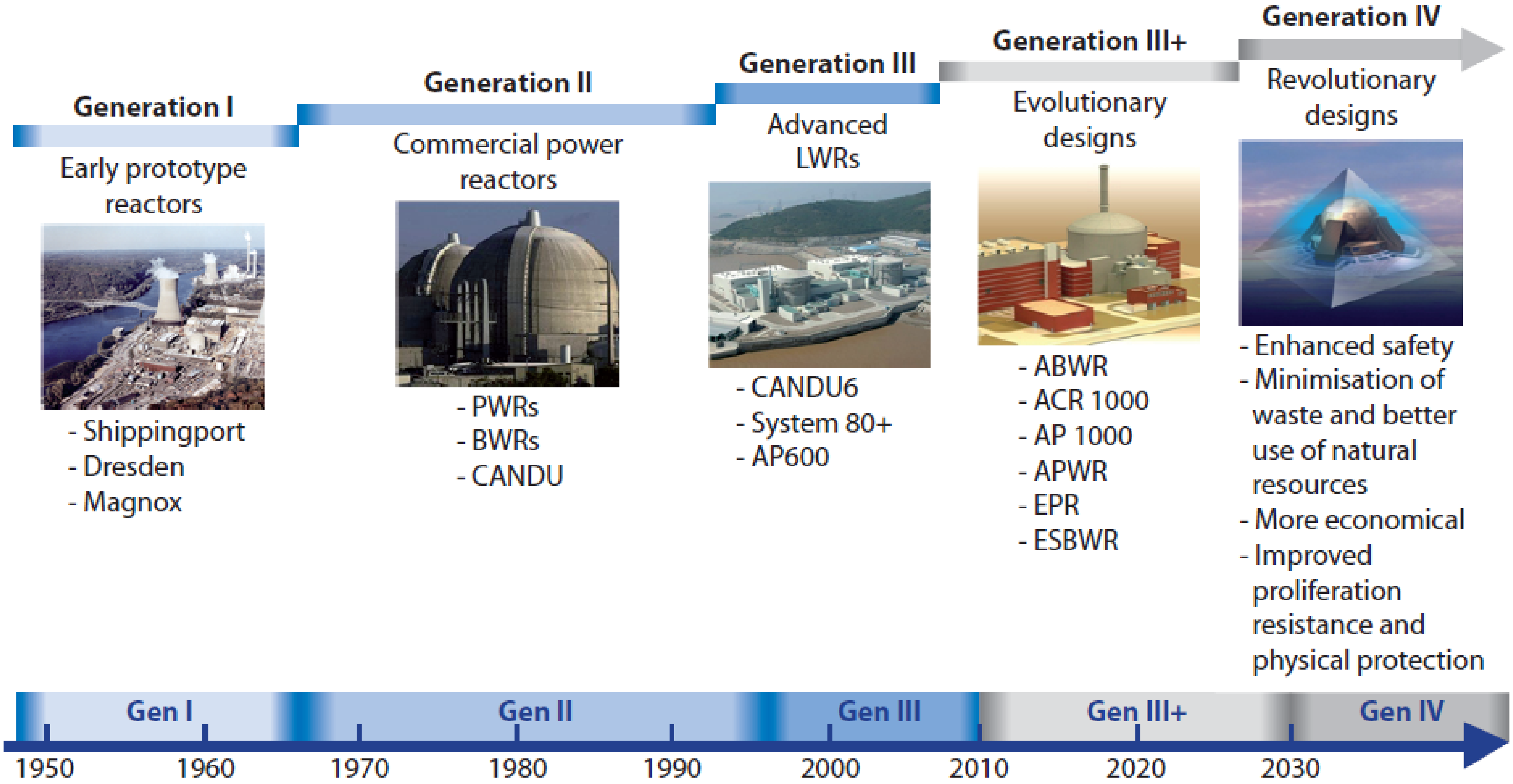
	Identified resources	Total conventional resources	Total conventional and unconventional resources
Present reactor technology	100	300	700
Fast neutron reactor systems	> 3 000	> 9 000	> 21 000

Source: OECD/NEA, Nuclear Energy Outlook, 2008

Uranium production and reactor requirements for major producing and consuming countries, as of end 2018, tU



Nuclear Reactors Generations



Generation I

Early prototype reactors

- Shippingport
- Dresden
- Magnox

Generation II

Commercial power reactors

- PWRs
- BWRs
- CANDU

Generation III

Advanced LWRs

- CANDU6
- System 80+
- AP600

Generation III+

Evolutionary designs

- ABWR
- ACR 1000
- AP 1000
- APWR
- EPR
- ESBWR

Generation IV

Revolutionary designs

- Enhanced safety
- Minimisation of waste and better use of natural resources
- More economical
- Improved proliferation resistance and physical protection

How much fuel ?

Suppose you've got a **reactor with 1 GW thermal power (1 GW_{th} → ~ 300 MW_e) = 10^9 Joule/sec**
Assume each fission releases order of 200 MeV energy = 3.2×10^{-11} Joule
→In the reactor the fission rate is about 3×10^{19} fissions/sec
→ which means that e.g. 3×10^{19} (nuclei of ^{235}U)/sec disappear (actually a bit more because of radiative capture)

Fuel	Istantaneous consumption (per second)	Yearly consumption (@90 % load factor*)
Uranium	0.012 g	340 Kg
Natural Gas	27 m^3	766 million m^3
Crude oil (average)	22.5 Kg	0.6 million tons
Lignite (average)	67 Kg	1.9 million tons
Coal (average)	34 Kg	1 million tons

For a thermal reactor (see later) loaded with mixed UO_2 fuel (density about 11 gr/cm^3) comprising 4 % ^{235}U and 96 % ^{238}U, this corresponds to 8500 Kg of fuel → 0.8 m^3

In practice, there has to be much more as the chain reaction needs the presence of fissile nuclei at all times → the reactor has to be critical at all times
However, ^{235}U consumption is partly compensated by Plutonium (^{239}Pu) burn up

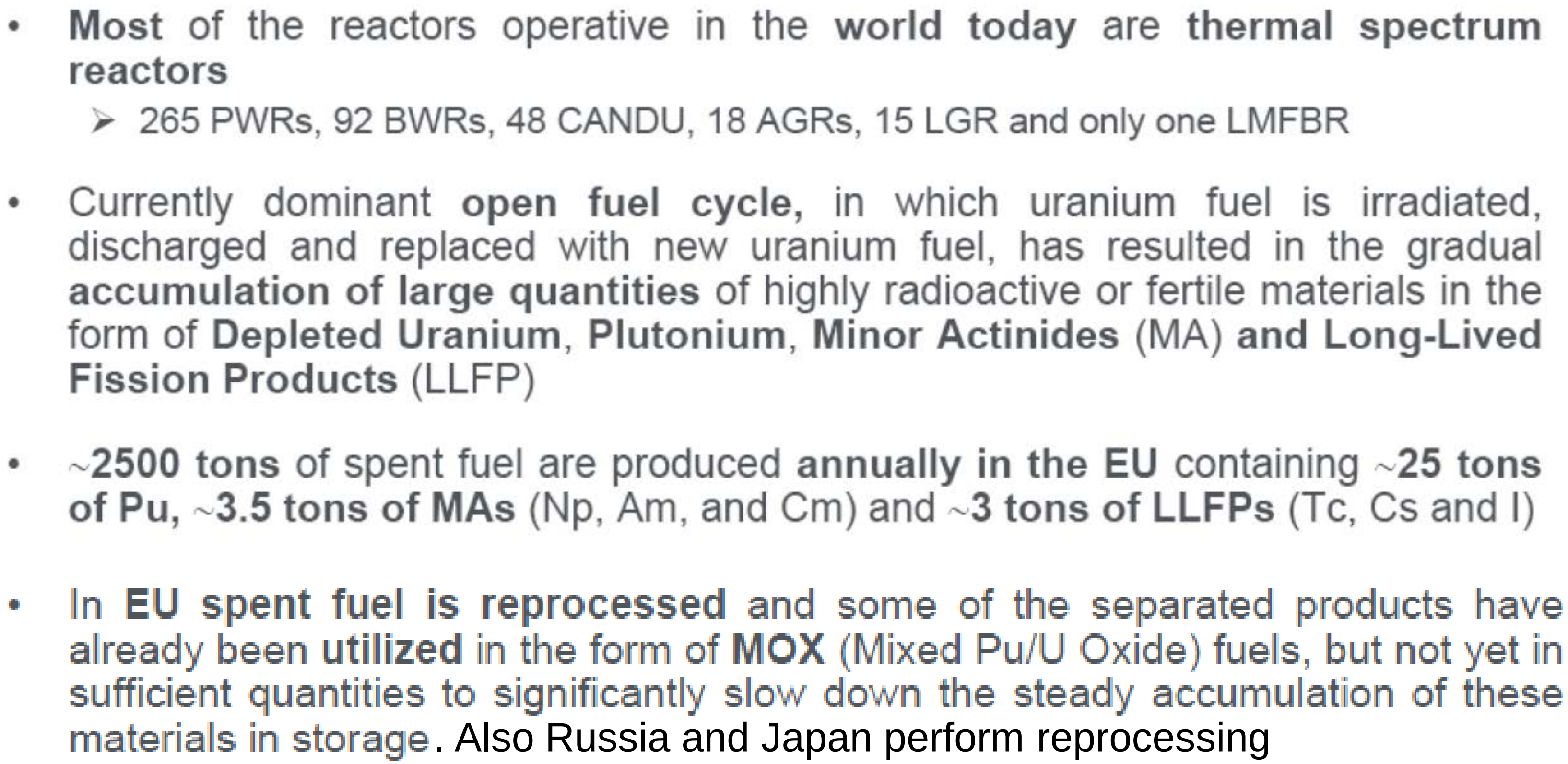
(*) load factor=percentage of time when the reactor is actually producing electricity

NUCLEAR WASTE MANAGEMENT

Indicative volumes (m^3) of radioactive waste produced annually by a typical
1 000 MWe nuclear plant, for once-through cycle and with reprocessing of spent fuel

Waste type	Once-through fuel cycle	Recycling fuel cycle
LLW/ILW	50-100	70-190
HLW	0	15-35
Spent Fuel	45-55	0

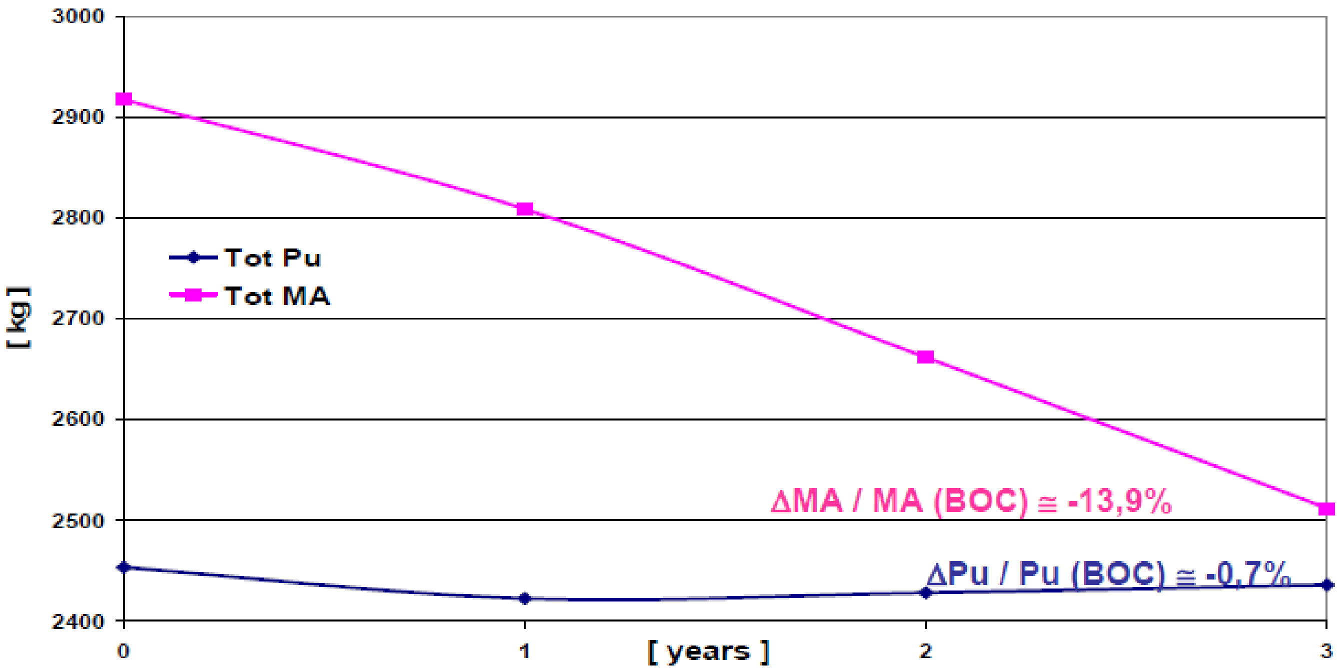
Source: OECD/NEA, Nuclear Energy Today, 2012



- **Most** of the reactors operative in the **world today** are **thermal spectrum reactors**
  - ➢ 265 PWRs, 92 BWRs, 48 CANDU, 18 AGRs, 15 LGR and only one LMFBR
- Currently dominant **open fuel cycle,** in which uranium fuel is irradiated, discharged and replaced with new uranium fuel, has resulted in the gradual **accumulation of large quantities** of highly radioactive or fertile materials in the form of **Depleted Uranium**, **Plutonium**, **Minor Actinides** (MA) **and Long-Lived Fission Products** (LLFP)
- ~**2500 tons** of spent fuel are produced **annually in the EU** containing ~**25 tons of Pu**, ~**3.5 tons of MAs** (Np, Am, and Cm) and ~**3 tons of LLFPs** (Tc, Cs and I)
- In **EU spent fuel is reprocessed** and some of the separated products have already been **utilized** in the form of **MOX** (Mixed Pu/U Oxide) fuels, but not yet in sufficient quantities to significantly slow down the steady accumulation of these materials in storage. Also Russia and Japan perform reprocessing

Example of ADS performance

- ✓ Main design missions of EFIT are effective transmutation rate of the Minor Actinides (MA) and effective electric energy generation
  - ❑ Fuelled with only MA (Uranium free fuel)
  - ❑CER-CER (Pu,Am,Cm)O2-x – MgO
  - ❑CER-MET (Pu,Am,Cm)O2-x – 92Mo
- ✓ Minimize the burn-up reactivity swing without burning and breeding Pu



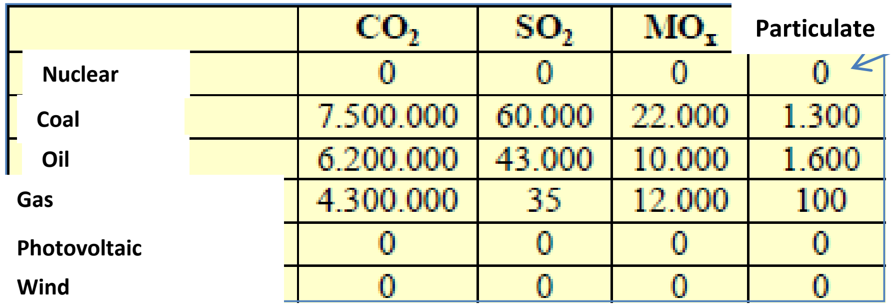
BU → {
-40,17 kg (MA) / TWh
-1,74 kg (Pu) / TWh

Emissions compared

The environmental impact of various energy sources is measured by looking at the release of pollutants and greenhouse gases (about 27 % of CO_2 emissions comes from electricity production).

Emissions from a 1000 MWe power plant [t/year]

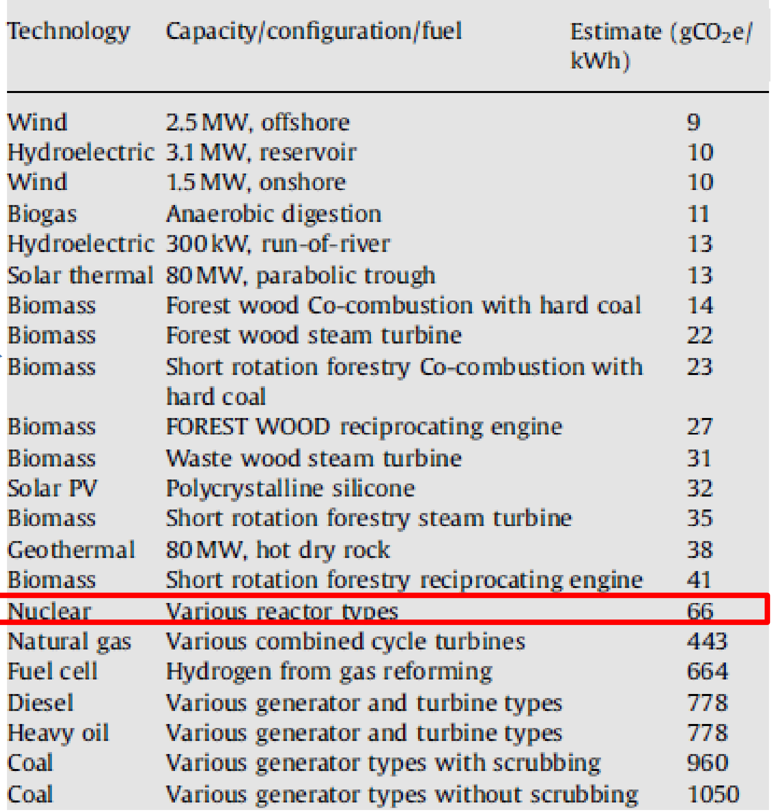
(Source: Energy in Italy: problems and perspectives (1990 - 2020) – Italian Physical Society 2008)



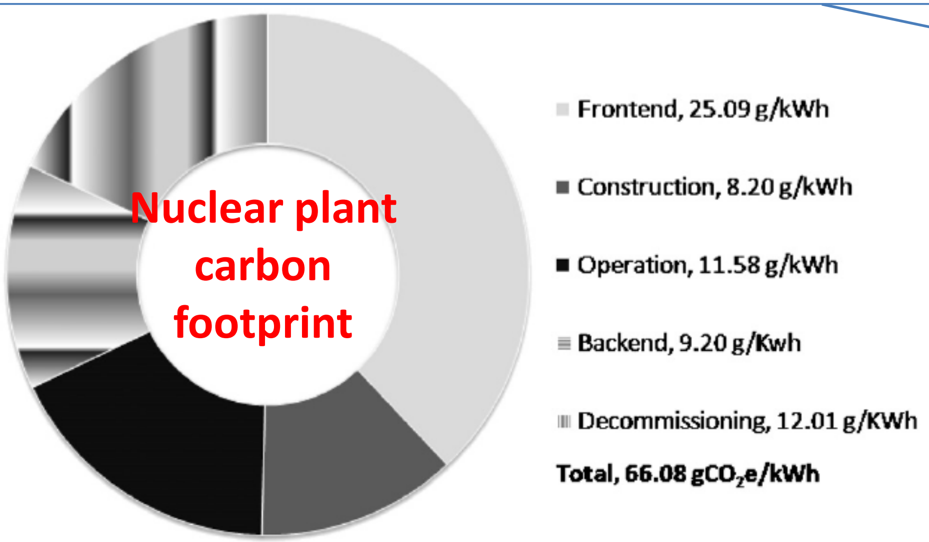
	CO_2	SO_2	MO_x	Particulate
Nuclear	0	0	0	0
Coal	7.500.000	60.000	22.000	1.300
Oil	6.200.000	43.000	10.000	1.600
Gas	4.300.000	35	12.000	100
Photovoltaic	0	0	0	0
Wind	0	0	0	0

Only fuel burnup

If one considers the whole plant lifetime (from fuel mining/extraction to decommissioning)

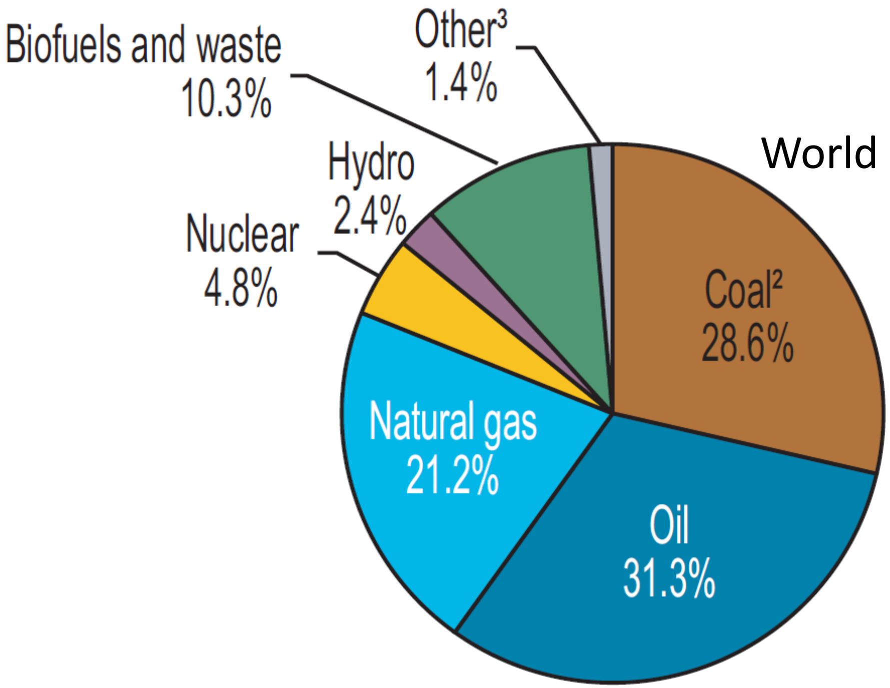


Technology	Capacity/configuration/fuel	Estimate (gCO_2e/kWh)
Wind	2.5 MW, offshore	9
Hydroelectric	3.1 MW, reservoir	10
Wind	1.5 MW, onshore	10
Biogas	Anaerobic digestion	11
Hydroelectric	300 kW, run-of-river	13
Solar thermal	80 MW, parabolic trough	13
Biomass	Forest wood Co-combustion with hard coal	14
Biomass	Forest wood steam turbine	22
Biomass	Short rotation forestry Co-combustion with hard coal	23
Biomass	FOREST WOOD reciprocating engine	27
Biomass	Waste wood steam turbine	31
Solar PV	Polycrystalline silicone	32
Biomass	Short rotation forestry steam turbine	35
Geothermal	80 MW, hot dry rock	38
Biomass	Short rotation forestry reciprocating engine	41
Nuclear	Various reactor types	66
Natural gas	Various combined cycle turbines	443
Fuel cell	Hydrogen from gas reforming	664
Diesel	Various generator and turbine types	778
Heavy oil	Various generator and turbine types	778
Coal	Various generator types with scrubbing	960
Coal	Various generator types without scrubbing	1050



Source: Benjamin K. Sovacool, Energy Policy 36 (2008) 2940– 2953

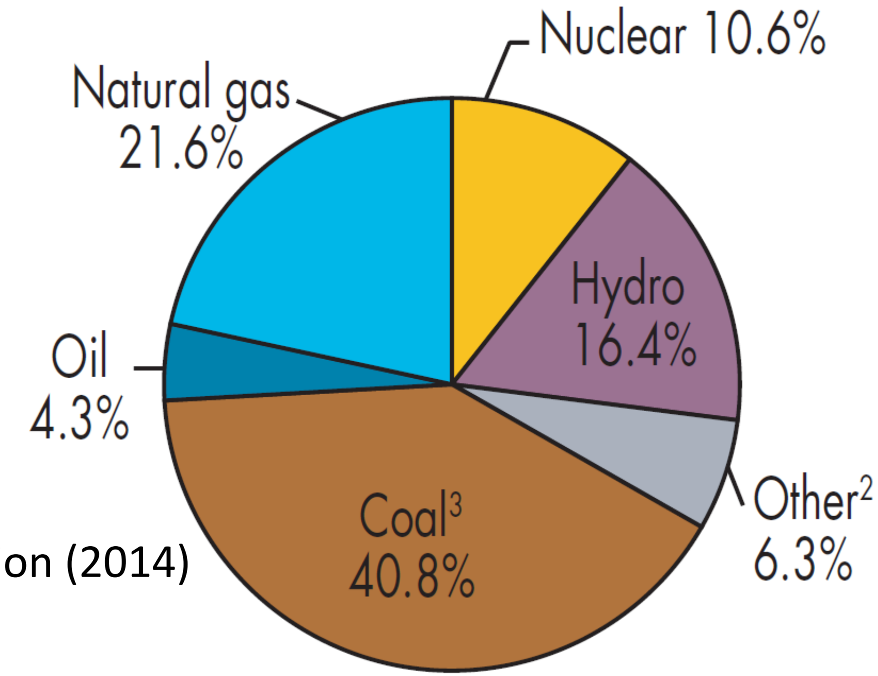
Nuclear energy in the worldwide perspective



World Total Primary Energy Supply (TPES, 2014)

13 699 Mtoe(*)

1. World includes international aviation and international marine bunkers.
2. In these graphs, peat and oil shale are aggregated with coal.
3. Includes geothermal, solar, wind, heat, etc.



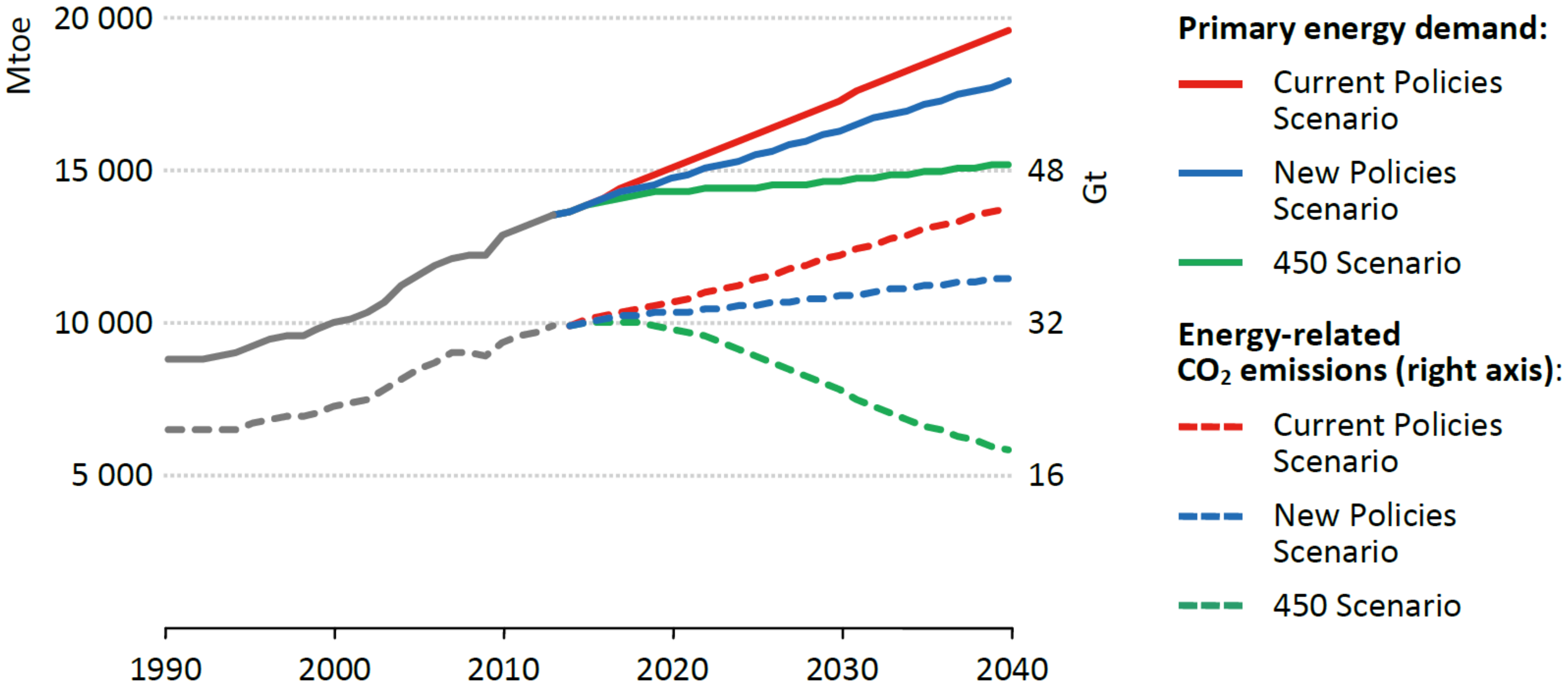
World electricity generation (2014)

23 816 TWh (**)

Source: IEA, Key World Energy Statistics, 2016

(*) 1 tonne oil equivalent (toe) = 41.868 GJ = 10 Gcal = 11.63 MWh
(**) 1 TW = 10^{12} Joule/s, 1 TWh = $3.6\cdot10^{15}$ J

World primary energy demand and CO_2 emissions by scenario

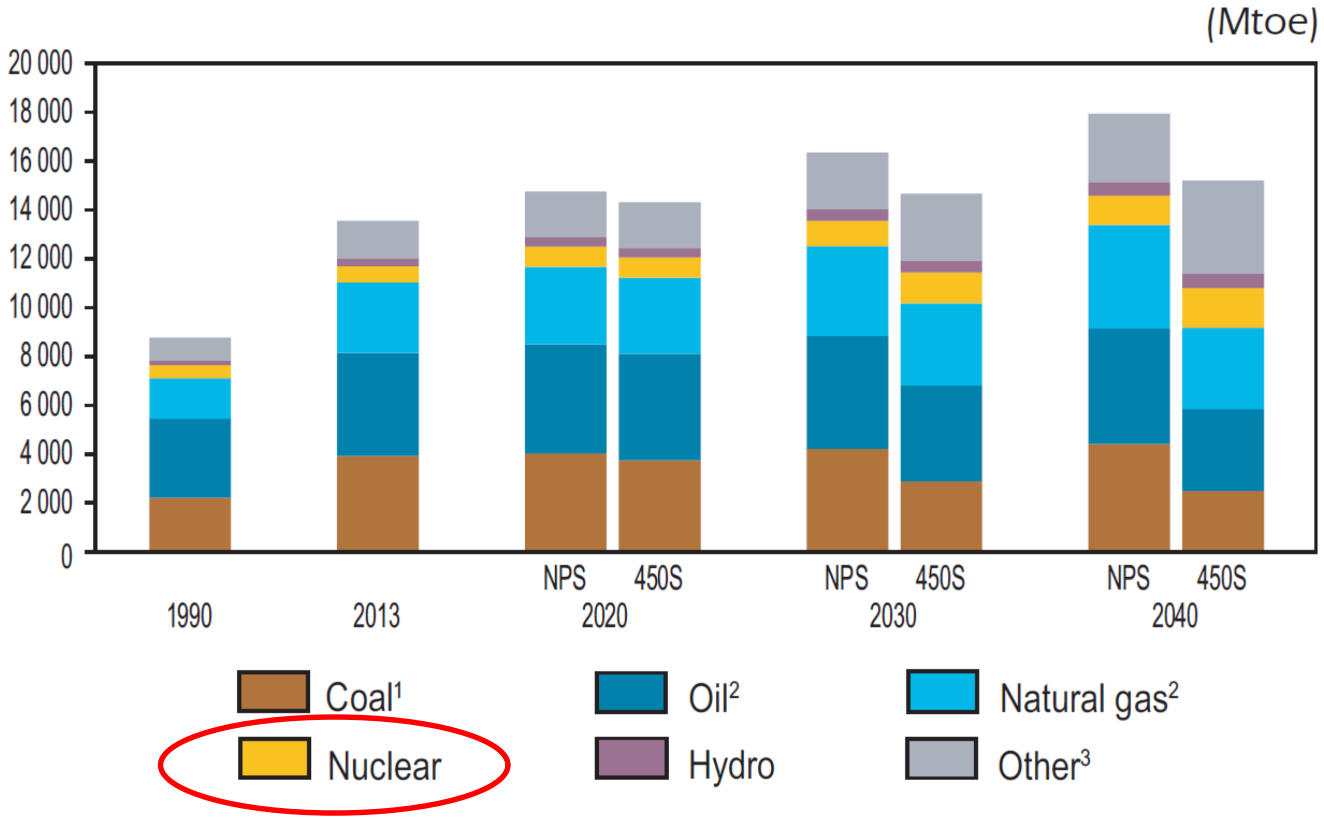


- **New Policies → continuation of existing policies and measures, cautious implementation of announced policy proposals**
- **Current Policies → only consider policies enacted as of mid-2015, can be used as baseline**
- **450 → CO_2 limited to 450 ppm → 50% chance of limiting long-term average global temperatures increase to < 2 °C**

Source: IEA - World energy outlook 2015

Worldwide energy trends: projection on energy supply

Total primary energy supply by fuel type (in million tonnes oil equivalent)



NPS: New Policies Scenario
(based on policies under consideration)

450S: 450 Scenario[4]
(based on policies needed to limit global average temperature increase to 2 °C)

Source: IEA, Key World Energy Statistics, 2016

---

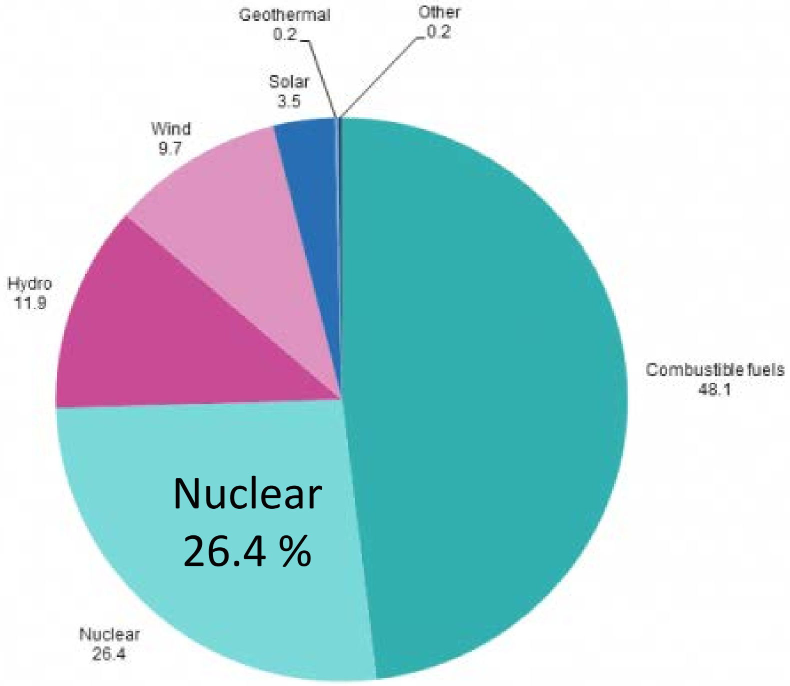
1. In these graphs, peat and oil shale are aggregated with coal.
2. Includes international aviation and marine bunkers.
3. Includes biofuels and waste, geothermal, solar, wind, tide, etc.
4. Based on a plausible post-2015 climate-policy framework to stabilise the long-term concentration of global greenhouse gases at 450 ppm CO2-equivalent.

NUCLEAR REACTORS IN EUROPE

As of November 2016 there was a total of 186 nuclear power plant units with an installed electric net capacity of 164 GWe in operation in Europe (five thereof in the Asian part of the Russian Federation) and 15 units with an electric net capacity 13.7 GWe were under construction in six countries

Country	in operation		under construction	
	number	net capacity MWe	number	net capacity MWe
Belarus	-	-	2	2.218
Belgium	7	5.913	-	-
Bulgaria	2	1.926	-	-
Czech Repuplic	6	3.930	-	-
Finland	4	2.752	1	1.600
France	58	63.130	1	1.630
Germany	8	10.799	-	-
Hungary	4	1.889	-	-
Netherlands	1	482	-	-
Romania	2	1.300	-	-
Russia	36	26.557	7	5.468
Slovakia	4	1.814	2	880
Slovenia	1	688	-	-
Spain	7	7.121	-	-
Sweden	10	9.651	-	-
Switzerland	5	3.333	-	-
Ukraine	15	13.107	2	1.900
United Kingdom	15	8.918	-	-
Total	**186**	**163.685**	**15**	**13.696**

Source: European Nuclear Society



Source: Eurostat

Source: Eurostat (online data code: nrg_105a)