DE LA RECHERCHE À L'INDUSTRIE

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CLOSED FUEL CYCLE AND TRANSITION FROM THERMAL TO FAST REACTORS

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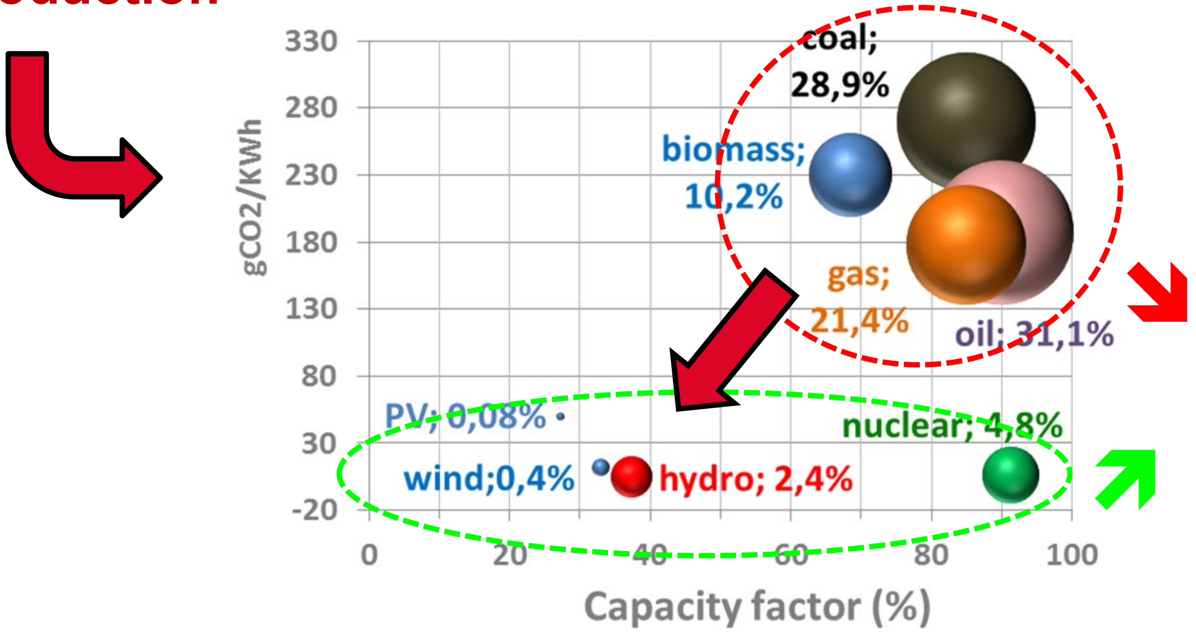
INTRODUCTION

The challenge of the Energy Transition

❶ Increase the energy production

❷ Mitigate the climate change



COP21 · CMP11
PARIS 2015
UN CLIMATE CHANGE CONFERENCE

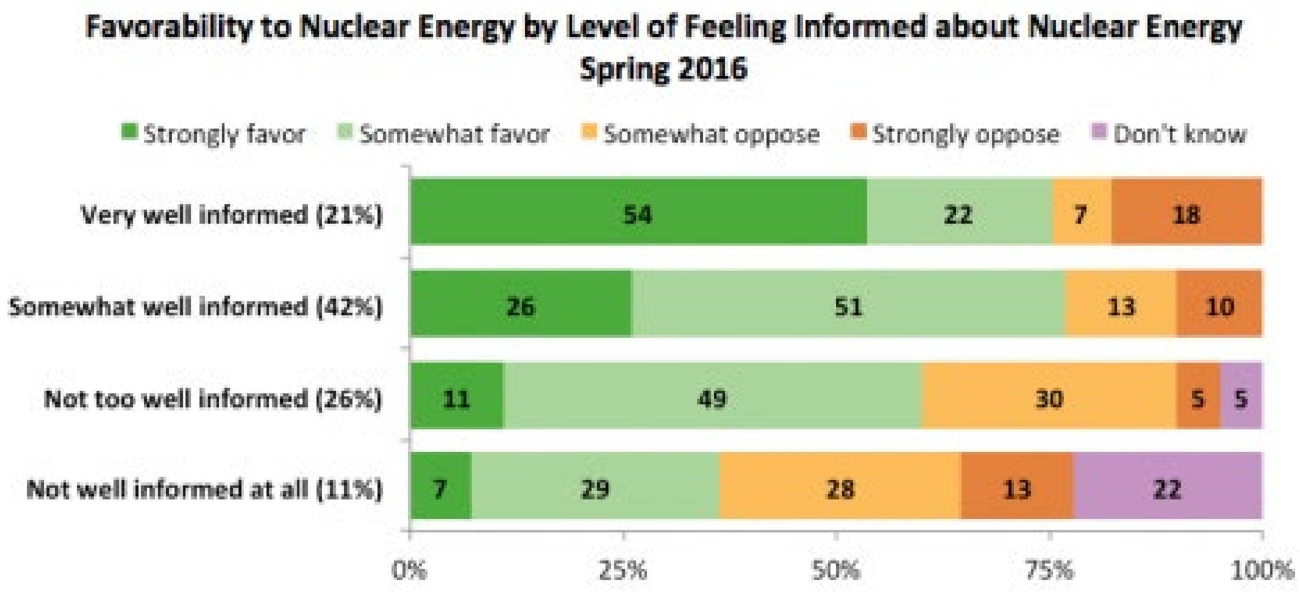
Energy transition

- ❶ ↗ Energy efficiency
- ❷ ↘ fossil energies ⇔ ↗ renewable energies + nuclear energy

Energy transition … will require energy technologies that are power dense and capable of scaling to many tens of TWh … Most forms of renewable energy are, unfortunately, incapable of doing so … Nuclear fission today represents the only present-day zero-carbon technology … able to meet …

Ecomodernist Manifesto, 2015

Technically, nuclear power could seem to be the most promising energy, but …



The less information people have, the most scared they are by nuclear

Need for a more systemic approach

« Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. (…) »

(Bruntland's commission, 1987)

Recent concern
Climate change
Overall Footprint

How to improve environmental footprint?

- *GHG-free energy*
- *Preservation of natural resource*
- *Reduce and manage ultimate waste*
- *Low environmental footprint*

Viable

Bearable

Equitable

Baseline for technology development

How to ensure affordability?

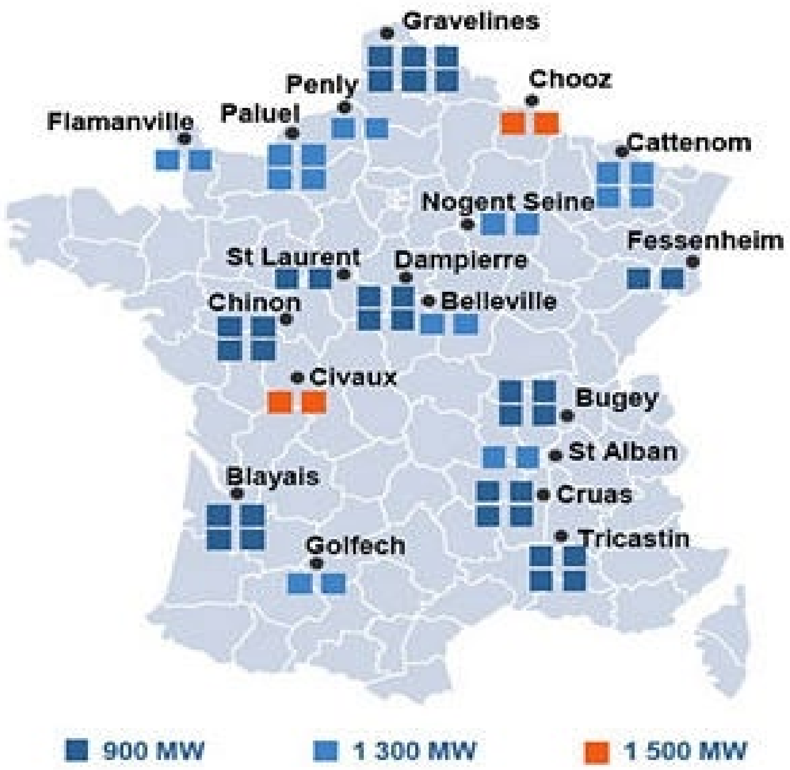
- *Predictable, stable and limited energy cost*
- *Economic stability through energetic independence*

reducing risks, democratic choice,

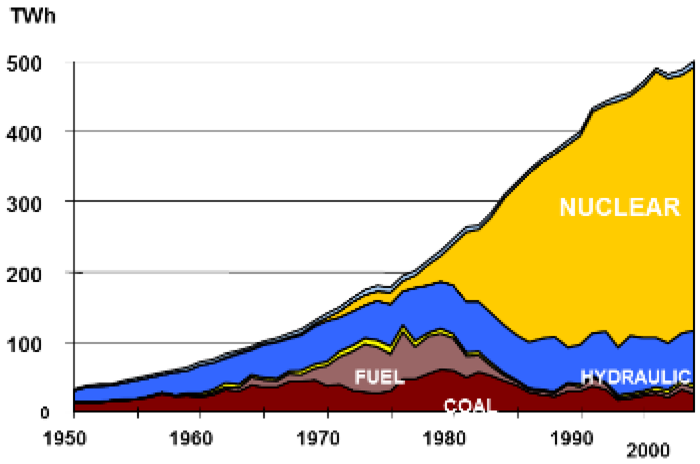
How to improve acceptability?

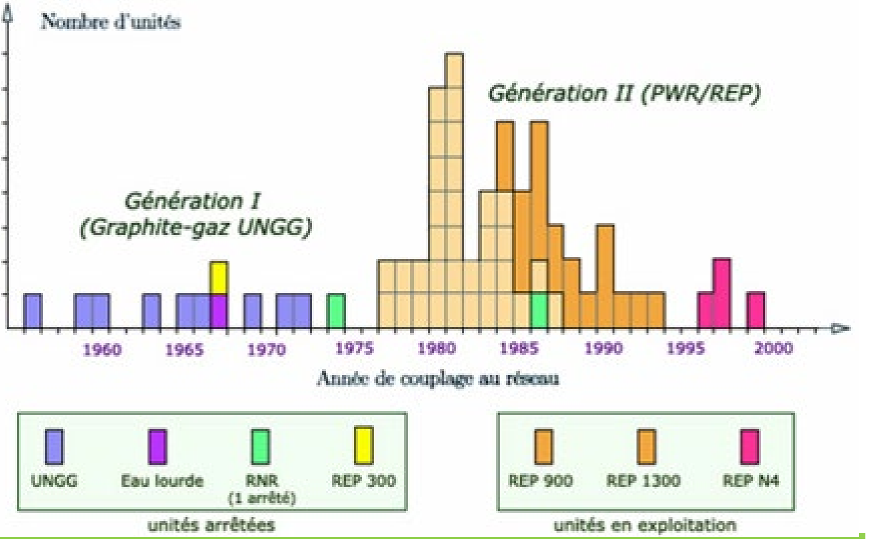
- *Highest level of safety and reliability*
- *Consensual choice of the society*
- *Promote the international stability*

Presentation of the reference case: French nuclear powerplants fleet



- **58** reactors located on 19 sites, capped at 63,2 GWe
- **Standardised fleet**: 1 single reactor types, with 3 different powers 900, 1300 et 1450 MWe
- Produce 70-80% of French electricity (~400-450 TWh), i.e. 40% of total French primary energy
- Reactors connected between 1977 and 1999
- **12** GEN1 generation reactors halted
- **1** GEN3 generation reactor under construction (Flammanville3, EPR)



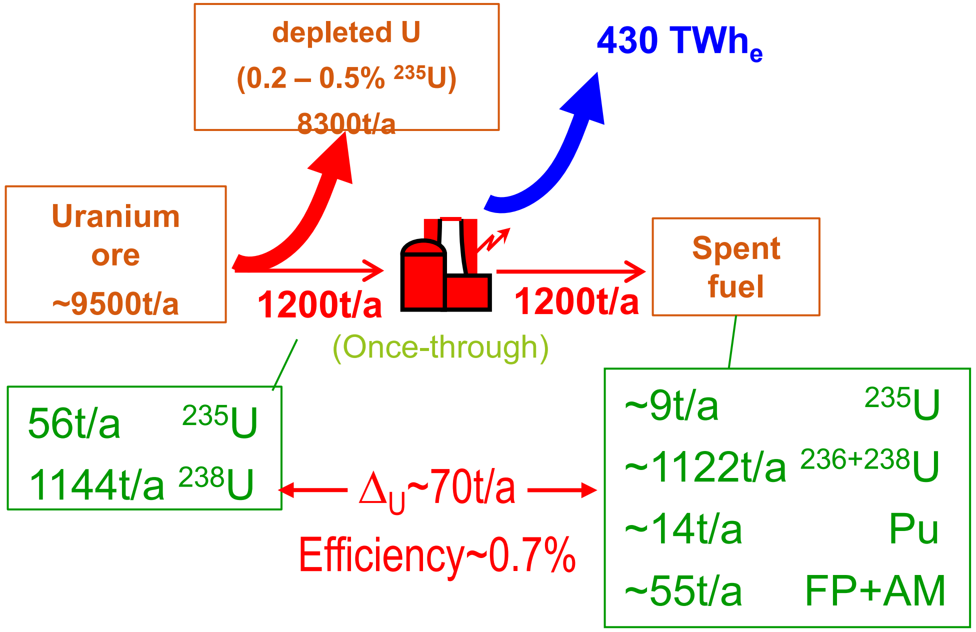


THE OPEN FUEL CYCLE

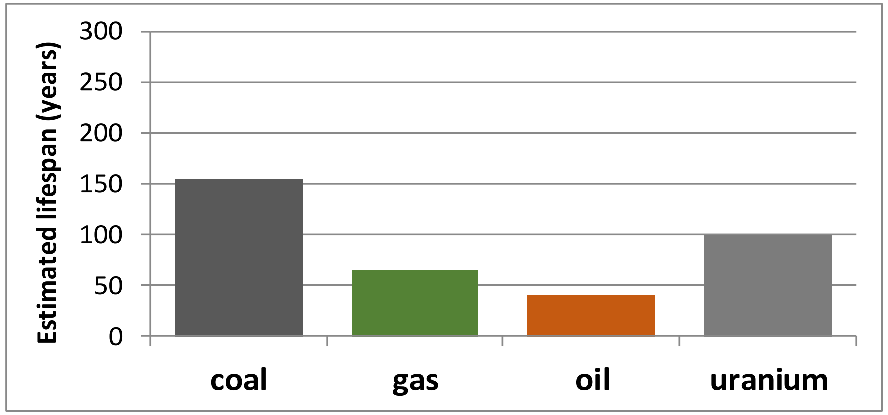
Nuclear Energy Today – open fuel cycle
Spent fuel as the ultimate waste

Does not preserve natural resource

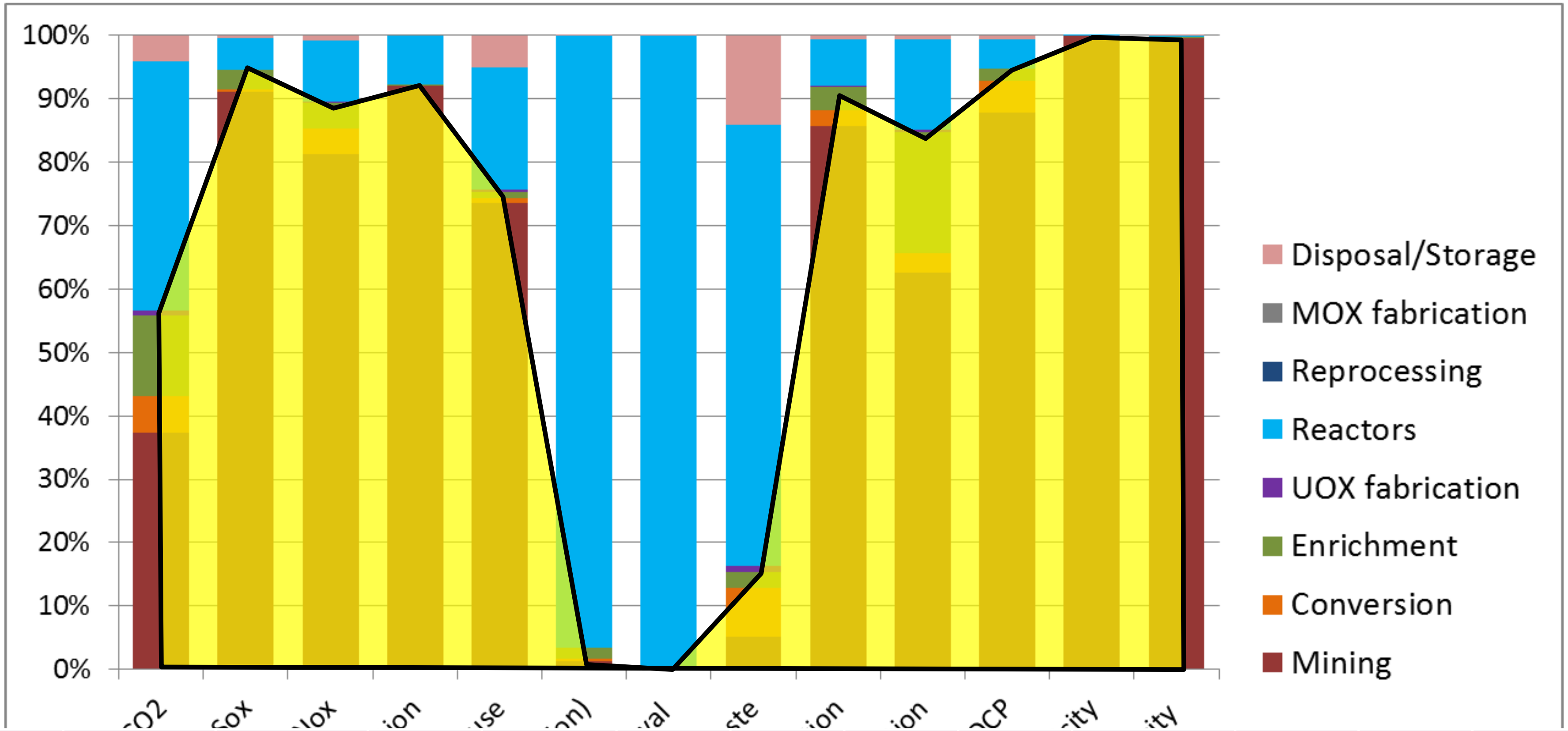
- Natural U is a limited resource
  - Although present everywhere, U-ores of reasonable economic interest are limited (260$/kg U)
  - Minimum lifespan ~135 years *(with current consumption 56kt/y)*
  - Need for preserving U-resource
- Global efficiency is currently very low: ~0.7%
  - ~70t from the initial ~9500t Uore
- **Need for improving U-efficiency**



Rough estimates derived from French Fuel cycle assuming no recycling



Environmental impact of the open fuel cycle

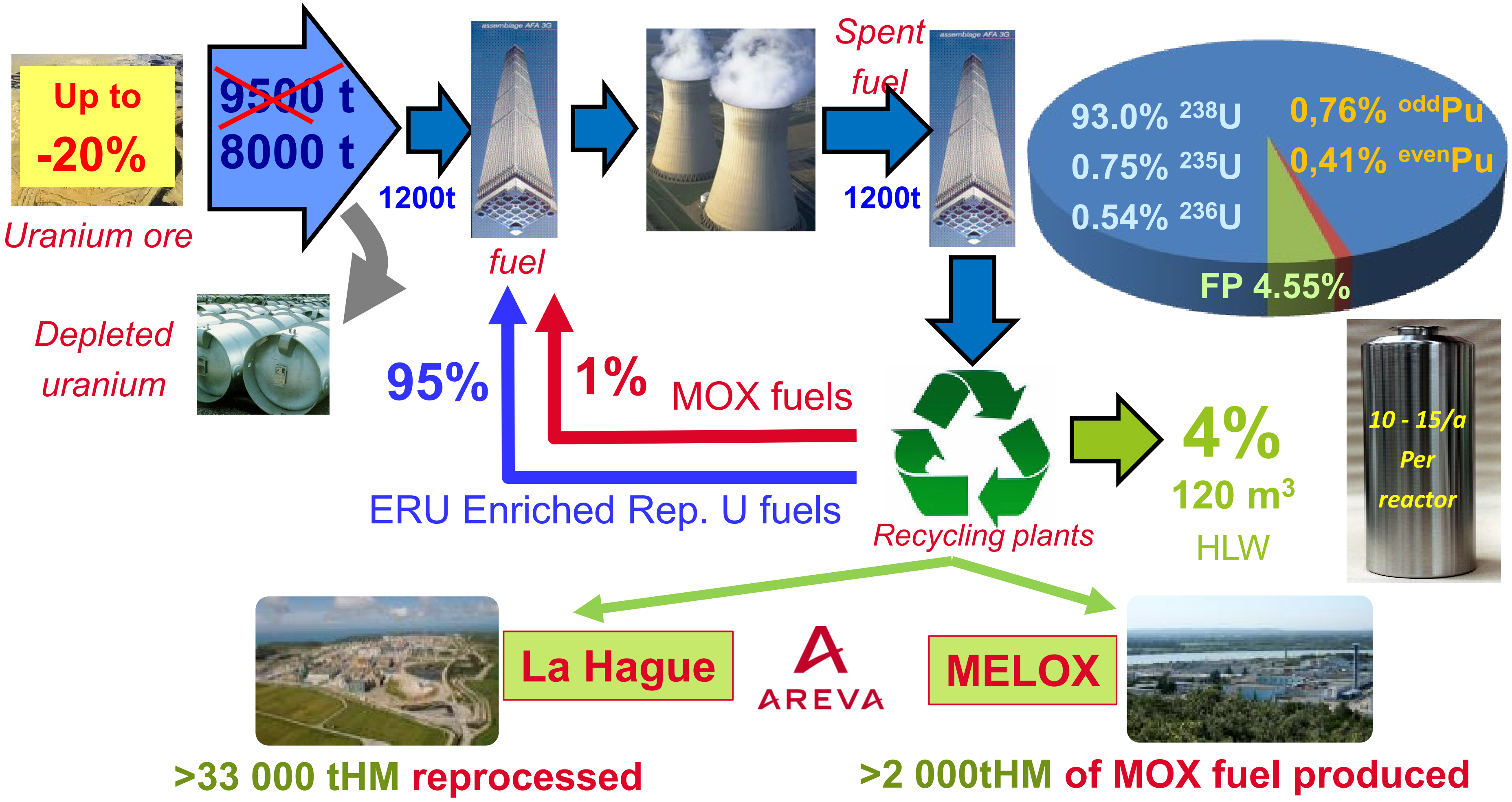


CO2 (g/KWhe)	Sox (g/KWhe)	Nox (g/KWhe)	Water pollution (mg/ kWhe)	Land use (m2year/M Whe)	Water cons (L/MWhe)	Water With (L/MWhe)	Techno Waste (g/MWHe)	Acidif (gSO2eq/ MWh)	Eutroph (gPO4eq/ MWh)	POCP (gC2H4eq/ MWh)	Ecotox (g1,4-DCBeq/ MWh)	Human toxicity (g1,4-DCBeq/ MWh)
5,45	0,0187	0,0290	341,67	234,63	1511,4	72369,2	28,9	39,15	5,31	3,32	761,60	1471,29

THE CLOSED FUEL CYCLE

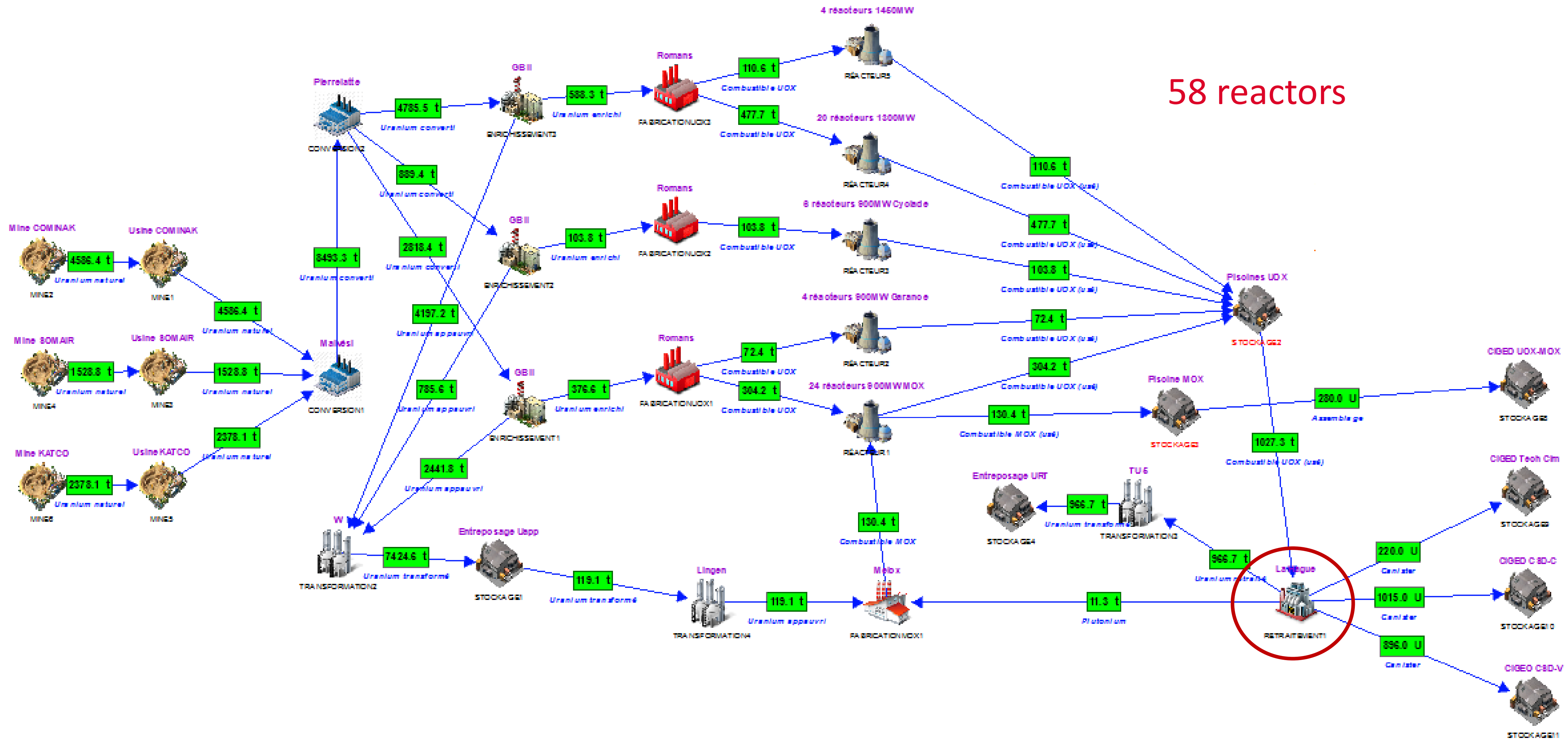
Nuclear Energy Today – French fuel cycle
Plutonium mono-recycling in MOX fuel

Or Twice-Through fuel Cycle (TTC), also known as closed fuel cycle



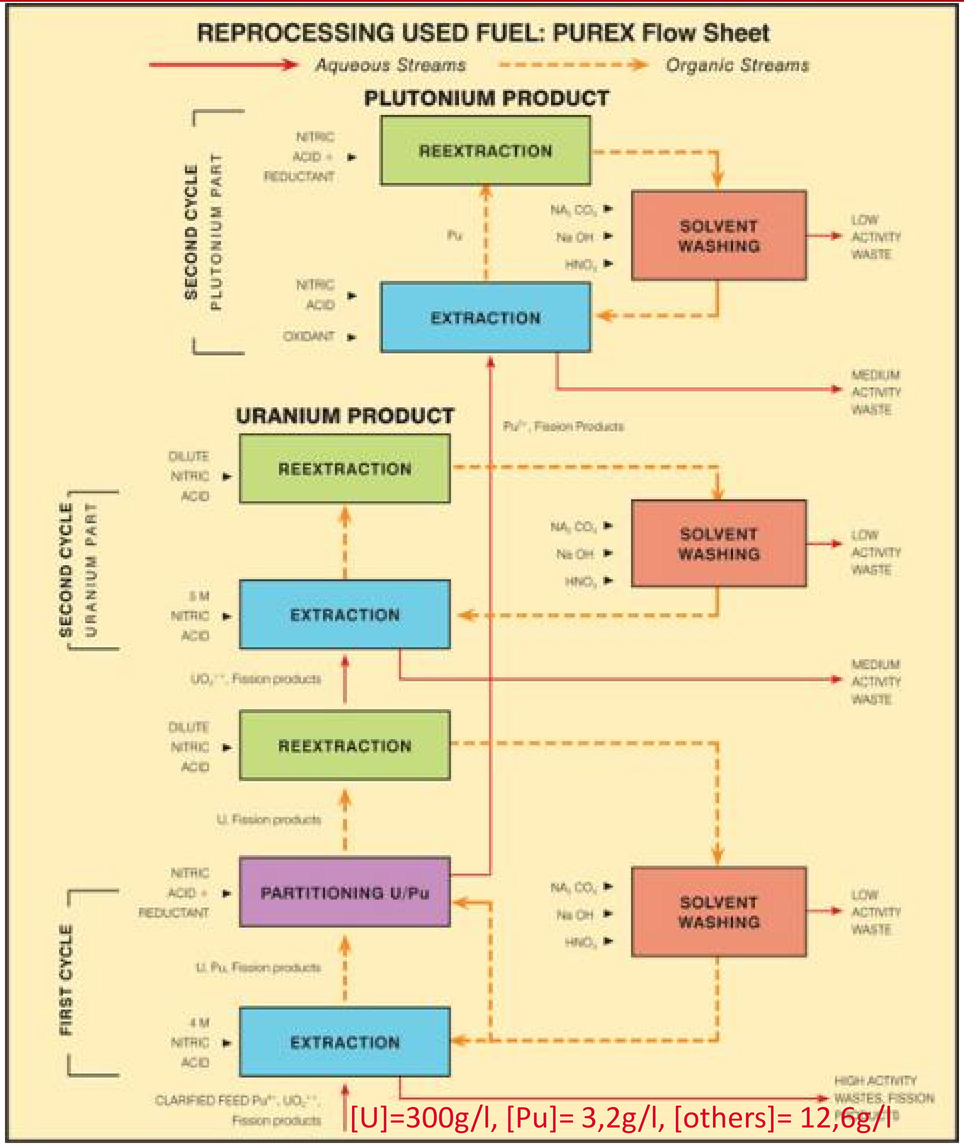
- 15 to 20% of French electricity yearly supplied by recycled materials
- ~1500t uranium ore yearly preserved
- No significant SNF interim storage ⇔ risk reduced

The current industrial French « closed » fuel cycle



58 reactors

The industrial PUREX process at la Hague: U and Pu recovery



Solvent extraction process

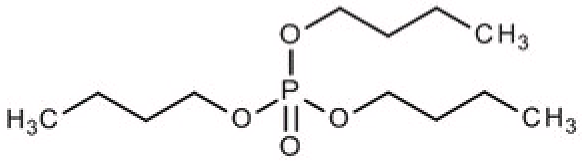
Aqueous phase: nitric acid

Organic phase: TBP in aliphatic diluent

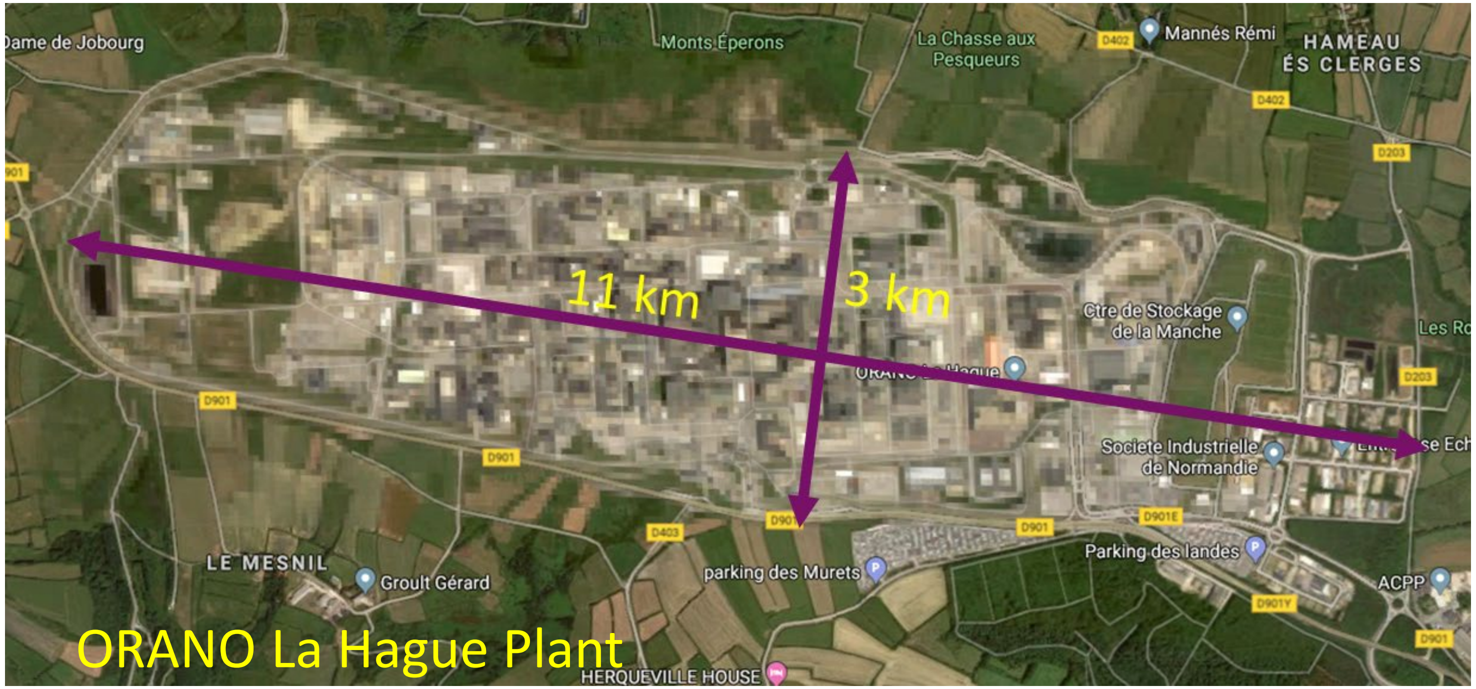
Recovery yields U/Pu >99,8%

Decontamination factor $>10^7$

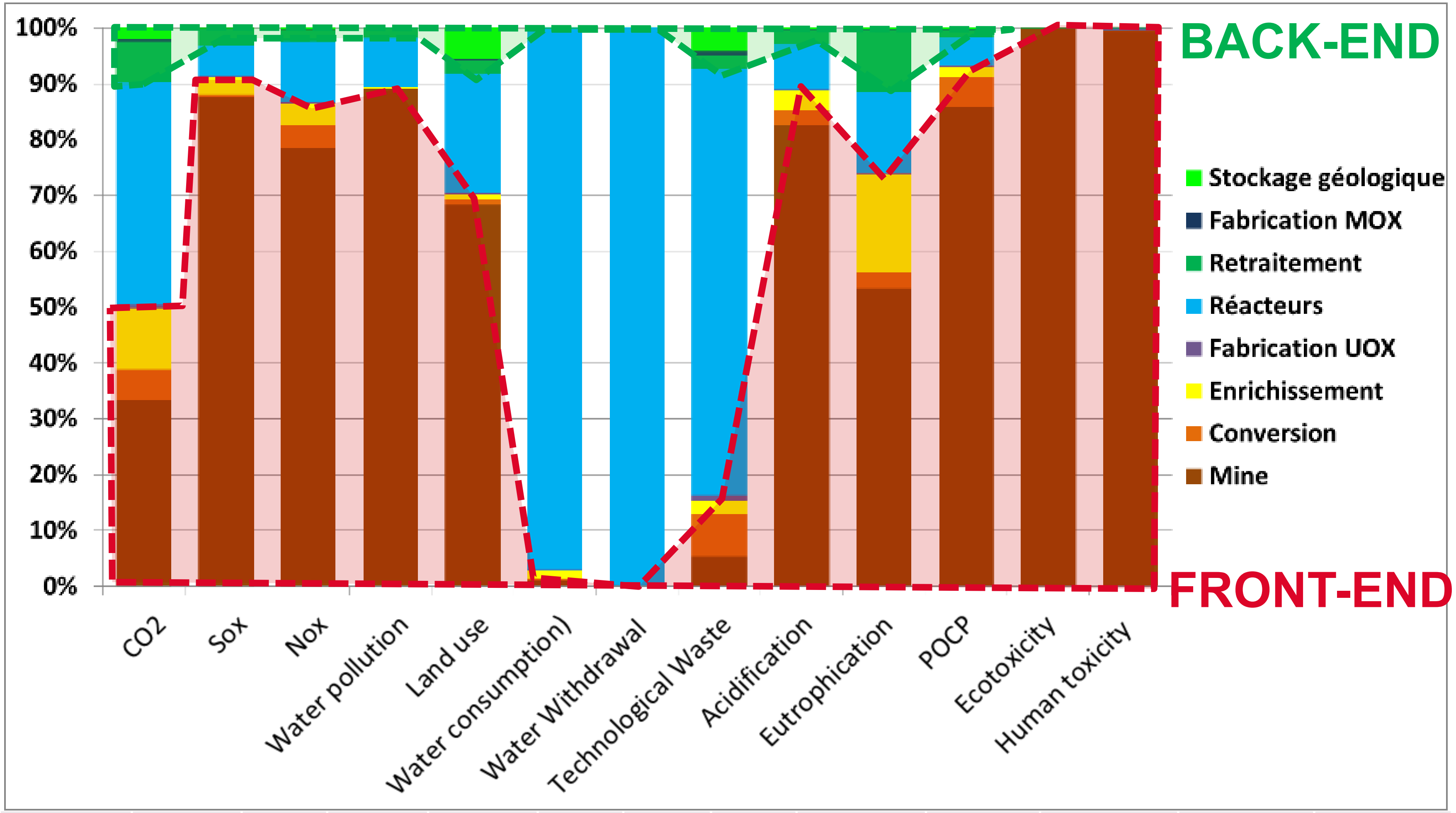
$$DF=\frac{\frac{[impurity]_{ini}}{[product]_{ini}}}{\frac{[impurity]_{final}}{[product]_{final}}}$$



TBP: tri-butyl phosphate

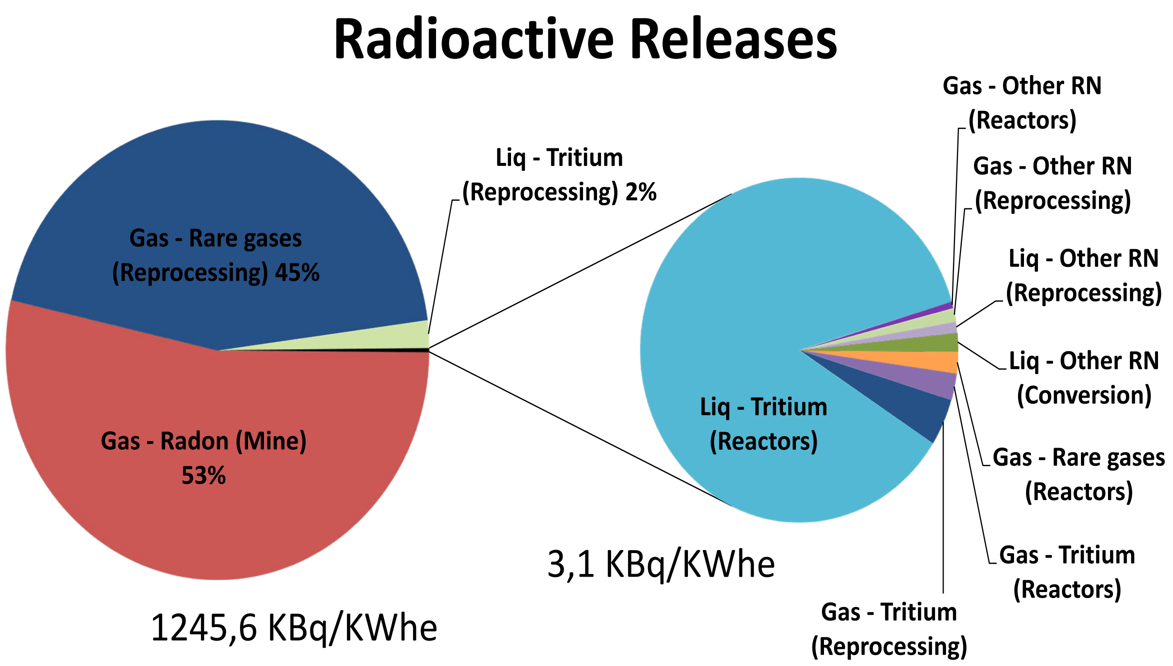


Environmental impact of the TTC

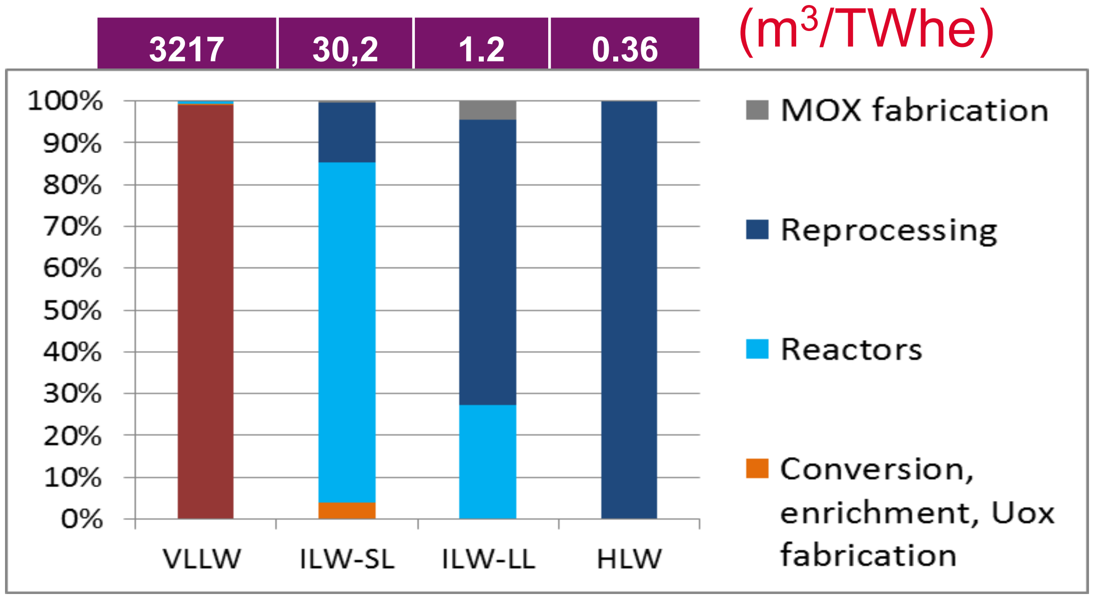


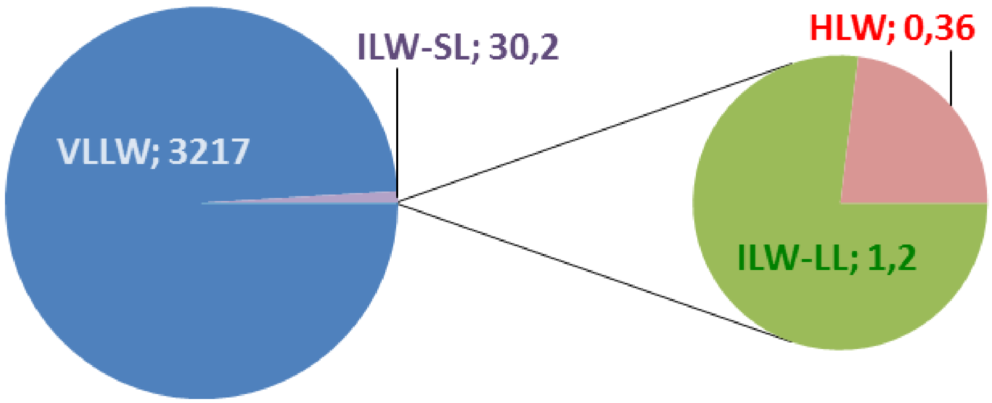
5,2 gCO_{2eq}/kWh	0,02 g/kWh	0,02 g/kWh	0,3 g/kWh	211 m²/MWh	1,5 m³/MWh	72 m³/MWh	26 g/MWh	34 gSO_{2eq}/MWh	5 gPO_{4eq}/MWh	3 gC_2H_{4eq}/MWh	638 $gDCB_{eq}$/MWh	1233 $gDCB_{eq}$/MWh

The radioactive releases of the TTC



- Radioactive releases (KBq!):
  - **53%** Rn release around mines … however strong overestimation since al the Rn is assumed to be instantaneously released (no kinetics)
  - **45%** Rare gases release during reprocessing:
    - The overall radiological impact is estimated to be ~1% of natural radioactivity
  - 2% liquid release
    - Dominated by ^{3}H release around reactors.
- Necessity for considering dose impact … but scenarii are highly subjective and site-dependent

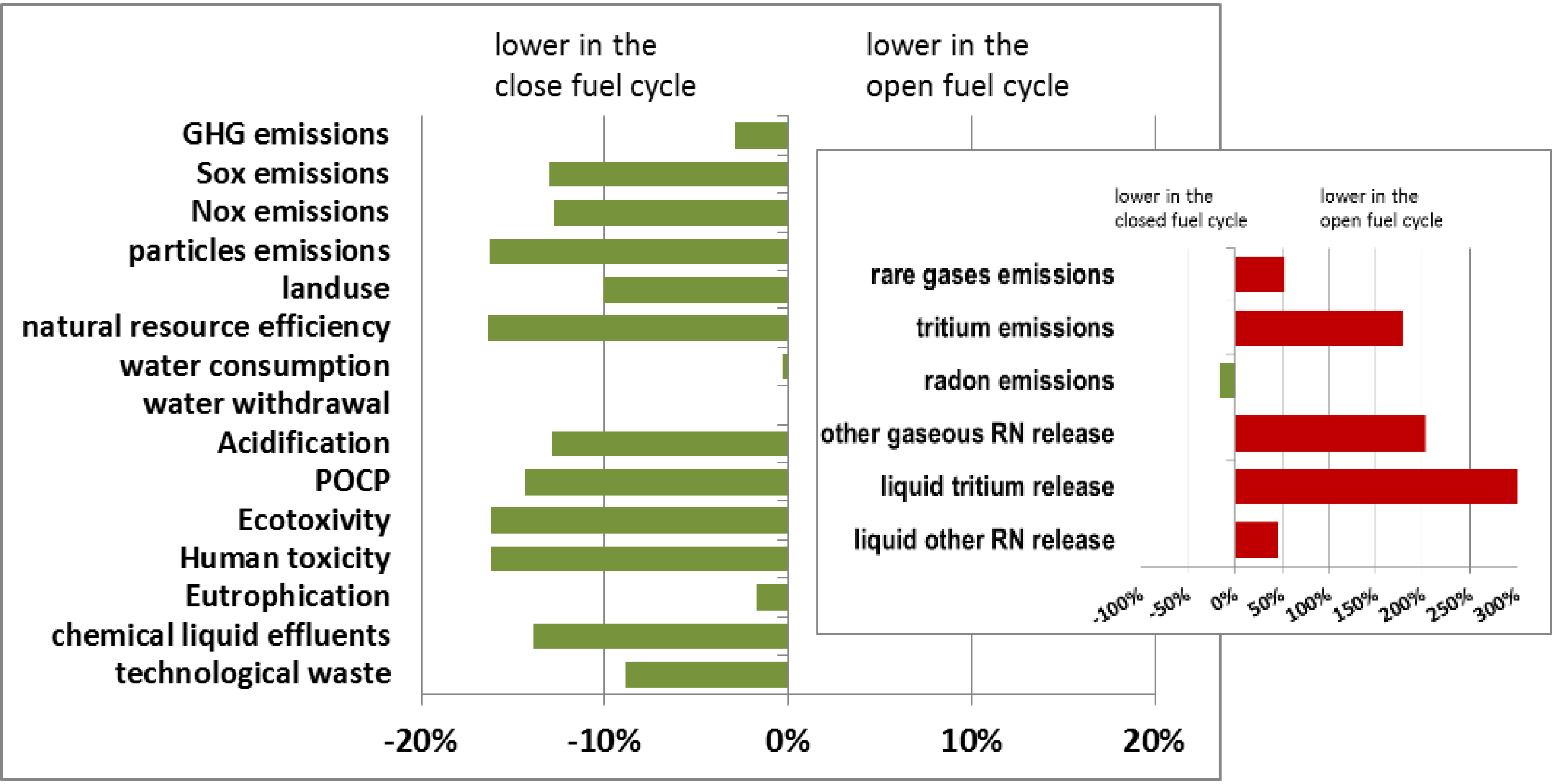




- A very sensitive indicators for public acceptance
- Main outcomes
  - VLLW: surface repository in operation since 2003 in Morvilliers.
    - Overestimation since mine tailings are included
  - ILW-SL: shallow repository in operation since 1994 in Soulaines-Dhuys
    - Dominated by reactors operation
  - ILW-LL and HLW are planned to be disposed of in a deep underground repository around Bure (2025 according to the French Law)
    - Dominated by reprocessing activities (replace spent fuel)

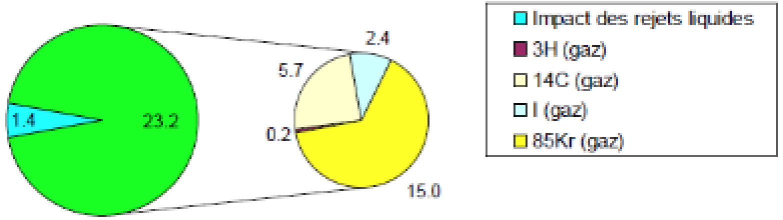
What do we gain when moving from open cycle to TTC ?

Anticipated evolution of environmental indicators when implementing the recycling (TTC)



Directly related to the decrease by 15-20% of the front-end activities

- ➚ Radioactive release (Bq !!)
  - Only ➘ = Rn, (time-dependent decay not accounted for).
- Linked to recycling activities:
  - Atmospheric release: ^{85}Kr, ^{14}C,
  - Liquid release: mainly ^{3}H, ^{129}I
- However, their impact is demonstrated to be negligible:
  - 17-24 µSv/yr for the most exposed population
  - **~1% natural radioactivity**

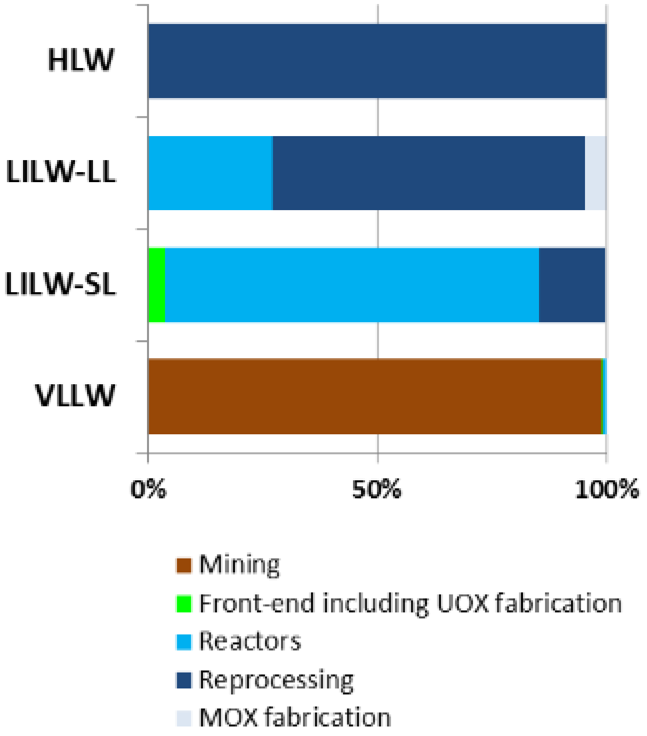


Total 24,7 µSv (agriculteur)

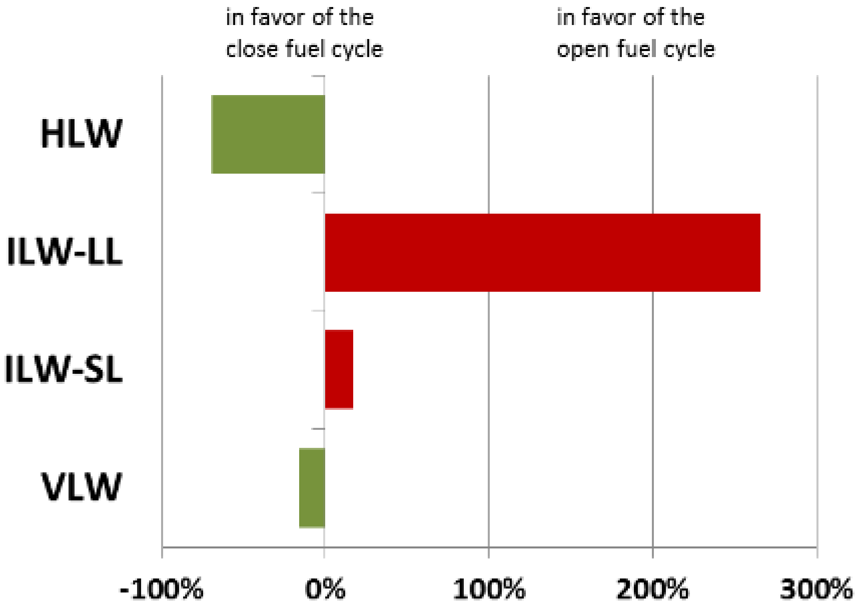
Conservative case assuming 1700t/y. of 60GWd/t fuels reprocessed

Evolution of the radioactive waste from OTC to TTC

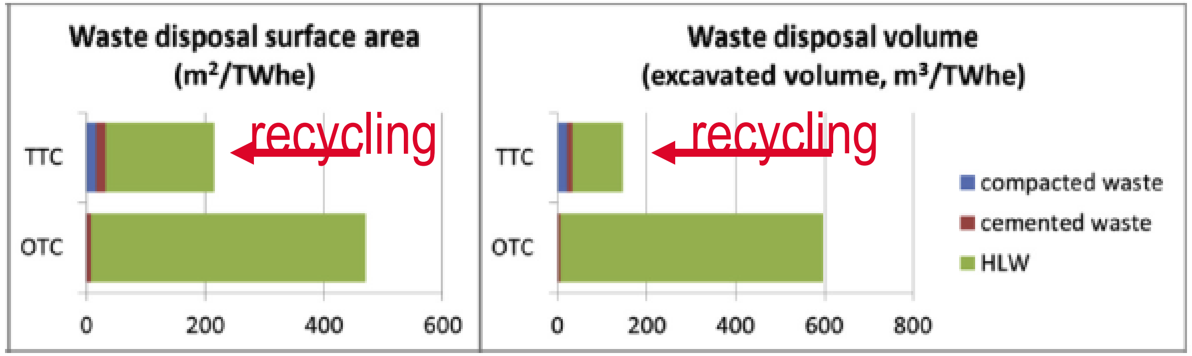
Relative contribution of each fuel cycle step (TTC)



Comparison TTC vs. OTC



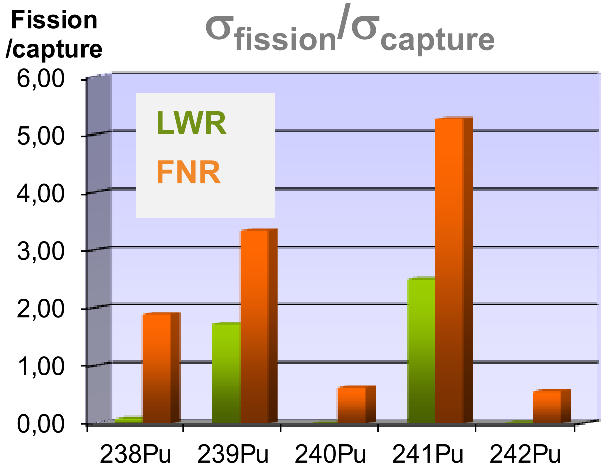
- Strong modification of the waste typology
  - Recycling reduces the repository surface area and excavated volume

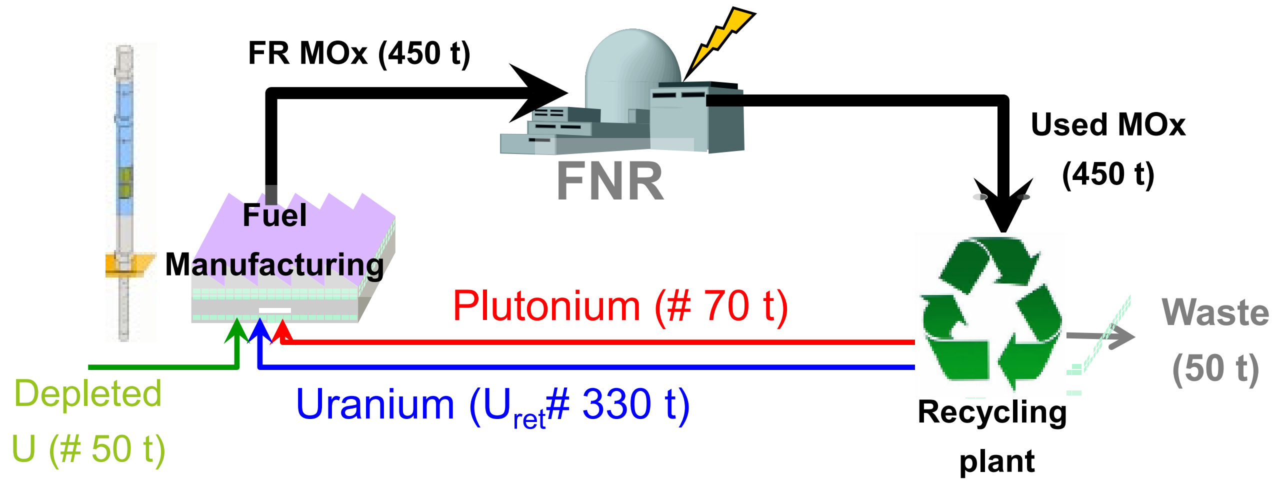


A GEN IV FAST REACTOR

FUEL CYCLE

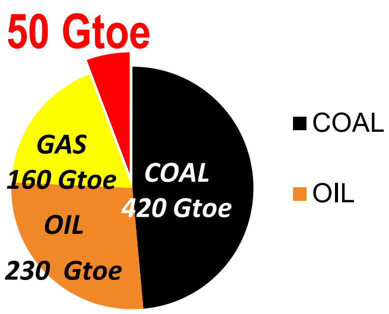
GEN4 systems with fast neutrons
Plutonium multi-recycling





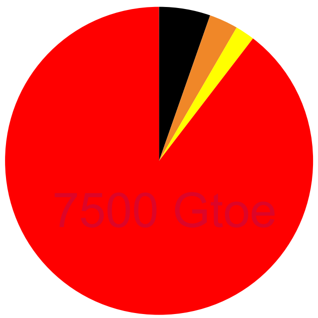
1GWe ~ 150t U_{nat}/y

With current reactors



U=6% world energy potential

With fast neutron reactors

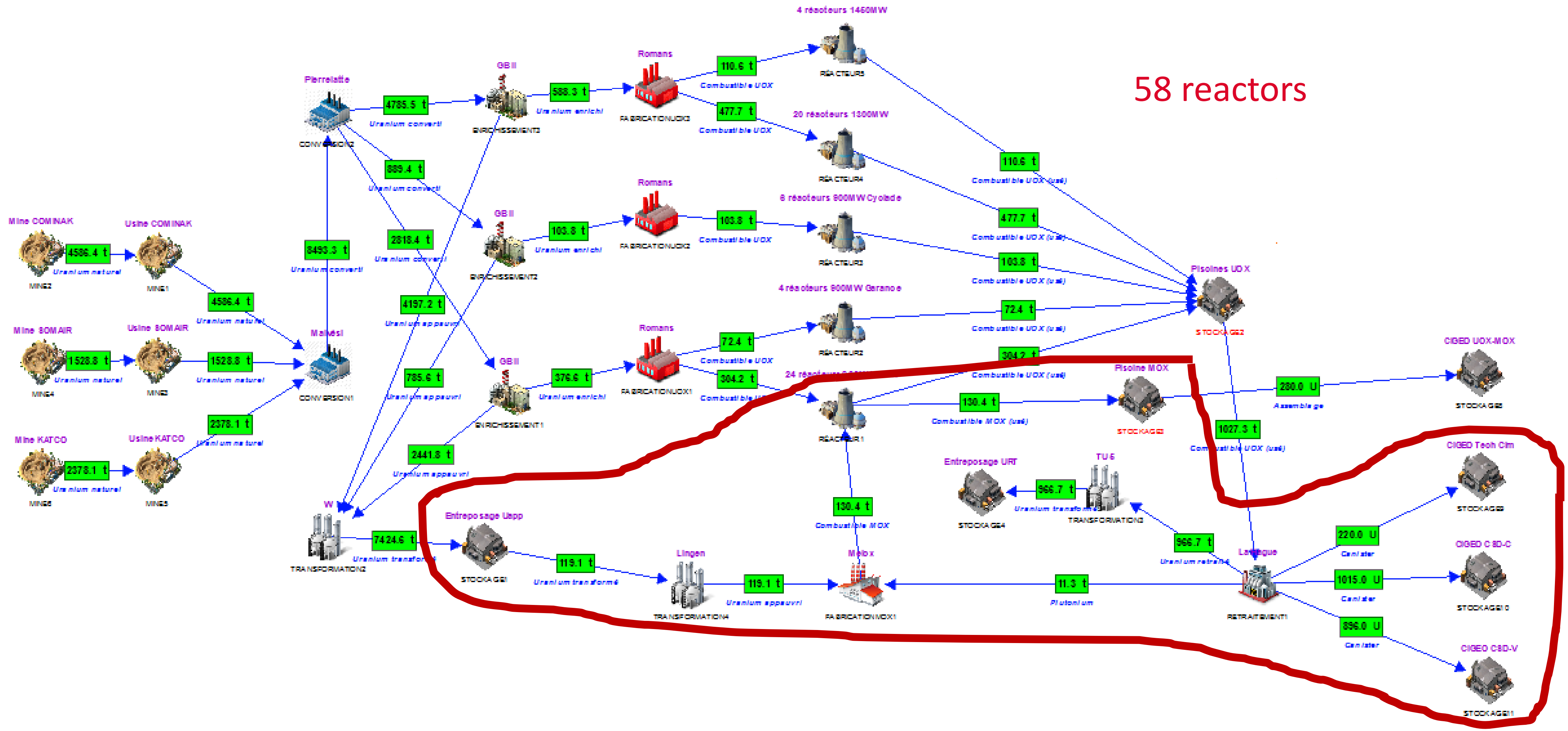


U=90% world energy potential

1GWe ~ 1t U_{nat}/y

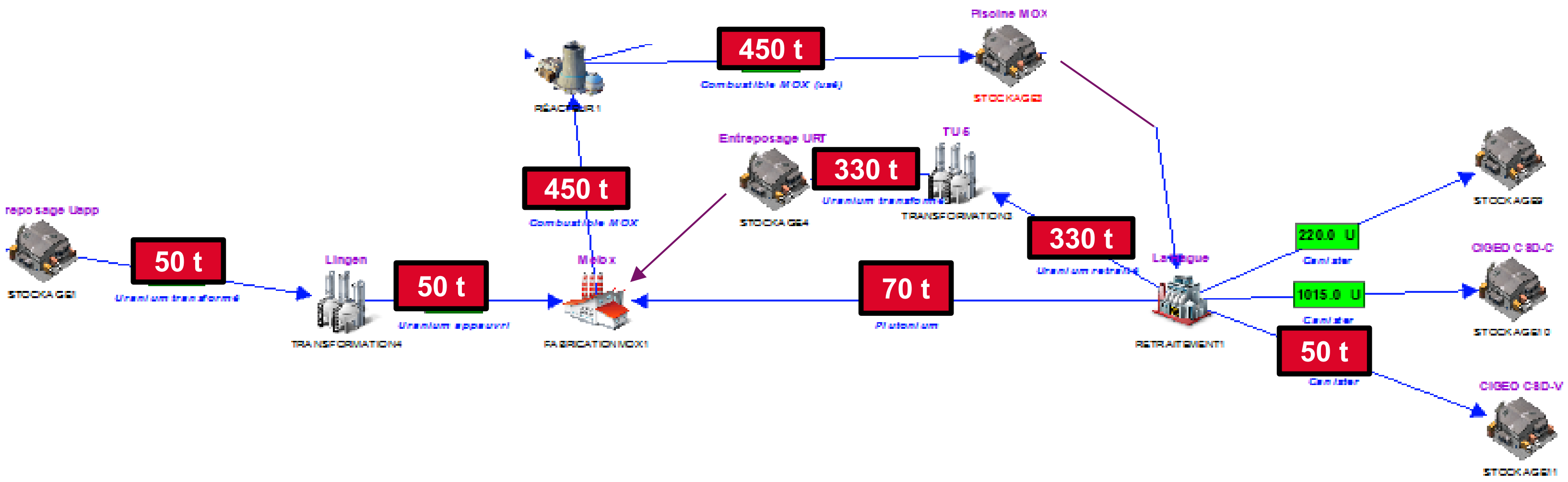
Very significant improvement of natural uranium efficiency

The current industrial French « closed » fuel cycle

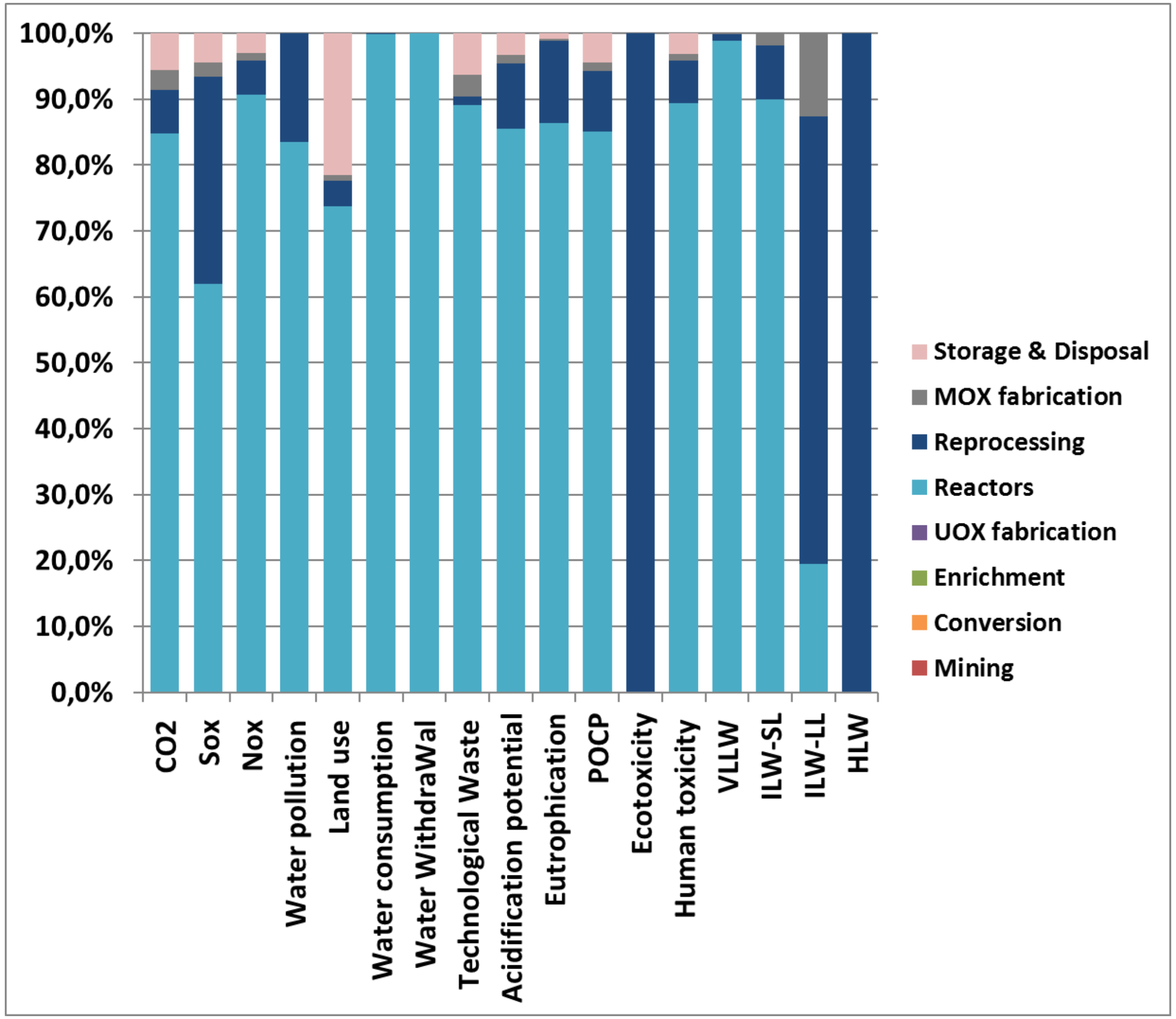


The potential FR fuel cycle producing the same energy

42 reactors 1450MWe

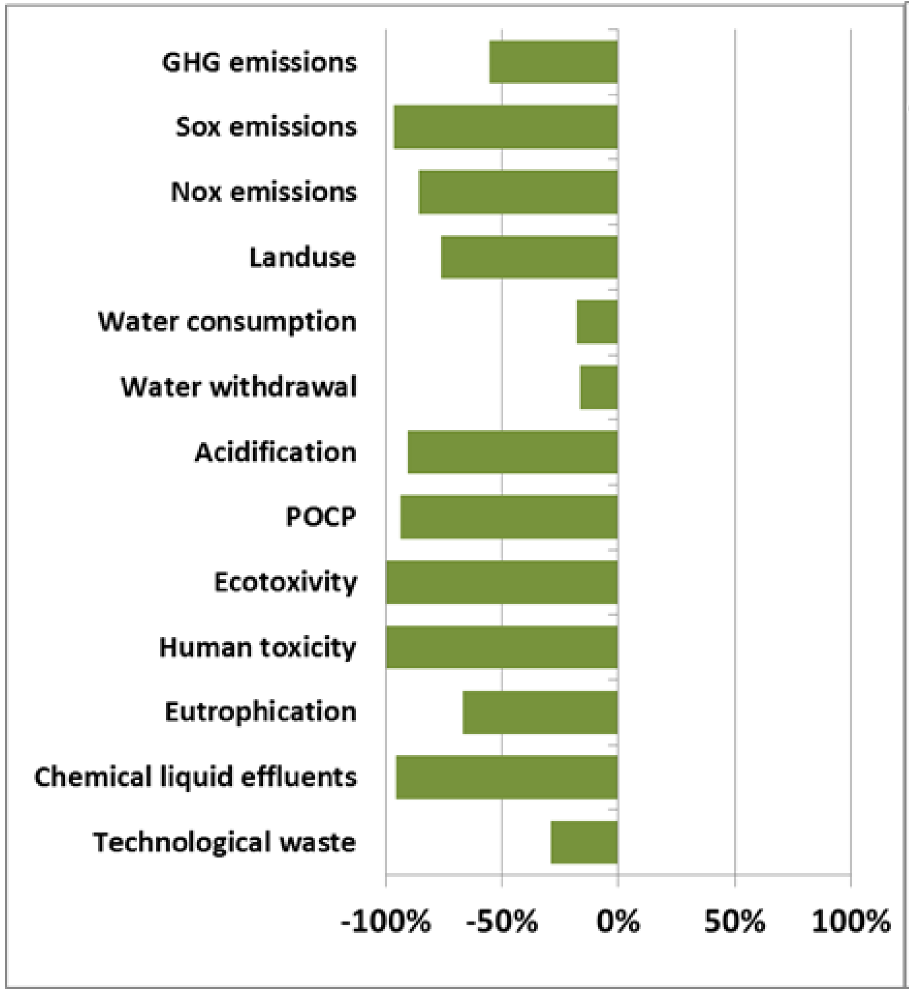


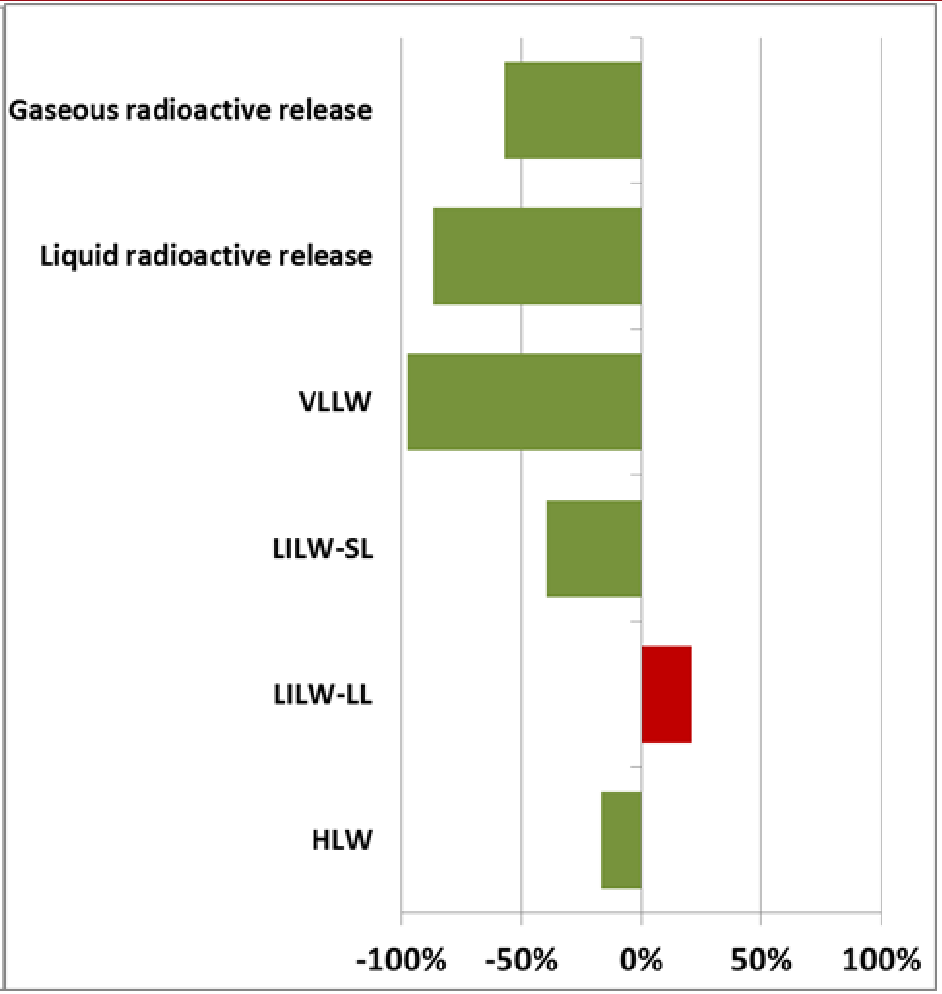
Impact of GEN4 fuel cycle: case of SFR



Impact indicators	Unit	SFR scenario
GHG emissions	gCO_2 eq/kWhe	2.33
SOx emissions	g/MWhe	0.59
NOx emissions	g/MWhe	3.83
Land-use	m^2/GWhe	50.2
Water consumption	L/MWhe	1237
Water withdrawal	L/MWhe	60336
Acidification	gSO_2 eq/MWhe	3.3
POCP	gC_2H_4 eq/MWhe	0.18
Ecotoxicity	g1,4-DCB eq/MWhe	0.07
Human toxicity	g1,4-DCB eq/MWhe	4.8
Eutrophication	gPO_4 eq/MWhe	1.8
Liquid chemical effluents	kg/GWhe	12.6
Technological waste	kg/GWhe	18.70
Gaseous radioactive release	Bq/KWhe	5.28E+05
Liquid radioactive release	Bq/KWhe	3557
VLLW	m^3/TWhe	72.4
LILW-SL	m^3/TWhe	18.2
LILW-LL	m^3/TWhe	1.4
HLW	m^3/TWhe	0.30

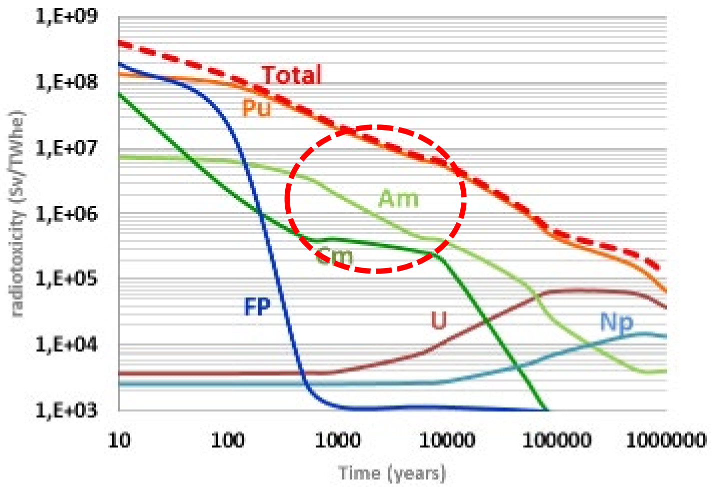
Comparison of SFR and current PWR TTC

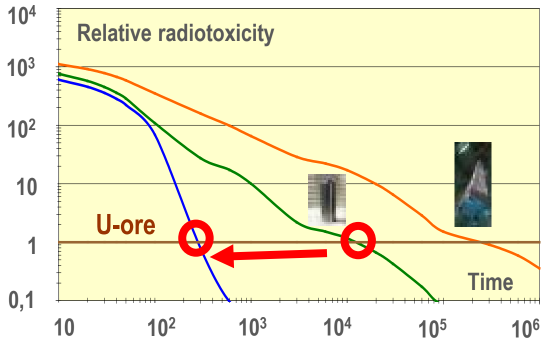


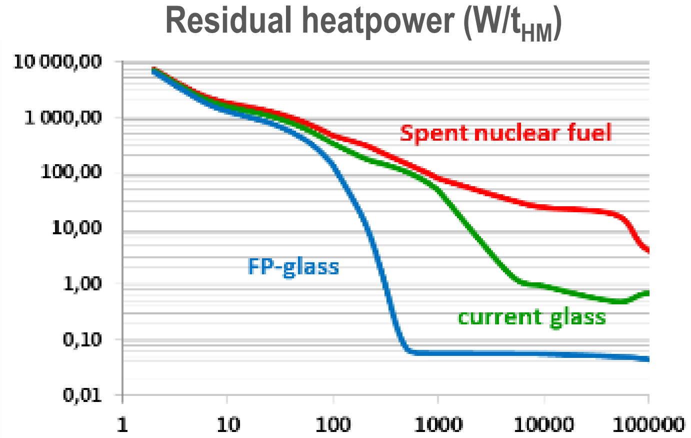


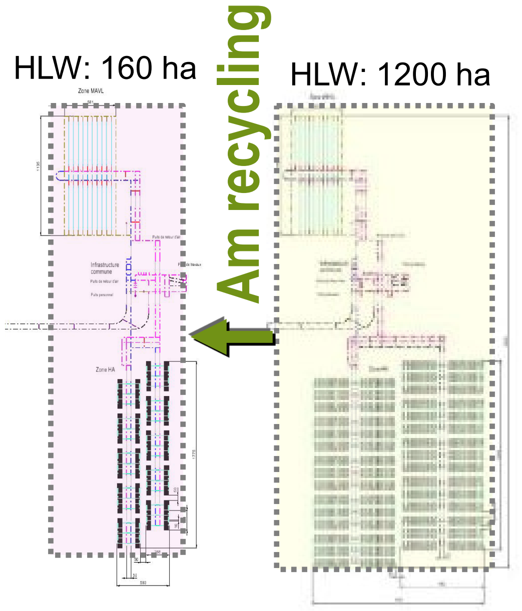
- Improvement related to (i) the suppression of front-end activities and (ii) the higher thermal efficiency (~40% ≠ 33%)

GEN4 systems with fast neutrons
Plutonium multi-recycling and minor actinides transmutation









Recycling the minor actinides: a potential contribution for decreasing the waste burden

- Waste toxicity dominated by MA
  - Recycling MA ⇔ decrease waste lifetime and toxicity
- Preserve the valuable repository resource
  - ➘ of the heat load ⇔ ➚ density of the repository
    - With Am recycling, reduction of the repository volume by a factor up to 8
  - Very significant increase of the repository "lifespan"

THE PROCESSING

Wednesday afternoon

Fuel reprocessing, recycling and radioactive waste (Part I)	Spent fuel reprocessing strategies (homogeneous/heregoneous cycle), proliferation issues	A. Geist, *KIT*
	Safety/criticality issues during reprocessing	L. Flint, NNL
	Coffee break	
	Modelling and simulation of processes	B. Dinh, *CEA DEN*
	Tutorial on modelling of processes (1h30)	B. Dinh, *CEA DEN*

Friday morning

Fuel reprocessing, recycling and radioactive waste (Part II)	Reprocessing of metallic fuels and pyrochemistry	J. Serp, *CEA*
	Radiolytic effects/radiological issues on the performance of the reprocessing	H. Galan, *CIEMAT*
	Coffee break	
	QUIZZ award	
	Dissolution issues	N. Dacheux, *ICSM*

LWR UOX fuel vs Fast MOX fuel

Spent UOX fuel (for 100g)	Spent MOX fuel (for 100g)
95 g of U	73,3 g of U
1 g of Pu	15,6 g of Pu
4g of FP	11,1 g of FP

Increasing the Pu content increases the refractoriness of the fuel and makes its (quantitative) dissolution an issue

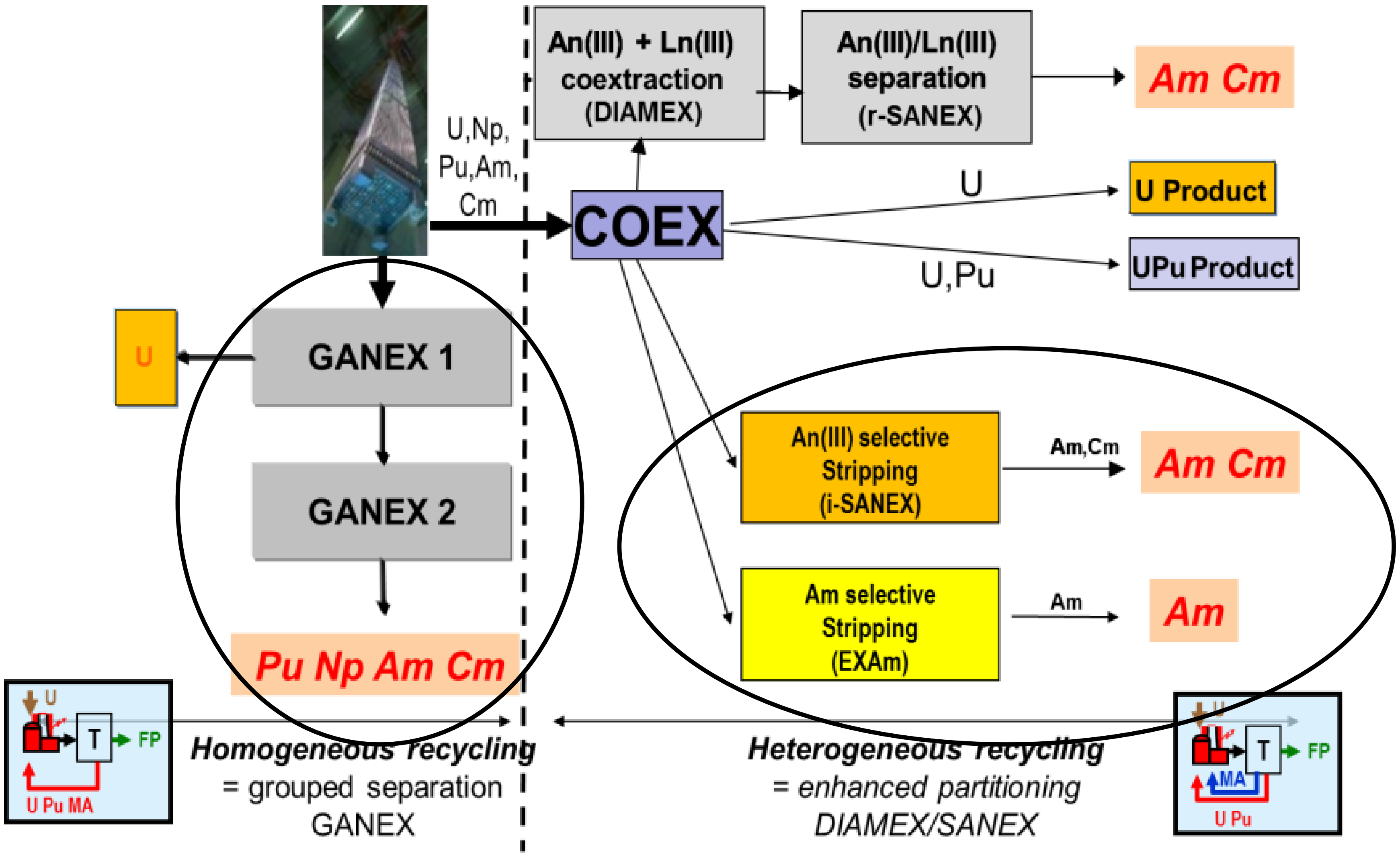
Dissolution liquor	Dissolution liquor (hypothesis)
[U] = 300g/l	[U] = 146,6g/l
[Pu] = 3,2g/l	[Pu] = 31,2g/l
[PF] = 12,6 g/l	[PF] = 22,2g/l

Increasing the Pu concentration increases the radiolysis degradation of the chemical system and some solubility issues

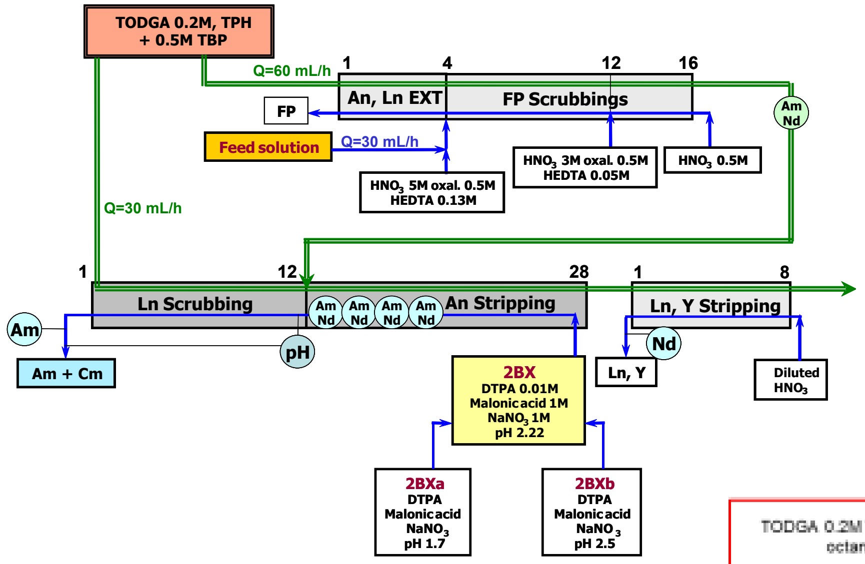
However, once the head-end step has been optimised (dissolution), the PUREX process can be used on a MOX dissolution liquor

An alternative is the co-management of U and Pu with the COEX process, derived from PUREX

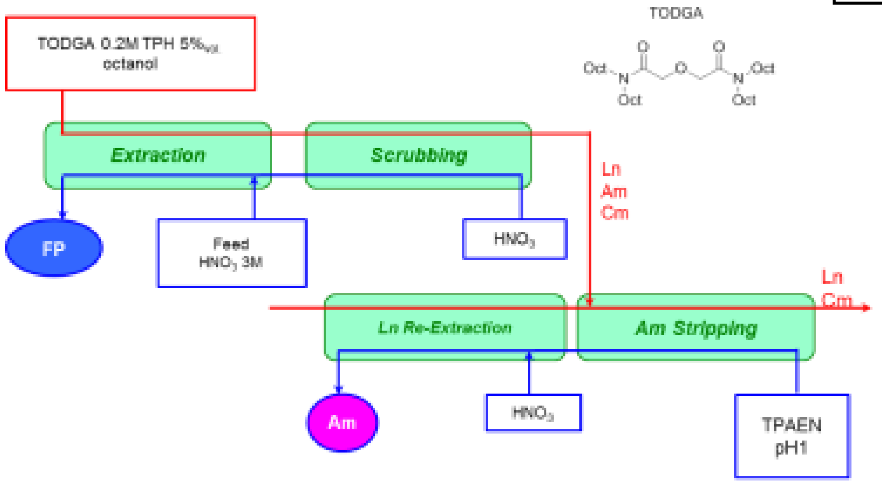
The management of minor actinides in advanced fuel cycles in Europe

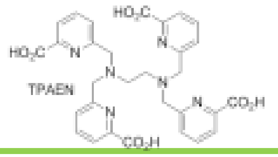


The SACSESS reference process flowsheets

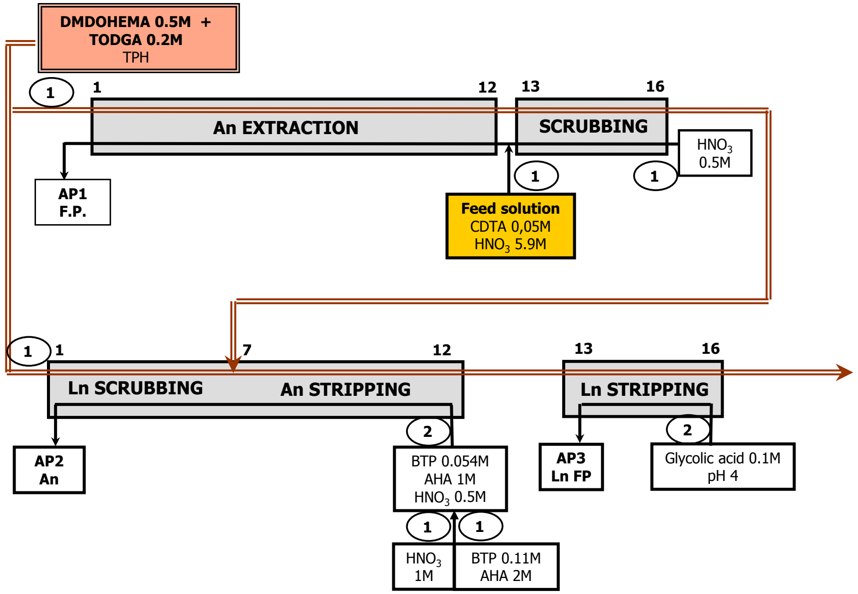


i-SANEX

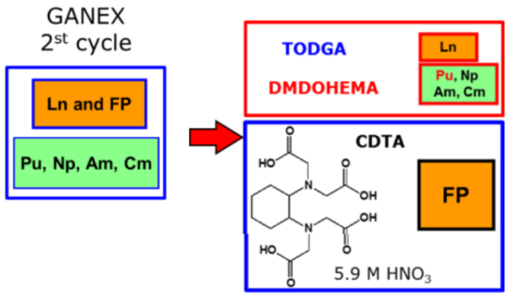




EURO-EXAM

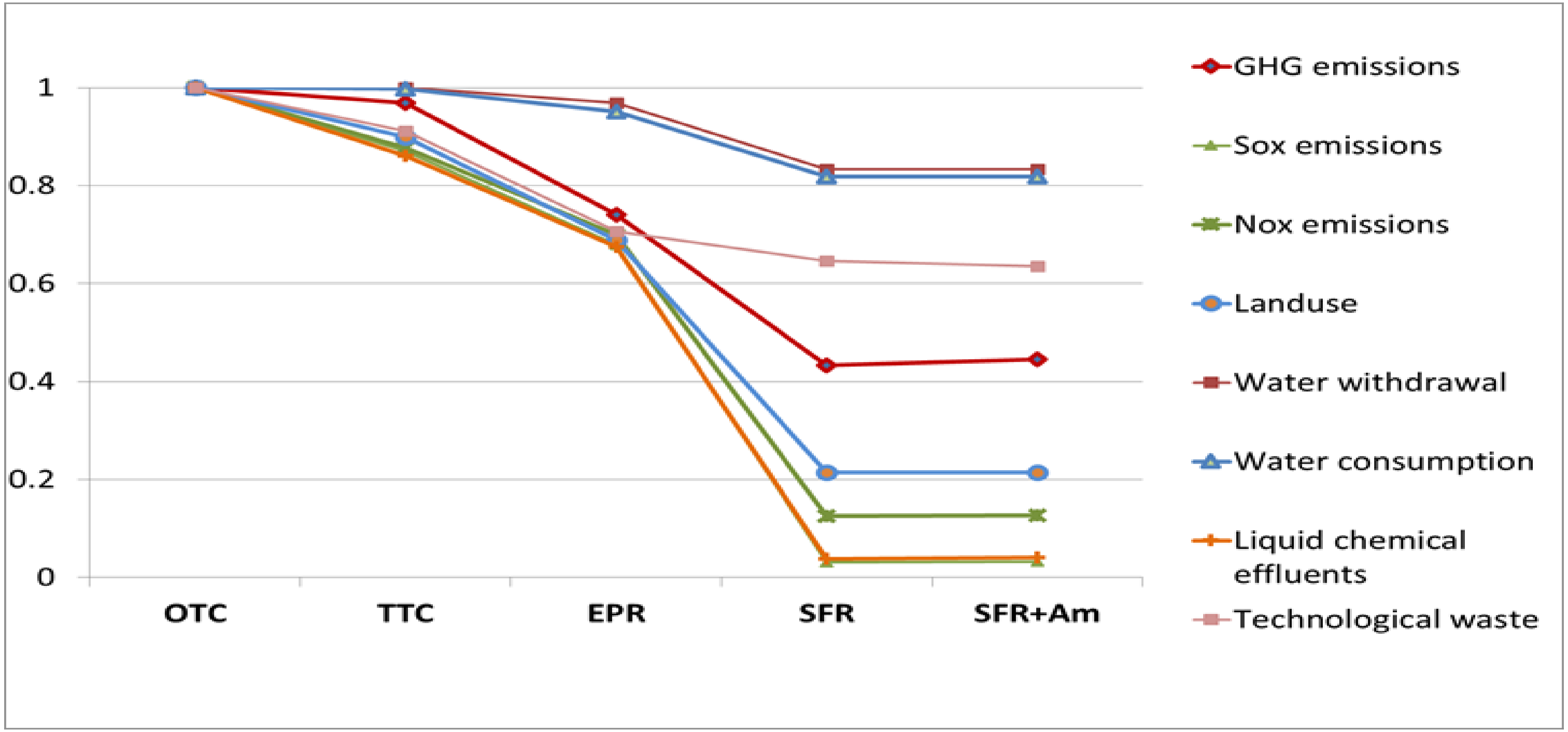


EURO-GANEX



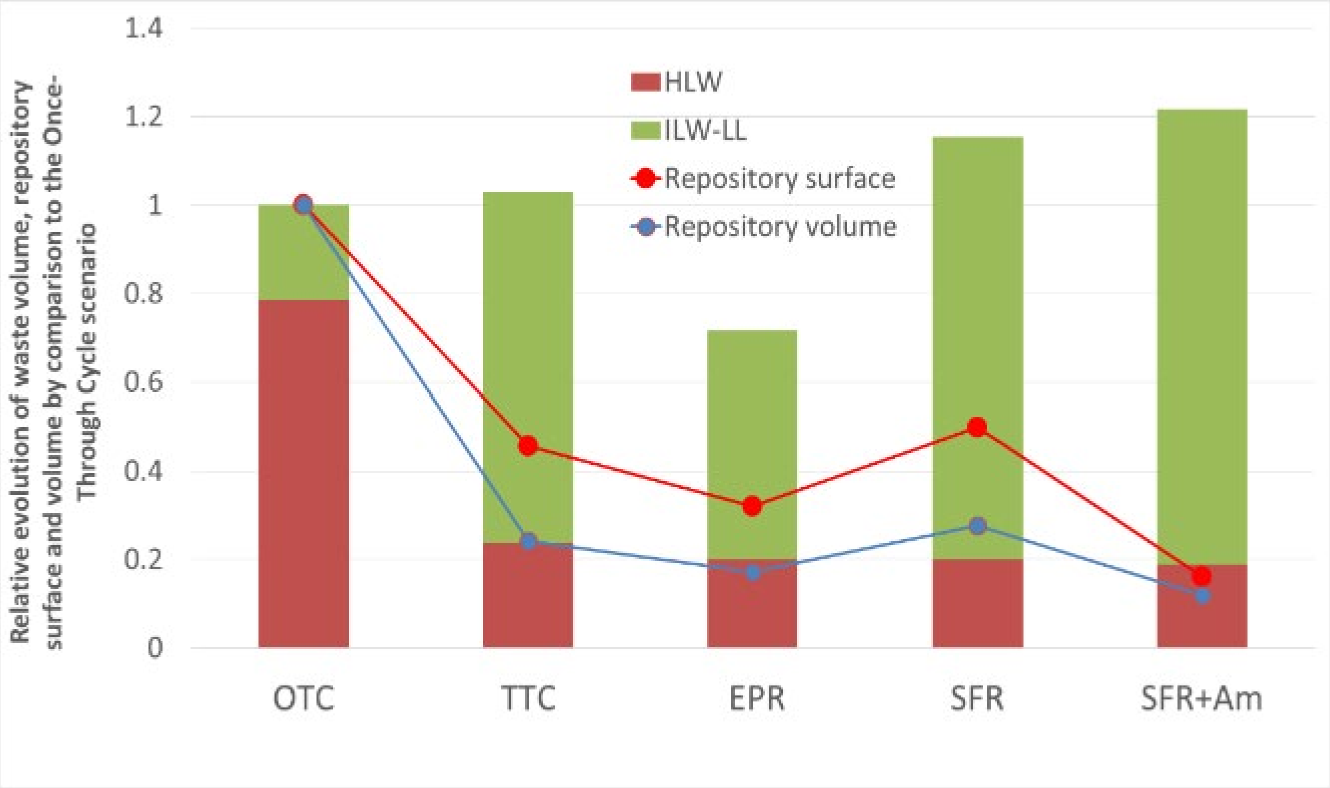
TO SUMMARIZE…

Anticipated beneficial impact of recycling activities



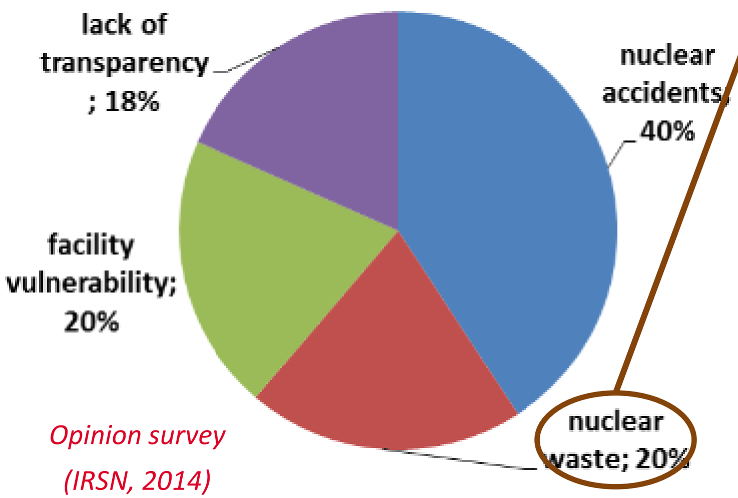
Actinides recycling significantly improve the nuclear energy environmental footprint

A significant Improvement of the nuclear waste issues



- Relative decrease of HLW vs. ILW while total volume of waste ~ constant +/- 20%
- Decrease of thermal power due to Pu-recycling ➔ significant gain for the repository surface and volume
- Decrease of radiotoxicity & lifetime

Societal drivers:
Improve waste management



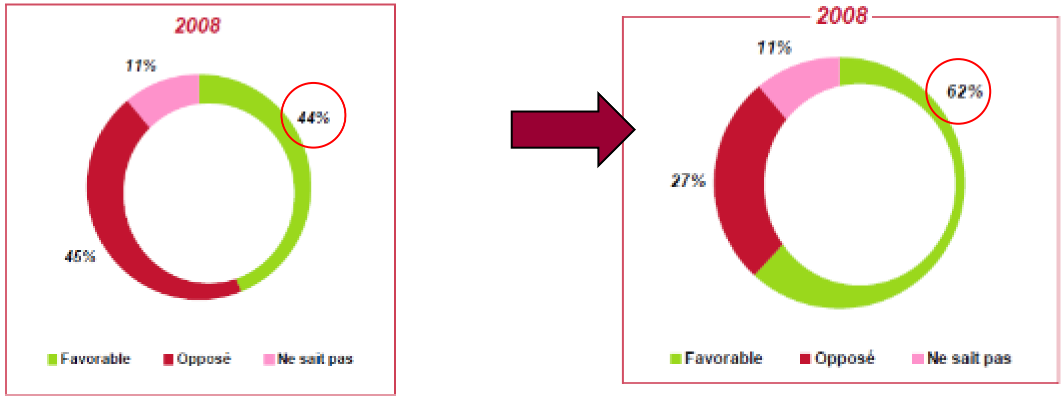
Opinion survey (IRSN, 2014)

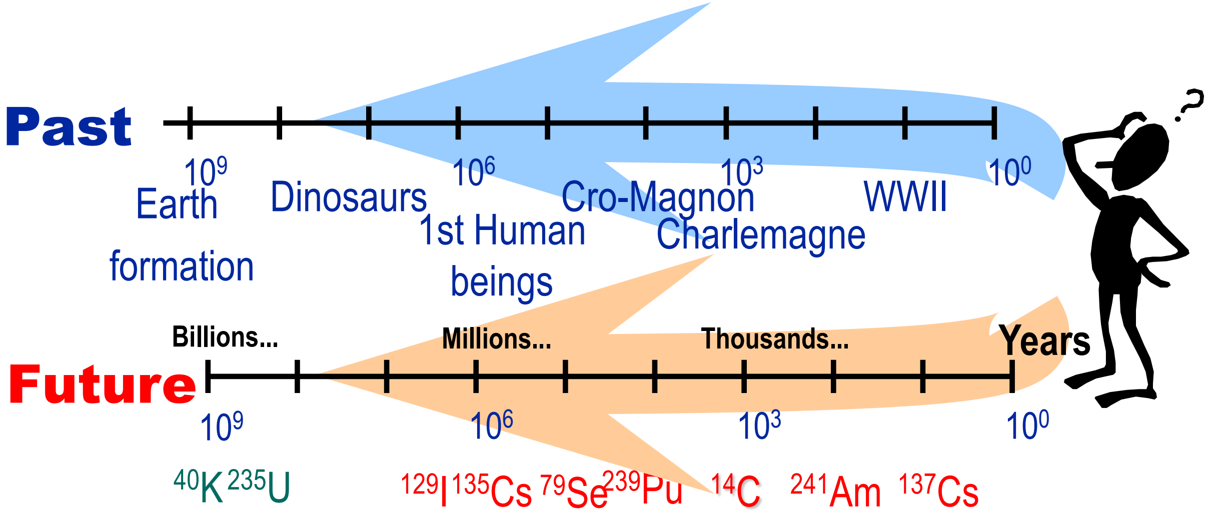
❷ Improve waste management

➢ Waste is severely questioned by public opinion

- Nuclear waste seen as Achille's heel of nuclear energy (due to lifetime)
- Main concern = waste lifetime. Any reduction could help to improve acceptability. *Could we reduce waste lifetime back within Human History?*

Eurobarometer 2008: % of EU citizens supporting nuclear energy with/without a permanent and safe solution for the HLW





The rationale of future nuclear fuel cycles for an improved sustainability

1980 — 2000 — 2200 — 2040 — 2060 — 2080 — 2100

Dates are purely indicative

TOWARDS INCREASING SUSTAINABILITY

Gen. II & III ***Pu-monorecycling***

Gen. IV ***Pu-multi-recycling***

Gen. IV ***…+ MA recycling***

Once-through cycle

Pu-mono-recycling

- Twice-Through Cycle
- LWR reactors
- Pu-recycling in MOX fuel

Breakthrough=reactors

Pu multi-recycling

- Multi-Through Cycle
- Fast-Reactors (FR)
- Pu multi-recycling

Evolution=cycle

Pu+MA multi-recycling

- Fast Reactors (FR)
- Pu multi-recycling
- MA burning

Main incentives

- 1st step towards U resource saving
- Efficient waste conditioning

Main incentives

- Major resource saving
- Energetic independence
- Economic stability

Main incentives

- Decrease of waste burden,
- Optimisation of the repository
- Public acceptance

To go further …

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Assessment of the environmental footprint of nuclear energy systems. Comparison between closed and open fuel cycles

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A B S T R A C T

Energy perspectives for the current century are dominat
energy needs. Particularly, electricity consumption is antic
before 2050. Energy choices are considered as structuring
and stable policy based on objective criteria. LCA (life cyc
relevant indicators which can allow the comparison of a
sources. Among the energy-mix, nuclear power is anticipat
its viability is severely addressed by the public opinion aft
LCA of the French nuclear fuel cycle was performed as a
terms of impact with other energy sources. It emphasized
less impacting energy, comparable with renewable energ
compared with an equivalent open fuel cycle scenario. It
require about 16% more natural uranium, would have a
radioactive indicators" and would produce a higher volun

energies

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Assessment of the Anticipated Environmental Footprint of Future Nuclear Energy Systems. Evidence of the Beneficial Effect of Extensive Recycling

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ury, our societies have to face a tremendous and increasing energy
al climate change and preserving the environment. Addressing this
insition from the current fossil energy-based system to a carbon-free
sed on a relevant energy mix combining renewables and nuclear
rgy transition will only occur if it is accepted by the population.
h as life cycle assessments (LCA), aiming at assessing the respective
mix for most of the environmental impact indicators are therefore
-informed decision-process at the societal level. Before studying the

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The Sustainability, a relevant Approach for defining the Roadmap for future Nuclear Fuel Cycles

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Abstract

In the framework of the COP21 agreement of December 2015, nuclear energy could help mitigating the global climate change together with the renewable energies, due to its low green-house-gases emissions, its reliability and its high base-load capacity. However, the political uncertainty in many countries about the future of nuclear energy source clearly illustrates that there is a need for a global approach to compare nuclear energy with other energy

DE LA RECHERCHE À L'INDUSTRIE