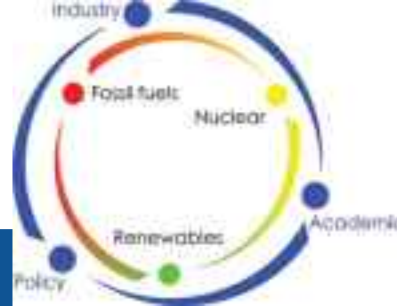

Académie royale des Sciences, des Lettres
et des Beaux-Arts de Belgique (ARB)

Cours-conférence du Collège Belgique

Palais des Académies (1, rue Ducale 1000 - Bruxelles)

Fission nucléaire de quatrième génération : stop ou encore ?

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Jeudi 20 avril 2017

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Fission nucléaire : stop ou encore ? 1/3

« Le cap »
et les « Invariants »

Quelques « quasi-certitudes »
et beaucoup d'incertitudes

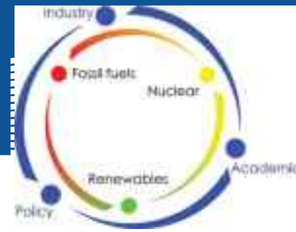
Fission nucléaire : stop ou encore ? 2/3

Aujourd'hui …

Forum Nucléaire belge: https://www.forumnucleaire.be/faq/

Fission nucléaire : stop ou encore ? 3/3

“Un miliardo per la sicurezza e uno per la cultura. La bellezza sarà più forte della barbarie”
"Per ogni euro in cybersecurity, uno in start-up; per ogni mezzo blindato in più, un campo di calcetto".
Matteo Renzi, Président du Conseil Italien, 24 novembre 2015



Fission nucléaire de quatrième génération : stop ou encore ?

1 – Introduction :

Génération IV - pourquoi ? comment ? avec qui ? quand ?

2 - Le cap («triangle énergétique européen») et les invariants (lois de la nature)

3 - La réalité des faits et des chiffres (« quasi-certitudes ») et défis technologiques et humains (incertitudes)

4 - Besoins et opportunités pour le nucléaire au 21ème siècle (objectifs de Génération IV)

4.1 Améliorer la durabilité (y compris l'utilisation efficace du combustible et la réduction des déchets)

4.2 Sûreté et fiabilité (notamment en l'absence de toute intervention extérieure d'urgence)

4.3 Economie (compétitivité par rapport aux sources d'énergie)

4.4 Lutte contre la prolifération des armes nucléaires et protection matérielle

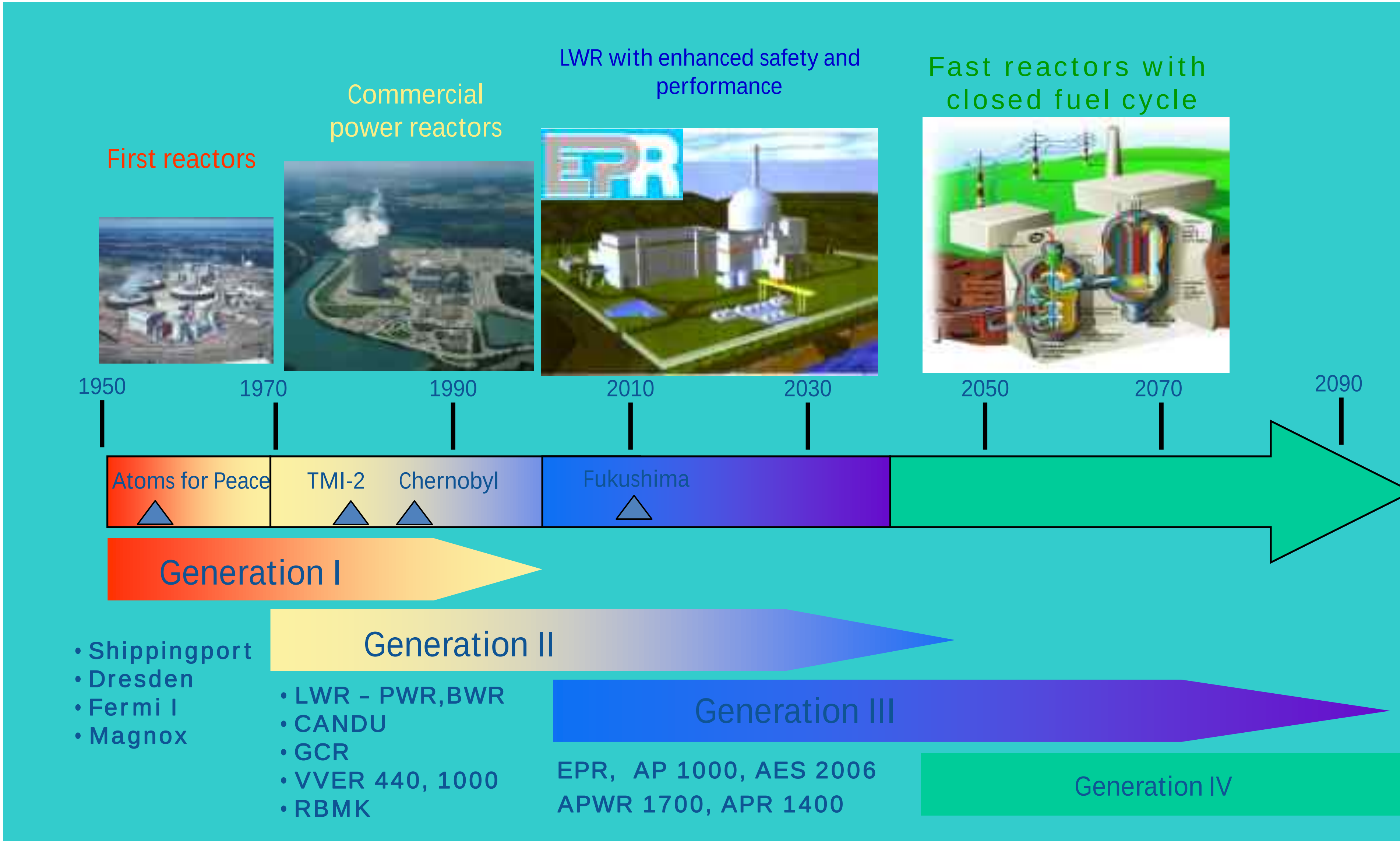
5 - Les systèmes-réacteurs nucléaires en projet de la Génération IV : SFR, LFR, GFR, VHTR, MSR et SCWR

6 - Conclusion : recherche, innovation et formation en fission nucléaire

Nuclear fission 1950 – 2100 (4 generations)

towards sustainable use of U fuel resources, including actinide recycling

Today, Gen II existing and Gen III upcoming reactors are vastly dominated by LWRs: thermal neutrons + enriched uranium + oxide pellets + fuel rods + light water moderator/coolant (variants : pressurized or boiling water)



Generation II : business challenges and key issues

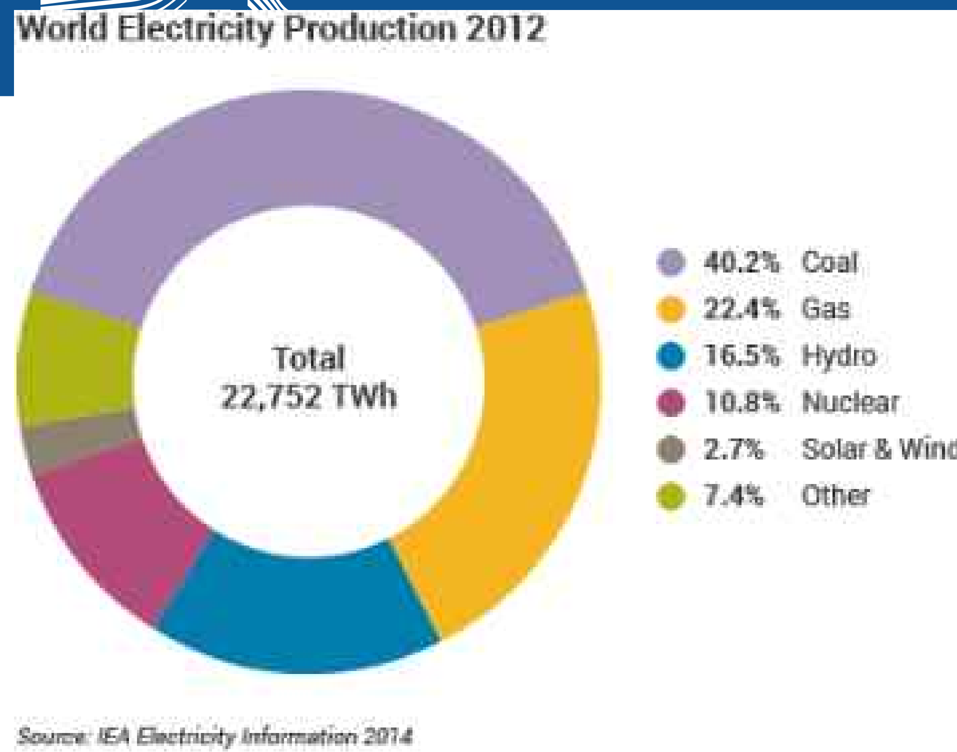
- ✓ **Maintain High quality Operation & Maintenance**
- ✓ **Availaibility & Load factor Improvement**
- ✓ **Fuel Management Improvement**
- ✓ **Safety reassessment process every 10 years with economically sustainable upgrades**
- ✓ **Ensure Life Duration of existing plants at least over 40 years (from 1st criticality) at competitive conditions**

  (Long Term Operation /LTO/ – e.g. USA: more than 80 out of 100 reactors have been granted license renewals from the original 40 out to 60 years)

⇒ **<u>In the EU: "stress tests" for all 131 reactors as a follow-up of Fukushima</u> (European Council, 24/25 March 2011) : targeted reassessments of safety margins, conducted in all EU Member States (+ Switzerland and Ukraine + Armenia, Turkey, Russia, Taiwan, Japan, S Korea, S Africa, Brazil)**

= > <u>World-wide experience with conventional reactors = 17 000 reactor-years</u> < =

World electricity and primary energy consumption by fuel

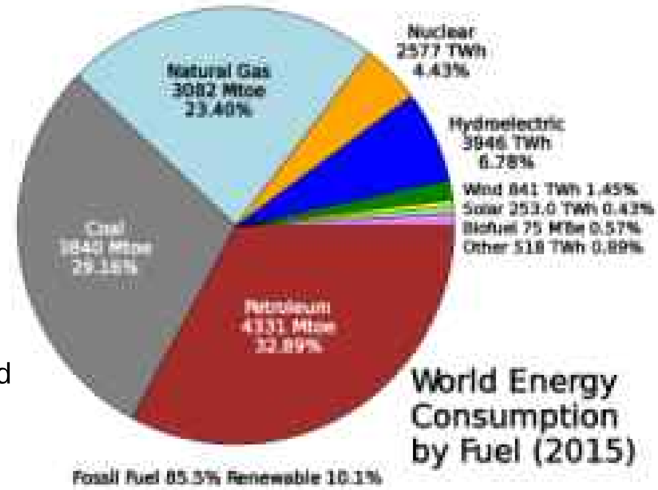


<u>Nuclear Power in the World Today(Jan 2017)</u>

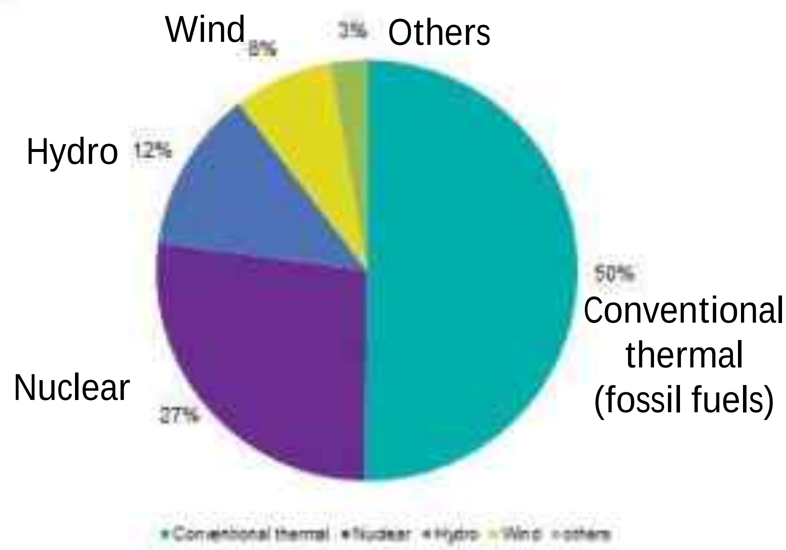
- The first commercial nuclear power stations started operation in the 1950s.
- There are over 440 commercial nuclear power reactors operable in 31 countries, with over 390,000 MWe of total capacity. About 60 more reactors are under construction.
- They provide over 11% of the world's electricity as continuous, reliable base-load power, without carbon dioxide emissions.
- 55 countries operate a total of about 245 research reactors, and a further 180 nuclear reactors power some 140 ships and submarines.

Centrale nucléaire de Cruas-Meysse en Ardèche (France)

<u>World primary energy consumption 2015 by fuel</u>, based on data from BP Statistical Review of World Energy 2016



Electricity production forms in EU in 2013 and projection until 2050



In the EU countries, <u>nuclear power is the most significant carbon dioxide-free electricity production form</u>, since over half of all the carbon dioxide-free electricity in the EU is produced with nuclear power. (<u>http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Electricity_production_and_supply_statistics</u>)

Percentages of electricity production forms in EU-28 countries in 2013

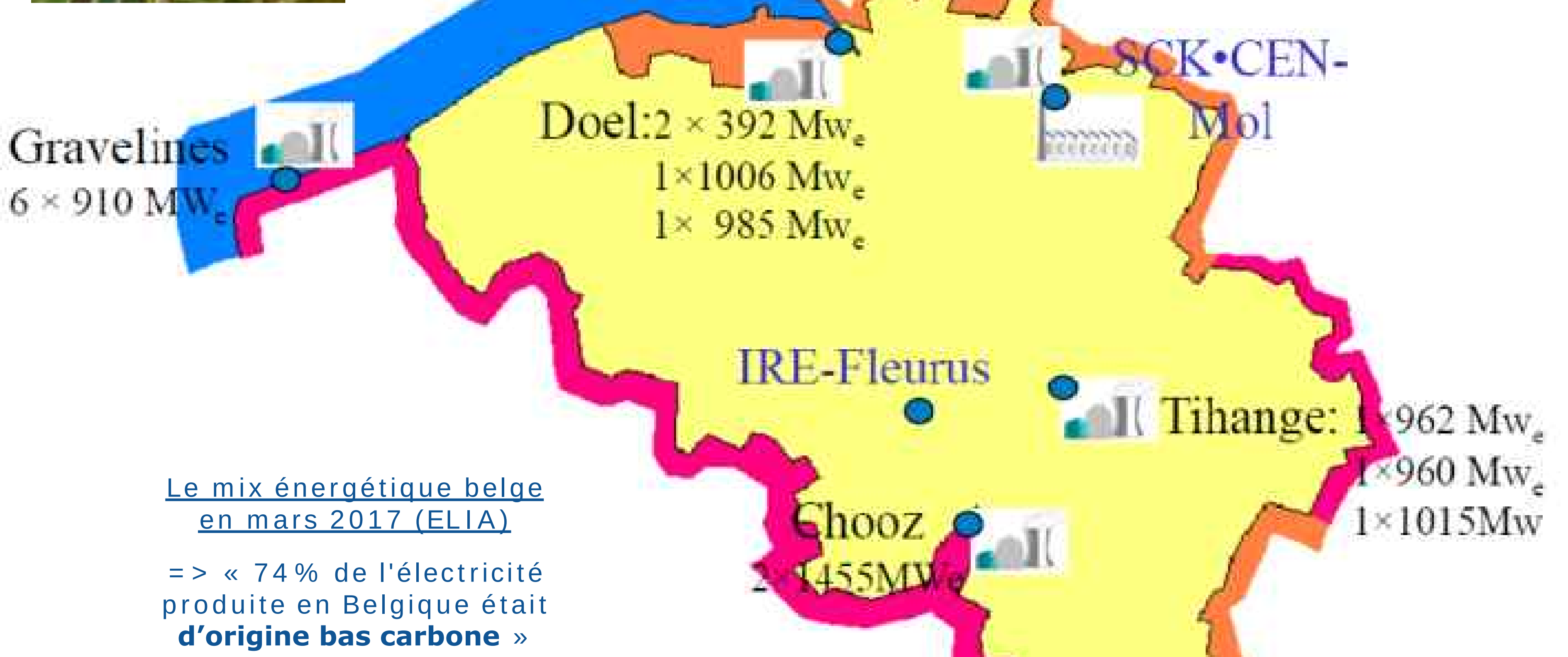
Projection until 2050 – "<u>Electricity will play a central role in the low carbon economy</u>"

Increasing electricity demand from fuel shifts (e.g. electrification of both transport and heating/cooling) and penetration of new technologies (due to an increase in overall energy use) outweigh decreasing demand from overall higher energy efficiency both at the demand and generation side. As a consequence, <u>the electricity demand is projected to increase substantially towards 2050, with up to 50% compared to current levels (2010)</u>. This 50% increase is also reported in the "EU 2050 Energy Roadmap", COM(2011) 885 of 15/12/2011, issued by the EC.

NB: As a result, European electricity demand will increase by 40 % until 2050, from expected 3500 TWh in 2020 to 4900 TWh. (Reminder: The demand for electricity in the EU 27 in 2008 amounted to 3173 TWh). Electricity demand will grow by 1.1 % per year from 2020 to 2050. Even though this rate is below the 1.5 % demand growth per year between 1990 and 2007, it is important to realize that the dependence of EU on electric power will increase not decrease.

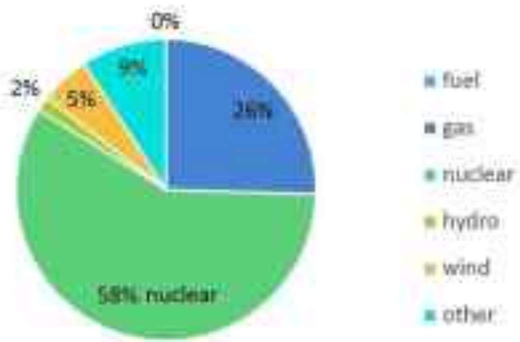
Source: "Decarbonizing the European Electric Power Sector by 2050", W. D'haeseleer et al., May 2011 - <u>https://www.mech.kuleuven.be/en/tme/research/energy_environment/Pdf/WPEN2010-11</u>
Reminder about total energy : Gross inland consumption of energy within the EU-28 in 2014 was 1 606 million tonnes of oil equivalent (Mtoe), i.e.: 18 677 TWh (circa 6 times amount of electricity) - Eurostat - July 2016 - <u>http://ec.europa.eu/eurostat/statistics-explained/index.php/Consumption_of_energy</u>

The Belgian nuclear sites



Le mix énergétique belge en mars 2017 (ELIA)

=> « 74% de l'électricité produite en Belgique était **d'origine bas carbone** »



SCK•CEN Mol has a long tradition of «first of a kind»

Expertise belge, renommée mondiale
Video National Geographic sur SCK-CEN
« Les jeunes experts nucléaires » 2016
https://youtu.be/jq2keG2hwTQ

1st pressurized water reactor (PWR) outside of US (BR3)

Inventor of innovative nuclear fuel (MOX fuel)

Highest performing material testing reactor in Europe (BR2)

World first underground laboratory for R&D on HL waste disposal (HADES)

World first lead based ADS (GUINEVERE)

MYRRHA

World premiere project for transmutation of nuclear waste

Generation III :« evolutionary » reactors

ABWR

EPR

AP1000

VVER-1200 (AES 2006)

- GEN I are all closed (1950-2000)
- GEN II are all in operation (1980–2030) – 436 world fleet in 31 countries, incl. 128 in 14 EU Member States)
- GEN III+ (e.g. EPR, AP-1000) are about to start operating (~2018 until 2080)

Third-generation (GEN III) reactors have:

• A standardised design for each type to expedite licensing, reduce capital cost and reduce construction time.
• A simpler and more rugged design, making them easier to operate and less vulnerable to operational upsets.
• Higher availability and longer operating life – typically 60 years.
• Further reduced possibility of core melt accidents.
• Substantial grace period, so that following shutdown the plant requires no active intervention for (typically) 72 hours.
• Resistance to serious damage that would allow radiological release from an aircraft impact.
• Higher burn-up to use fuel more fully and efficiently and reduce the amount of waste.
• Greater use of burnable absorbers ('poisons') to extend fuel life.

Who is marketing large commercial reactors (> 700 Mwe) ?

• Areva: EPR, Atmea1, Kerena
• Westinghouse/Toshiba: AP-1000
• GE Hitachi: ABWR, ESBWR
• KHNP South-Korea: APR-1400
• Mitsubishi: APWR, Atmea1
• Rosatom: AES 92 (1000 MWe), AES 2006 (1200 MWe), etc
• Candu Canada: EC6
• CNNC & CGN: Hualong One (HPR-1000 based on French design)
• SNPTC: CAP-1400 (modular design, passive safety systems)
/Mainland China has 36 nuclear power reactors in operation, 21 under construction, and more about to start construction/

NB: "European utility requirements" (EUR): the EUR utilities promote EU-wide and world-wide harmonisation of the design bases of the next nuclear power plants (GEN III).

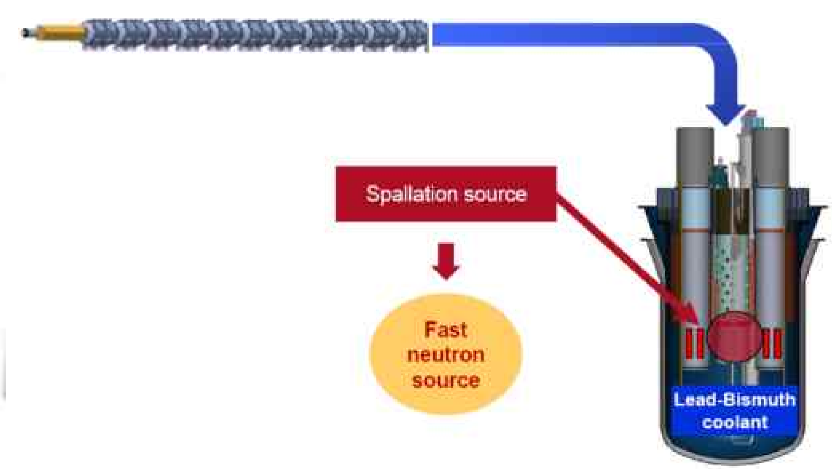
Operational: in Japan (ABWR 1380), South-Korea (APR-1400), Russia (VVER-1200 and BN-800, demonstration fast reactor and test plant)
Under construction: in China (EPR 1750, AP-1000, Hualong one (PWR-1150 for export), HTR-200 module), in France and Finland (EPR), in USA (AP-1000)
Source: http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/advanced-nuclear-power-reactors.aspx

Génération IV: stop ou encore ?

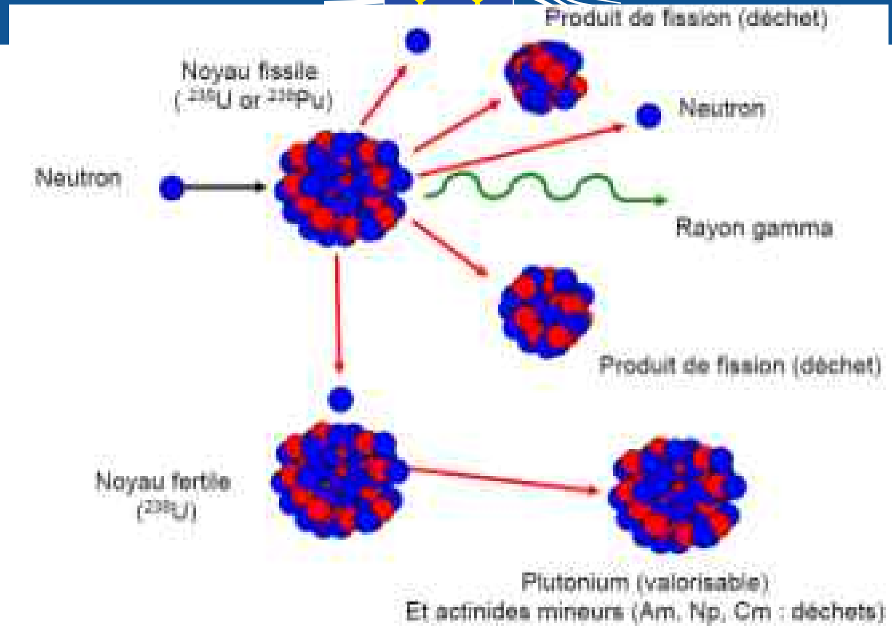
... demain (> 2030)

Sustainable development of nuclear energy (waste minimization through transmutation in an accelerator driven system /ADS/)

= > *MYRRHA, large research infrastructure under construction at SCK-CEN, Mol, Belgium, to replace BR2 ("Multi-purpose hYbrid Research Reactor for High-tech Applications")*



Effect of neutrons in motion on heavy nucleus: fission (=> fission products) or capture (=> transuranic elements)



Proportions of uranium-238 (blue) and uranium-235 (red) found naturally versus enriched grades (Wikipedia)

Nuclear fission is the main process generating nuclear energy

- **Neutrons in motion are the starting point for everything that happens in a nuclear reactor.**

When a neutron passes near to a heavy nucleus, for example uranium-235 (U-235), the neutron may be captured by the nucleus and this may or may not be followed by fission. Capture involves the addition of the neutron to the uranium nucleus to form a new compound nucleus. A simple example is (fertile) U-238 + n ==> U-239, which represents formation of the nucleus U-**239. The new nucleus may decay into a different nuclide (i.e. a "transuranic element"). In** this example, U-239 becomes Np-239 after emission of a beta particle (electron), which then becomes Pu-239 (fissile).

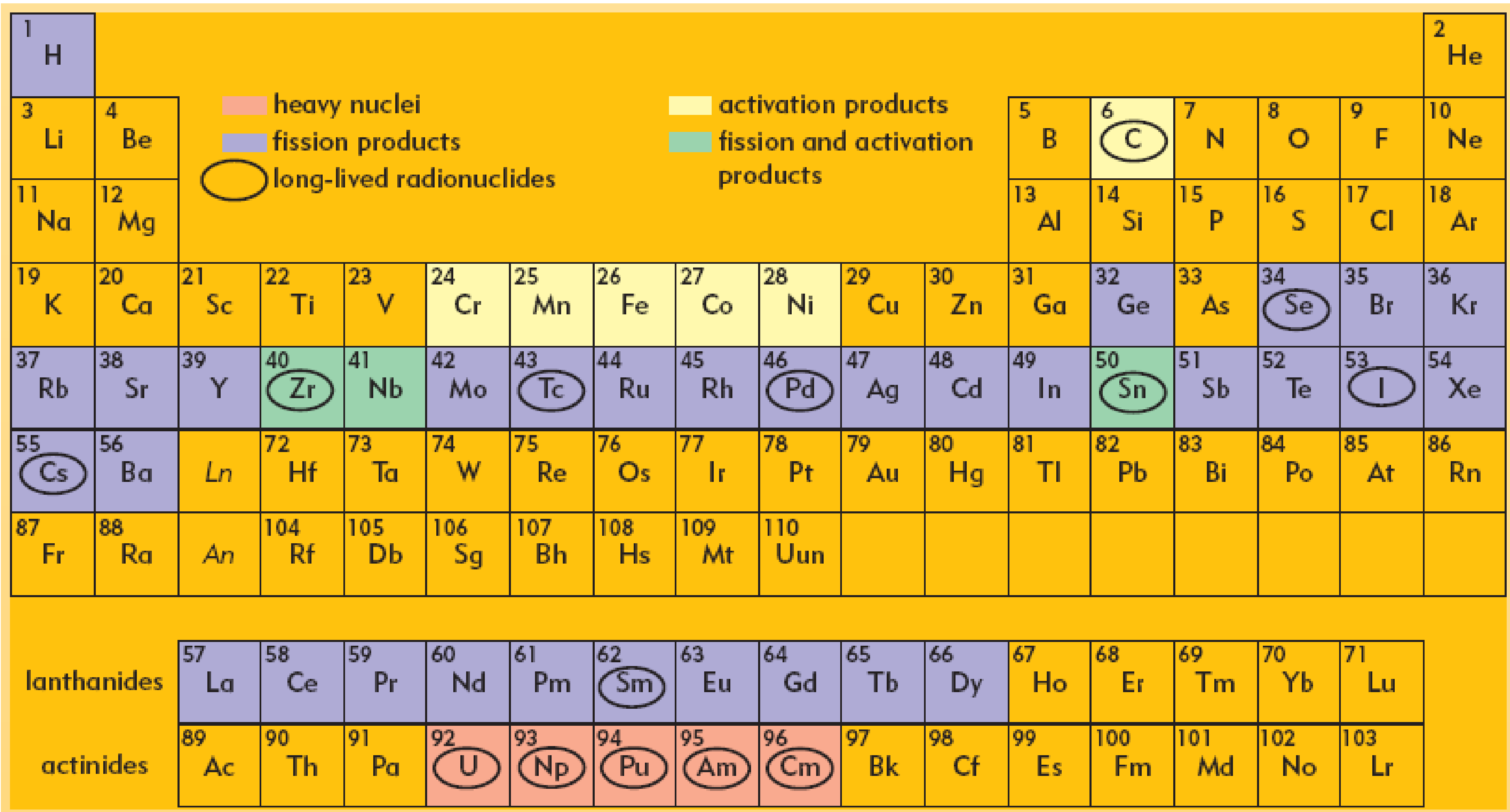
In certain cases, the initial capture is rapidly followed by the fission of the new nucleus. This new nucleus is relatively unstable, and it is likely to break into **two fragments (i.e. the "fission products") of around half the mass. These fragments are nuclei found around the middle of the Periodic Table and the** probabilistic nature of the break-up leads to several hundred possible combinations. Creation of the fission fragments is followed almost instantaneously by emission of a number of neutrons (typically 2 or 3, average 2.5), which enable the chain reaction to be sustained.

Whether fission takes place, and indeed whether capture occurs at all, depends on the velocity of the passing neutron and on the particular heavy nucleus involved. For example, slow neutrons (low-energy, or thermal / circa eight times the speed of sound) are able to cause fission only in those isotopes of uranium and plutonium whose nuclei contain odd numbers of neutrons (e.g. U-233, U-235, and Pu-239). For nuclei containing an even number of neutrons, fission can only occur if the incident neutrons have energy above about one million electron volts (MeV), i.e. fast neutrons (circa 7% of the speed of light).

http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/introduction/physics-of-nuclear-energy.aspx

"Periodic Table" of the elements

(Russian chemist Mendeleev, 1869)



Source = Clefs CEA n° 46 – Spring 2002

A multitude of nuclear options (1/3)

- Choice of the neutron velocity (2)
  - thermal (2 km/s) : high fission probability for a couple of nuclei (^{233}U, ^{235}U, ^{239}**Pu…)**
  - fast (20'000 km/s) : low fission probability – for all heavy nuclei
- Choice of the fissile nucleus (which can fission immediately) (3)
  - ^{233}U, ^{235}U, ^{239}Pu
- Choice of the breeding substance (nuclei that can become fissile) (2)
  - ^{238}U, ^{232}Th
- Choice of the chemical form of the nuclear fuel (4)
  - oxide, metal, carbide, nitride

Source: J.M. Cavedon, PSI, FISA-2009

A multitude of nuclear options (2/3)

- Choice of the moderator (light atomic nuclei) (4)
  - liquid: light water H_2O, heavy water D_2O
  - solid: graphite
  - nothing – if the neutrons shall remain fast
- Choice of the coolant (7)
  - liquids (H_2O, D_2O, molten salts)
  - liquid metals (Na, Pb/Bi)
  - gases (He, CO_2)
- Choice of the number of barriers (2)
  - 2 or 3 confinement barriers
- Choice of the fuel cycle (3)
  - open, closed for selected elements, fully closed

A multitude of nuclear options (3/3)

- In short, $2 \times 3 \times 2 \times 4 \times 4 \times 7 \times 2 \times 3 =$

  8064 possible concepts for nuclear reactors

  without counting:

- Geometry of the fuel:
  - 1D = rods in a square or hexagonal arrangement,
  - 2D = plates,
  - **3D =pebbles…;**
- Different temperatures and pressures of the primary coolant
- Geometric disposition of the coolant: pool, loop, tubes…
- Choice of a secondary loop and of its coolant
- Choice of power conversion system
- Choice of final heat sink : sea, river, air cooling tower (natural or hybrid)

Generation IV
(« visionary Charter 2001»)
* horizon after 2030
* 14 members (11 active)

Generation IV International Forum

* Charter 2001 signed by 14 members
* State Agreement (2005 – 2009)
* 6 Systems Arrangements (2006 – 2011)
* Project Arrangements (2007 – 2010)
  (= SFR 5, VHTR 4, SCWR 4, GFR 2)

- Among the signatories to the Charter, ten Members *(Canada, Euratom, France, Japan, the People's Republic of China, the Republic of Korea, the Republic of South Africa, Russian Federation, Switzerland and the United States)* have signed or acceded to the Framework Agreement. Australia is following (11-th active Member).

Selection criteria for GIF systems:
1 - sustainable
2 - safe and reliable
3 - competitive
4 - proliferation resistant

* The Euratom Joint Research Centre (JRC) is entrusted with the co-ordination of the EU contribution to GIF (JRC is implementing agent).

* Australia became the 14th member of the Forum on 22 June 2016 (GIF Charter signed by Australian Nuclear Science and Technology Organisation /ANSTO/).

"Industrial and societal goals" for Generation IV

1. Sustainability

1. Generate energy sustainably, and promote long-term availability of nuclear fuel
2. Minimize nuclear waste and reduce the long term stewardship burden

2. Safety & Reliability

3. Excel in safety and reliability
4. Have a very low likelihood and degree of reactor core damage
5. **Eliminate the "technical" need for offsite emergency response**

3. (Socio-)economics

6. Have a life cycle cost advantage over other energy sources
7. Have a level of financial risk comparable to other energy projects

4. Proliferation resistance and Physical protection

8. Be a very unattractive route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism

Selection of Generation IV systems (2001) : from > 130 down to 6

19 system groups for the final selection

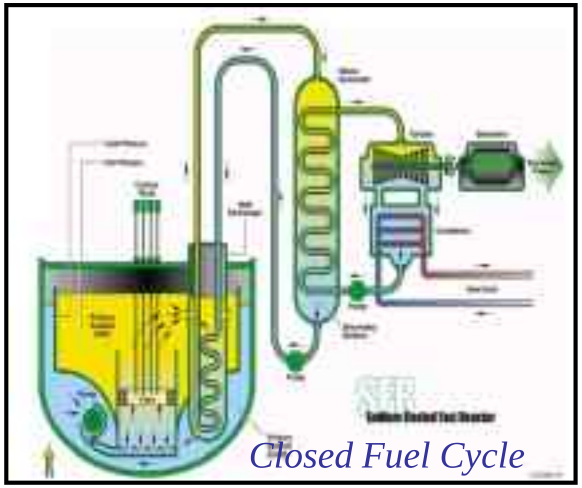
110 systems compatible with GIF goals

>130 proposals of international origin

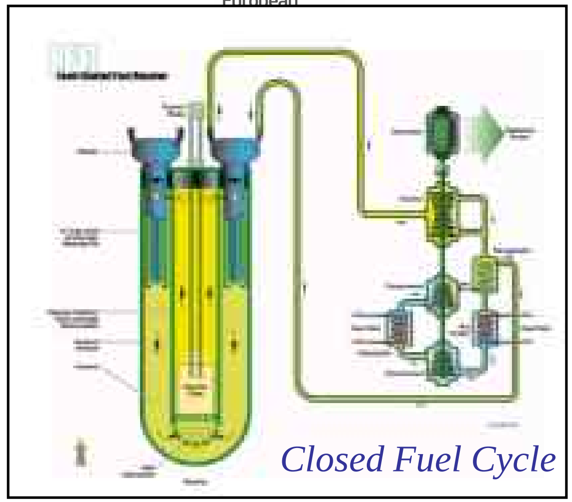
reliable, affordable, sober, clean and harmless

	Acronym	Spectrum	Fuel Cycle
1. Sodium-Cooled Fast	**SFR**	fast	closed
2. Lead Alloy-Cooled Fast	**LFR**	fast	closed
3. Gas-Cooled Fast	**GFR**	fast	closed
4. Very High Temperature	**VHTR**	thermal	open
5. Supercritical Water-Cooled	**SCWR**	thermal & fast	both
6. Molten Salt	**MSR**	epithermal	closed

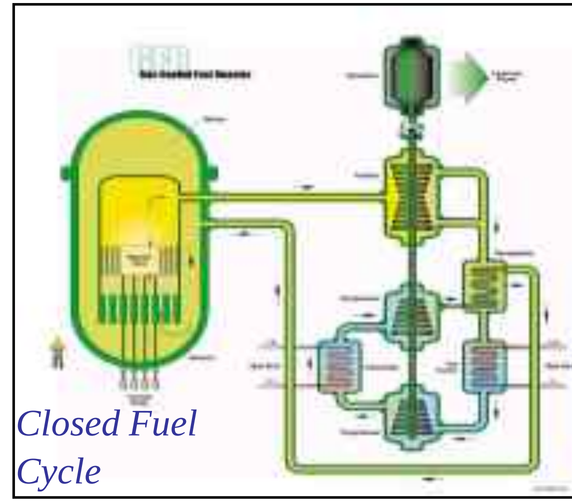
Generation-IV systems : « breakthrough » technologies



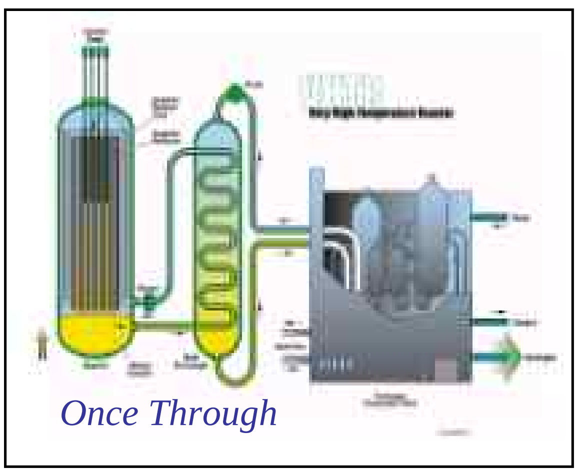
Sodium Fast reactor



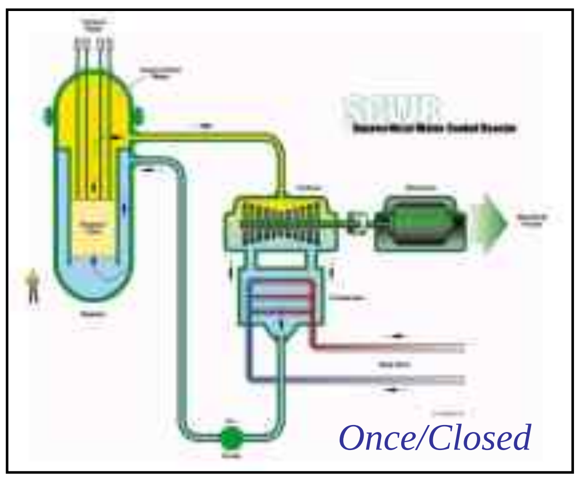
Lead Fast Reactor



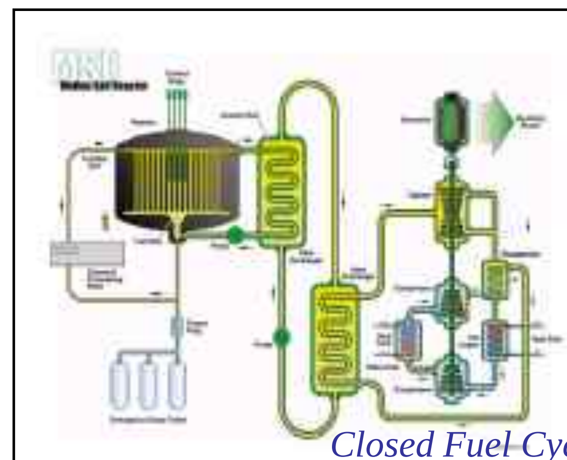
Gas Fast Reactor



Very High Temperature Reactor



Supercritical Water Reactor

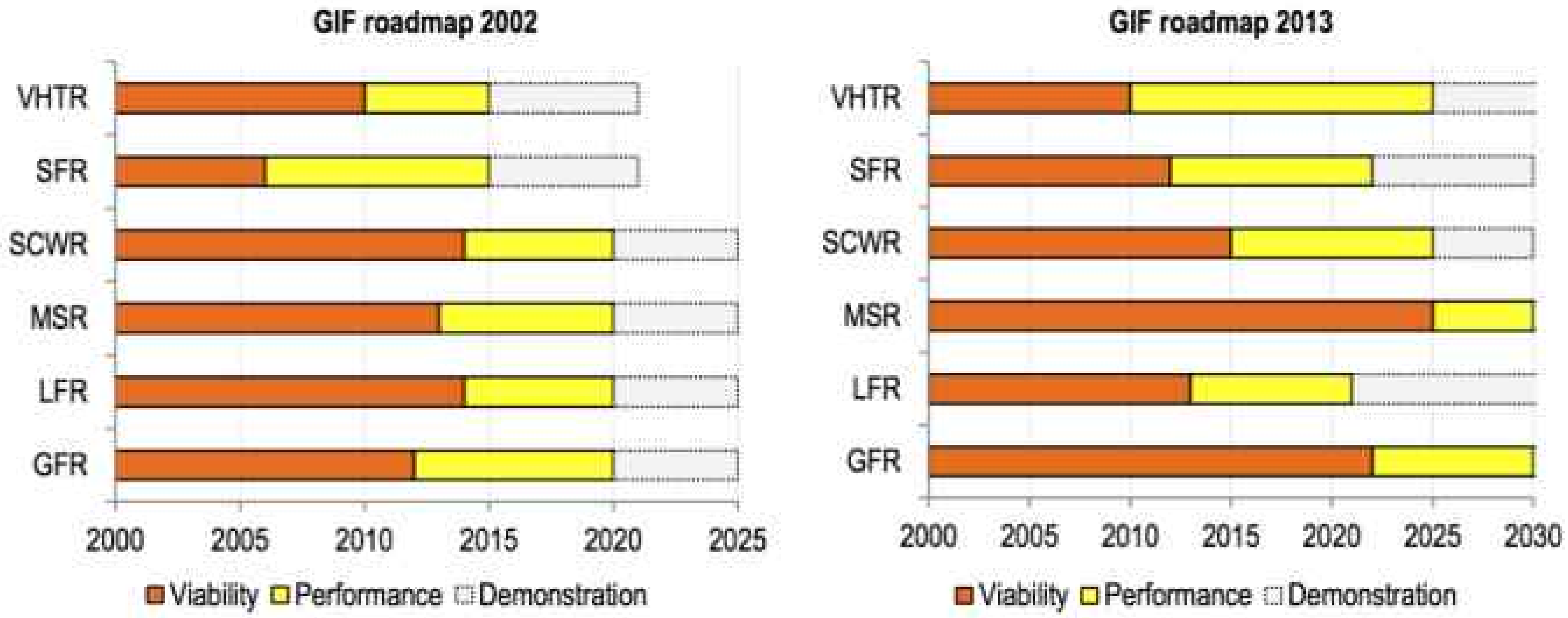


Molten Salt Reactor

Parameters of Reference GenIV Systems

	LWR	VHTR	SFR	SCWR	GFR	LFR	MSR
Electrical Power (MWe)	600-1000	100-300	50-2000	300-700	1000	20-1200	1000
Coolant	water	helium	sodium	water	helium	Lead or lead-bismuth eutectic	Fluoride salt
Moderator	water	graphite	--	water	--	--	--
System Pressure (MPa)	8-16	6-9	0.3	>22	7	0.3	0.6
Coolant Temperature at Outlet	325	700-1000	500-550	510-625	750-850	480-570	700-800
Average Core Power Density (W/cm^3)	100	3-8	>200	~70	100	70-120	330

Generation IV International Forum (GIF): system development timelines as defined in the original 2002 Roadmap (left) and in the 2013 update (right)

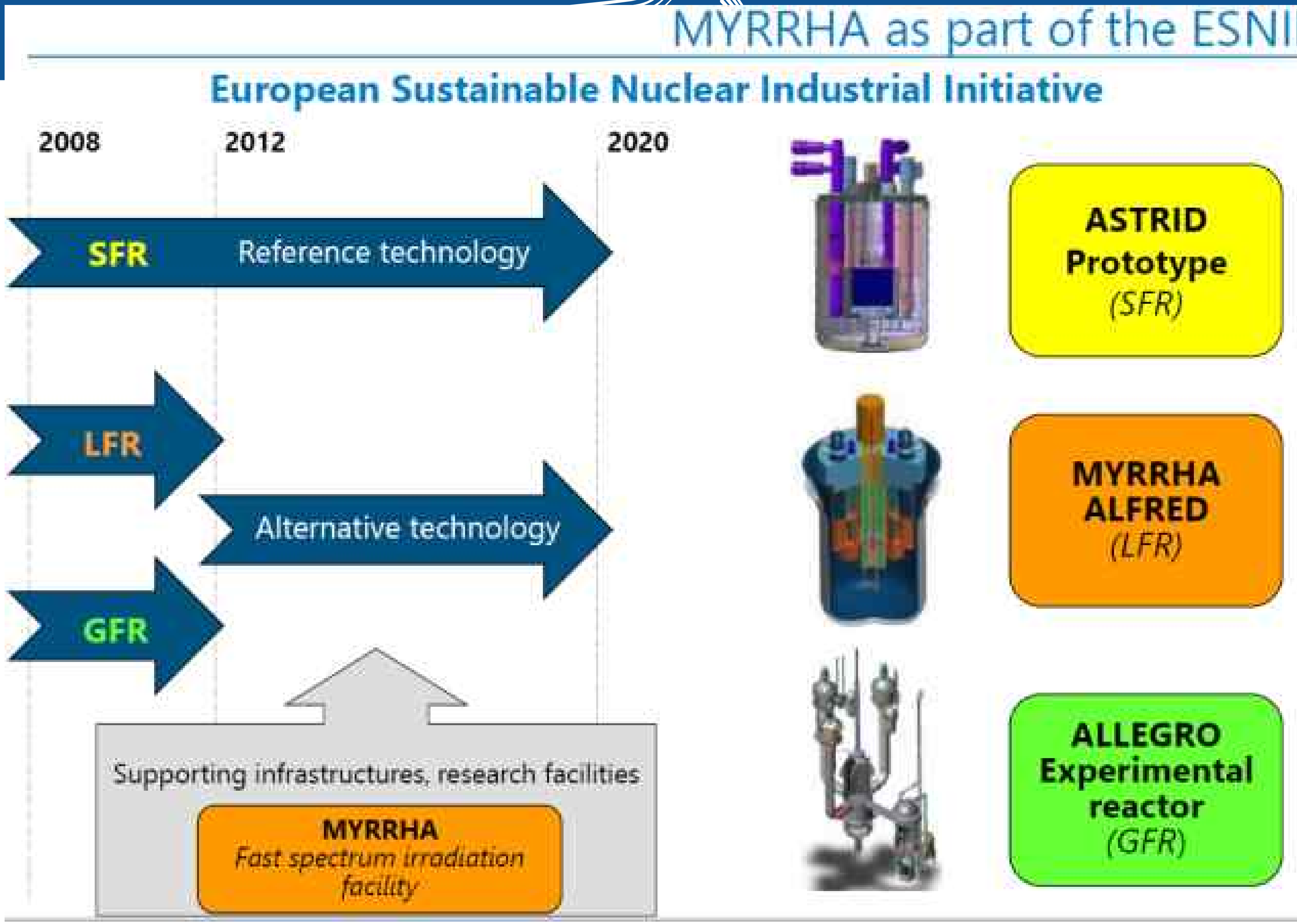


=> Generation IV reactor systems : industrial deployment in the middle–long term 2030–2050

NB: Above timelines are indicative and may change, for example, if structural materials, fuel or other important components are not validated at the planned dates.

Source: GIF Roadmap 2013 / "*Technology Roadmap Update for Generation IV Nuclear Energy Systems: Preparing Today for Tomorrow's Energy Needs*", January 2014, issued by the OECD Nuclear Energy Agency for the Generation IV International Forum / https://www.gen-4.org/gif/upload/docs/application/pdf/2014-03/gif-tru2014.pdf

Generation IV in the EU (SET Plan, 2008)



"European Sustainable Nuclear Industrial Initiative" (ESNII, 2010): ESNII addresses the need for demonstration of Gen-IV Fast Neutron Reactor technologies, together with the supporting research infrastructures, fuel facilities and R&D work. - http://www.snetp.eu/esnii/

Generation IV: key questions requiring Research & Innovation and good governance in nuclear fission (1/2)

European Commission

(1) Sustainability

- S-Q1: how to enhance fuel utilisation ?

(is spent nuclear fuel recyclable material or waste ?)

- Is Plutonium a valuable asset or a liability ? (U-238 in FRs => Pu-239)

- S-Q2: How to minimise volume, heat and toxicity of ultimate radioactive waste ?

(fast versus thermal neutron spectrum, Generation IV, partitioning and transmutation)

=> strategies for the reactor system (= power generation + fuel cycle management)

(2) Safety and Reliability

- *SR-Q1: how safe is safe enough ? (integral approach needed)*

(eliminate the "technical" need for offsite emergency response)

- *SR-Q2: What is the impact of managerial and human factors on safety performance ?*

(safety culture)

⇒ *strategies to optimise the "risk / benefit" factor in all nuclear fission applications*

Generation IV: key questions requiring Research & Innovation and good governance in nuclear fission (2/2)

(3) Socio-Economics

- SE-**Q1: How to evaluate the "total social costs" of energy technologies ?**

= private (capital + O&M + fuel) + external (system effects + accidents + avoided CO2)

- SE-Q2: How to improve public engagement in decision making (energy governance) ?

⇒ strategies to improve competitiveness and public participation in decision making

(4) Proliferation Resistance

- *PR-Q1: Is the nuclear proliferation risk over-estimated ?*

(weapons of mass destruction and CBRN threats versus radiological terrorism)

- *PR-Q2: To what extent is nuclear proliferation an obstacle to the development of civilian nuclear energy ?*

⇒ *strategies for counter-terrorism measures (including cyber-attacks) e.g. advanced detection techniques (including "big data" applications)*


WEAPONS
You Tube
OF MASS DISTRACTION

Toute réflexion doit partir de quelques constats:
le cap, les lois de la nature, des quasi-certitudes et des incertitudes

« Le cap » = triangle énergétique européen

=> transition vers une économie compétitive, sûre et sobre en carbone

⇒ le futur système économique et industriel doit être sobre non seulement en carbone, mais également en énergie et en ressources naturelles (économie circulaire)

« Invariants » : les lois de la nature
(e.a. **sciences de l'énergie et sciences humaines)**

La réalité des faits et des chiffres : deux domaines de « quasi-certitude »

1. L'accroissement de la population mondiale restera massif

2. Changement climatique et pollution de l'air en ville: impacts majeurs sur environnement et économie

Les défis de type technologique et humain : trois domaines d'incertitudes

1. **La « grande transition » : convergence d'un développement technologique accéléré et d'une** révolution digitale irréversible

2. **Le stockage de l'énergie, le chaînon manquant de la transition énergétique**

3. Le comportement humain (vers une nouvelle gouvernance pour une gestion optimale de l'énergie)

« Le cap » pour 50 ans = énergie, eau, nourriture, environnement, …

Source: "Top Ten Problems of Humanity for Next 50 Years", R. E. Smalley, Energy & NanoTechnology Conference, Rice University, May 3, 2003.

Richard Errett Smalley (1943 –2005), Rice University, in Houston, Texas. In 1996, he was awarded the Nobel Prize in Chemistry for the discovery of a new form of carbon, buckminsterfullerene.
“Energy is not just “any old issue.” Most people, in fact, understand its importance very well. In short, energy is the single most important factor that impacts the prosperity of any society.”
- https://en.wikipedia.org/wiki/Richard_Smalley and http://chemicalsareyourfriends.com/sliders/buckminsterfullerene/ // http://www3.nd.edu/~pkamat/pdf/energy.pdf

Fission nucléaire de quatrième génération : stop ou encore ?

1 – Introduction : Génération IV - pourquoi ? comment ? avec qui ? quand ?

2 - Le cap («triangle énergétique européen») et les invariants (lois de la nature)

3 - La réalité des faits et des chiffres (« quasi-certitudes ») et défis technologiques et humains (incertitudes)

4 – Besoins et opportunités pour le nucléaire au 21ème siècle (objectifs de Génération IV)

4.1 Améliorer la durabilité (y compris l'utilisation efficace du combustible et la réduction des déchets)

4.2 Sûreté et fiabilité (notamment en l'absence de toute intervention extérieure d'urgence)

4.3 Economie (compétitivité par rapport aux sources d'énergie)

4.4 Lutte contre la prolifération des armes nucléaires et protection matérielle

5 - Les systèmes-réacteurs nucléaires en projet de la Génération IV : SFR, LFR, GFR, VHTR, MSR et SCWR

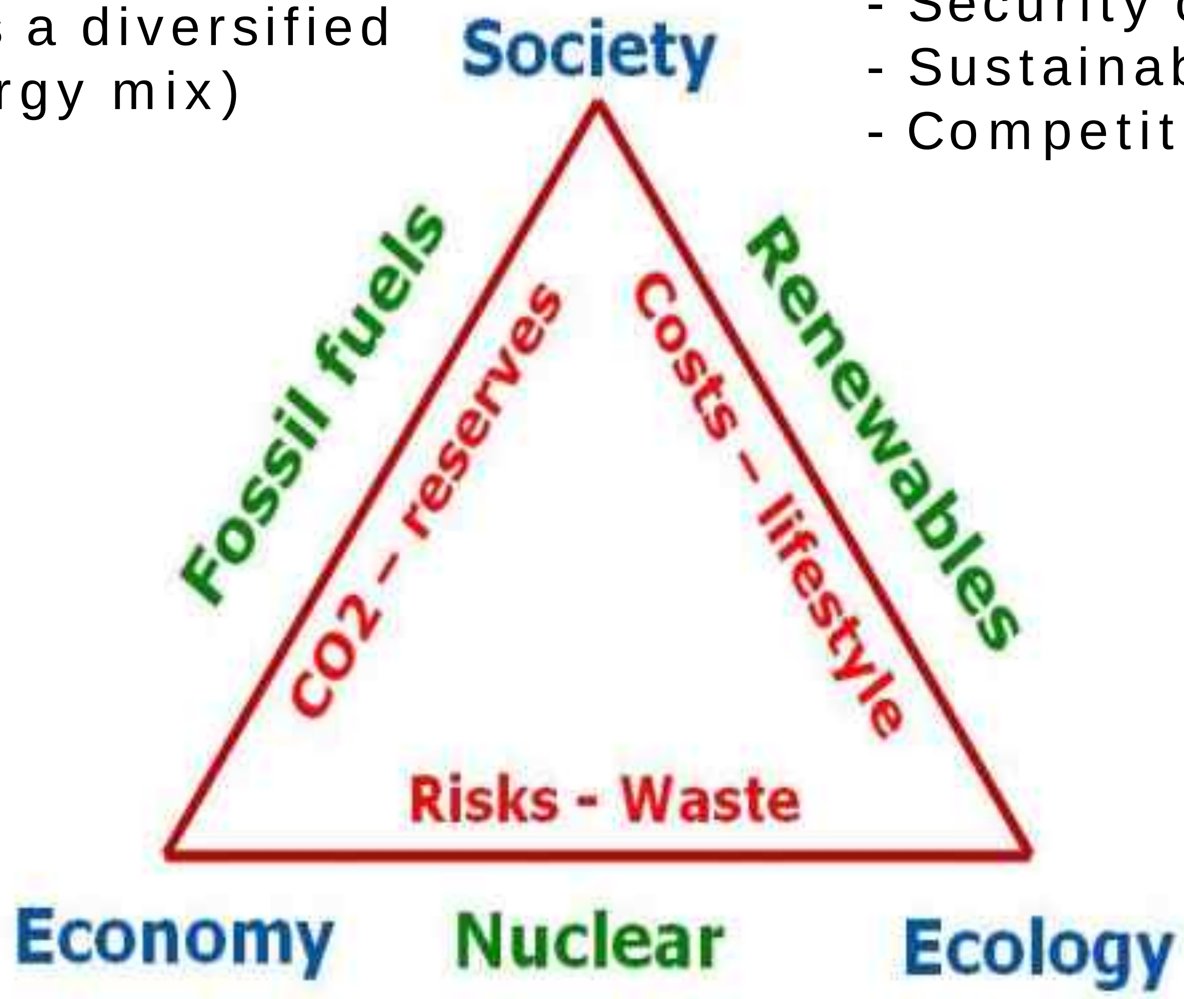
6 – Conclusion : recherche, innovation et formation en fission nucléaire

(2.1) « Le cap » = le triangle énergétique européen

Triangle of sustainable energy

(towards a diversified energy mix)

- Security of supply
- Sustainability
- Competitiveness



UE : « union de l'énergie » et objectifs 2030 pour GES, REN et EE

European Commission

A Resilient Energy Union with a Forward-Looking Climate Change Policy

= > about the transition to a low-carbon, secure and competitive economy

The Energy Union is a European priority project, identified by the Juncker Commission (2014 – 2019) as one of the 10 political priorities, in which five dimensions are closely interlinked:

- **energy security, solidarity and trust**
- **a fully integrated European energy market**
- **energy efficiency contributing to moderation of demand**
- decarbonising the economy
- **and research, innovation and competitiveness.**

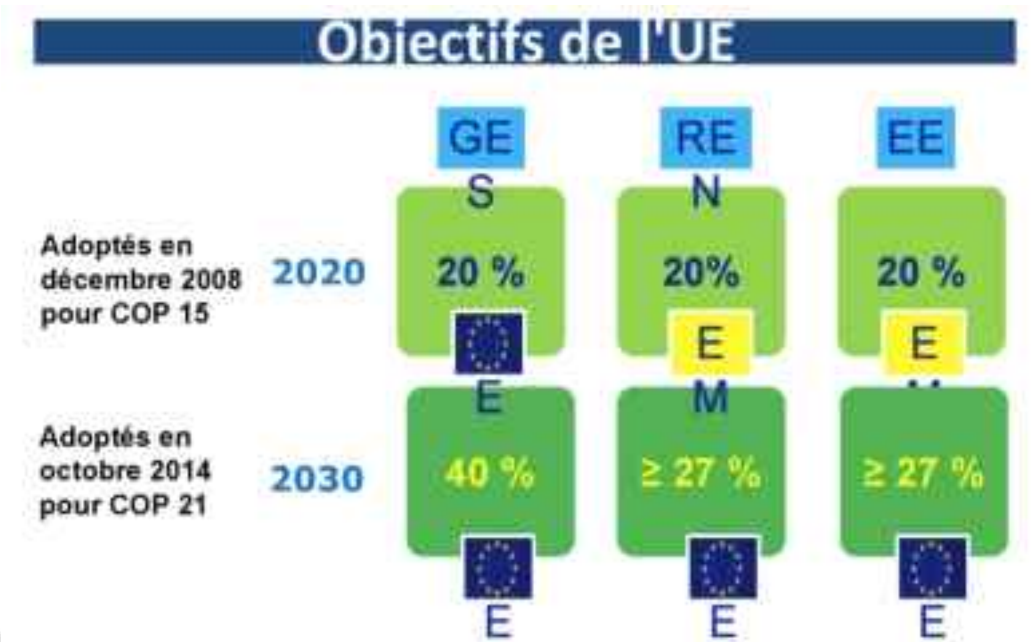
2030 Framework for Energy and Climate for the Union
(European Council, 24 October 2014): 4 key targets

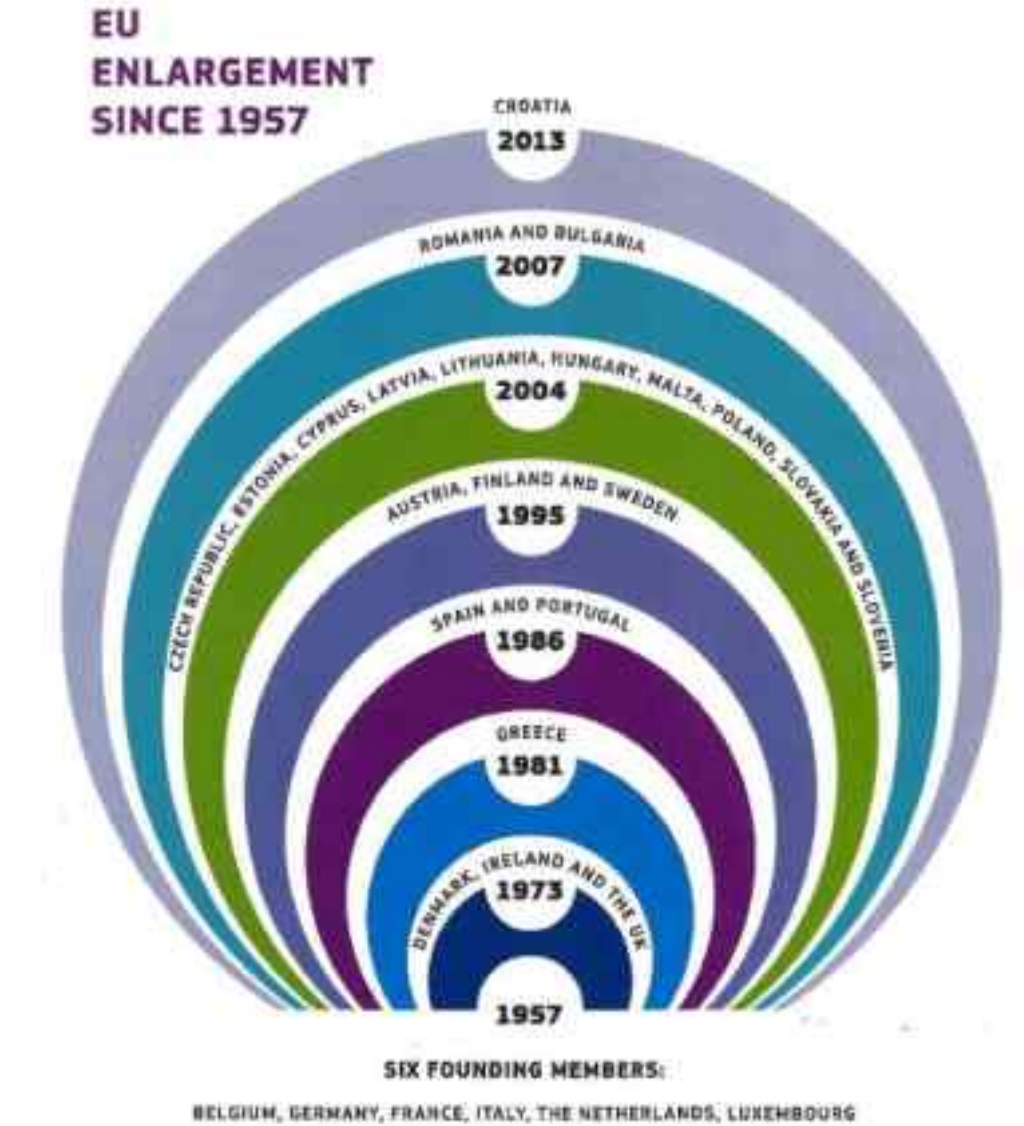
(1) domestic greenhouse gas emissions: reduction by 40 % below the 1990 level for 2030 (binding target at the EU level, formally approved as the Intended Nationally Determined Contribution (INDC) of the Union and its Member States to the Paris Agreement (ratified by the Union on 5 October 2016 and entered into force on 4 November 2016).
(NB: results in 2015, GHG emissions were 22% below the 1990 level)

(2) share of renewable energy: target of at least 27 % by 2030 (binding at the EU level)
(NB: results in 2014, the share of renewables reached 16% of the gross final energy consumption of the EU)

(3) energy efficiency improvement: at least 27 %, with a view to a level of 30% (indicative at the EU level)
(NB: results in 2016, OK for energy efficiency in the EU - 2020 final energy consumption target reached)

(4) **interconnection of EU's electricity markets**: target of 15 % for 2020.





Energy has been at the heart of the European project from the start (ECSC 1952 and Euratom 1957)

(1) "European Coal and Steel Community" (ECSC),
18 July 1952, Luxembourg

(2) The two Treaties of Rome:
EEC ("Common Market Agreement") and "European Atomic Energy Community" (EAEC or Euratom),
25 March 1957

Article 194 of the Lisbon Treaty :
"Union policy on energy shall aim, in a spirit of solidarity … :
.. Such measures shall not affect a Member State's right to determine the conditions for exploiting its energy resources, its choice between different energy sources and the general structure of its energy supply**".**
= > Treaty on the Functioning of the European Union = > Part 3 - Union policies and internal actions
Title XXI - Energy (Article 194) - http://europa.eu/lisbon_treaty/index_en.htm

Euratom Treaty (1957) - 4 fields of action

- Nuclear energy development
  (Including Research and Training Activities) (art. 4-11)

- Health and safety (art. 30-39)

- Safeguards (Guarantees for peaceful uses) (art. 77-85)

- External relations (art. 101-106)

<u>Euratom Treaty</u> (1957), pioneer in many fields (including protection of the environment)

- Title II, chapter 1 - <u>**Promotion of Research and Training**</u>
  Article 7:"Community <u>research and training</u> programmes shall be determined by the Council, acting unanimously on a proposal from the Commission, …"

- Title II, chapter 4 (Articles 40 – 44) - <u>**Investments**</u>: investments and associated action plans must be communicated to Euratom and should be in line with the objectives of the Euratom Treaty, which include compliance with radiation protection requirements for workers and the public, nuclear safety, safe management of spent fuel and radioactive waste, security of supply and safeguards.

- Title II, chapter 6: - <u>**EURATOM Supply Agency (ESA)**</u>
  Main mission is to ensure that <u>all users in the Community receive regular and equitable supply of ores and nuclear fuels</u> (Article 52: ESA has the right to acquire ores, source materials, and special fissile materials produced in the community and an exclusive right to conclude contracts for the supply of such materials from inside the community or from outside.

Sobriété en carbone, en énergie et en ressources naturelles (économie circulaire)

Le système économique et industriel doit être d'une part sobre en carbone et en énergie et d'autre part sobre en ressources naturelles (économie circulaire)

● **Pour assurer à l'UE une croissance durable, nous devons utiliser nos ressources de** manière plus intelligente, plus durable. **C'est la fin du modèle linéaire de croissance** économique consistant à « prélever-fabriquer-jeter ». De nombreuses ressources naturelles étant limitées, nous devons trouver un mode d'utilisation durable tant sur le plan économique que sur le plan environnemental.

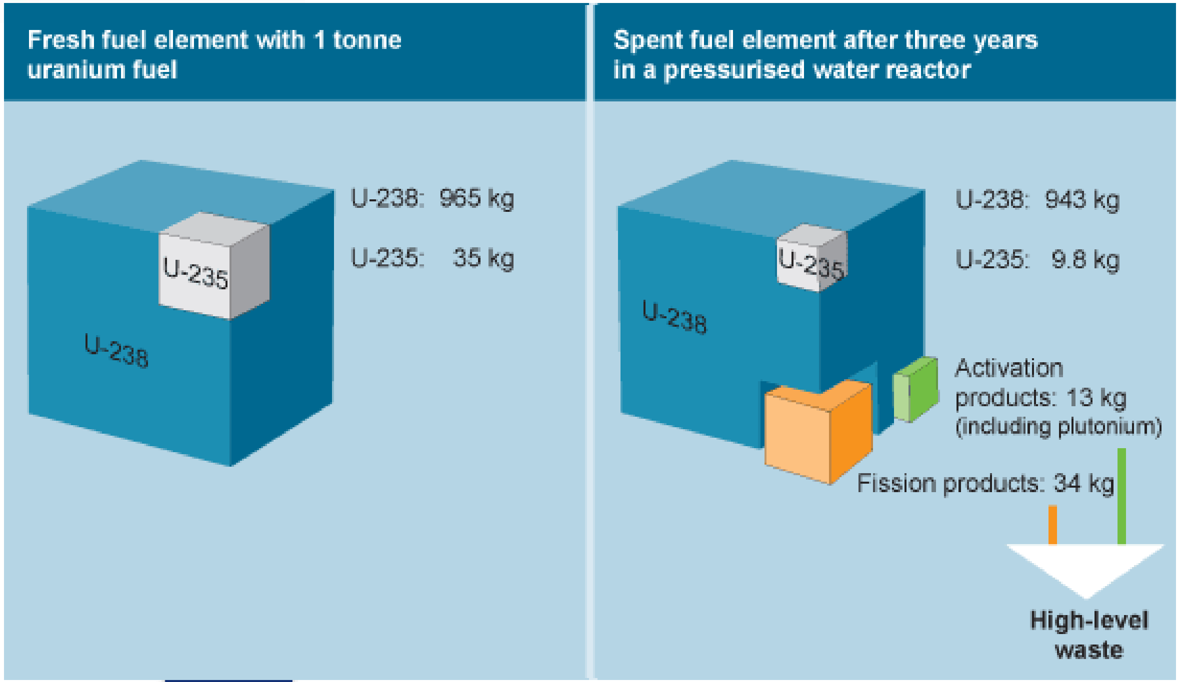
● **Dans une économie circulaire, les produits et les matières conservent leur valeur le plus** longtemps possible ; les déchets et l'utilisation des ressources sont réduits au minimum. **Grâce à l'économie circulaire, les consommations de matières et d'énergies deviennent de** plus en plus efficaces, sans gaspillage (selon le principe du recyclage au meilleur coût).

● L'efficacité énergétique est le moyen le plus efficace de combiner décarbonation de l'économie et amélioration de la sécurité énergétique de l'Union européenne. Elle a **progressé dans tous les domaines. On remarque même que la consommation d'énergie dans le monde n'est plus proportionnelle au PIB depuis plusieurs décennies.**

Source : Commission européenne :
(1) Paquet «économie circulaire», Bruxelles, 2 décembre 2015 / « Économie circulaire: la Commission tient ses promesses » (http://europa.eu/rapid/press-release_MEMO-17-105_fr.htm)
(2) « Une stratégie européenne pour une énergie sûre, compétitive et durable », Livre vert de la Commission (8 mars 2006) (http://eur-lex.europa.eu/legal-content/FR/TXT/?uri=URISERV%3Al27062)

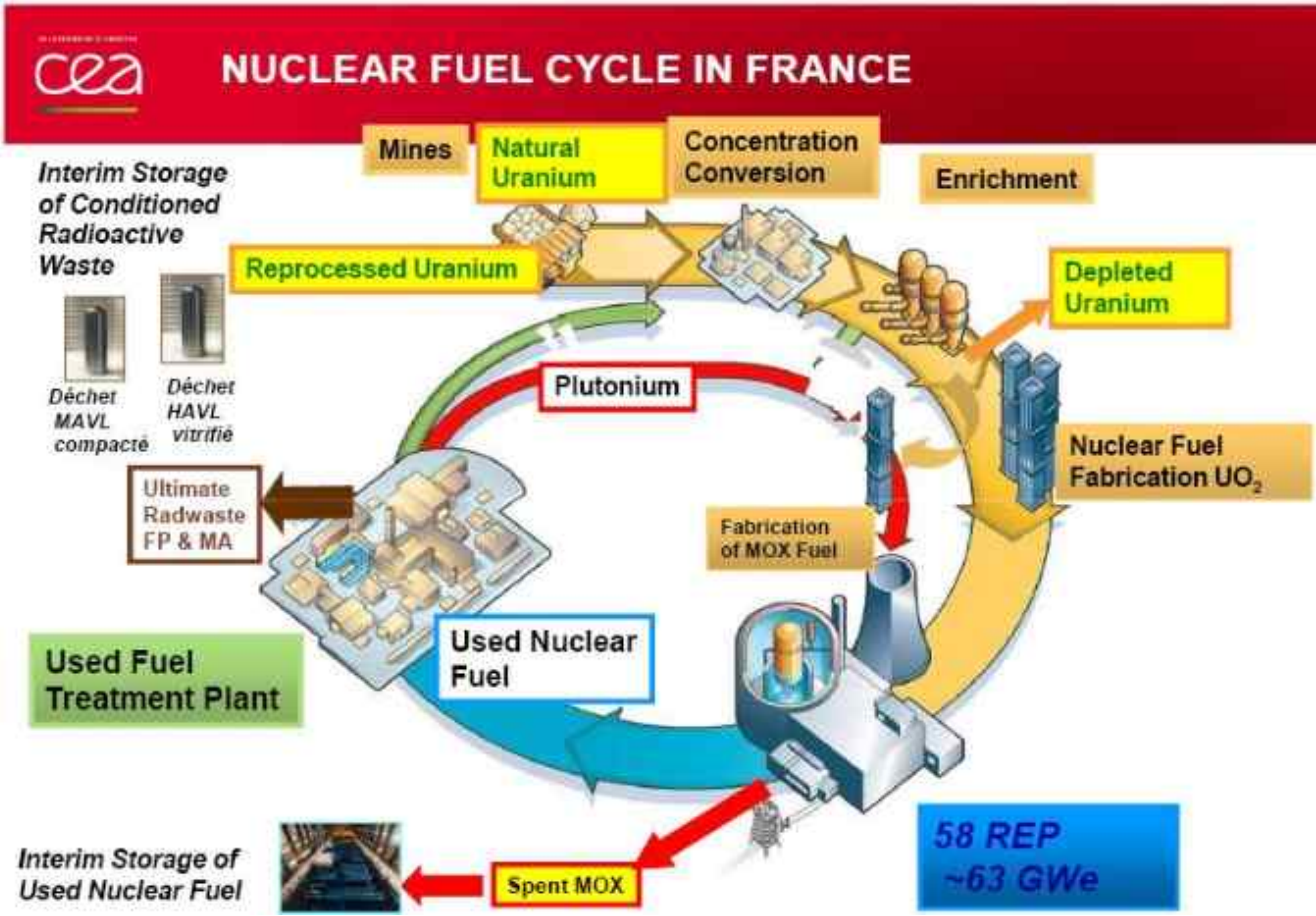
Economie circulaire dans l’ UE <=> cycle du combustible nucléaire

EU: modernising waste policy and targets: waste as a resource
http://ec.europa.eu/environment/circular-economy/index_en.htm



Nuclear fuel cycle. With appropriate fuel reprocessing, a Fast Neutron Reactor (FNR) can recycle about 95% of the used fuel.

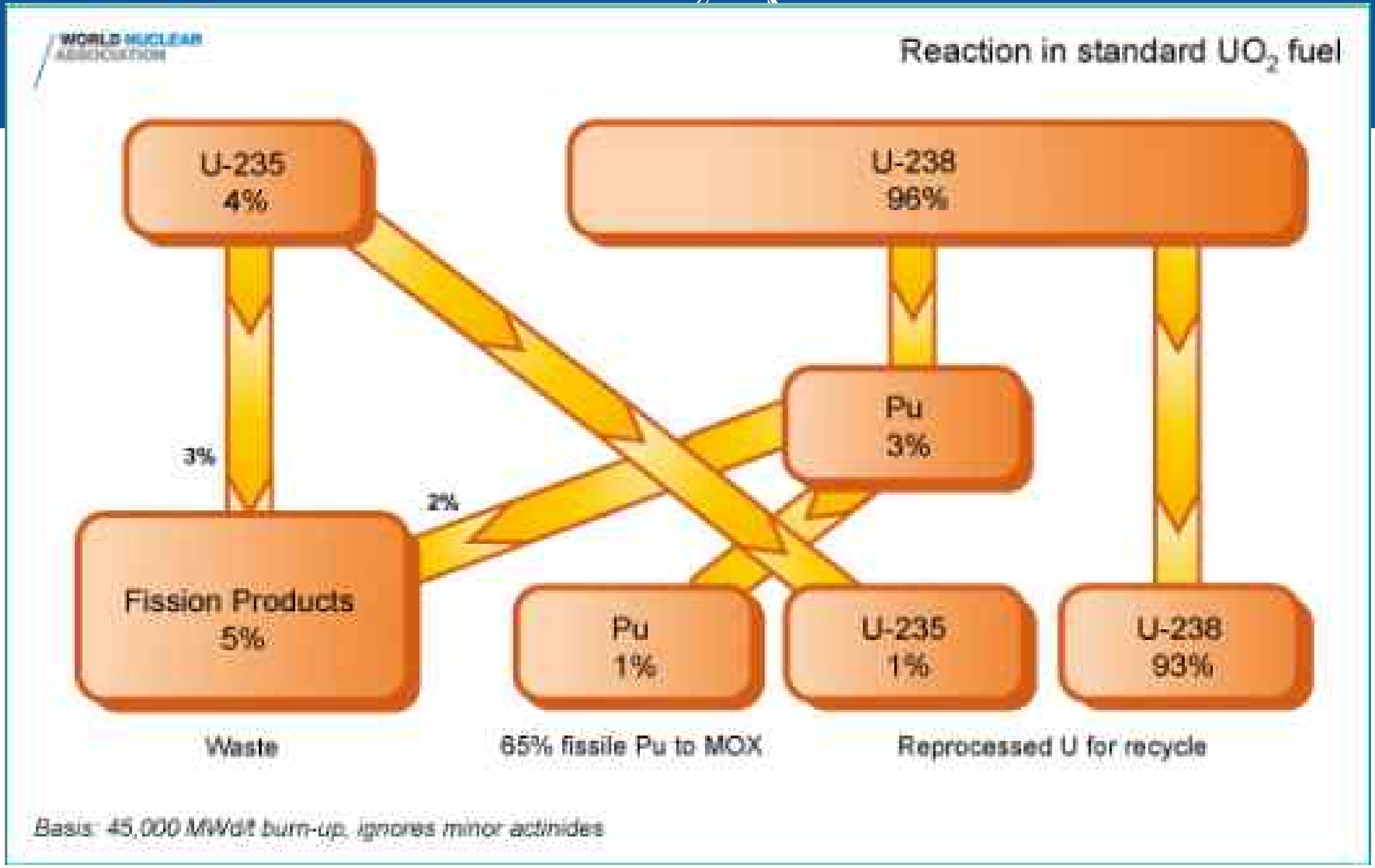
About 95% of the resulting fission products decay to safe levels in 300 years.



Fuel removed from a reactor, after it has reached the end of its useful life, can be reprocessed to produce new fuel

Source: LOW CARBON COMPETITIVE ENERGY SUPPLY - FRANCE's PERSPECTIVE, Frank CARRE (SET-Plan Conference 2013, May 7-8, 2013)

Nuclear fuel cycle – standard UO_2 fuel

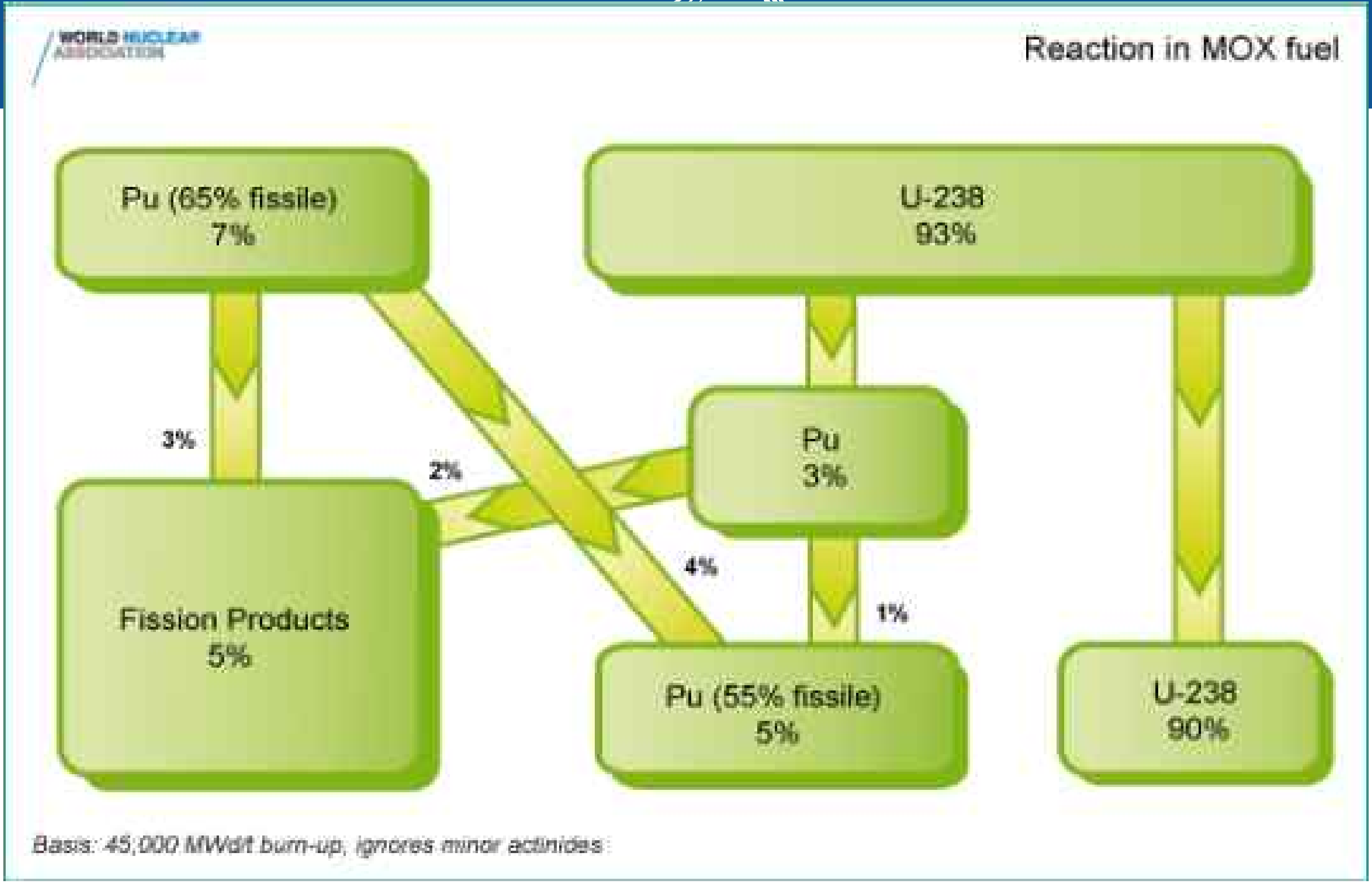


Inventory of separated recyclable materials (OECD/NEA 2007)

	Quantity (tonnes)	Natural U equivalent (tonnes)
Plutonium from reprocessed fuel	320	60,000
Uranium from reprocessed fuel	45,000	50,000
Ex-military plutonium	70	15,000
Ex-military high-enriched uranium	230	70,000

Source: * http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/plutonium.aspx
* http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Fuel-Recycling/Mixed-Oxide-Fuel-MOX/

Nuclear fuel cycle – MOX fuel



- Mixed oxide (MOX) fuel was first used in a thermal reactor in 1963 (BR3, Belgium), but did not come into commercial use until the 1980s.
- MOX fuel provides almost 5% of the new nuclear fuel used today (40 reactors in Europe /BE, CH, DE, FR/ and 30 in other countries ww).
- MOX fuel is manufactured from plutonium recovered from used reactor fuel, mixed with depleted uranium.
- MOX fuel also provides a means of burning weapons-grade plutonium (from military sources) to produce electricity.

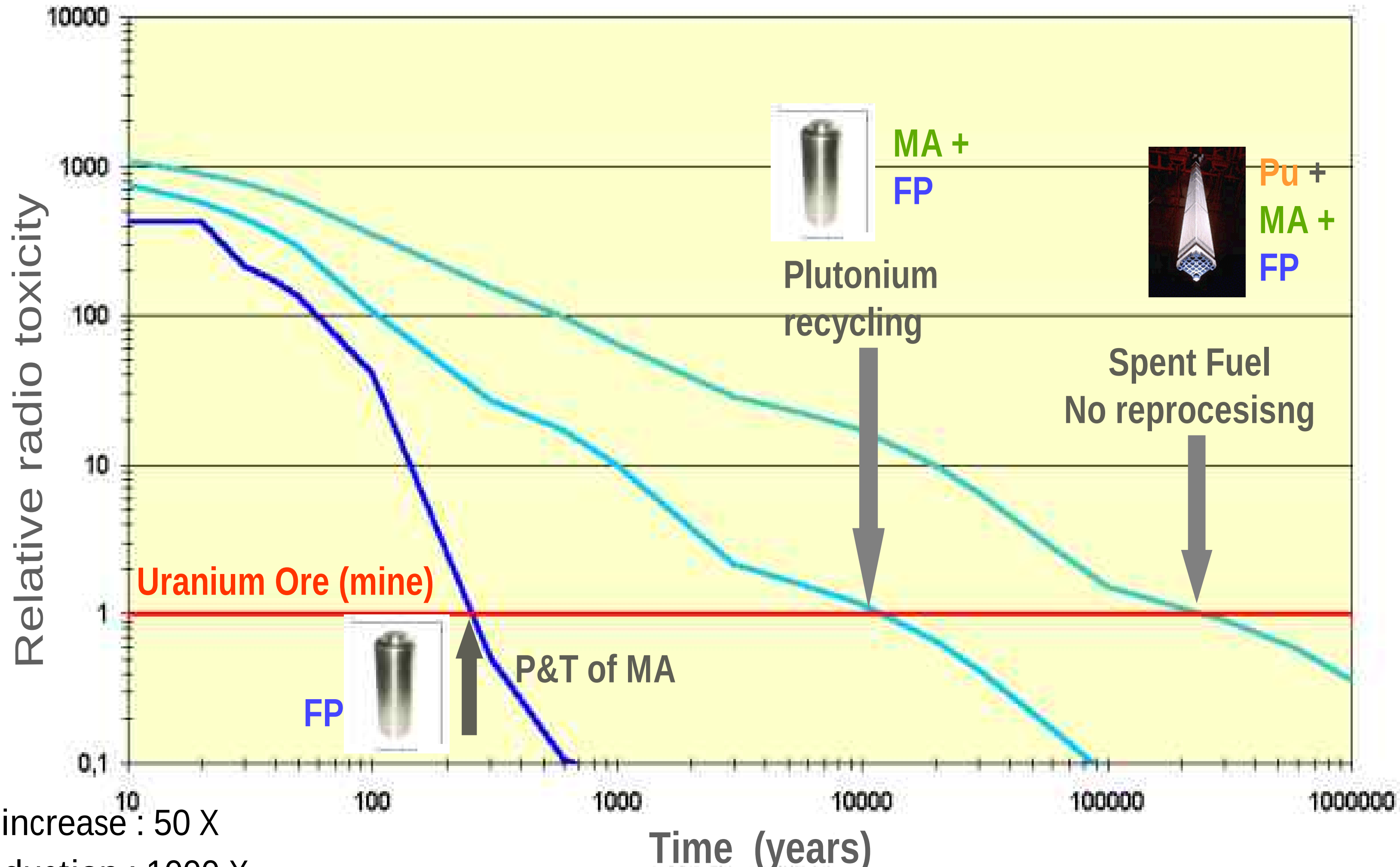
Source: http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Fuel-Recycling/Mixed-Oxide-Fuel-MOX/

Sustainability: optimal radioactive waste management

(Partitioning and Transmutation <=> recycling of all minor actinides)

Generation IV

Generations II, III, III+



Energy increase : 50 X

Time reduction : 1000 X

Volume reduction : 100 X

Research and Innovation

UN Agenda-**2030 : 17 “Sustainable Development Goals” (Sept 2015)**

« Small Smurfs – Big Goals » (UN campaign for SDGs, Febr 2017)

Clean Energy

Technology and Innovation

Great schools

Source: campaign launched by the United Nations and UNICEF, New York, NY, 15 February 2017
- "Smurfs team up with United Nations in 2017 for a happier, more peaceful and equitable world" (NB: SDGs = Sustainable Development Goals")
- http://www.smallsmurfsbiggoals.com/ and "Smurfs for the SDGs!", 20 February 2017 - https://www.youtube.com/watch?v=_V--qw-kTrA

"Looking at the 17 goals, I am struck by the very close overlap with the work of the IAEA," **Director General Yukiya Amano has said.** *"The new goals cover poverty, hunger, human health, clean water, affordable and clean energy, industry and innovation, and climate change, to name just a few. These are all areas in which nuclear science and technology have much to offer."*

IAEA movie:
"How the Atom Benefits Life"
(5 min, March 2015)
https://www.iaea.org/newscenter/multimedia/videos/how-atom-benefits-life

UN website: http://www.un.org/sustainabledevelopment/sustainable-development-goals/

IAEA website: https://www.iaea.org/newscenter/news/how-iaea-will-contribute-sustainable-development-goals

(2.2) Les lois de la nature

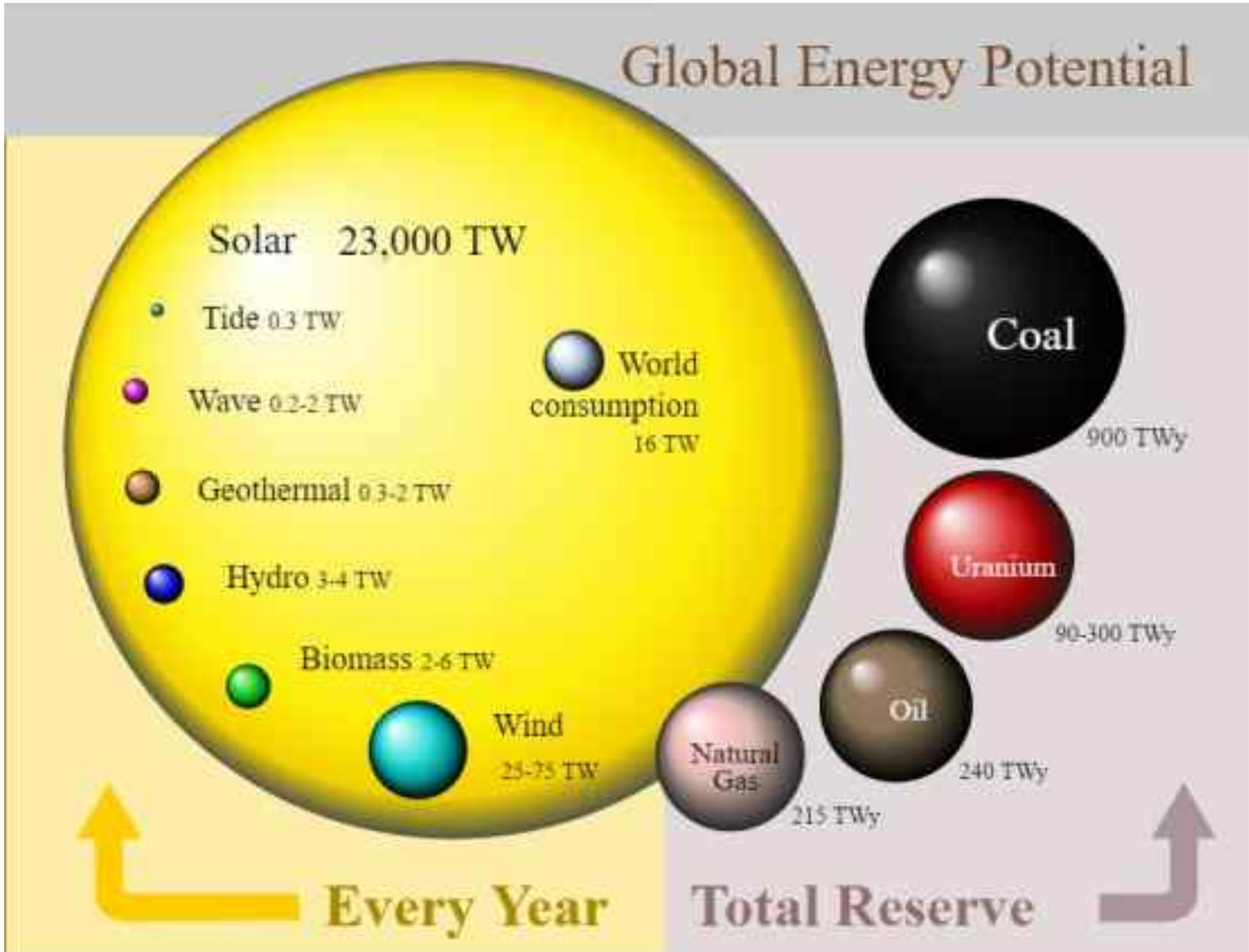
Comparing the world's energy resources: every year and total reserve

All the renewable sources of energy are depicted in this diagram as annual outputs (i.e. power, TW)

whereas the non-renewables like fossils and nuclear are shown in their totality (i.e. energy, TWy).

All these energy sources exist on Earth – and they are dwarfed by the monstrous capacity of the one thing that enters our planetary closed system – solar energy.

=> Where should we invest for the long-term ?



Source: http://waitbutwhy.com/2015/06/the-deal-with-solar.html

Energies de flux (vent, soleil): production non continue et prédictibilité difficile

Intermittent Renewable Energy Sources (RES)

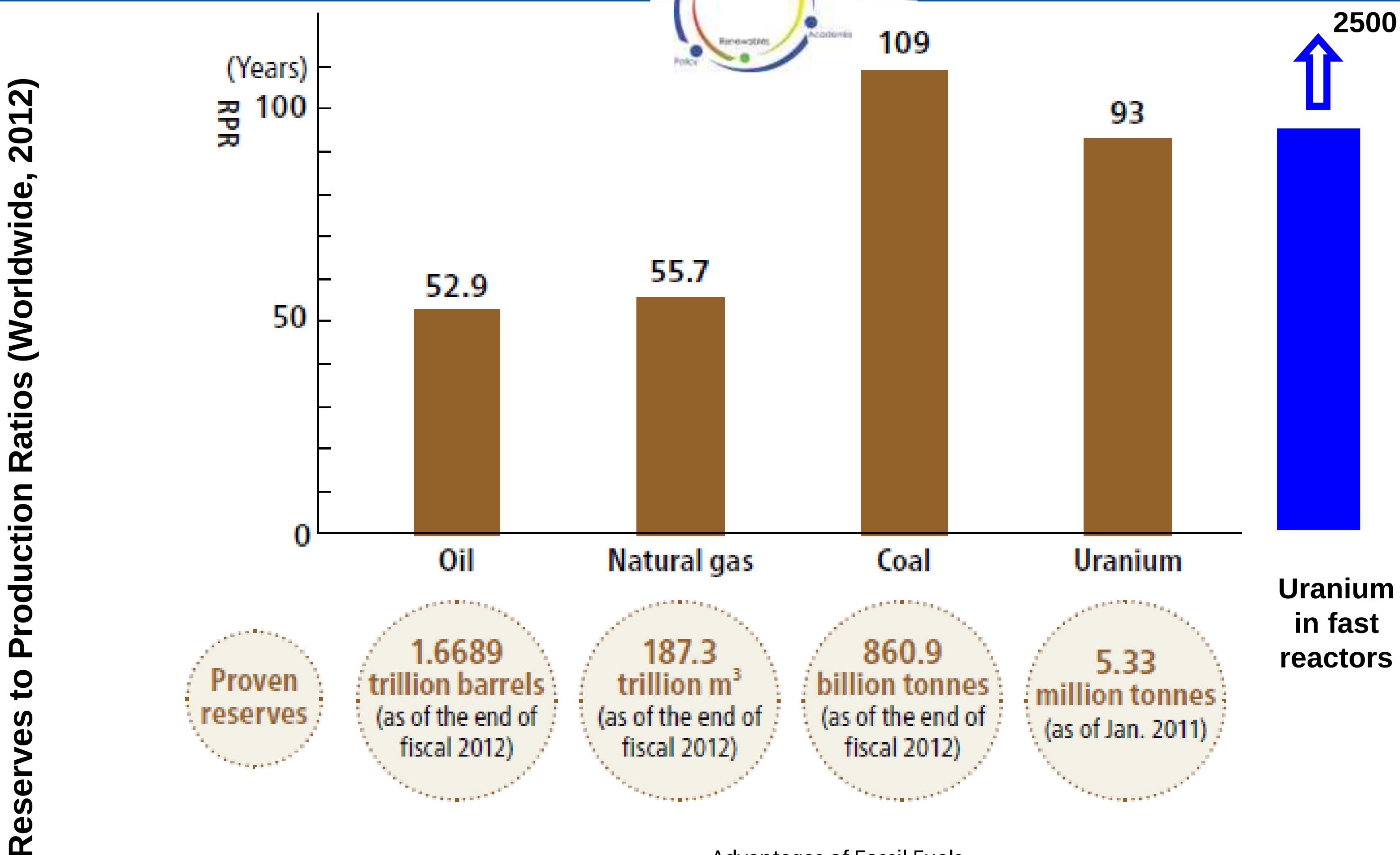
RES specificities, such as production variability and low-predictability, zero marginal-cost of generation, and strong site specificity, result in a set of technical and economic challenges.

NB: Day ahead forecasts of generation by a single wind-farm feature up to 20% errors => need for better physical models and meteorological data mixed with statistical models

NB: Threats to grid stability for large penetration rates (up to 20%) => need for requirements for fault-ride through capacity, provision of reactive power, frequency and voltage control, and incentives to minimize deviations.

Source: MIT Energy Initiative (2012)

Energies de stock (charbon, gaz, pétrole, uranium) 2012:
réserves limitées dans le temps et l'espace



Ratios for Reserves to Production: Proven reserves divided by annual production

Source: http://www.hitachi.com/csr/highlight/2014/renewable.html

- Oil, natural gas, and coal: BP Statistical Review of World Energy, June 2013
- Uranium: OECD-NEA Uranium 2011: Resources, Production and Demand

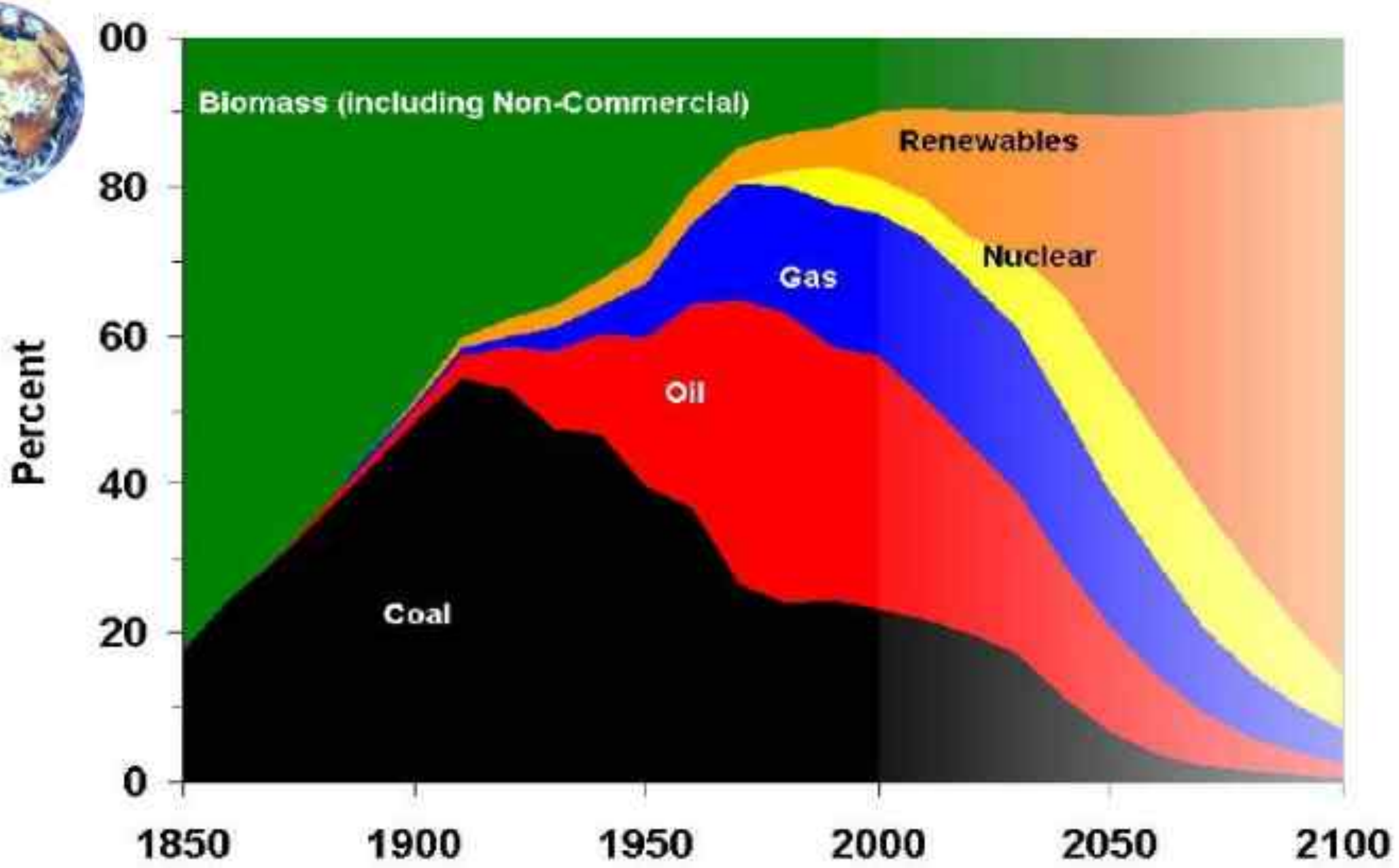
Advantages of Fossil Fuels

1. Well developed technology: fossil fuels have been used to power our world for decades.
2. Cheap and Reliable. Fossil fuels are cheap and reliable sources of energy (excellent to use for the energy base-load)

Disadvantages of Fossil Fuels

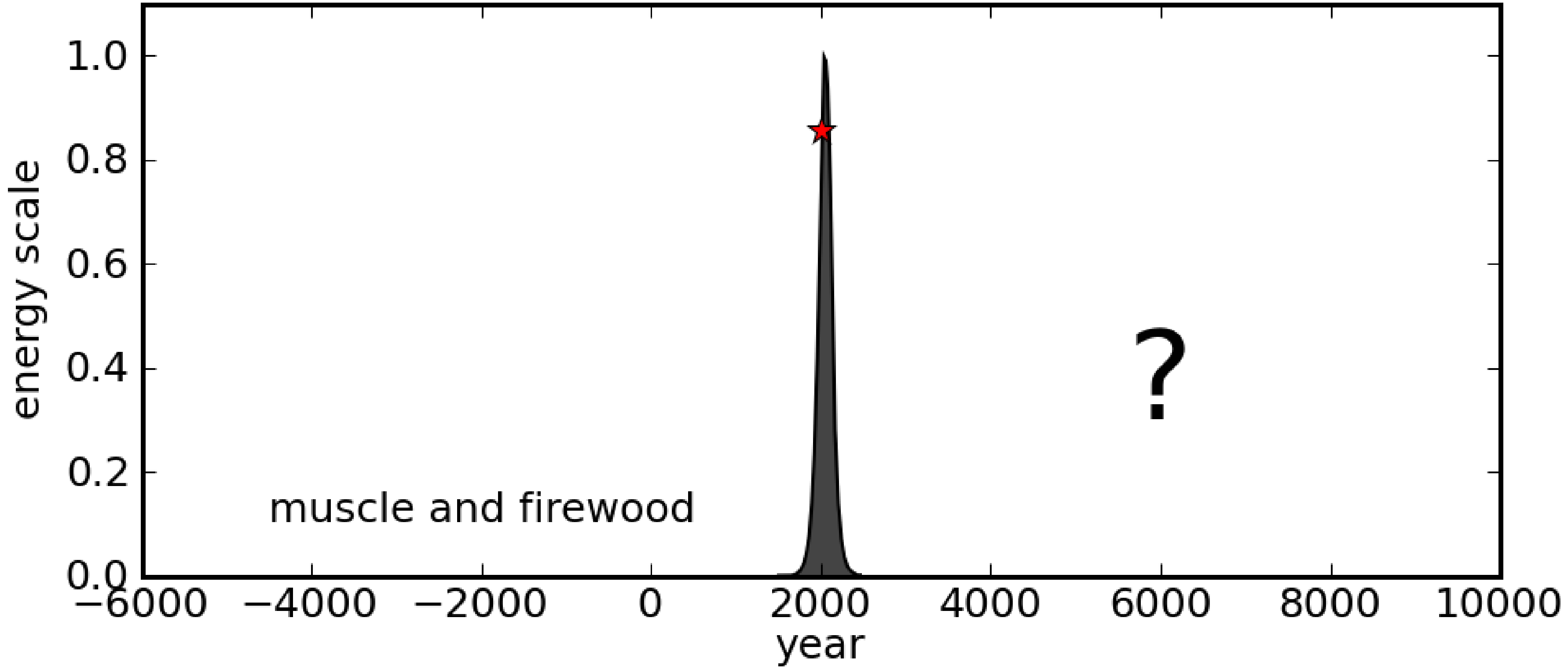
1. Contribute to Global Warming: fossil fuels contain high amounts of carbon.
2. Non-Renewable (unsustainable): in fact, it takes millions of years before the formation of fossil fuels takes place in any noteworthy quantities).

Evolution of global primary energy sources (1/2)



Evolution of global primary energy / substitution of fossil, fissile, renewables
(a great variety of energy scenarios have been developed since C. Marchetti, IIASA,1985)

Evolution of global primary energy sources (2/2)



"<u>We live like kings today</u>, on the backs of roughly 100 energy slaves each (human metabolism is 100 Watts, but Americans enjoy 10 000 W of continuous power).

Our richness is very much tied to surplus energy availability, and that so far has been a story of finite fossil fuels. But even under solar power, we can't continue our track record of 3% energy growth per year for even several hundred years!

Global physical limits—thermodynamic, energy return on energy invested, finite arable land, water, fisheries, climate change, etc.—are all asserting themselves to remind us that <u>nature doesn't care about our dreams</u>."

(http://physics.ucsd.edu/do-the-math/ by Tom Murphy, professor of physics at the University of California, San Diego, March 2015)

Energy conversion: the heat values of various fuels

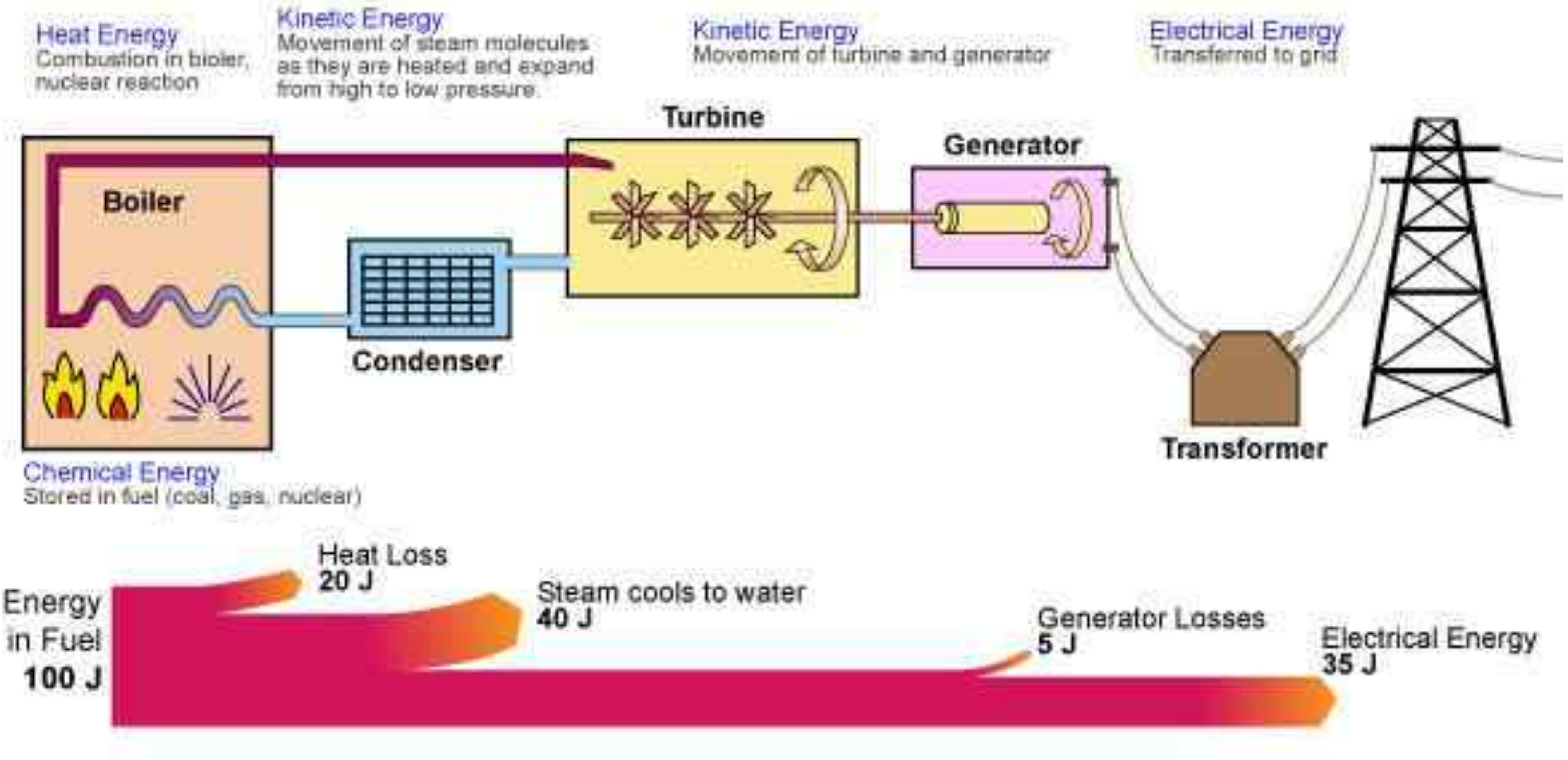
(nuclear power is very energy-dense, an extremely concentrated form of energy)

Fuel	Heat value	
Hydrogen	121	MJ/kg
Petrol/gasoline	44-46	MJ/kg
	32	MJ/L
Diesel fuel	45	MJ/kg
	39	MJ/L
Crude oil	42-44	MJ/kg
	37-39	MJ/L
Liquefied Petroleum Gas (LPG)	49	MJ/kg
Natural gas (UK, USA, Canada, Australia)	37-39	MJ/m3
Natural gas (Russia)	34	MJ/m3
Natural gas as LNG (Australia)	55	MJ/kg
Hard black coal (IEA definition)	>23.9	MJ/kg
Sub-bituminous coal (IEA definition)	17.4-23.9	MJ/kg
Lignite/brown coal (IEA definition)	<17.4	MJ/kg
Lignite (Australia, electricity)	c 10	MJ/kg
Firewood (dry)	16	MJ/kg
Natural uranium, in LWR (normal reactor)	500	GJ/kg
Natural uranium, in LWR with U & Pu recycle	650	GJ/kg
Natural uranium, in FNR	28,000	GJ/kg
Uranium enriched to 3.5%, in LWR	3900	GJ/kg

Uranium figures are based on 45,000 MWd/t burn-up of 3.5% enriched U in LWR

Source : OECD/IEA Electricity Information 2008 and World Energy Needs and Nuclear Power (WNA, January 2014)
- http://www.world-nuclear.org/info/Current-and-Future-Generation/World-Energy-Needs-and-Nuclear-Power/

Energy transfer from chemical (to heat, to kinetic) to electricity => 35 %



Efficiency levels of cycles driven by steam, CO2 and He (Rankine, Brayton, Stirling vs Carnot)

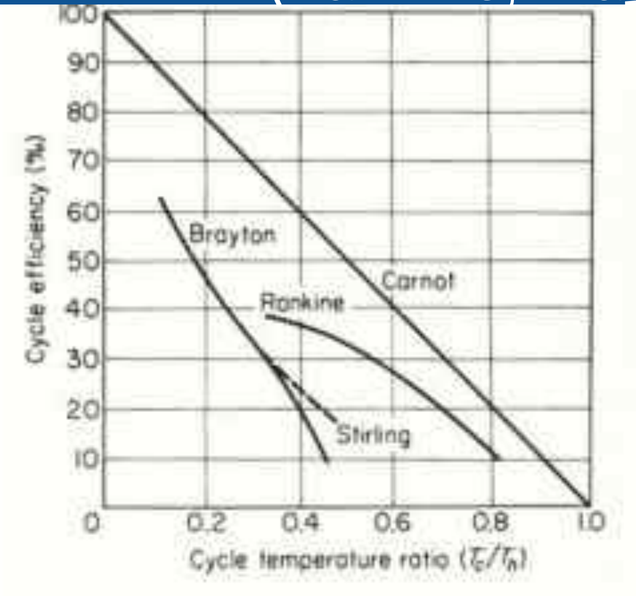
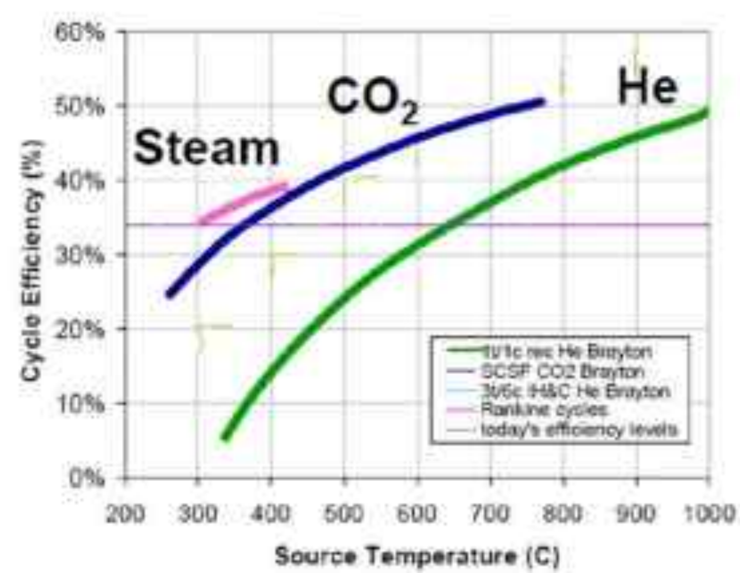


Figure left - Comparison of dynamic power conversion cycle typical efficiencies versus the temperature ratio between the cold and hot side of the cycle.

efficiencies *vs* source temperature for steam, CO_2 and He



Carnot's theorem : *No engine operating between two heat reservoirs can be more efficient than a Carnot engine operating between the same reservoirs.*

$$\eta_{\mathrm{I}} = \frac{W}{Q_{\mathrm{H}}} = 1 - \frac{T_{\mathrm{C}}}{T_{\mathrm{H}}} \qquad (1)$$

$$W = Q_{\mathrm{H}} - Q_{\mathrm{C}} \qquad (2)$$

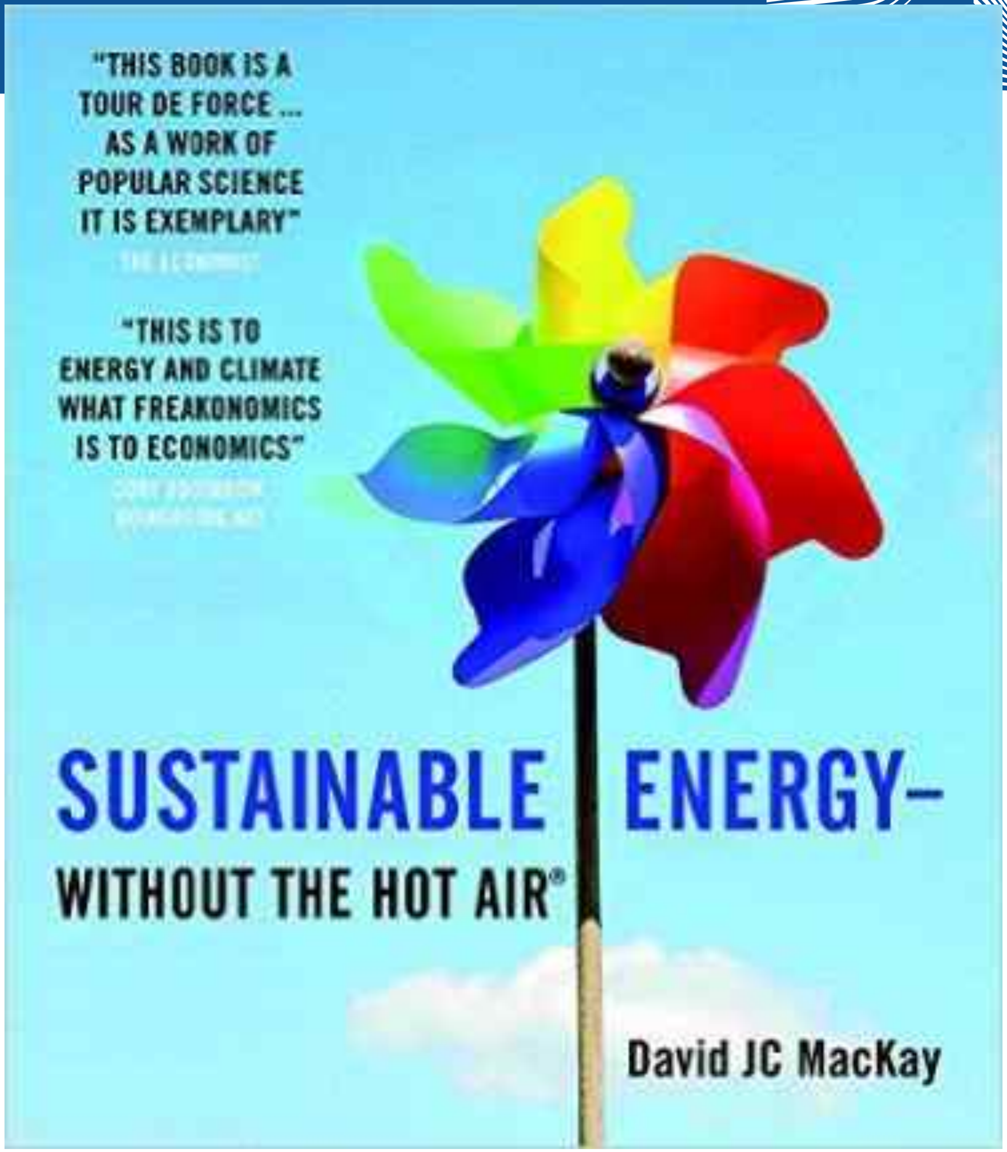
Explanation

This maximum efficiency η_{I} is defined as above:

- W is the work done by the system (energy exiting the system as work),
- Q_{H} is the heat put into the system (heat energy entering the system),
- T_{C} is the absolute temperature of the cold reservoir, and
- T_{H} is the absolute temperature of the hot reservoir.

Source: "Supercritical CO2 cycles application in power generation", Samuel SAYSSET, ENGIE Lab CRIGEN / at SRBE-KBVE workshop of 23 November 2016, Siemens Huizingen (Belgium), "Production d'électricité: Evolutions des technologies, nouvelles opportunités et empreintes environnementales"

"Sustainable Energy: Without the Hot Air", David Mackay (1967 - 2016), Cambridge (UK)



"……….Like Lord Kelvin before him, Professor MacKay realises that in many fields, and certainly in energy, unless you can quantify something you can never properly understand it.

As a result, his fascinating book is also a mine of quantitative information for those of us who sometimes talk to our friends about how we supply and use energy, now and in the future."

Dr Derek Pooley CBE
Former Chief Scientist at the Department of Energy, Chief Executive of the UK Atomic Energy Authority and Member of the European Union Advisory Group on Energy

Reference: "Sustainable Energy: Without the Hot Air"
Sir David Mackay, 2009, UIT Cambridge
(download pdf file for free / read translations in 15 languages thanks to kind volunteers and supporters)
(www.withouthotair.com)

David Mackay - from 2009 to 2014 - Chief Scientific Adviser to the UK Department of Energy and Climate Change (DECC).
He was "the low-carbon advisor" of DECC. *NB: "The Chief Scientific Advisor's role is to ensure that the Department's policies and operations, and its contributions to wider Government issues, are underpinned by the best science and engineering advice available."*

Generation/consumption balance: a physical reality

Why is balance needed between electricity generation and consumption?

<u>Electricity cannot be stored in large quantities</u>

⇒ Generation must always equal consumption at any time of day and on any day of the year.

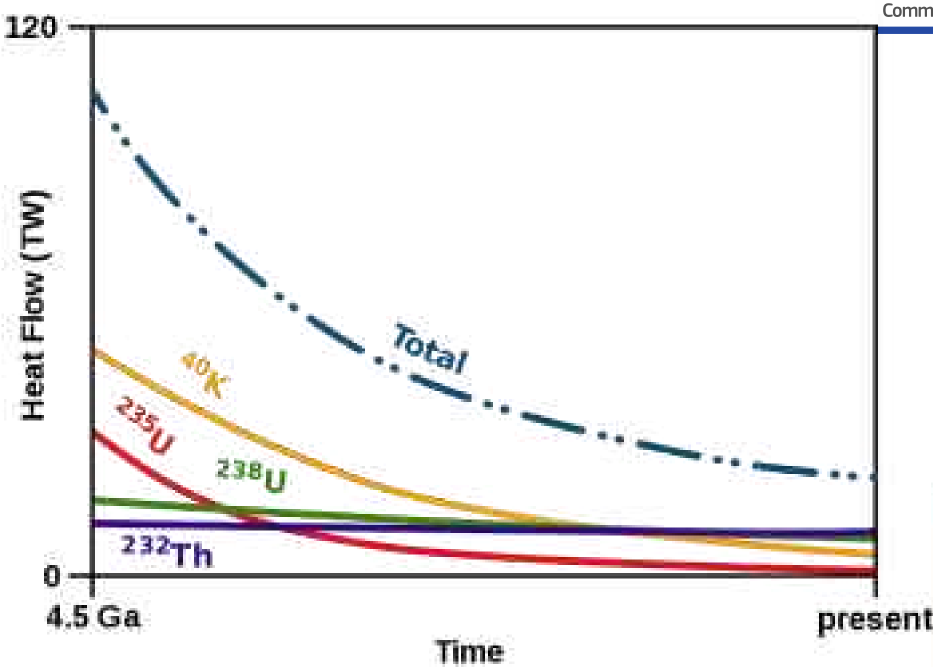
This <u>physical reality</u> is called the 'generation/consumption balance'.

<u>Main electric system challenges</u>: maintaining

- *grid stability (frequency control)*
  - *=> generation / consumption balance*
- *power quality (voltage support)*
  - *=> reactive power in AC systems*

Radioactivity has not been invented by man: it has been there, existing in the universe since time immemorial

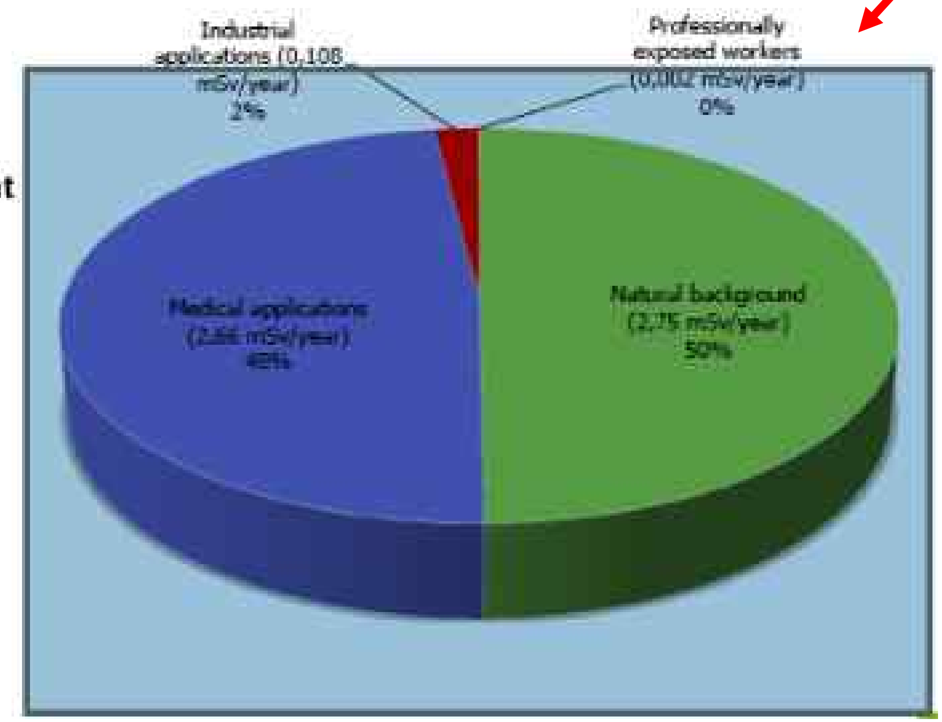
European Commission



The evolution of Earth's radiogenic heat flow over time

The radioactive decay of elements in the Earth's mantle and crust results in production of daughter isotopes and release of particles and heat energy, or radiogenic heat. Four radioactive isotopes are responsible for the majority of radiogenic heat, uranium-238 (U-238), uranium-235 (U-235), thorium-232 (Th-232), and potassium-40 (K-40).
Initial results from measuring the geoneutrino products of radioactive decay from within the Earth, a proxy for radiogenic heat, yielded a new estimate of half of the total Earth internal heat source being radiogenic, and this is consistent with previous estimates.
(https://en.wikipedia.org/wiki/Earth%27s_internal_heat_budget)

Exposure of the Belgian population
Average dose per caput : 5,5 mSv (FANC 2013)



The "problem" at low radiation doses

European Commission

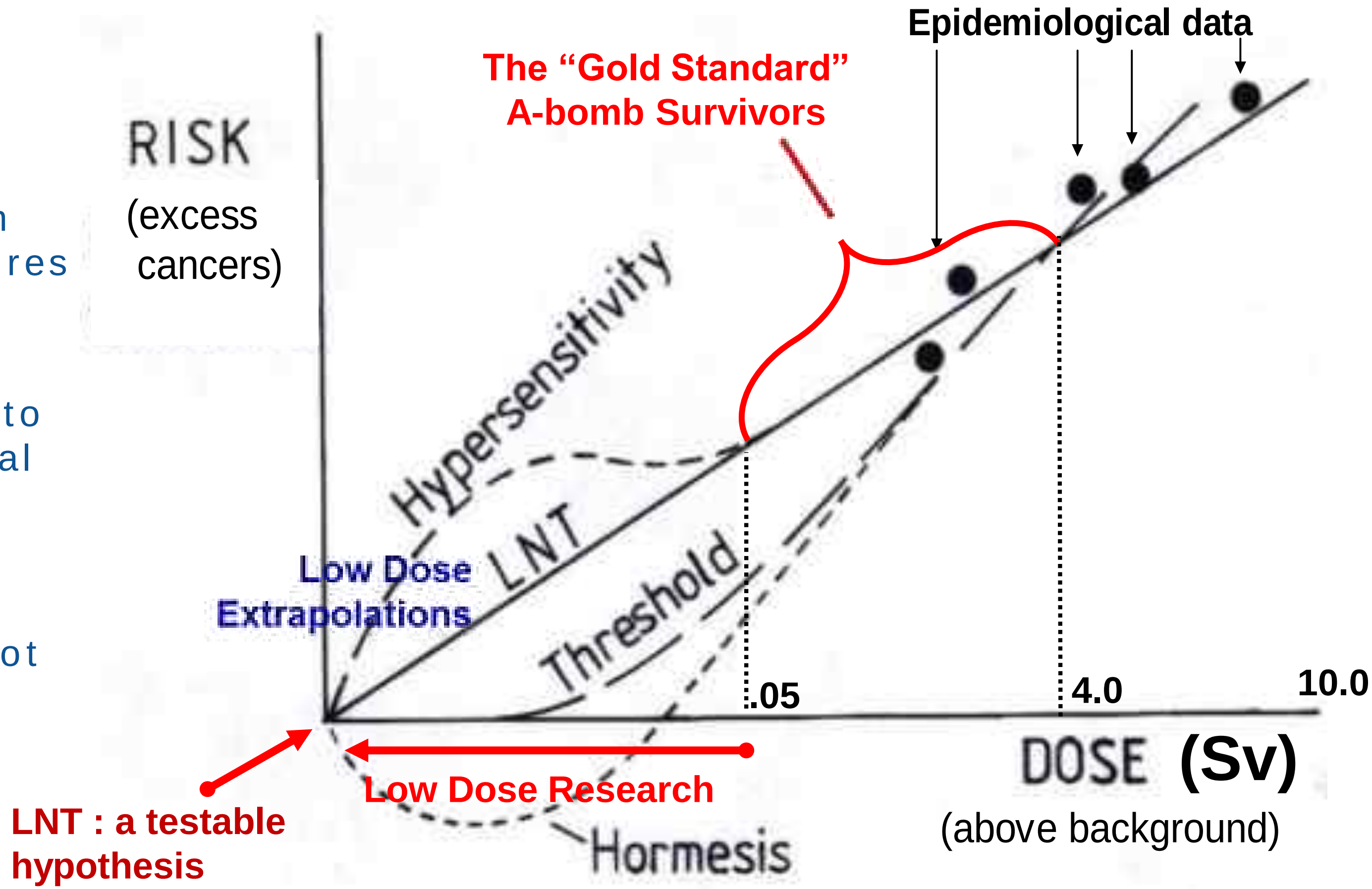
Radiation protection: low dose risk extrapolation

("Linear No-Threshold" /LNT/ model versus others, e.g. "hormesis")

Epidemiological models use human population exposures and outcomes.

Models confirmed to an extent by animal research.

Molecular and cellular data are not fully utilized.



statistical significance below 100 mSv ? (UNSCEAR 2006) => pros and cons of epidemiology versus fundamental sciences

"Best Available Science": science to support decision making

European Commission

"2012 Interdisciplinary Study" + 2013 Symposium (26-27 February 2013)

"Benefits and limitations of nuclear fission for a low carbon economy:

- Defining priorities for Euratom fission research & training (Horizon 2020)"

(organised by the European Commission and by the European Economic and Social Committee, Brussels)

including "Ethics Opinion n°27 - 16/01/2013 - An ethical framework for assessing research, production and use of energy"

(http://www.eesc.europa.eu/?i=portal.en.events-and-activities-symposium-on-nuclear-fission)

Questions asked to 20 socio-economic experts in the 2012 study

* Decision Making

• Should Euratom research be driven principally by public concerns or by industrial needs?

* Risk Governance

• How to deal with and how to communicate about uncertainties? (e.g. climate change, GMOs, stem cells, industrial risks)

* EU Energy Research programme

• How to better incorporate social sciences and humanities in EU energy research programmes? (policy makers and opinion leaders)

=> a new way of "making science": how to select the *Best Available Science /BAS/* ? aiming at improving decision making in energy policy matters (good governance)

=> concerted effort needed to describe RTD results in a language that is understandable to knowledgeable non specialists (e.g. policy maker)

Fission nucléaire de quatrième génération : stop ou encore ?

1 – Introduction : Génération IV - pourquoi ? comment ? avec qui ? quand ?

2 - Le cap («triangle énergétique européen») et les invariants (lois de la nature)

3 - La réalité des faits et des chiffres (« quasi-certitudes ») et défis technologiques et humains (incertitudes)

4 – Besoins et opportunités pour le nucléaire au 21ème siècle (objectifs de Génération IV)

4.1 Améliorer la durabilité (y compris l'utilisation efficace du combustible et la réduction des déchets)
4.2 Sûreté et fiabilité (notamment en l'absence de toute intervention extérieure d'urgence)

4.3 Economie (compétitivité par rapport aux sources d'énergie)

4.4 Lutte contre la prolifération des armes nucléaires et protection matérielle

5 - Les systèmes-réacteurs nucléaires en projet de la Génération IV : SFR, LFR, GFR, VHTR, MSR et SCWR

6 – Conclusion : recherche, innovation et formation en fission nucléaire

Deux domaines de « quasi-certitude » 1/2
(1) accroissement de la population mondiale

(3.1.1) L'accroissement de la population mondiale restera massif (10 milliards en 2050 contre 7,5 aujourd'hui)

- **dix milliards d'habitants en 2050, deux et demi de plus qu'aujourd'hui, avec en** particulier une explosion en Afrique (+ augmentation de la classe moyenne et des habitudes de consommation axées sur celles des pays riches).

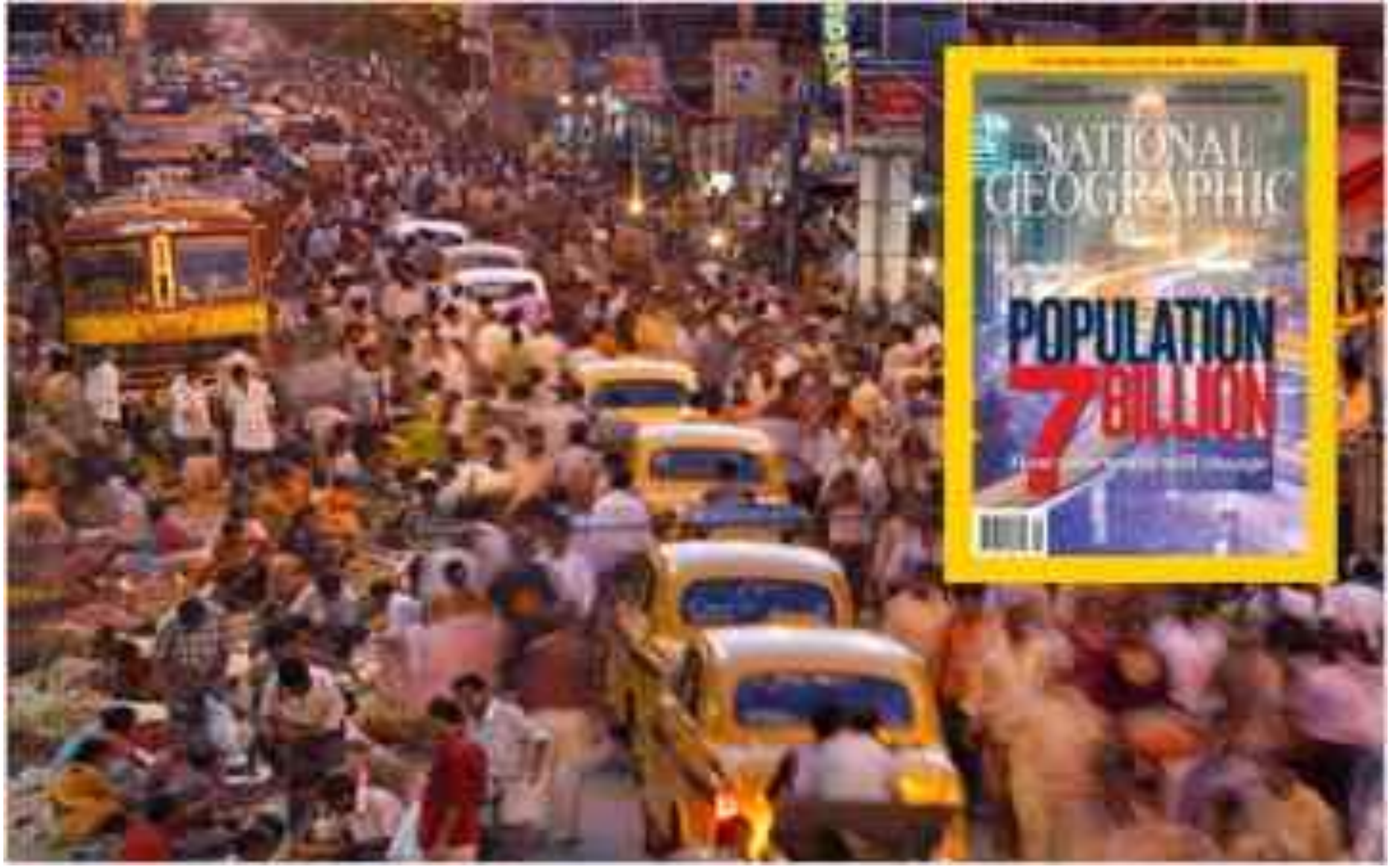
  La population mondiale a besoin et a droit à un système énergétique moderne **(basé, en particulier, sur un accès universel à l'électricité et aux transports).**

- **forte urbanisation: le taux mondial, de 54% aujourd'hui, devrait dépasser 65% en** 2050, soit un accroissement de 2,5 milliards de citadins, portant à 6 milliards la population totale vivant dans des agglomérations.

  Plus des deux tiers de l'énergie mondiale sera consommée dans les villes.

= > *Le développement de l'humanité (en particulier, dans l'hémisphère Nord) a reposé sur des sources d'énergie abondantes et bon marché mais souvent polluantes.*

= > *L'humanité saura-t-elle procéder en douceur à la transition vers un système plus respectueux de l'environnement et une croissance plus inclusive mais à énergie chère ?*



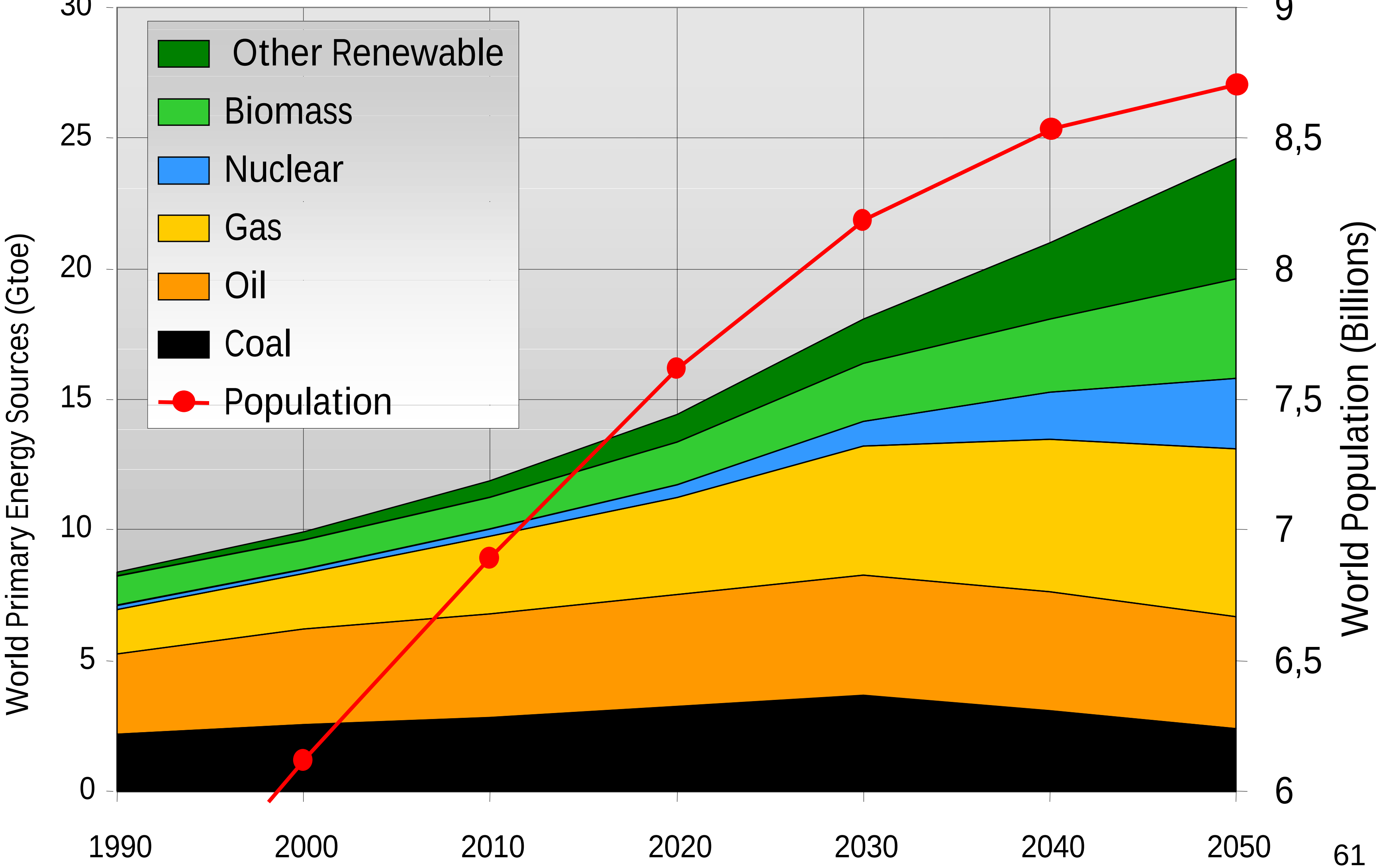
"National Geographic", Jan 2011 issue

The human population is going to cross the 7 Billion mark some time this year (2011), and it is in a trend of continuous growth towards 9 Billion mark in the next 30 over years!

Does this planet earth sill has enough natural resources to sustain such growth in a peace and harmony way?

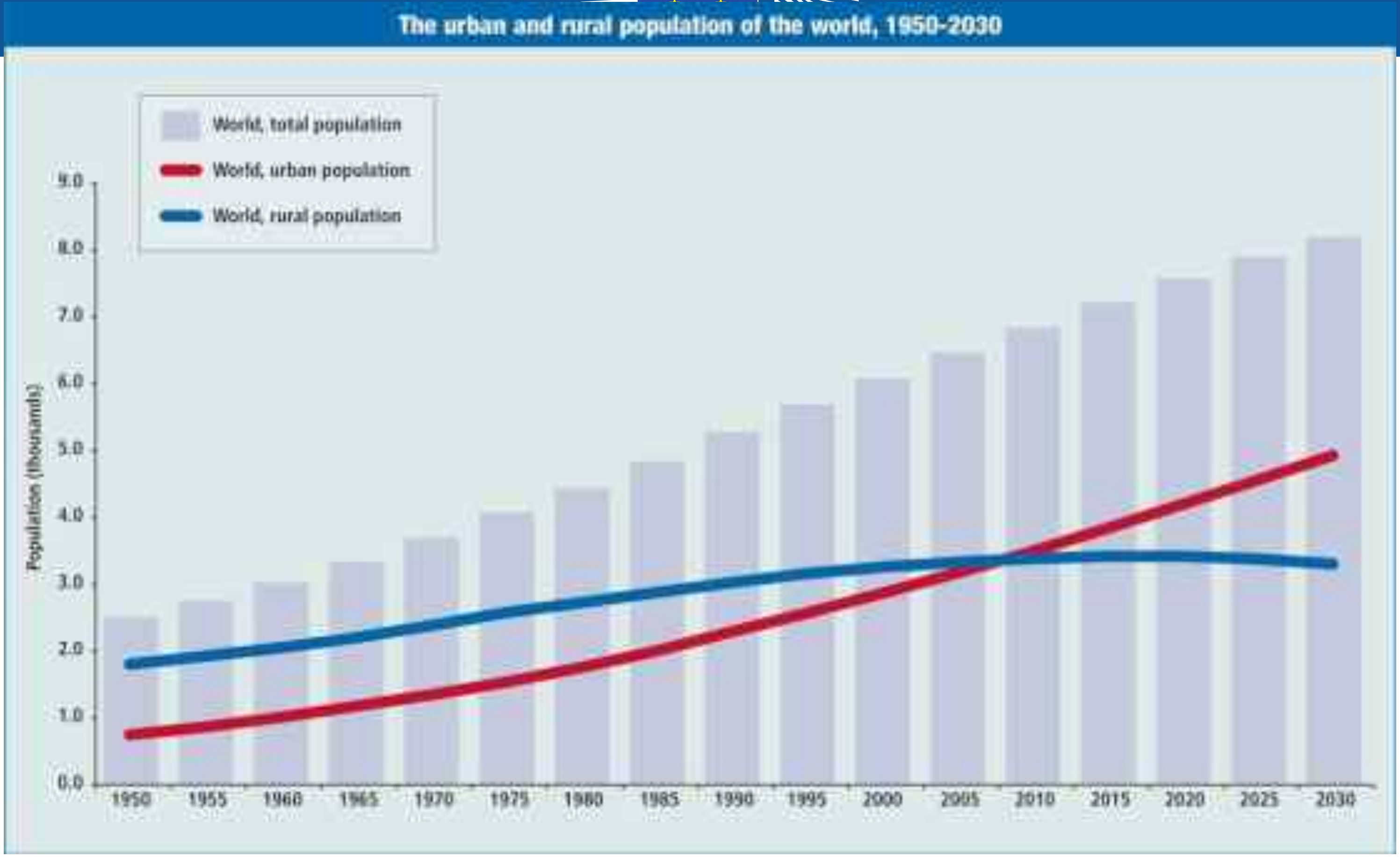
NB: human population was 1 billion in 1800, 2 billion in 1930, 3 billion in 1960
(Source: United Nations and US Population Reference Bureau, Washington
http://www.prb.org/Publications/DataSheets/2016/2016-world-population-data-sheet.aspx)

Energy sources (diversified energy mix) and world population: 1990 - 2050



Source IEA : Energy to 2050 - Scenarios for a Sustainable Future

World Urbanization Prospects (urban and rural) 1950 - 2030:
(UN Department of Economic and Social Affairs, 2005)



Michel Serres, philosophe des sciences (1930 -) : « Nous traversons la plus importante mutation depuis la préhistoire ! »
« Le premier changement qui me paraît le plus important dans le siècle qui précède, c'est le fait que nous étions 79% de paysans et aujourd'hui 1,1% seulement. Nous étions des paysans depuis le Néolithique et nous ne le sommes plus du tout. » dans « Biogée », 2013, http://www.cles.com/enquetes/article/michel-serres-nous-traversons-la-plus-importante-mutation-depuis-la-prehistoire

The twentieth century witnessed the rapid urbanization of the world's population. The global proportion of urban population increased from a mere 13 per cent in 1900 to 29 per cent in 1950 and, according to the 2005 Revision of World Urbanization Prospects, reached 49 per cent in 2005. Since the world is projected to continue to urbanize, 60 per cent of the global population is expected to live in cities by 2030. According to the latest United Nations population projections, 4.9 billion people are expected to be urban dwellers in 2030. (http://www.un.org/esa/population/publications/WUP2005/2005wup.htm)

Deux domaines de « quasi-certitude » 2/2

(2) changement climatique et pollution de l'air en ville => <u>électrification massive</u>

<u>(3.1.2) Le climat change de façon beaucoup plus rapide et plus perturbante **que prévu. Son corollaire, la pollution de l'air en ville est une préoccupation** environnementale et économique majeure</u>

● **La lutte contre les émissions de gaz à effet de serre est non seulement un impératif, mais aussi une** urgence, selon des approches bien sûr différentes selon les situations du Nord au Sud. Pour rester sous les 2°C en 2100, il faudrait atteindre « zéro émission nette de CO_2 » en 2050, c'est-à-dire un équilibre entre ce qui est émis et ce qui peut être absorbé notamment par les océans et les forêts. <u>**L'objectif de rester sous les 2°**C en 2100 est extrêmement ambitieux et coûteux.</u>

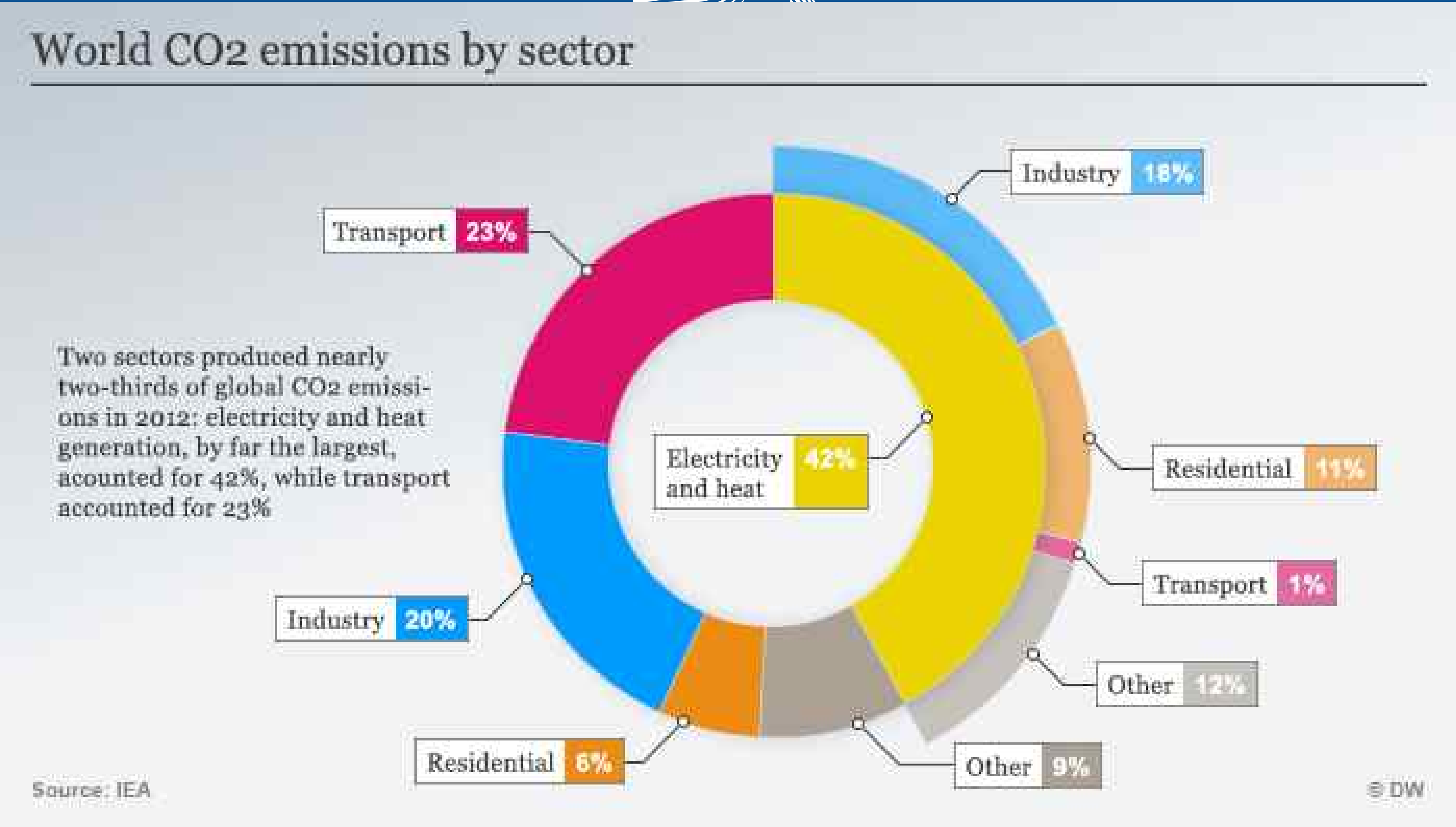
● **Les pays émergents, Chine hier, Inde aujourd'hui, Afrique demain, ont soif d'énergie bon marché** mais <u>**la pollution galopante (surtout l'air dans les grandes villes) et ses conséquences sur les** individus les conduisent à la sagesse en matière de choix de politiques et technologies énergétiques</u>.

● <u>Les ressources en énergie fossile ne vont pas manquer</u>**. C'est la conséquence des récentes découvertes d'hydrocarbures non conventionnels mais aussi de l'inflexion de la courbe de demande, sous l'effet des politiques d'efficacité énergétique et de développement des énergies renouvelables.**

= > Le moteur des développements dans le domaine de l'énergie sera la <u>décarbonation de l'économie</u>.

= > En particulier, l' <u>électrification massive</u> à partir de sources décarbonées sera la parade principale à la pollution de l'air dans les villes : cela rendra les villes à la fois plus respirables, saines, climatisées, mais aussi circulantes, communicantes et résilientes.

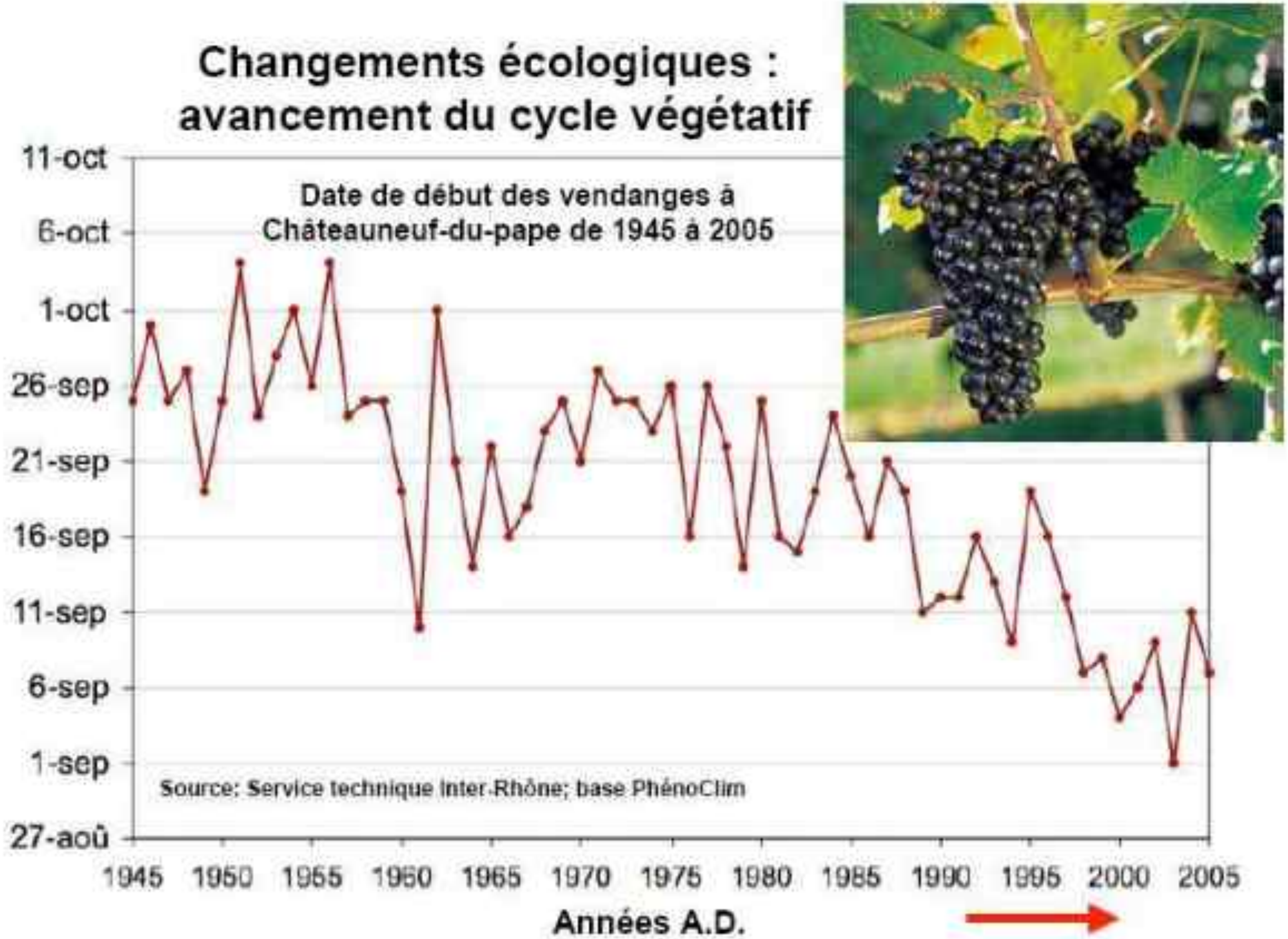
World CO2 emissions by sector in 2012 (IEA)



NB: <u>World-wide, net electricity generation is projected to increase 69% by 2040</u>, from 21.6 trillion kWh in 2012 to 25.8 trillion kWh in 2020 and 36.5 trillion kWh in 2040. ("International Energy Outlook 2016" /IEO-2016/ Reference case)

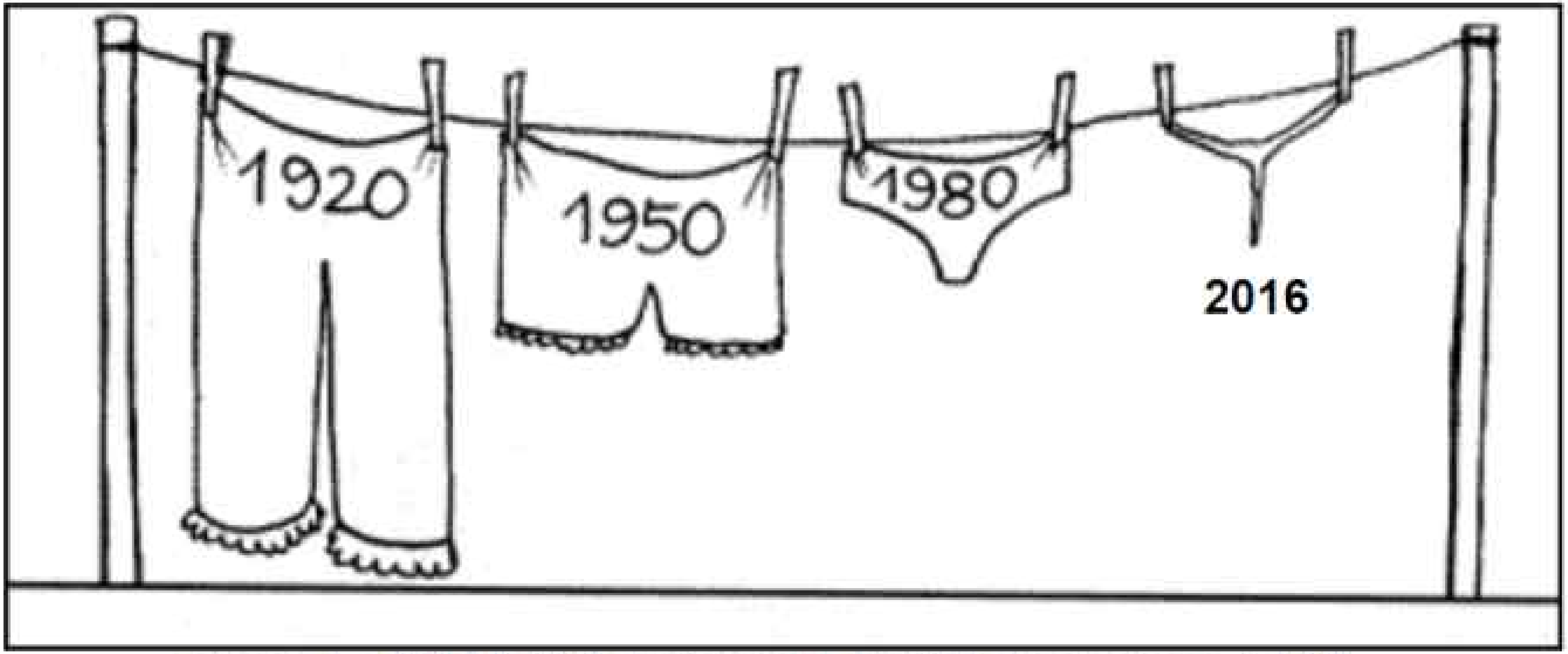
https://www.iea.org/media/statistics/topics/emissions/CO2_Emissions_Overview.pdf

Le réchauffement global est réel 1/2



« RÉCHAUFFEMENT GLOBAL - **état des lieux 2011 », A. Berger, Institut d'Astronomie et de Géophysique G. Lemaître,** Louvain-la-Neuve (Cercle Gaulois, Fondation pour l'Environnement Urbain Pierre Laconte, Bruxelles 18 février 2011)

Obviously climate skeptics didn't take into account all available evidence



Impact of global warming on underwear since 1920.
Source: Petit Bateau; Playtex; Aubade; Princesse Tam Tam

Can't wait for 2020?

Source: Jean-Marc Jancovici, "The energy and climate challenge in Europe: rocking times ahead" (Professor, www.mines-paristech.fr), Forum nucléaire belge, Séminaire académique : « La coexistence du nucléaire et des énergies renouvelables » (29 Novembre 2016, Palais des Académies, Bruxelles) https://www.forumnucleaire.be/theme/energie/seminaire-academique-la-coexistence-du-nucleaire-et-des-energies-renouvelables

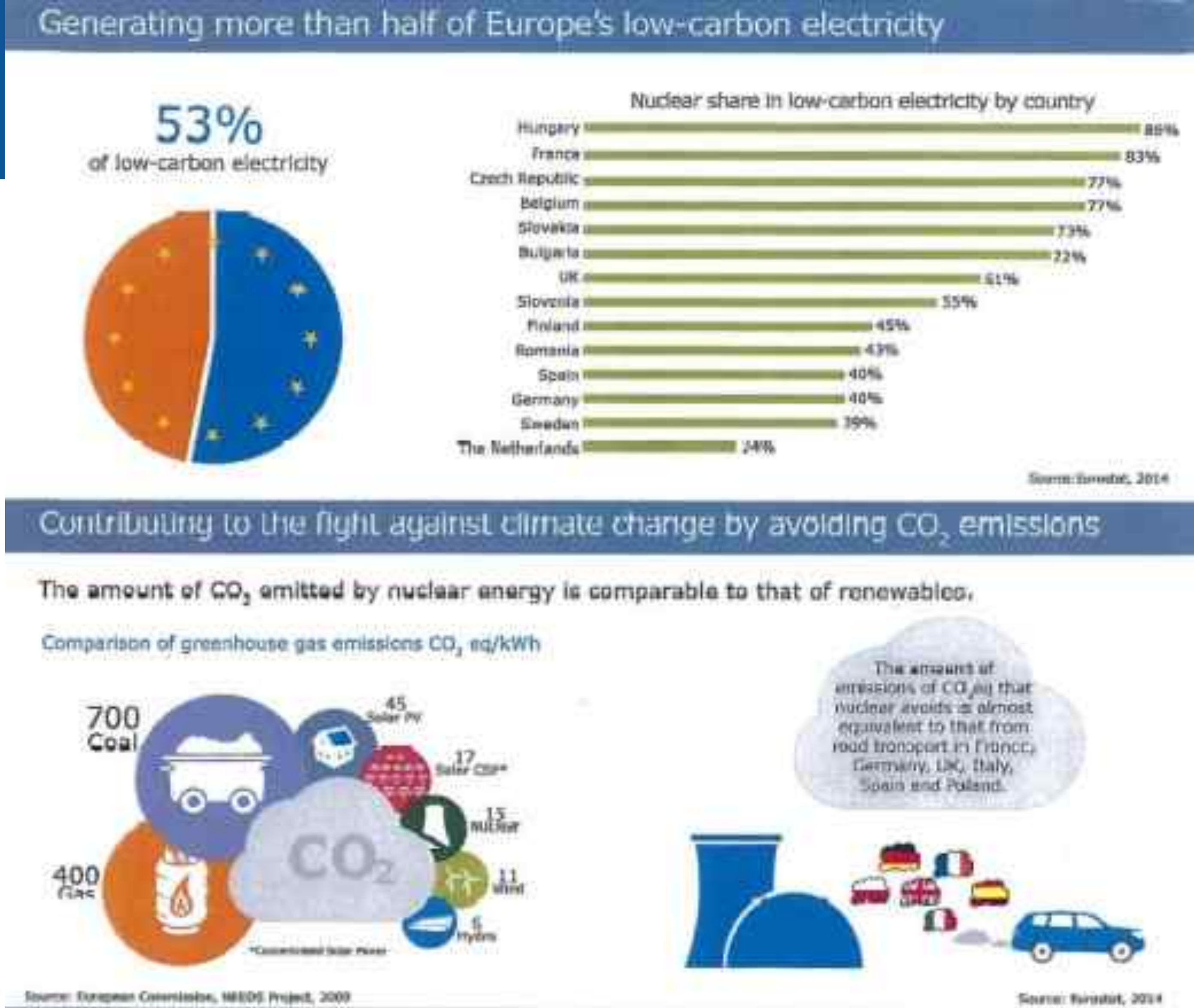
Air pollution in China has turned into a major social problem

Three factors are contributing to the air pollution problem in China:

- <u>Coal for industry</u>: China is one of the leading countries in some of the most polluting and energy-intensive industries, such as cement, iron and steel and mining. China burns coal to produce most of its electricity (more than 65% of its energy mix and 80% of its electricity are coal-derived).

- <u>Coal for heating</u>: China also uses coal to heat up water used for district-heating during winter and many small houses that do not have access to district-**heating systems (like those in Beijing's** Hutongs) also use coal.

- <u>Transportation</u>: China has had an amazing expansion of its total number of cars and flights, which undoubtedly contribute to the air pollution problem. Urbanization in China and middle class consumption modes are developing in an extremely high speed.



- The 128 nuclear power reactors - with a combined capacity of 119 GWe - operating in 14 of the 28 EU member states account for more than a quarter of the electricity generated in the whole of the EU. (WNN, April 2017)

- CO_2 "emitted" by nuclear is lower than/comparable to what is emitted by renewable energies (and roughly 50 times lower than coal)

Technical miracles of the 20-th century: no 1 = electrification

Technical miracles of the 20-th century

1. Electrification
2. Automobile
3. Airplane
4. Safe and Abundant Water
5. Electronics
6. Radio and Television
7. Agricultural Mechanization
8. Computers
9. Telephone
10. Air Conditioning and Refrigeration
11. Interstate Highways
12. Space Exploration
13. Internet
14. Imaging Technologies
15. Household Appliances
16. Health Technologies
17. Petroleum and Gas Technologies
18. Laser and Fiber Optics
19. Nuclear Technologies
20. High Performance Materials

Source: "Great Achievements and Grand Challenges", US National Academy of Engineering, The Bridge (Washington, D.C.), Vol. 30, Nos. 3 & 4, Fall/Winter 2000 (https://www.nae.edu/File.aspx?id=7327)

Ordres de grandeur de puissance (1 MW => 1650 MW)

European Commission

Exemples de puissances (de type mécanique, électrique, chimique, nucléaire et thermique) *produites* ou consommées

1 MW : la puissance du moteur de la super voiture Koenigsegg One (1360 hp - "Hypercar of the Year in 2010" - Sweden)
1,3 MW : la puissance du moteur du Mustang P-51, un avion de combat américain de la Seconde Guerre mondiale.
3 MW : la puissance de sortie mécanique d'une locomotive diesel.
8,2 MW : la puissance consommée par l'ordinateur le plus puissant en 2012, le Titan (17,59 pétaFLOPS) de Cray.
9,1 MW : la puissance de sortie mécanique d'un TGV duplex alimenté en 25 kV alternatif.
10 MW : la puissance électrique de la première centrale solaire thermique de type CSP (Solar 2) en 1996 en Californie.
28 MW : la puissance consommée par Facebook's datacenter in Prineville, Oregon, USA, en pointe (2012).
100 MW : la puissance électrique du barrage de Verbois, dans le canton de Genève, en Suisse.
117 MW : la puissance totale (propulsion et besoins divers) du paquebot Queen Mary 2 (lancé en 2004)
240 MW : la puissance de l'usine marémotrice de la Rance (EDF, 1966) ou du barrage de Bort-les-Orgues (EDF, 1952).
400 MW : la puissance électrique moyenne des centrales à gaz à cycle combiné en France comme celle de Pont-sur-Sambre (KKR - Kohlberg Kravis Roberts – fonds d'investissement américain) ou Bayet (Direct Énergie – premier fournisseur alternatif d'électricité et de gaz de France).
900 MW : la puissance électrique d'un réacteur nucléaire (400 MW => 1650 MW / ex. 392 MW pour D1 et 1015 pour T3).

Source: https://fr.wikipedia.org/wiki/Ordres_de_grandeur_de_puissance

Google has 12 data centers all over the planet (supporting at least one million servers), 6 of which in North America. Those data centers use around 260 million watts of power which accounts to 0.01% of global energy. This power is enough to consistently power 200,000 average homes. Exact server numbers, specifications, and other details are tightly controlled by the computer companies. Source (year 2012): https://www.quora.com/Data-Centers-How-much-energy-does-a-server-farm-consume

<= Picture left = Facebook's massive Arctic Sever Farm, built on the edge of the Arctic Circle in Northern Sweden. This server farm is able to let go of air conditioning for cooling and instead just use fresh Arctic air.

Overall, in the EU, an additional electrical capacity of 150 GW will be needed to charge electric cars (2016 study)

A total of 7 energy mix scenarios were proposed in the EU Energy Roadmap 2050, as a basis for policy action. One of the main conclusions of decarbonisation of the energy system by 2050 is:

<u>in the EU, electricity will have to play a much greater role than now (almost doubling its share in final energy demand to 36-39 % in 2050 – today it is 21 %)</u>

and will have to contribute to decarbonisation of transport and heating / cooling.

NB: Gross electricity production in the EU is estimated at 4900 TWh per year in 2050 (compared to 3280 TWh in 2011).

<u>Elektrische auto in de EU vereist equivalent van 150 kerncentrales</u>

De Standaard 28/09/2016 (Belgian newspaper, 100 000 copies)
"Een grootschalige introductie van elektrische wagens in Europa zou 150 gigawatt aan bijkomende elektriciteitsopwekking vereisen. Dat berekende het Europese Milieuagentschap. Dat is het equivalent van 150 kerncentrales."
http://www.standaard.be/cnt/dmf20160927_02490059

⇒ <u>Overall, in the EU, an additional electrical capacity of 150 GW will be needed to charge electric cars</u>

Source: "Electric vehicles and the energy sector - impacts on Europe's future emissions", European Environment Agency (EEA, Copenhagen), briefing published 26 Sep 2016 - http://www.eea.europa.eu/themes/transport/electric-vehicles/electric-vehicles-and-energy

Trois grands domaines d' incertitudes 1/3

(1) la « grande transition » : vers des systèmes intégrés **d'énergie, de transport et TIC**

European Commission

(3.2.1) La « grande transition » : convergence d'un développement technologique accéléré et d'une révolution digitale irréversible

• **Actuellement, les énergies « vertes » ont beau se développer très rapidement,** 86% de l'énergie mondiale est encore produite par les énergies fossiles. De plus, les cours des combustibles fossiles fluctuent de façon imprévisible**. A l'échelle mondiale en 2014, le solaire et l'éolien représentent 1% de la consommation** primaire totale, contre 2% pour la biomasse et la valorisation des déchets, 4% pour **le nucléaire et 7% pour l'hydraulique (BP** statistics 2015).

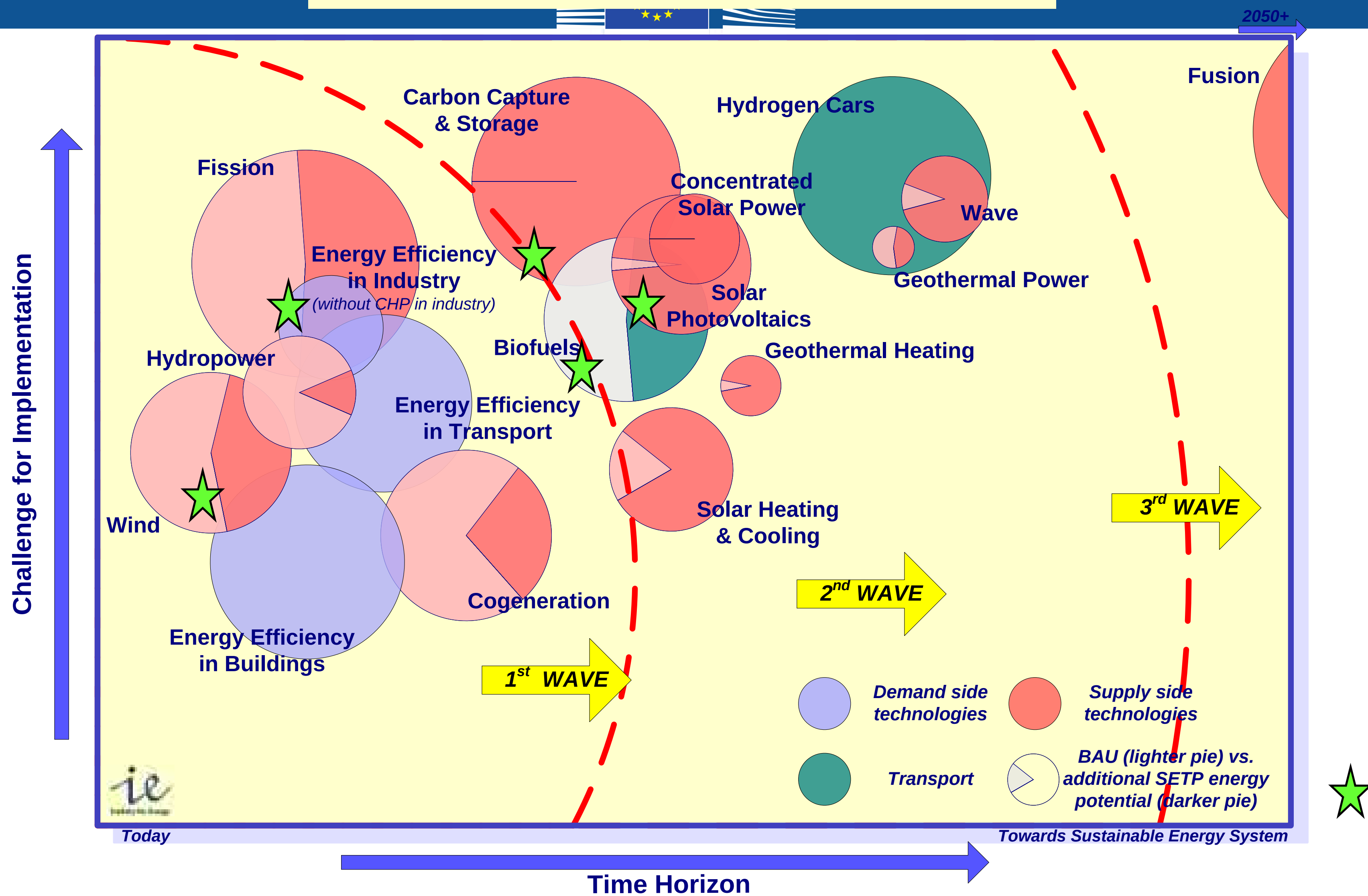
NB: « Resilient Energy Union »: objective n° 3: share of renewable energy: target of at least 27 % by 2030 (binding at the EU level)
Key question => where will the remaining 73 % of energy come from ?

• **Dans les cités émergentes, la révolution digitale accompagnera partout l'électrification.** Production et consommation électriques seront harmonisées par des logiciels puissants**, mis en œuvre dès la conception des infrastructures et des bâtiments, capables de piloter ensuite globalement l'efficacité énergétique de** grandes agglomérations (« réseaux intelligents »).

=> Towards integrated energy, transport and ICT systems
(strong links between energy production, distribution and use; mobility and transport; and information and communication technologies (ICT)

EU "Strategic Energy Technology" Plan (SET-Plan) adopted in 2008

SET-Plan priorities



For further information: https://setis.ec.europa.eu/publications

Competitiveness

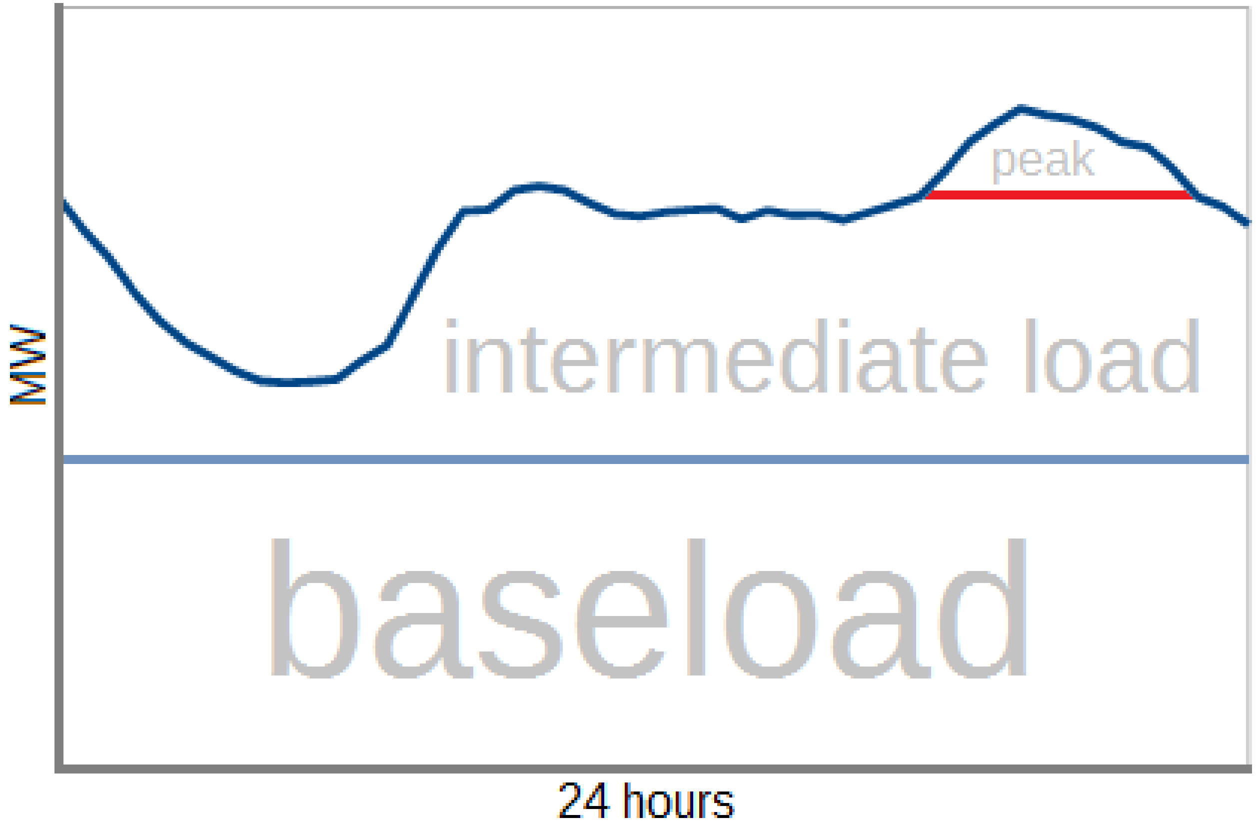
Development – paradigm shift

New avenues

"Renewables have "grid priority", meaning the grid must take their electricity first"

"According European utilities - How to lose half a trillion euros :
Europe's electricity providers face an existential threat"
Oct 12th 2013 **|** The Economist
http://www.economist.com/news/briefing/21587782-europes-electricity-providers-face-existential-threat-how-lose-half-trillion-euros

Load on the electrical grid: base, intermediate and peak



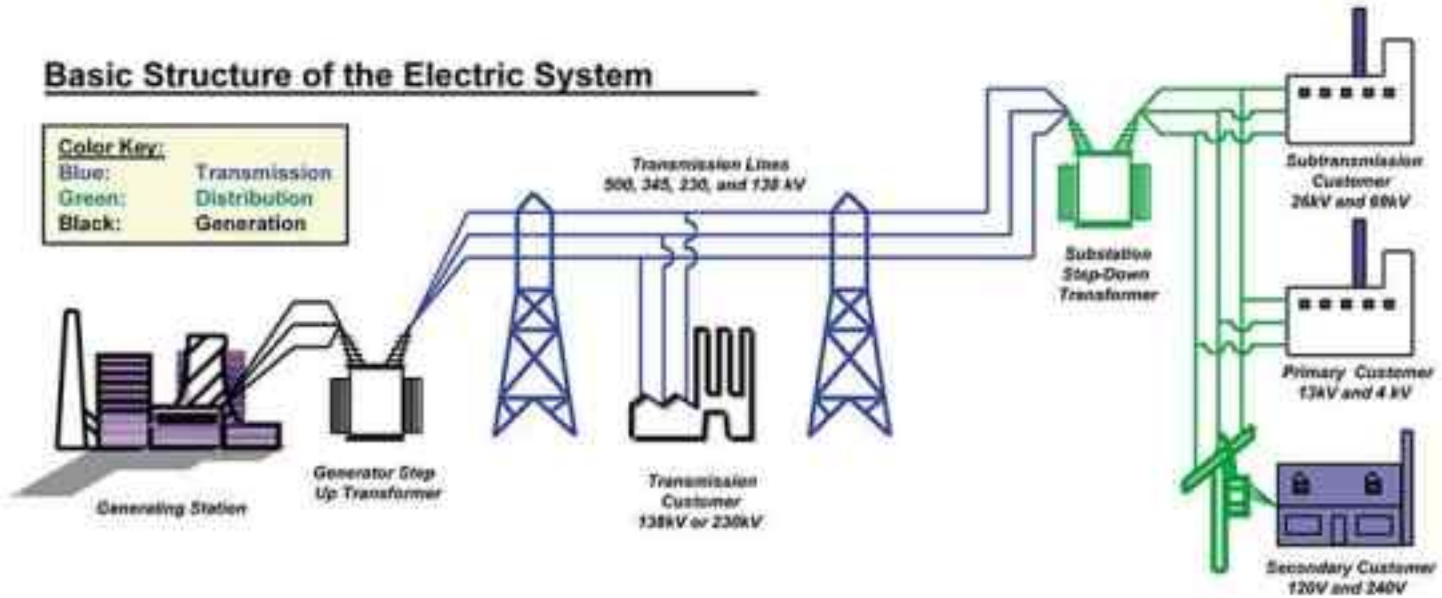
Certain types of power plants are valued for their constant output and reliability at relatively low operating costs, providing the base of this curve. This is the baseload of an established electrical supply market. The remaining intermediate and peak load above this is met with generators which operate more sporadically, often for a mere few hours, requiring higher market prices (or government assistance) to meet their costs.

Taken all together, this supply, universally measured in megawatts (MW, or thousands of kilowatts), must equal the load at all times to maintain the stability of the distribution system.

The order in which different generators supply their market is determined by their marginal cost, and is known as the merit order.

(http://actinideage.com/electrical-energy-literacy-numeracy-primer/)

Traditional power grid and future smart grid:
paradigm change - from central to decentralised power generation



<u>SMART GRIDS</u>
(users become “<u>prosumers</u>”)

According to the “European Electricity Grid Initiative” (EEGI), particular challenges arise from

- the <u>paradigm change</u> from **“supply follows load” to “load follows supply”**
- real-time balancing
- the introduction of aggregators
- and the multi-layer control structure of smart grids.

Trois grands domaines d' incertitudes 2/3
(2) Le stockage de l'énergie (le « chaînon manquant »)

(3.2.2) Le stockage de l'énergie, le « chaînon manquant de la transition énergétique » vers une économie sobre en carbone

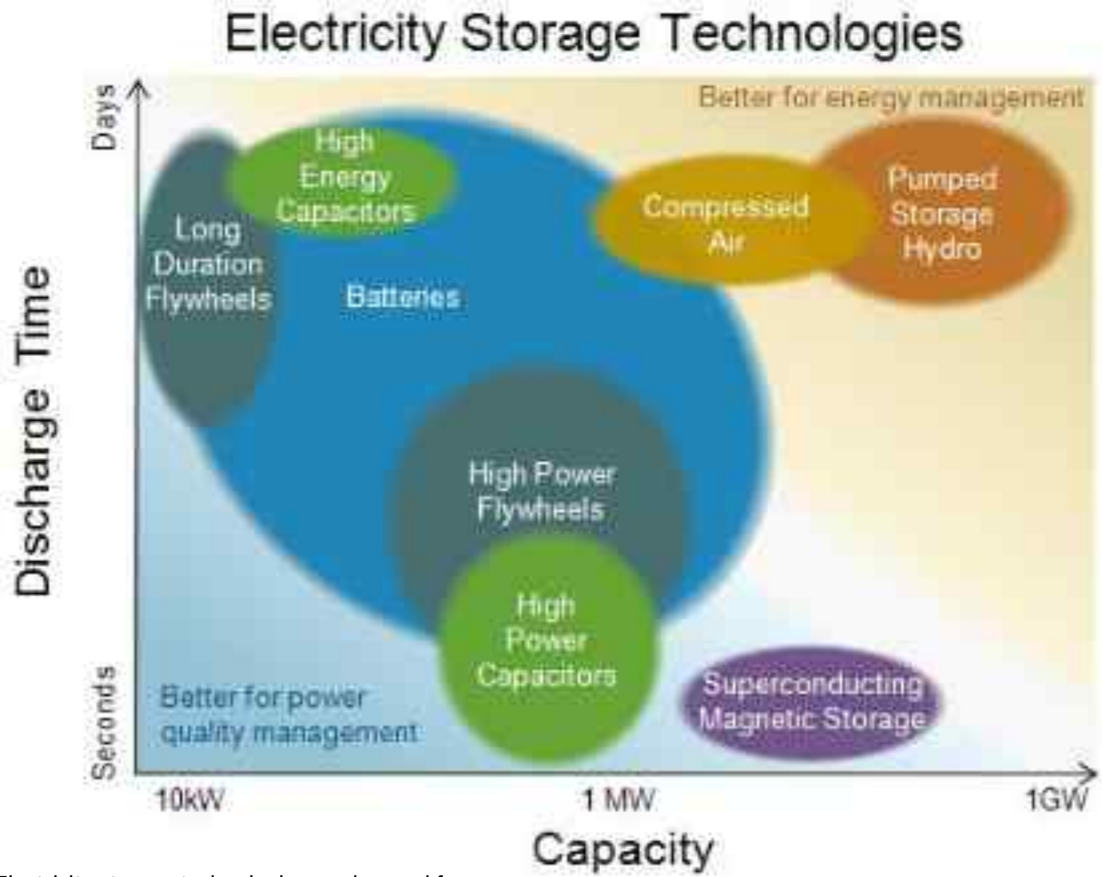
- **Le stockage massif et bon marché de l'électricité**, y compris sur une période annuelle, sera-t-**il une réalité commerciale ? Il s'agit du Saint Graal de l'énergie, celui que convoitent toutes les sources d'énergie primaire. En effet, l'électricité peut toujours être produite sans émission de CO2, mais l'offre comme la demande d'électricité seront de plus en plus variables et le stockage permet d'éviter des investissements de surcapacité ruineux en production et transport d'électricité.**

- **Est**-ce que le couple hydrogène-électricité envahira **l'énergétique humaine au**-delà de 2050 ? Pour cela, il faudra **d'abord maîtriser la production de l'hydrogène décarboné compétitif, qui offre un accès direct au stockage de l'électricité.**

- **En l'absence d'un produit de stockage compétitif, sûr et « nomade » (c'est**-à-**dire que l'on puisse embarquer dans un** véhicule), les usages répartis comme le transport et le chauffage resteront majoritairement le domaine des hydrocarbures.

Est-**ce à dire qu'il faut faire son deuil de la protection du climat ?**

Electricity storage in the power sector:
the missing link to renewable energy



Electricity storage technologies can be used for:

- energy management / long timescales. Daily, weekly, and seasonal variations in electricity demand are fairly predictable (e.g. pumped hydroelectric storage or compressed air energy storage)
- power quality management / shorter timescales. Demand fluctuations on shorter timescales - from a few minutes down to fractions of a second - require rapidly-responding technologies (e.g. flywheels, super-capacitors, or a variety of batteries)

Source: U.S. Energy Information Administration, based on Energy Storage Association (2011)

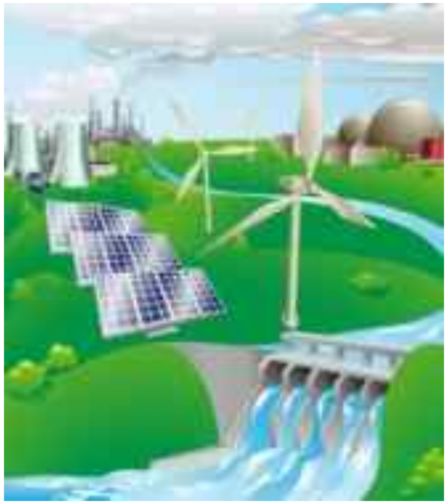
Forms of energy storage

- **Mechanical:**
  - Compressed air energy storage
  - Flywheel energy storage
  - Gravitational potential energy storage
  - Pumped hydroelectric storage, or pumped storage hydropower
- **Thermal:**
  - Cool water, hot water or ice thermal storage
  - Liquid air or liquid nitrogen energy storage (Cryogenic energy storage)
  - Molten salt storage
- **Chemical:**
  - Battery, Battery Energy Storage System flow battery, secondary battery (Rechargeable battery)
  - Hydrogen storage
  - Power to gas
- **Electromagnetic**
  - Storage coil, superconducting storage coil (superconducting magnetic energy storage)

Le stockage de l'énergie est le « chaînon manquant » de la Transition Energétique

For further information: http://setis.ec.europa.eu/technologies/Electricity-storage-in-the-powersector/info

Centrale hydroélectrique de pompage-turbinage de Coo : lien étroit avec Tihange = stockage d'électricité d'origine nucléaire

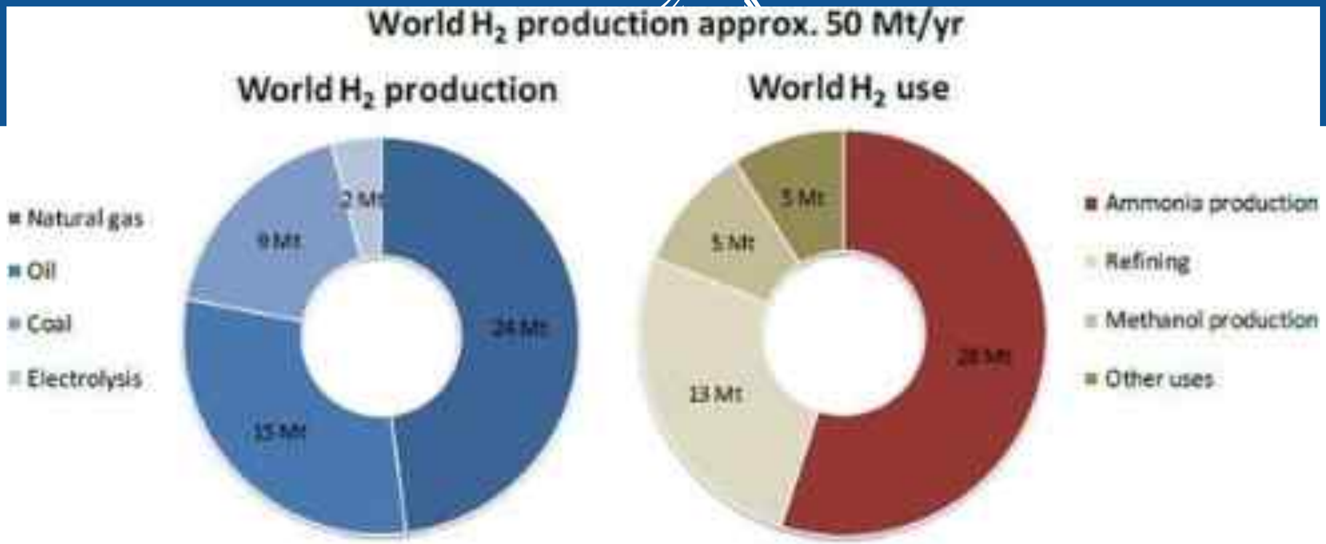


La centrale hydroélectrique de Coo-Trois-Ponts appartient à Engie Electrabel et est située en Belgique non loin de la cascade de Coo (sur l'Amblève, près de l'abbaye de Stavelot). A la différence des autres centrales hydrauliques classiques, cette centrale est équipée de machines réversibles (six turbines Francis réversibles convertibles en pompes). Le passage du mode pompage au mode turbinage s'effectue en quelques minutes (temps de démarrage inférieur à 2 minutes). Le turbinage est capable de fournir 1 164 MW pendant 5 heures (un stockage de 5 000 mégawattheures). Par an, cela représente un stockage/restitution de 1 000 GWh avec un rendement de 75 %. Le rendement global de la centrale est de 75%. Cela veut dire que 3/4 de **l'énergie** prélevée en heures creuses sont restitués aux heures de pointe.

Le rôle de cette centrale est étroitement lié à celui de Tihange. Les réacteurs nucléaires ne pouvant pas suivre les variations de demande du réseau électrique, ils doivent maintenir leur production au-dessus **d'un** niveau incompressible. Pendant les creux de demande électrique, **l'énergie** électrique d'origine nucléaire est "stockée" en accumulant de l'eau pompée du bassin inférieur vers le bassin supérieur pour être restituée au moment des pointes de consommation ou en cas de problème technique sur **d'autres** unités de production. Avec le développement des énergies intermittentes (éolien/solaire), la centrale de Coo est amenée à jouer un rôle de plus en plus important dans **l'équilibre** du parc de production.

Source : http://www.walloniebienvenue.com/ambassadeur.php?id_mem=6472

Hydrogen production and use



Estimated world hydrogen production and use (2008)

Globally, around 50 million tonnes of H2 are produced each year, the majority of which is produced using fossil fuel feedstocks. Around half is used to produce ammonia (80% of ammonia /NH3/ is used to produce synthetic nitrogen based fertilisers), around a quarter is used for hydrocracking in petroleum refining, with the balance used to produce synthetic fuels and to make other industrial applications. https://hub.globalccsinstitute.com/publications/ccs-roadmap-industry-high-purity-co2-sources-sectoral-assessment-%E2%80%93-final-draft-report-1

Nuclear hydrogen production (water splitting technologies based on electrolysis or thermochemistry)

(1) near-term option: conventional low temperature electrolysis using cheap off-peak electricity from present nuclear power plants (the water molecule is dissociated by applying an electrical current) – overall hydrogen conversion efficiencies are between 80 and 95 %.

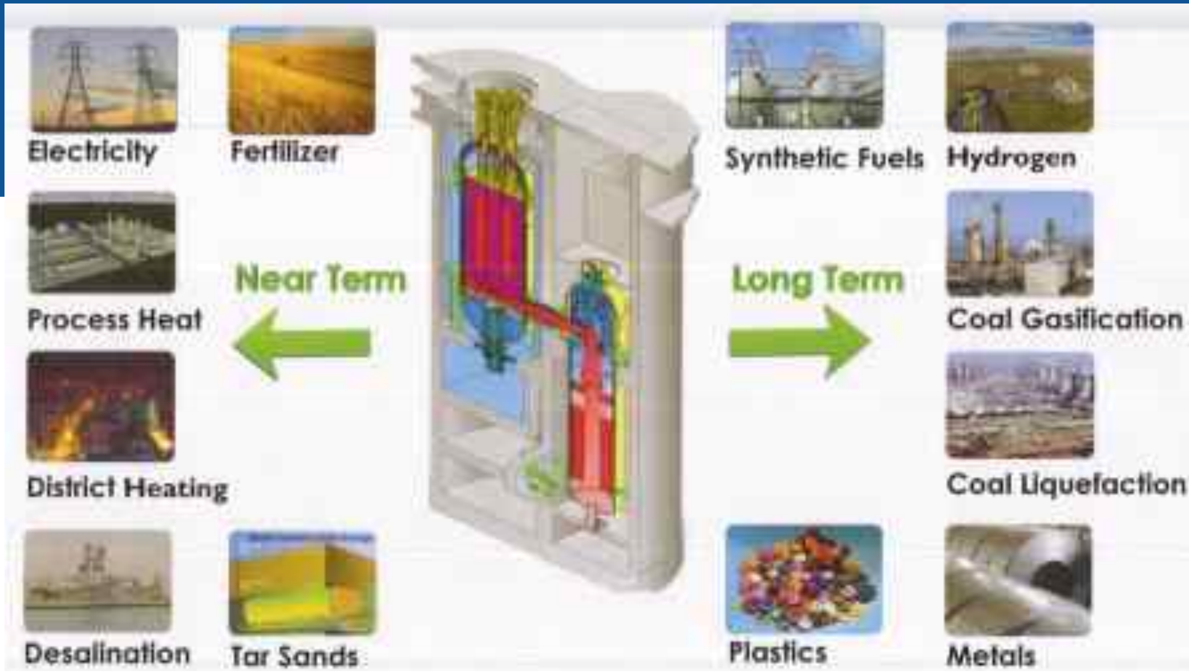
(2) still under development:

(a) high temperature electrolysis (HTE), making use of high temperature heat and steam from an HTGR - the vapor phase is generated – much cheaper – by thermal (in the range of 800-1000°C) rather than of electric energy (hydrogen production up to 2.5 kg/s or 238 t/d @ 50 % overall efficiency)

(b) thermochemical (hybrid) cycles, such as the sulfur-iodine /S-I/ cycle (hydrogen conversion efficiencies in the range of 35 %, if operated at 950°C), the Westinghouse hybrid-sulfur HyS cycle (using an electrolytical cell, net efficiency around 49 %, if operated at 900°C), and the copper–chlorine (Cu-Cl) cycle using heat sources around 500°C-550°C (energy efficiency around 43 %)

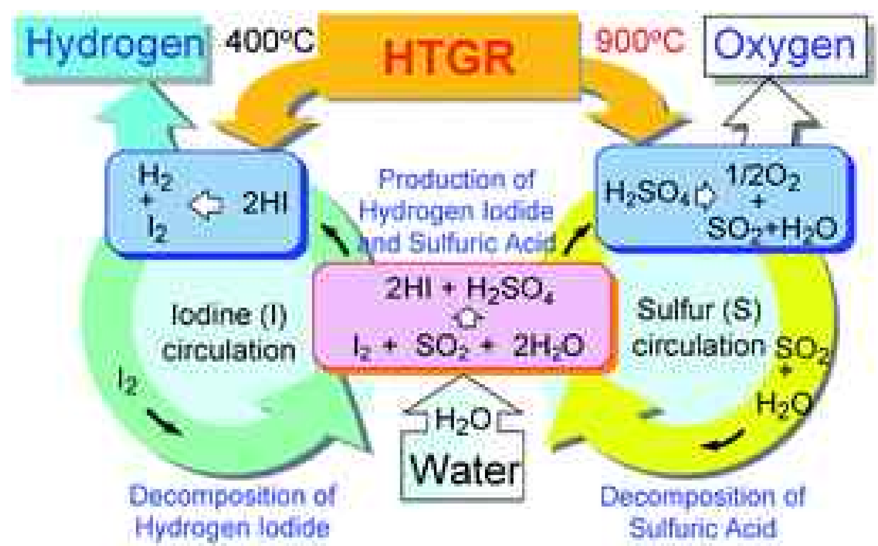
Source: "Nuclear Energy for Hydrogen Production", Karl Verfondern (Editor), Institut für Sicherheitsforschung und Reaktortechnik, Forschungszentrum Jülich GmbH, Germany, 2007 - http://juser.fz-juelich.de/record/58871/files/Energietechnik_58.pdf

Hydrogen production: e.g. sulfur-iodine process (thermochemical cycle)



H_2 production capability was initial driver for Generation IV "Very High Temperature Reactor" (VHTR) development in GIF based on iodine-sulfur /I-S/ process requiring heat input at 850°C

Very large and growing global H_2 market in industry and transport:
•short/medium term: cogeneration (process steam)
•long term: very high T applications (steel and chemical industry, transportation fuel, households)



H2 production technologies based on thermochemistry or electrolysis
- Participation of GIF signatory countries in R&D activities:

1. Iodine-Sulfur Process (850°C): KR, JA, CN
 (NB: INET in CN – Construction of 100l/h H2 loop, in operation in 2014)
2. Copper-Chlorine Process (530°C): CDN, US
3. High Temperature Steam Electrolysis (650°C): US, EU, CN

"Very High Temperature Reactor System Activities in GIF", Euratom GIF Coordination meeting, Brussels, 12 December 2016

(3.2.3) Le comportement humain
(vers une nouvelle gouvernance pour une gestion optimale de l'énergie)

La recherche dans le domaine de l'énergie doit faire une place importante aux sciences humaines et sociales aux côtés des autres disciplines. De manière générale, les citoyens doivent être étroitement associés, en amont, aux choix en matière de politiques et de technologies énergétiques afin de devenir les acteurs de ces transformations.

De nombreuses questions se posent, par ex. :

● **comment garantir et renforcer** les objectifs européens visant à « une énergie sûre, compétitive et durable » **? On n’est pas à l’abri de scénarios extrêmes liés, par ex. à la montée des populismes, au rejet des accords internationaux ou à l’adoption de politiques nationales protectionnistes qui donnent** lieu à des choix de développement peu compatibles avec les objectifs européens.

● **quels sont les instruments à mettre en œuvre pour accompagner « la grande transition » ?**
« La vraie urgence, c’est de donner un coût important aux émissions, afin de les pénaliser. On peut **espérer qu’en 2050, un prix élevé du carbone sera une banalité dans le monde. » (Claude Mandil, ancien directeur exécutif de l’Agence Internationale de l’Énergie /2003**-2007/)

● **va**-t-**on assister au déploiement massif d’une production d’énergie décentralisée?** Un système 100 % renouvelables est-il réaliste ? **à côté du solaire et de l’éolien, verra t’on émerger, par exemple,** un nucléaire « léger » de nouvelle génération, avec de petites centrales modulaires (« SMR ») ?

● **la population acceptera**-t-**elle les forêts d’éoliennes et les centaines de milliers d’hectares de** panneaux solaires ? **comment démocratiser l’accès au stockage d’énergie (= «** le chaînon manquant ») ? (coût toujours plus faible et capacités toujours plus grandes)

Trois grands domaines d' incertitudes 3/3 suite

(3) Le comportement humain

(3.2.3) Le comportement humain /suite/
(vers une nouvelle gouvernance pour une gestion optimale de l'énergie)

• **comment va évoluer l'opinion publique p. r. aux grosses installations d'hydroélectricité et de nucléaire ? comment financer ces investissements lourds à rentabilités lointaines ? (rôle de l'état,** partenariat privé – public, accords internationaux)

• **comment améliorer la communication sur la fission nucléaire ? Cela passe par une opération vérité sur les aspects émotionnels liés à cette énergie (effets des rayonnements sur l'homme, stockage des** déchets, démantèlement)

• **quelle énergie pour la production massive d'électricité et d'hydrogène dans le futur ?**
y aura-t-il une place pour les centrales nucléaires de la Génération 4 qui résout les limites **d'approvisionnement en uranium et la production de déchets radioactifs ?**

= > La transformation énergétique en cours bouleverse nos façons de produire et de consommer l'énergie et elle provoque une révision en profondeur des fondements de nos économies.

= > Les gens sont passés de « conSUMER » à « PROsumer » en participant d'une manière ou d'une autre au concept et/ou au développement du produit (« PROducer »).

= > Nous ne ferons pas l'économie d'un changement profond des comportements : on ne peut pas maintenir ou souhaiter le mode nord-américain de consommation de ressources et d'énergie. N'oublions pas qu'un Américain moyen consomme 32 fois plus qu'un Kenyan moyen.

Trying to understand what is the ideal energy mix 1/2

Source: Dr Makoto Akashi, National Institute of Radiological Sciences, Chiba, Japan (HRD int'l Conf, 27 Febr 2012, Bangkok)

Trying to discuss what is the ideal energy mix 2/2

Comment garder notre mode de vie …? 1/2

tout en contribuant à améliorer celui des autres

… sans “impacter” notre environnement ? 2/2

énergie < = > climat, pollution, ressources

What will fuel future highways?

Gasoline ? Diesel? Compressed or Liquefied Natural Gas ? Hydrogen? Electricity?

Hydrogen for cars - Fuel cells could become a battery supplement

The True Cost of Powering an Electric Vehicle (EV)

Rather than worry about autonomy (km/battery), cost-conscious EV buyers should focus on how to get car-charging kWh at the lowest rates.

http://www.edmunds.com/fuel-economy/the-true-cost-of-powering-an-electric-car.html

European energy market design is dysfunctional 1/2

"one of the root causes: we CANNOT have it all ! "

- Minimal costs
- Security of supply
- Stable prices
- Low CO2
- Competition
- Energy independence
- No nuclear
- Nothing in my backyard

?

can "best available science" (BAS) help reduce uncertainties ?

European energy market design is dysfunctional 2/2

Decisions taken without view on economic implications

RES making system more complex to balance...

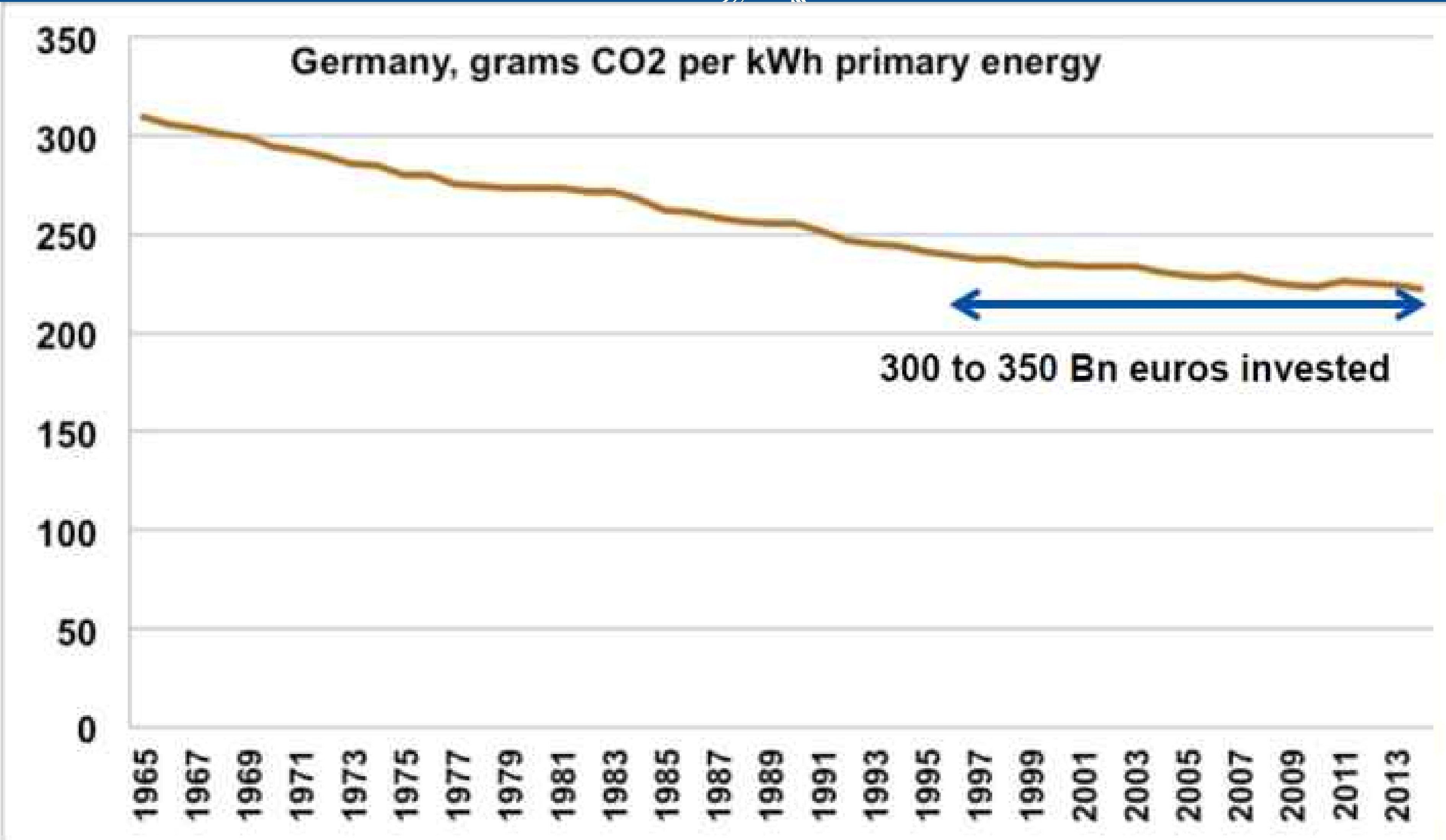
...and killing conventional plants, that we will need

Fluctuating rules of the game

Ineffective CO2 policies

The Boston Consulting Group
KBVE/SRBE Studiedag «Welke energietransitie?»
Palais des Académies, Brussels, May 8th, 2014

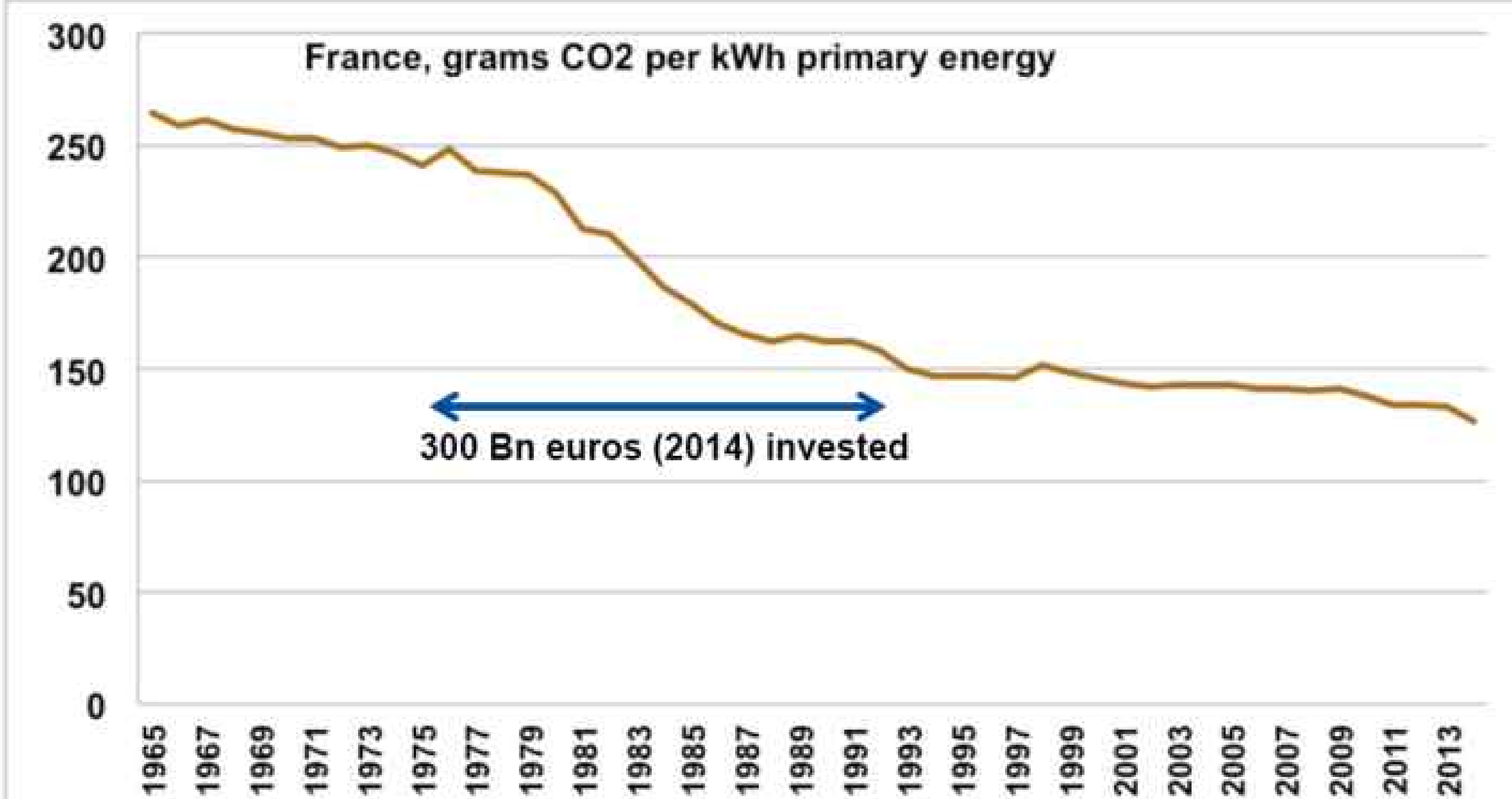
Germany's energy policy = > 220 g CO_2/kWh primary energy ($\Delta = 100$)



CO2 emissions per kWh of primary energy in Germany. Jancovici, on data from BP Statistical Review

300 billion Euros to decrease CO2 emissions (1995 – 2015) = > 220 g CO2 / kWh primary energy (DELTA = 100)

France's energy policy = > 125 g CO2/kWh primary energy (Δ = 150)



CO2 emissions per kWh of primary energy in France. Jancovici, on data from BP Statistical Review

300 billion Euros to decrease CO2 emissions (1975 – 1995) = > 125 g CO2/kWh primary energy (DELTA = 150)

Swedish energy policy 2016: Framework agreement between the Social Democratic Party, the Moderate Party, the Green Party, the Centre Party and the Christian Democrats

- Basis

The Swedish energy policy should be based on the same three pillars used in the energy cooperation of the European Union. The policy thus seeks to reconcile: (1) Ecological sustainability; (2) Competitiveness ; (3) Security of supply.

Sweden should have a robust electricity system with high reliability, low environmental impact and with access to electricity at competitive prices. It creates long-term perspectives and clarity for market participants and brings new jobs and investments to Sweden. The energy policy is based on the fact that Sweden is closely linked with its neighbouring countries in northern Europe, and aims to find common solutions to the challenges of the common electricity market.

- Goal

At the latest in the year 2045, Sweden shall have no net emissions of greenhouse gases to the atmosphere, and will thereafter achieve negative emissions.

The goal in 2040 is 100% renewable electricity production. This is a goal, not an end date which prohibits nuclear power and it does not mean the closure of nuclear power through political decisions.

A goal for energy efficiency for the time period 2020-2030 will be developed and be approved no later than 2017.

(http://www.analys.se/publikationer/rapporter/english-translation-of-the-swedish-energy-policy-agreement-of-10-june-2016/)

NB about French energy situation (electricity industry point of view): Low carbon intermittent renewables need a stable low carbon base

«EDF est le leader européen des énergies renouvelables», Jean-**Bernard Lévy, PDG d' EDF (27/11/2015, peu avant la conférence COP**-21, Paris)
« EDF est engagé depuis toujours dans la lutte contre le changement climatique, grâce à un mix énergétique à 98% sans CO2. ………. Le développement des énergies renouvelables associé à une production nucléaire stable et sûre, est le moyen de parvenir à un nouvel équilibre du **mix de production d'EDF, véritable atout de la transition énergétique et de la lutte contre le changement climatique.** »
(http://www.ladepeche.fr/article/2015/11/27/2225982-jean-bernard-levy-edf-est-leader-europeen-energies-renouvelables.html)

Fission nucléaire de quatrième génération : stop ou encore ?

1 – Introduction : Génération IV - pourquoi ? comment ? avec qui ? quand ?

2 - Le cap («triangle énergétique européen») et les invariants (lois de la nature)

3 - La réalité des faits et des chiffres (« quasi-certitudes ») et défis technologiques et humains (incertitudes)

4 - Besoins et opportunités pour le nucléaire au 21ème siècle (objectifs de Génération IV)

4.1 Améliorer la durabilité (y compris l'utilisation efficace du combustible et la réduction des déchets)

4.2 Sûreté et fiabilité (notamment en l'absence de toute intervention extérieure d'urgence)

4.3 Economie (compétitivité par rapport aux sources d'énergie)

4.4 Lutte contre la prolifération des armes nucléaires et protection matérielle

5 - Les systèmes-réacteurs nucléaires en projet de la Génération IV : SFR, LFR, GFR, VHTR, MSR et SCWR

6 - Conclusion : recherche, innovation et formation en fission nucléaire

"Industrial and societal goals" for Generation IV

Sustainability

1. Generate energy sustainably, and promote long-term availability of nuclear fuel
2. Minimize nuclear waste and reduce the long term stewardship burden

Safety & Reliability

3. Excel in safety and reliability
4. Have a very low likelihood and degree of reactor core damage
5. **Eliminate the "technical" need for offsite emergency response**

(Socio-)economics

6. Have a life cycle cost advantage over other energy sources
7. Have a level of financial risk comparable to other energy projects

Proliferation resistance and Physical protection

8. Be a very unattractive route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism

Sustainability = enhanced fuel utilisation (breeding) and waste minimization (volume, heat, toxicity)

Fuel utilisation, waste management and P&T

Fuel utilisation

- current limitation (LWR without MOX fuel) = neutronic characteristics that reduce their capability to extract the full potential energy in the uranium fuel.
- innovation in GEN IV (fast reactor option) = conversion of fertile into fissile waste management (sustainability)

Waste management

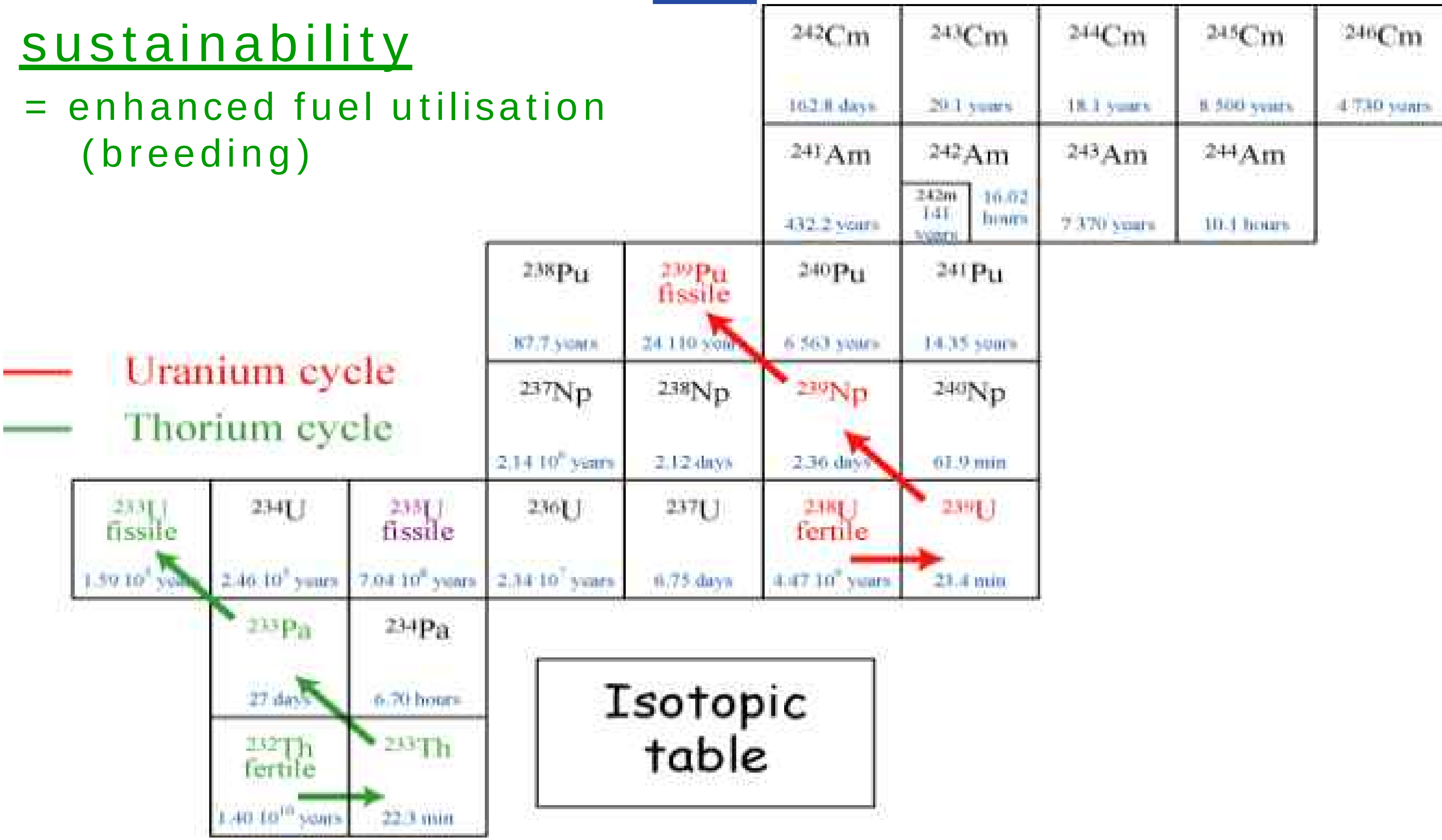
- current limitation (LWR) = presence of heavy actinides and long-lived fission products in the high-level waste from spent fuel
- innovation in GEN IV = fast neutron reactor options with fully closed fuel cycles (fuel containing all transuranics and optionally some long-lived fission products)

Partitioning and transmutation

- complementary to the full actinide recycling approach of Generation IV
- (P&T of longer-lived fission products Tc-99 and I-129: another approach)
- innovation in GEN IV: combination of GEN IV and P&T will be able to release
- “clean waste" and to recycle "dirty fuel" back to the nuclear power plants

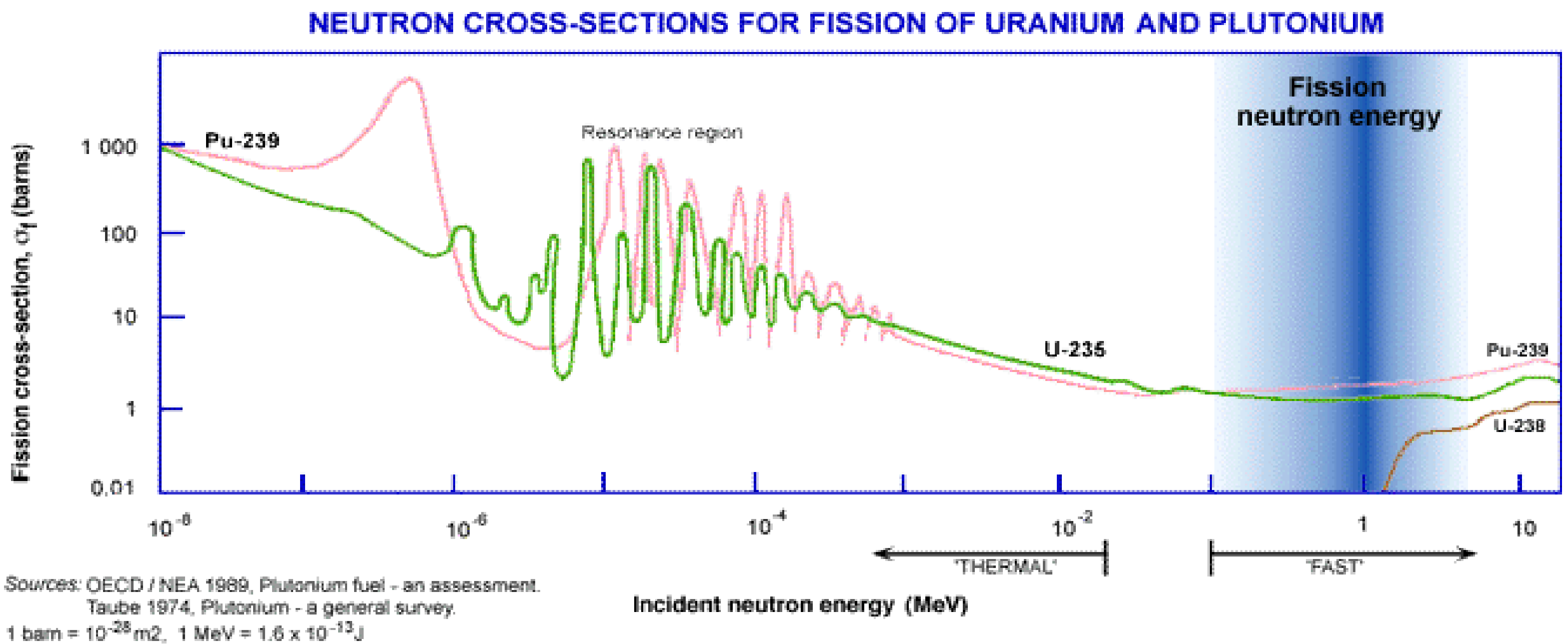
sustainability

= enhanced fuel utilisation (breeding)



Isotopic table

Neutron cross-sections for fission of U and Pu in thermal and fast neutron spectrum systems



A thermal neutron is a free neutron with a kinetic energy of about 0.025 eV (hence a speed of 2.2 km/s), which is the energy corresponding to the most probable velocity at a temperature of 290 K (17 °C), the mode of the Maxwell–Boltzmann distribution for this temperature.

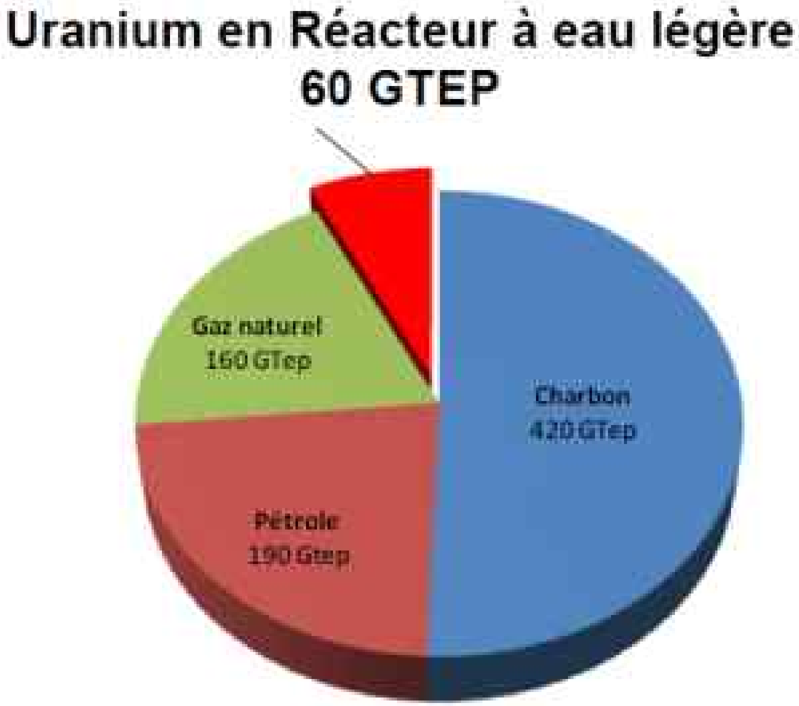
A fast neutron is a free neutron with a kinetic energy close to 1 MeV (100 TJ/kg), hence a speed of 14 000 km/s, or higher. Fast neutrons are produced by nuclear fission with a mean energy of 2 MeV (200 TJ/kg, i.e. 20 000 km/s).

https://en.wikipedia.org/wiki/Neutron_temperature

The probability that fission or any another neutron-induced reaction will occur is described by the neutron cross-section for that reaction. The cross-section may be imagined as an area surrounding the target nucleus and within which the incoming neutron must pass if the reaction is to take place. The fission and other cross sections increase greatly as the neutron velocity reduces from around 20 000 km/s to 2 km/s, making the likelihood of some interaction greater. In nuclei with an odd-number of neutrons (e.g. U-233, U-235, and Pu-239) the fission cross-section becomes very large at the thermal energies of slow neutrons.

http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Introduction/Physics-of-Nuclear-Energy/

Total energetic contents of various sources of energy according to confirmed stocks 2011 (combustibles fossiles / gaz, pétrole, charbon / et fissiles / Uranium /)



Current reserves
of fossile and fissile resources

For FR systems, sustainability of fissile resources is not a practical issue

Source : BP statistical review of world energy, 2011
AIEA, red book (pour les ressources conventionnelles en uranium)

On earth, there are 189 billions of tons of oil, 187 Tm3 of Natural Gas, 860 billions of tons of coal and 4 millions of tons of Natural Uranium. If we consider the uranium is used only in thermal neutrons reactors, converting these stocks into energy makes the above chart.

This uranium-238 cannot be used in water-cooled reactors but could be used in fast neutron reactors, multiplying the energy content of uranium by a factor of more than 100. Thus the chart becomes the above. Global reserves of this uranium-235 (the 1%-part) could be exhausted in less than a century if the rate of use follows the current trend.

Des solutions pour la gestion des déchets radioactifs à long terme

➢ Séparation poussée

➢ Transmutation

<= (Axe 1) =>

(Axe 3)

➢ Conditionnement
➢ Entreposage de longue durée

➢ Stockage (réversible ?)

(Axe 2 =>)

CEA Journées ST7 des 5 et 6 décembre 2013

« Loi relative aux recherches sur la gestion des déchets radioactifs » en France, basée sur 3 axes :

- Axe 1 : séparation et transmutation (=> CEA responsable)
- Axe 2 : stockage en couche géologique (=> ANDRA responsable)
- Axe 3 : conditionnement et entreposage de longue durée (=> CEA responsable).

Loi no 91-1381 dite « loi Bataille » (30 décembre 1991), profondément rénovée en juin 2006

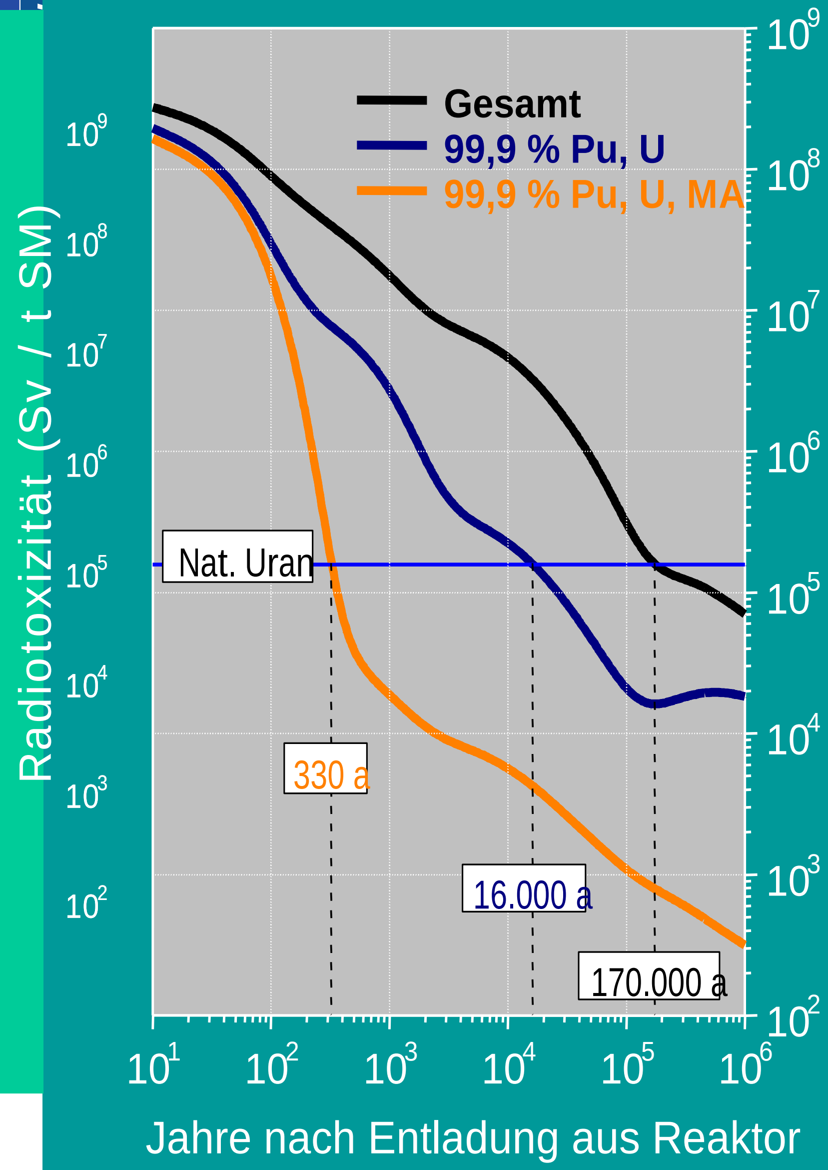
Source: J. Guidez, CEA, “Le nucléaire est-il une énergie durable ?”, JT-SFEN event, 5-6 Dec 2013 “Les réacteurs nucléaires de demain”

Radiotoxicity

- Separation and transmutation of 99.9% of Pu, U and minor actinides (MA)
  NB: The minor actinides include neptunium, americium, curium, berkelium, californium, einsteinium, and fermium

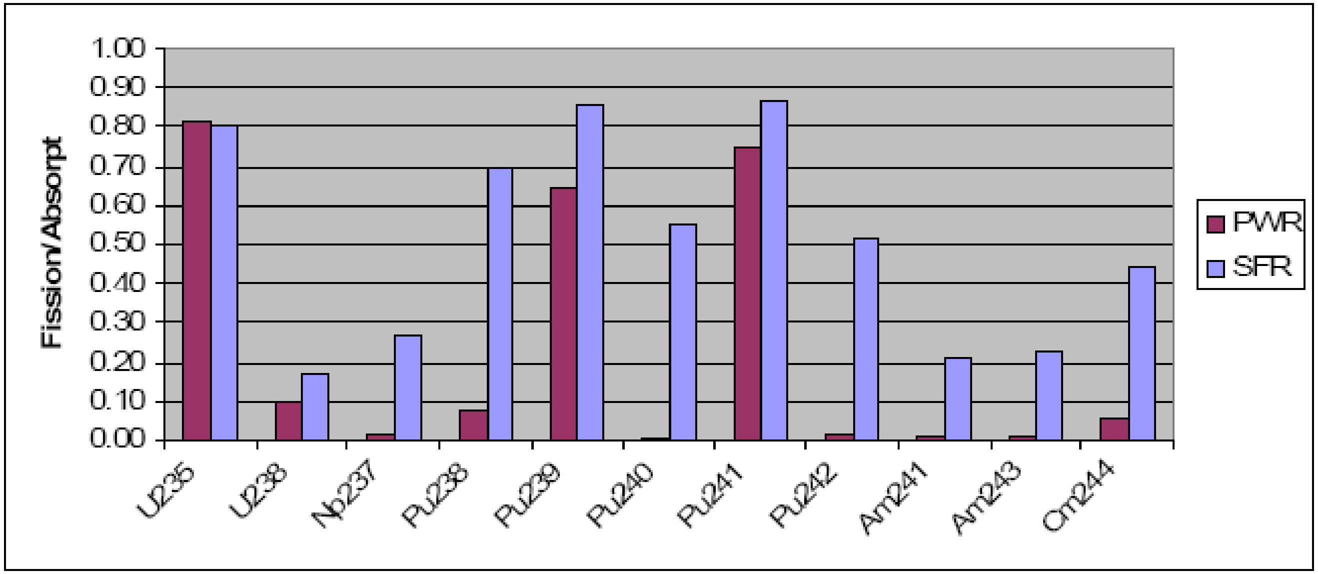
- Achievement:
  Disposal times are shifted from geological to historical time scales in nuclear waste disposal.

NB: Environ 90% de la *radiotoxicité* proviennent du *plutonium* : c'est dire que brûler celui-ci peut être vu comme la première action à entreprendre - Paul REUSS, 2003



Fissioning of MAs in fast reactors

Fission-to-Absorption Ratio for PWR and SFR



- **Fissile isotopes are likely to fission in both thermal/fast spectrum**
  - **Fission fraction is higher in fast spectrum**
- **Significant (up to 50%) fission of fertile isotopes in fast spectrum**

Net result is more excess neutrons generated by fast fission

Transmutation probabilities (%)

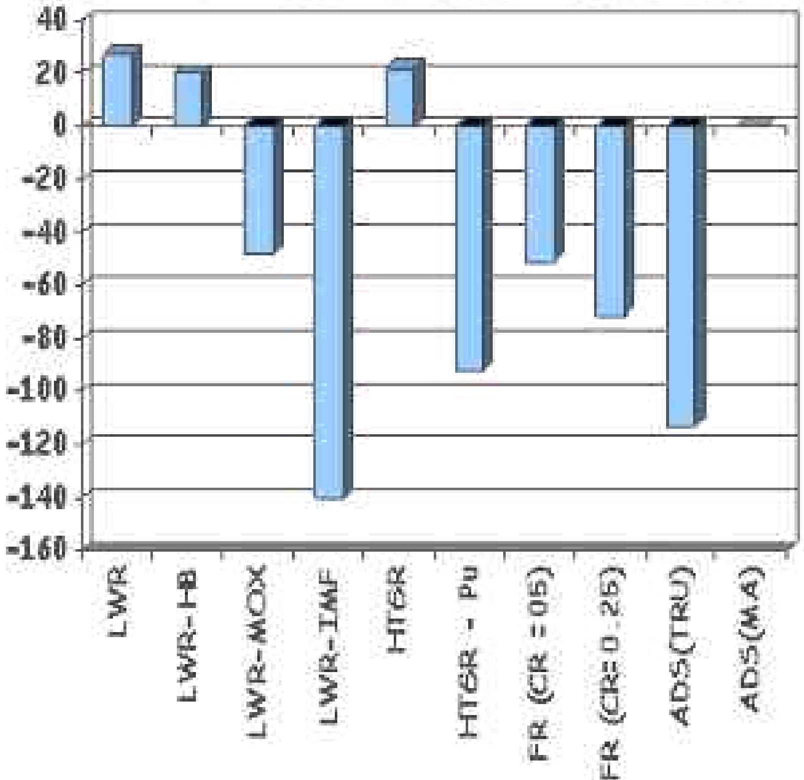
Isotope	thermal spectrum	fast spectrum
Np-137	3	27
Pu-238	7	70
Pu-239	63	85
Pu-240	1	55
Pu-241	75	87
Pu-242	1	53
Am-241	1	21
Am-242m	75	94
Am-243	1	23
Cm-242	1	10
Cm-243	78	94
Cm-244	4	33

The minor actinides Np, Am and Cm (as well as the higher isotopes of plutonium), all highly radiotoxic, are readily destroyed by fissioning in a fast neutron energy spectrum, where they can also contribute to the generation of power.

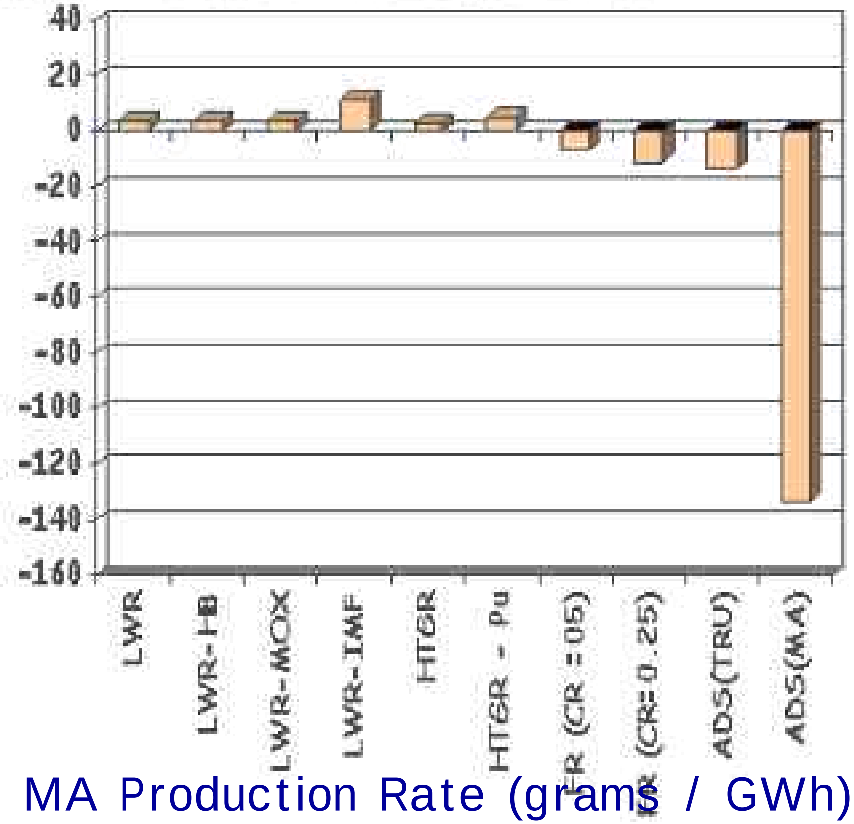
From mid-2007, France's Phenix fast neutron reactor (net 233 MWe, total of 24,44 TWh of electricity generation, prototype fast breeder reactor, Marcoule, France,1973 – 2010) irradiated four fuel pins containing high concentrations of minor actinides from the US DoE, two from the CEA, and two from the Euratom Institute for Transuranics (ITU, Karlsruhe).

Efficiency of different reactor types for MA transmutation

The ADS is most efficient at Minor Actinide Transmutation



Pu Production Rate (grams / GWh)

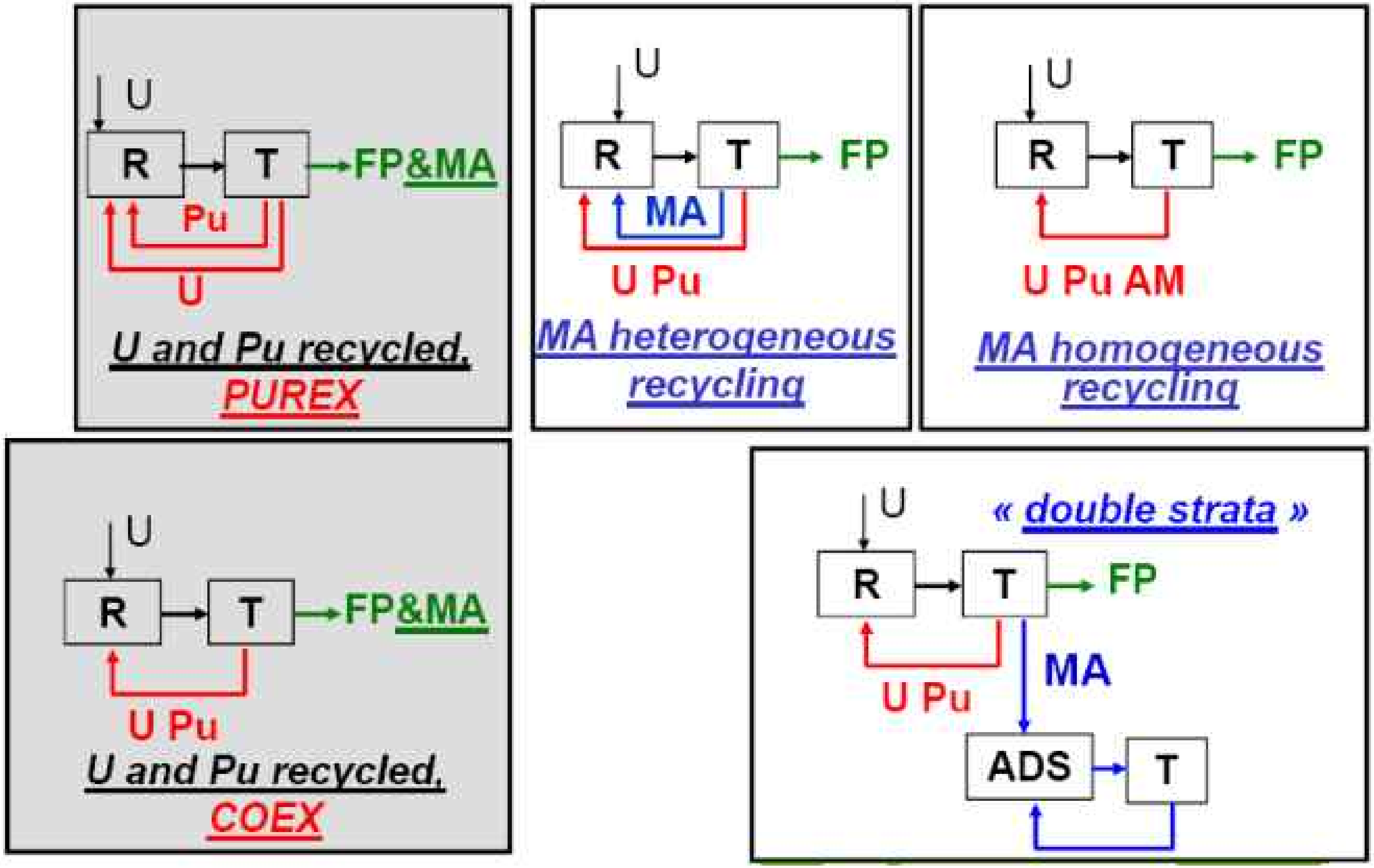


MA Production Rate (grams / GWh)

NB: An average PWR of 1000 MWe (i.e.: 8 TWh of electricity in one year) requires 25 tonnes of fresh enriched fuel at 4% enrichment over one year: 90% is low level waste, 7% is intermediate and 3% is high-level radioactive waste made of fission products (FP) and minor actinides (i.e.: some 750 kg per year from a 1000 MWe reactor). Neptunium, americium and curium. Minor Actinides (MAs) constitute a very small minority of high activity nuclear waste : around 600 grams per ton of irradiated fuel = > about 15 kg of MAs per year for a 1000 MWe reactor.

Source of above figures: M. Capiello & G. Imel (ANL) (ICRS-10/RPS2004)

Future fuel cycle options: Reactor (R) and Treatment (T, processing)



Source: CEA / IEMPT, Oct 08 : http://www.nea.fr/html/pt/iempt10/presentation/SIII01Warin.pdf

SCK•CEN, Mol, Belgium: fields of activity = Nuclear Materials Science; Advanced Nuclear Systems; Environment, Health and Safety; Education and Training

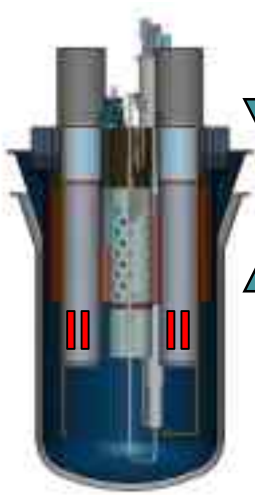
1962

BR2

Material
Testing Reactor
(fission)

Fuel testing
For LWR
& GEN II/GEN III

Irradiation Services:
- Medical RI
- Silicium doping
- Others



2020

MYRRHA

Fast Neutron
Material
Testing Reactor
(fission + fusion)

ADS-Demo
+
P&T testing
(Partitioning &
Transmutation)

Irradiation Services:
- Medical RI
- Silicium doping
- Others

Fuel testing
For LFR GEN IV

LFR GEN IV technology demonstration

SCK-CEN (founded in 1952) - Important installations: BR1, BR2, BR3 (resp. Belgian Reactor 1, 2, 3), VENUS (Vulcain Experimental Nuclear Study), MYRRHA (subcritical Accelerator-Driven System), HADES (Belgian Underground Research Laboratory, located at a depth of -223 m in Boom clay).

NB: **l'exploitation planifiée du BR2 se poursuivra jusqu'en 2026 de telle sorte que l'installation MYRRHA puisse prendre la relève** à la date prévue. (https://www.sckcen.be/~/media/Files/Public/Publications/BR2_brochure/BR2_brochure_FR_WEB.pdf)

MYRRHA at SCK-CEN, Mol, Belgium, to replace BR2 ("Multi-purpose hYbrid Research Reactor for High-tech Applications")

Sustainable development of nuclear energy (waste minimization through transmutation)

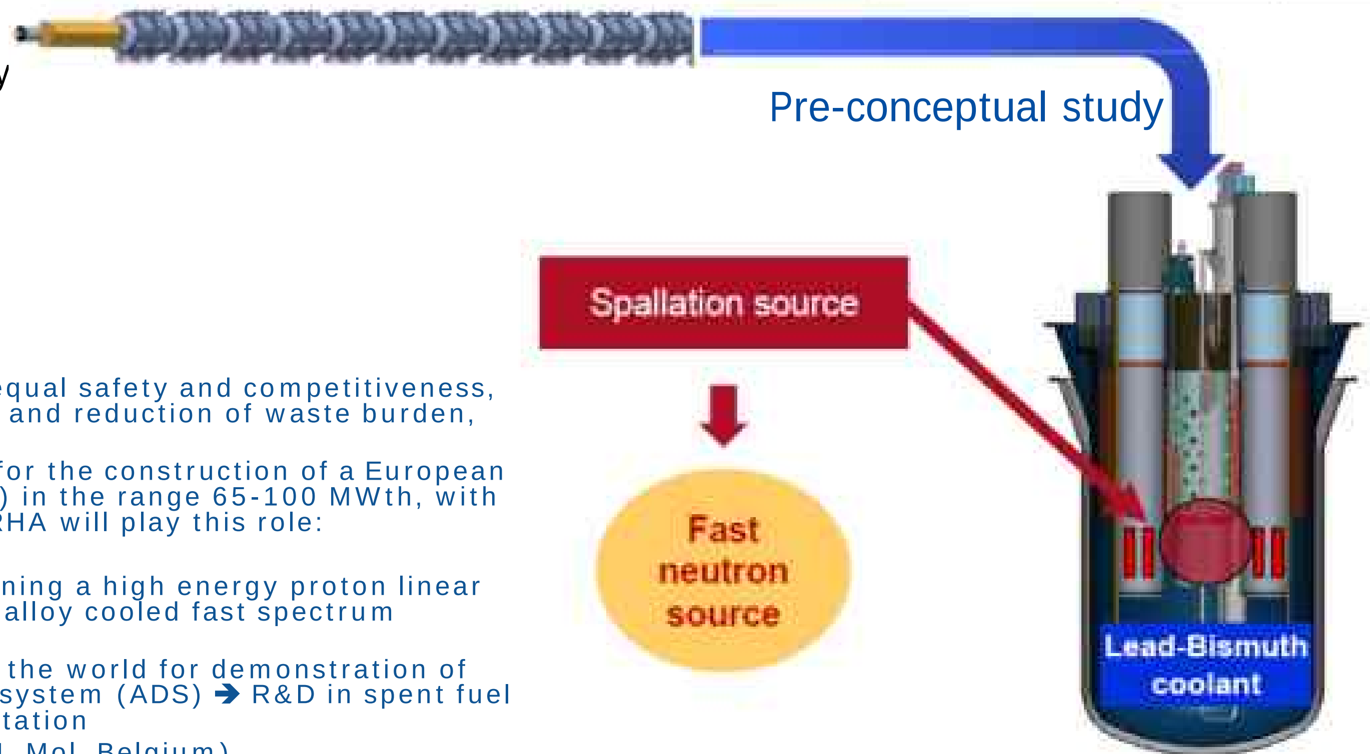
A Belgian large research infrastructure identified as a priority by Europe (2010):

MYRRHA is among the 50 priority projects identified by ESFRI (*European Strategic Forum on Research Infrastructures*)

MYRRHA is also part of ESNII.

Accelerator
600 MeV – 4 mA proton

Reactor
- sub-critical mode (65 – 100 MWth)
- * critical mode (100 MWth)



- Develop a LFR system with equal safety and competitiveness, and with uranium utilisation and reduction of waste burden, comparableto SFR
- Design and obtain a license for the construction of a European Technology Pilot Plan (ETPP) in the range 65-100 MWth, with full operation in 2023; MYRRHA will play this role:
    - A hybrid system combining a high energy proton linear accelerator and a lead-alloy cooled fast spectrum irradiation facility
    - Unique large facility in the world for demonstration of the accelerator driven system (ADS) ➔ R&D in spent fuel partitioning & transmutation
    - Site selected (SCK-CEN, Mol, Belgium)
    - FP7 and Horizon-2020 support with contribution from industrial partners (IBA, FEED Consortium led by AREVA)

Source: http://myrrha.sckcen.be/en/Media_gallery/MYRRHA_technical#!prettyPhoto[gallery]/3/

http://myrrha.sckcen.be/

Belgium support maintained

MYRRHA in the 2014 BE Gov. Declaration

De regering zal het behoud van excellentie in het onderzoek naar de nucleaire veiligheid en informatie voor de burger, de omgeving en nucleaire infrastructuren op Belgisch grondgebied nastreven.

Ze zal het MYRRHA-project of evenwaardige projecten van het SCK progressief ondersteunen om het noodzakelijke onderzoek naar innovatieve oplossingen voor hoogradioactief afval, naar de kwalificatie van fusiereactormaterialen, naar het behoud van de medische radio-isotopenproductie in ons land en naar fundamenteel kernfysisch onderzoek optimaal verder te zetten in een internationale context, in samenwerking met universiteiten, onderzoekscentra en zusterorganisaties van het SCK.

Le gouvernement visera le maintien de l'excellence dans la recherche dans les domaines de la sûreté nucléaire et de l'information du citoyen, de l'environnement et des infrastructures nucléaires sur le territoire belge.

Il soutiendra progressivement le projet MYRRHA ou des projets équivalents du CEN en vue de poursuivre de manière optimale, dans un contexte international, les recherches nécessaires concernant des solutions innovantes pour les déchets hautement radioactifs, la qualification des matériaux des réacteurs à fusion, le maintien de la production de radio-isotopes médicaux dans notre pays et de recherche nucléaire fondamentale, en collaboration avec les universités, les centres de recherche et les organisations sœurs du CEN.

The Belgian Government will support in a progressive way the MYRRHA project or any equivalent project at SCK•CEN aiming to continue the needed research for innovative solutions for High level waste, qualification of materials for fusion, the production of radioisotopes for medical applications in our country and fundamental nuclear research in collaboration with the universities and sister organisation of SCK•CEN

NB: "Large research infrastructure" (LRI) means research infrastructure of a total value of at least EUR 20 million (EU Horizon-2020)

Other lead-based reactor engineering projects worldwide: the China LEAd-based research Reactor (CLEAR-I), a lead-bismuth-cooled research reactor of the ADS type for nuclear waste transmutation; the SVBR-100 (modular lead-bismuth-cooled fast neutron reactor) and BREST-OD-300 projects (lead--cooled fast neutron reactor with onsite nuclear fuel cycle facilities, construction started in 2016 near Tomsk) in Russia; the ALFRED project in the European Union; various design and technology development activities in the United States, Japan, and Korea.

Fission nucléaire de quatrième génération : stop ou encore ?

4 – Besoins et opportunités pour le nucléaire au 21ème siècle (objectifs de Génération IV)

4.2 Sûreté et fiabilité (notamment en l'absence de toute intervention extérieure d'urgence)

"Industrial and societal goals" for Generation IV

Sustainability

1. Generate energy sustainably, and promote long-term availability of nuclear fuel
2. Minimize nuclear waste and reduce the long term stewardship burden

Safety & Reliability

3. Excel in safety and reliability
4. Have a very low likelihood and degree of reactor core damage
5. **Eliminate the "technical" need for offsite emergency response**

(Socio-)economics

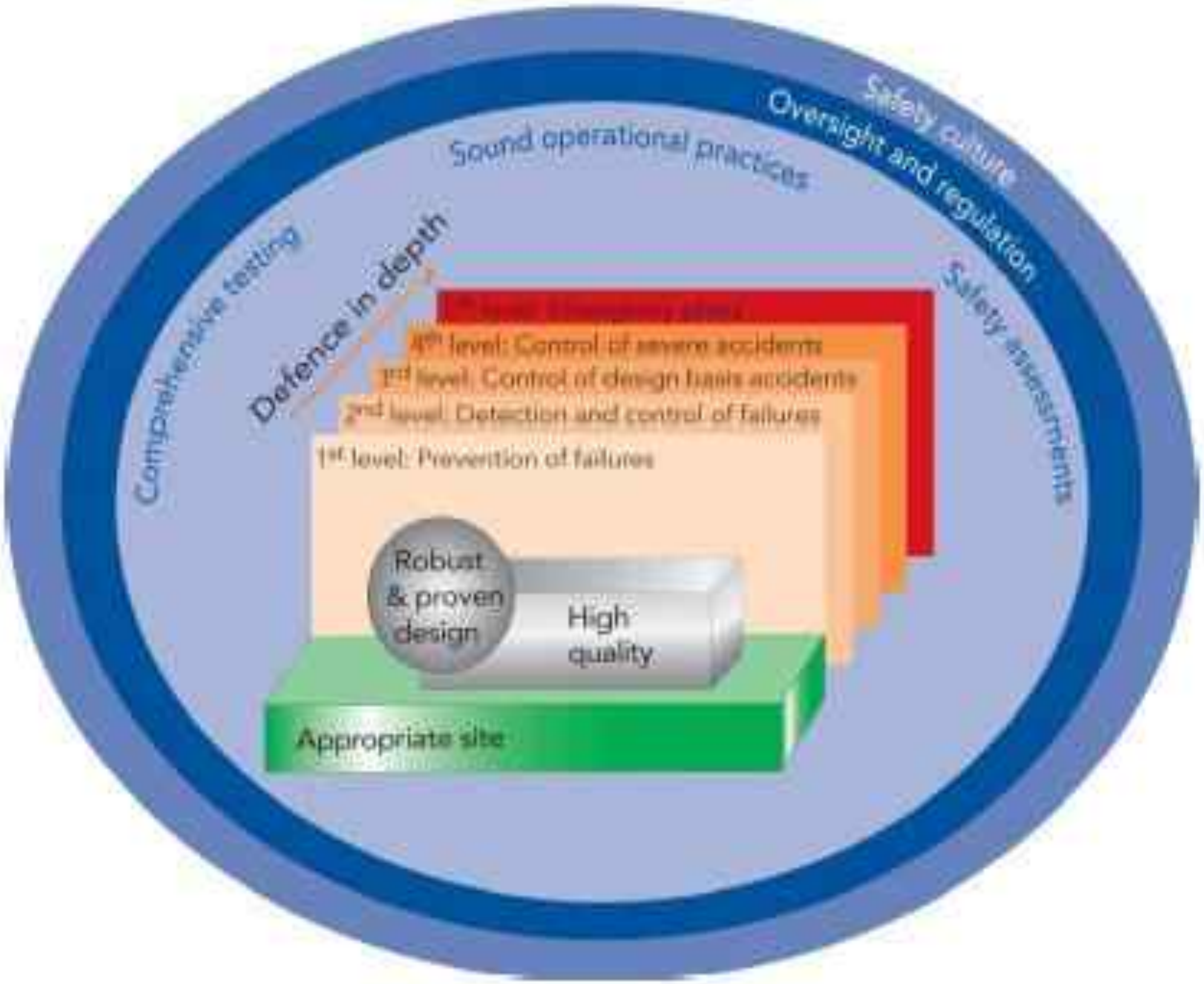
6. Have a life cycle cost advantage over other energy sources
7. Have a level of financial risk comparable to other energy projects

Proliferation resistance and Physical protection

8. Be a very unattractive route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism

Basic Safety Principles (IAEA)

Defence-in-depth concept
(5 "levels") and regulation + safety culture



Physical barriers

Physical barriers between fission products and environment

Multiple technical and physical barriers between the fission products in the reactor core and the environment:

1. Fuel matrix

2. Fuel cladding

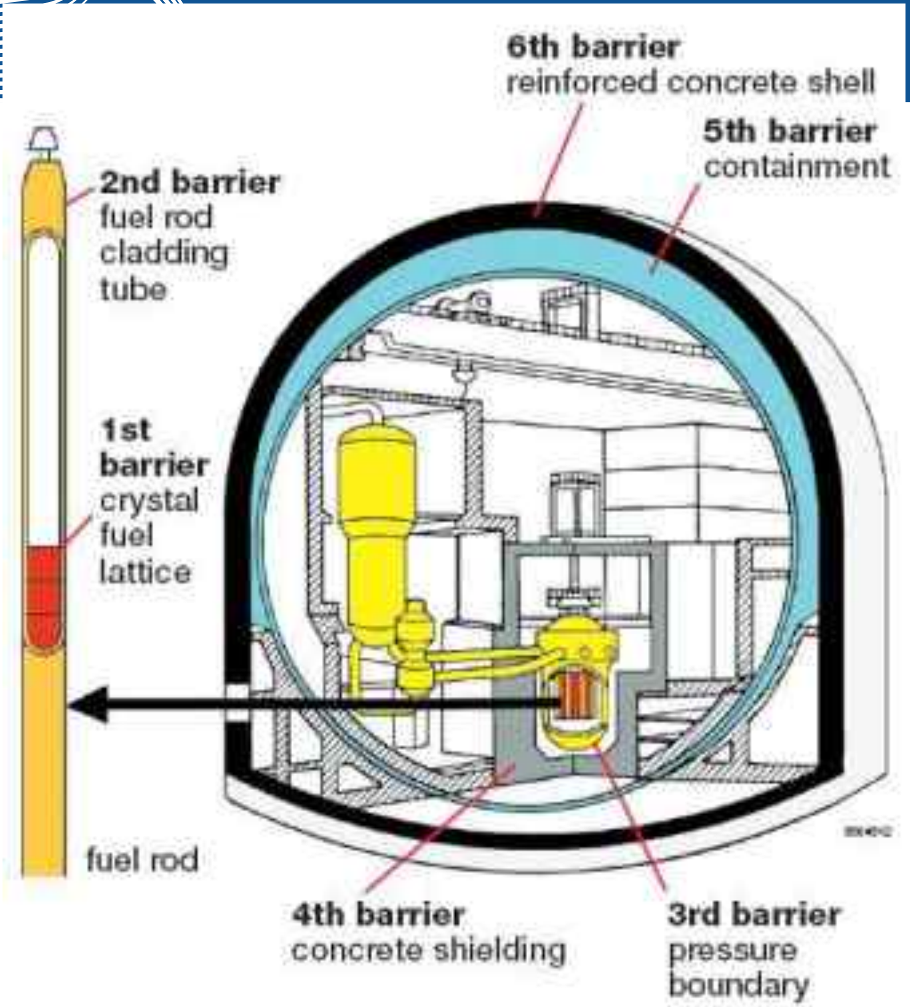
3. Pressure retaining boundary of the reactor coolant

4. Concrete shielding

5. Containment

6. Containment Building

Barriers are supported by additional retaining functions like water layers, pressure differences, filters in ventilation systems.



NB - Of the eleven PWRs and six BWRs operating in Germany before March 2011 phase-out decision, the three PWRs of the Convoy model (designed by Siemens KWU; called Isar 2, Emsland and Neckar 2) with an output of approx. 1400 MWe were the most advanced. A Convoy type reactor building consists of a spherical reinforced concrete shell with very thick walls (h=1.80m) designed to withstand an aircraft crash. This encloses a steel safety container as containment, which maintains integrity even in an anomaly. Isar 2 - see photo left - operational since 1988, to be shutdown in 2022, is equivalent to EPR. Today in Germany, 8 reactors are still in operation.

Three Mile Island accident (USA, Pennsylvania, Harrisburg, 28 March 1979)

<u>INES level 5</u>

Facts: while the reactor involved was destroyed, all radioactivity was contained – as designed – and there were no deaths or injuries.

=> *<u>Institute of Nuclear Power Operations</u>* <u>(INPO - 1980)</u> : promote "excellence" in safety and reliability in the operation of NPPs

<u>Some lessons learned from TMI:</u>

- specific design choices: e.g. far more attention on other than worst **case scenarios, such as the possible impact of "small break" LOCA**

- *<u>more robust safety assessment methods</u>* (based on PSA /level 1, 2, 3/ + deterministic approach) and study of accident consequences

- specific operating procedures: e.g. emergency operator procedures and severe accident management guidelines (SAMG)

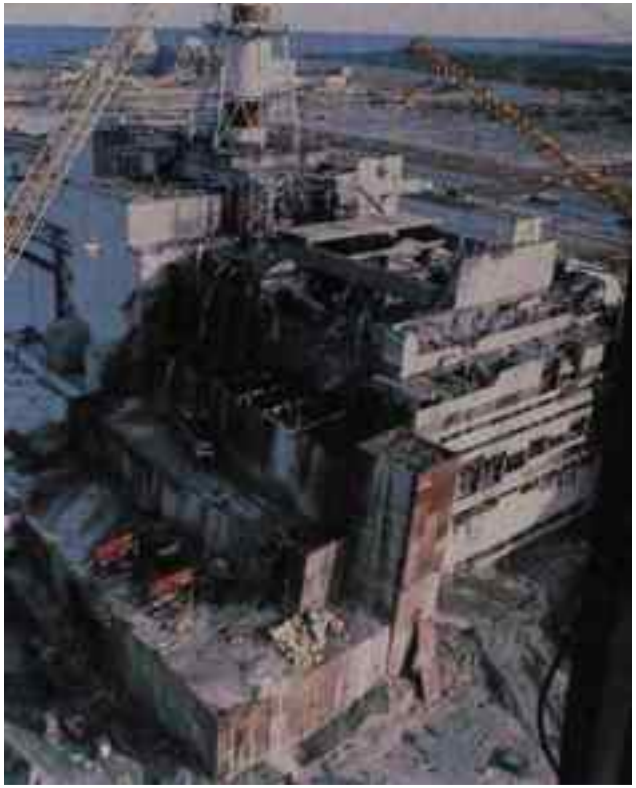
- importance of human failures: MTO (Man – Technology - Organisation) => comprehensive system perspective on NPP safety.

Chernobyl disaster (Ukraine, ex-Soviet Union, 25 April 1986)

INES level 7

Facts: soviet reactor RBMK-1000 – unique design: a boiling light water **reactor made of graphite moderated pressure tubes with “positive void coefficient” under certain conditions**

⇒ *World Association of Nuclear Operators* (WANO – 1989):
NPPs worldwide work together to assess, benchmark and improve performance through mutual support, exchange of information and emulation of best practices (> 130 members, > 430 NPPs)



Some lessons learned from Chernobyl:

- "*an event at one plant impacts every plant and nuclear safety is everyone's business*" => development of the *"safety culture"* concept and strategy based on prevention and workers' participation

- *development of laws and regulations related to safety and health at work*, in particular, regarding radiation protection (e.g. Euratom BSS) and prevention of severe accidents as well as preparedness and response for a nuclear and radiological emergency (e.g. INSAG, 1986)

Fukushima Daiichi accident (Great East Japan Earthquake, 11 March 2011)

INES level 7

Some lessons learned from Fukushima:

- improvements of plant (multi-reactor) robustness in extreme situations (seismic events, fires, floods, extreme weather conditions)

- safety improvements in areas beyond the design basis (severe accident management) including w.r.t. Spent Fuel Pools

- importance of organizational and societal preconditions that might lead to major structural and/or societal failure (e.g. combination of cultural, political, financial, professional, and industrial pressures)

=> *absolute need for independent national regulatory authorities*.

=> "stress tests" for all 131 reactors (European Council on 24/25 March 2011) : targeted reassessments of safety margins (conducted in all EU Member States + Switzerland and Ukraine + Armenia, Turkey, Russia, Taiwan, Japan, S Korea, S Africa, Brazil)

=> Revised Euratom Safety Directive "*establishing a Community framework for the nuclear safety of nuclear installations*" (Council Directive 2014/87/Euratom of 8 July 2014)

Fukushima Nuclear Accident Independent Investigation Commission (NAIIC), inquiry report (chairman = Prof. K. Kurokawa, 5 July 2012) :

"Its fundamental causes are to be found in the ingrained conventions of Japanese culture: our reflexive obedience; our reluctance to question authority; our devotion to 'sticking with the program'; our groupism; and our insularity…"

European Commission

"Stress Tests" after the Fukushima accident (Great East Japan Earthquake, magnitude 9, 11/03/2011)

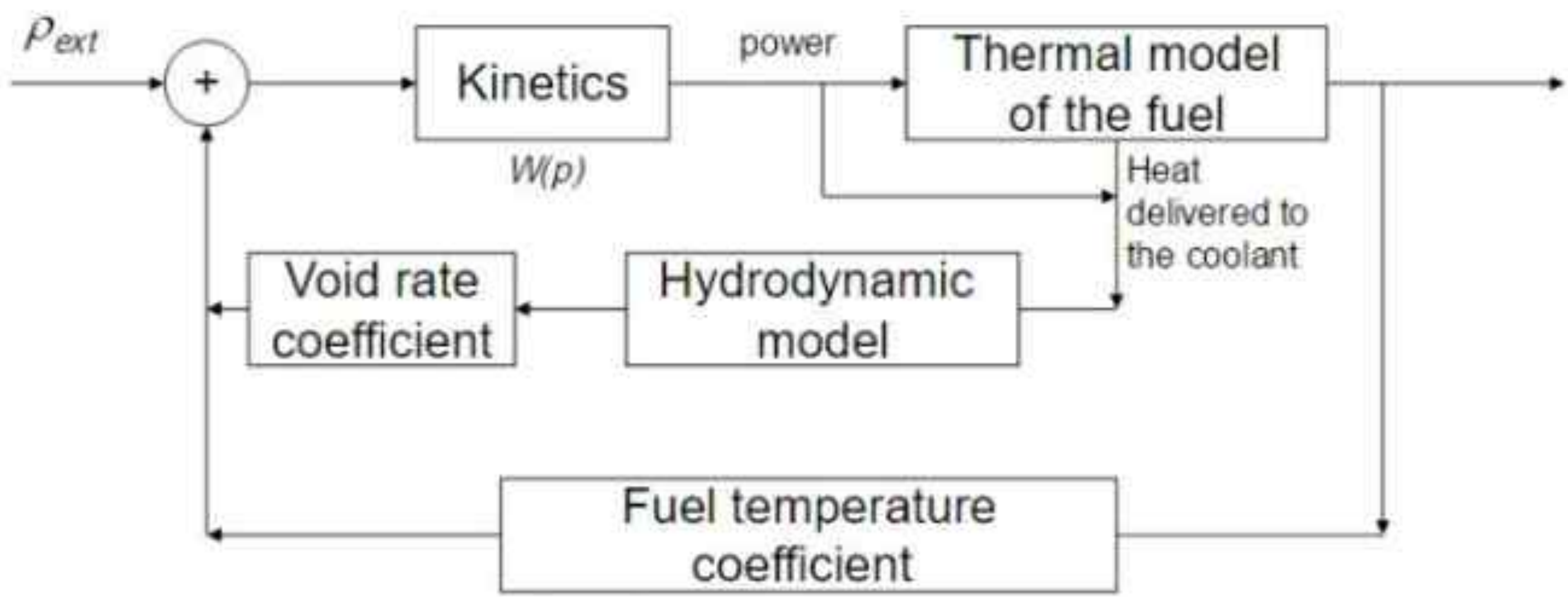
The European Council requested on 24/25 March 2011 that the safety of all EU nuclear plants should be reviewed, on the basis of a comprehensive and transparent risk and safety assessment ("stress tests").

These “stress tests” are defined as targeted reassessments of the safety margins of nuclear power plants, developed by ENSREG, including the EC.

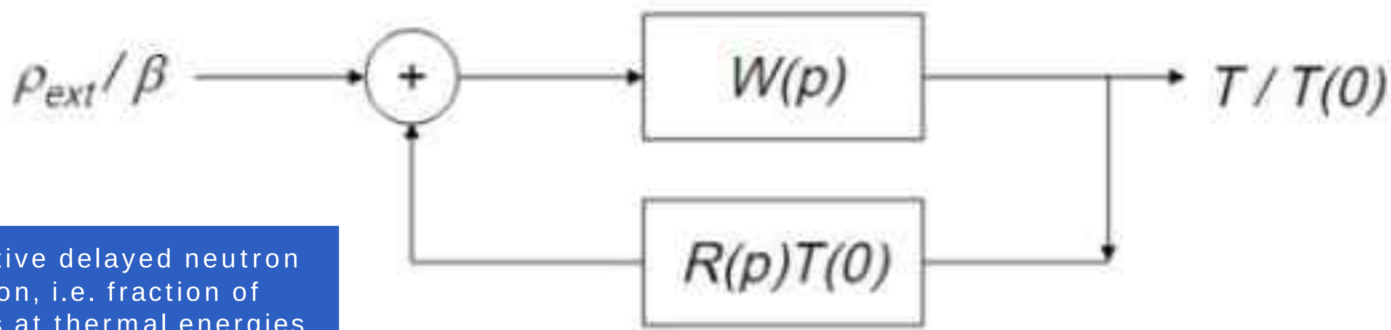
"Final report on the Peer Review of EU Stress Tests”, 26 April 2012 - http://www.ensreg.eu/node/407

Ensuring the Required Safety Level, Adjusting New Generation Power Units for External Hazards

=> impact on revised "Euratom Safety Directive" (Council Directive 2014/87/Euratom 08/07/2014)



Schematic of the feedback

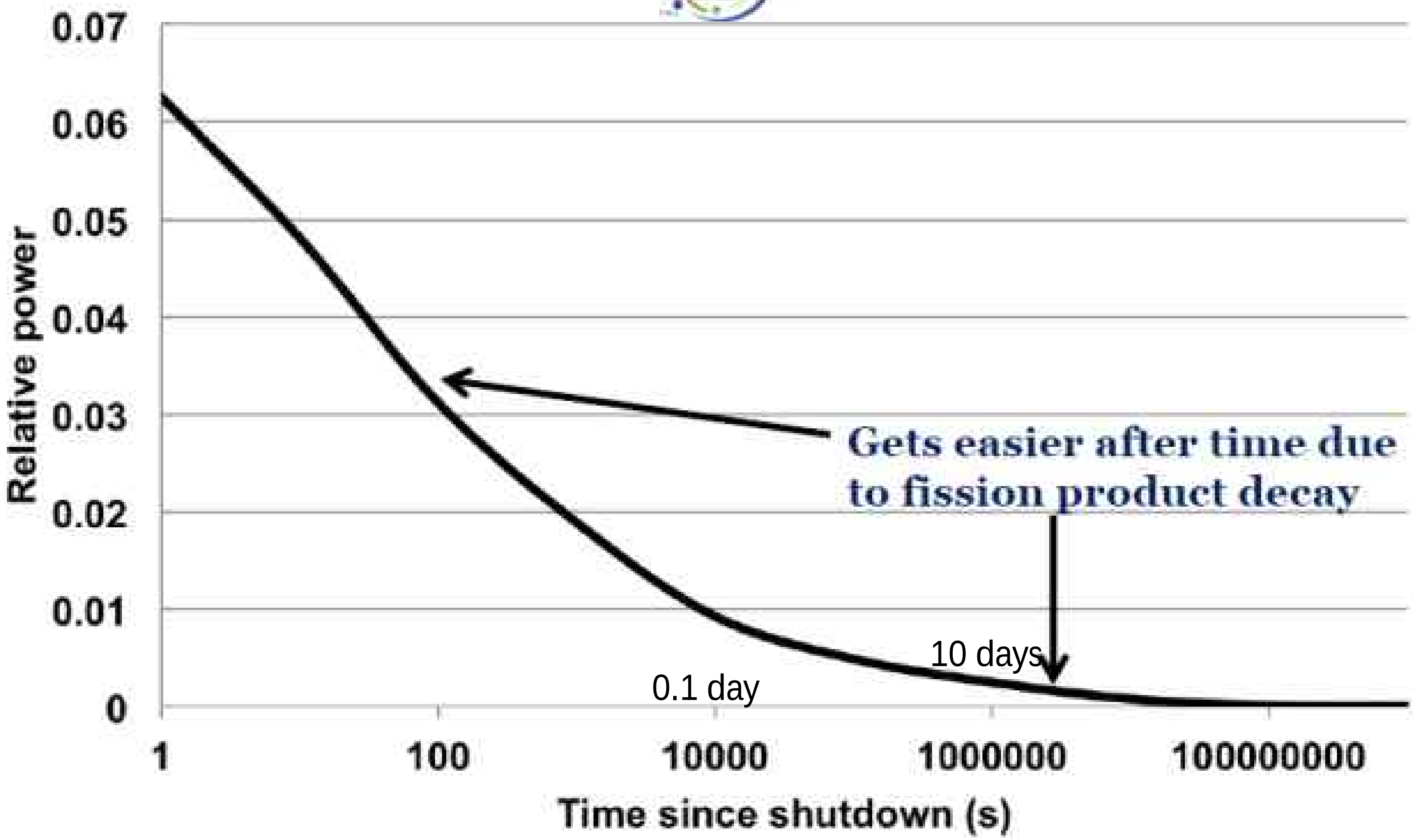


$\bar{\beta}_{eff}$ = effective delayed neutron fraction, i.e. fraction of neutrons at thermal energies which were born delayed

$\rho = \frac{k_{eff} - 1}{k_{eff}}$ = reactivity, i.e.: relative distance to criticality

Transfer function of the reactor with feedback
(fuel temperature reactivity coefficient and void rate reactivity coefficient)

Removal of fission product decay heat : the main reactor safety challenge in case of severe nuclear reactor accident (LOCA)



Relative power of 7 % = heat of about 200 MWth in the case of a 3000 MWth plant (i.e. 1 GWe reactor)

Source: "Overview of Nuclear Reactors: History, Technology, and Future", Blomquist - https://www.icln.org/default/assets/File/Overview%20of%20Nuclear%20Reactors.pdf

Probabilistic Safety Assessment (PSA) for NPPs: structure and levels

Plant response to initiating events	→ Level 1	Frequency of core damage (CDF) • includes accident management measures
Physical effects, containment response	→ Level 2	Frequency and amount of radionuclides released (source term, PDF)
Athmospheric dispersion, potential and expected doses, dose-effect/risk relation	→ Level 3	Frequency and quantities of environmental and health effects

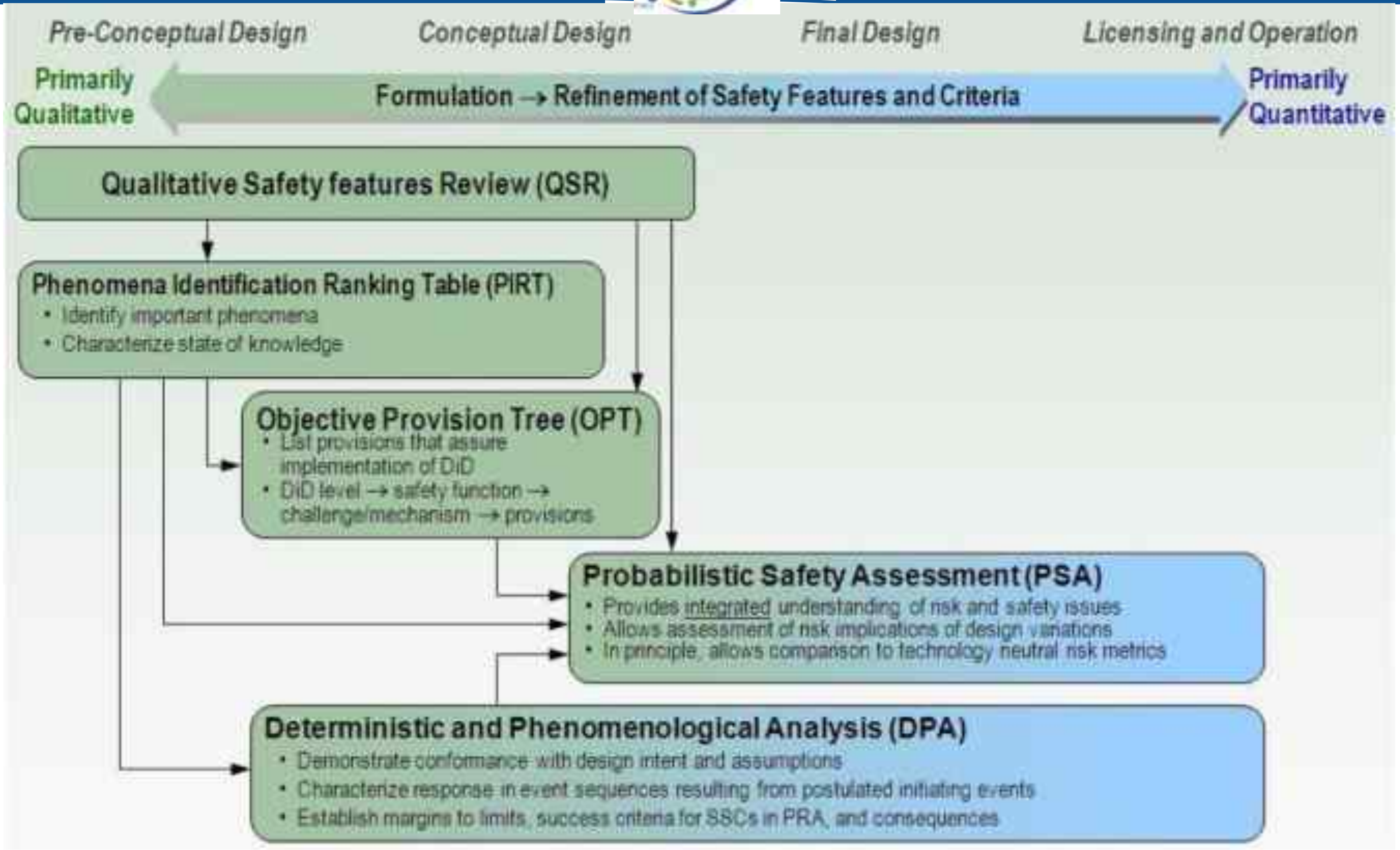
(1) Core Damage Frequency (CDF) – Level 1 PSA
(usual definition: e.g. local fuel temperature above 1204 ºC) (desired target value = CDF < E-5/yr, following IAEA - INSAG-12)

(2) Plant Damage Frequency (PDF) or Larger Early Release Frequency (LERF) – Level 2 PSA
(basic definition: e.g. limit of 100 TBq Cesium-137) (desired target value = LERF < E-6/yr)

(3) Frequency of Doses (assessment of consequences from the release, e.g. fatal acute or fatal late health risks) – Level 3 PSA

NB: above target values are per reactor-year for operating plants - for future plants, the aim is to achieve one tenth of these values (IAEA and OECD-NEA)

"An Integrated Safety Assessment Methodology (ISAM) for Generation IV Nuclear Systems"



GIF Portal (public): https://www.gen-4.org/gif/jcms/c_9260/public

ISAM Report 2011: https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/gif_rsgw_2010_2_isamrev1_finaforeg17june2011.pdf

Fission nucléaire de quatrième génération : stop ou encore ?

1 – Introduction : Génération IV - pourquoi ? comment ? avec qui ? quand ?

2 - Le cap («triangle énergétique européen») et les invariants (lois de la nature)

3 - La réalité des faits et des chiffres (« quasi-certitudes ») et défis technologiques et humains (incertitudes)

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4.1 Améliorer la durabilité (y compris l’utilisation efficace du combustible et la réduction des déchets)

4.2 Sûreté et fiabilité (notamment en l’absence de toute intervention extérieure d’urgence)

4.3 Economie

(compétitivité par rapport aux sources d’énergie)

4.4 Lutte contre la prolifération des armes nucléaires et protection matérielle

5 - Les systèmes-réacteurs nucléaires en projet de la Génération IV : SFR, LFR, GFR, VHTR, MSR et SCWR

6 - Conclusion : recherche, innovation et formation en fission nucléaire

"Industrial and societal goals" for Generation IV

Sustainability

1. Generate energy sustainably, and promote long-term availability of nuclear fuel
2. Minimize nuclear waste and reduce the long term stewardship burden

Safety & Reliability

3. Excel in safety and reliability
4. Have a very low likelihood and degree of reactor core damage
5. **Eliminate the "technical" need for offsite emergency response**

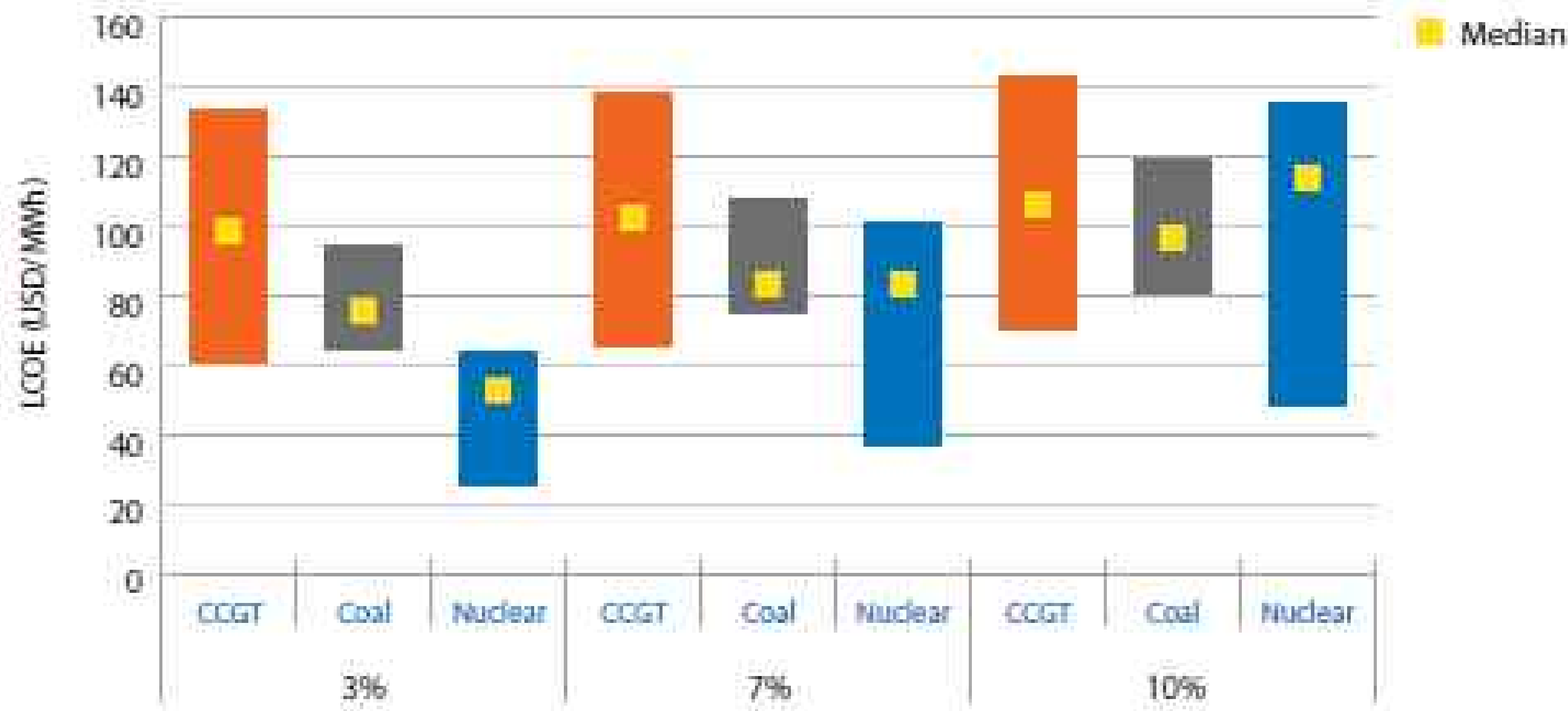
(Socio-)economics

6. Have a life cycle cost advantage over other energy sources
7. Have a level of financial risk comparable to other energy projects

Proliferation resistance and Physical protection

8. Be a very unattractive route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism

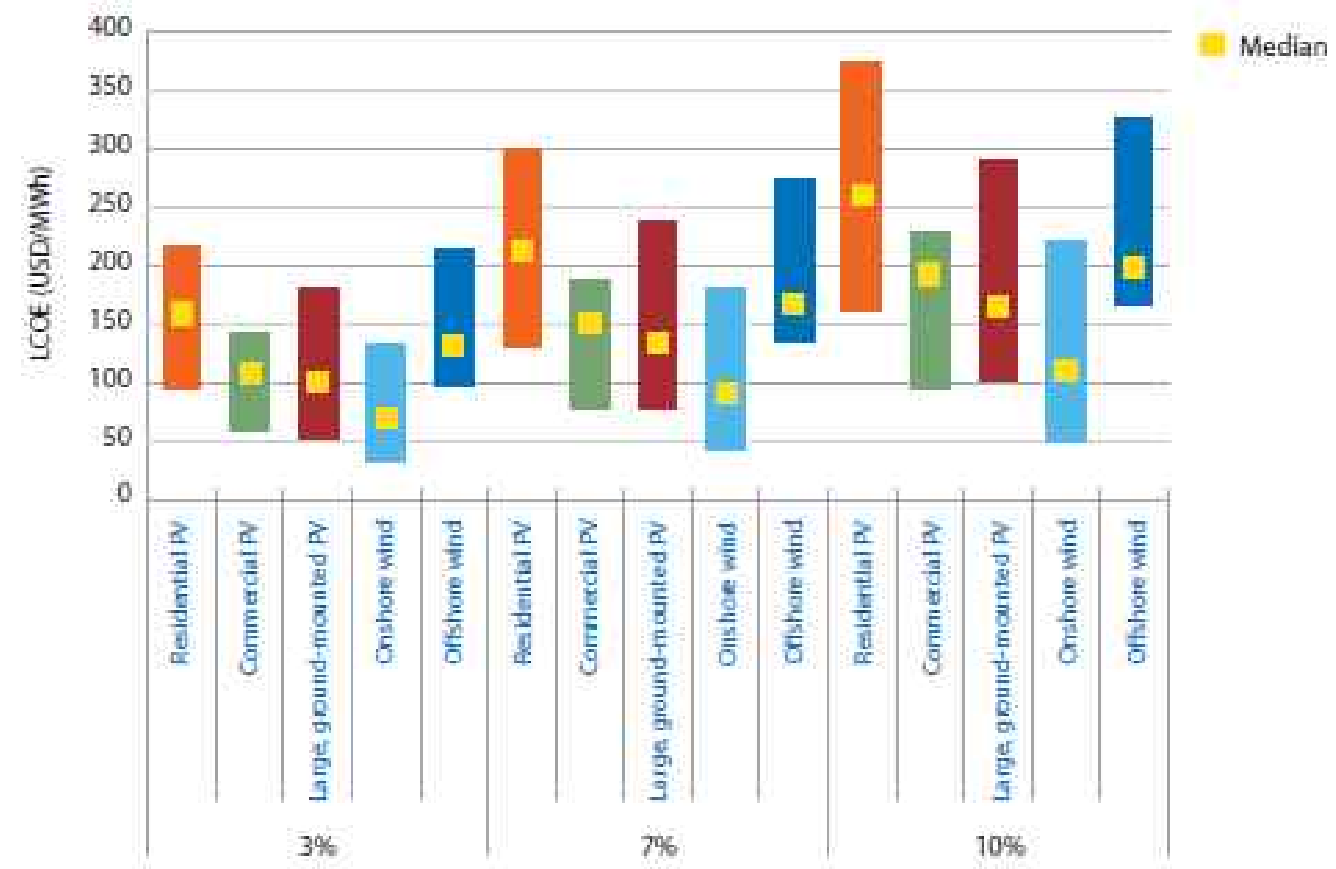
LCOE ranges for baseload technologies 2015 (at each discount rate)



Above Figure shows the range of LCOE results for the three baseload technologies analysed in the IEA/NEA report (natural gas-fired CCGTs, coal and nuclear).
At a 3% discount rate, nuclear is the lowest cost option for all countries. However, consistent with the fact that nuclear technologies are capital intensive relative to natural gas or coal, the cost of nuclear rises relatively quickly as the discount rate is raised.
As a result, at a 7% discount rate the median value of nuclear is close to the median value for coal, and at a 10% discount rate the median value for nuclear is higher than that of either CCGTs or coal. These results include a carbon cost of USD 30/tonne, as well as regional variations in assumed fuel costs.

Comparison of levelised costs of generating electricity (LCOE) for both baseload electricity generated from fossil fuel thermal and nuclear power stations, and a range of renewable generation, including variable sources such as wind and solar.
“Projected Costs of Generating Electricity”, IEA – OECD/NEA (2015) - http://www.iea.org/Textbase/npsum/ElecCost2015SUM.pdf

LCOE ranges for solar PV and wind technologies 2015 (at each discount rate)



Above Figure shows the LCOE ranges for various renewable technologies – namely, the three categories of solar PV in the study (residential, commercial and large, ground-mounted) and the two categories of wind (onshore and offshore). It is immediately apparent that the ranges in costs are significantly larger than for baseload technologies. It is also notable that the costs across technologies are relatively in line with one another. While at the high end, the LCOE for renewable technologies remains well above those of baseload technologies, at the low-end costs are in line with – or even below – baseload technologies. Solar PV in particular has seen significant declines in cost since the previous study, though onshore wind remains the lowest cost renewable technology. NB: Plant-level costs are becoming of lesser importance. What is needed is the ability to ensure secure and cost-effective supply at the system level.

Comparison of levelised costs of generating electricity for both baseload electricity generated from fossil fuel thermal and nuclear power stations, and a range of renewable generation, including variable sources such as wind and solar.
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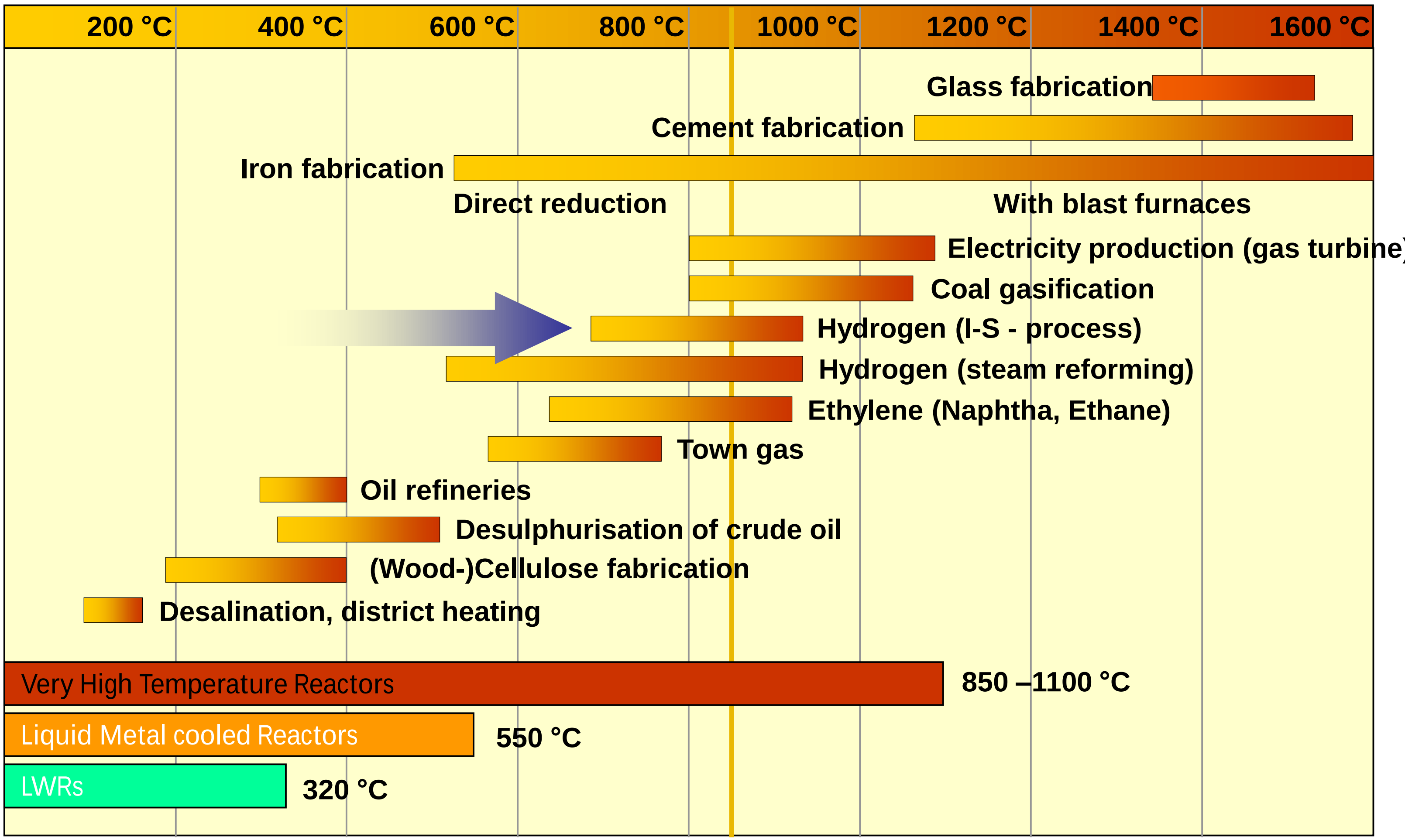
As reactor temperatures go up, industrial uses increase

Generation IV reactor systems (industrial deployment in the middle–long term 2030–2050): broadening the application field: cogeneration of heat and power (new markets)

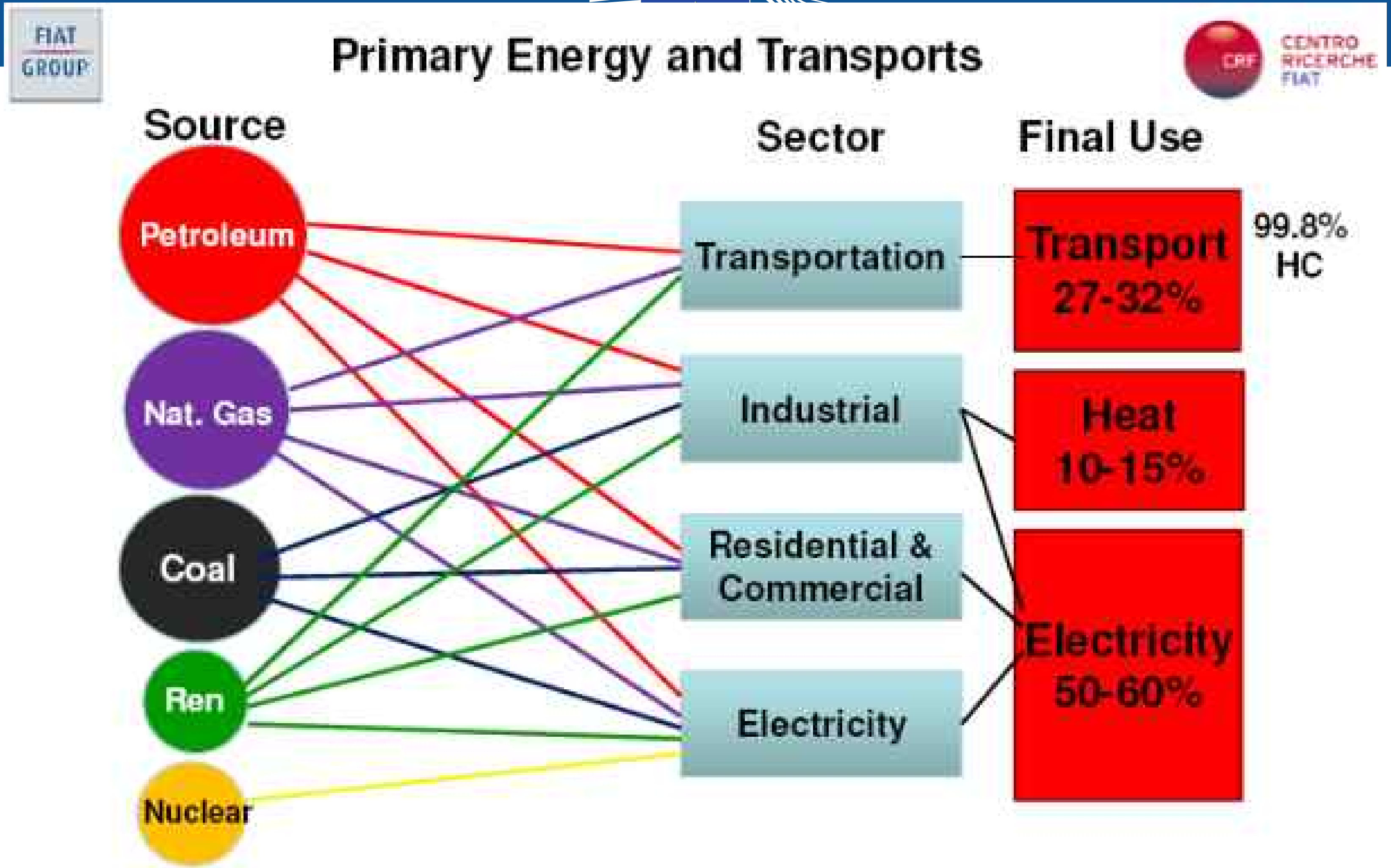


Source: Forschungszentrum Jülich, 2002

The nuclear cogeneration concept: providing heat and power to industrial and district heating applications

http://www.snetp.eu/nc2i/

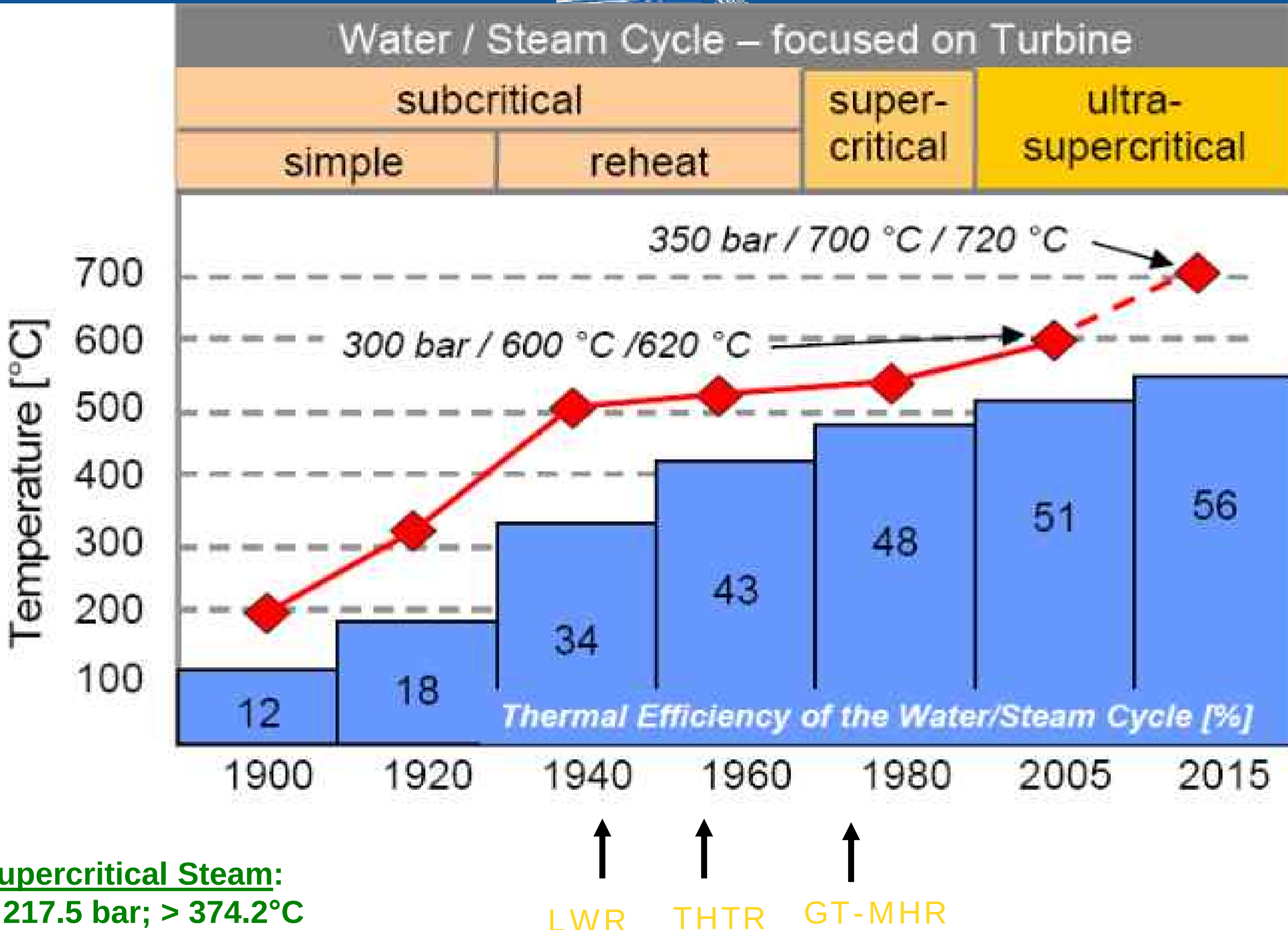
Decarbonisation of the energy system by 2050 (EU Energy Roadmap 2050) => electricity almost doubling its share in final energy demand



Projection until 2050 – "Electricity will play a central role in the low carbon economy" = >What really matters is the final use. With the advent of e-mobility from 2025 most primary energy will be converted into electricity > 70 % (FIAT Group)

Source: Electromobility WG in ARTEMIS Joint Undertaking ("*Advanced Research & Technology for EMbedded Intelligence and Systems*" - http://www.artemis-ia.eu/project/index/view?project=49)

Thermal Efficiency Evolution

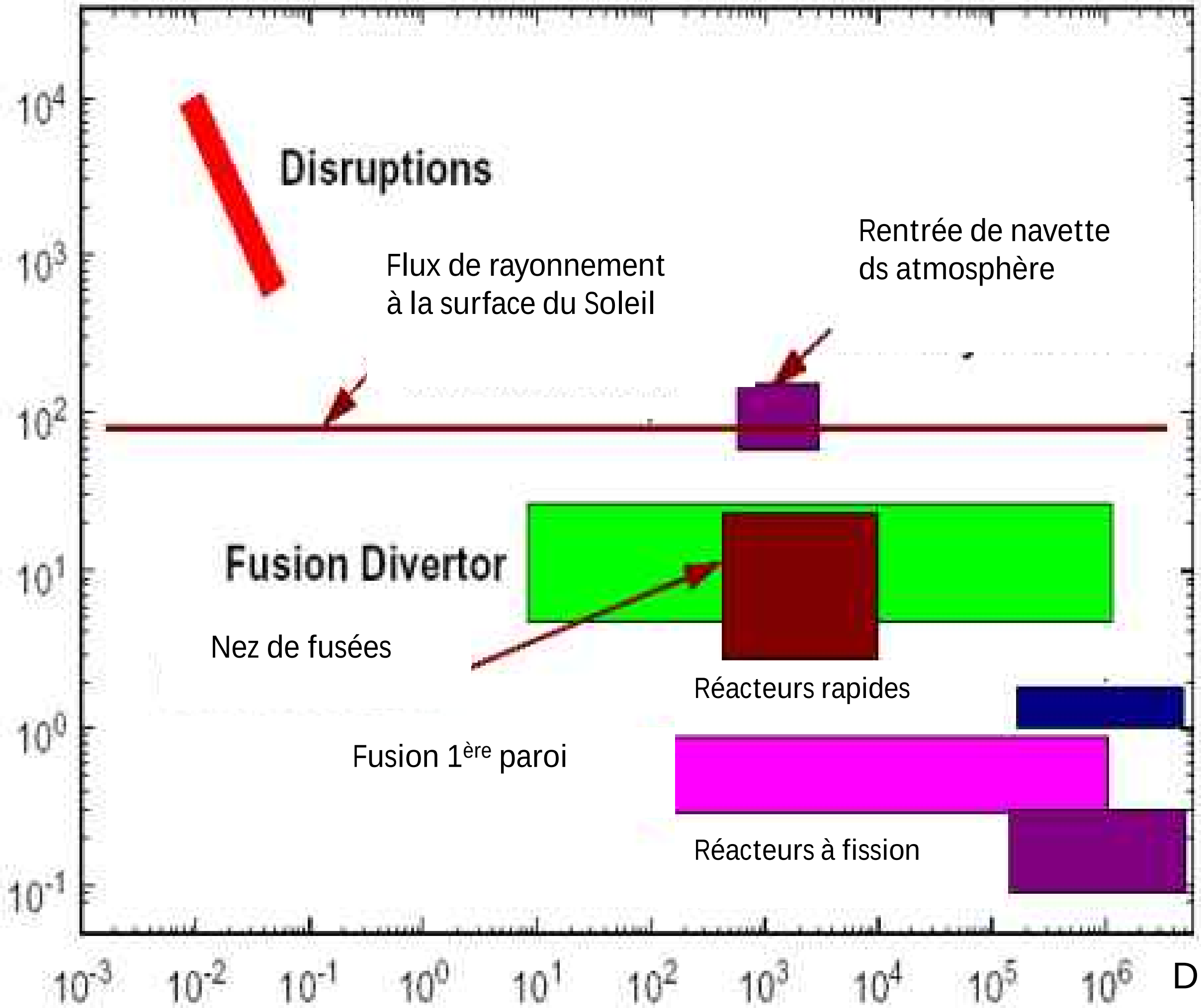


Supercritical Steam:
> 217.5 bar; > 374.2°C

Source: FZJ Juëlich GmbH

Fusion (ITER) and Gen IV fission reactors: extreme heat flux values (20 MW/m² or 2 kW/cm²)

flux thermique MW/m²

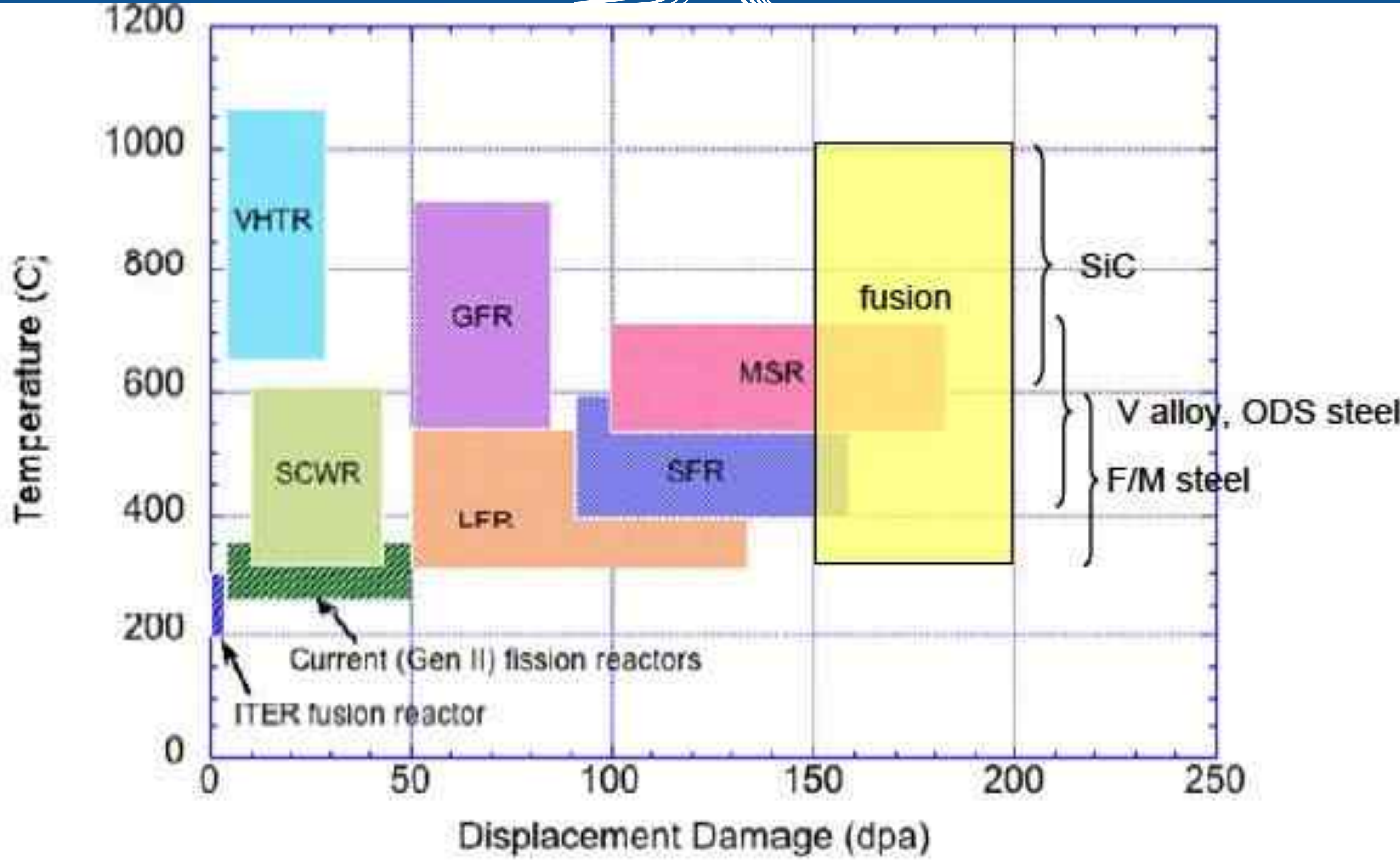


NB: 10^7 sec = 115 days

Durée (secondes)

Source: « La fusion thermonucléaire: Rêve de physicien ou réalité industrielle ? », Janvier 2016, V. Massaut, anciennement Chef de l'Unité de recherche sur la fusion, SCK•CEN Mol

Overview of operating temperatures and displacement damage dose regimes for structural materials in current (generation II) and proposed future (Generation IV) fission and fusion energy systems



On top of thermal aging, fatigue and corrosion, irradiation damage is a key issue when considering extended reactor lifetimes. Since the materials within the reactor core could be used in an intense high-energy neutron field, it must exhibit good dimensional, mechanical and microstructural stability to neutron displacement damage. The radiation-resistance is often the most challenging requirement to evaluate since the key degradation mechanisms are sensitive to the specific radiation conditions.

"Structural materials for fission & fusion energy", Steven J. Zinkle , Jeremy T. Busby, ORNL, available online 22/12/2009, Materials Today, Volume 12, Issue 11, November 2009 - http://www.sciencedirect.com/science/article/pii/S1369702109702949

Evolution of five generations of elevated-temperature steels for power-generation industry over 60 years => gain is 2 °C per year !

Evolution of ferritic/martensitic steels for power-generation industry.

Generation	Years	Steel Modification	10^5 h Rupture Strength (MPa)	Steels	Max-Use Temperature (C)
0	1940-60		40	T22, T9	520-538
1	1960-70	Addition of Mo, Nb, V to Simple Cr-Mo steels	60	EM12, HCM9M, HT9, HT91	565
2	1970-85	Optimization of C, Nb,V	100	HCM12, T91, HCM2S	593
3	1985-95	Partial Substitution of W for Mo and Add Cu	140	NF616, E911, HCM12A	620
4	Future	Increase W and Add Co	180	NF12, SAVE12	650

NB: because the fourth-generation steels contain cobalt, they are not suitable for nuclear use (reminder: the strong gamma ray “source” cobalt-60 /half-life of 5.3 years/ is produced by neutron bombardment in a nuclear reactor of cobalt-59 – it may influence the entire decommissioning process)

Source: “Lead-Cooled Fast Reactor Systems and the Fuels and Materials Challenges”, T. R. Allen (University of Wisconsin) and D. C. Crawford (General Electric Nuclear Energy), Hindawi Publishing Corporation, Science and Technology of Nuclear Installations, Volume 2007, Article ID 97486, 11 pages

RD&DD: from preconceptual to final design (development of large innovative technological projects)

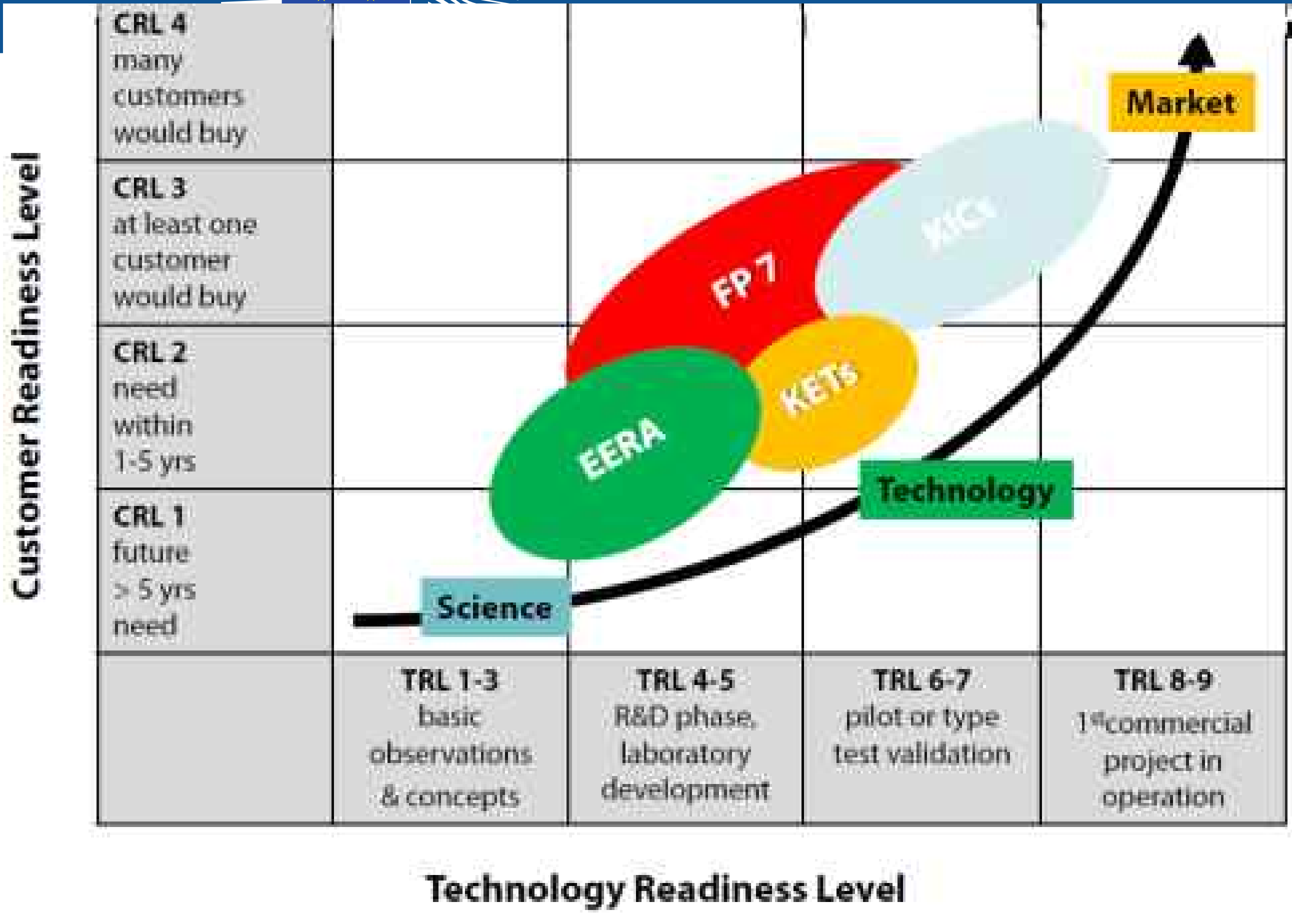
RD&DD	Stages	Definition	Contact with Regulators	Design Authority
Research	***1.Preconceptual***	***Options and ideas***	***Global Principle.*** ***Is the concept licensable?***	***Originator (RTD)***
	2. Conceptual	*Viability report* ***Design & Fuels Requirements***		***Systems Integration & Assessment***
Development	***3. Preliminary***	*Performance report*		***Systems Integration & Assessment***
Demon-stration	***4. Basic Design***	*Demonstration report* ***First quote.*** ***Formal guidance.***	***Formal license*** ***Discussions.***	***Vendor***
	5. Detailed Design	***Procurement.***		***Vendor***
Deployment	***6. Final Design***			***User***

Life cycle of 100 years for NPP: from design, manufacturing, construction, commissioning, operation, decommissioning up to green field

Technology Readiness Level (TRL)
TRLs versus Customer Readiness Level

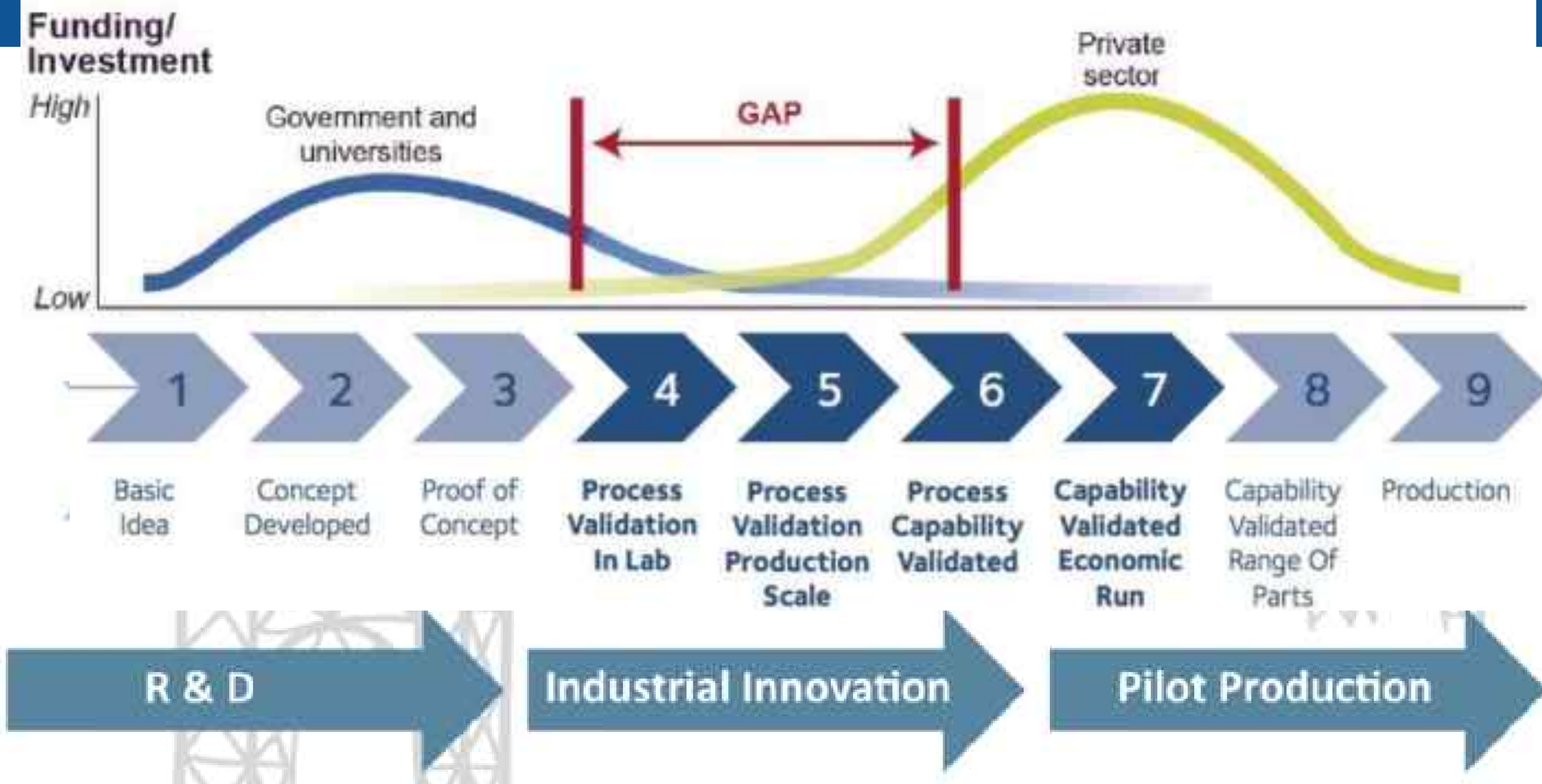
- TRL 1 Basic principles observed and reported
- TRL 2 Technology concept and/or application formulated
- TRL 3 Analytical and experimental proof of concept
- TRL 4 Component /subsystem / technology validation in laboratory environment
- TRL 5 Component /subsystem /technology validation in relevant environment
- TRL 6 Prototyping demonstration in relevant environment
- TRL 7 Prototyping demonstration in operational environment
- TRL 8 System completed and qualified (demonstration in operational environment)
- TRL 9 Technology proven through successful mission operations.

Source: Technology Readiness Levels (NASA 1980's) http://www.nasa.gov/content/technology-readiness-level/



Source: *EuroMaster in Nuclear Energy - European Institute of Innovation and Technology - Knowledge and Innovation Communities" (KIC)*
- http://www.kic-innoenergy.com/education/msc-programmes/msc-emine.html

"Valley of Death", the place where ideas go to die



Participation in developing TRLs

The gap in the middle is sometimes referred to as "The Valley of Death" :
it is an analogy to describe the possible discontinuity in innovation processes.
The valley tends to be at the point where a conceptual idea needs to be turned into a working prototype to demonstrate that it works, to assess production costs and outline the equipment and processes needed for manufacture.

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Proliferation Resistance and Physical Protection

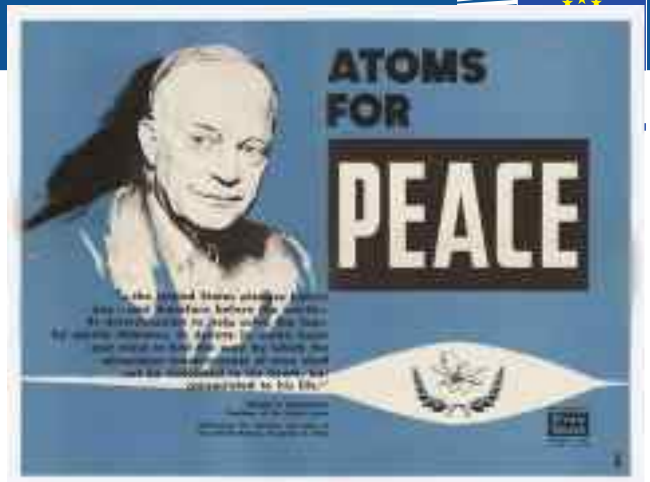
e.g. = no separated plutonium

- Pure Pu-239 (from short term n-irradiation of U-238) can be used as weapon material and should be avoided

Strategy for fast reactors:

- Produce fissile material for power generation which cannot be used for nuclear weapons (contamination with minor actinides)
- developing a closed fuel cycle (see above, under "sustainability")
- operating at a breeding ratio of (near) 1 (no need for an uranium blanket)
- fabricating the fuel so that it is difficult to extract fissile material from spent fuel

"Atoms for Peace" speech to the United Nations
(UN New-York, 8 December 1953)



Former U.S. President Dwight D. Eisenhower, who had been Allied commander-in-**chief during World War II, delivered the famous "**Atoms for Peace**" speech to the United Nations (UN) General Assembly in New** York City on 8 December 1953.

He unveiled a plan to share nuclear energy technology, then a top secret among a handful of countries, with any nation that pledged to use it peacefully. The United States then launched the "Atoms for Peace" program that supplied equipment and information to schools, hospitals, and research institutions within the U.S. and throughout the world.

"To the making of these fateful decisions, the United States pledges before you--and therefore before the world - its determination to help solve the fearful atomic dilemma - to devote its entire heart and mind to find the way by which the miraculous inventiveness of man shall not be dedicated to his death, but consecrated to his life."

https://www.eisenhower.archives.gov/research/online_documents/atoms_for_peace/Binder13.pdf
and http://www.presidency.ucsb.edu/ws/?pid=9774

Atoms for Peace created the ideological background for the creation of the International Atomic Energy Agency (IAEA) and the Treaty on the Non-Proliferation of Nuclear Weapons (NPT).
The NPT is an international treaty whose objective is (1) to prevent the spread of nuclear weapons and weapons technology, (2) to promote cooperation in the peaceful uses of nuclear energy, and (3) to further the goal of achieving nuclear disarmament and general and complete disarmament.
Opened for signature in 1968, the treaty entered into force in 1970. The treaty defines nuclear-weapon states as those that have built and tested a nuclear explosive device before 1 January 1967: these are the United States, Russia, the United Kingdom, France, and China. As of August 2016, 191 states have adhered to the treaty.

Dr. Mohamed ElBaradei, IAEA Director General and Nobel Peace Prize Laureate 2005 together with IAEA

IAEA Nobel Peace Prize Ceremony 2005
10 December 2005 | Oslo, Norway
Both the IAEA and its then Director General, M. ElBaradei, were awarded the Nobel Peace Prize

Three excerpts of the Nobel Lecture

(excerpt 1) "But why has this security so far eluded us?

I believe it is because our security strategies have not yet caught up with the risks we are facing. The globalization that has swept away the barriers to the movement of goods, ideas and people has also swept with it barriers that confined and localized security threats.

A recent United Nations High-Level Panel identified five categories of threats that we face:

- *Poverty, Infectious Disease, and Environmental Degradation;*
- *Armed Conflict - both within and among States;*
- *Organized Crime;*
- *Terrorism; and*
- *Weapons of Mass Destruction.*

These are all "threats without borders" - where traditional notions of national security have become obsolete. We cannot respond to these threats by building more walls, developing bigger weapons, or dispatching more troops. Quite to the contrary. By their very nature, these security threats require primarily multinational cooperation."

(excerpt 2) Consider our development aid record. Last year, the nations of the world spent over $1 trillion on armaments. But we contributed less than 10 per cent of that amount - a mere $80 billion - as official development assistance to the developing parts of the world, where 850 million people suffer from hunger.

"My friend James Morris heads the World Food Programme, whose task it is to feed the hungry. He recently told me, "If I could have just 1 per cent of the money spent on global armaments, no one in this world would go to bed hungry.""

(excerpt 3) "I have no doubt that, if we hope to escape self-destruction, then nuclear weapons should have no place in our collective conscience, and no role in our security.

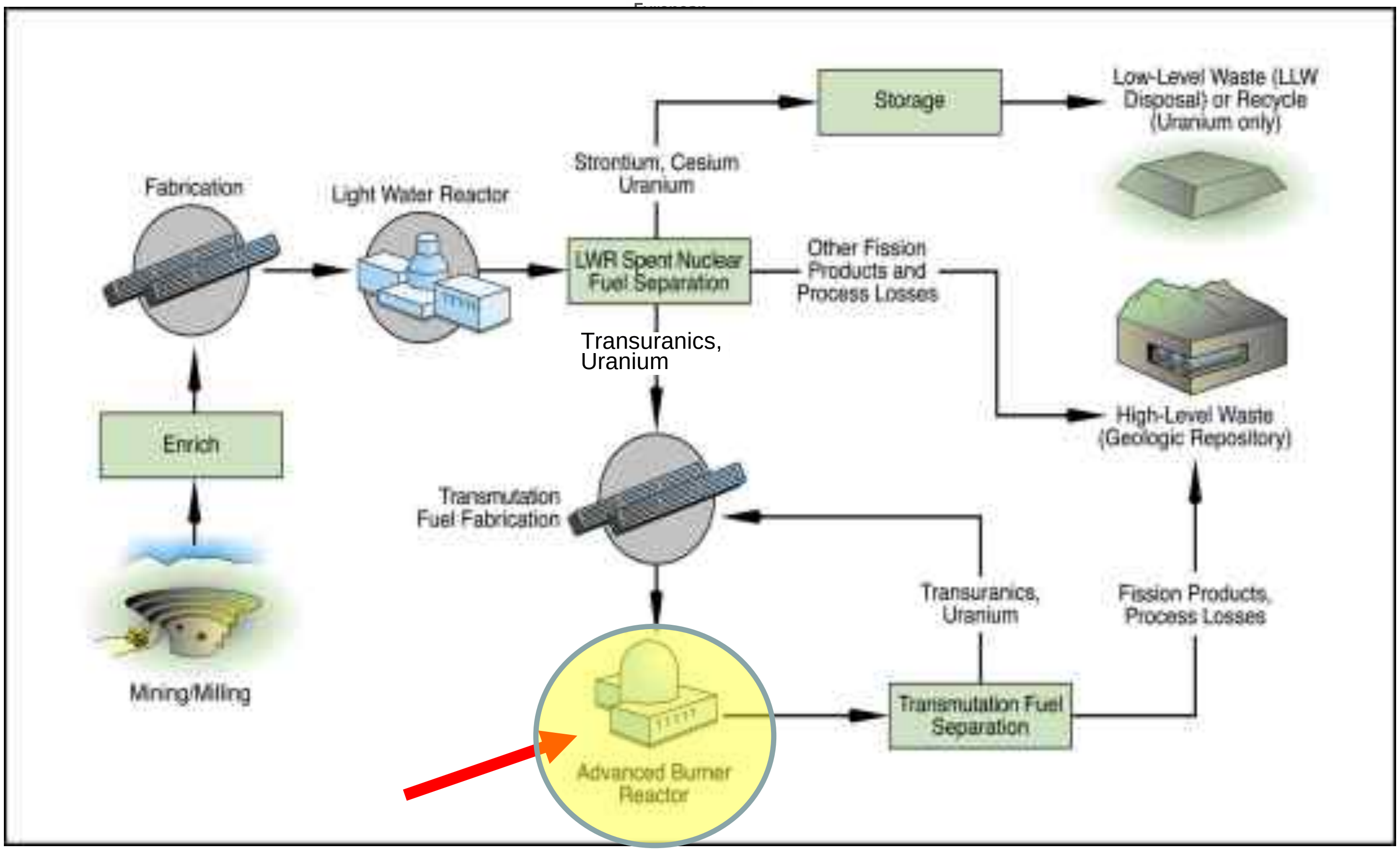
To that end, we must ensure - absolutely - that no more countries acquire these deadly weapons.

We must see to it that nuclear-weapon States take concrete steps towards nuclear disarmament.

And we must put in place a security system that does not rely on nuclear deterrence."

https://www.iaea.org/newscenter/statements/nobel-lecture

Closed Fuel Cycle Strategy : IFNEC (International Framework for Nuclear Energy Cooperation)



=> e.g. recycle used nuclear fuel to minimize waste and reduce proliferation concerns (https://www.ifnec.org/ifnec/)

* 34 Participants: Argentina, Armenia, Australia, Bahrein, Bulgaria, Canada, China, Estonia, France, Germany, Ghana, Hungary, Italy, Japan, Jordan, Kazakhstan, Kenya, Republic of Korea, Kuwait, Lithuania, Morocco, Netherlands, Niger, Oman, Poland, Romania, Russian Federation, Senegal, Sierra Leone, Slovenia, Ukraine, United Arab Emirates, United Kingdom, United States
* 4 Observer Organizations: NEA, IAEA, GIF, Euratom
* 31 Observers: Algeria, Bahrain, Bangladesh, Belgium, Brazil, Chile, Czech Republic, Egypt, Finland, Georgia, Greece, Indonesia, Latvia, Malaysia, Mexico, Mongolia, Nigeria, Philippines, Qatar, Saudi Arabia, Singapore, Slovakia, South Africa, Spain, Sweden, Switzerland, Tanzania, Tunisia, Turkey, Uganda, Vietnam

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The selected six reactor technologies are the subject of further development internationally, with expenditure of about US $ 6 billion over 15 years (2005 – 2020). About 80% of the cost is being met by the USA, Japan and France.

<u>« European Nuclear Education Network Association » (ENEN)</u>

(69 members from 17 EU Member States)

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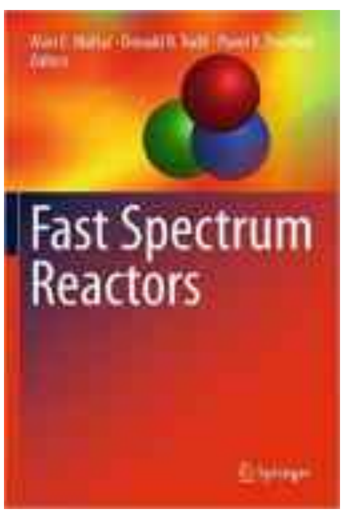
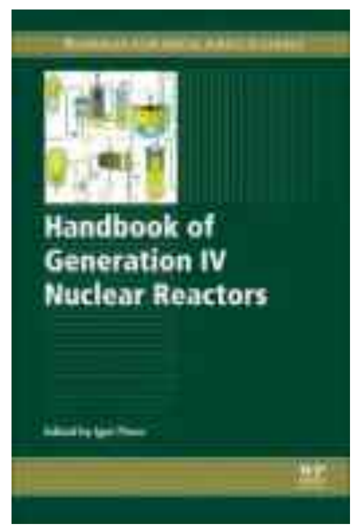
Secretariat e-mail : sec.enen@cea.fr

http://www.enen-assoc.org/en/publications/educational-and-training.html



<u>Fast Spectrum Reactors</u>
Editors: Waltar, Alan E., Todd, Donald R., Tsvetkov, Pavel V. (Eds.), 720 p, Springer 2012

(= update of the classic 1981 <u>FAST BREEDER REACTORS</u> textbook authored by Alan E. Waltar and Albert B. Reynolds)



<u>Handbook of Generation IV Nuclear Reactors</u>

Edited by Igor L. Pioro
Woodhead Publishing
Published Date: 20th June 2016
Page Count: 940

“Les filières à neutrons rapides de 4-e génération” (CEA, déc 2012)

http://www.cea.fr/multimedia/Documents/publications/rapports/rapport-gestion-durable-matieres-nucleaires/Tome%201.pdf

http://www.cea.fr/multimedia/Documents/publications/rapports/rapport-gestion-durable-matieres-nucleaires/Tome%202.pdf

http://www.cea.fr/multimedia/Documents/publications/rapports/rapport-gestion-durable-matieres-nucleaires/Tome%203.pdf

http://www.cea.fr/multimedia/Documents/publications/rapports/rapport-gestion-durable-matieres-nucleaires/Tome%204.pdf

http://www.cea.fr/multimedia/Documents/publications/rapports/rapport-gestion-durable-matieres-nucleaires/Tome%205.pdf

“Sustainable Nuclear Energy Technology Platform”
(SNETP), launched in the EU in September 2007
http://www.snetp.eu/wp-content/uploads/2014/05/esnii-folder-full.pdf

EU Member States contributions to GIF reactor systems

"Review of Generation IV Nuclear Energy Systems", Institut de Radioprotection et de Sûreté Nucléaire (IRSN, i.e.: French Institute for Radiological Protection and Nuclear Safety), April 2015 - http://www.irsn.fr/EN/newsroom/News/Documents/IRSN_Report-GenIV_04-2015.pdf

NB regarding EU collaboration as stated in above figure: Euratom (GIF implementing agent) represents all EU Member States except France, a direct GIF member => French contribution to above EU collaboration listed in other document

Historical Perspective on Reactor Coolants

- In the 1950s and 1960s, scientists and engineers considered (and in many cases built) nearly everything imaginable at the time:

– Water (light, heavy)

– Liquid-metal (NaK, sodium, lithium, mercury, rubidium, lead, bismuth, lead-bismuth, gallium, tin, etc. and numerous other alloys)

– Gas (air, argon, carbon dioxide, helium, hydrogen, nitrogen)

– Fluid Fuel (aqueous: UO2/phosphoric acid, U(SO4)2, UO2SO4/ThO2;molten salt: NaF-BeF2-UF4, LiF-BeF2-ZrF4-UF4/FLiBe; liquid metal: U-Bi)

– Organic (polyphenyls/terphenyls, kerosene, Santowax)

- Combinations of coolant and moderator were also studied:

– Sodium-cooled, graphite moderated (SRE, Hallam)

– Organic-cooled, heavy water moderated (Whiteshell 1, ESSOR)

NB: The Essor (Essai Orgel) test reactor, constructed under the Orgel ("modéré à l'eau lourde et réfrigéré à l'organique") programme, went critical in 1967 at the Euratom JRC site of Ispra (Italy).

Facility	Country	First Critical	Coolant
Clementine	USA	1946	Mercury
EBR-I	USA	1951	NaK
BR-2	Russia	1956	Mercury
BR-5/BR-10	Russia	1958	Sodium
DFR	UK	1959	NaK
Fermi	USA	1963	Sodium
EBR-II	USA	1963	Sodium
Rapsodie	France	1967	Sodium
BOR-60	Russia	1968	Sodium
SEFOR	USA	1969	Sodium
KNK-II	Germany	1972	Sodium
BN-350	Kazakhstan	1972	Sodium
Phenix	France	1973	Sodium
PFR	UK	1974	Sodium
FFTF	USA	1980	Sodium
BN-600	Russia	1980	Sodium
JOYO	Japan	1982	Sodium
FBTR	India	1985	Sodium
Super-Phenix	France	1985	Sodium
MONJU	Japan	1995	Sodium

Data from IAEA Fast Reactor Database. Does not include submarine (S1G/S2G) or space reactors (SNAP).
Source: "Sodium as a Fast Reactor Coolant", U.S. Department of Energy and U.S. Nuclear Regulatory Commission, Topical Seminar Series on Sodium Fast Reactors, ANL, 3 May 2007
- http://www.sustainablees.com/asme/Shanahan_Fast_Reactors_3.pdf

Nuclear projects worldwide vs. GIF systems (non exhaustive) 2016

For further information, 2015 Annual Report - Published in June 2016 and available on GIF website (www.gen-4.org)

GEN-4 system	Canada	China	France	Japan	ROK	Russia	US	EU
SFR		CEFR, CFR-600, CFR-1200	ASTRID (CEA)	JSFR	PGSFR	BN-800, 1200, MBIR	(PRISM), AFR100 TWR (TerraPower)	ESNII/ ESFR
VHTR		HTR-10, HTR-PM		HTTR	NHDD (H_2 prod.)		NGNP, Xe-100	NC2I
GFR							EM²(GA)	ESNII/ ALLEGRO
SCWR	Pressure-tube SCWR	CSR-1000		SCR2000				(HPLWR), NUGENIA/ SCWR-FQT
LFR		CLEAR				BREST-OD-300 SVBR-100	SSTAR, DLFR (Westinghouse)	ESNII/ ALFRED, MYRRHA
MSR		TMSR (SINAP)				MOSART	MCFR (TerraPower) FHR	SAMOFAR

Fast Reactors: recent history (1976 – 2016), under construction and future prospects

- Operable fast reactors (all sodium-cooled): 7 in 1976 ; 11 in 1986 ; 7 in 1996 ; 6 in 2006 ; 6 in 2016
- Fast reactors under construction: CEFR (China) 2008 - 25 MWe / PFBR (India) 2010 - 500 MWe / BN-800 (Russia) – 800 MWe OK Nov 2016
- **China has an ambitious vision to deploy 200 GWe of sodium**-cooled fast breeder reactors by 2050 (12% of projected capacity)

NB: restart of Monju FBR: abandoned in September 2016 by Japanese government (but possible restart of Joyo, shutdown since 2007)

IAEA "International Project on Innovative Nuclear Reactors and Fuel Cycles"

IAEA initiative in the millennium year 2000, focusing more on assessment methodology for developing country needs

Aim: "help ensure that nuclear energy is available to contribute to meeting the energy needs of the 21-st **century in a sustainable manner"**

To achieve this, INPRO involves users as much as technology holders and has 40 countries including several which do not yet have nuclear power. INPRO supports countries as they develop long-range national nuclear energy strategies using INPRO's nuclear energy systems assessment (NESA) and the INPRO Methodology.

In summary, INPRO focuses on the needs of the "end-users" of innovative systems (i.e.: focus on the demand side) while GIF is more concerned with the relevant international Research – Development & Demonstration – Deployment (RD&DD) collaboration (i.e.: focus on the supply side).

INPRO produced in the early 2000's a methodology to assess the sustainability of Innovative Nuclear energy Systems (INS) as part of the general IAEA Nuclear Energy System Assessments (NESA)

= > in 2005, INPRO produced an assessment manual in 9 volumes: an overview volume (no 1), and eight additional volumes (available on the IAEA website) covering the areas of economics (Volume 2), infrastructure (Volume 3), waste management (Volume 4), proliferation resistance (Volume 5), physical protection (Volume 6), environment (Volume 7), safety of reactors (Volume 8), and safety of nuclear fuel cycle facilities (Volume 9).

https://www.iaea.org/INPRO/inpro_methodology/index.html

INPRO's membership consists of 41 Members (as of June 2016) **–** 40 IAEA Member States and the European Commission (EC):
Algeria, Argentina, Armenia, Bangladesh, Belarus, Belgium, Brazil, Bulgaria, Canada, Chile, China, Czech Republic, Egypt, France, Germany, India, Indonesia, Israel, Italy, Japan, Jordan, Kazakhstan, Kenya, Republic of Korea, Malaysia, Morocco, Netherlands, Pakistan, Poland, Romania, Russian Federation, Slovakia, South Africa, Spain, Switzerland, Thailand, Turkey, Ukraine, United States of America, Vietnam and the EC.
Several other countries participate on a working level or as observers in INPRO meetings.

"Modelling Nuclear Energy Systems with MESSAGE: A User's Guide", 2016, IAEA Nuclear Energy Series No. NG-T-5.2
(Assessing nuclear energy transition scenarios requires appropriate modelling tools: IAEA tool MESSAGE = Model for Energy Supply System Alternatives and their General Environmental Impacts)
http://www-pub.iaea.org/books/IAEABooks/10861/Modelling-Nuclear-Energy-Systems-with-MESSAGE-A-User-s-Guide

“Multinational Design Evaluation Program” (MDEP) on the regulatory side

International collaboration in the development of next generation systems was also stimulated on the regulatory side. A number of national regulatory authorities agreed to share the resources and the knowledge accumulated during their assessment of new reactor designs.

= > the Multinational Design Evaluation Program (MDEP) was established in 2006 as a multinational initiative (launched by the US Nuclear Regulatory Commission (NRC) and the French Nuclear Safety Authority (ASN)) to develop innovative approaches to leverage the resources and knowledge of the national regulatory authorities that are currently or will be tasked with the review of new nuclear power reactor designs. The nuclear regulatory authorities of 15 countries participate in MDEP .

MDEP's main objectives can be defined as follows:

- **to enhance multilateral co**-operation within existing regulatory frameworks
- **to encourage multinational convergence of codes, standards and safety goals**
- **to implement the MDEP products in order to facilitate the licensing of new reactors, including those being developed by the** GIF.

The MDEP focusses notably on EPR, AP-1000, APR-1400, VVER and ABWR.

Particular attention is devoted to "common regulatory practices and regulations that enhance safety", in particular in the 3 domains: Digital Instrumentation and Controls; Codes and Standards; Vendor Inspection Co-operation.

Ultimately MDEP aims to develop multinational regulatory standards for design of Generation IV reactors. The US NRC has proposed a three-stage process culminating in international design certification for new reactor types, notably Generation IV types.

As of January 2017, the MDEP members include national regulators from: Canada (CNSC) ; People's Republic of China (NNSA) ; Finland (STUK) ; France (ASN) ; Hungary (OAH) ; India (AERB) ; Japan (NRA) ; Korea (NSSC) ; Russian Federation (Rostechnadzor) ; South Africa (NNR) ; Sweden (SSM) ; Turkey (TAEK) ; United Arab Emirates (FANR) ; United Kingdom (ONR) ; United States (NRC).
The International Atomic Energy Agency (IAEA) also participates in key aspects of MDEP's activities. Other international organisations are also involved such as: the Western European Nuclear Regulators' Association (WENRA) as well as NEA Committees on Nuclear Regulatory Activities (CNRA) and Safety of Nuclear Installations (CSNI). The technical secretariat is with OECD/NEA.

“MDEP 2015-2016 Annual Report”
https://www.oecd-nea.org/mdep/annual-reports/mdep-annual-report-2015.pdf

5.1 Sodium-cooled Fast Reactor (SFR)

electricity production and actinide management (enhanced fuel utilization)

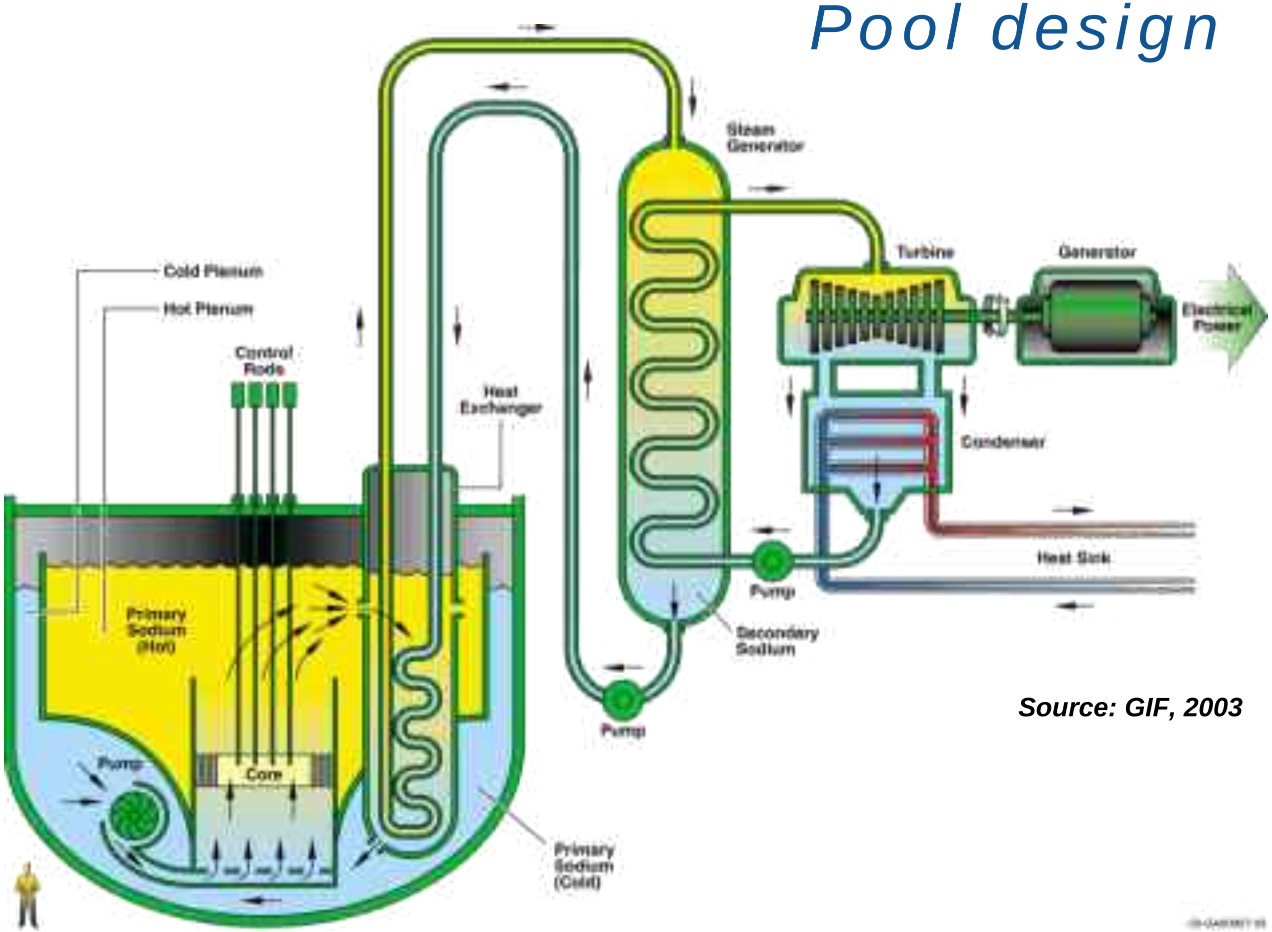
Characteristics

- Coolant Na
- T_{out}: 550°C
- P: 50 – 1500 MWe
- Metallic fuel with pyro-processing or
- MOX fuel with advanced aqueous reprocessing

Advantages

- Waste minimisation and efficient use of the uranium resources

Pool design



Source: GIF, 2003

SFR system latest developments (2016)

<u>Advanced Fast Reactor-100 (AFR, 100 MWe)</u>

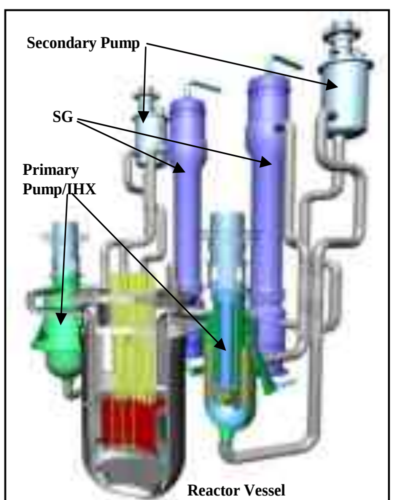
= small modular option (US-DoE) with compact sodium-to-CO2 heat exchanger (supercritical CO2 Brayton cycle power converter)

NB: nitrogen is also investigated – does not chemically interact with sodium

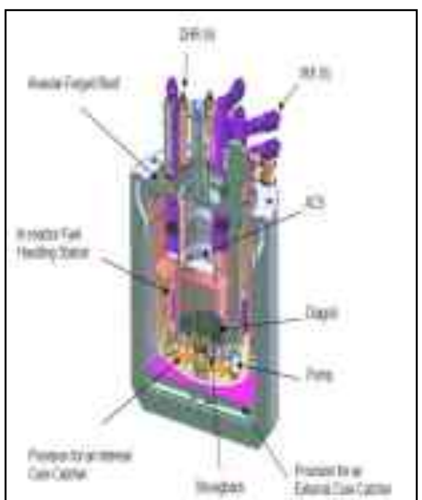
NB: GE-Hitachi PRISM design of 425 MWth **(i.e. "Power Reactor Innovative Small Module")** = underground reactor with a dome over the reactor vessel (based on inherently safe IFR or EBR-2 (1965 – 1995), US-DoE ANL Idaho National Engineering Laboratory /INEL/ => test of 1986)

<u>Loop</u>

JSFR

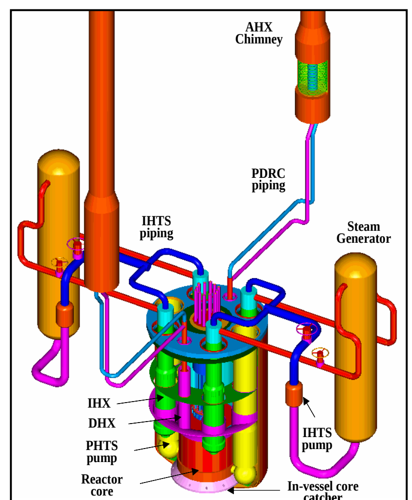


ESFR



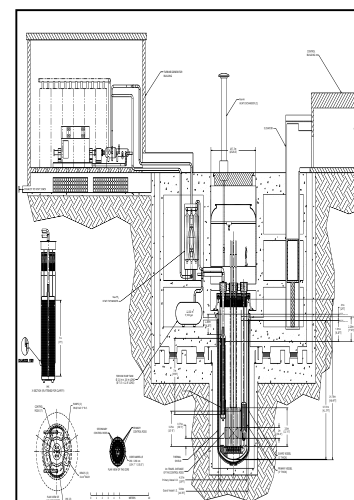
<u>Pool</u>

KALIMER (PGSFR)



<u>Small Modular</u>

SMFR (AFR-100)



Sodium-cooled Fast Reactor: research and innovation

Technological options and progress

* *In service inspection and repair: progress on sensors and repair experience*

* *SC-CO2 Brayton cycle turbine : data all around the critical point*

* *Fuel bearing minor actinides evaluated*

size	fuel matrix	secondary coolants
50-150 MWe	Oxide	Na
300-1500 MWe	Metal	Steam/ Water
600-1500 MWe	Nitride	CO_2

Studies w.r.t. fuel, fuel element, core & fuel cycle

Cores with improved performances

- *Fuel, fuel element and cores with improved physical performances versus :*
  - the energy production;
  - the ultimate waste management – transmutation of minor actinides.
- *Fuel element and cores with improved safety performances where :*
  - the sodium void or other negative effects are balanced by other reactivity feedbacks;
  - the risks of compaction are intrinsically mastered;
  - the performances are improved for managing the fuel dilution, poisoning and relocation in case of fuel element degradation;

Innovative fuels fabricability

- *Advanced (carbide and nitride) MA bearing fuel fabrication and properties for homogeneous recycling of minor actinides*
- *Oxide fuel for heterogeneous MA recycling in ESFR*
- *Nitride and carbide fuel inter comparison, relocation and vaporization behavior*

"Overview of the GIF SFR System Activities", INPRO Dialogue Forum on Generation IV Nuclear Energy Systems, IAEA, Vienna, 13-15 April 2016, Alexander Stanculescu, Director of Nuclear Systems at INL and GIF Technical Director - https://www.iaea.org/INPRO/12th_Dialogue_Forum/023_A._Stanculescu_Overview_of_the_GIF_SFR_System_activities_Compatibility_Mode.pdf

SFR Precursor technologies

Worlwide experience to the end of 2010:
400 reactor-years with fast reactors

<=> 17 000 reactor-years with conventional reactors to the end of 2016 (https://www.iaea.org/pris/)

In USSR / Russia: accumulated operational experience = about 140 reactor-years (1/3 of entire world experience)

NB: by the end of 2010, about 20 FNRs have been operating, some since the 1950s, and some supplying electricity commercially.
In addition, there is considerable experience with lead-bismuth (eutectic) cooled propulsion (submarine) reactors operated in Russia.

BN-600
(1980, Zarechny)

BN-350
(1972-1999, Aktau)

BOR-60
(1969, Dimitrovgrad)

BR-5/10
(1959-2002, Obninsk)

Fast Neutron Reactors

Output	MWe	MW (thermal)	Operation
USA			
EBR 1	0.2		1951-63
EBR 2	20		1963-94
Fermi 1	66		1963-72
SEFOR		20	1969-72
Fast Flux TF		400	1980-93
UK			
Dounreay FR	15		1959-77
Prototype FR	270		1974-94
France			
Rapsodie		40	1966-82
Phenix*	250		1973-
Superphenix 1	1240		1985-98
Germany			
KNK 2	21		1977-91
India			
FBTR		40	1985-
Japan			
Joyo		140	1978-
Monju	280		1994-96-?
Kazakhstan			
BN 350*	135		1972-99
Russia			
BR 5 /10		5 /10	1959-71, 1973-
BOR 60	12		1969-
BN 600*	560		1980-

In France:
Accumulated experience
– about 65 reactor-years

(http://www.igorr.com/home/liblocal/docs/Proceeding/Meeting%2011/Guidez.pdf)

Phénix
(1973-2009, Marcoule)

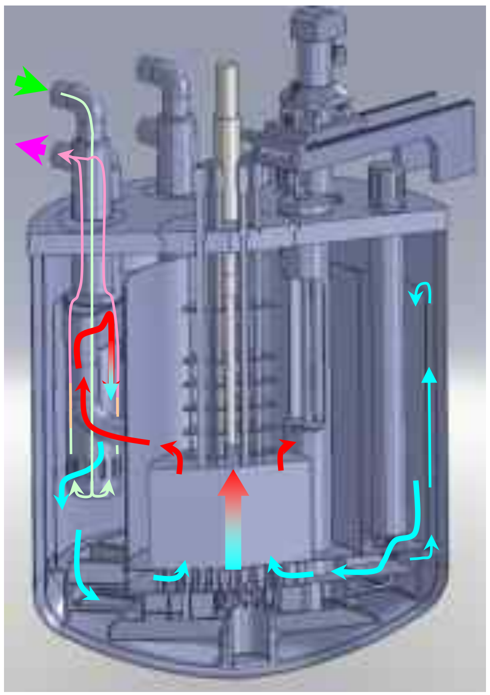
Superphénix
(1985-1997, Creys-Malville)

SFR System Options

- Sodium core outlet temperature 500 – 550 °C
- Large size (600 – 1500 MWe): JSFR (JP)
  - Loop concept
  - MOX (MOX + MA)
- Intermediate – large size (300 – 1500 MWe): ESFR (EU), KALIMER (KR), BN-1200 (RU, new SFR design track in 2016)
  - Pool concept
  - Oxide or metal fuel
- Small size (50 – 150 MWe): AFR-100 (US), replaces SMFR in 2016
  - Modular type
  - U-Pu-MA-Zr metal fuel, integrated pyro-metallurgical processing facility

"Overview of the GIF SFR System Activities", INPRO Dialogue Forum on Generation IV Nuclear Energy Systems, IAEA, Vienna, 13-15 April 2016, Alexander Stanculescu, Director of Nuclear Systems at INL and GIF Technical Director - https://www.iaea.org/INPRO/12th_Dialogue_Forum/023_A._Stanculescu_Overview_of_the_GIF_SFR_System_activities_Compatibility_Mode.pdf

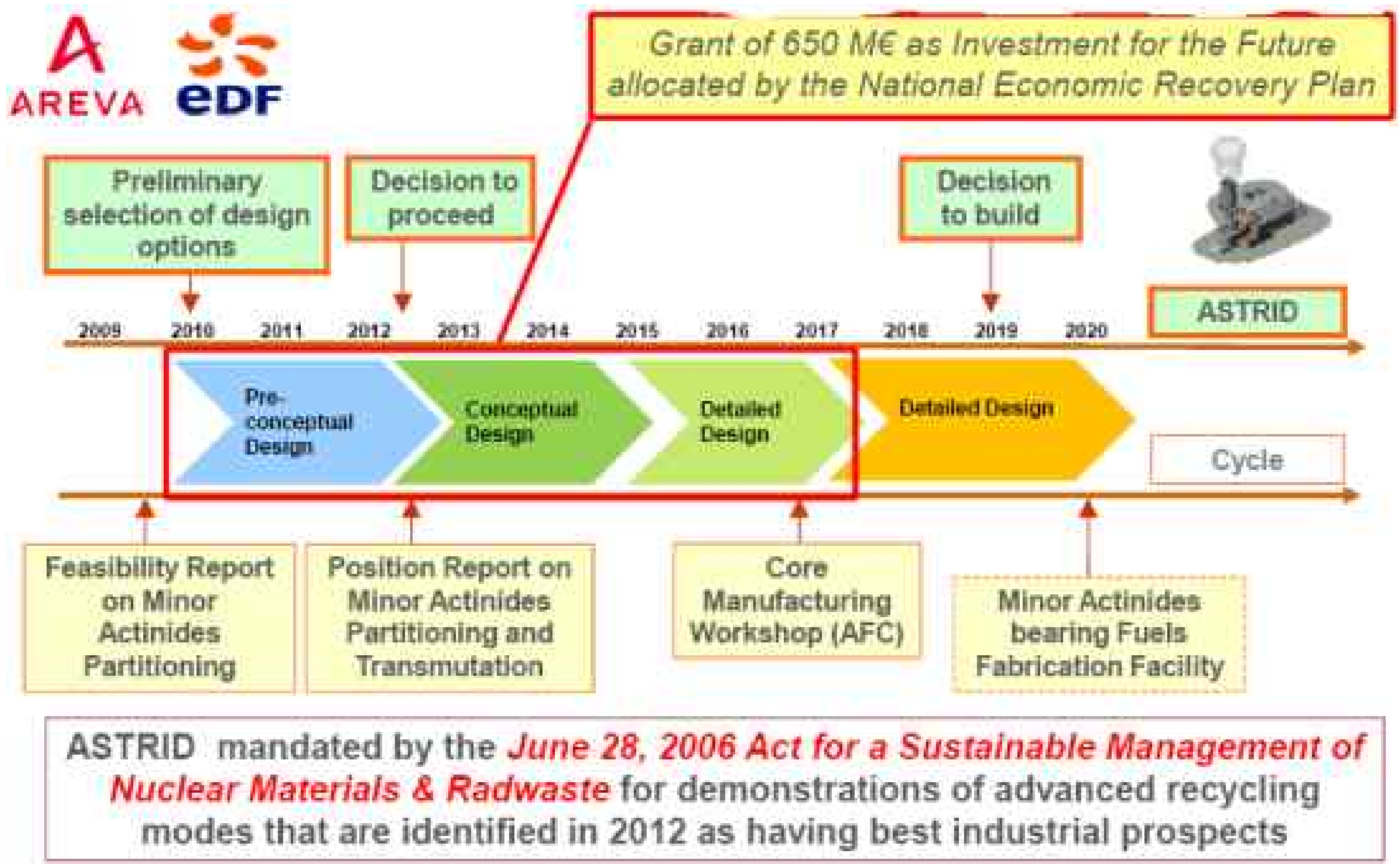
Advanced Sodium Technological Reactor for Industrial Demonstration (600 MWe)



Pre-conceptual study by AREVA

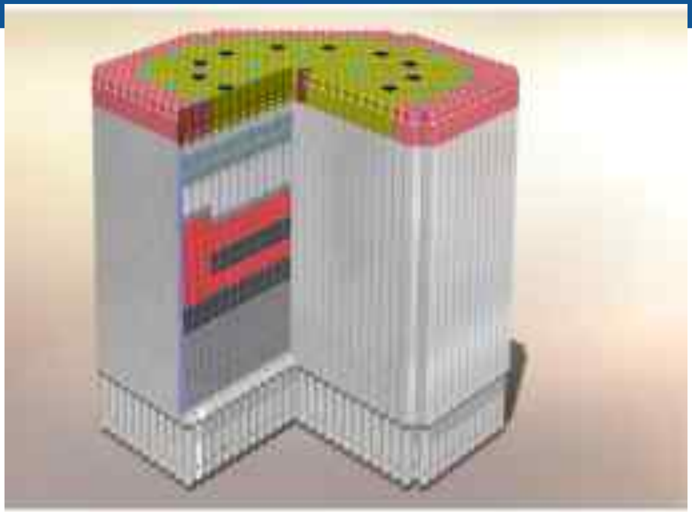
- French government (CEA) led project : national loan 650 M€
- Industry participation
  - ➔ EDF operations feedback from previous reactors, utility requirements and design, safety
  - ➔ AREVA : from pre-conceptual to detailed design studies for the Nuclear Steam Supply System
  - ➔ Other industrial partners are invited by CEA
- Current project phase
  - ➔ design choices to move from pre-conceptual design to conceptual design coupled to ongoing R&D and
  - ➔ discuss with the regulator the safety orientations (2012)
  - ➔ Euratom FP7 and Horizon-2020 support with important contribution from industrial partners

TIME LINE FOR THE NEXT GENERATION SODIUM FAST REACTOR

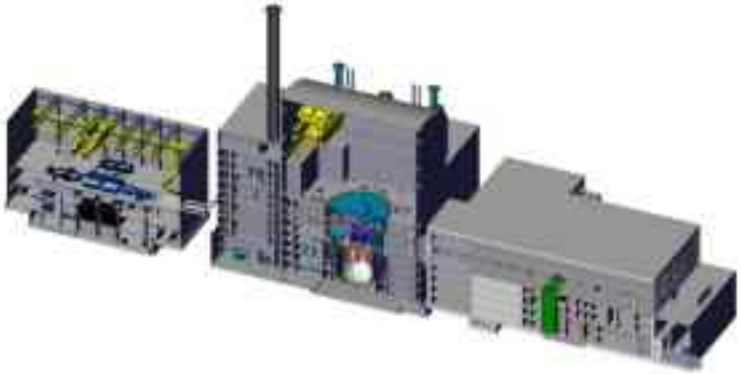


Source: LOW CARBON COMPETITIVE ENERGY SUPPLY - FRANCE's PERSPECTIVE, Frank CARRE (SET-Plan Conference 2013, May 7-8, 2013)

= > CFV: Cœur à Faible effet de Vidange sodium < =



Cœur d'Astrid à Faible effet de réactivité en cas de Vidange (CFV) du sodium (vue en coupe - CEA, breveté en 2010)



Vue globale du démonstrateur technologique Astrid

Nucléaire du futur / CEA (70 ans) - Publié le 23 septembre 2015
http://www.cea.fr/70ans/Pages/innover-pour-demain/nucleaire-du-futur.aspx

Pour obtenir un effet négatif – voire faible – **sur la réactivité, le CEA a développé avec ses partenaires un cœur dont le princip**e est **d'amplifier la composante de fuite, grâce à la combinaison de plusieurs dispositions géométriques :**

- **la réduction de la proportion volumique du sodium dans le cœur, obtenue en diminuant le diamètre du fil espaceur situé entre** les aiguilles de combustible ;
- **le concept de plénum sodium, qui se matérialise sous la forme d'une cavité remplie de sodium et placée au-**dessus du faisceau **d'aiguilles, à l'intérieur des assemblages combustibles (ce plénum, en situation vidangée, favorise la fuite des neutrons hor**s du **cœur) ;**
- **Le concept d'un cœur à géométrie hétérogène, avec une plaque non fissile placée à environ mi-hauteur du cœur ;**
- **le concept de cœur « en creuset », dans lequel la différence de hauteur des zones fissiles interne et externe augmente l'eff**et de fuite **des neutrons du plénum et contrebalance ainsi l'apport de réactivité en cas de vidange.**

Les développements réalisés se sont appuyés sur les résultats d'études expérimentales et de simulations numériques. Pour maîtriser la **spécificité du cœur CFV et certifier les calculs, plusieurs programmes ont été menés par les équipes du CEA. Il s'agit en par**ticulier **d'essais effectués en Russie sur un réacteur expérimental et d'analyses comparatives menées indépendamment par le CEA et le D**OE (le Department of Energy des États-**Unis), qui ont toutes les deux confirmé les performances de ce cœur.**

5.2 Lead-cooled Fast Reactor (LFR)

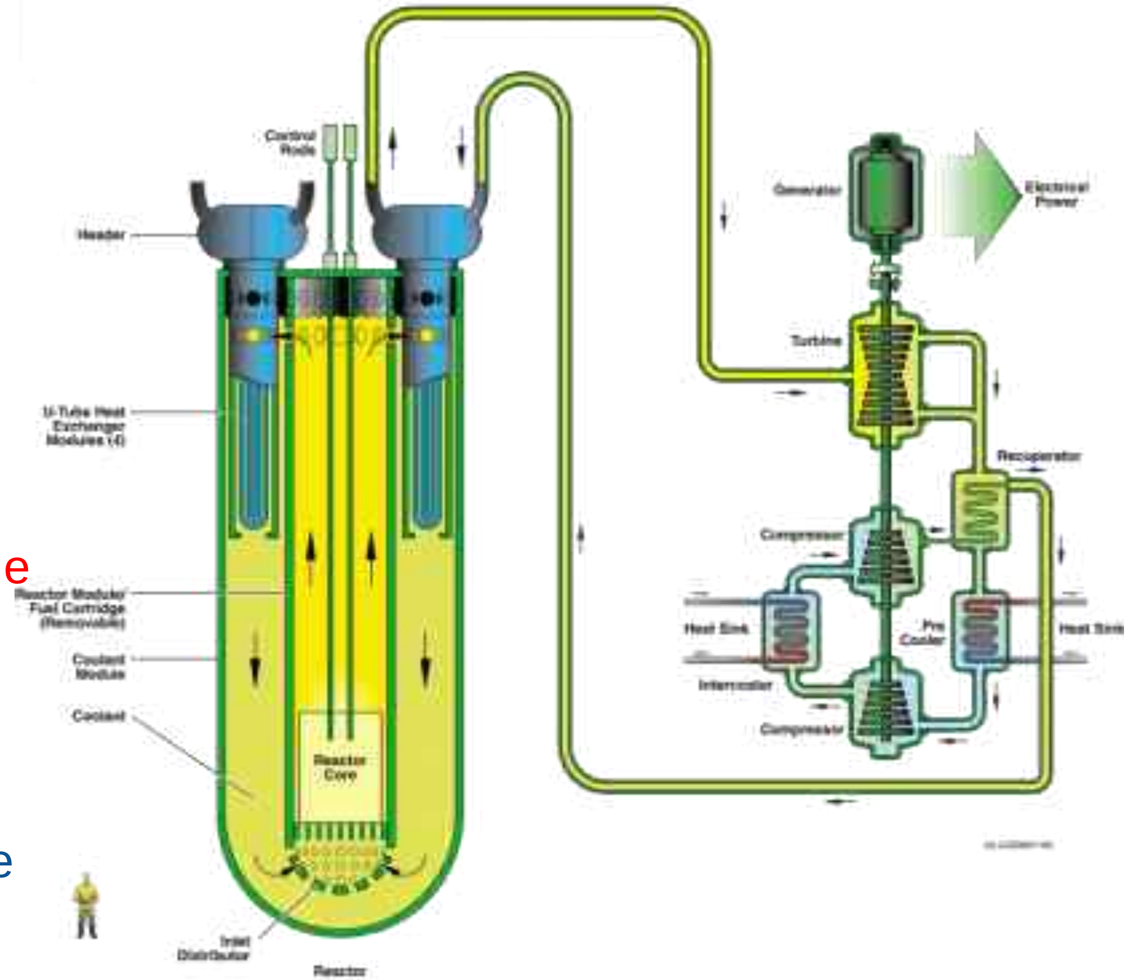
cogeneration of heat and electricity (full actinide management)

Characteristics

- Coolant Pb or Pb/Bi
- T_{out}: 550 - 800°C
- P: 50 - 1200 MWe
- Lifetime 15–30 years
- Cartridge core for regional reprocessing

Advantages

- Proliferation resistance of the long-living core
- Distributed electricity generation
- Hydrogen production
- High degree of passive safety



Source: GIF, 2003

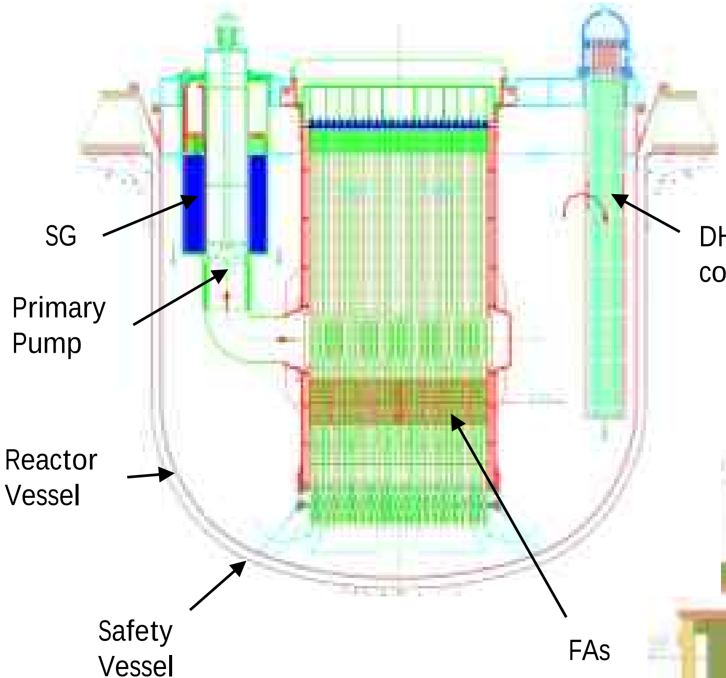
GIF–LFR REFERENCE SYSTEMS

Three reference systems for GIF–LFR activities:

ELFR (600 MWe), BREST (300 MWe), and SSTAR (small size)

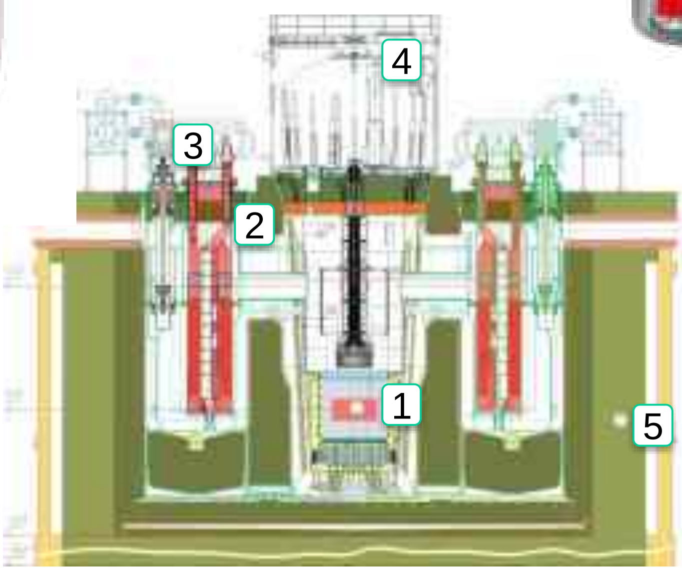
Members of provisional System Steering Committee: **EURATOM, RUSSIA, JAPAN, KOREA**

Observers to pSSC activities: **USA & CHINA**

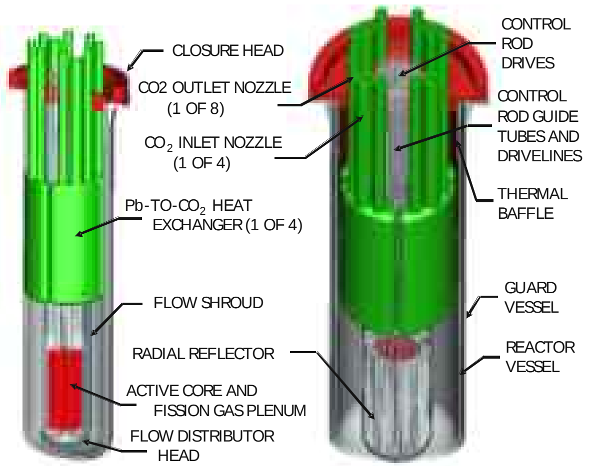


ELFR
system for central station power generation

BREST
system of intermediate size

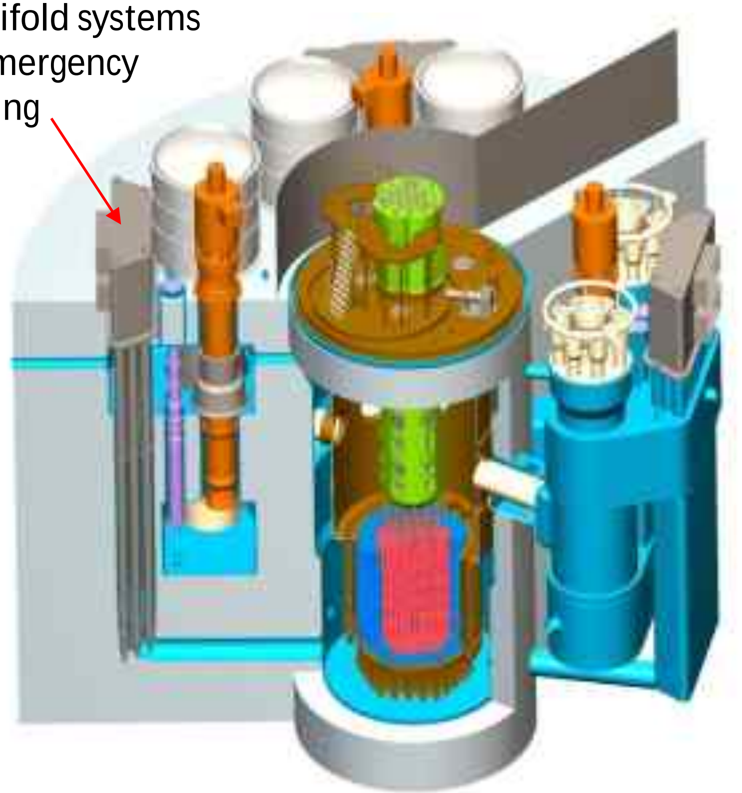


1 - Core
2 - Steam Generator
3 - Pump
4 - Refueling Machine
5 - Reactor Vault



SSTAR
system of small size with long core life

BREST-OD-300: a prototype of commercial LFR units



- Design concept of BREST is based on an **integral primary circuit arrangement combined with a multilayer metal-concrete vessel** to exclude risk for primary coolant losses
- There are no shutoff valves in the primary circuit and **a high degree of natural circulation flow** can be maintained in the primary circuit of BREST during the loss of AC power
- BREST employs **a passive emergency cooling system** with natural circulation and removal of decay heat to the atmospheric air
- The use of highly dense and highly heat-conductive **nitride fuel (NMUP)** allows breeding inside the BREST core (BR~1.05). This limits excess reactivity requirements and excludes risks for severe accidental reactivity insertions. **BREST has capability for transmutation of MAs in closed fuel cycle**

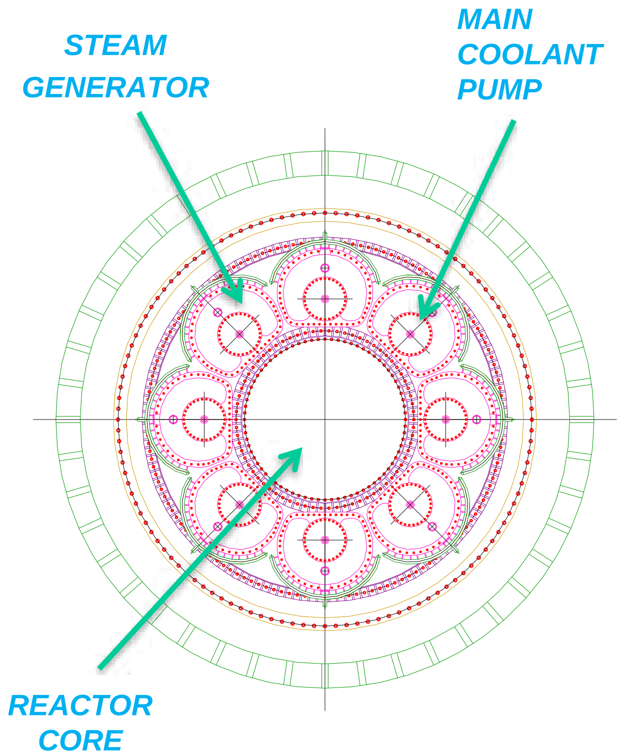
NB: Russia's state nuclear corporation Rosatom will allocate $120m (€113m) in 2017 for a federal R&D project to develop a fast neutron reactor and closed fuel cycle technology. As part of the project, a pilot demonstration power complex (PDPC) with a fast neutron Brest OD-300 reactor and onsite nuclear fuel cycle facilities will be built at the Siberian Chemical Combine (SCC) near the city of Seversk (formerly called Tomsk-7 / perhaps the largest nuclear complex on earth and also one of the oldest), western Siberia, central Russia. The PDPC will be supported by a centre of competence for research and processing of nitride mixed uranium-plutonium (NMUP) fuel.

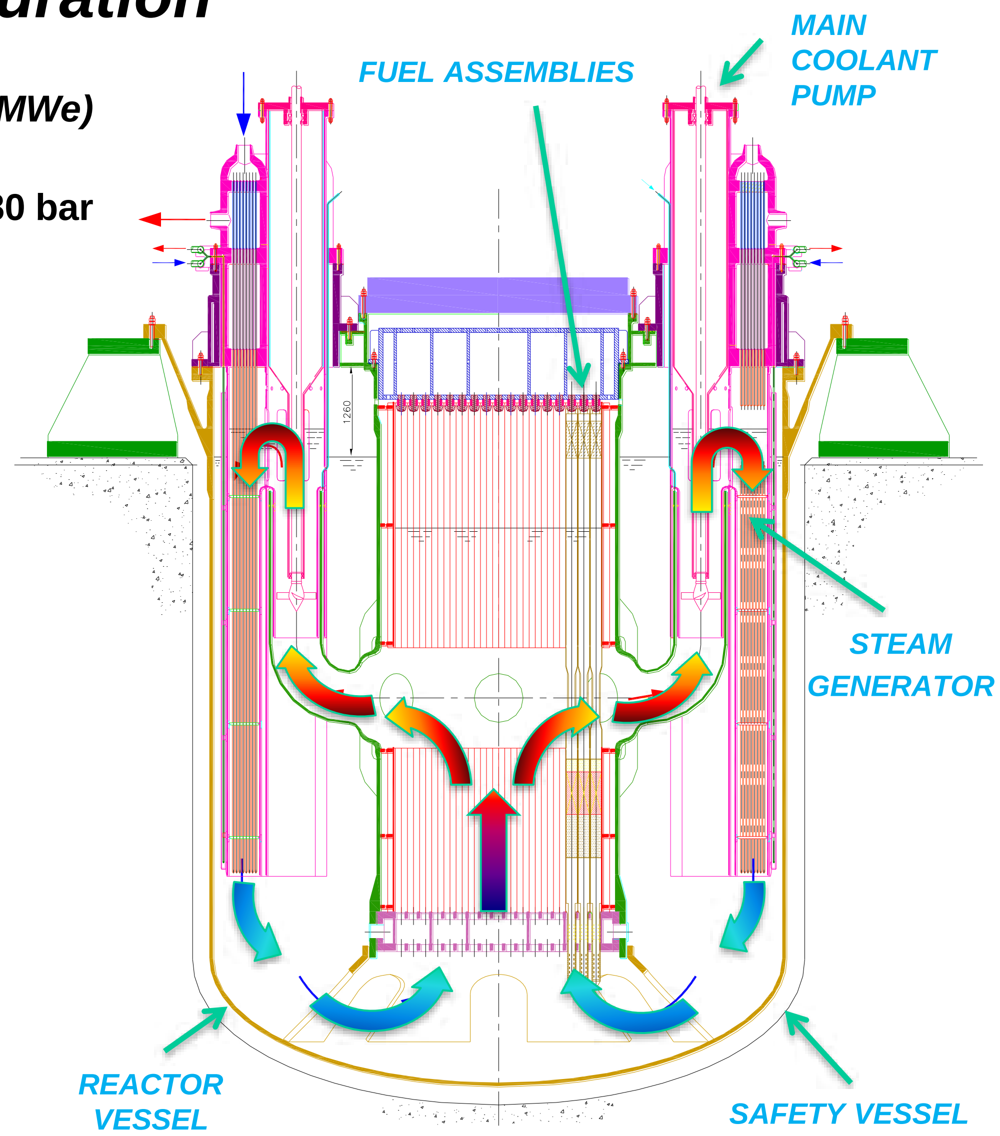
Source: NucNet, 21.02.2017_No37 / News in Brief

"Status of Lead-cooled Fast Reactor Activities in GIF", Euratom GIF Coordination meeting, Brussels, 12 December 2016

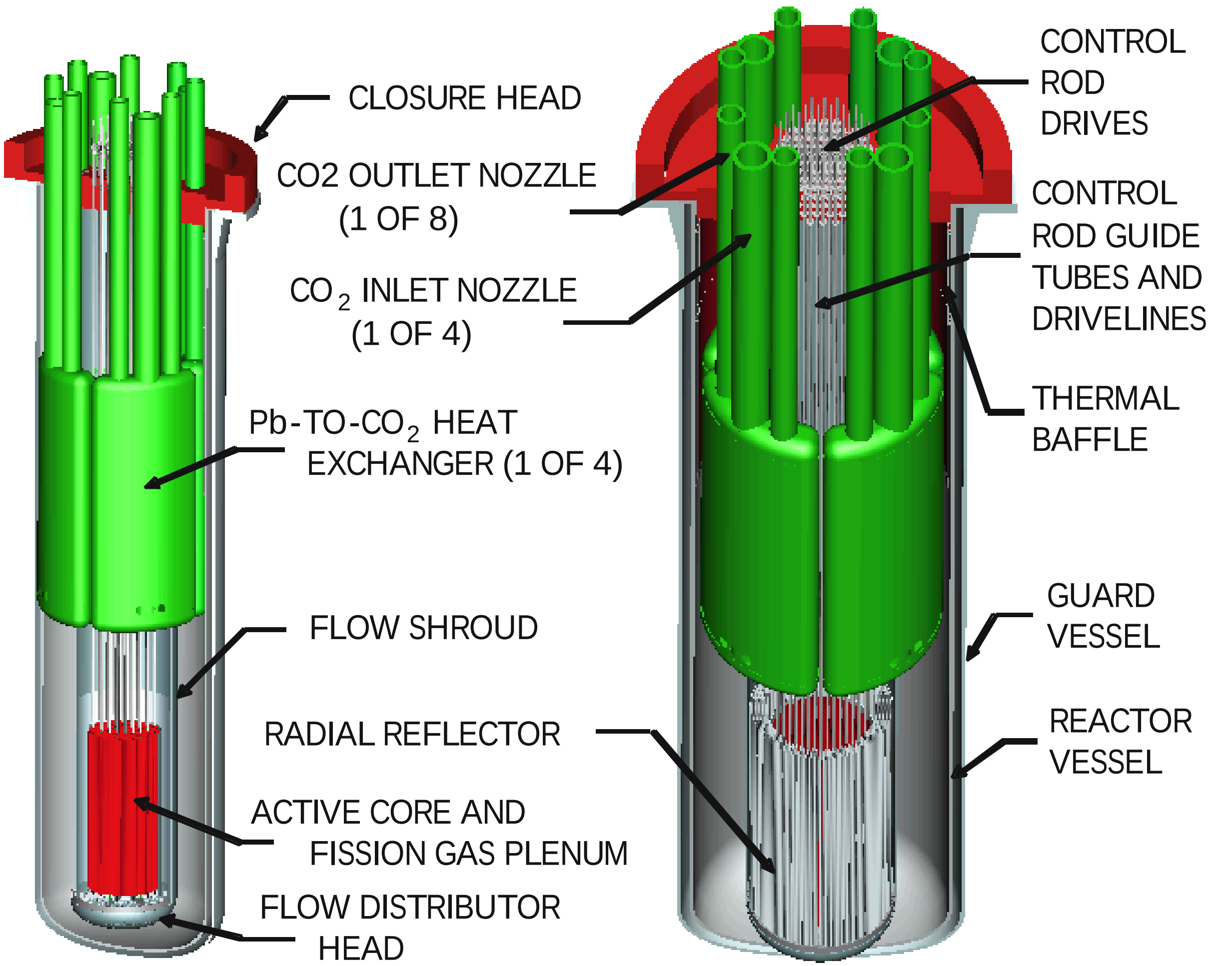
ALFRED: Reactor Configuration

Power:	***300 MWth (125 MWe)***
Primary cycle:	***400 – 480ºC***
Secondary cycle:	***335 – 450ºC*, 180 bar**
(superheated steam)	





Small Secure Transportable Autonomous Reactor (SSTAR)



SSTAR is a small natural circulation fast reactor of 20 MWe/45 MWt, that can be scaled up to 180 MWe/400 MWt.

The compact active core is removed as a single cassette during refueling and replaced by a fresh core.

Source: GIF, 2013

5.3 Gas cooled Fast Reactor (GFR)

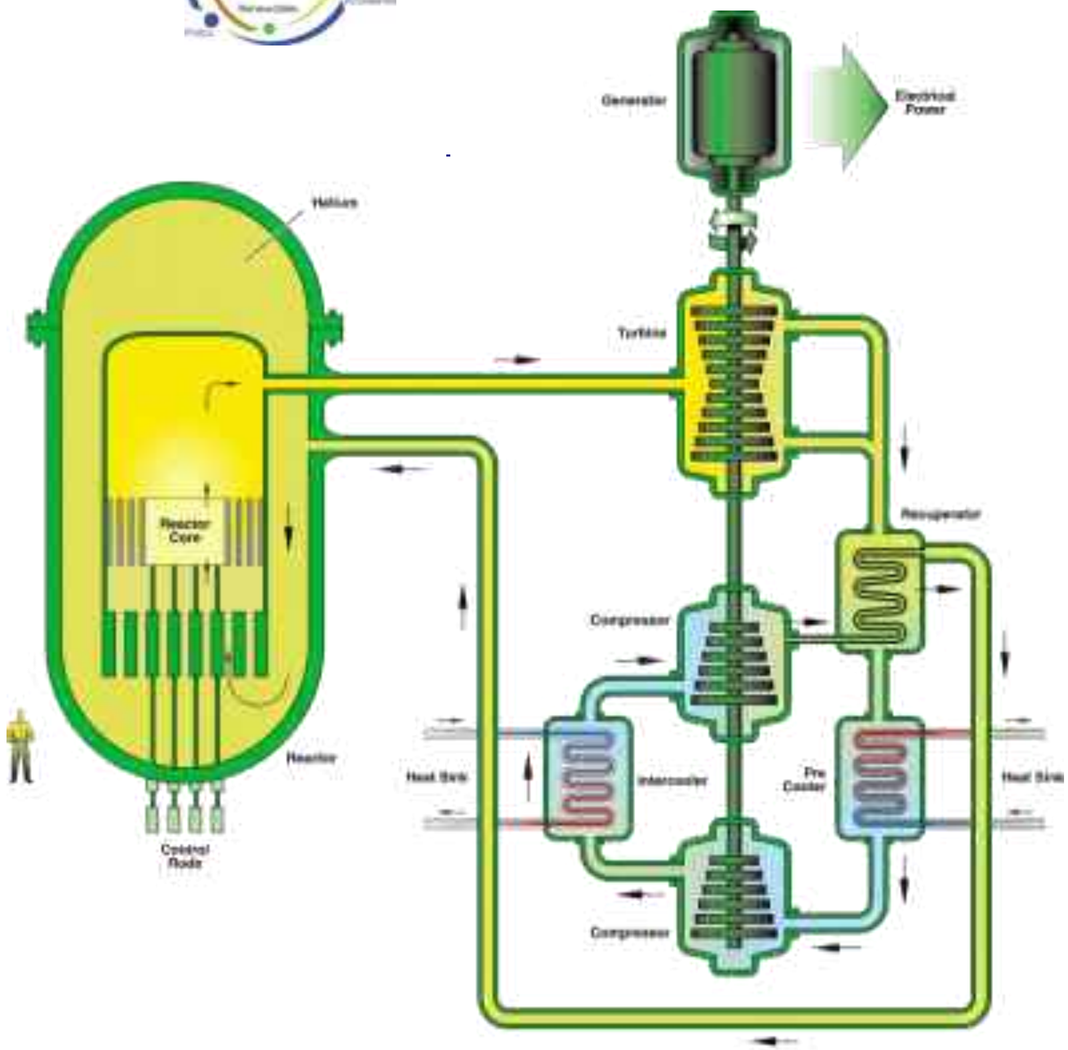
cogeneration of electricity and heat (enhanced fuel utilisation)

Characteristics

- Coolant He
- T_{out}: 850°C
- P: 300 - 600 MWe
- Direct gas turbine cycle

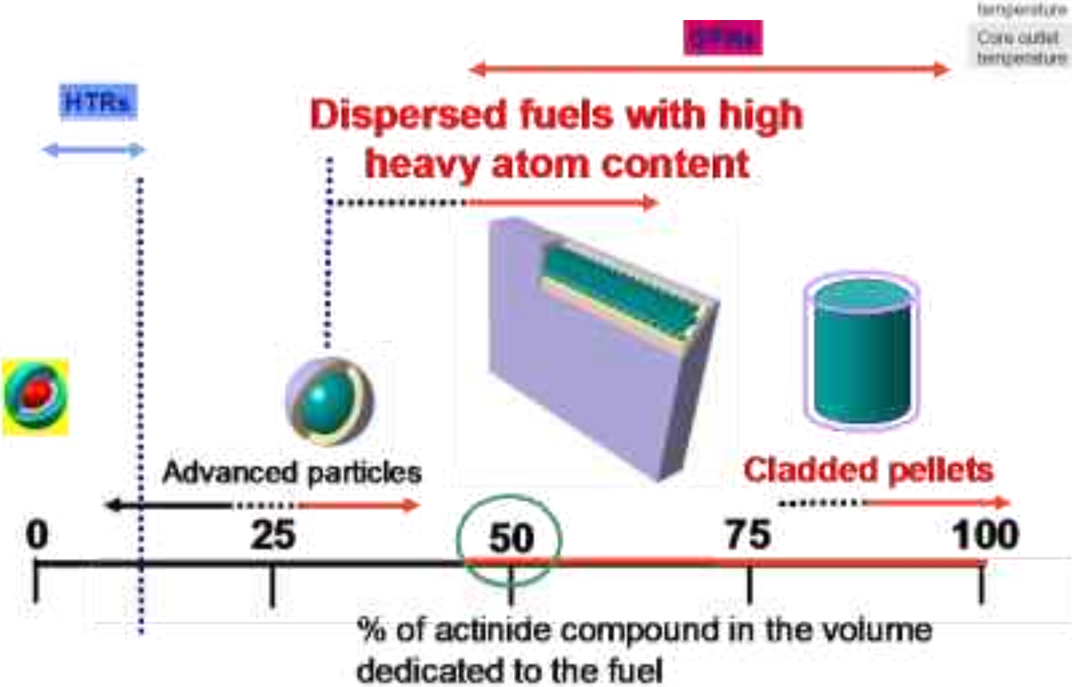
Advantages

- Waste minimisation and efficient use of the uranium resources



Source: GIF, 2003

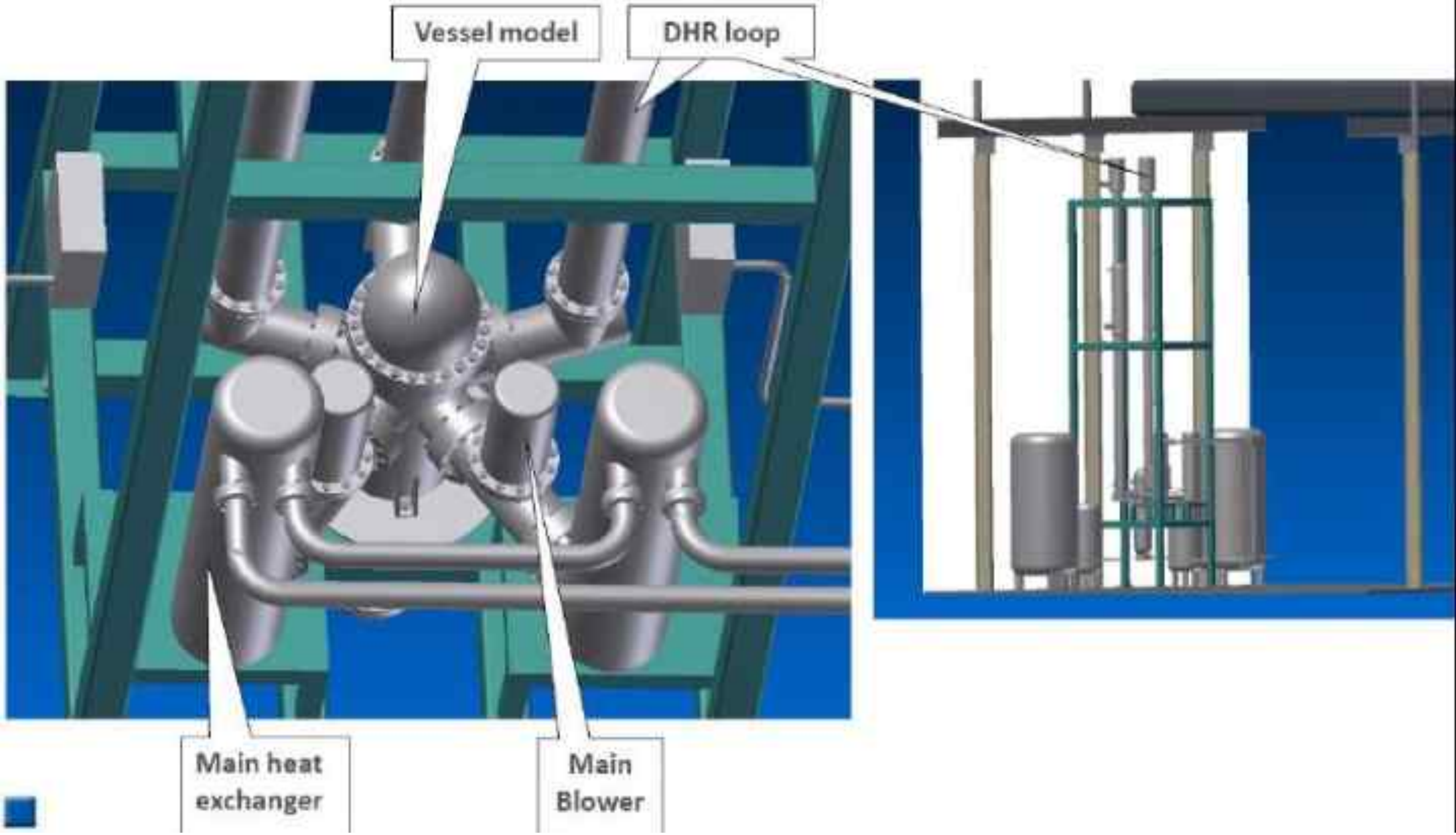
GFR fuel development and ALLEGRO



The greatest challenge facing GFR is the development of high temperature, high rating, high burn-up fuel that has good fission product retention and is tolerant to fault conditions.

“Gas Cooled Fast Reactor”, 10th GIF-INPRO/IAEA Interface Meeting IAEA Headquarters, Vienna. 11-12 April 2016, Branislav Hatala VUJE, a.s., Slovak Republic, (Euratom) - https://www.iaea.org/NuclearPower/Downloadable/Meetings/2016/2016-04-11-04-12-INPRO/014_Gas_Fast_Reactor.pdf

Experimental facility S-ALLEGRO



The experimental facility S-ALLEGRO (1 MW power) is located at Centrum výzkumu **Řež** s.r.o., Czech Republic. It is part of the EU **Project "Sustainable Energy" (SUSEN) under Operation** Programme **"Research and Development for Innovations". This facility will** have two loops for normal operation with heat exchangers and circulators. There will be also three decay heat removal (DHR) loops.

5.4 Very High Temperature Reactor (VHTR)

cogeneration of high temperature heat and electricity (efficiency ~ 50 %)

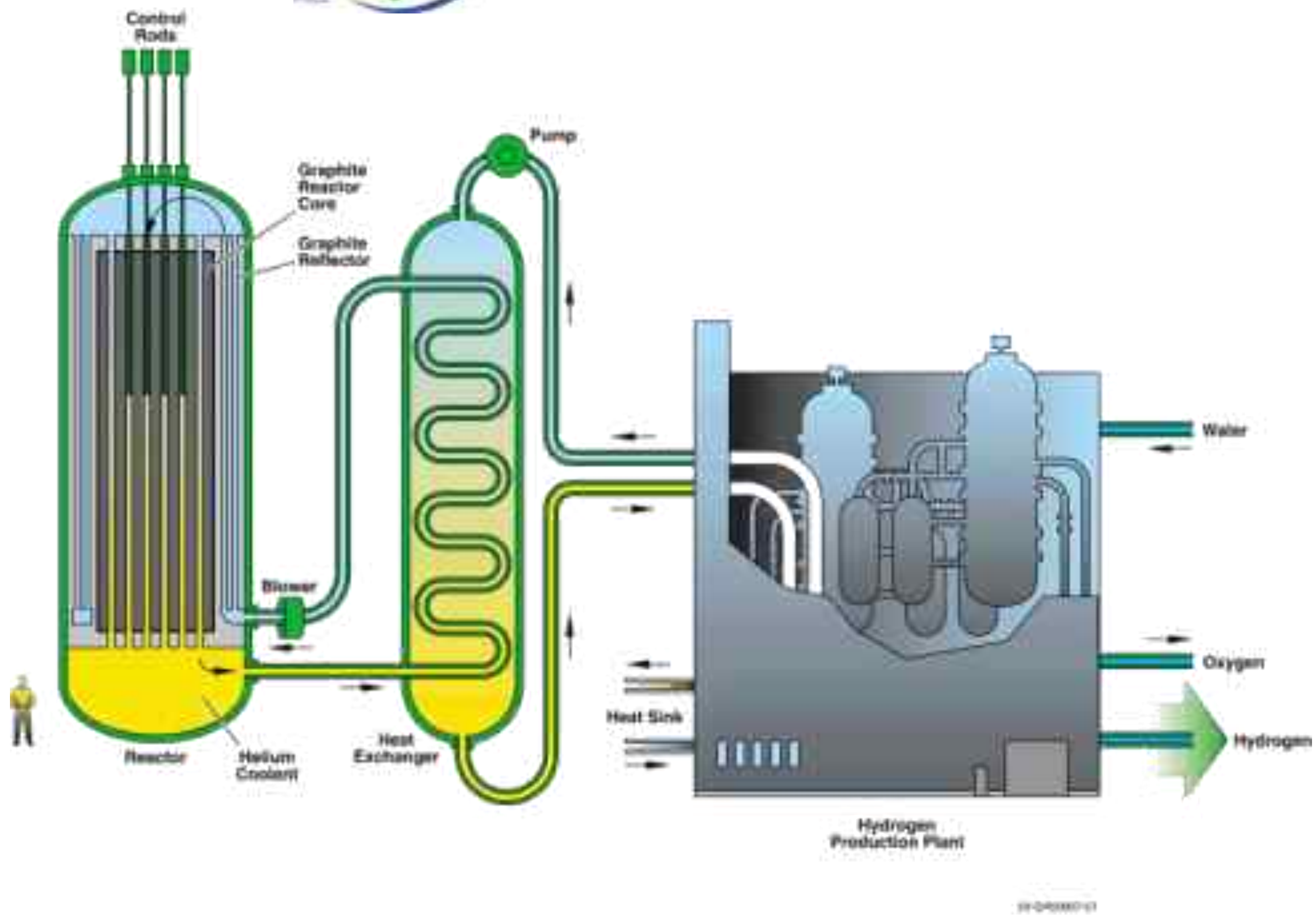
Characteristics

- Coolant He
- T_{out} **≥1000**°C
- P: 600 MWth

Advantages

- Hydrogen production
- High degree of passive safety
- High thermal efficiency
- Process heat applications

=>



Source: GIF, 2003

(Very) High Temperature Reactor System

- Today, mostly modular design with steel vessels, but formerly also pre-stressed concrete vessel (e.g. Fort St Vrain)
- Hex blocks: Fort St Vrain (US), Dragon (UK), HTTR-2000 (J) // pebbles: THTR (DE), AVR (DE), HTR-10 (CN)
- Long-term operating experience up to 950°C (AVR, HTTR)
- Power conversion : either direct (today high-performance He turbines) or indirect (water/steam Brayton cycle)

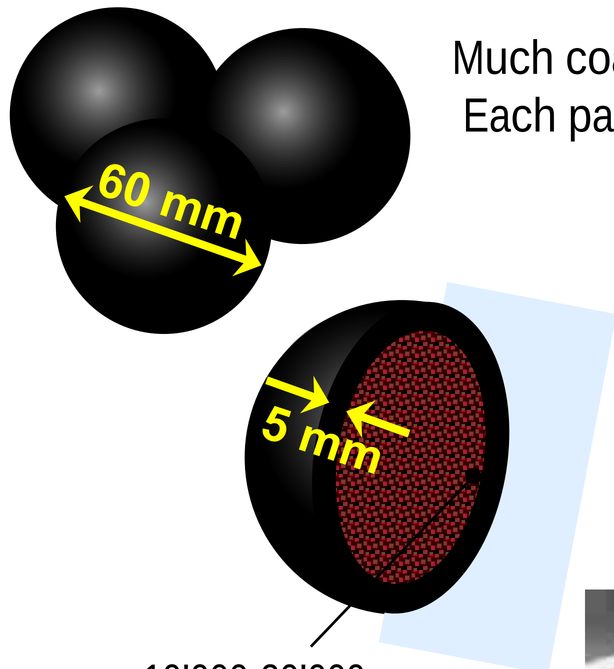
Power Reactors

Research Reactors

	Peach Bottom 1 1966-1974	Fort St Vrain 1976-1989	THTR 1986-1989	Dragon 1966-1975	AVR 1967-1988	HTTR 2000-	HTR-10 2003-
Power Level: MW(t)	115	842	750	20	46	30	10
MW(e)	40	330	300	-	15		–
Coolant: Pressure, Mpa	2.5	4.8	4	2	1.1	4	3
Inlet Temp, °C	344°C	406°C	250°C	350°C	270°C	395°C	250°C/300°C
Outlet Temp, °C	750°C	785°C	750°C	750°C	950°C	850°C/950°C	700°C/900°C
Fuel type	$(U\text{-}Th)C_2$	$(U\text{-}Th)C_2$	$(U\text{-}Th)O_2$	$(U\text{-}Th)C_2$	$(U\text{-}Th)O_2$	$(U\text{-}Th)O_2$	$(U\text{-}Th)O_2$
Peak fuel temp, °C	~1000°C	1260°C	1350°C	~1000°C	1350°C	~1250°C	
Fuel form	Graphite compacts in hollow rods	Graphite Compacts in Hex blocks	Graphite Pebbles	Graphite Hex blocks	Graphite Pebbles	Graphite compacts in Hex blocks	Graphite Pebbles

(V)HTR fuel with coated particles (tristructural-isotropic /TRISO/)

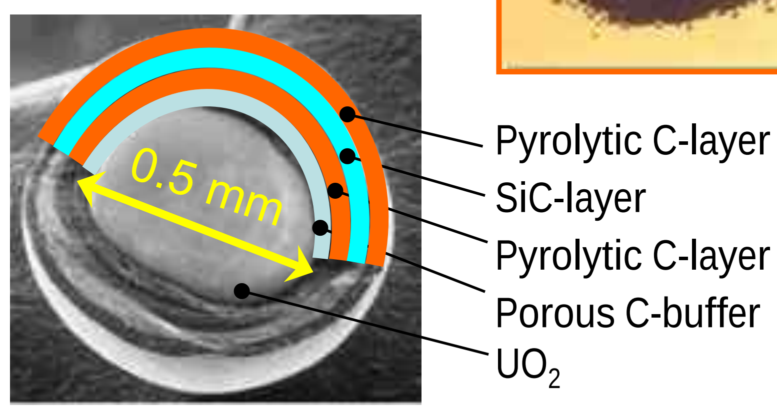
Pebbles



10'000-20'000
TRISO particles
in graphite matrix

Much coating – little fuel, fully confined !
Each particle is a separate containment
(up to 98 MPa)

TRISO



(Very) High Temperature Reactor System

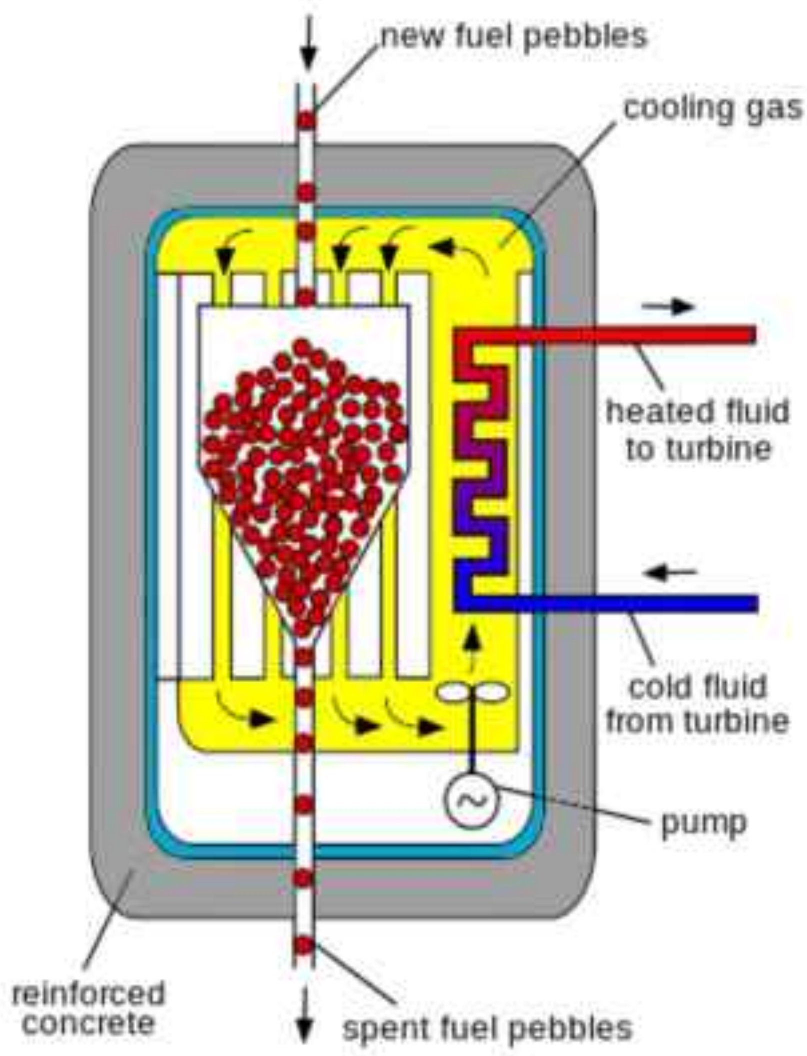
- The AVR reactor was a prototype pebble bed research reactor, located immediately adjacent to Jülich Research Centre in West Germany, constructed in 1960, grid connected in 1967 and shut down in 1988. A consortium of 15 community electric companies owned and operated the plant (AVR in German means "Arbeitsgemeinschaft Versuchsreaktor") . It was a 15MWe, 46 MWt test reactor used to develop and test a variety of fuels (in particular, TRISO pebble fuel) and machinery.

- THTR-300 : thorium high-temperature nuclear power reactor rated at 300 MW electric, located at 50 km NW from Dortmund, Germany. It started operating in 1983, synchronized with the grid in 1985, operated at full power in February 1987 and was shut down in September 1989. It served as a prototype HTR to use the TRISO pebble fuel produced by the AVR.

- The Gas Turbine Modular Helium Reactor (GT-MHR) is under development by a group of Russian enterprises (OKBM Afrikantov, Kurchatov Institute, etc), an American group headed by General Atomics, French AREVA NP and Japanese Fuji Electric. It is a helium cooled, graphite moderated reactor (thermal spectrum, modules of 285 MWe, coolant outlet temperature of 850 ° C), using TRISO fuel compacts in a prismatic core design. The project started in 1995 with the aim to dispose of surplus weapons grade plutonium in Russia.

NB: GT-MHR utilizes the Brayton cycle turbine arrangement (efficiency of up to 48%). This sort of cooling cycle design was enabled by developments in large aviation and industrial turbines along with high-temperature high-strength alloys for the pressure vessels. Commercial light water reactors (LWRs) generally use the Rankine cycle, which is what coal-fired power plants use (average 32% efficiency).

Pebble Bed Reactor scheme

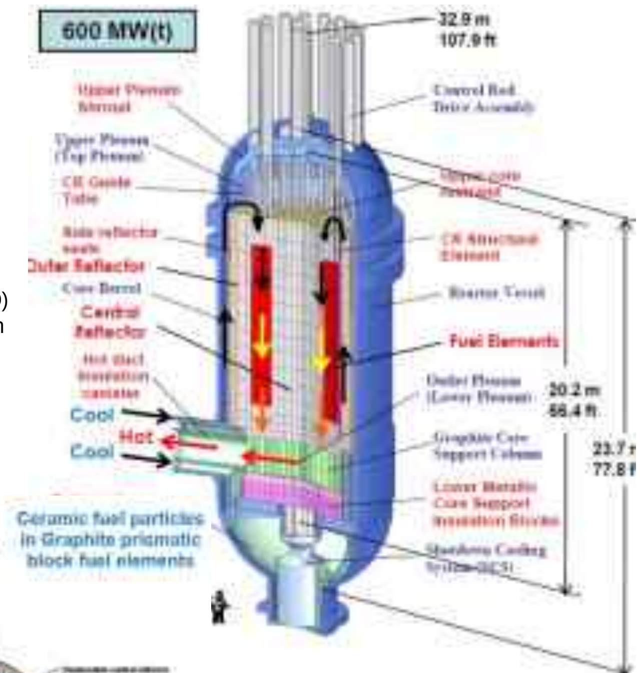


(Very) High Temperature Reactor System

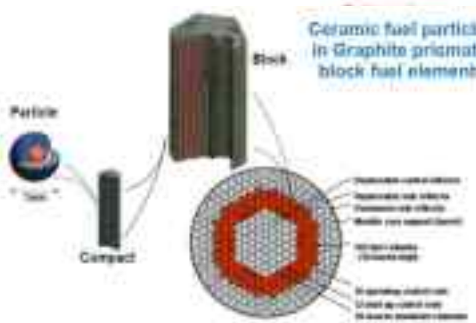
- He-cooled, graphite moderated
- Definition: “high temperature gas reactor” HTGR ≤ 850 C < = > “very high temperature reactor” VHTR > 850 C
- Initially open U fuel cycle, but suitable for Pu and MA burning, deep burn, symbiotic fuel cycles, and (long term) closed Th-U cycle
- Low power density, high thermal inertia → OK for safety

GIF: Two core options, power limited to enable passive decay heat removal

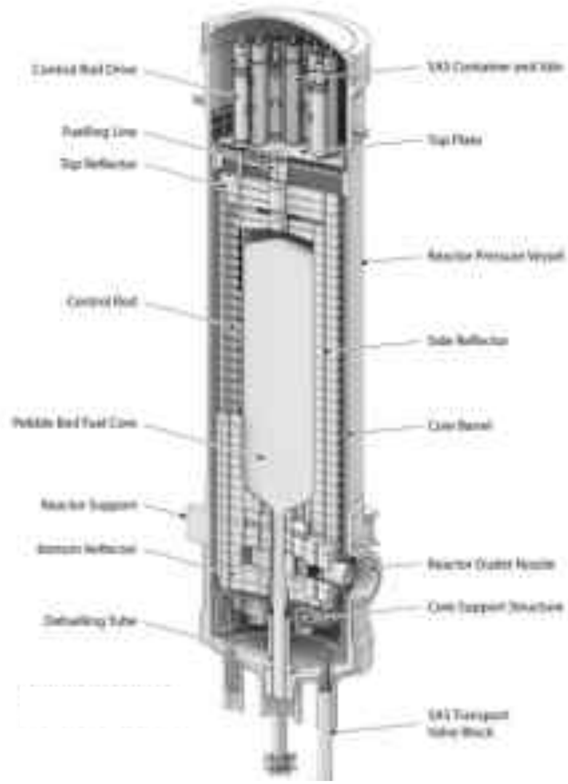
Hexagonal block (< 625 MWth)



The tristructural-isotropic (TRISO) coated particles are embedded in cylindrical compacts of graphite matrix material with a diameter of slightly more than 1 cm, and the compacts are loaded into graphite fuel blocks.



Pebble bed (< 250 MWth)



High-temperature gas-cooled reactors in China: 10 HTR-PM units, each made of two 250 MWth modules, start 2017

Shidao Bay Nuclear Power Plant: ten HTR-PM units of 200 MWe (Rongcheng, Weihai, Shandong, China)

Status : under construction (construction began in December 2012)
Construction cost : US$ 16 billion (units 1–7)
Owner(s): China Huaneng Group Shandong Shidao Bay Nuclear Power Co., Ltd (HSNPC) and Tsinghua University

Nuclear power station - Reactor type :

- HTR-PM (Units under const. 1 × 210 MW and Units planned 9 × **210 MW ("High Temperature Reactor – Pebble Module")**
- **CAP**-1400 PWR (Units planned 2 × 1500 MW

The plant will have the first fourth generation of nuclear reactors in the world: the HTR-PM, a HTGR concept. The plant will ultimately have ten 210 megawatt (MWe) units of these type. Each unit is made of two HTR-PM reactors driving a single 210 megawatt (MWe) steam turbine.

The plant will also host the construction of the two demonstration 1,500 megawatt (MWe) CAP-1400 pressurized water reactor in China, a larger AP-1000 design, worked together by Westinghouse and State Nuclear Power Technology Corporation (SNPTC) and other institutes.

The total investment of 100 billion yuan (US$ 15.7 billion) and the 20 years construction duration makes it China largest planned nuclear project

=> The first HTR-PM unit is scheduled to begin operating later this year (2017). Eighteen further reactors are proposed.

For further information:
https://en.wikipedia.org/wiki/Shidao_Bay_Nuclear_Power_Plant
and CCTV news April 2016 https://www.youtube.com/watch?v=JRCIwSV7NMk
and http://www.sciencedirect.com/science/article/pii/S2095809916301552

Foundation of HTR-PM's conventional island (Sept 2014)

The plant will initially comprise twin HTR-PM reactor modules driving a single 210 MWe steam turbine. The thermal power of a single HTR-PM reactor module is 250 MWth, the helium temperatures at the reactor core inlet / outlet are 250/750 °C, and a steam of 13.25 MPa/567 °C is produced at the steam generator outlet. (http://www.world-nuclear-news.org/NN-China-passes-construction-milestones-1509144.html)

Workers inspect the spherical moderator elements prior to their loading

The first of the graphite moderator spheres was loaded within the reactor's core on 5 April 2017. Ultimately the reactor cavity will be filled with a total of 245 318 elements, to a depth of over 11 meters. (http://www.world-nuclear-news.org/NN-Fuel-loading-starts-at-Chinese-demonstration-HTGR-0704175.html)

5.5 Molten Salt Reactor (MSR)

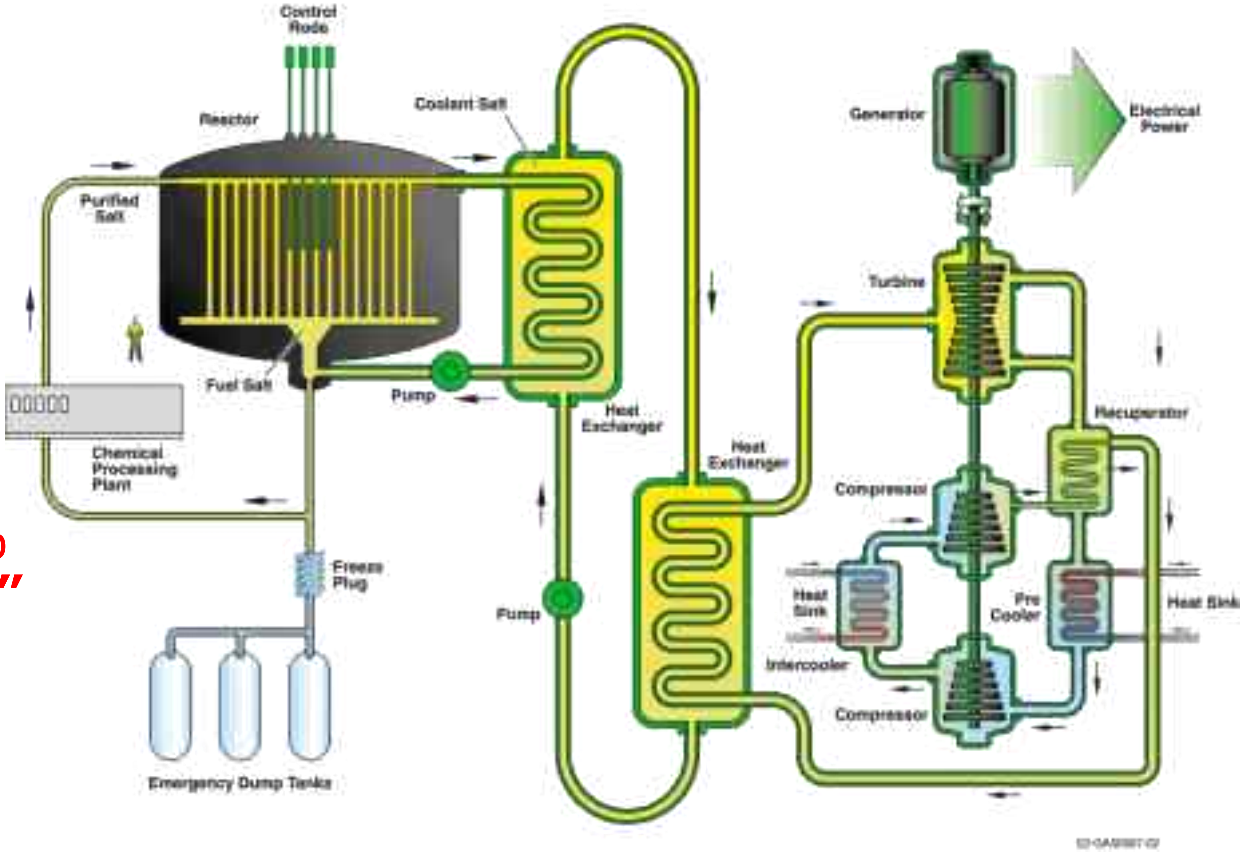
cogeneration of heat and electricity (full actinide management, breeding in Th cycle)

Characteristics

- Fuel / coolant: liquid fluoride salts
- T_{out}: 700 – 800°C
- P: 1000 MWe
- Low pressure (<0.5 MPa)

Advantages

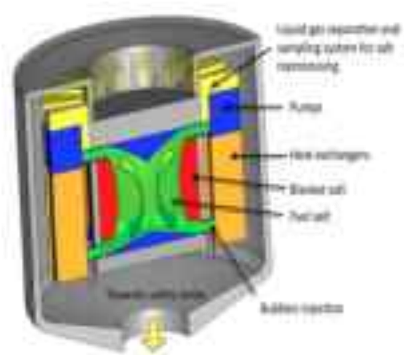
- Transmutation up to **a "ultimate burn-up"**
- Avoidance of fuel development
- Proliferation resistance through low fissile inventory



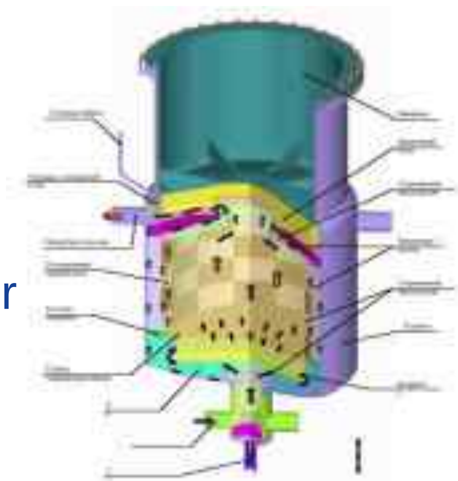
Source: GIF, 2003

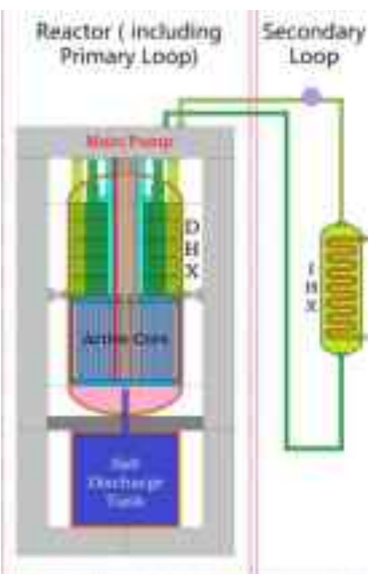
Main MSR concepts studied

European Molten Salt Fast Reactor (MSFR) (2.45 GW_{th})



Molten Salt Actinide Recycler and Transmuter (MOSART)(2.24 GW_{th})

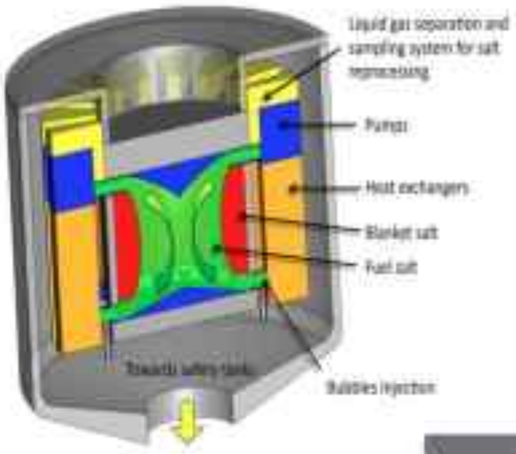


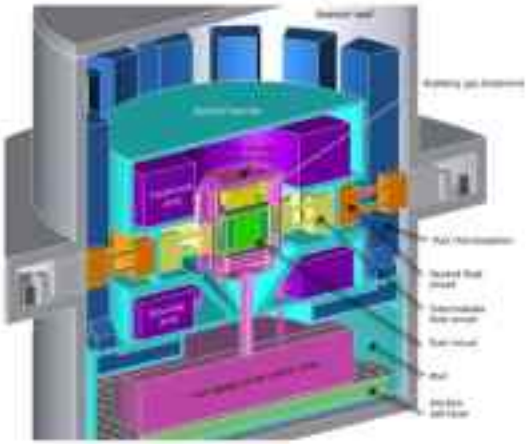


Chinese Thorium-breeding Molten-Salt Reactor (Th-MSR or TMSR) (TMSR-LF2: 373 MW_{th})

MSFR concept - EU

Fuel circuit	MSFR (EU)
Fuel salt, mole %	$78.0LiF\text{-}20.0ThF_4\text{-}2.5UF_4$ $77.5LiF\text{-}6.6ThF_4\text{-}12.3UF_4\text{-}3.6TRUF_3$
Temperature, °C	650 - 750
Core radius / height, m	1.13 / 2.26
Core specific power, W/cm³	270
Container material in fuel circuit	Ni-W alloy EM 721
Removal time for soluble FPs, yrs	1 - 3

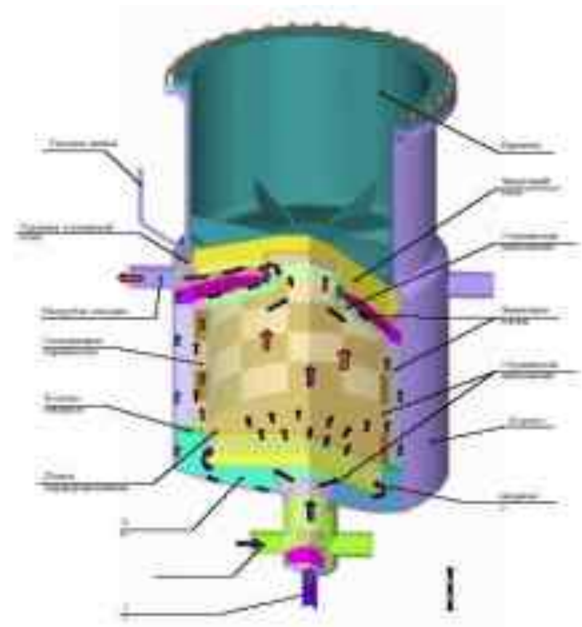




"Status of Molten Salt Reactor Activities in GIF", Euratom GIF Coordination meeting, Brussels, 12 December 2016

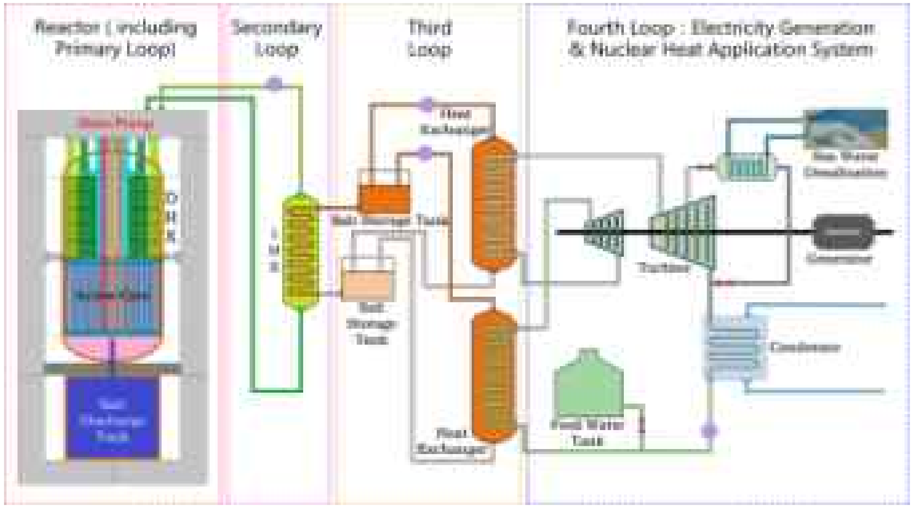
MOSART concept - Russia

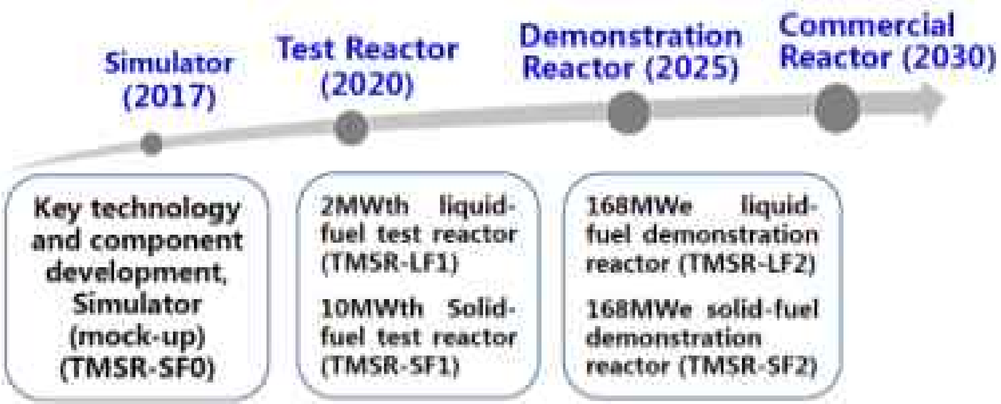
Fuel circuit	**MOSART (RF)**	MSFR (EU)
Fuel salt, mole %	$LiF\text{-}BeF_2 + 1TRUF_3$ $LiF\text{-}BeF_2 + 5ThF_4 + 1UF_4$	$78.0LiF\text{-}20.0ThF_4\text{-}2.5UF_4$ $77.5LiF\text{-}6.6ThF_4\text{-}12.3UF_4\text{-}3.6TRUF_3$
Temperature, ^oC	620 - 720	650 - 750
Core radius / height, m	1.4 / 2.8	1.13 / 2.26
Core specific power, W/cm^3	130	270
Container material in fuel circuit	Ni-Mo alloy HN80MTY	Ni-W alloy EM 721
Removal time for soluble FPs, yrs	1 - 3	1 - 3



TMSR concept - China

Reactor type	Small modular liquid-fueled Molten Salt Reactor
Power of one unit	373MWth / 168 MWe
In / Out temperature	600 / 700 ℃
Generator	Open Air Brayton Cycle & Super CO_2 cycle, et.al
Fuel salts	LiF-BeF_2-UF_4-ThF_4 (19.75% U-235)
Moderator	Graphite
Structural material	Nickel-based alloy , stainless steel
Processing for Fuel cycle	Online degassing (Xe, Kr, T), off-line remove solid fission products
Residual Heat removal	Whole passive residual heat removal system





Start-up companies

moltex energy
safer, cheaper, nuclear

COPENHAGEN ATOMICS

SEABORG

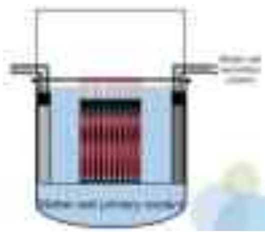


Image courtesy of TerraPower

ONE
TerraPower
Fast
Breeder
Liquid Fuel
Salt Cooled
Uranium
(Could use Th)

$68M funding
(B. Gates)

TWO
Thorcon
Thermal
Burner
Liquid Fuel
Salt Cooled
Thorium

THREE
Terrestrial Energy
Thermal
Burner
Liquid Fuel
Salt Cooled
Uranium
(Could use Th)

FOUR
Flibe Energy
Thermal
Breeder
Liquid Fuel
Salt Cooled
Thorium

FIVE
Transatomic Power
Hybrid
Burner
Liquid Fuel
Salt Cooled
Uranium

SIX
Elysium Industries
Liquid Fuel
Salt Cooled

"Status of Molten Salt Reactor Activities in GIF", Euratom GIF Coordination meeting, Brussels, 12 December 2016

5.6 Super-Critical Water Reactor (SCWR)

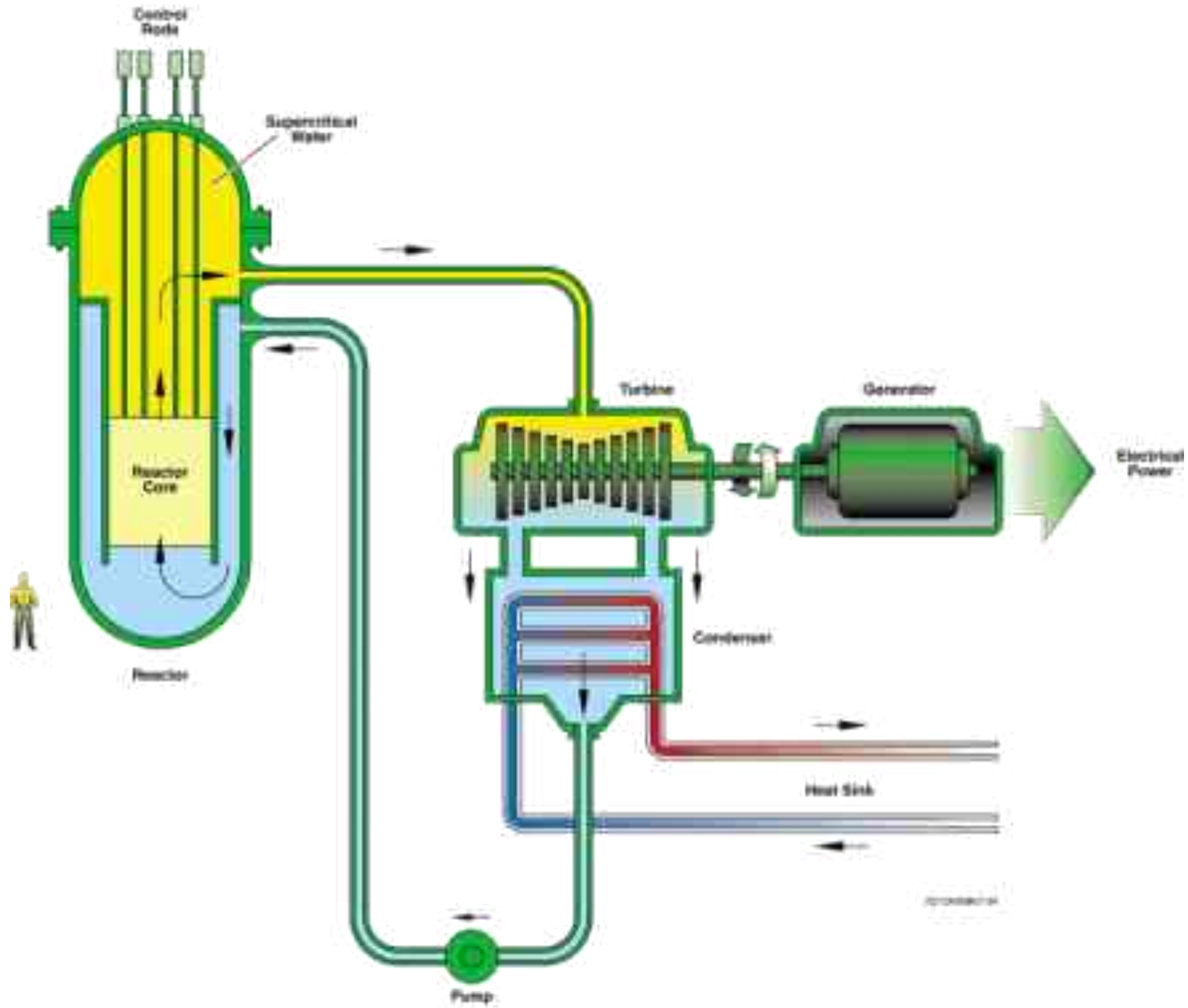
next step in LWR development (improved economics for electricity production)

Characteristics

- Coolant H_2O at super-critical condition
- T_{out}: 550°C
- P: 1700 MWe
- Simplified Balance-of-Plant

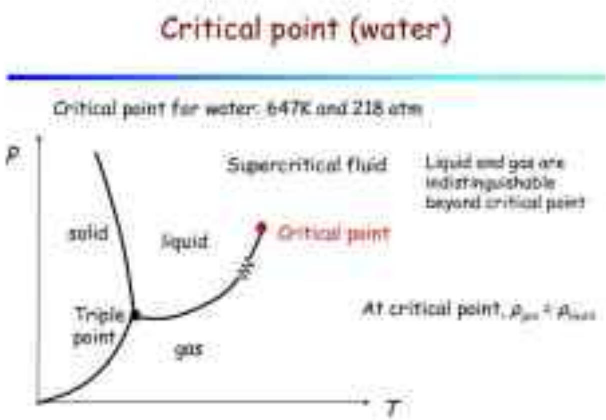
Advantages

- Efficiency almost 45% with excellent economics

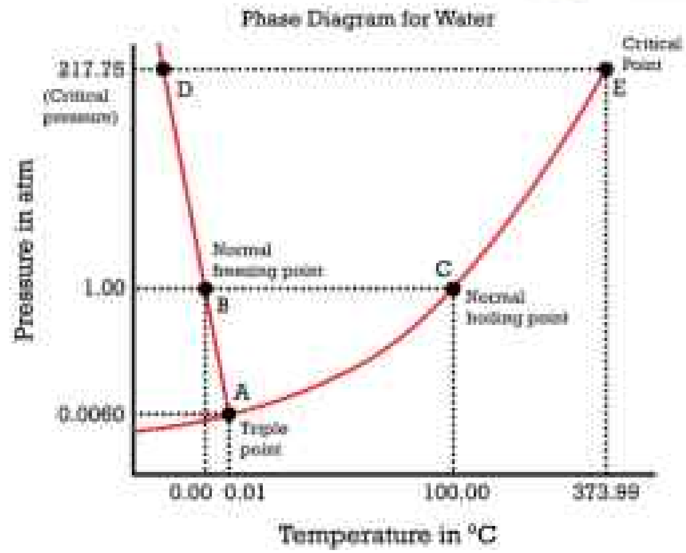


Source: GIF, 2003

Precursor technologies (non-nuclear)



At any temperature higher than the critical point, the gas phase cannot be made to liquefy, no matter how much pressure is applied to the gas.



Yuhuan, China, coal-fired plant with super-critical steam turbines 4 x 1000 MWe, 45% efficiency. NB: supercritical steam is much more efficient at driving the giant turbines that spin the plant's generators.

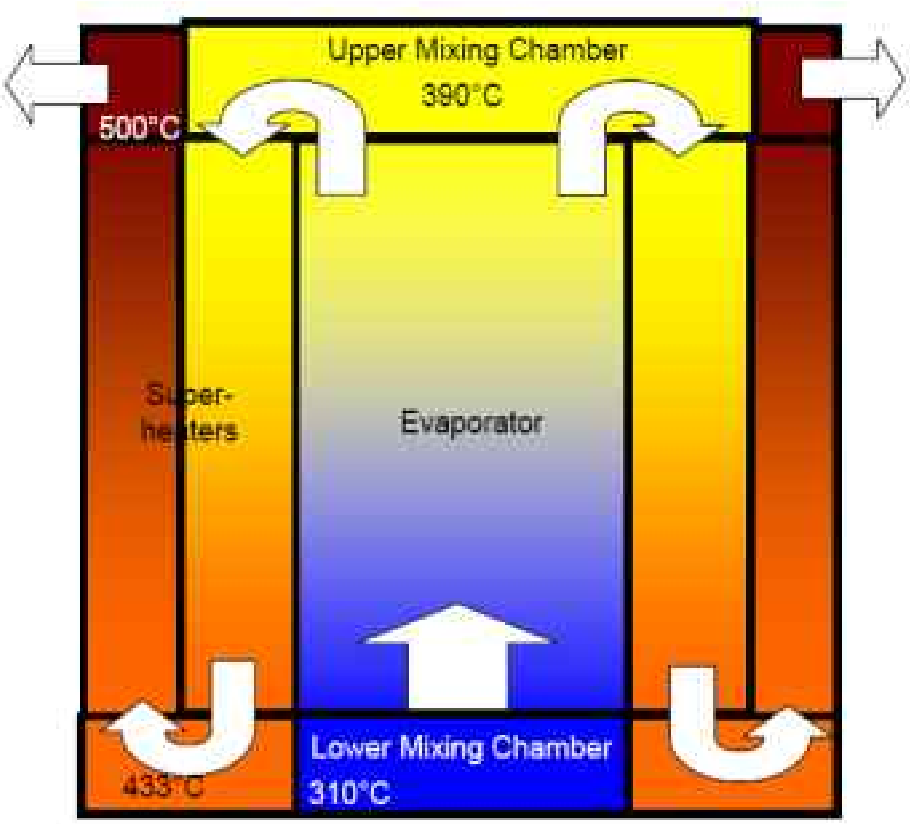
(Shanghai Electric Group and Siemens Power Generation Group, 2007)

Germany, Ultra-SuperCritical steam (USC) power plants. This technology is operational at a new coal-fired power plant. Operated by German utility EnBW, the plant achieves 47.5% net thermal efficiency while producing 912MW of electricity, making it one of the world's most efficient hard coal-fired steam power plants.

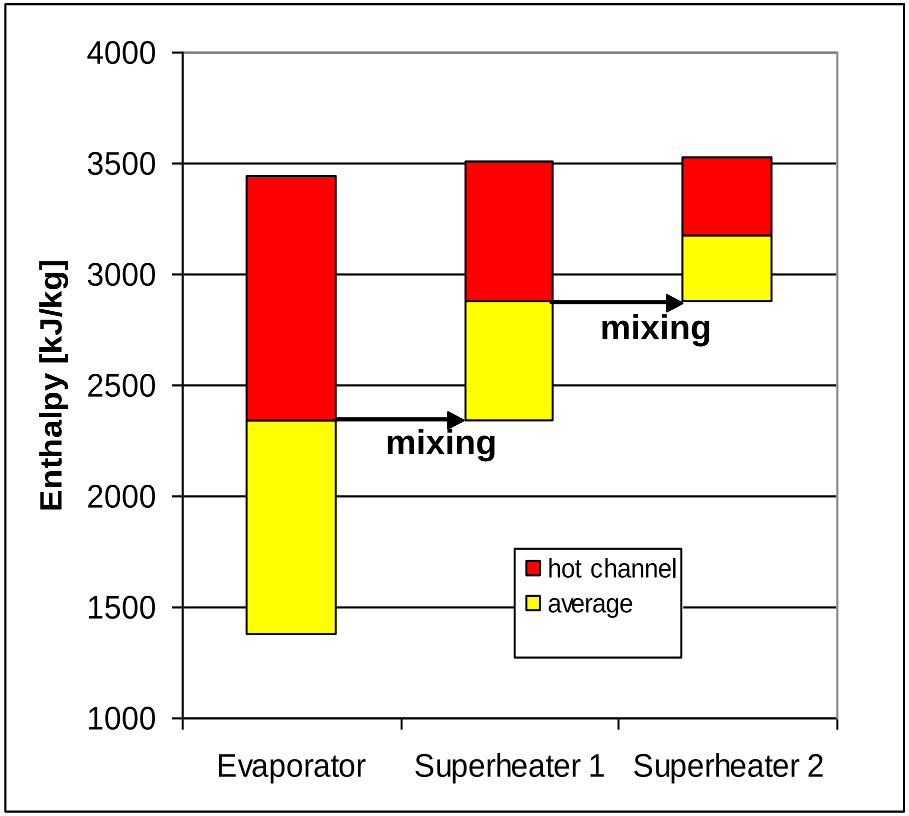
(General Electric (GE) – 2016 - RDK 8 (Rheinhafen-Dampfkraftwerk), Karlsruhe)

"High Performance Light Water Reactor" (HPLWR) (Euratom co-funded project 2013)

280 °C feedwater temperature
500 °C average core exit temperature
630 °C peak cladding temperature
25 MPa feedwater pressure

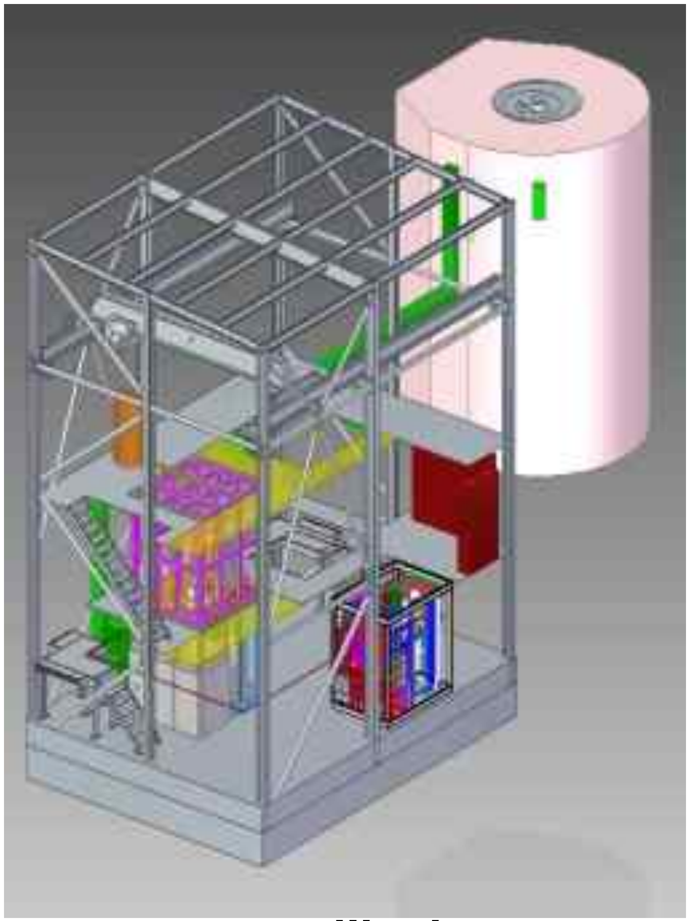


Innovative three pass core concept



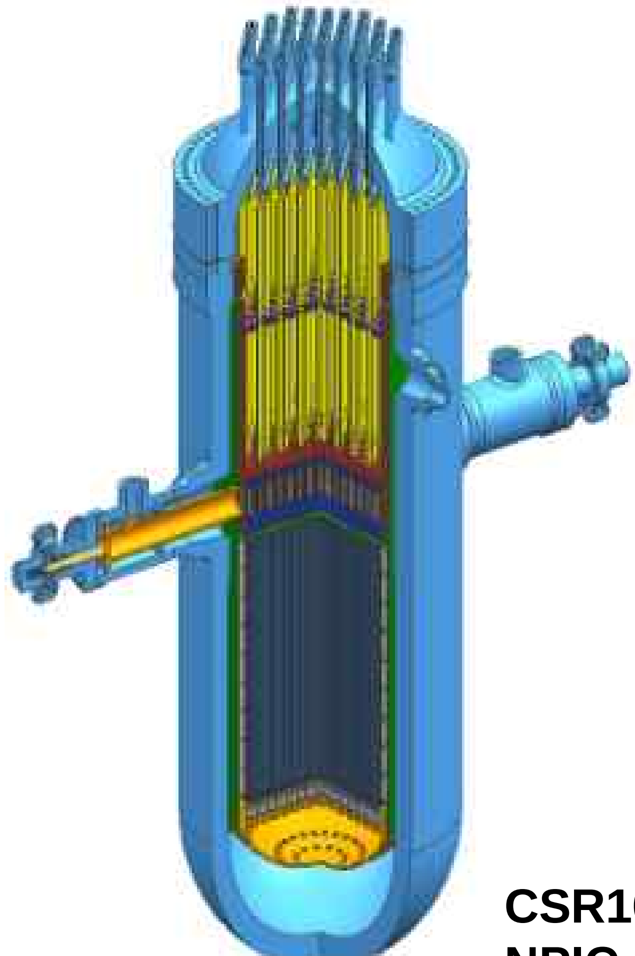
SCWR "Fuel Qualification Test" in EU and SCWR design concept CSR1000 in China

Euratom: Project SCWR-FQT (2012 – 2014)
30 deliverables, 4 M$, 25 person years total



FQT Facility in Rez
(Czech Republic)

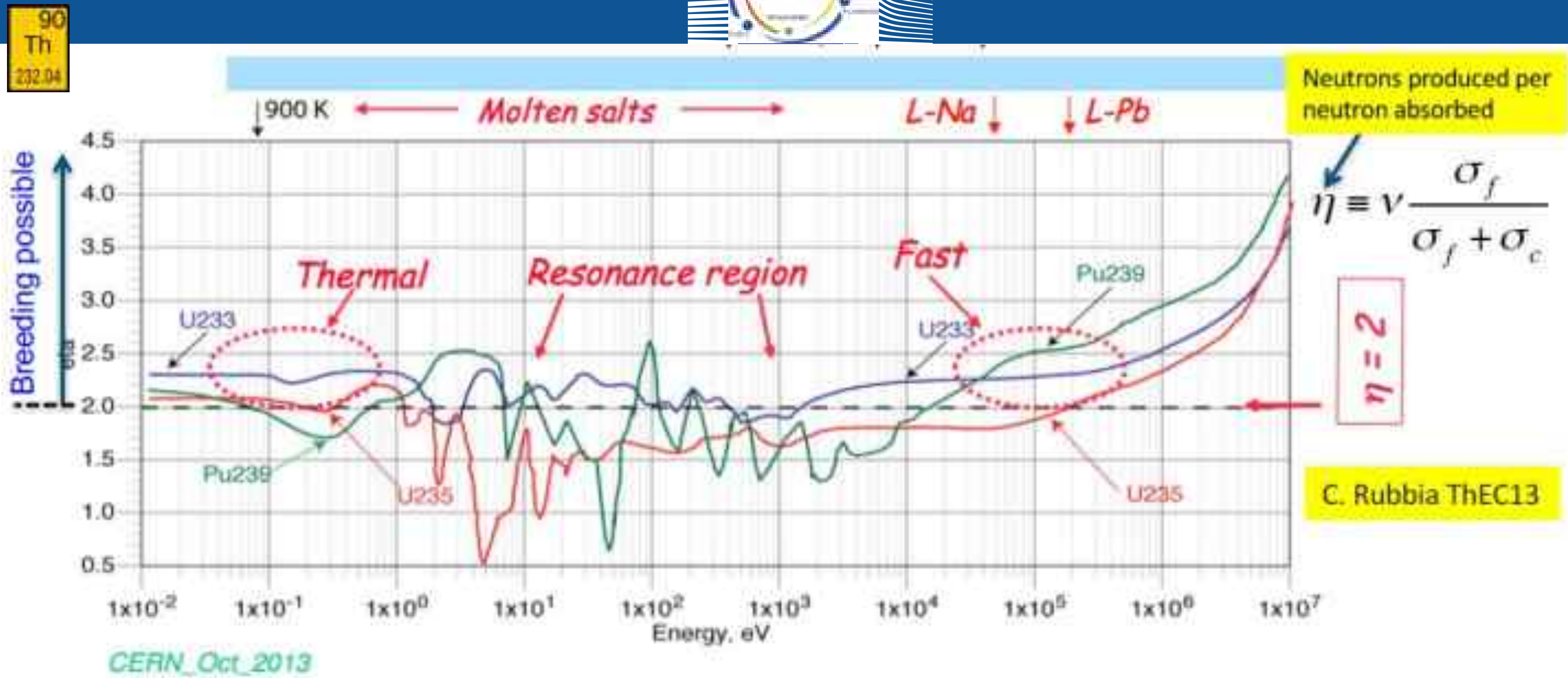
China: Project SCRIPT completed in 2015,
12 deliverables, , ~2M$, 42 person years total



CSR1000,
NPIC-CNNC

"Status of SuperCritical Water Reactor Activities in GIF", Euratom GIF Coordination meeting, Brussels, 12 December 2016

Appendix: Fission energy from Thorium-232



Th-232 is the only naturally occurring thorium nuclide. It is three times as abundant as uranium.
It is a fertile nuclide that generates fissile U-233 on capturing a neutron.
U-233 is an excellent fuel for a breeder system, especially with fast neutrons

FUTURE PROSPECTS AND RECOMMENDATIONS (IAEA, 2005) - **…. The future reactor types and fuel cycle options in different countries wi**ll depend on resource utilization, environmental impact, safety, public acceptance and energy politics including energy security and sustainable ener**gy supply. …**

Source: "Thorium fuel cycle — Potential benefits and challenges », May 2005, IAEA-TECDOC-1450 - http://www-pub.iaea.org/mtcd/publications/pdf/te_1450_web.pdf

Thorium utilization in different experimental and power reactors

Name	Country	Reactor type	Power	Fuel	Operation period
AVR	(West) Germany	HTGR, experimental (pebble bed reactor)	15 MW(e)	Th+235 U Driver fuel, coated fuel particles, oxide & dicarbides	1967–1988
THTR-300	(West) Germany	HTGR, power (pebble type)	300 MW(e)	Th+235 U , Driver fuel, coated fuel particles, oxide & dicarbides	1985–1989
Lingen	(West) Germany	BWR irradiation-testing	60 MW(e)	Test fuel (Th,Pu)O_2 pellets	1968-1973
Dragon (OECD-Euratom)	UK (also Sweden, Norway and Switzerland)	HTGR, Experimental (pin-in-block design)	20 MWt	Th+235 U Driver fuel, coated fuel particles, oxide & dicarbides	1966–1973
Peach Bottom	United States	HTGR, Experimental (prismatic block)	40 MW(e)	Th+235 U Driver fuel, coated fuel particles, oxide & dicarbides	1966–1972
Fort St Vrain	United States	HTGR, Power (prismatic block)	330 MW(e)	Th+235 U Driver fuel, coated fuel particles, Dicarbide	1976–1989
MSRE ORNL	United States	MSR	7.5 MWt	233 U molten fluorides	1964–1969
BORAX-IV & Elk River Station	United States	BWR (pin assemblies)	2.4 MW(e); 24 MW(e)	Th+235U Driver fuel oxide pellets	1963 - 1968
Shippingport	United States	LWBR, PWR, (pin assemblies)	100 MW(e)	Th+233 U Driver fuel, oxide pellets	1977–1982
Indian Point 1	United States	LWBR, PWR, (pin assemblies)	285 MW(e)	Th+233 U Driver fuel, oxide pellets	1962–1980
SUSPOP/KSTR KEMA	Netherlands	Aqueous homogenous suspension (pin assemblies)	1 MWt	Th+HEU, oxide pellets	1974–1977
NRX & NRU	Canada	MTR (pin assemblies)	20 MW; 200 MW (see)	Th+235 U , Test Fuel	1947 (NRX) + 1957 (NRU); Irradiation–testing of few fuel elements
CIRUS; DHRUVA; & KAMINI	India	MTR thermal	40 MWt; 100 MWt; 30 kWt (low power, research)	Al+233 U Driver fuel, 'J' rod of Th & ThO2, 'J' rod of ThO_2	1960-2010 (CIRUS); others in operation
KAPS 1 &2; KGS 1 & 2; RAPS 2, 3 & 4	India	PHWR, (pin assemblies)	220 MW(e)	ThO_2 pellets (for neutron flux flattening of initial core after start-up)	1980 (RAPS 2) +; continuing in all new PHWRs
FBTR	India	LMFBR, (pin assemblies)	40 MWt	ThO_2 blanket	1985; in operation

Thorium fuels have fuelled several different reactor types, including light water reactors, heavy water reactors, high temperature gas reactors, sodium-cooled fast reactors, and molten salt reactors (*IAEA TECDOC-1450 "Thorium Fuel Cycle - Potential Benefits and Challenges"*)

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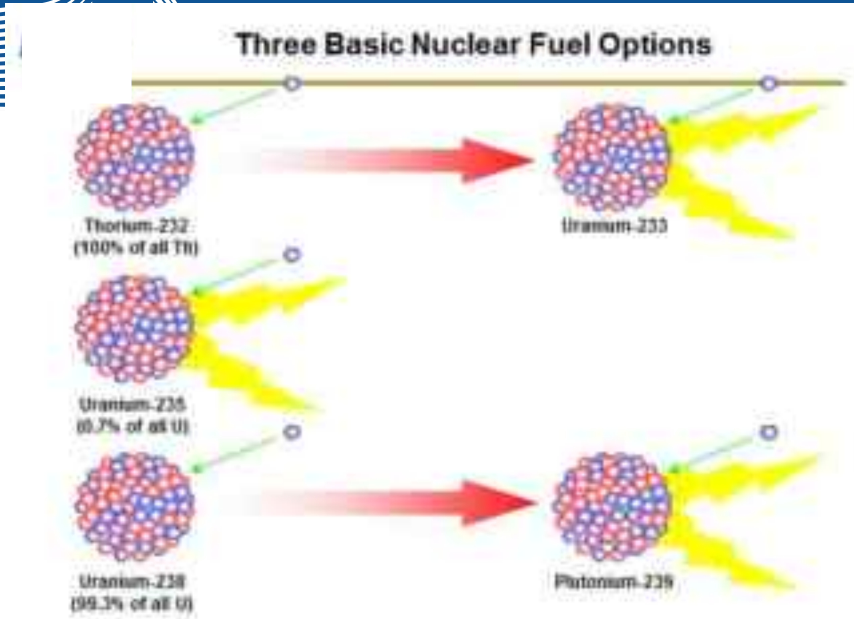
In the very long term, after the 21st century, production of fissile nuclei in the core of the reactor, called breeding, will be required for the production of nuclear energy.

Two options are then possible (see Figure):

- uranium-plutonium cycle: most of Uranium (99.3%, i.e. Uranium-238) cannot be used for nuclear power unless bred into useful Plutonium-239 – breeding of U-238 is carried out in fast neutron reactors using MOX fuel
- thorium-uranium cycle: thorium has 3 times the thermal neutron cross section as U-238, which means that heavy water and even light water-based thorium breeders are possible.



"Thorium cycles and Thorium as a nuclear fuel component"

In the Sustainable Nuclear Energy Technology Platform (SNETP) Strategic Research Agenda - Annex January 2011

http://www.snetp.eu/portfolio/sra-annex-thorium-cycles-and-thorium-as-a-nuclear-fuel-component-january-2011/

« Le thorium et le nucléaire du futur », CEA Sciences

Colloque de l'Orme du 15 mars 2012 par Daniel HEUER (Laboratoire de Physique Subatomique et de Cosmologie, CNRS, Grenoble) (duration = 1h31)

https://www.youtube.com/watch?v=M4MgLixMrz8

History of MSRs and HTRs

There seem to be two alternative reactor options for a breeding thorium cycle in the longer run: molten salt reactors (MSRs) and high temperature reactors (HTRs). The thorium fuel cycle has been successfully demonstrated in over 20 reactors worldwide in both MSRs and HTRs. Research and development of thorium-fuelled nuclear reactors is underway in China, India, Norway, France, Russia, and the Czech Republic.

Extensive research into molten salt reactors (MSRs) started with the U.S. aircraft reactor experiment (ARE) in support of the U.S. Aircraft Nuclear Propulsion program. It was based on the Molten Salt Reactor Experiment /MSRE/ at the U.S.'s Oak Ridge National Laboratory /ORNL/, in particular, the Liquid Fluoride Thorium Reactor (LFTR) which was strongly supported by Alvin Weinberg, who patented the light-water reactor and was a director of ORNL. MSRE operated as hot as 650 °C and operated for the equivalent of about 1.5 years of full power operation during the period 1965 – 1969, using 71%LiF/16%BeF2/12%ThF4/0.3%UF4.

High Temperature Reactors (HTRs) of the graphite pebble bed type using (U-Th)O_2 fuel, were developed in **Germany in the 1980's, such as: Arbeitsgemeinschaft Versuchsreaktor (AVR, 15 MWe, 1967** - 1988) and Thorium High-Temperature Reactor (THTR-300 MWe, 1986 - **1989). The UK's 'Dragon' High Temperature Gas** Reactor operated from 1966 to 1975 as a OECD/Euratom project, using graphite hex blocks with (U-Th)C_2 fuel.

Research and development of thorium-fuelled nuclear reactors 2/3

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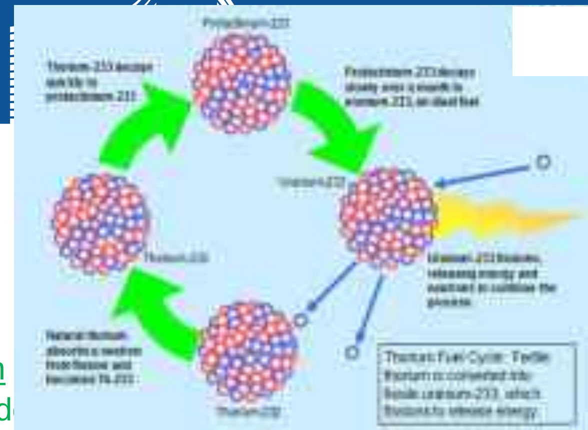

The thorium-uranium cycle has a number of theoretical advantages:

• **Th**-232 is the only naturally occurring thorium nuclide. is a mildly radioactive element, three times as abundant as uranium. It is a fertile nuclide that generates fissile U-233 on capturing a neutron (see Figure). Reserves of thorium are widely dispersed around the world. NB: In Europe, Norway has 132 000 **tons of proven reserves, 5% of the world's total.**

• **Thermal breeding.** Fertile conversion occurs with thermal neutron captures. In the period 1977 **–** 1982, in Shippingport, a thermal breeder reactor experiment was performed in the third core of by Bettis Atomic Power Laboratory (Pennsylvania, USA). This was a standard light water moderated design of 100 MWe and one of the first commercial PWRs (started in 1957). The breeding ratio attained after 29 000 full power hours was 1.01. **This LWBR program was seen as Admiral Rickover's pet project.**

• **U**-233 has a high thermal fission cross-section and a low thermal neutron capture cross-section. The fission/capture ratio for U-233 is higher than the other major fissile nuclides U-235, Pu-239 and Pu-241. This is very favourable for the neutron multiplication factor.

• **The high fission/capture ratio also minimises the probability of** neutron captures leading to transuranics. As a consequence, the thorium fuel cycle is relatively clean as it produces almost no plutonium (and no minor actinides) and a much smaller quantity of toxic fission products than the uranium cycle.

• ThO2 properties generally more favourable than UO2: high melting point of thorium dioxide (one of the best refractory materials - 3300°C compared to 2865°C for UO2), thermal conductivity; single oxidation state

• **ThO2 is potentially a** more stable matrix for geological disposal than UO2

Thorium fuel in fast neutron Accelerator Driven System (ADS)

ADSs are also referred to as energy amplifiers since more energy is released from the fission reactions in the blanket assembly than is needed to power the particle accelerator. Professor Carlo Rubbia, a former director of the international CERN laboratory and Nobel Prize laureate 1984, is credited with proposing the concept of the energy amplifier ("Rubbiatron"), using natural thorium fuel. Thorium in a fast neutron flux may also be used to destroy nuclear waste produced by present nuclear power plants.

« Thorium, la face gâchée du nucléaire »
Arte Télévision - 20 septembre 2016
GILLES GIRARD (duration = 1h40)
https://www.youtube.com/watch?v=uTyTpEVGpnA

"PROSPECTS FOR ACCELERATOR-DRIVEN THORIUM SYSTEMS"
Jean-Pierre Revol, Centro Fermi, Rome, LINAC-2014
http://accelconf.web.cern.ch/AccelConf/linac2014/papers/friob03.pdf

Research and Innovation

Research and development of thorium-fuelled nuclear reactors 3/3

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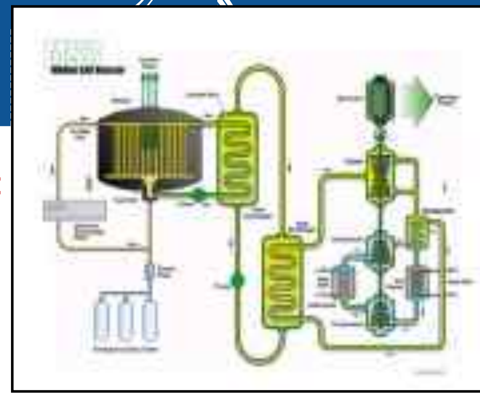


The thorium-uranium cycle also has a number of drawbacks:

- Thorium is not fissile and therefore cannot sustain a nuclear chain reaction on its own: thorium itself cannot be used to start up a power plant. Thorium is fertile, which means that if it is bombarded by neutrons from a separate fissile driver material (U-233, U-235 or Pu-239 /above Figure/), or from a particle accelerator, it will transmute into the fissile element U-233 which is an excellent nuclear fuel. The conversion rate however is very low, so the time taken to build up usable amounts of U-233 are very long.

- Reprocessing is a challenge for the potential development of a closed thorium fuel cycle. U-233 recycle is complicated by presence of ppm quantities of U-232 - radiologically significant for fuel fabrication at ppb. Protactinium-233 problem : formation of Pa-**231, an α**-emitting isotope with long half-life (3x10**4 years) in the THOREX (THORium uranium Extraction) process. The THOREX process has been demonstrated at small scale, but will require extensive R&D to develop it to commercial readiness.

- Pure U-233 can be derived from the molten salt coming **out of thorium reactors "which is easier to make bombs with than plutonium." U**-233 is weapons useable material with a low fissile mass and low spontaneous neutron source. Reminder: in a so called "Bare (untamped) spherical critical mass" condition, U-233 required is 15 kg, whereas U-235 required is 50 kg and Pu-239 required is 10 kg (these values are approximate).

Development of MSRs under Generation IV (see Figure)

- Gen IV MSR will be a fast spectrum system (closed fuel cycle)
- Molten salt fuel circulates through core and heat exchangers
- Transmutation up to a "ultimate burn-up"
- On-line reprocessing to remove fission products
- Proliferation resistance through low fissile inventory
- Ideally suited to thorium fuel as fuel fabrication is avoided
- Equilibrium fuel cycle will have low radiotoxicity (fission products only)

There are a number of technical issues to resolve ("viability stage")

- **In fact,** Th-**MSR's are still considered to be in a technical "viability" assessment stage** by the international physics community in this area (GIF roadmap), for a variety of reasons. **Dr. Alvin Weinberg, the "guru" of thorium nuclear technology, called it a "Faustian bargain" and said it was "a great energy source, but you've got to worry about proliferation and waste."**

Research and Innovation

"Thorium – an alternative nuclear fuel cycle"
Kevin Hesketh, UK National Nuclear Laboratory, 5th Smart Grids & Clean Power Conference, Cambridge, 5 June 2013
http://www.cir-strategy.com/uploads/sgcp13hesketh.pdf

Fission nucléaire de quatrième génération : stop ou encore ?

1 – Introduction : Génération IV - pourquoi ? comment ? avec qui ? quand ?

2 - Le cap («triangle énergétique européen») et les invariants (lois de la nature)

3 - La réalité des faits et des chiffres (« quasi-certitudes ») et défis technologiques et humains (incertitudes)

4 - Besoins et opportunités pour le nucléaire au 21ème siècle (objectifs de Génération IV)

4.1 Améliorer la durabilité (y compris l'utilisation efficace du combustible et la réduction des déchets)

4.2 Sûreté et fiabilité (notamment en l'absence de toute intervention extérieure d'urgence)

4.3 Economie (compétitivité par rapport aux sources d'énergie)

4.4 Lutte contre la prolifération des armes nucléaires et protection matérielle

5 - Les systèmes-réacteurs nucléaires en projet de la Génération IV : SFR, LFR, GFR, VHTR, MSR et SCWR

6 - Conclusion : recherche, innovation et formation en fission nucléaire

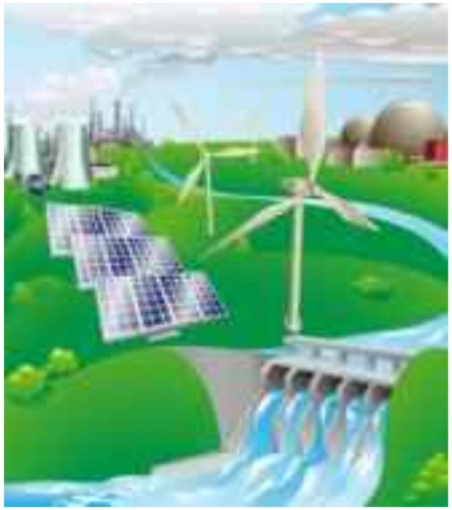
Conclusion

Meeting industrial and societal needs through international research, innovation and training

- improve continually sustainability, safety & reliability, socio-economics and proliferation resistance of nuclear installations
- contribute to the creation and transfer not only of *knowledge* but also of *skills* and *competences* to new generations of experts
- ensure scientific and technological excellence in all parts of the European Union (and world-wide) through shared programmes
- develop a new governance for nuclear fission (i.e. rules, processes and behaviour) based a.o. on research and innovation

=> **a new way of "developing / teaching science" aiming at continuously** improving applications of nuclear fission energy and, more generally, aiming at improving decision making in nuclear energy policy matters

Towards convergence of nuclear and renewable energy ?



« Etude sur la transition énergétique belge aux horizons 2030 et 2050 », PwC Enterprise Advisory, octobre 2016 (https://www.forumnucleaire.be/theme/energie/le-role-du-nucleaire-et-des-renouvelables-au-sein-de-la-transition-energetique)

Why invest in research ?

"Attracting more people and investing more in science and research are the keys to our future, if we want to be competitive in global markets.

** Some of our trading partners are competing with primary resources, which we do not have.*

** Some compete with cheap labour, which we do not want.*

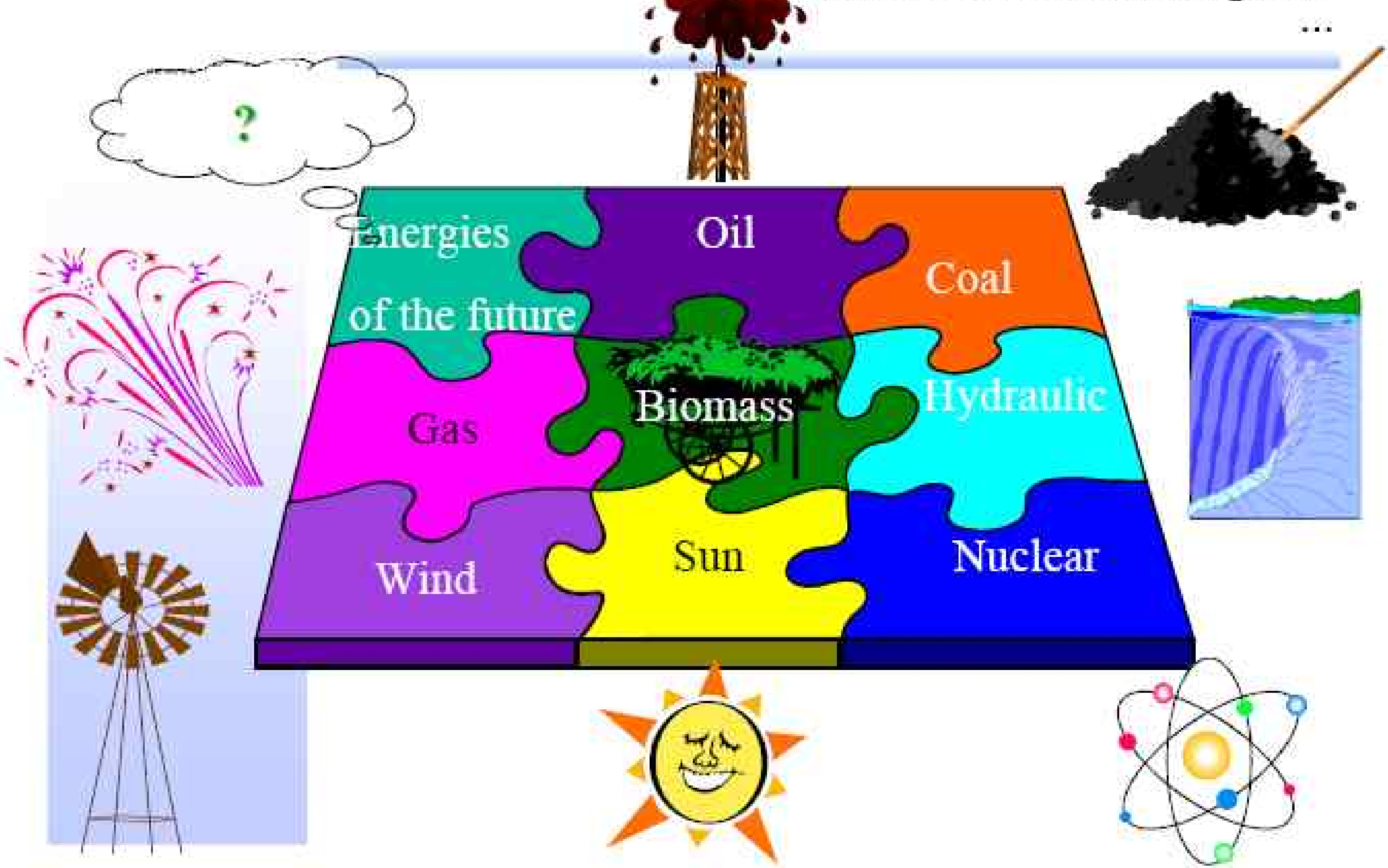
** Some compete at the cost of the environment, which we cannot accept.*

Building the knowledge society is probably the best, and maybe only, way to sustain the European model of society, without having to make a trade-off between economic growth, social cohesion and environmental protection."

Source: Janez Potočnik, European Commissioner for Science and Research (2004-2009), speech in Ljubljana, Slovenia, March 21, 2005 (ERA News, 2005-02-03)

We need all the energies !

...



Article 194 of the Lisbon Treaty :
"Union policy on energy shall aim, in a spirit of solidarity ...: .. Such measures shall not affect a Member State's right to determine the conditions for exploiting its energy resources, its choice between different energy sources and the general structure of its energy supply**".** (http://europa.eu/lisbon_treaty/index_en.htm)

Générations futures: no 5, 6, et 7 sont déjà sur le marché !

Evolution énergétique (renouvelables, fossiles, fissile): les technologies de Génération 1, 2, 3 et 4 ont pris du retard ?

Génération no 5

Génération no 6

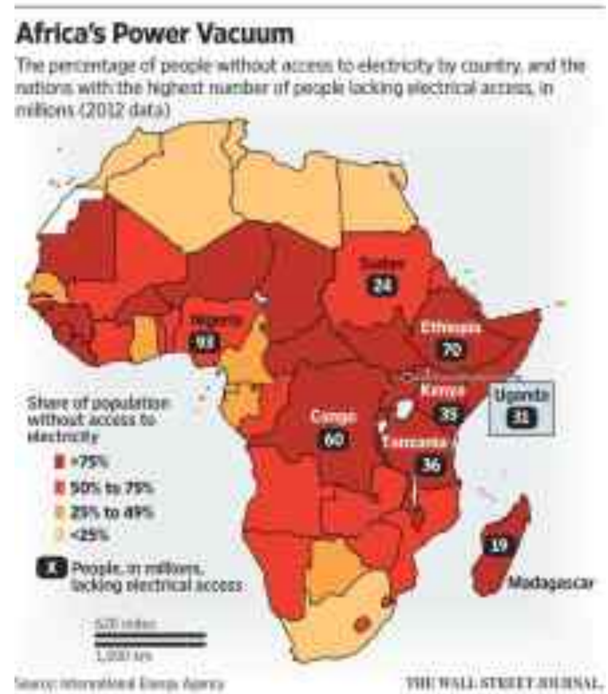
Génération no 7

Announcement: « Sustainable Energy for Africa »

2017, October 23 – 25, Palace of the Academies, Brussels

"Sustainable Energy for Africa",
2017, October 23 – 25,
Palace of the Academies, Brussels

International Conference organized by
the "Royal Academy for Overseas Sciences" (RAOS) of Belgium



PROGRAMME

After a general introduction, the conference will treat the following topics:

1. Energy is crucial for achieving the UN Sustainable Development Goals (23 October)

2. Energy mix: towards robust, equitable and socially acceptable energy systems (24 October)

3. Research, innovation and education in support of sustainable energy policies (25 October)

(registration fees : 100 Euros for full participants)

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