Italian National Agency for New Technologies, Energy and Sustainable Economic Development

Nuclear as a *Green* source? That's a *Deal*!

APERITIVI SCIENTIFICI - Seminari con le noccioline

@ INFN Bologna, April 22nd, 2022

Giacomo Grasso, ENEA, CR Bologna

Abstract

Energy has always been one of the main quests for humanity. But today, the matter of the quest lies in the attributes we pretend for it: we want it available, and to secure this availability; we want it cheap, and affordable for everyone; and we want it green, with no harm for people and the planet. In one word: sustainable!

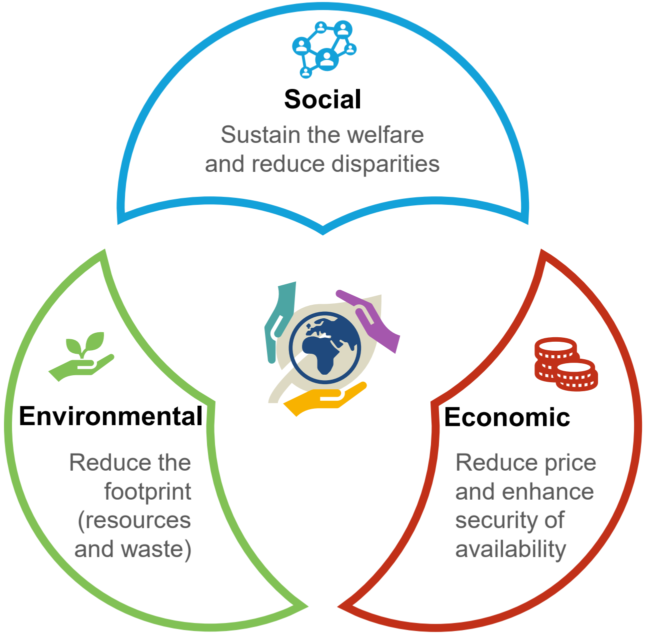
The debate lies in facts on which sources should we pursue to achieve all our (ambitious) objectives. No need to say: in the debate, nuclear is the least popular. Notwithstanding, nuclear entered the European taxonomy of green sources – and not without rumors or oppositions.

The talk will try to touch the attributes acknowledged to nuclear energy, which motivated its inclusion in the European taxonomy, comparing past, current and future plant "generations" and discussing the state-of-the-art researches ongoing worldwide.

The energy quest

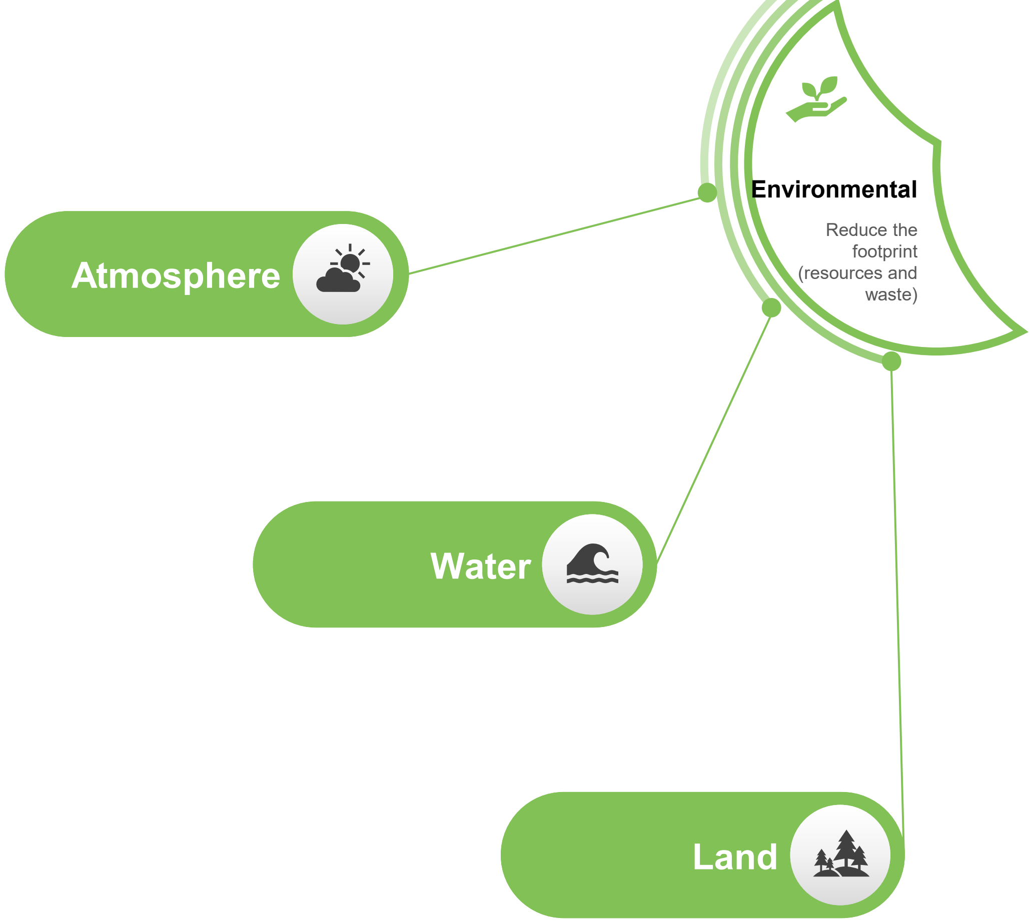
What do we want?

Sustainability



Environmental attributes

- Reduced GHG emissions
- Reduced pollutants emissions and concentrations
- Reduced contaminant discharges
- Reduced acidified area
- Reduced deforestation rate
- Reduced solid waste produced/ disposed per unit energy
- Reduced solid radwaste produced/disposed per unit energy



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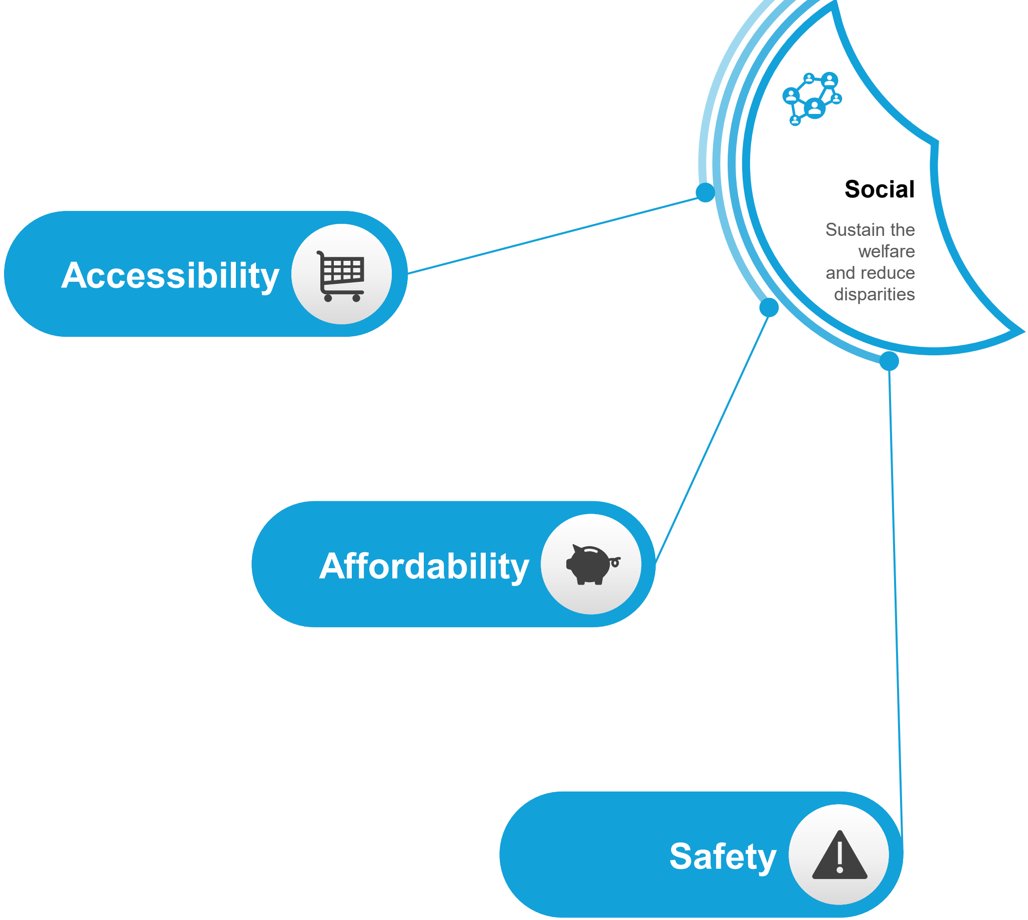
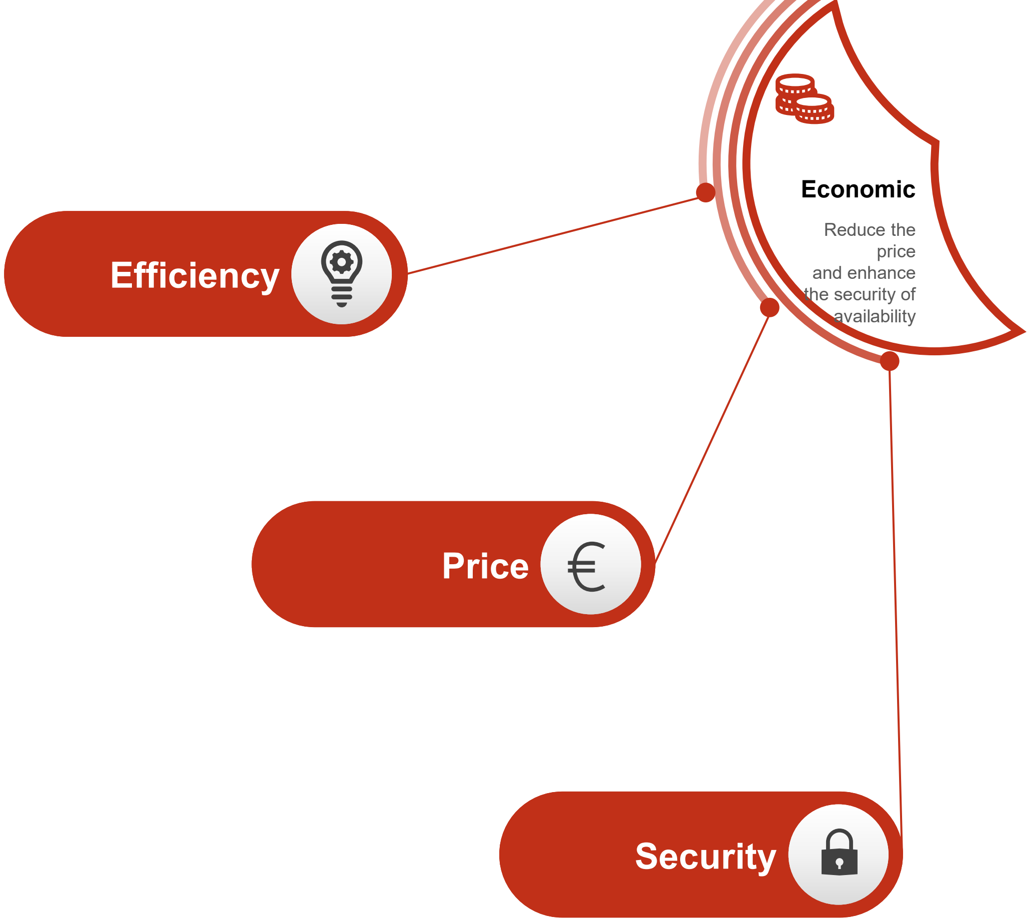
Social attributes

- Reduced % population without energy
- Reduced % income spent for energy
- Reduced disparity of energy use per income group
- Reduced fatalities per unit energy produced



Economic attributes

- Increased efficiency in production and distribution
- Reduced reserve/production and resources/production ratios
- Reduced end-use price by fuel and sector
- Reduced net import dependency
- Reduced stocks of critical fuels per fuel consumption

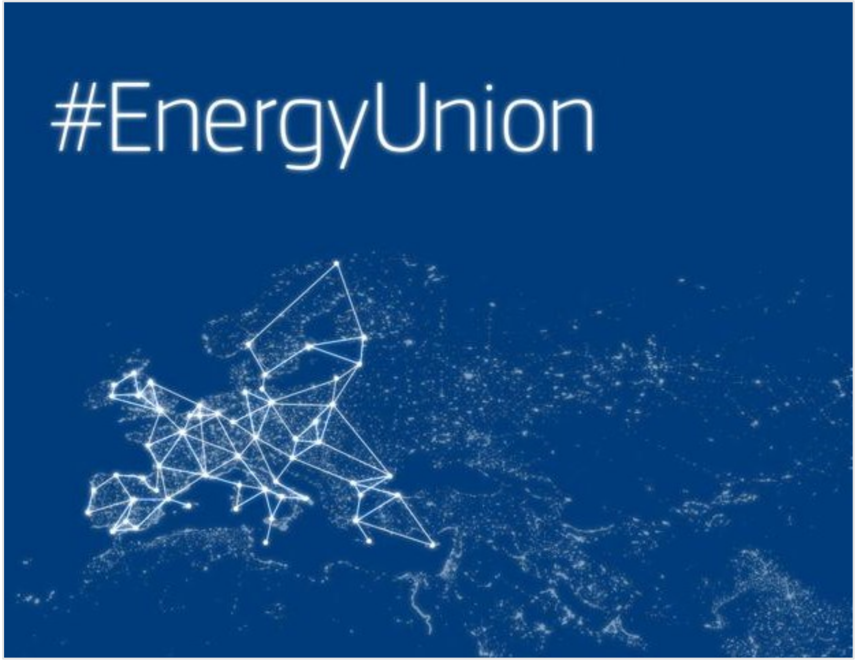


European policies

Energy Union

Objectives:

- diversify Europe’s sources of energy, ensuring energy security;
- ensure the functioning of a fully integrated internal energy market;
- improve energy efficiency;
- decarbonise the economy;
- promote research in low-carbon and clean energy technologies.



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European policies

Greed Deal

Overarching objective:

- for the EU **to become the first climate neutral continent by 2050**, resulting in a cleaner environment, more affordable energy, smarter transport, new jobs and an overall better quality of life.

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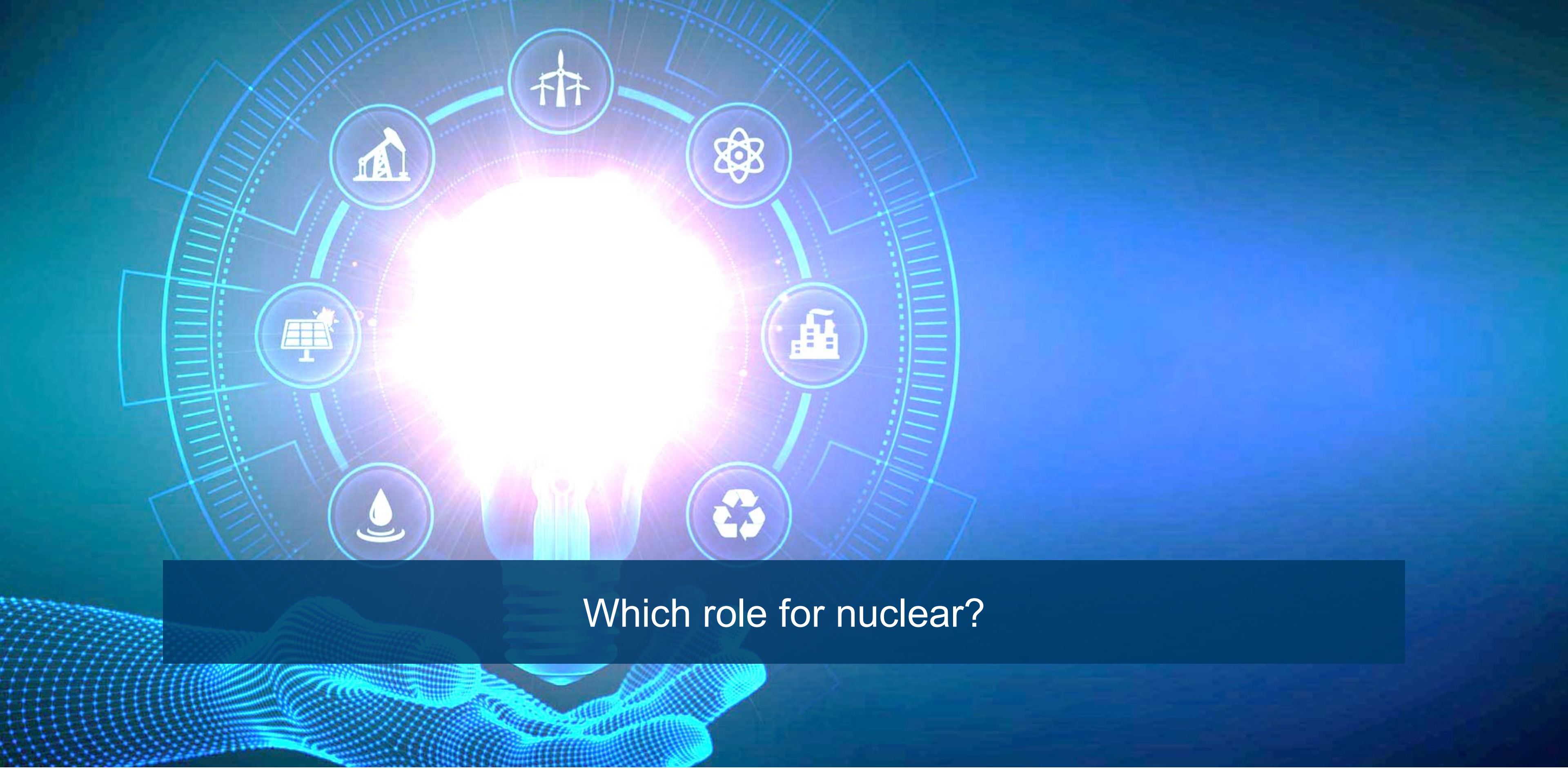
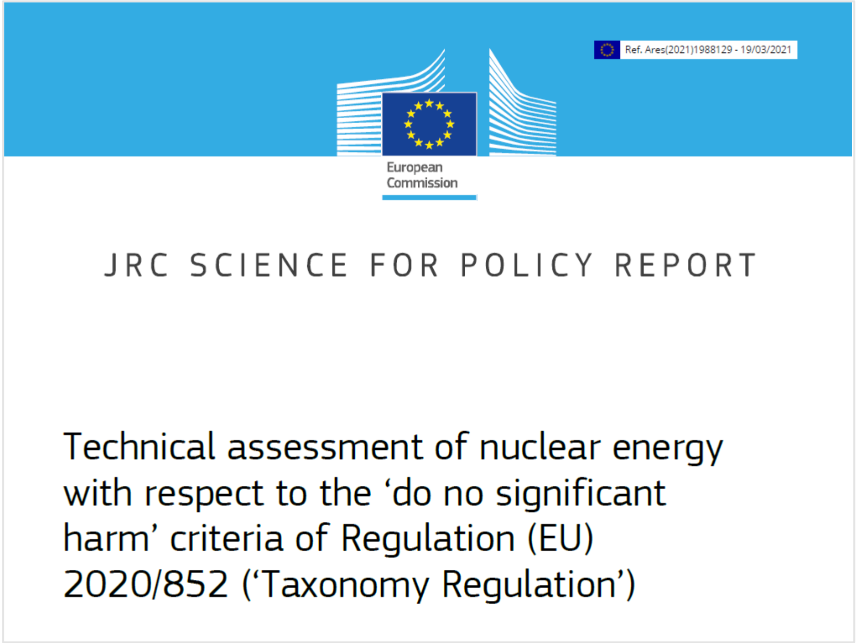


Which role for nuclear?

Nuclear potential for the Green Deal

Findings of the JRC report


Ref. Ares(2021)1988129 - 19/03/2021

European Commission

JRC SCIENCE FOR POLICY REPORT

Technical assessment of nuclear energy with respect to the 'do no significant harm' criteria of Regulation (EU) 2020/852 ('Taxonomy Regulation')

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Nuclear potential for the Green Deal

Findings of the JRC report

The detailed assessment of the impacts of nuclear energy in its various lifecycle phases […] did not reveal any science-based evidence that nuclear energy does more harm to human health or to the environment than other electricity production technologies already included in the Taxonomy as activities supporting climate change mitigation.

Nuclear potential for the Green Deal

Current generation reactors

No combustion

- ✓ no GHG/pollutants emission during operation
- ✓ no land acidification
- ✓ no deforestation

Nuclear potential for the Green Deal

Findings of the JRC report

- Average lifecycle GHG emissions determined for electricity production from nuclear energy are comparable to the values characteristic to hydropower and wind;
- Nuclear energy has very low NO_x (nitrous oxides), SO_2 (sulphur dioxide), PM (particulate matter) and NMVOC (non-methane volatile organic compounds) emissions. The values are comparable to or better than the corresponding emissions from the solar PV and wind energy chains;
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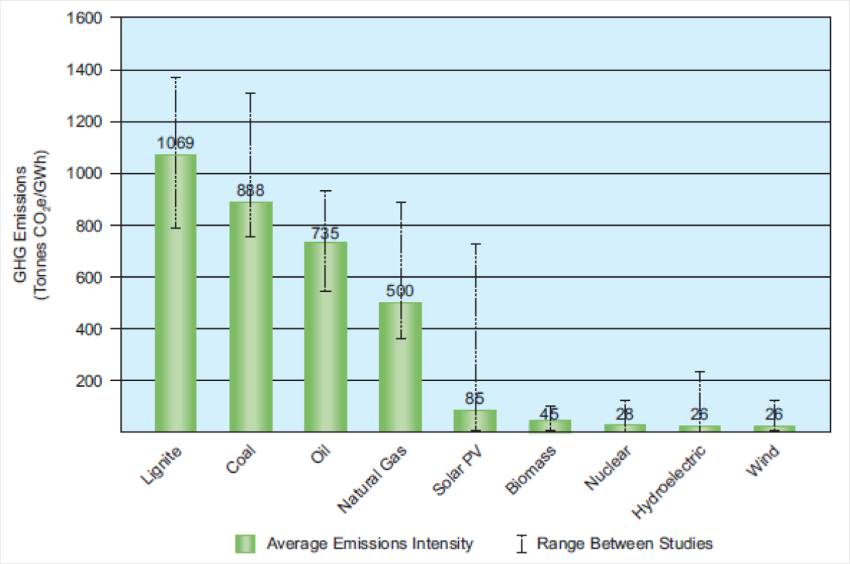
- The same is true for freshwater and marine eco-toxicity, ozone depletion and POCP (photochemical oxidant creation potential).



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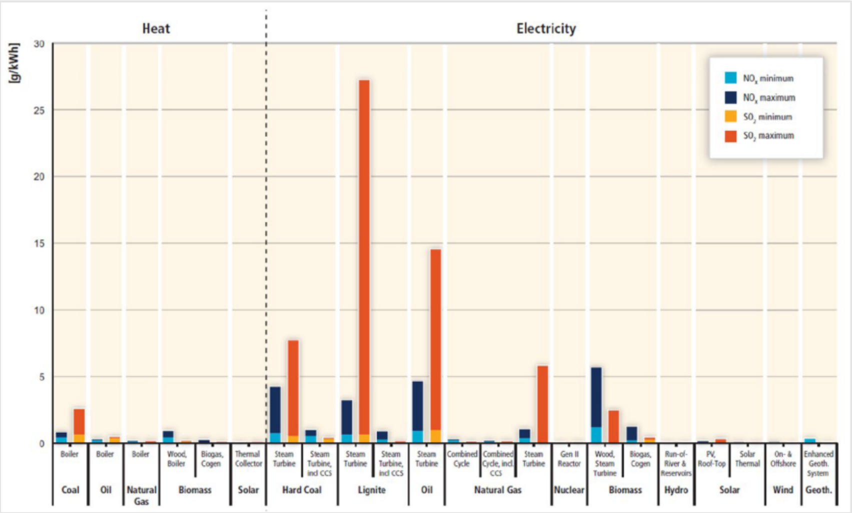

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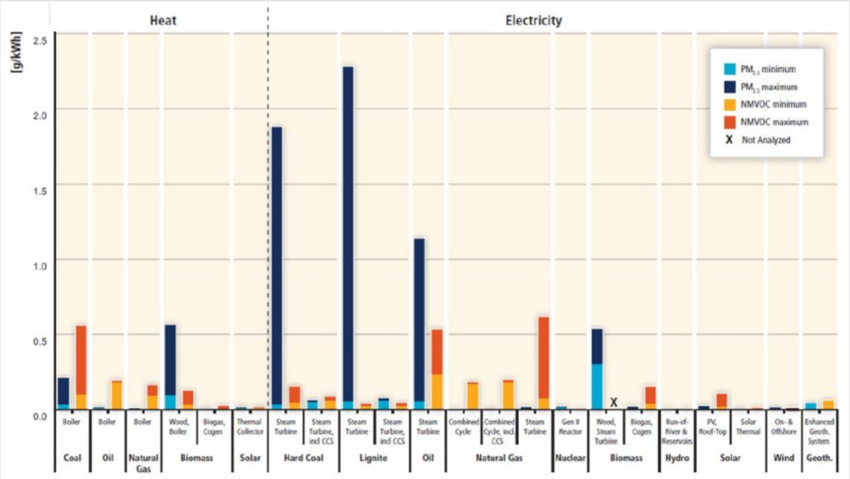

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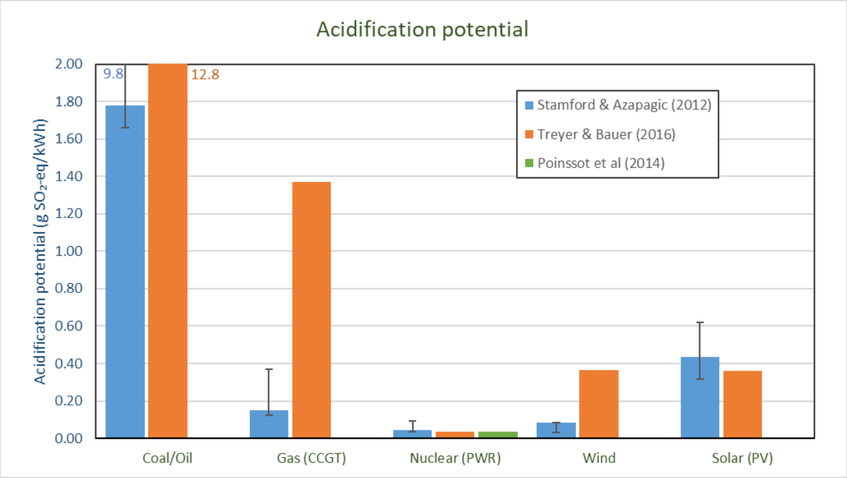

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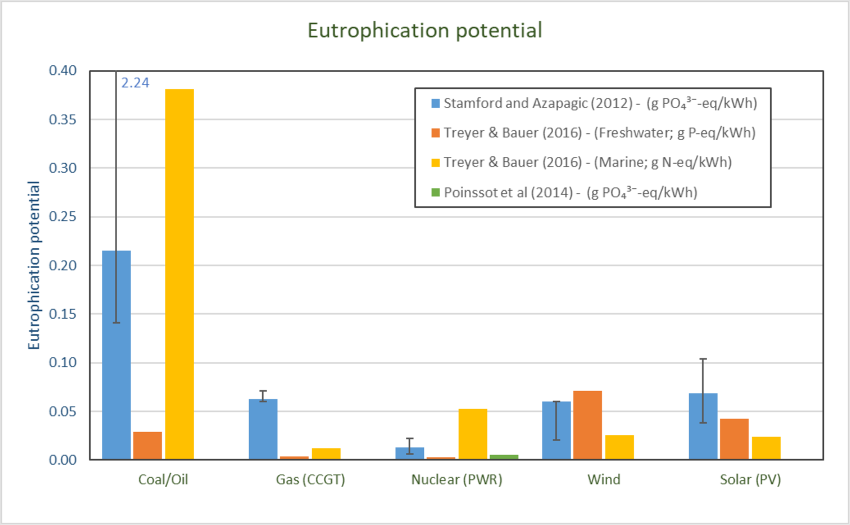

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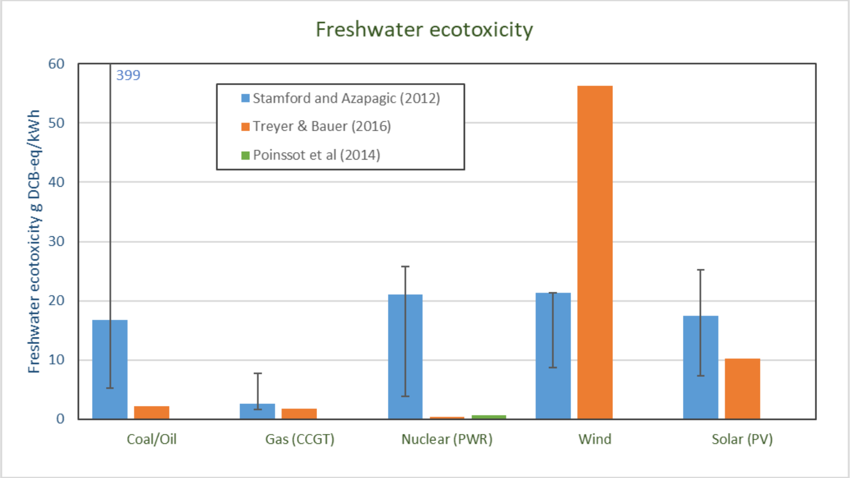

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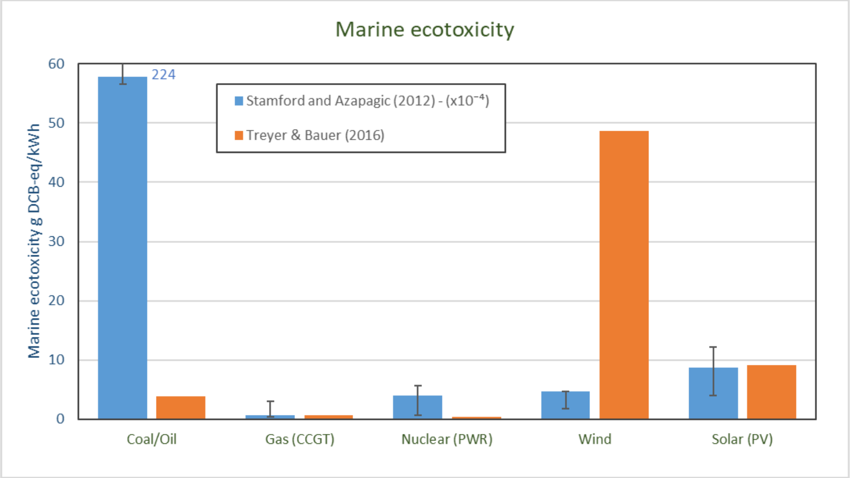

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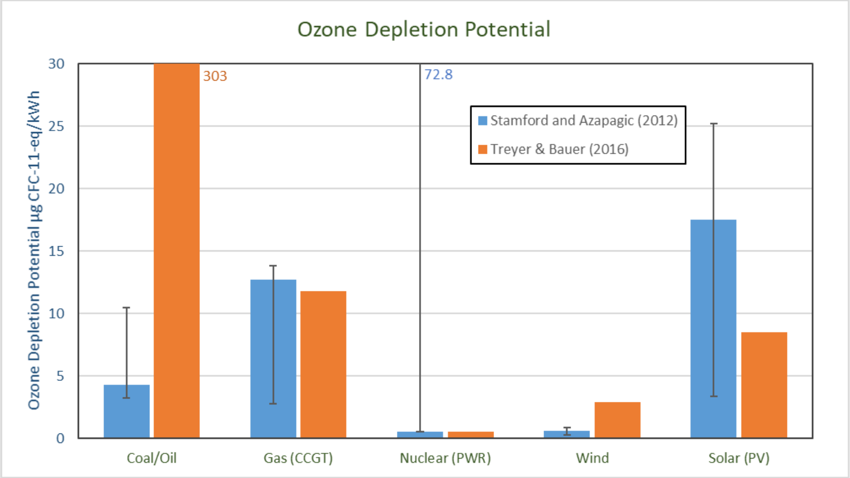

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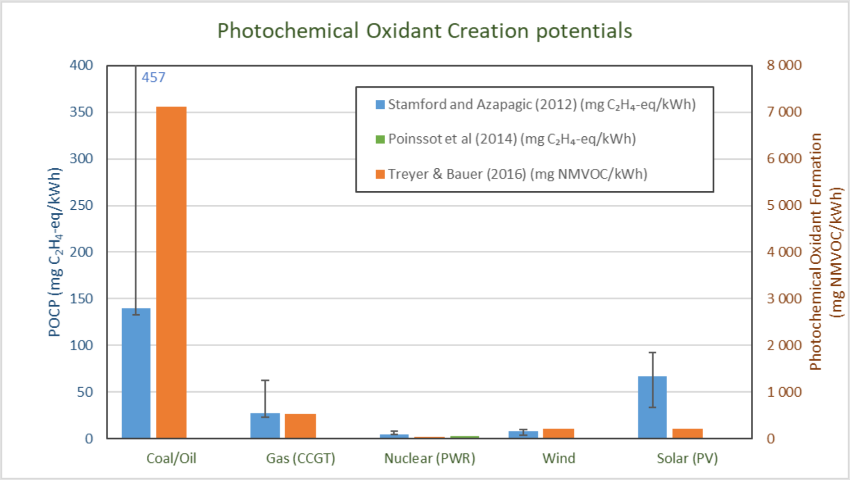


Nuclear ID

Current generation reactors

No combustion

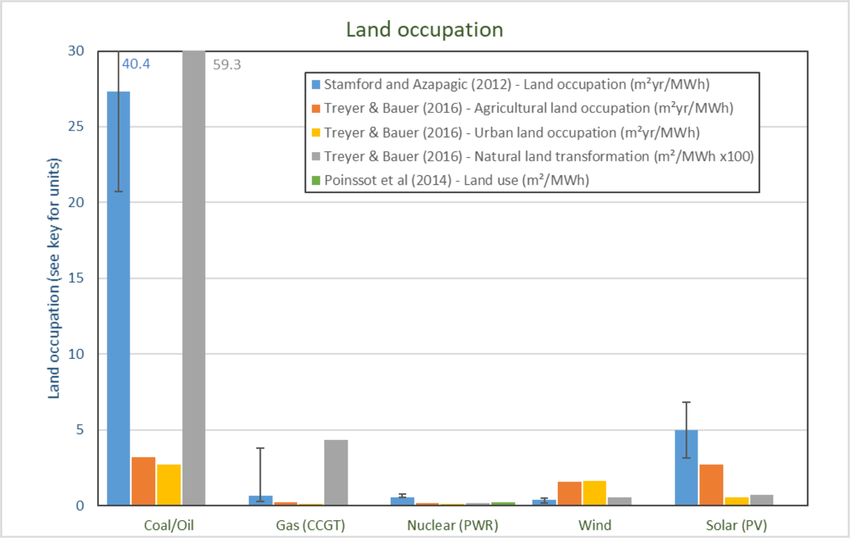
High energy concentration

- ✓ minimal GHG and pollutants emission during the whole life cycle;
- ✓ low use of resources/production;
- ✓ minimal import dependency;
- ✓ minimal stocks of critical fuels;
- ✓ low end-use price;
- ✓ high efficiency;
- ✓ low waste;
- ✓ minimal contaminants.

Nuclear potential for the Green Deal

Findings of the JRC report

- Land occupation of nuclear energy generation is about the same as for an equivalent capacity gas-fired power plant, but significantly smaller than wind or solar PV;
- Nuclear and gas have the lowest abiotic depletion potential, referring to the depletion of non-living (abiotic) resources such as metals, minerals and fossil energy;
- Specifically focusing on the depletion of fossil fuels, nuclear and wind have very low use;
- A significant portion of the potential radioactive waste is in fact non-radioactive and can be reused, recycled, or further managed as conventional waste.



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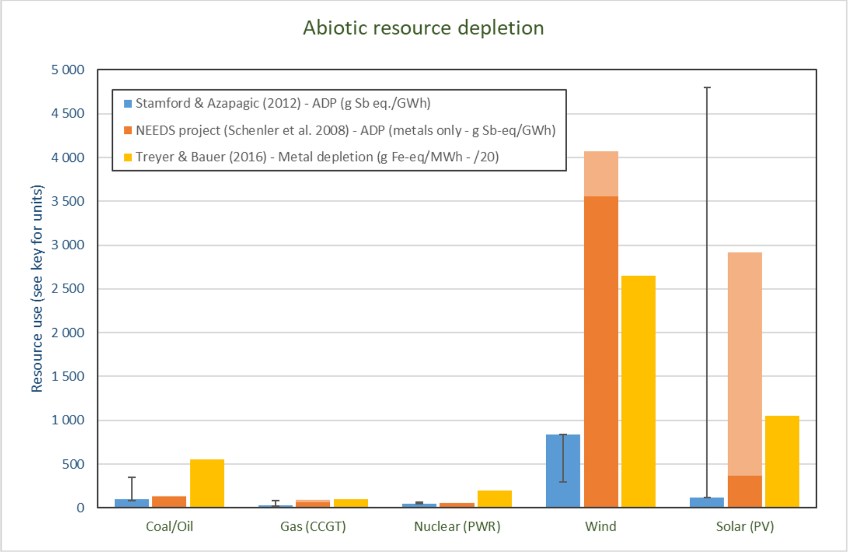

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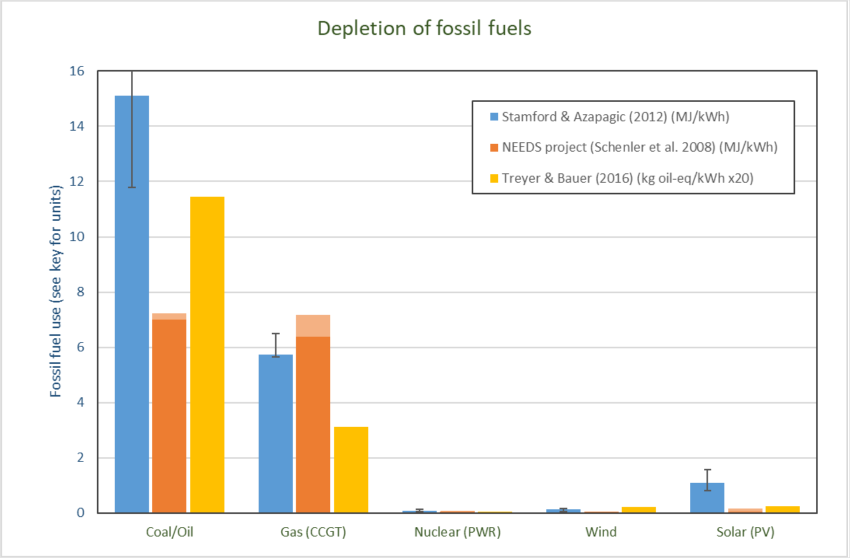

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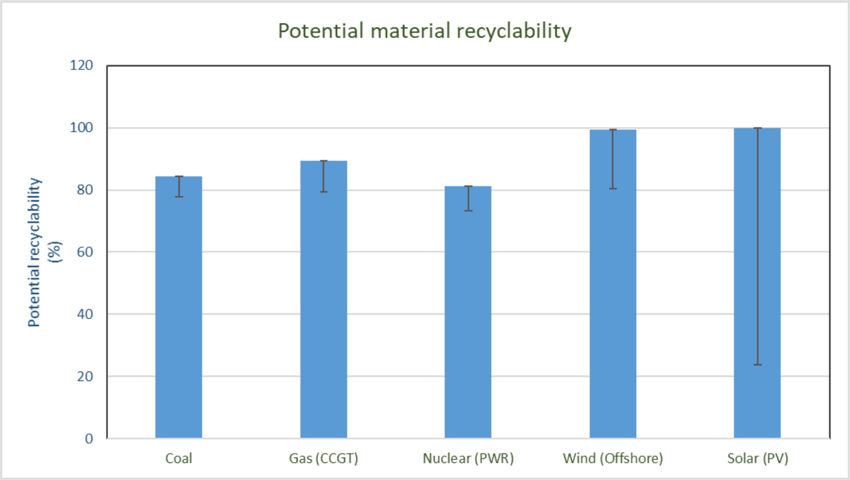
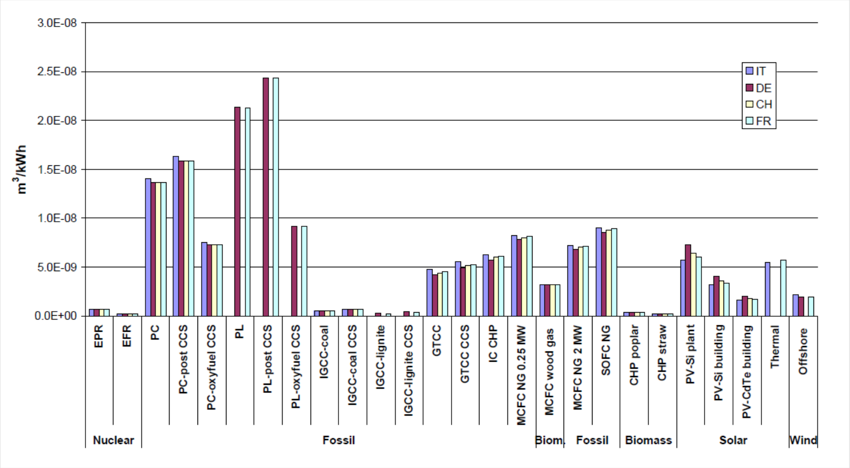


Nuclear potential for the Green Deal

Findings of the JRC report

- Nuclear energy produces relatively small quantities of chemical wastes requiring storage, even compared to renewable technologies;
- Of course, nuclear energy produces the largest amount of radioactive wastes;
- In volumetric terms, the amount of radioactive waste produced by nuclear energy is somewhat less than the amount of chemical waste requiring storage/disposal in a repository produced by some fossil technologies and comparable with the amount of chemical waste from some solar PV technologies;
- Radioactive waste quantities produced by Fast Reactors are considerably less than for current Light Water Reactors as the fuel is recycled so spent fuel assemblies do not go into the waste stream.



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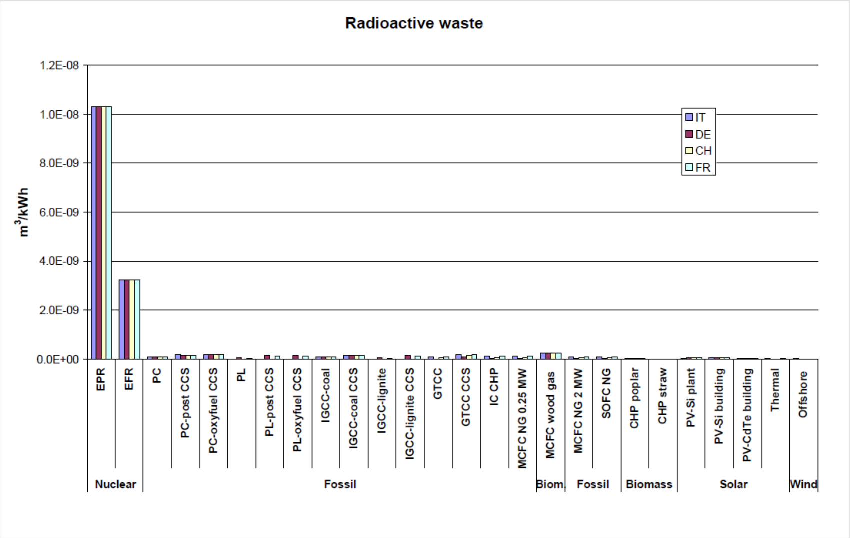

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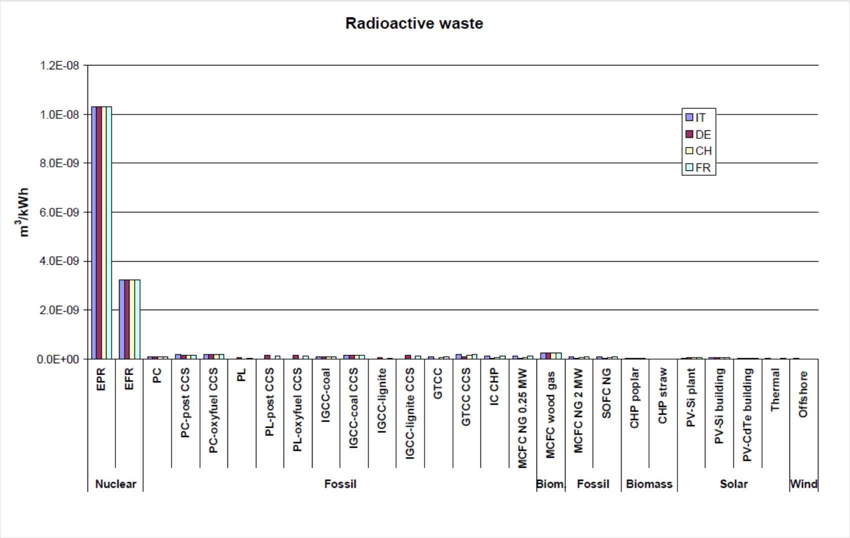

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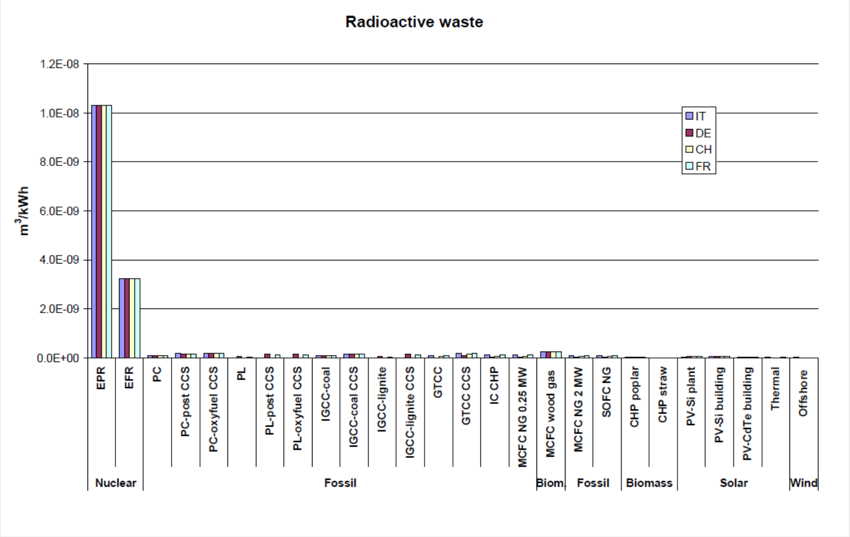


Nuclear ID

Current generation reactors

No combustion

High energy concentration

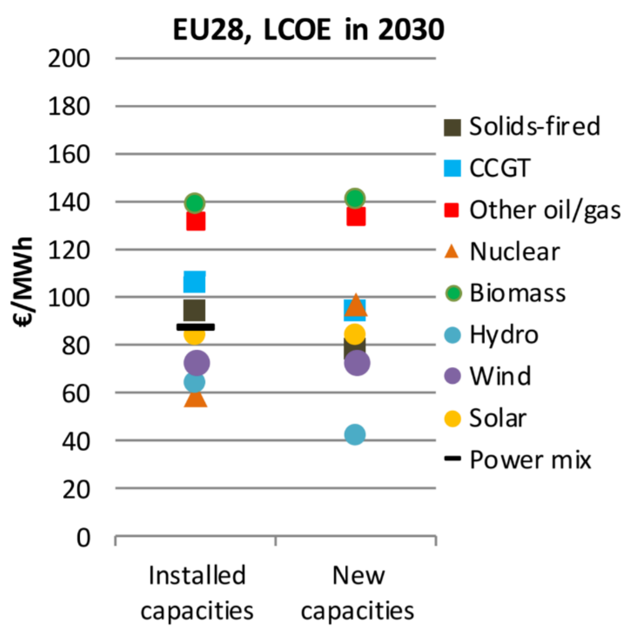
Low cost

- ✓ low end-use price
- ✓ low % population without energy
- ✓ low % income spent for energy
- ✓ low disparity of energy use per income group

Nuclear potential for the Green Deal

Findings of the JRC report

- Considering the existing capacities, nuclear power represents the lowest generation costs in 2030;
- The cost increases when considering new installed capacities, but nuclear remains competitive and close to the levelized cost of the current power mix;
- When considering the closure (partial or complete) of the nuclear fuel cycle, a maximum increase in generating costs of 20% is found compared to the open cycle.



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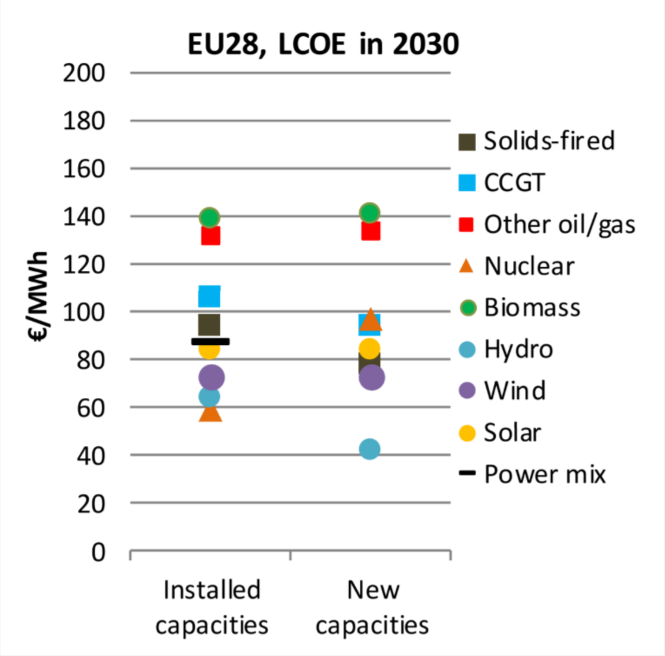

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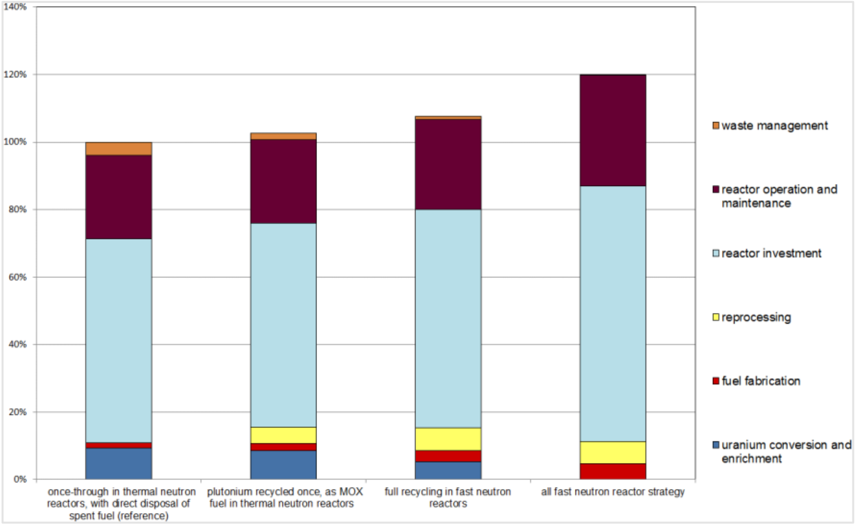

Nuclear ID

Current generation reactors

No combustion

High energy concentration

Low cost

High reliability

- ✓ low end-use price;
- ✓ minimal import dependency;
- ✓ minimal stocks of critical fuels;
- ✓ low % population without energy;
- ✓ minimal fatalities.

Nuclear ID

Current generation reactors

No combustion

High energy concentration

Low cost

High reliability

High safety

- ✓ minimal contaminants
- ✓ minimal fatalities

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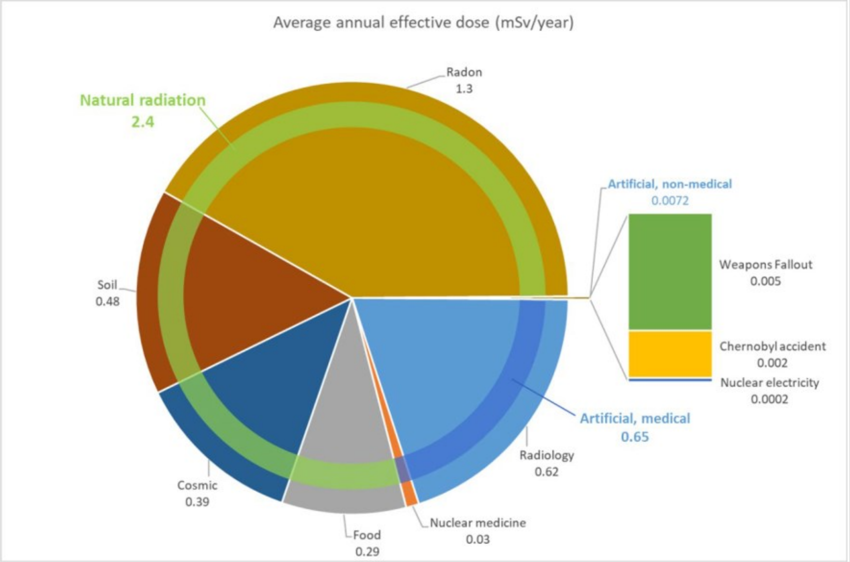
Nuclear potential for the Green Deal

Findings of the JRC report

- Radiation resulting from the whole lifecycle of nuclear electricity generation results in an average annual effective dose which is less than 0,007% of the total average dose to the public from all sources;
- Considering the maximum credible number of fatalities in a single accident, nuclear has high rates;
- Considering however the fatality rates (expected number of fatalities due to severe accidents normalized to the amount of electricity generated), current Generation II nuclear power plants have a very low fatality rate, while Generation III plants have by far the lowest rate.



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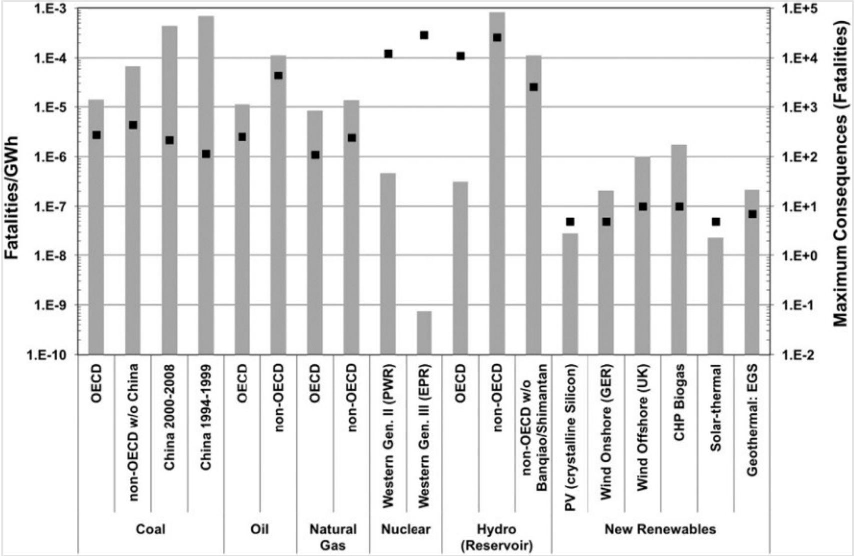

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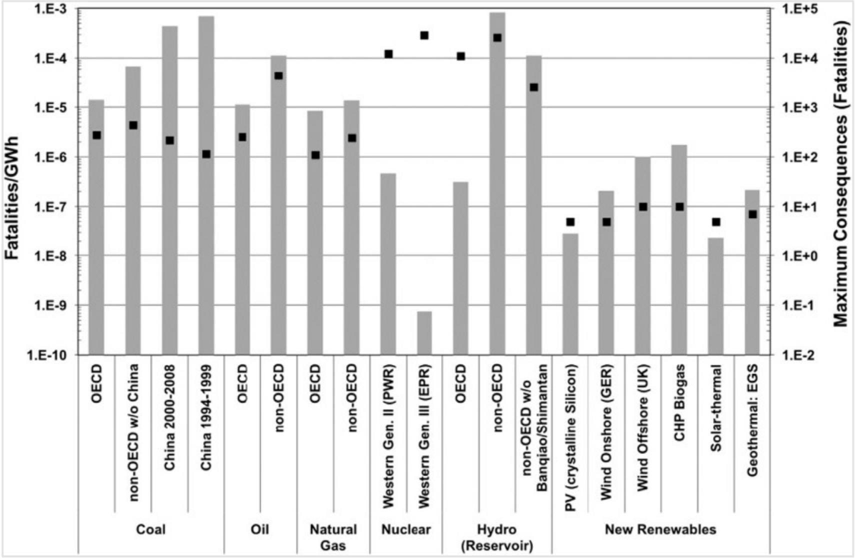
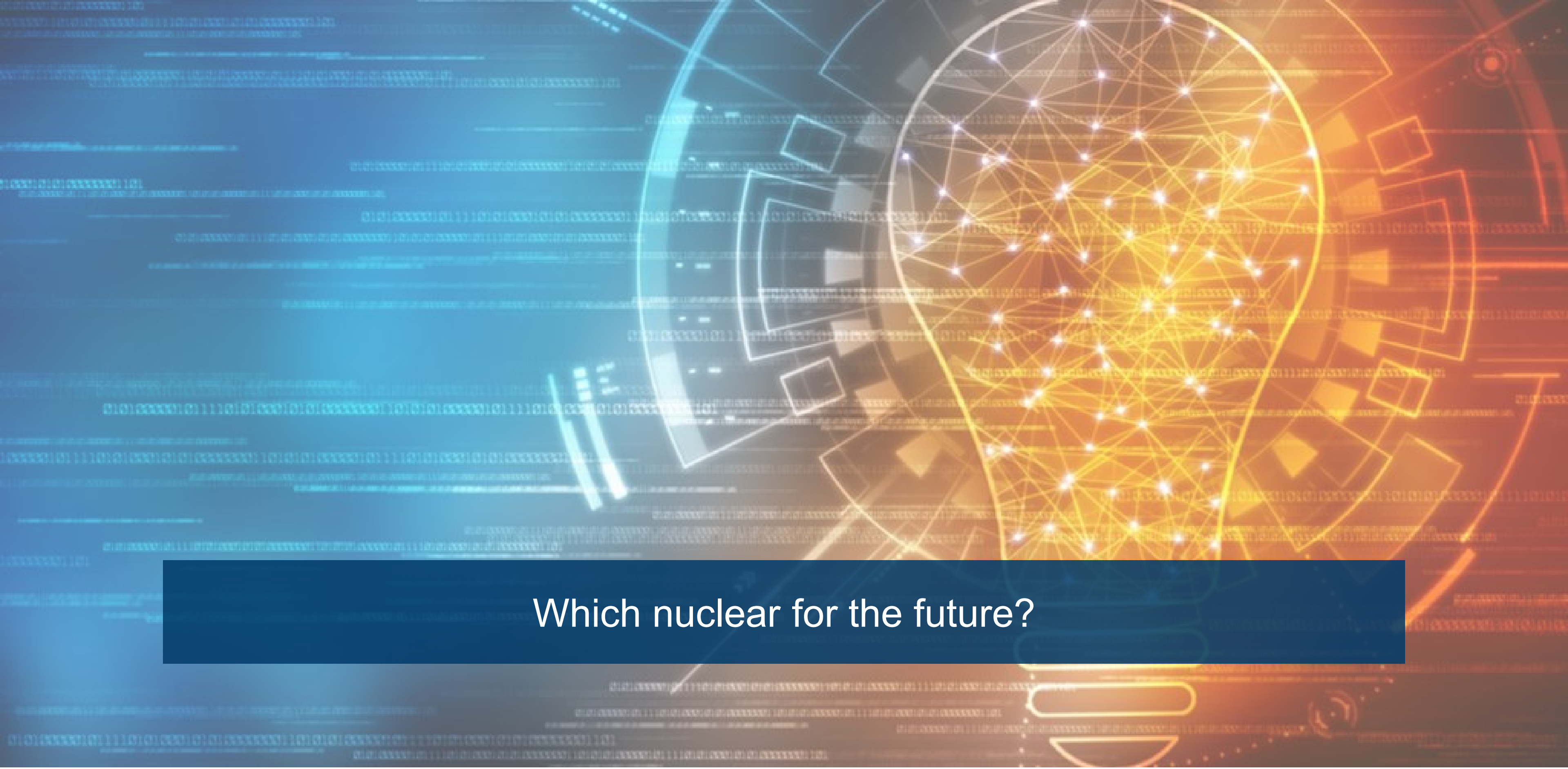
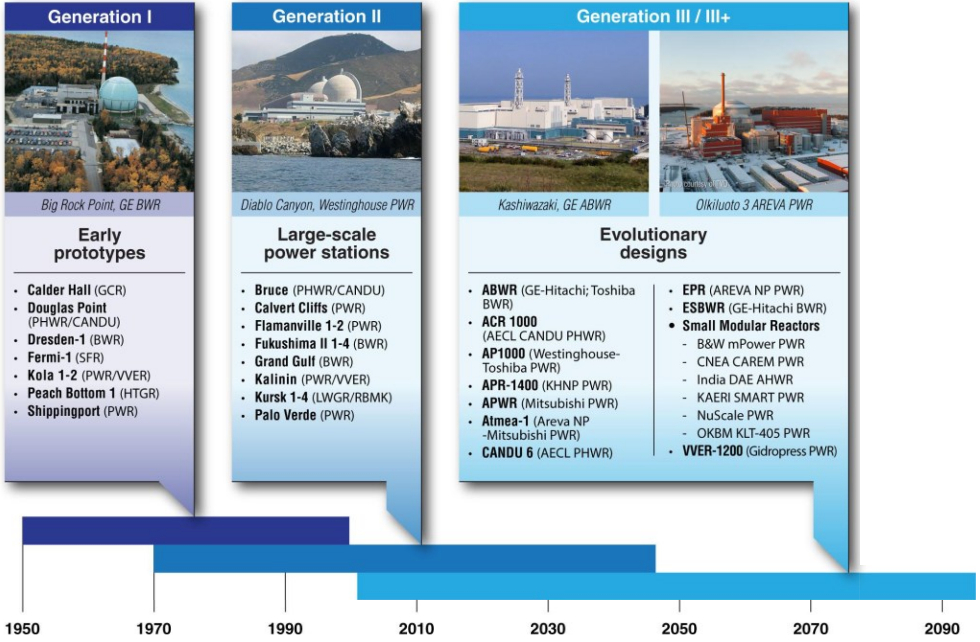




Which nuclear for the future?

A long way done…

Evolution of nuclear reactors



I

Generation I

Early, prototypical reactors

Reactor generations

Generation I

- All early power plants of the ‘50s and 60’s.

- Manyfold technologies pursued and investigated

Obnisk

II

Generation II

Commercial power reactors

Reactor generations

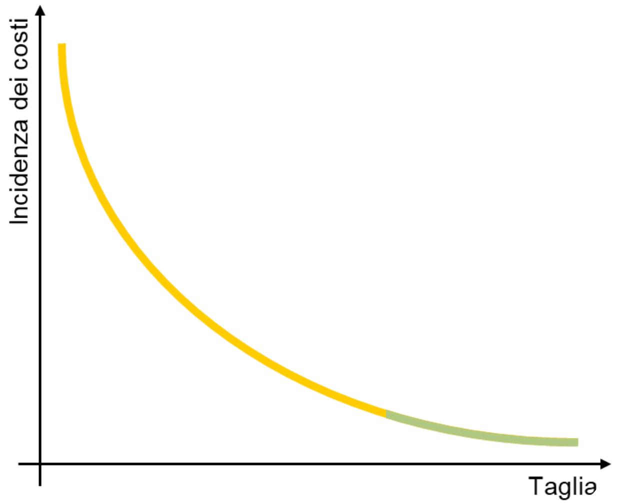
Generation II

- Achievement of maturity and high economics
- Affirmation of the most promising technologies
- Establishment of international safety standards and safety culture
- Learning curve leading to steady increase of the power (up to 1000 MW and beyond)

Economy of scale

By increasing the power output (the size), the fixed costs due to construction could be diluted when charged on a larger amount of produced energy.

Along with the very low costs of fueling, operation and maintenance, this made Generation II reactors one of the cheapest power systems ever.



Centrale «Enrico Fermi»

Trino Vercellese, Italy

III

Generation III

Advanced water-cooled reactors

Reactor generations

Generation III

- Further improvement (notably, of safety) by optimization and enhancement

- Further downselection of the established technologies
    - light water reactors (both PWR and BWR)
    - heavy water reactors

- Further increase in size (up to 1700 MW)

ENEA

Passive safety

Is based on inherent characteristics or engineered provisions standing on physical principles (e.g., gravity, natural circulation), exploited in such a way that a system can spontaneously react to an initiating cause to mitigate its consequences without any intervention from the outside (including operators).

Category A

- No signal input of intelligence
- No external power sources or forces
- No moving mechanical parts
- No moving working fluid

Category B

- No signal input of intelligence
- No external power sources or forces
- No moving mechanical parts
- Moving working fluids

Category C

- No signal input of intelligence
- No external power sources or forces
- Moving mechanical parts

Category D

- Signal input of intelligence to initiate (no manual initiation)
- Energy to initiate, but only from stored sources
- Active components only for control

ENEA

Olkiluoto 3

III+

Generation III+

Evolutionary concepts

Reactor generations

Generation III+

- Still based on the same established technologies, with optimization pushed even further

- Massive use of passive provisions

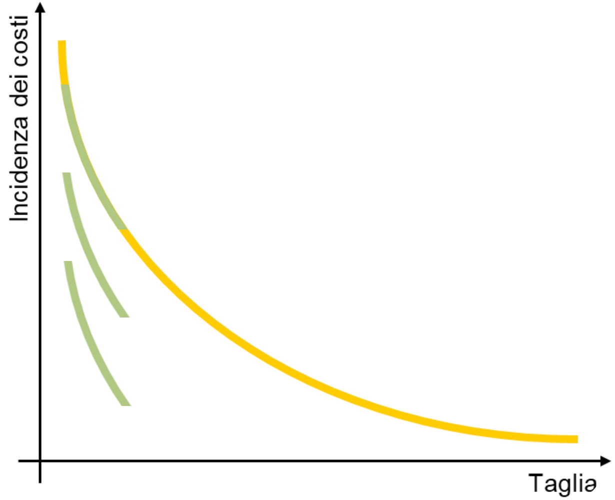
- Often, shift to integral layouts and small scale (< 300 MW) for broader affordability

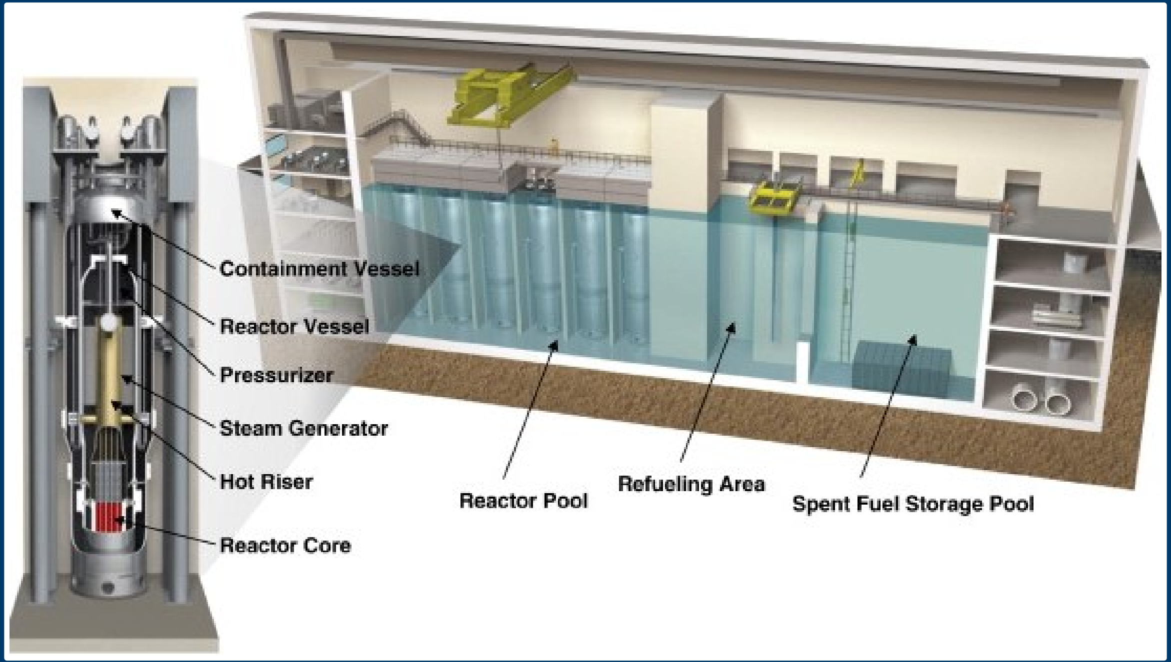
ENEA

Economy of series

Without the benefits of the economy of scale, economics is pursued by

- modularization
- factory production
- series fabrication

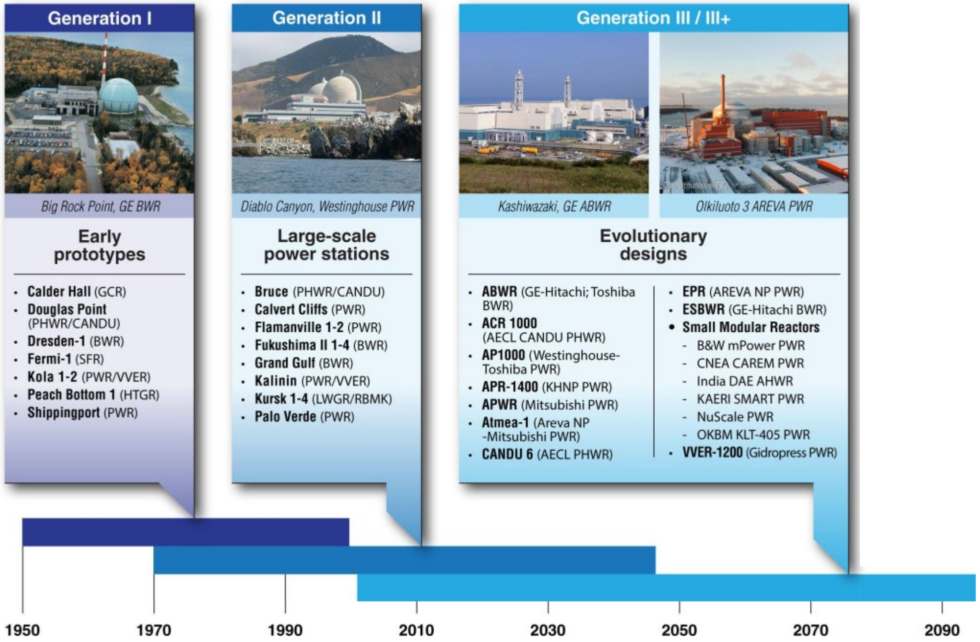




NuScale Power Module™

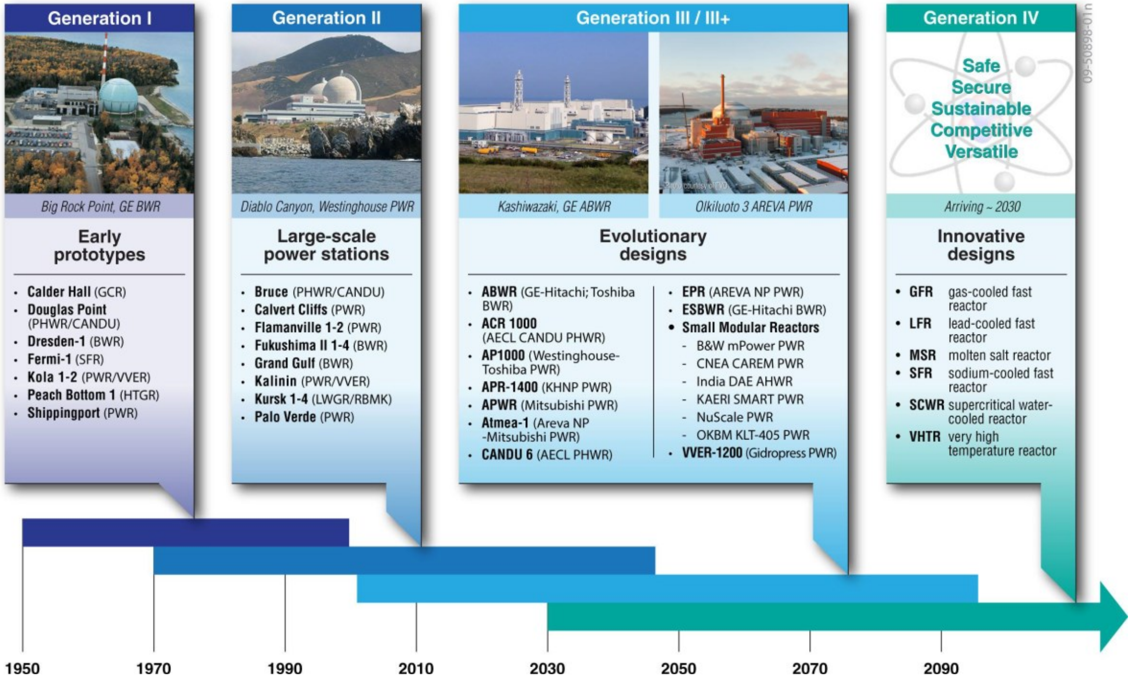
A long way done…

Evolution of nuclear reactors



…a new perspective forward!

Evolution of nuclear reactors



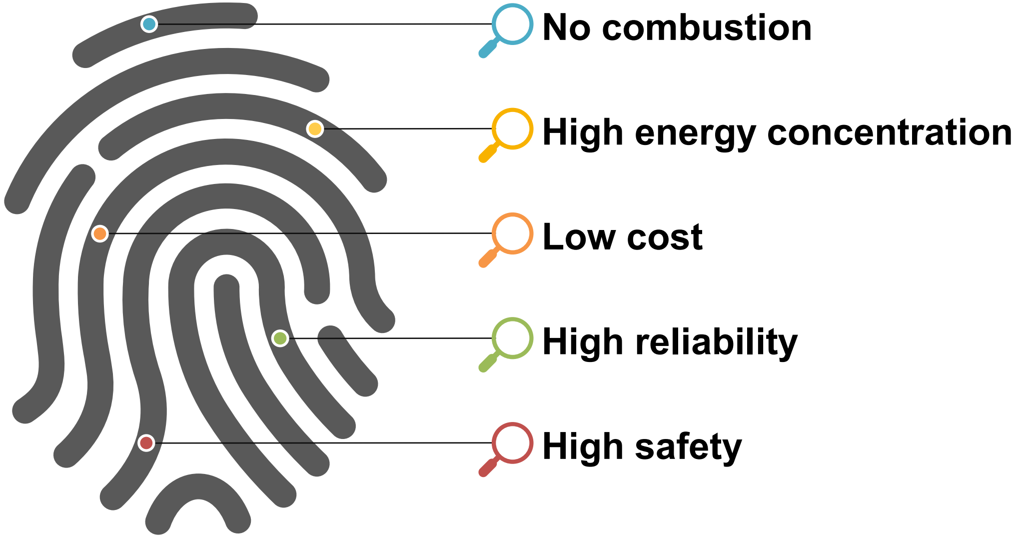
IV

Generation IV

Revolutionary concepts

Nuclear ID

Current generation reactors



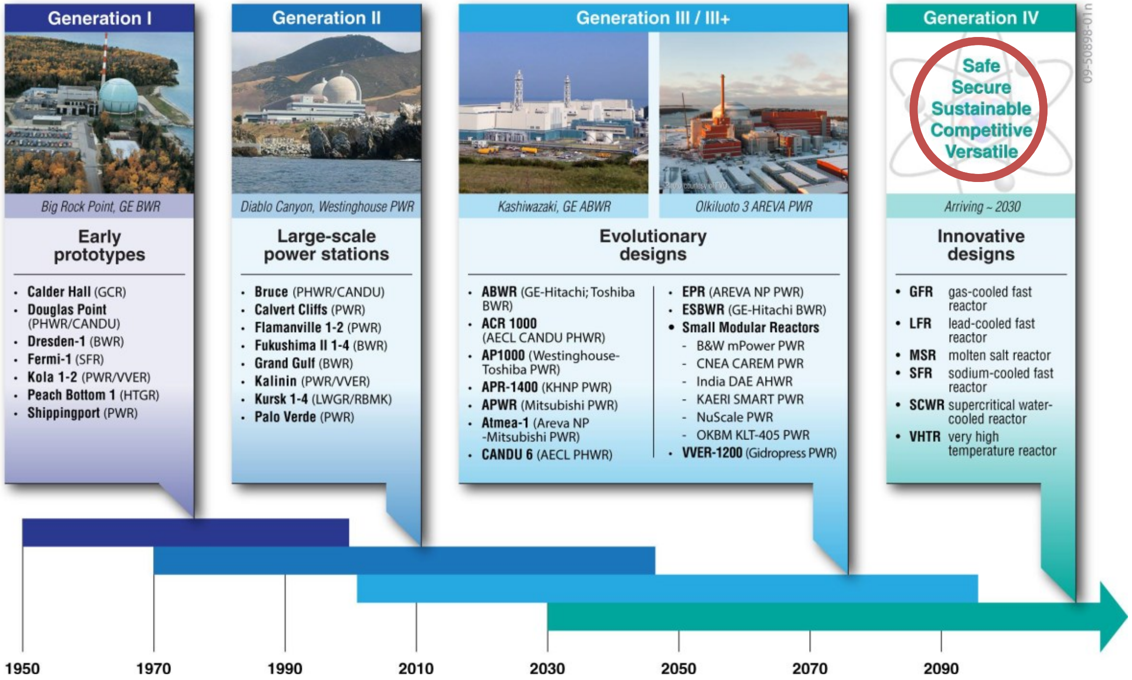
Nuclear ID

Next generation reactors

- No combustion
- High energy concentration and minimal waste
- Low cost and low investment
- High reliability
- Inherent safety

…a new perspective forward!

Evolution of nuclear reactors

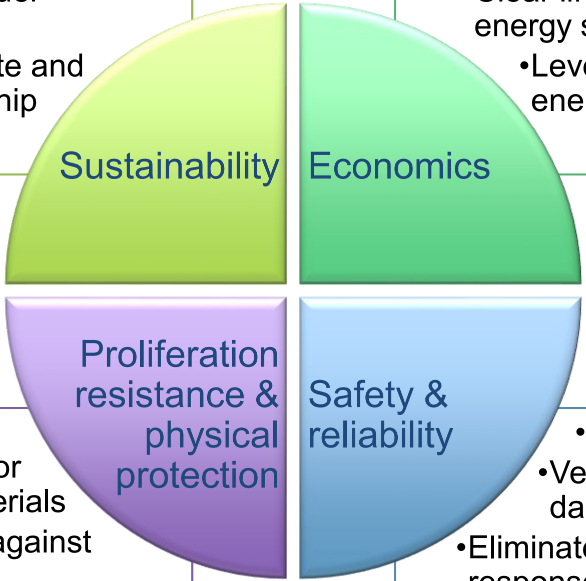


Vision

Next generation nuclear systems: Generation IV

- Meet clean air objective and effective fuel utilization
- Minimise and manage the nuclear waste and notably reduce the long-term stewardship burden

- Clear life-cycle cost advantage over other energy sources
- Level of financial risk comparable to other energy projects



- Increase assurance of being very unattractive and least desirable route for diversion/theft of weapons-usable materials
- Provide increased physical protection against acts of terrorism

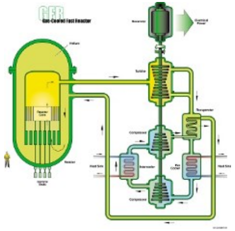
- Excel in safety & reliability of operation
- Very low likelihood and degree of core damage
- Eliminate the need for offsite emergency response

Vision

Next generation nuclear systems: Generation IV

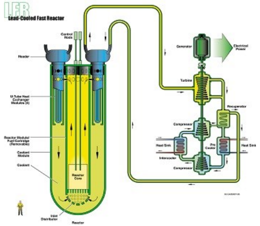
GFR

Gas-cooled Fast Reactor



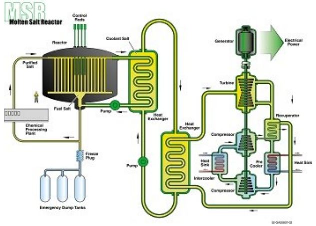
LFR

Lead-cooled Fast Reactor



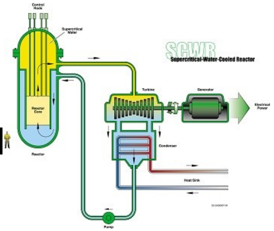
MSR

Molten Salt Reactor



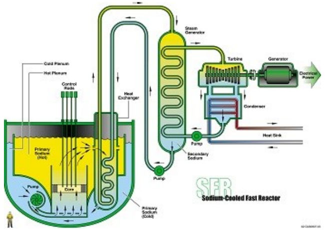
SCWR

Supercritical Water Reactor



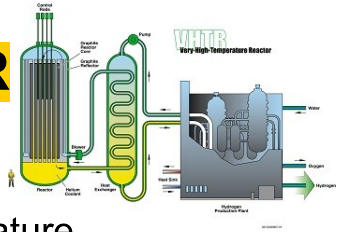
SFR

Sodium-cooled Fast Reactor



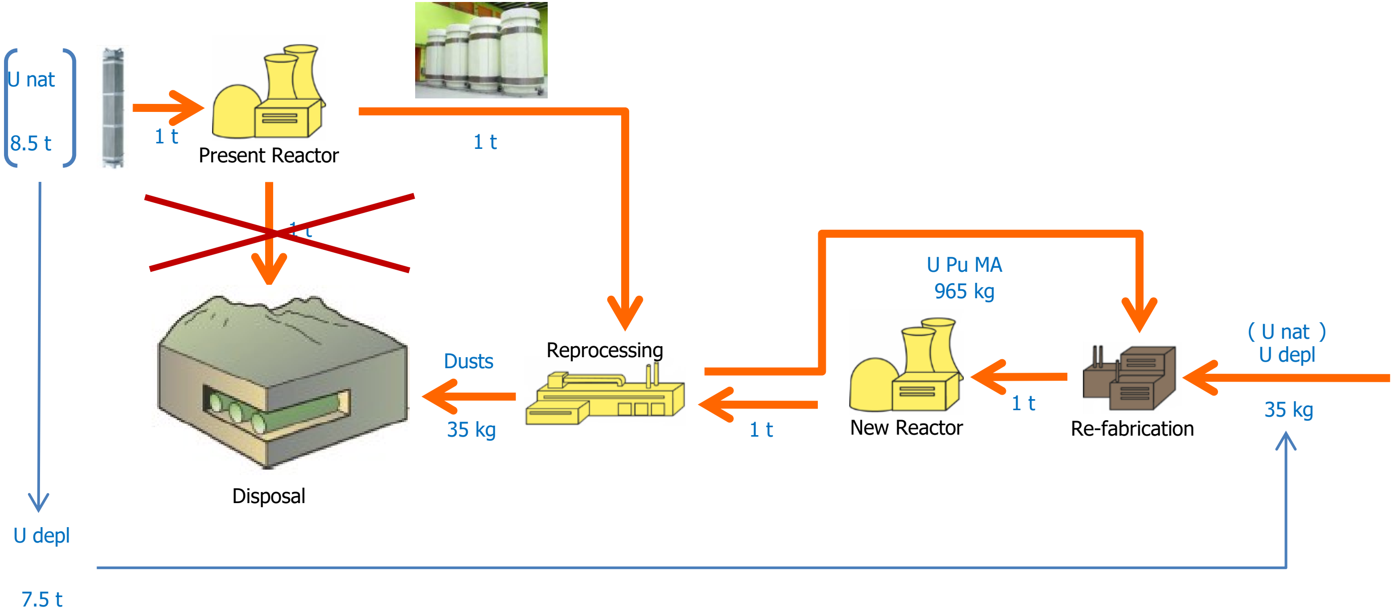
VHTR

Very-High Temperature Reactor



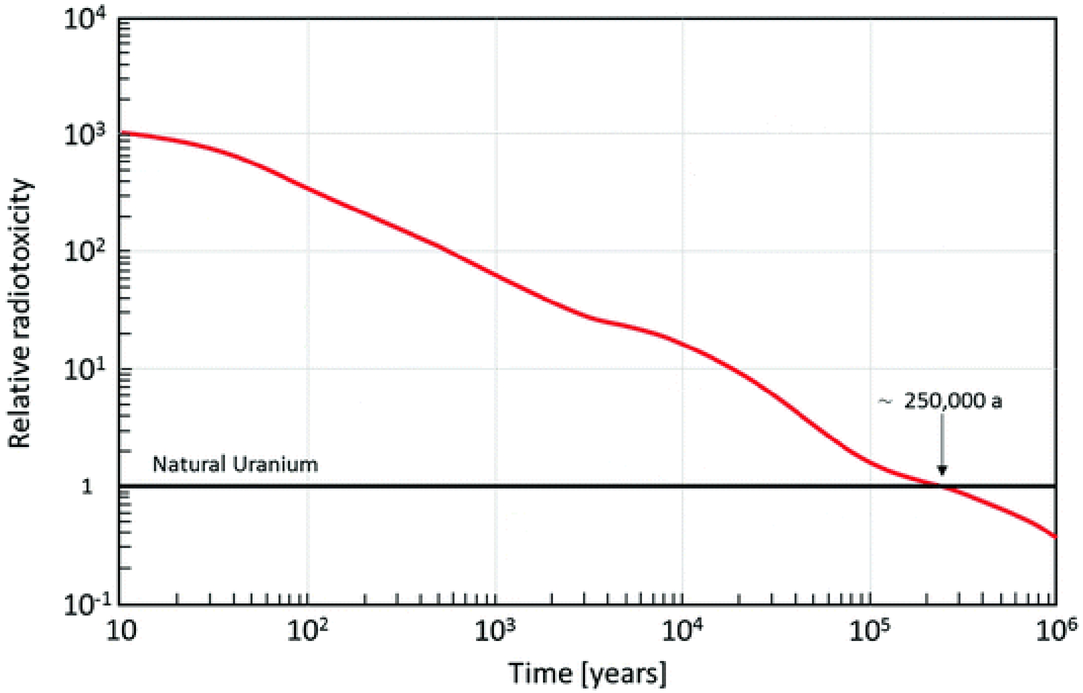
ENEA

Just a refresh on fuel cycle closure...



Enhanced sustainability

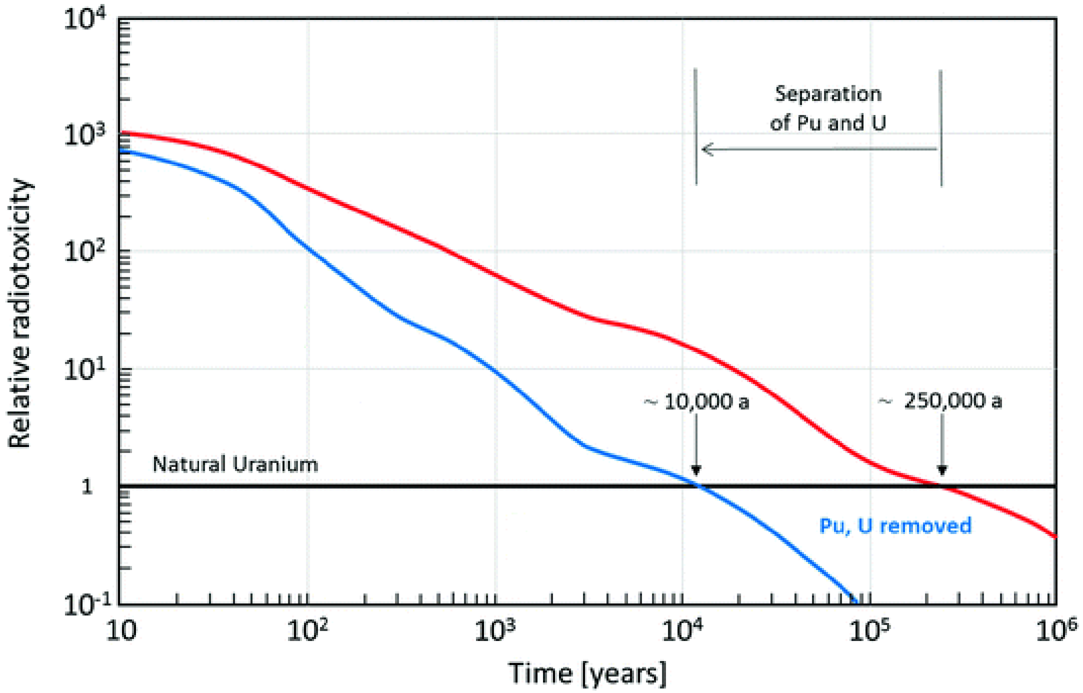
Even though the volume is small, thus the management is simple, the spent fuel from a plant of current generation has a high radiotoxicity, which reduces down to that of Uranium ore in times of the order of a hundred thousand years.



Enhanced sustainability

Current reactors moreover do not burn all the loaded fuel. In the spent fuel, hence, there are still valuable materials.

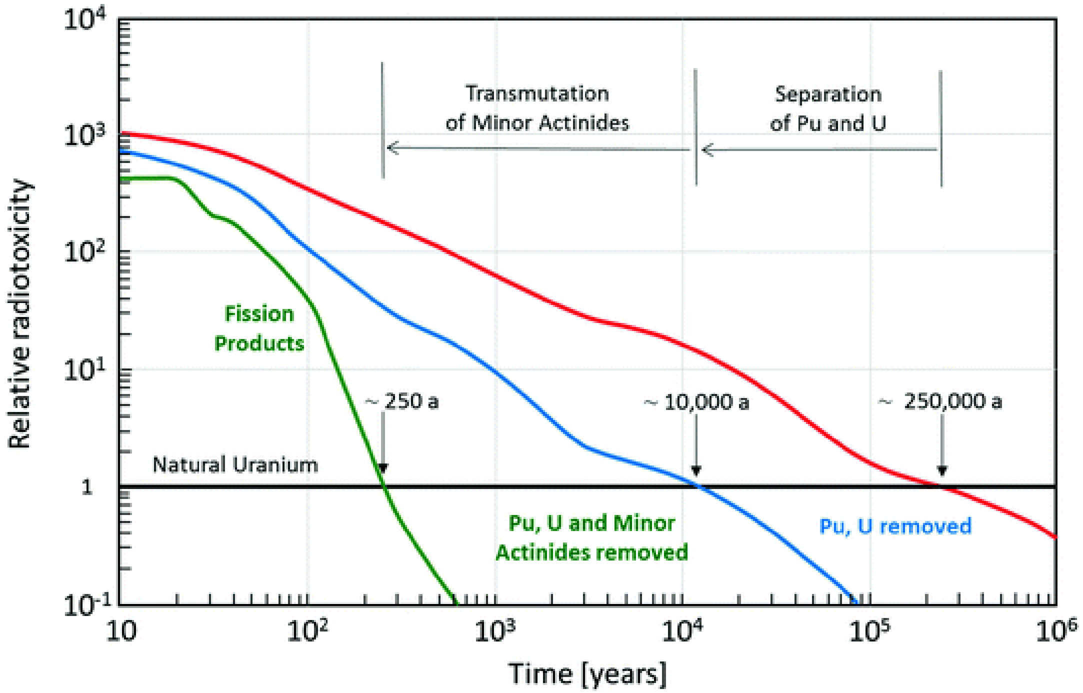
Some countries pursue the technique of reprocessing, to recover part of what is still useful for its reuse in the same reactors.



Enhanced sustainability

Fast spectrum reactors have the chance to fission (thus use) all actinide isotopes (and not just those of U and Pu).

By this, also other species can be recovered in reprocessing, leaving as actual waste only the fission products. This allows reducing the time of surveillance for the waste down to few centuries.



Generation IV concepts

Overview of pros and cons

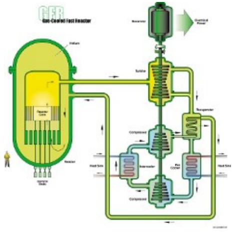
Aspect	GFR	LFR	MSR	SCWR	SFR	VHTR
Fuel cycle	Closed	Closed	Open/closed	Open/closed	Closed	Open

Generation IV concepts

Sustainability attribute: environmental

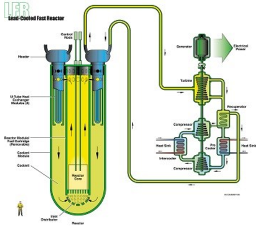
GFR

Gas-cooled Fast Reactor



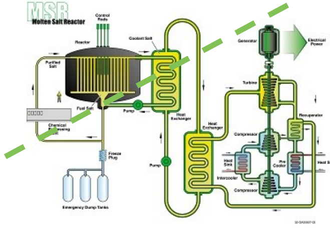
LFR

Lead-cooled Fast Reactor



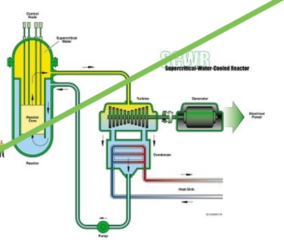
MSR

Molten Salt Reactor



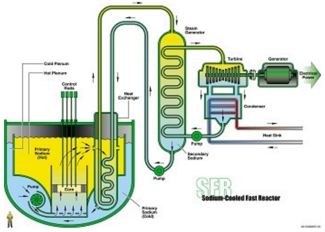
SCWR

Supercritical Water Reactor



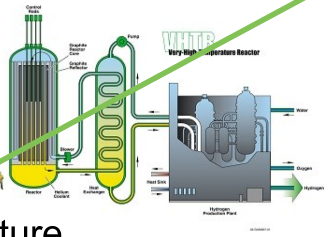
SFR

Sodium-cooled Fast Reactor



VHTR

Very-High Temperature Reactor



Generation IV concepts

Overview of pros and cons

Aspect	GFR	LFR	MSR	SCWR	SFR	VHTR
Fuel cycle	Closed	Closed	Open/closed	Open/closed	Closed	Open
Safety	*[see next slide for detailed discussion]*					

Generation IV concepts

Overview of safety pros and cons

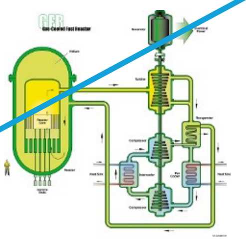
Aspect	GFR	LFR	MSR	SCWR	SFR	VHTR
Operation	High pressure Small reactivity swing	Ambient pressure Small reactivity swing	Ambient pressure Small/large reactivity swing	Very high pressure Small/large reactivity swing	Ambient pressure Small reactivity swing	High pressure Large/small reactivity swing
Incident	No thermal inertia	Natural circulation for decay heat High margin to boiling	Natural circulation for decay heat Little decay heat [if online refueling]		Natural circulation for decay heat Little margin to boiling	Little decay heat [if online refueling]
Accident	No thermal capacity No heat removal if LOCA	Natural circulation even at full power Production of ^{210}Po	Core already molten Delayed neutrons out of core	Risk of loss of coolant [if RCB breaks]	Positive void effect	Inherent heat removal by radiation
Severe accident		Fission product retention in lead	Lack of 1 barrier Reactivity with water, air [if fluorides]		Reactivity with water, air, fuel	Fission product retention in fuel

Generation IV concepts

Sustainability attribute: social (i.e., safety)

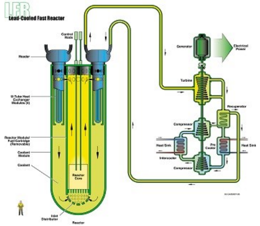
GFR

Gas-cooled Fast Reactor



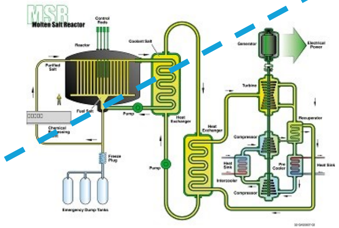
LFR

Lead-cooled Fast Reactor



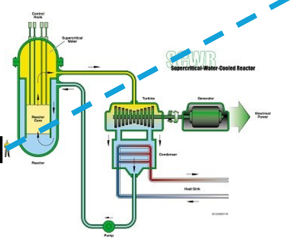
MSR

Molten Salt Reactor



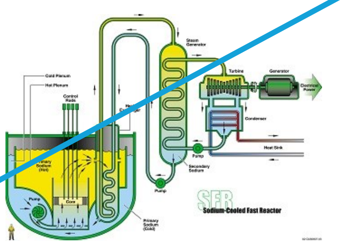
SCWR

Supercritical Water Reactor



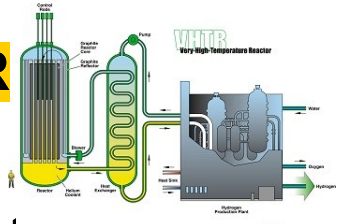
SFR

Sodium-cooled Fast Reactor



VHTR

Very-High Temperature Reactor



ENEA

Generation IV concepts

Overview of pros and cons

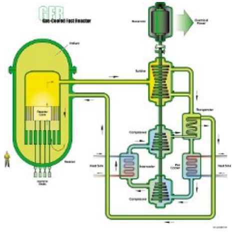
Aspect	GFR	LFR	MSR	SCWR	SFR	VHTR
Fuel cycle	Closed	Closed	Open/closed	Open/closed	Closed	Open
Safety	*[see next slides for detailed discussion]*					
Economy	Believed cheap (designs exist)	Believed cheap (designs exist)	Aimed cheap (no design yet)	Believed cheap (designs exist)	Proved expensive	Proved very expensive

Generation IV concepts

Sustainability attribute: economic

GFR

Gas-cooled Fast Reactor



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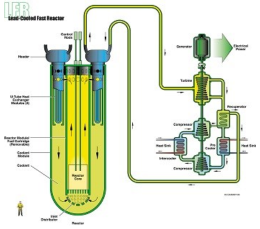

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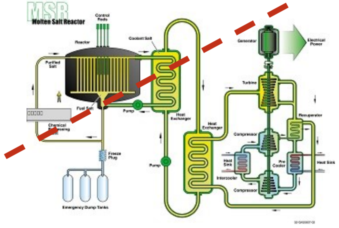

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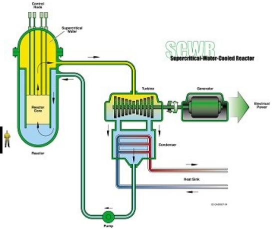

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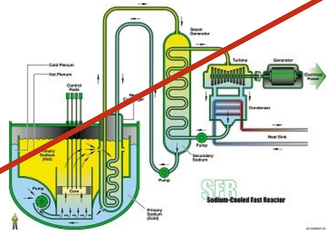

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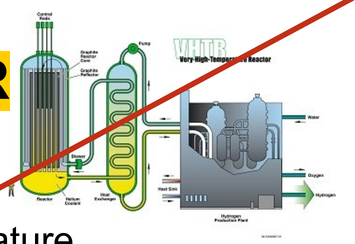
Very-High Temperature Reactor

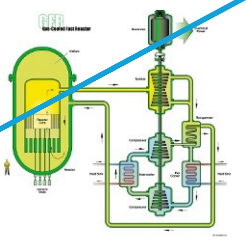


Generation IV concepts

Sustainability attributes: environmental, social, economic

GFR

Gas-cooled Fast Reactor



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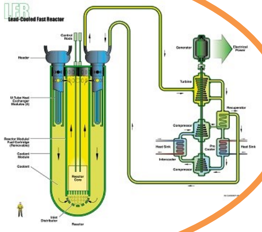

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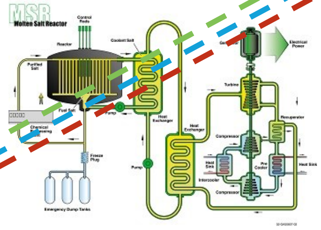
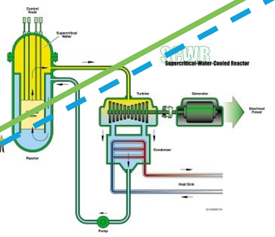
Molten Salt Reactor



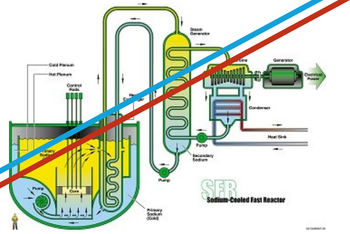
SCWR

Supercritical Water Reactor



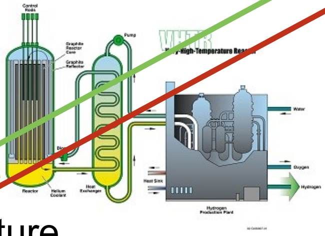
SFR

Sodium-cooled Fast Reactor



VHTR

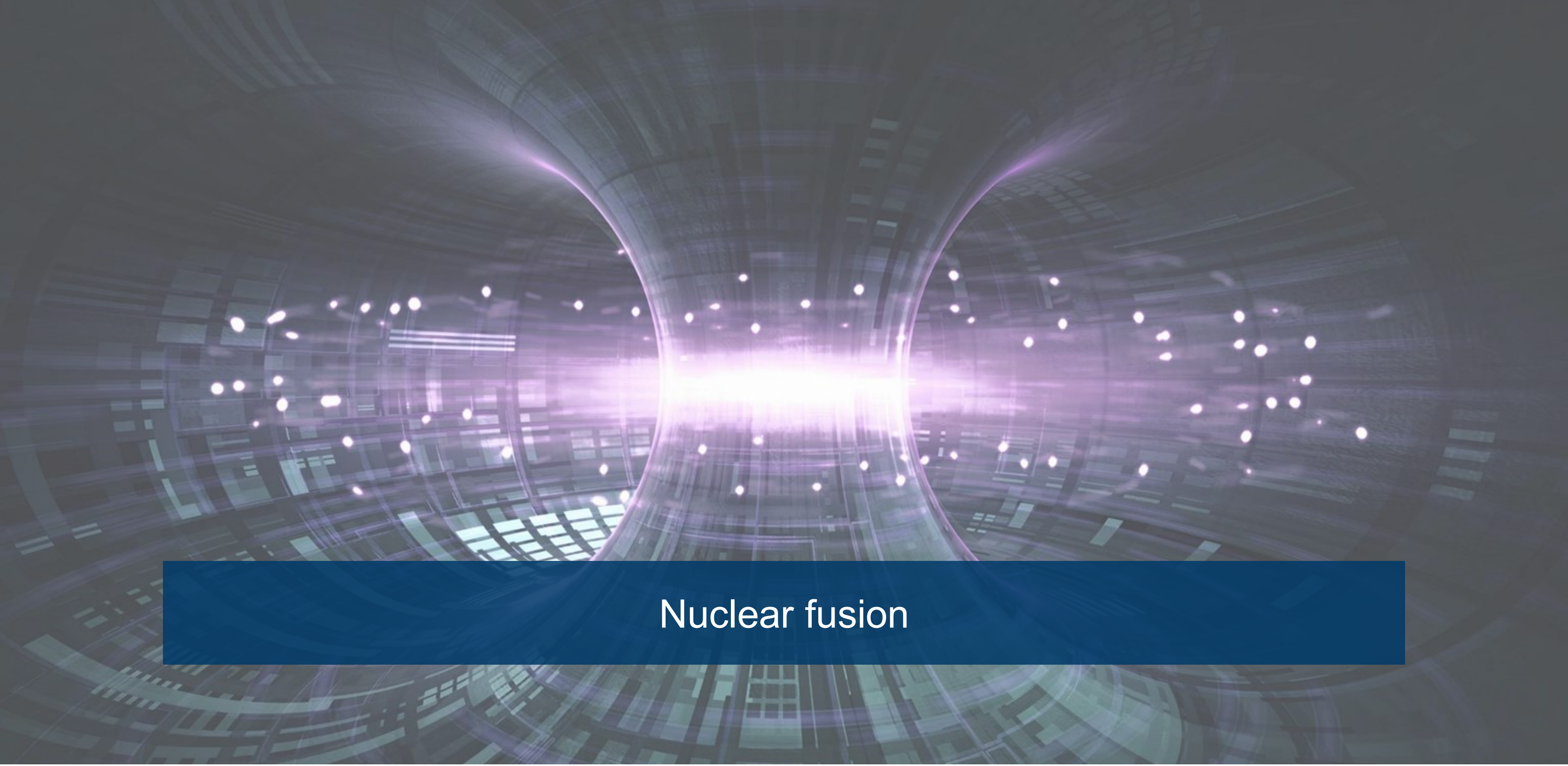
Very-High Temperature Reactor



Generation IV concepts

Overview of pros and cons

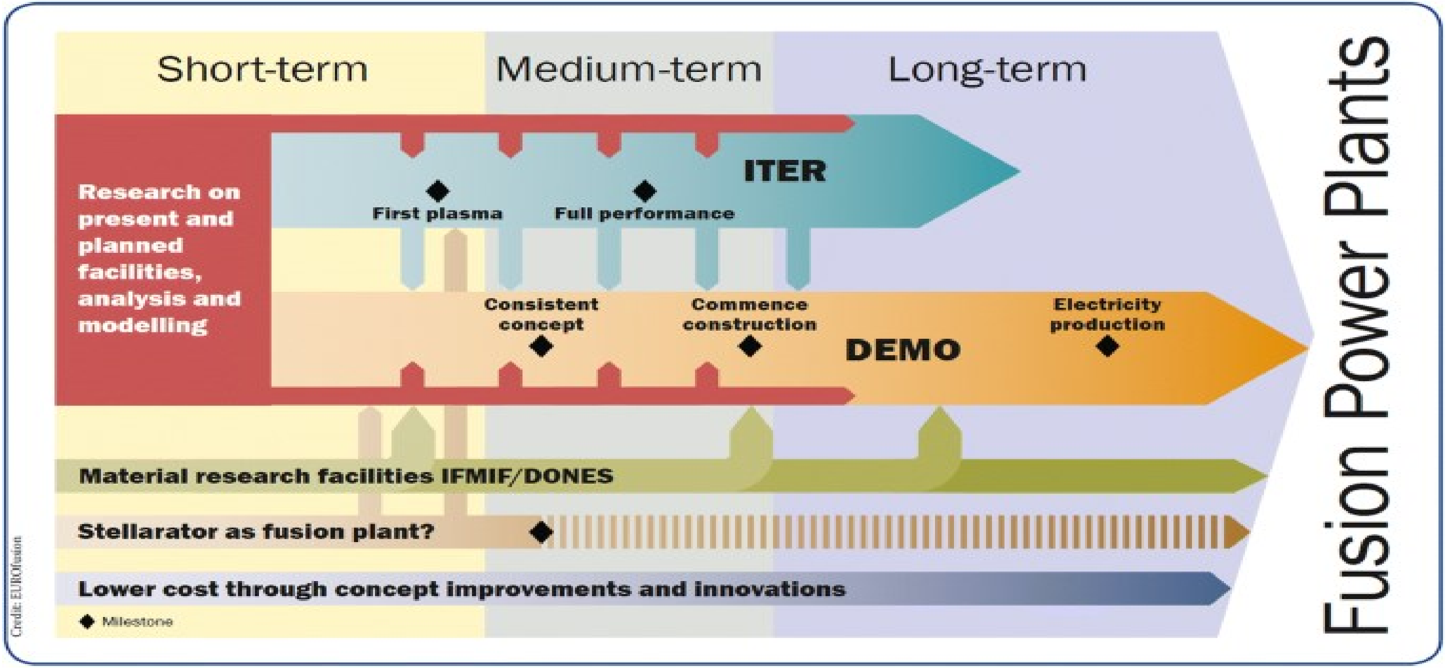
Aspect	GFR	LFR	MSR	SCWR	SFR	VHTR
Fuel cycle	Closed	Closed	Open/closed	Open/closed	Closed	Open
Safety	*[see next slides for detailed discussion]*					
Economy	Believed cheap (designs exist)	Believed cheap (designs exist)	Aimed cheap (no design yet)	Believed cheap (designs exist)	Proved expensive	Proved very expensive
Readiness	Never tested	Tested in USSR (7 military submarines)	Tested in USA (1 experiment)	Never tested (but leverages LWRs)	Largely tested	Never tested (but leverages HTRs)
Challenges	Refractory fuel and materials	Corrosion resistance	Corrosion resistance			Refractory materials



Nuclear fusion

Nuclear fusion

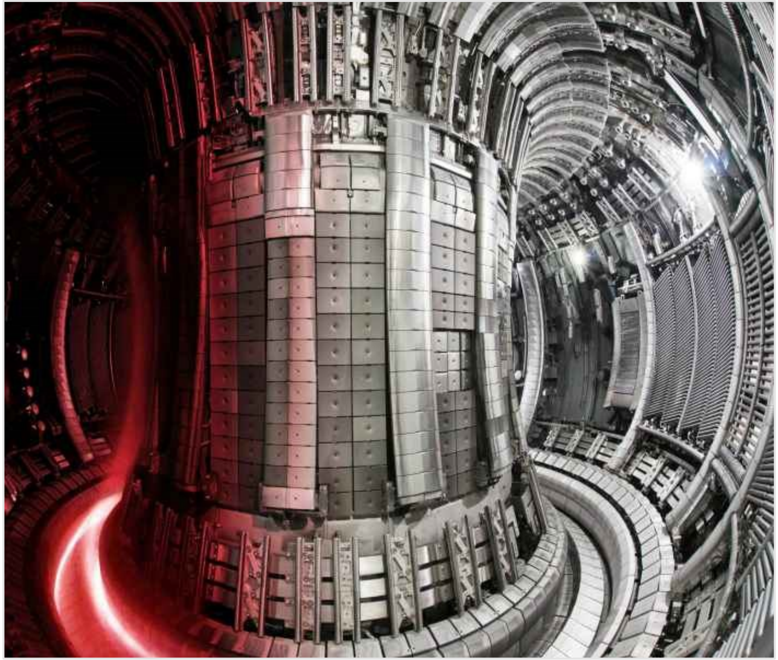
In the meantime



Nuclear fusion

Short term: fusion is feasible

Until now, in the world, several experimental machines have been built for basic research on the physics and technology of magnetic confinement fusion.

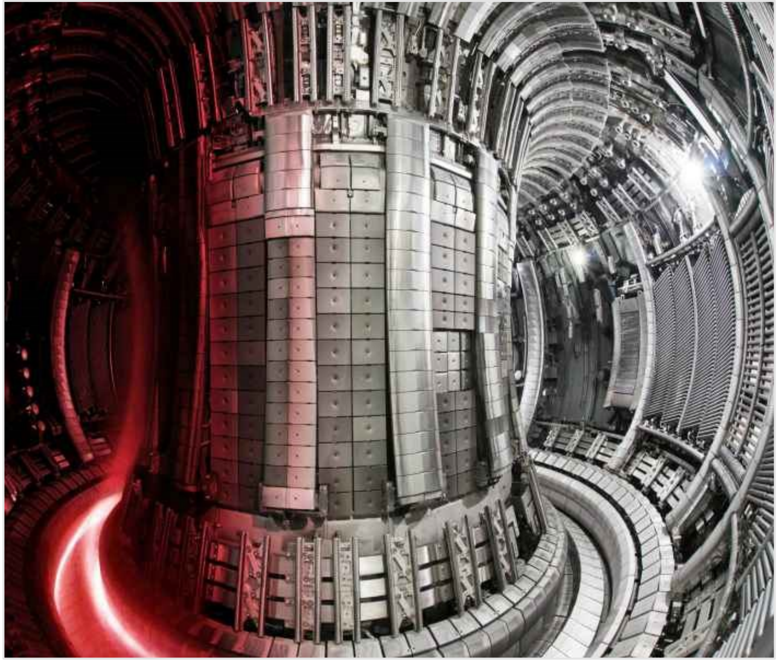


Nuclear fusion

Short term: fusion is feasible

Until now, in the world, several experimental machines have been built for basic research on the physics and technology of magnetic confinement fusion.

To address the next steps of development, much larger machines are needed, whose cost and complexity requires international cooperation.

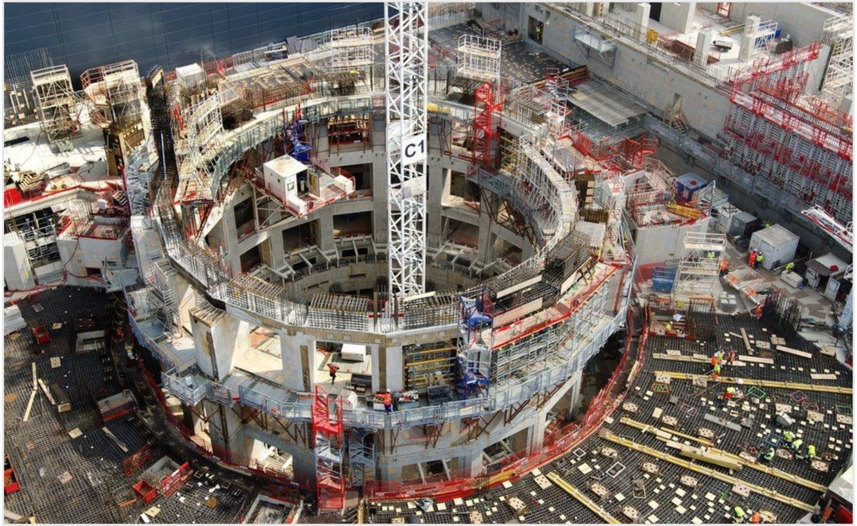


Nuclear fusion

Short term: fusion is feasible

The first of such large machines, made through an international cooperation, is ITER, currently under construction in Cadarache, Provence.

ITER will be fully operational by 2030, and will be used to demonstrate the scientific and technological feasibility of fusion.

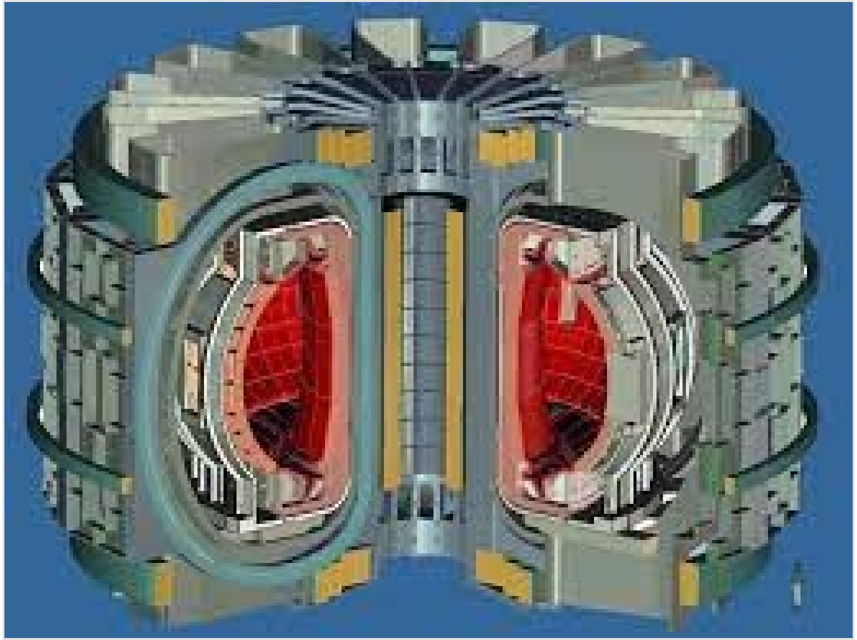


Nuclear fusion

Medium term: fusion is practicable

On the basis of the results gathered thanks to ITER, it will be possible to refine the design of the next fusion machine: DEMO.

DEMO will be requested to demonstrate the feasibility of generating, and providing to the grid, electric energy from nuclear fusion.

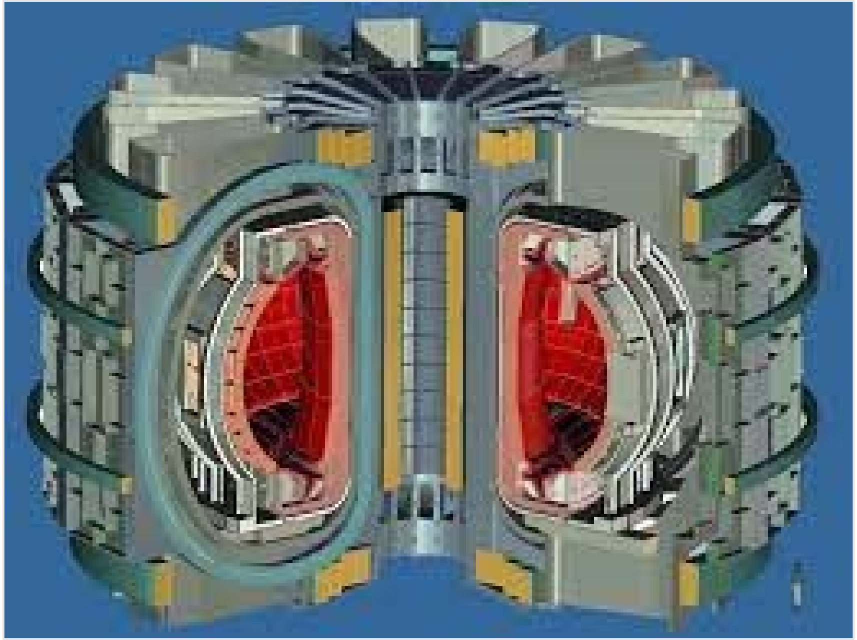


ENEA

Nuclear fusion

Medium term: fusion is practicable

The operation of DEMO will allow to gather precious information to solve the problem of retrieving more energy than what is needed to make a fusion machine work.

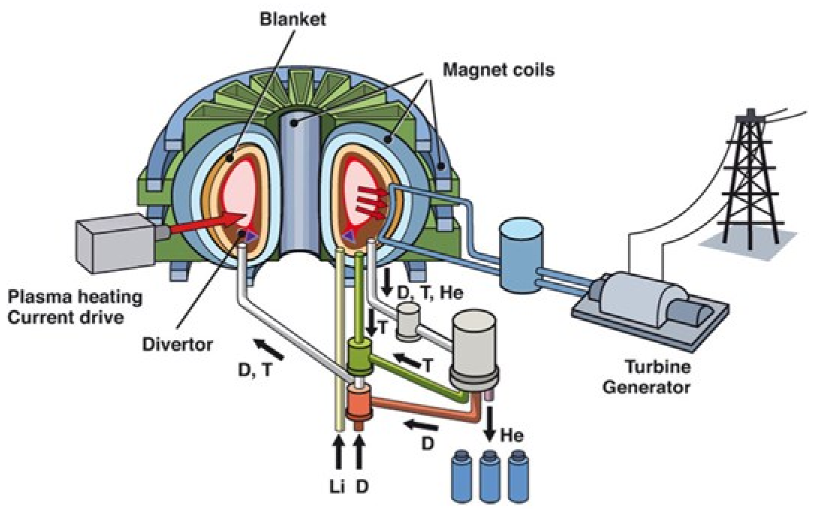


Nuclear fusion

Long term: fusion is exploitable

The operation of DEMO will allow to gather precious information to solve the problem of retrieving more energy than what is needed to make a fusion machine work.

This information will therefore be used in support of the design of what will be the first fusion reactor for electricity production.



Giacomo Grasso
giacomo.grasso@enea.it