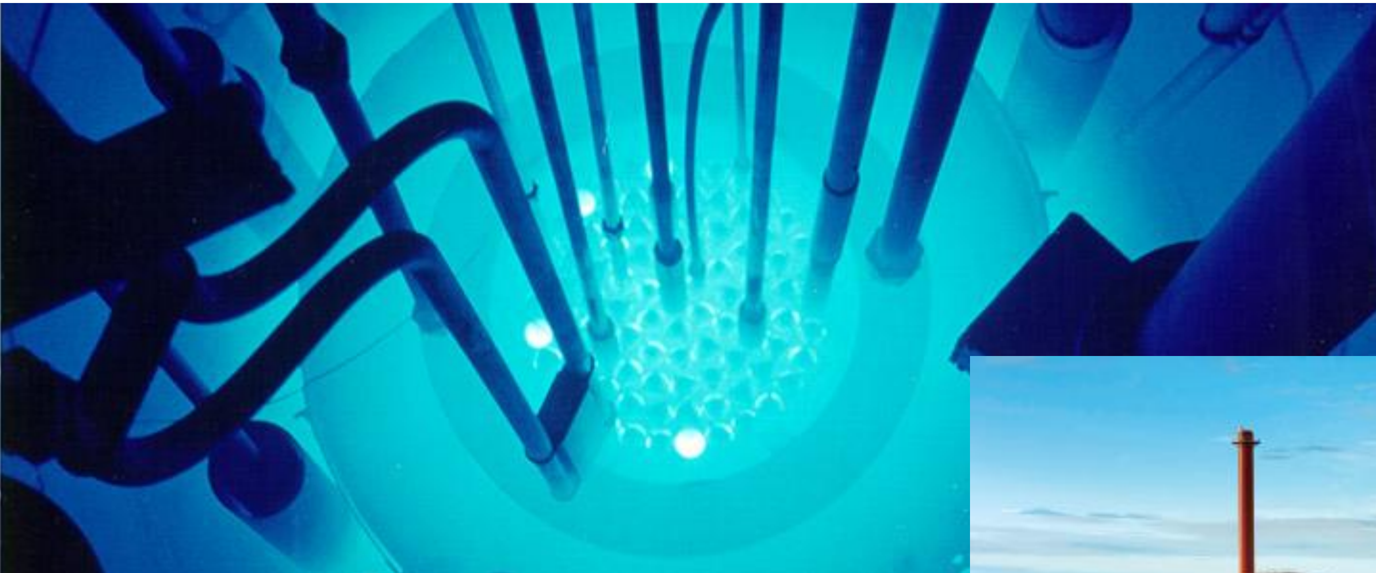
Energy from nuclear fission



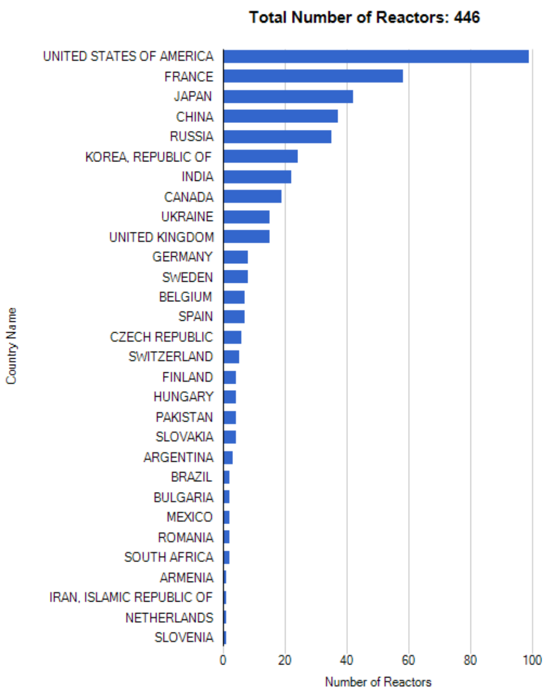
M. Ripani
INFN Genova, Italy

Joint EPS-SIF International School on Energy 2017

Plan

- ✓ Figures about nuclear energy worldwide
- ✓ Safety
- ✓ Fuel resources
- ✓ Fuel cycle
- ✓ Radioactive waste
- ✓ Fast systems
- ✓ Generation IV
- ✓ ADS
- ✓ The European Roadmap
- ✓ Lead-based systems
- ✓ Waste processing and fuel cycle

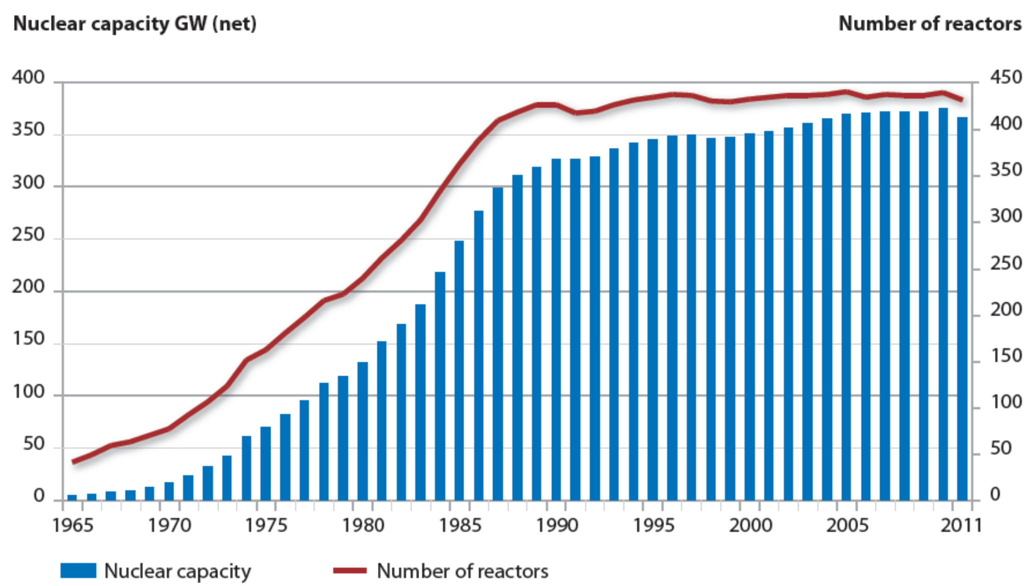
Nuclear energy today in the world



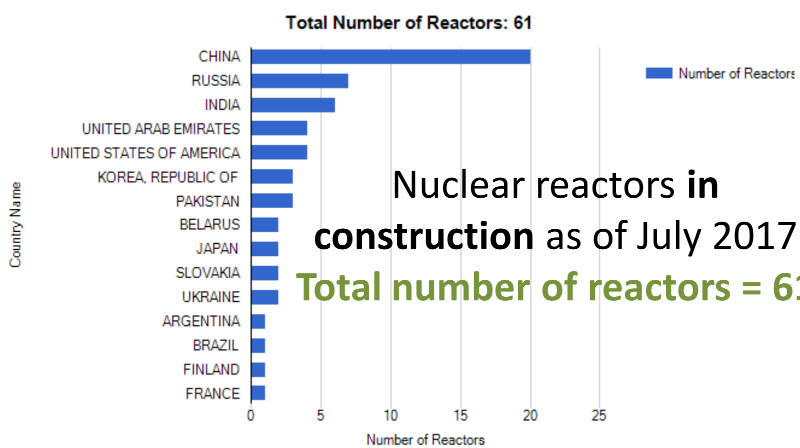
Nuclear reactors **in operation or in long-term shutdown** as of July 2017

Total number of reactors = 446

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



Source: OECD/NEA – Nuclear Energy Today 2012

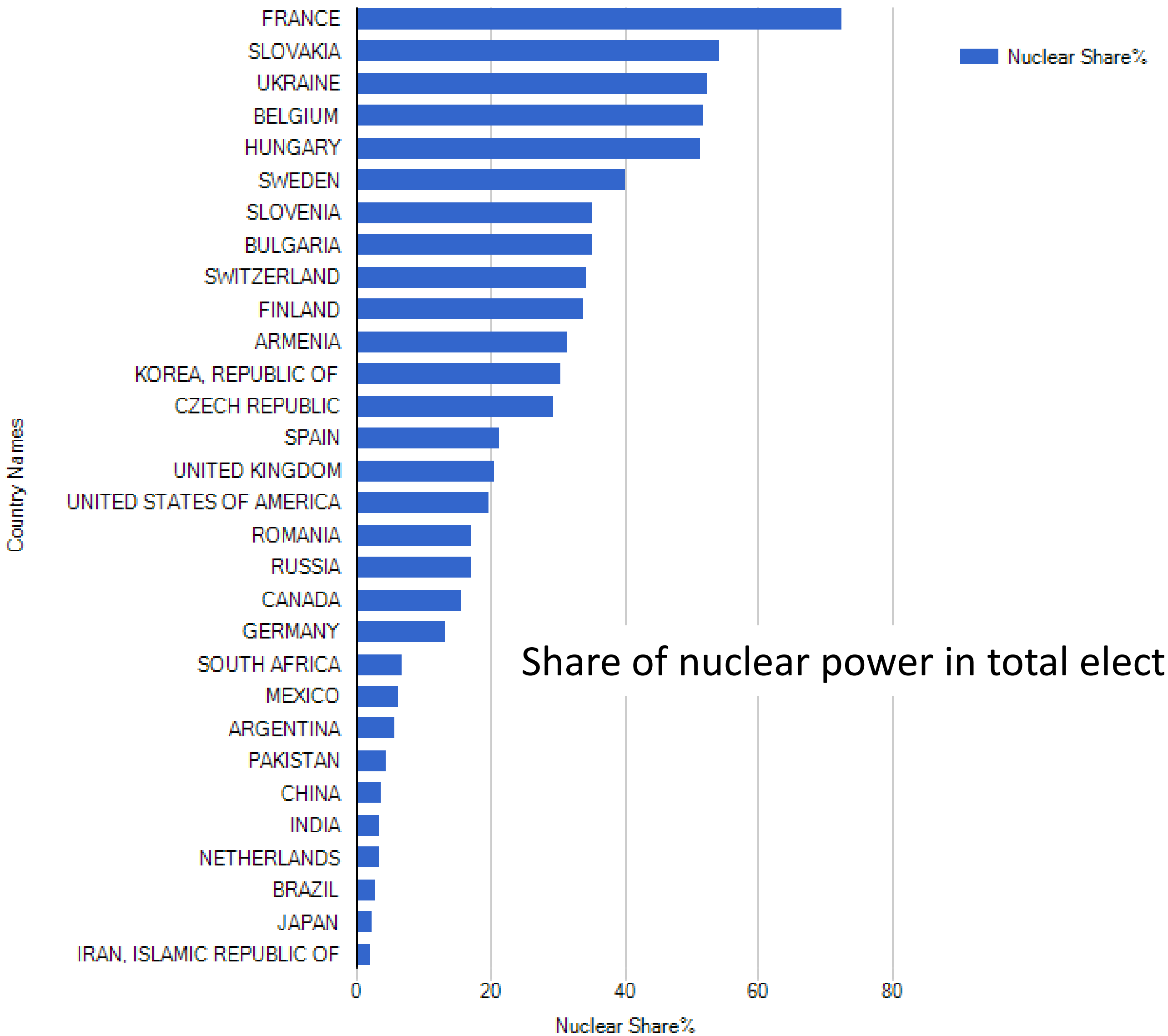


Nuclear reactors **in construction** as of July 2017

Total number of reactors = 61

Source: IAEA Power Reactor Information System (PRIS)

Share of electricity

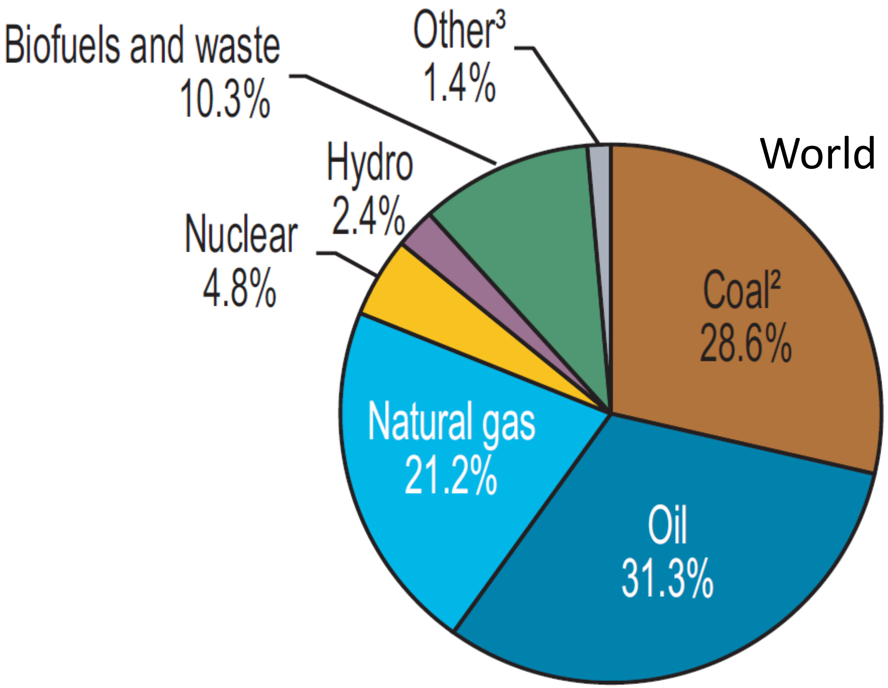


Share of nuclear power in total electricity (July 2017)

Source: IAEA Power Reactor Information System (PRIS)

Nuclear energy in the worldwide perspective

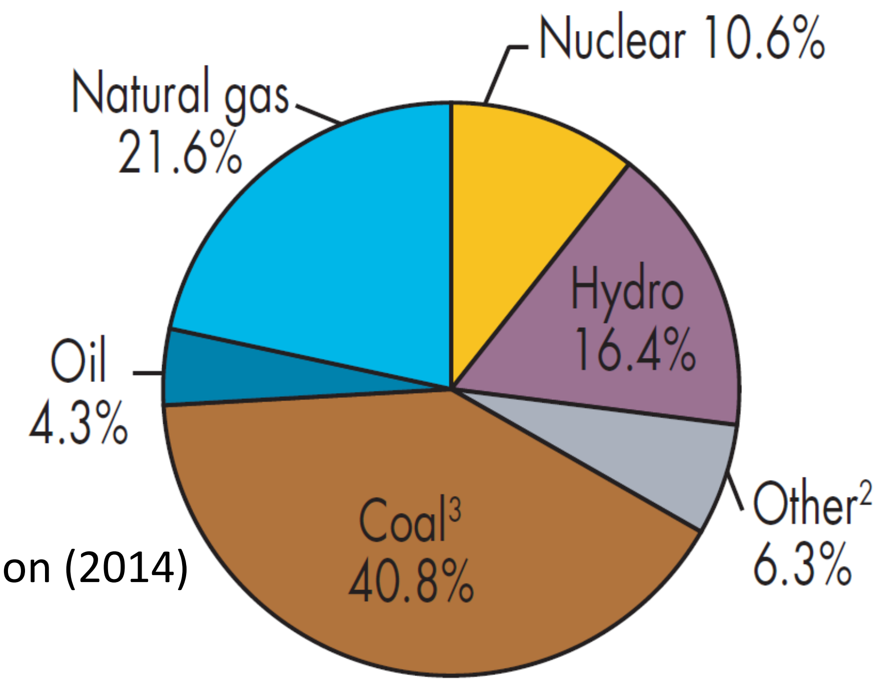
World Total Primary Energy Supply (TPES, 2014)



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)

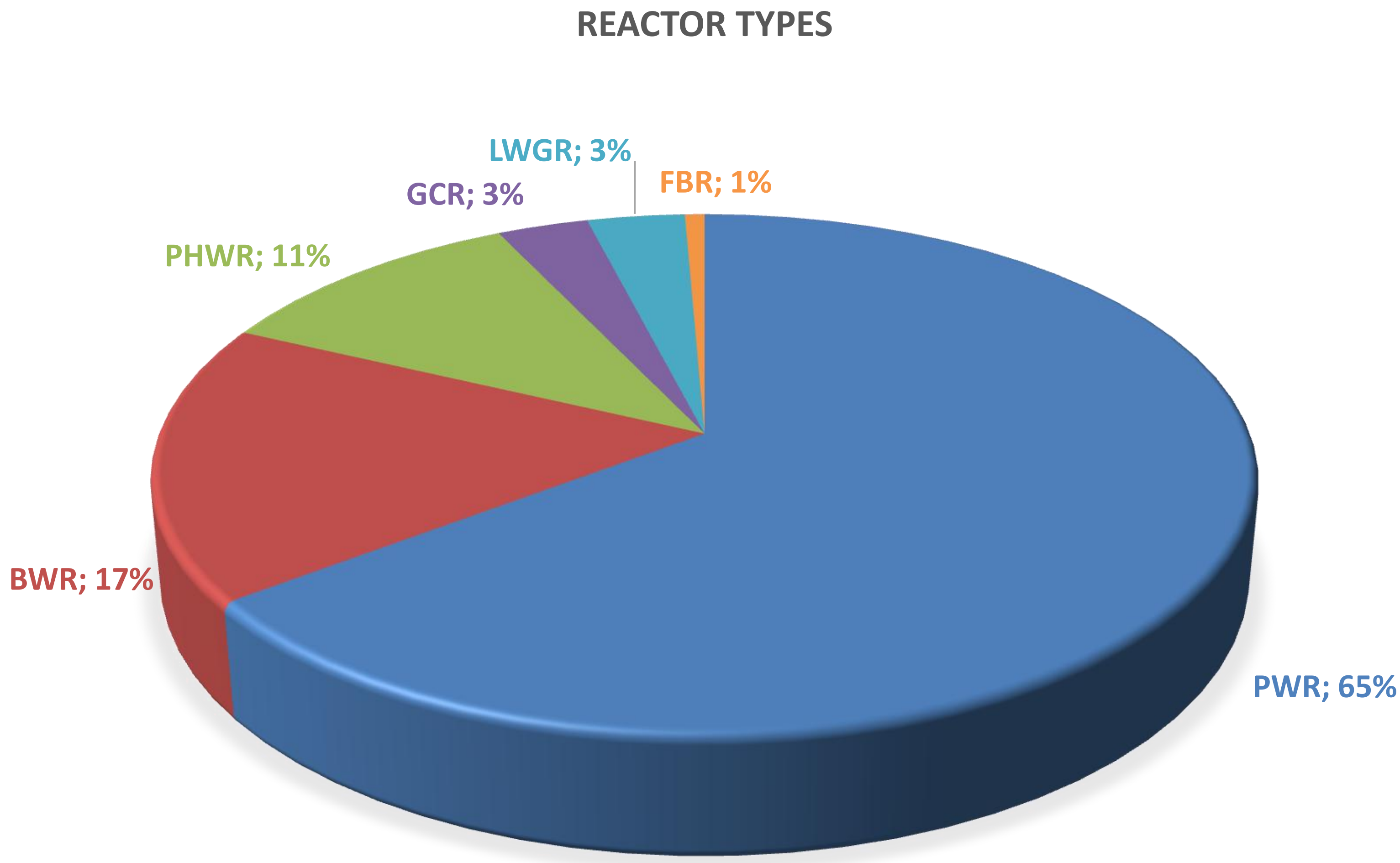


Source: IEA, Key World Energy Statistics, 2016

23 816 TWh (**)

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

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

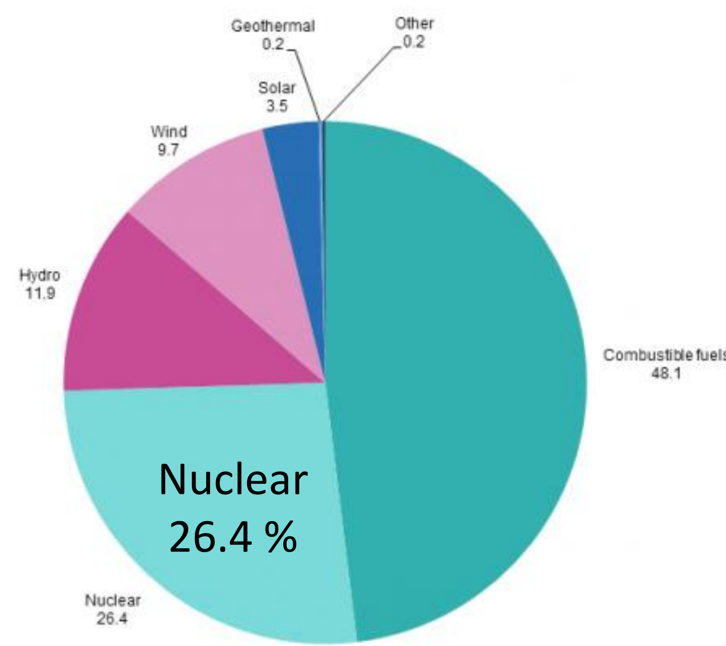
Source: European Nuclear Society

The situation 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

Source: European Nuclear Society

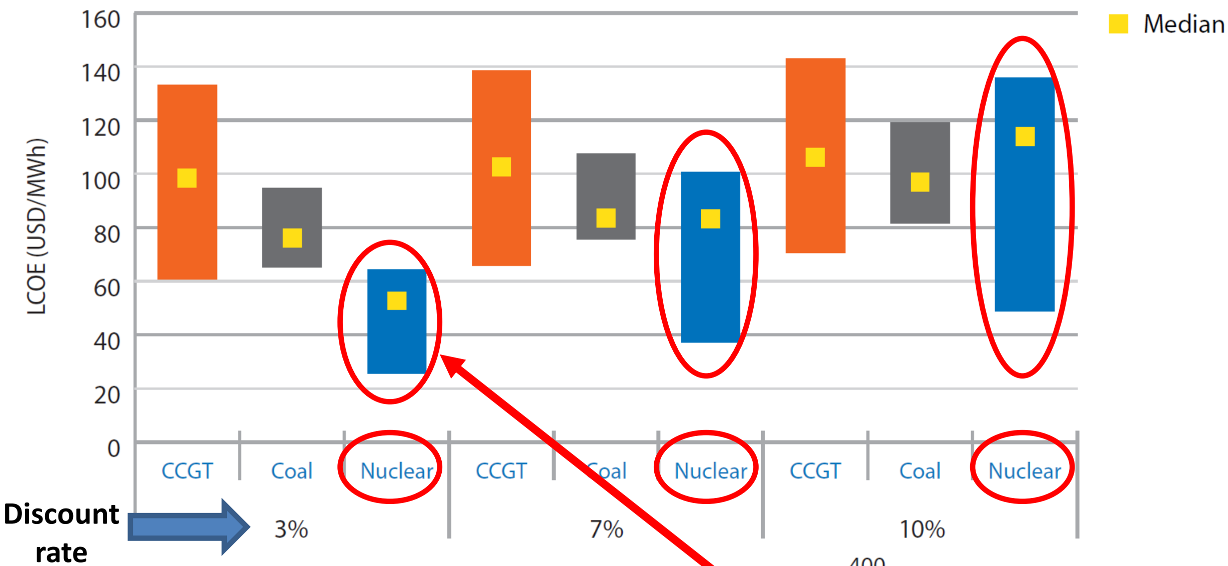
Country	in operation		under construction	
	number	net capacity MWe	number	net capacity MWe
Belarus	-	-	2	2.218
Belgium	7	5.913	-	-
Bulgaria	2	1.926	-	-
Czech Repuplic	6	3.930	-	-
Finland	4	2.752	1	1.600
France	58	63.130	1	1.630
Germany	8	10.799	-	-
Hungary	4	1.889	-	-
Netherlands	1	482	-	-
Romania	2	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**

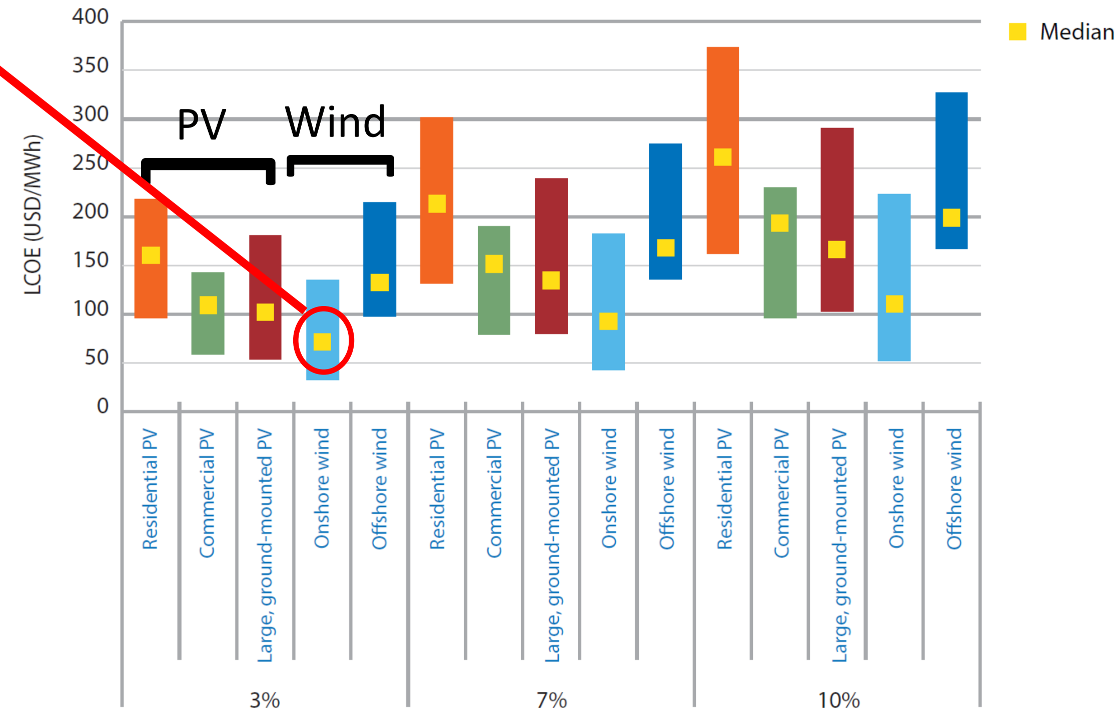


Source: Eurostat

ta code: nrg_105a)

Cost of electricity





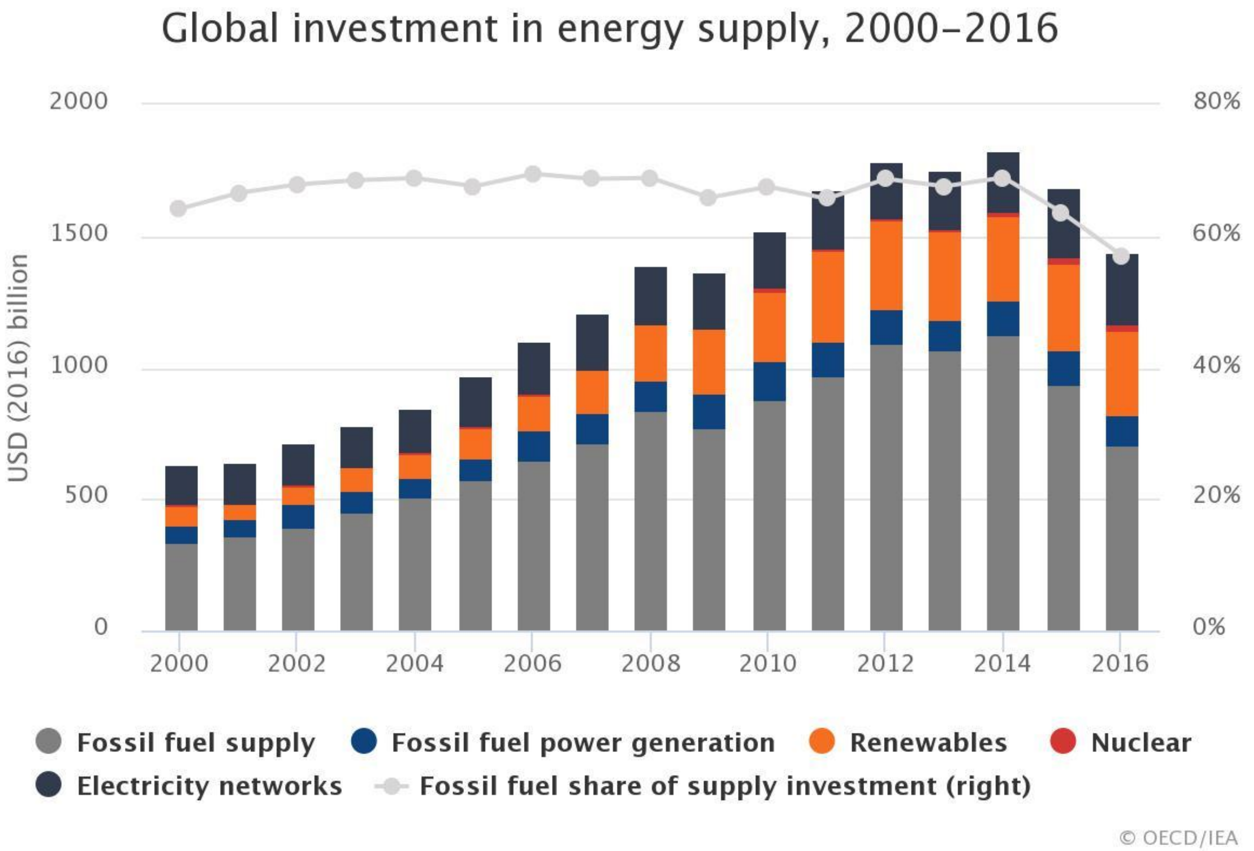
LCOE (Levelized Cost Of Electricity) for various technologies (USD/MWh)

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

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

Investments

Source:
[IEA - World Energy Investment 2017]



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]

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).

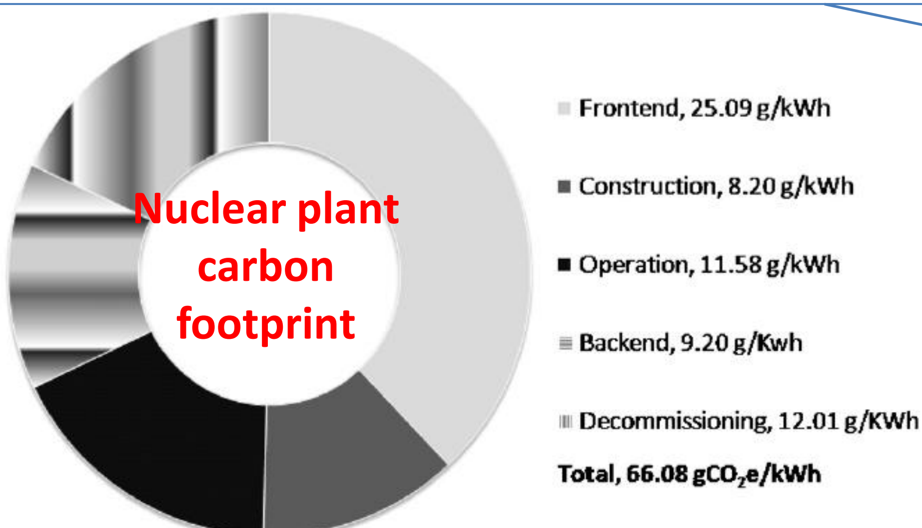
Emissions from a 1000 MWe power plant [t/year]

(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

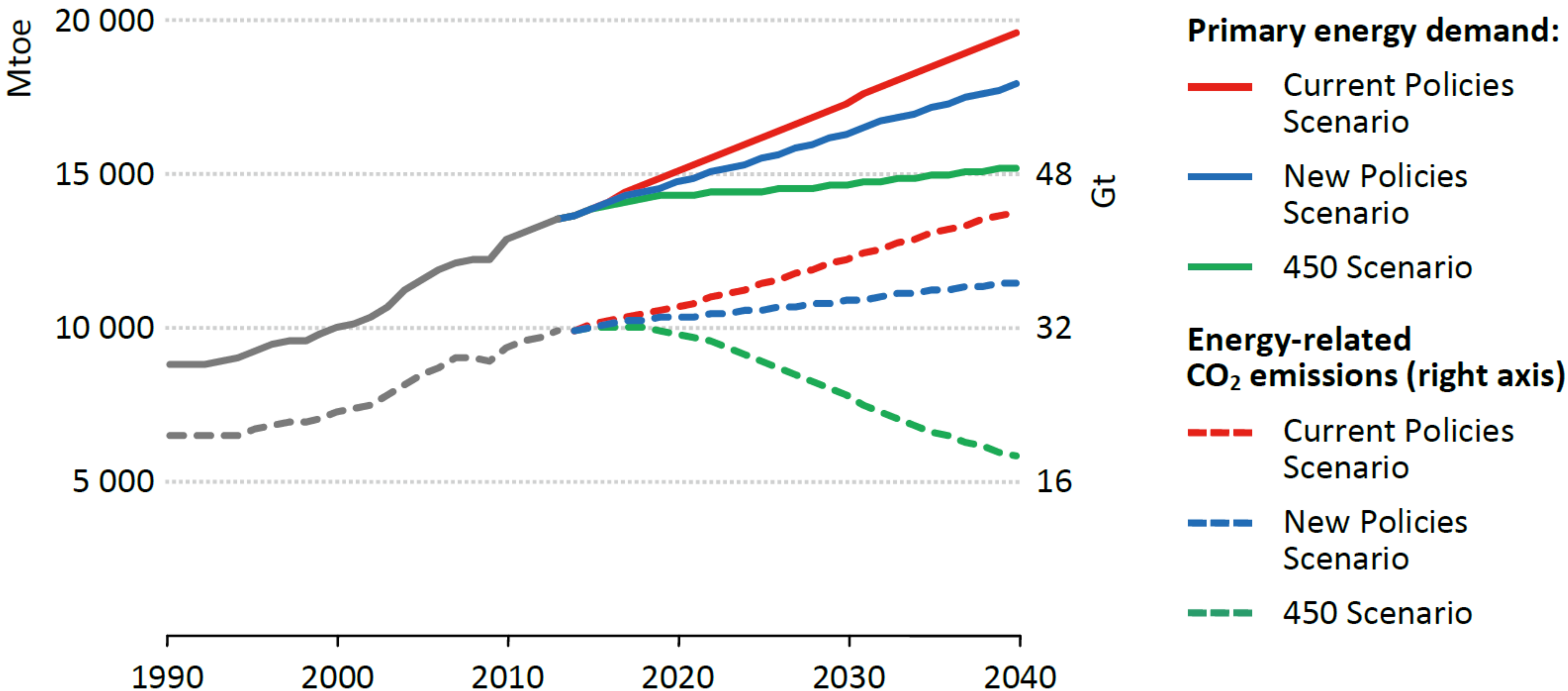
If one considers the whole plant lifetime (from fuel mining/extraction to decommissioning)



Technology	Capacity/configuration/fuel	Estimate (gCO$_2$e/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

World primary energy demand and CO_2 emissions by scenario

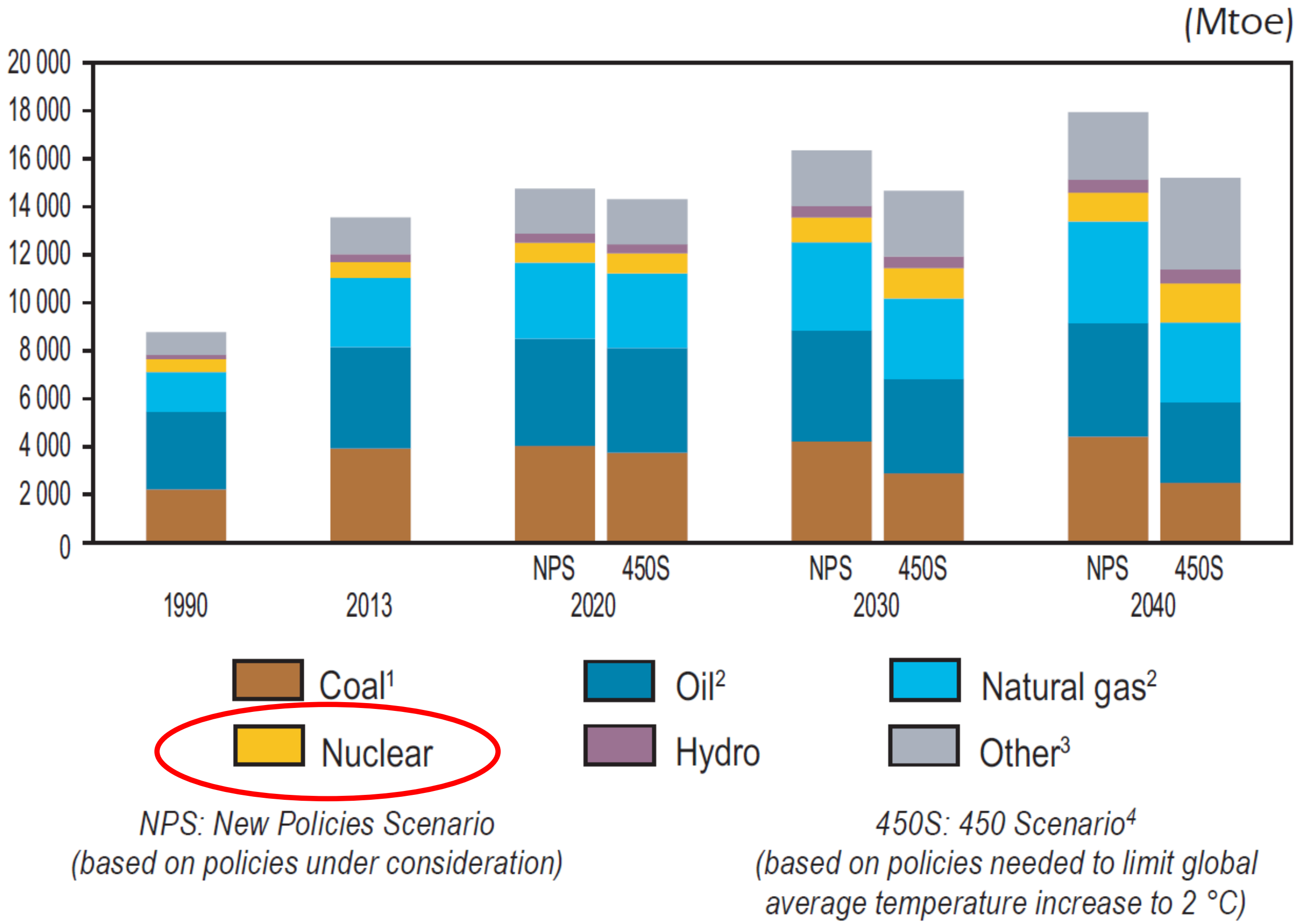


- **New Policies → continuation of existing policies and measures, cautious implementation of announced policy proposals**
- **Current Policies → only consider policies enacted as of mid-2015, can be used as baseline**
- **450 → CO_2 limited to 450 ppm → 50% chance of limiting long-term average global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



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.*

Source: IEA, Key World Energy Statistics, 2016

Safety

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 and activities**

Facilities and activities that give rise to radiation risks must yield an overall benefit.

- **Principle 5: Optimization of protection** → *Concept of "defence in depth"*

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** → *Provisions for radioactive waste management*

People and the environment, present and future, must be protected against radiation risks.

- **Principle 8: Prevention of accidents** → *Concept of "defence in depth"*

All practical efforts must be made to prevent and mitigate nuclear or radiation accidents.

- **Principle 9: Emergency preparedness and response**

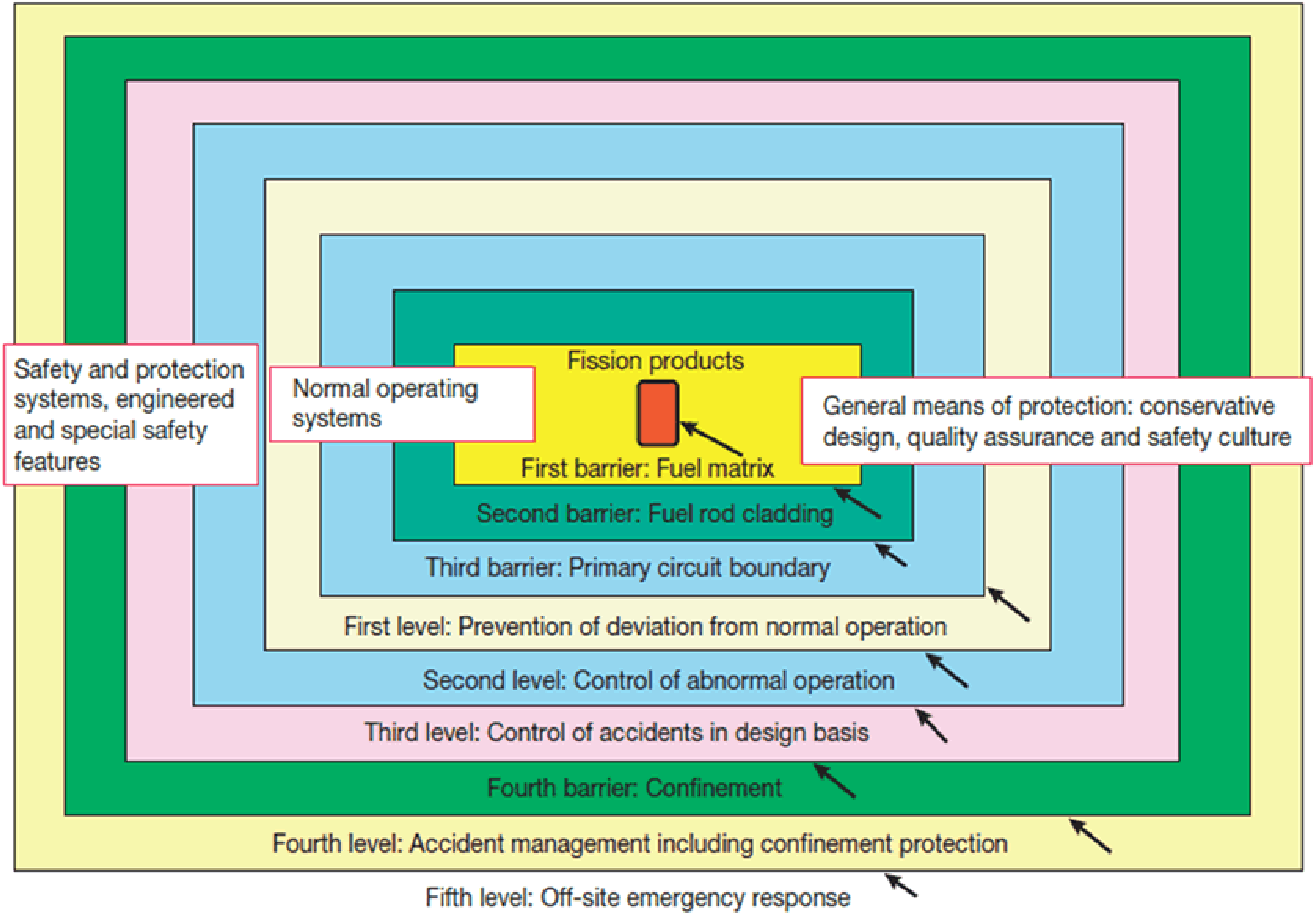
Arrangements must be made for emergency preparedness and response for nuclear or radiation incidents.

- **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

Defence in depth



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

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

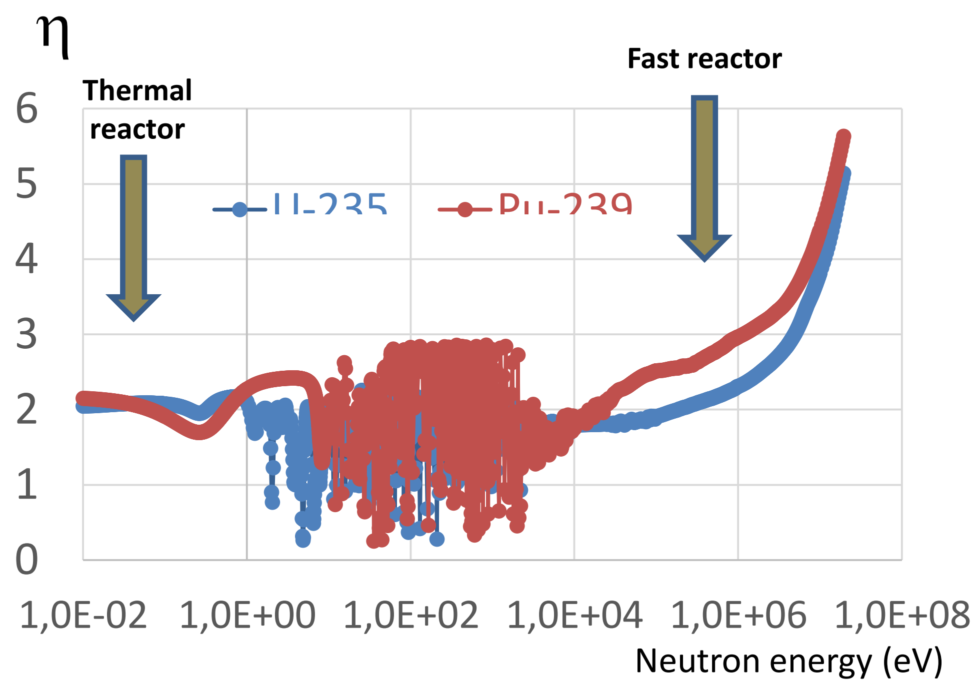
Source: OECD/NEA, Nuclear Energy Outlook, 2008

Uranium resources

Need to produce new fuels
non-natural with fertilization factor
(ratio produced fuel/burnt fuel) ≥ 1

$^{238}U\ (n,\gamma) \rightarrow {}^{239}U \rightarrow {}^{239}Np \rightarrow {}^{239}Pu$ (fissile)
$^{232}Th\ (n,\gamma) \rightarrow {}^{233}Th \rightarrow {}^{233}Pa \rightarrow {}^{233}U$ (fissile)

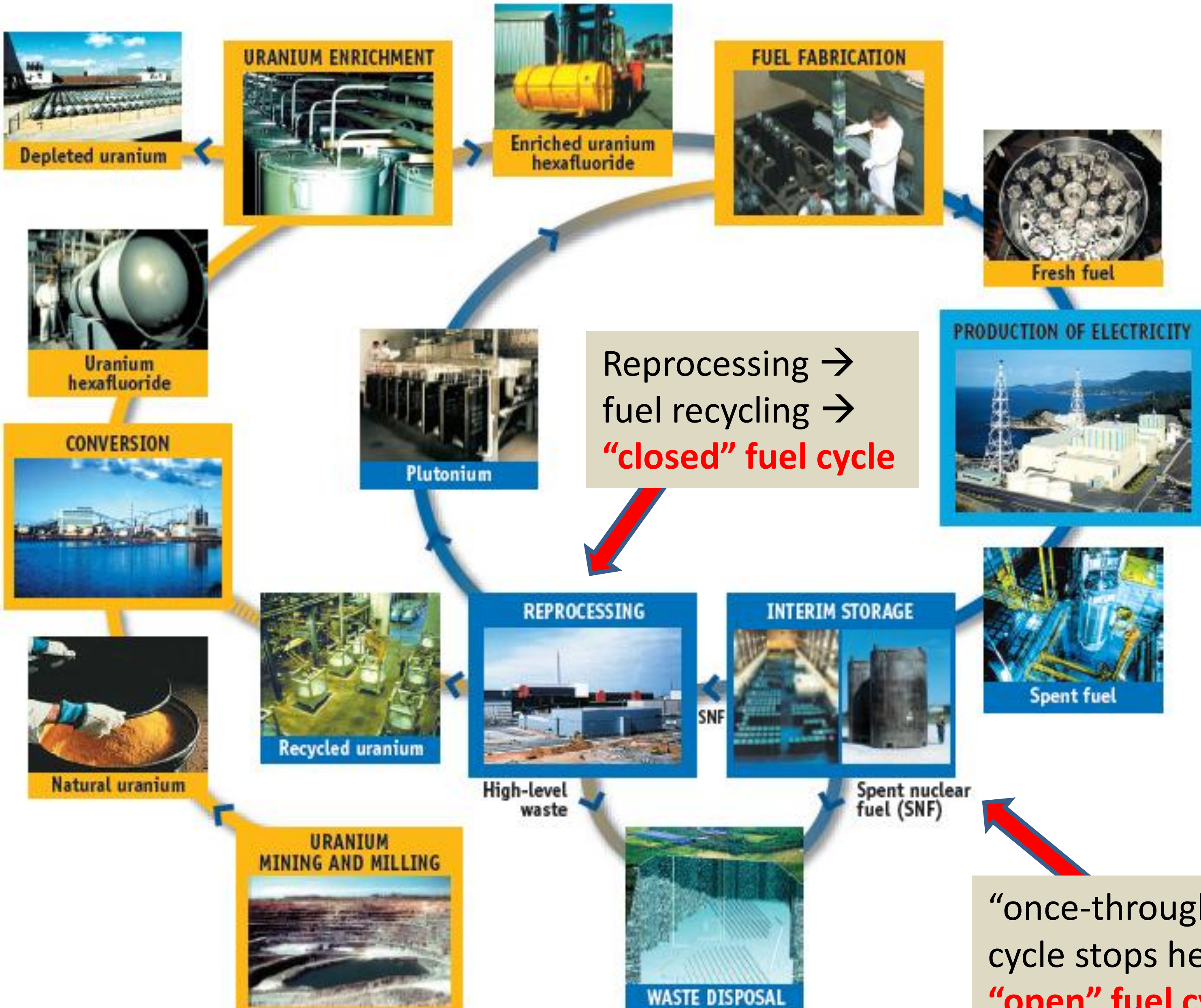
Advantageous in the fast chain reaction
(number of produced neutrons per
absorbed neutron>2)



- Conversion of ^{238}U in fissile material (Pu^{239}) in fast reactors would allow to increase by 60 the quantity of produced energy starting from natural U

- The possibility of producing energy from Thorium in the cycle $Th^{232} \rightarrow U^{233}$ would enormously increase fuel availability and would reduce the waste (less production of Transuranics)

The nuclear fuel cycle



Reprocessing → fuel recycling → **"closed" fuel cycle**

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

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

^{239}Pu: 125 Kg/yr

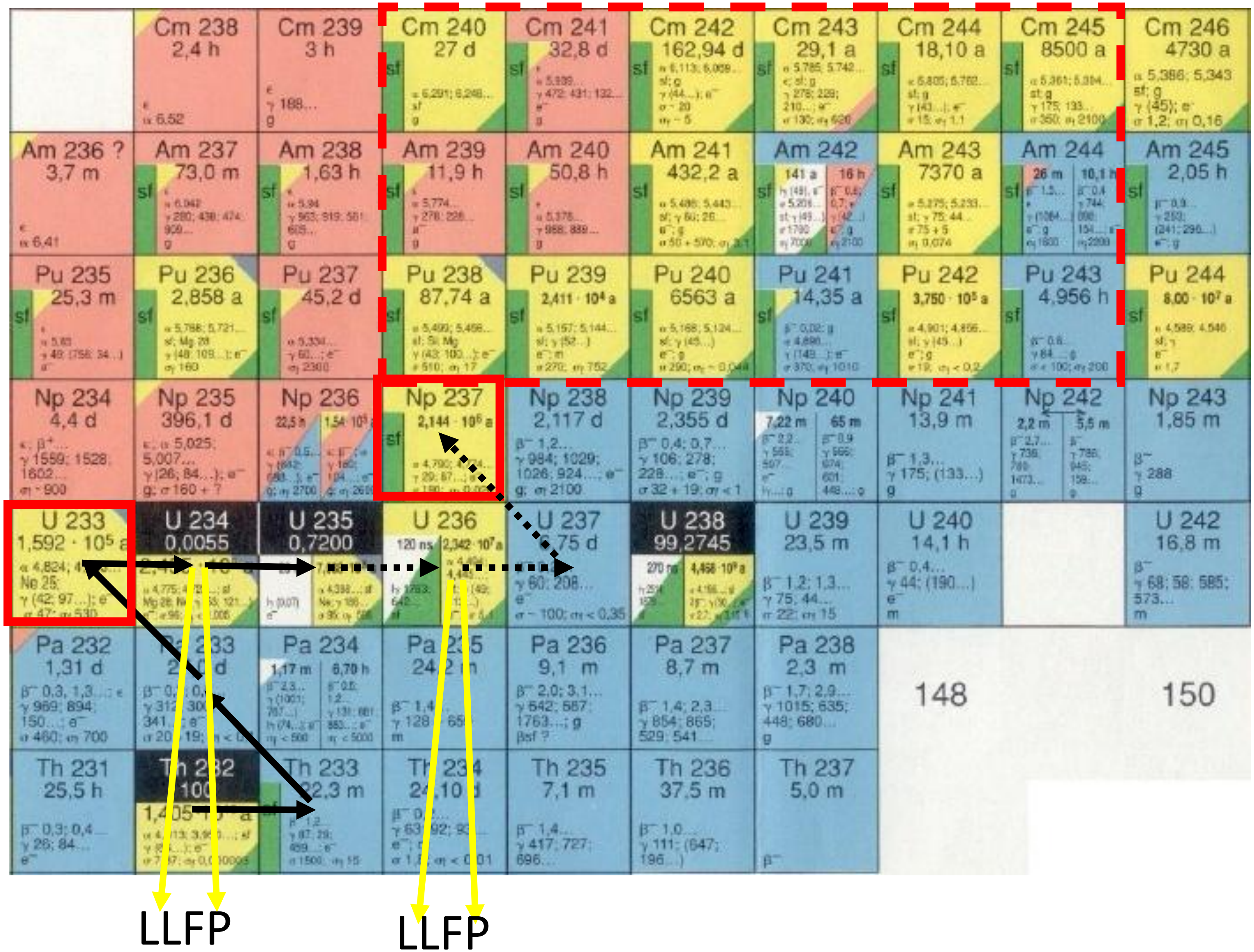
^{237}Np: 16 Kg/yr

LLFP
76.2 Kg/yr

LLFP=Long Life Fission Products

Transuranics = Minor Actinides + Pu

The thorium cycle



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 radionuclides 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) - this waste has a high radioactivity content but contains limited amounts of long-lived radionuclides. **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**

Often surface and deep repository are designed together and comprise additional infrastructures, such as to form a High-Tech Campus

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

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) $\rightarrow$ ^{100}Tc (16 s) $\rightarrow$ ^{100}Ru

Pu and Minor Actinides

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

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

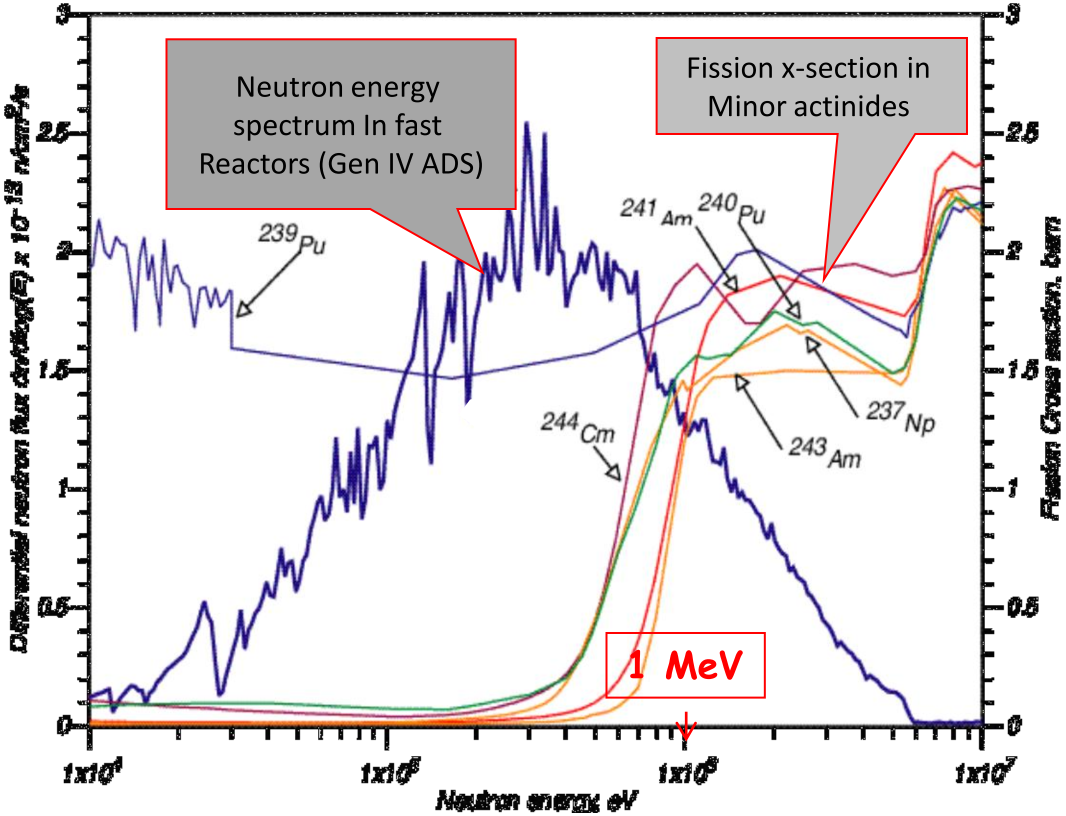
neutron **capture** (n, γ)

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)

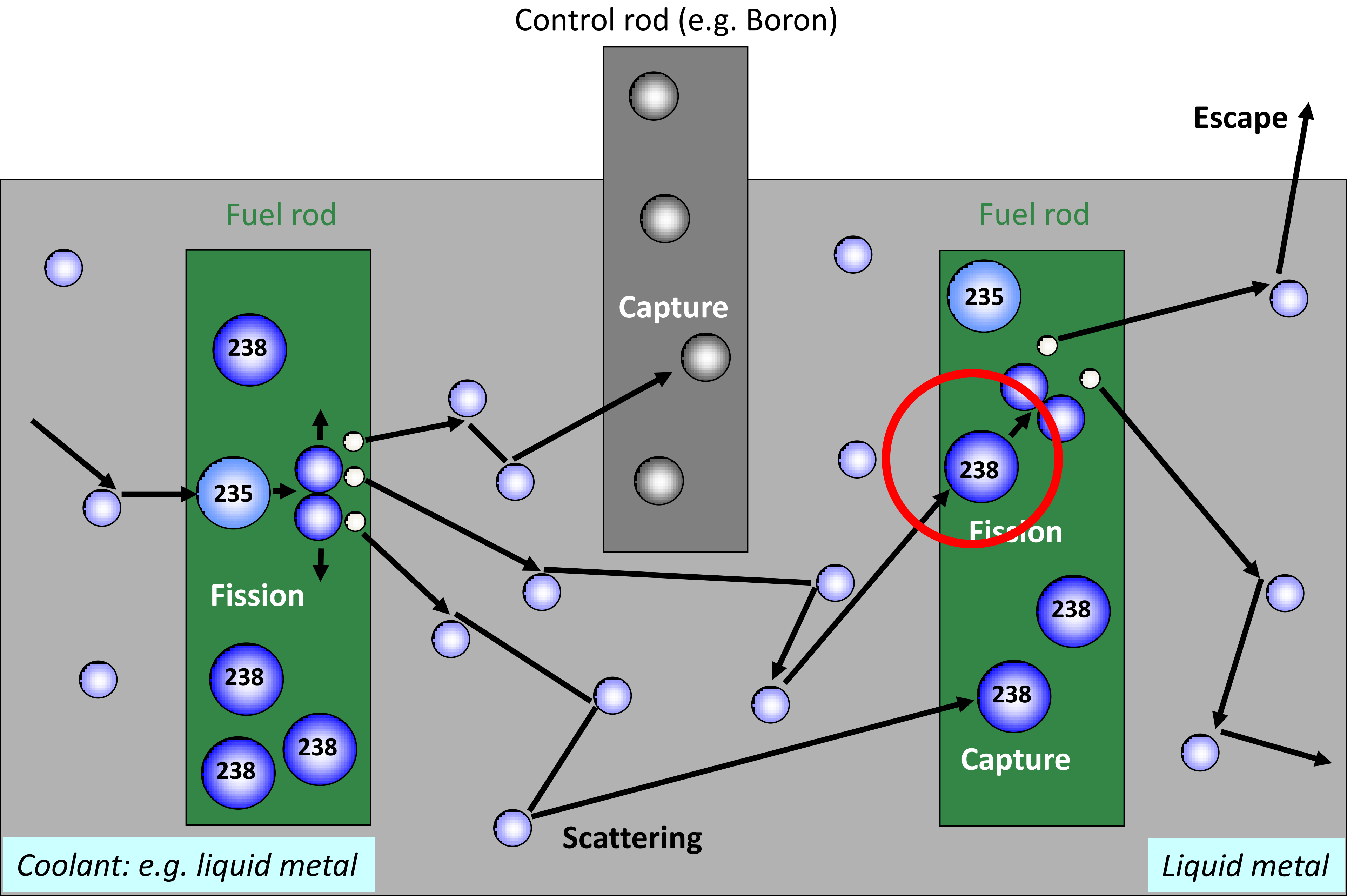


Delayed neutron fraction from FF, e.g.: $^{235}U = 0.65$ % $^{241}Am = 0.113$ %

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

The fast reactor



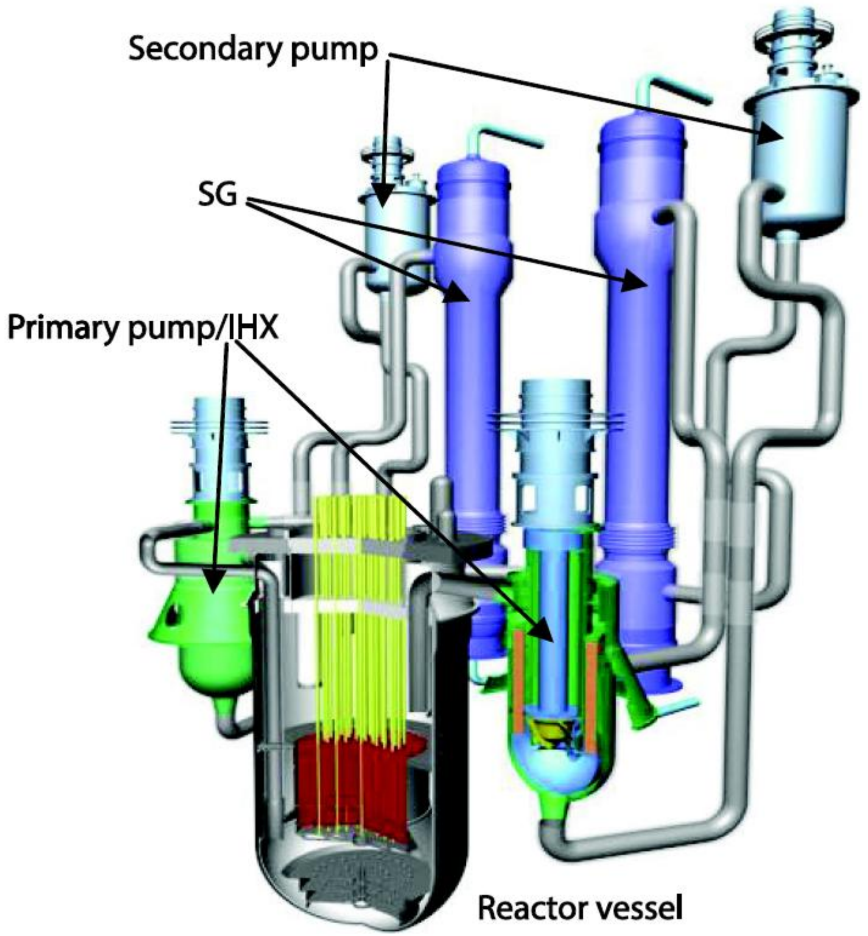
Generation IV: the future of nuclear power from fission

Six conceptual nuclear energy systems selected by Gen. IV International Forum (GIF)

	neutron spectrum (fast/ thermal)	coolant	temperature (°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

Sodium-cooled Fast Reactor (SFR)

- Liquid sodium as the reactor coolant, allowing a **low-pressure coolant system**
- High-power-density operation with low coolant volume fraction in the core
- **Fast-neutron spectrum in the core**
- advantageous thermo-physical properties of sodium:
  - ✓ high boiling point
  - ✓ heat of vaporization
  - ✓ thermal conductivity
  - ✓ oxygen-free environment prevents corrosion
- → significant thermal inertia in the primary coolant
- **Important safety features**:
- a long thermal response time
- reasonable margin to coolant boiling (by design)
- primary system that operates near atmospheric pressure
- **intermediate sodium system** between the radioactive sodium in the primary system and the power conversion system



Issues:
sodium reacts chemically with air and water and requires a sealed coolant system

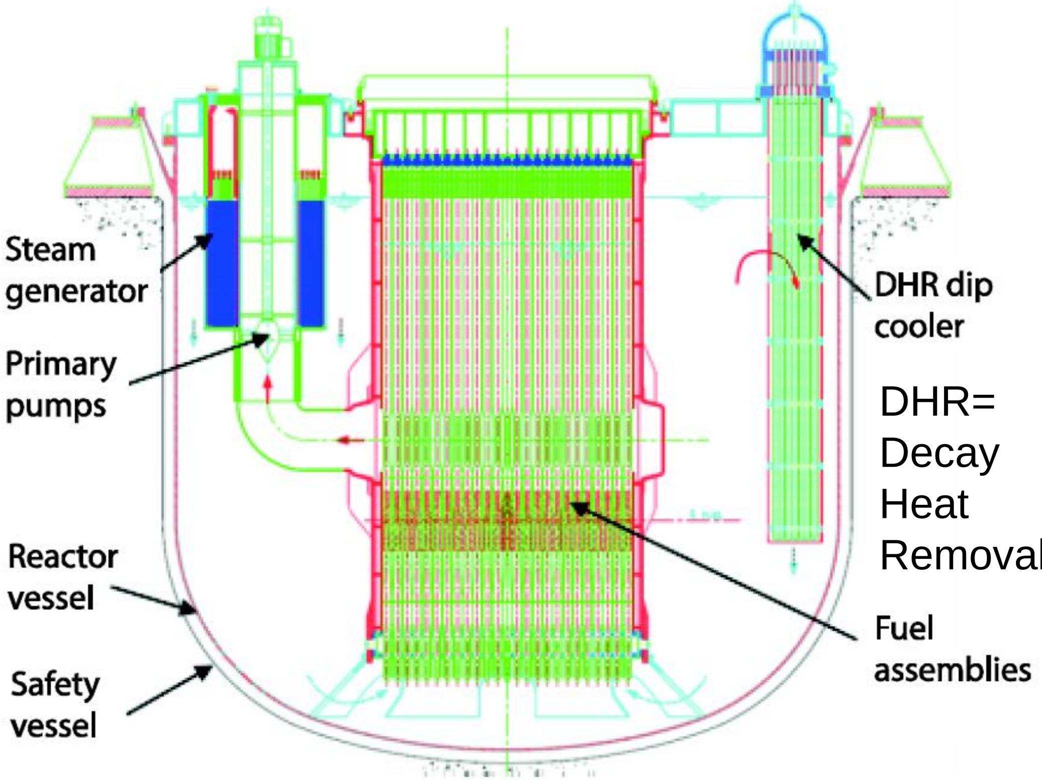
Previous experience from Phénix, Superphénix (France), BN-600 (Russia), Monju (Japan)

Lead-cooled Fast Reactor (LFR)

- LFRs → Pb or Pb-Bi-alloy-cooled reactors
- Operate at atmospheric pressure and at **high temperature** (very high boiling point of coolant up to 1743 ºC)
- **Fast-neutron spectrum in the core**
- Pb and Pb-Bi coolants are chemically inert and possess several attractive properties:
  - ✓ No exothermic reaction between lead and water or air. High boiling point of lead eliminates the risk of core voiding due to coolant boiling
  - ✓ High density of coolant contributes to fuel dispersion instead of compaction in case of core destruction
  - ✓ High vaporization heat and high thermal capacity of lead provide **significant thermal inertia in case of loss-of-heat-sink**
  - ✓ **Lead shields gamma-rays and retains iodine and caesium at temperatures up to 600 ºC**, thereby reducing the source term in case of release of volatile fission products from the fuel
  - ✓ Low neutron moderation of lead → greater spacing between fuel pins, leading to low core pressure drop and reduced risk of flow blockage
  - ✓ Simple coolant flow path and low core pressure drop allow **natural convection cooling** in the primary system for shutdown heat removal (**passive safety** system)

Issues:
lead chemistry, corrosion,…

Previous experience from Russia's BREST fast reactor technology → lead-cooled, builds on 80 reactor-years' experience of lead or lead-bismuth cooling, mostly in submarine reactors (but with softer spectrum and lower temperatures)



DHR= Decay Heat Removal

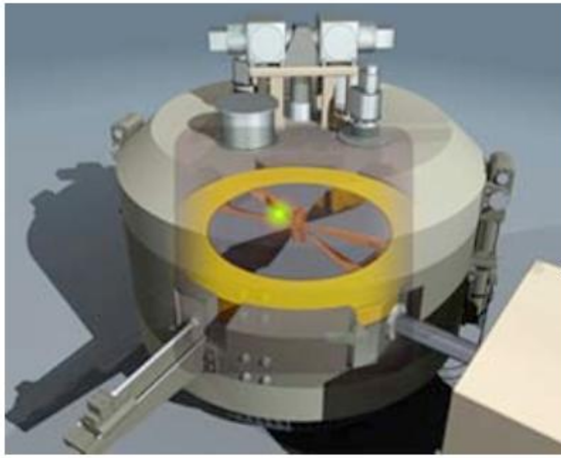
Current FNRs

Reactor	Type, coolant	Power thermal/elec (MW)	Fuel (future)	Country	Notes
BOR-60	Experimental, loop, sodium	55/10	oxide	Russia	1969-
BN-600	Demonstration, pool, sodium	1470/600	oxide	Russia	1980-
BN-800	Experimental, pool, sodium	2100/864	oxide	Russia	2014-
FBTR	Experimental, pool, sodium	40/-	oxide & carbide (metal)	India	1985-2030
PFBR	Demonstration, pool, sodium	1250/500	oxide (metal)	India	(2015)
CEFR	Experimental, pool, sodium	65/20	oxide	China	2010-
Joyo	Experimental, loop, sodium	140/-	oxide	Japan	1978-2007, maybe restart 2021
Monju	Prototype, loop, sodium	714/280	oxide	Japan	1994-96, 2010, shutdown

FNR designs for near- to mid-term deployment – active development

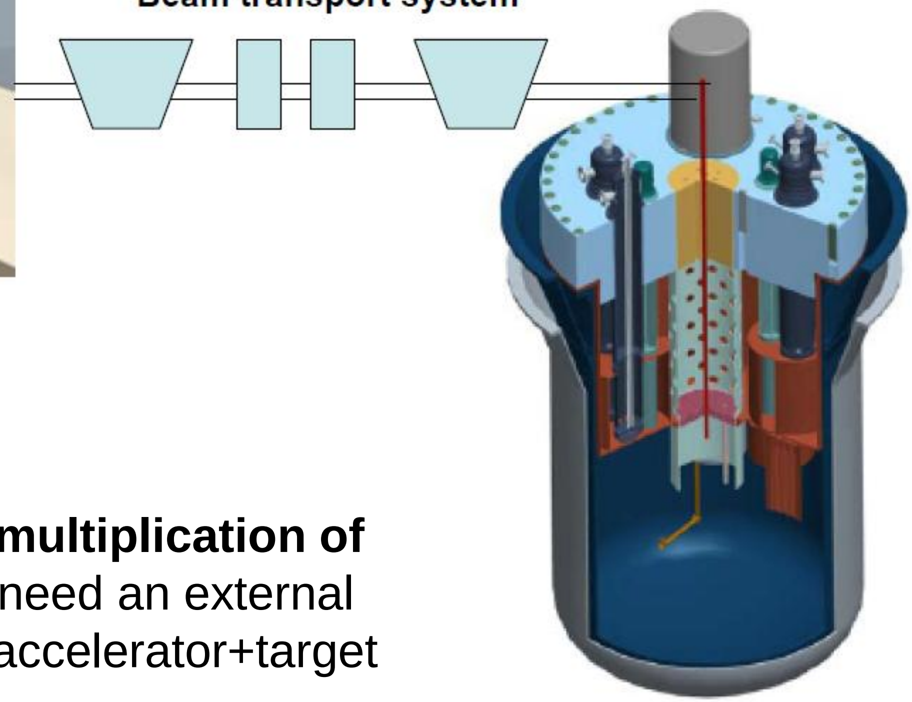
Reactor	type, coolant	Power thermal/elec	Fuel (future)	country	notes
PRISM	Demonstration, pool, sodium	840/311	metal	USA	From 2020s
ACR-100	Prototype, pool, sodium	260/100	metal	USA	Working with GEH
Astrid	Demonstration, pool, sodium	1500/600	oxide	France, with Japan	About 2030
Allegro	Experimental, loop?, gas	50-100 MWt	oxide	France	About 2025
MYRRHA	Experimental, Pb-Bi	57/-	oxide?	Belgium, with China	Early 2020s
ALFRED	Prototype, lead	300/120	oxide	Romania, with Italy & EU	From 2025
BN-1200	Commercial, pool, sodium	2800/1220	oxide, nitride	Russia	From mid-2020s
BREST-300	Demonstration, loop, lead	700/300	nitride	Russia	From 2020
SVBR-100	Demonstration, pool, Pb-Bi	280/100	oxide (variety)	Russia	From 2019
MBIR	Experimental, loop, sodium (Pb-Bi, gas)	100-150 MWt	oxide	Russia	From 2020
CDFR-1000	Demonstration, pool, sodium	/1000	oxide	China	From 2023
CDFBR-1200	Commercial, pool, sodium	/1200	metal	China	From 2028
PGSFR	Prototype, pool, sodium	/150	metal	South Korea	From 2028
JSFR	Demonstration, loop, sodium	/500	oxide	Japan	From 2025?
TWR	Prototype, sodium	/600	metal	China, with USA	From 2023?

ADS: a 3-component infrastructure

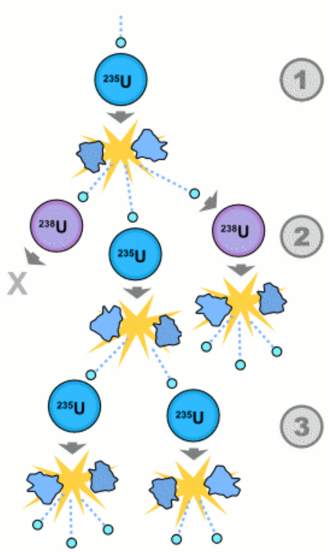


Proton accelerator

Beam transport system



Subcritical reactor



In ADS, **effective multiplication of neutrons is < 1**→ need an external neutron source → accelerator+target

The maximum thermal power P_{th} from the **subcritical reactor** is limited (and controlled !) by the input beam power P_{beam}

The neutron source

✓ Accelerated protons impinging on a thick target are the typical way to produce neutrons

✓ Accelerators today are capable of providing about 1 GeV proton energy with around 1 mA average current → a MW beam !

✓ At this energies, the process occuring on heavy nuclei (Fe,W,Pb,…) is **spallation** → e.g. in Pb about 20 neutrons/proton are produced at 1 GeV proton energy

Accelerator requirements

- High neutron production rate (proton or deuteron beams)
- High beam power (high energy E_p and/or current i_p)
- Very high stability (for high-power ADS):very few beam trips during long running times
- Minimal electric power consumption P_{plug}: i.e. optimal P_{plug} /P_{beam} ratio (from 4 to 25 in existing accelerators)

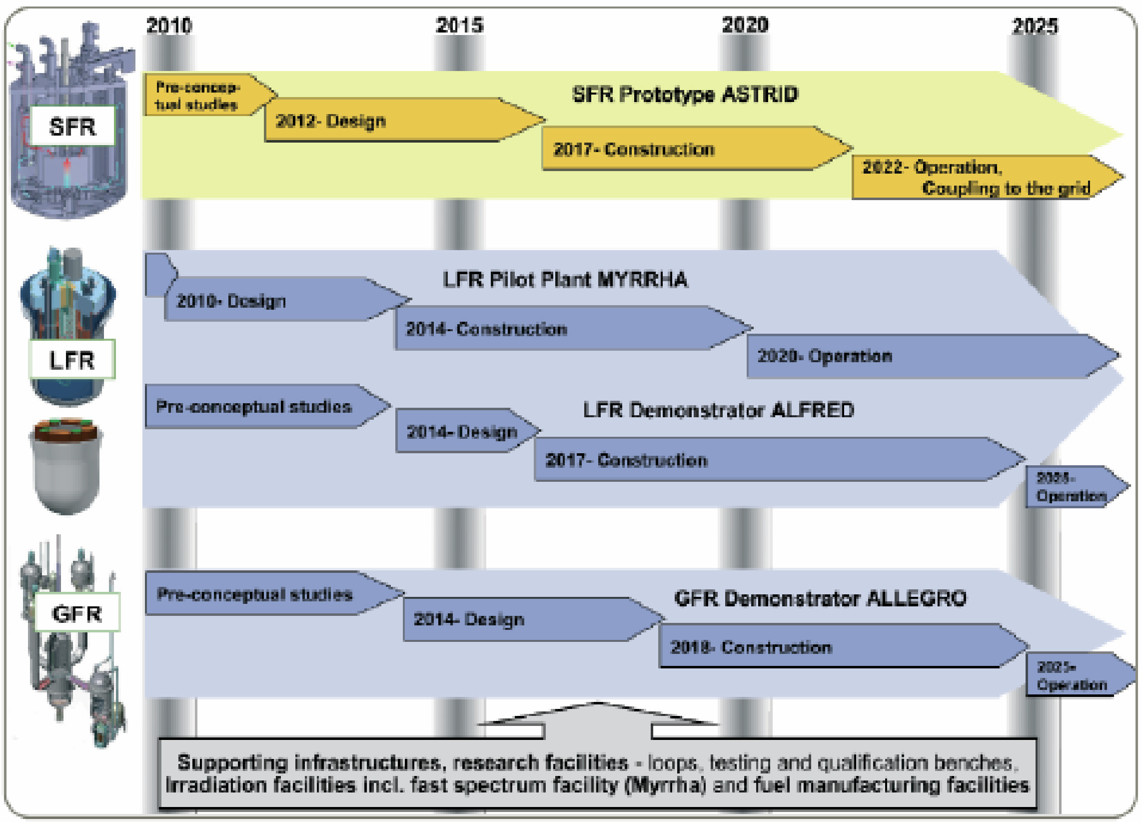
Most of these requirements are more severe than in conventional research accelerators and require, at least for high power ADS, a special design

The European roadmap

Fast Neutron Reactors in the frame of the European Sustainable Nuclear Industrial Initiative (ESNII)

AnsaldoNucleare
A Finmeccanica Company

ESNII Roadmap



ADS are envisaged as dedicated facilities for transmuting large amounts of MA in a concentrated approach

ADS technology development has considerable synergy with the R&D required for FNRs and in particular for LFR

ADS is not considered as a potential energy production system (economic reasons), but as a fast neutron irradiation and testing tool which can support the development of FNRs

European Lead Fast Reactor (LFR)/ADS Activities

Accelerator

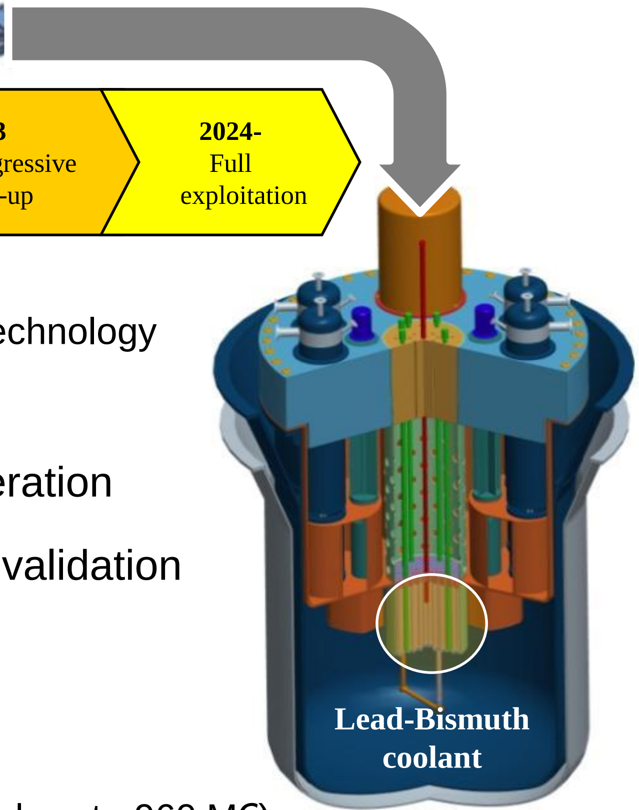
(600 MeV - 4 mA proton)

Reactor

Subcritical mode - 65 to 100 MWth

MYRRHA
project schedule

- **2010-2014** Front End Engineering Design
- **2015** Tendering & Procurement
- **2016-2018** Construction of components & civil engineering
- **2019** On site assembly
- **2020-2022** Commissioning
- **2023** Progressive start-up
- **2024-** Full exploitation



GUINEVERE and MYRRHA

the first two steps of the EU Road Map for the development of LFR technology

GUINEVERE

The Zero-Power facility – solid Lead – critical and sub-critical operation

Nuclear data, nuclear instrumentation, Keff measurements, code validation

Criticality reached in February 2011

Subcritical coupling performed in October 2011

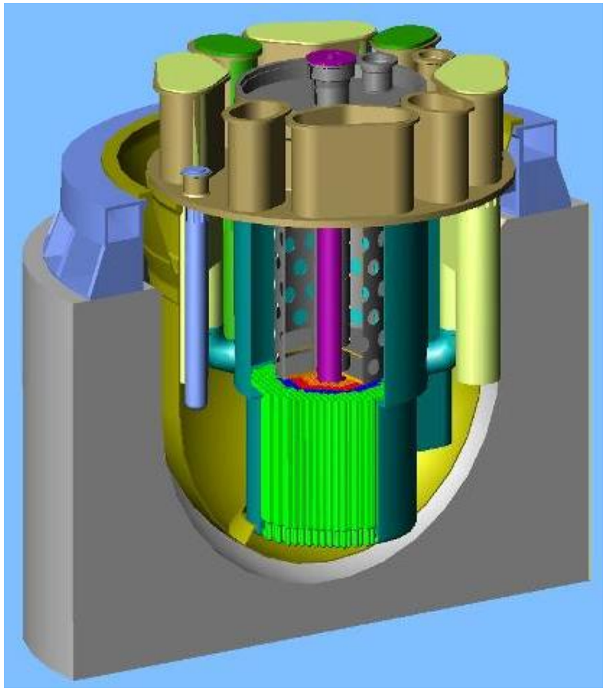
MYRRHA

(Multipurpose hYbrid Research Reactor for High-tech Applications, estimated cost - 960 M€)

European Technology Pilot Plant of LFR

European Lead Fast Reactor (LFR)/ADS Activities

ADVANCED PROJECT: EFIT
(European Facility for
Industrial Transmutation)

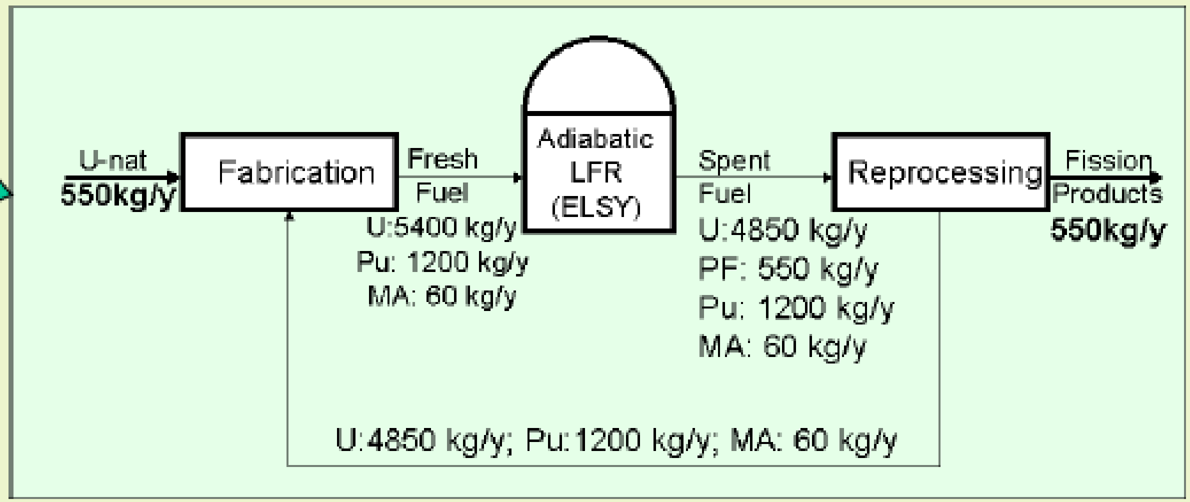


Pure lead-cooled reactor of about 400 MWth with MA burning capability and electricity generation at reasonable cost

- ⇨ EFIT shall be an effective **burner of MA**
- ⇨ EFIT will be loaded with **U-free fuel** containing MA
- ⇨ EFIT will **generate electricity** at reasonable cost
- ⇨ EFIT will be **cooled by pure lead** (a cooled gas option is also studied)

Fast Reactor Fuel cycle: an example

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

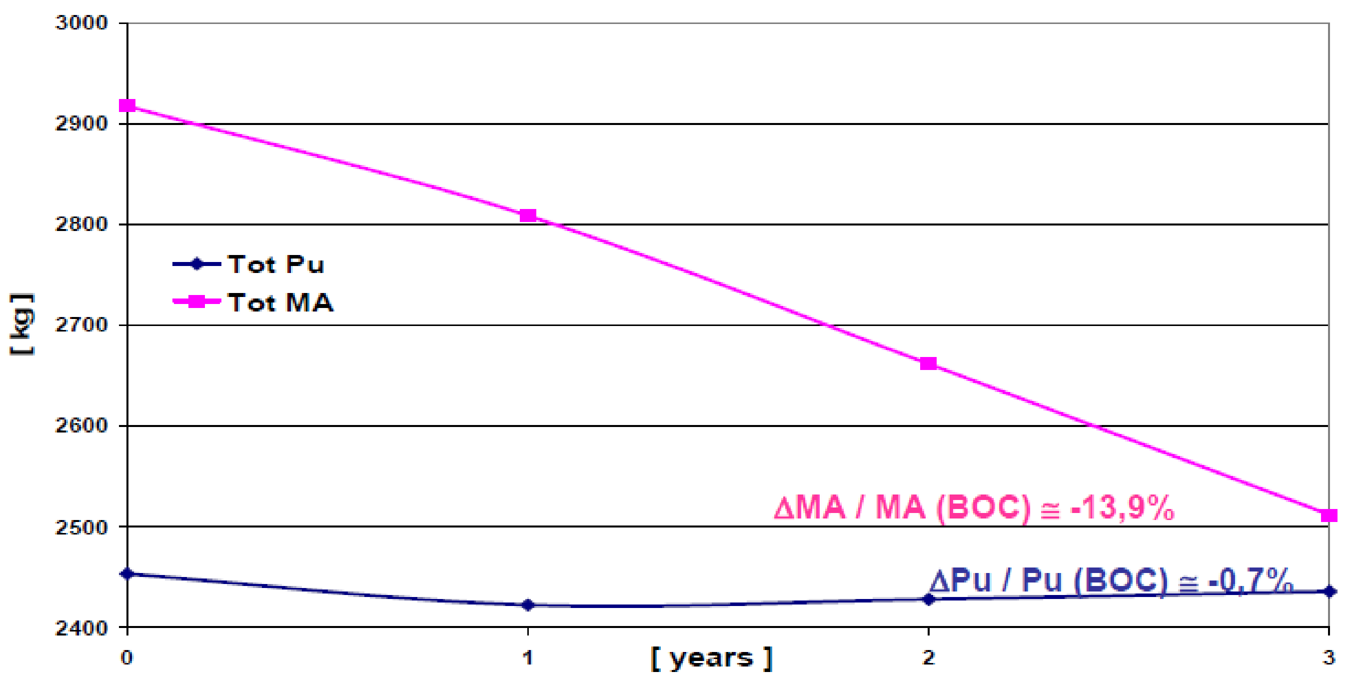


Considering 0.5% losses in the reprocessing:

- 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

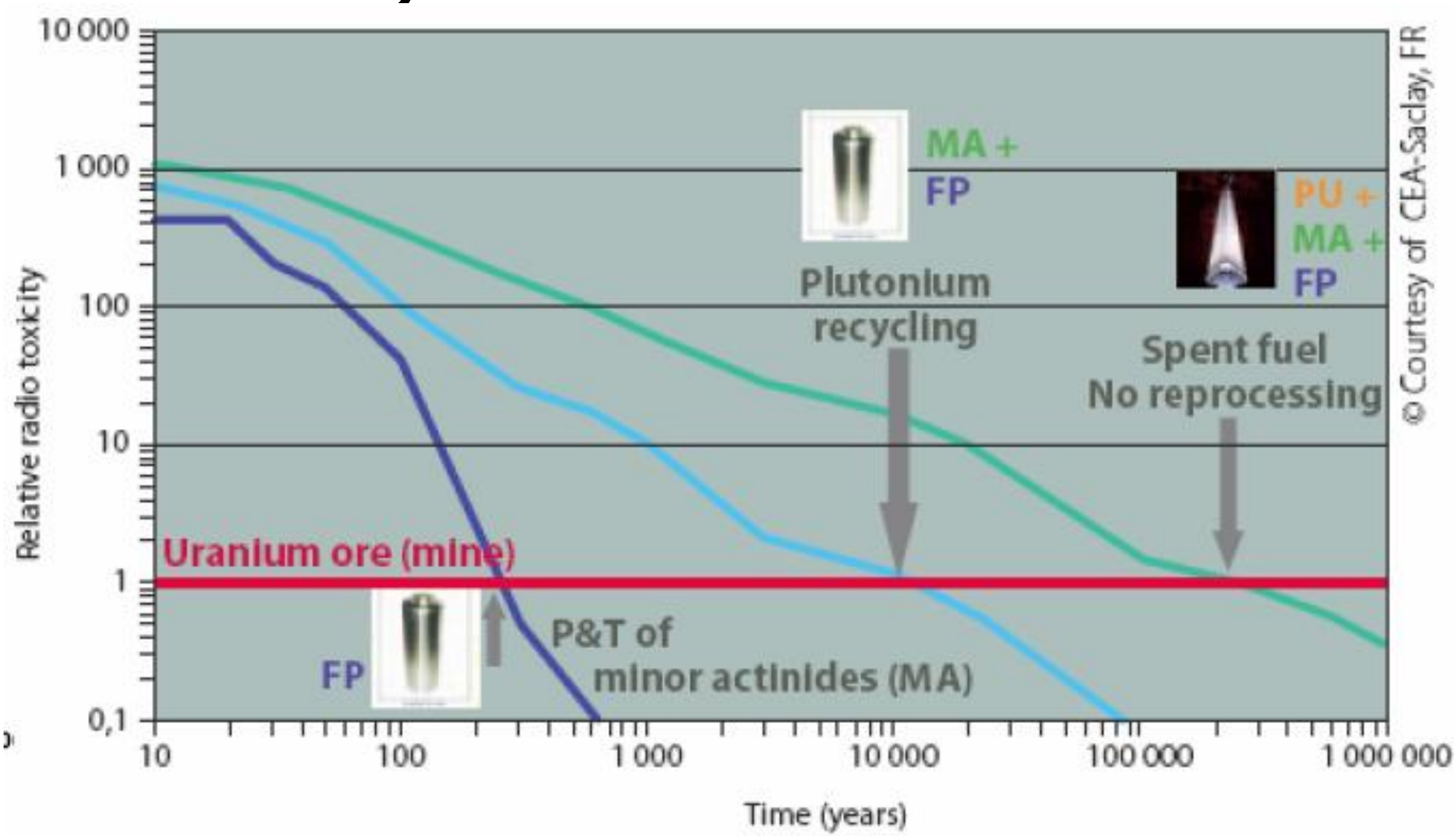
Example of ADS performance

- ✓ 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**

Fuel cycle and transmutation



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)

Thank you for your attention !