GEN IV International Forum℠

SUSTAINABILITY, A POWERFUL AND RELEVANT APPROACH FOR DEFINING FUTURE NUCLEAR FUEL CYCLES

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French Atomic and Alternative Energies Commission CEA

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NEA Nuclear Energy Agency · SCK•CEN · cea · Los Alamos National Laboratory · Canadian Nuclear Laboratories / Laboratoires Nucléaires Canadiens · National Nuclear Laboratory · Argonne National Laboratory · INL Idaho National Laboratory · Berkeley University of California · Brookhaven National Laboratory · NPS · Tsinghua University

Meet the presenter

Prof. Christophe POINSSOT has been working at CEA (The French Alternative Energies and Atomic Energy Commission) for more than 25 years in **fuel cycle R&D**. He is currently **heading the Research Department on Mining and Fuel Recycling Processes** (DMRC), where he is in charge of developing actinides recycling processes and operating the **Atalante hot-lab facility**. He is also a CEA **international expert** in actinides chemistry and **professor in nuclear chemistry** at INSTN.

He graduated from the Ecole Normale Supérieure de Paris. He obtained his PhD in Material Science in 1997 from the University Pierre & Marie Curie (Paris) and his Habilitation Degree in Chemistry in 2007. He first worked during 15 years on the French geological disposal program. He launched in 1998 and coordinated the French research program on spent nuclear fuel long-term evolution in storage and disposal. In 2003, he took the responsibility of the Service for the Studies of radionuclides behaviorat the CEA Saclay where he also coordinated the CEA research on geological repository, including the contribution to the underground research experiments. In 2008, he joined the CEA Marcoule where he was successively the deputy head, then the head of the Radiochemistry and Processes Department in charge of the Atalante operation and the development of the reprocessing processes. His responsibility is extended to the whole recycling activities with the creation in 2017 of the DMRC department.
Dr. Poinssot has long been involved in **teaching**, currently on nuclear fuel cycle strategy in several chemical engineering schools and universities in France. He is the **(co)author of more than 50 scientific papers and 100 oral communications** in international conferences. He has been decorated as "**Chevalier des Palmes Académiques**" in 2016 and was awarded the **Roger Van Geen Chair** by SCK-CEN, FNRS and FNO in 2017.

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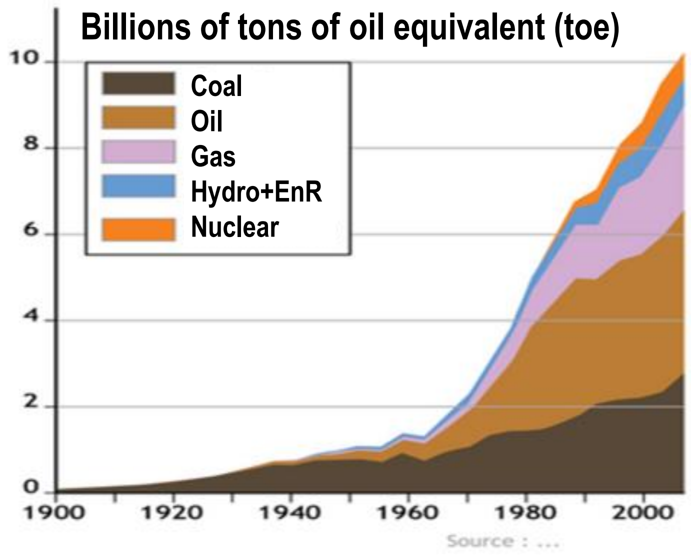
OUTLINE

1. Introduction: from the energy transition to the sustainability
2. Environmental drivers
3. Societal drivers
4. Economic drivers
5. Conclusion: the rationale of future fuel cycles

This presentation has been given in Bruxelles on November 20th 2017 as the introduction lecture of the R.Van Geen Chair Award (SCK-CEN & FNRS/FNO)

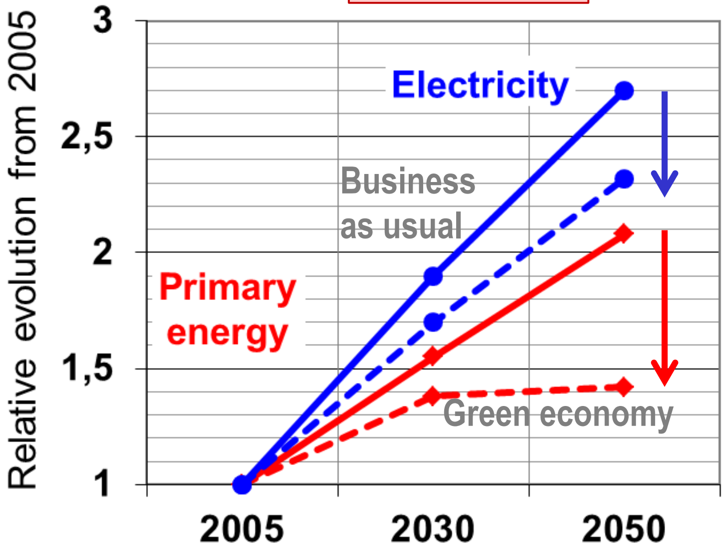
1. INTRODUCTION: The Energy Transition (1/3)

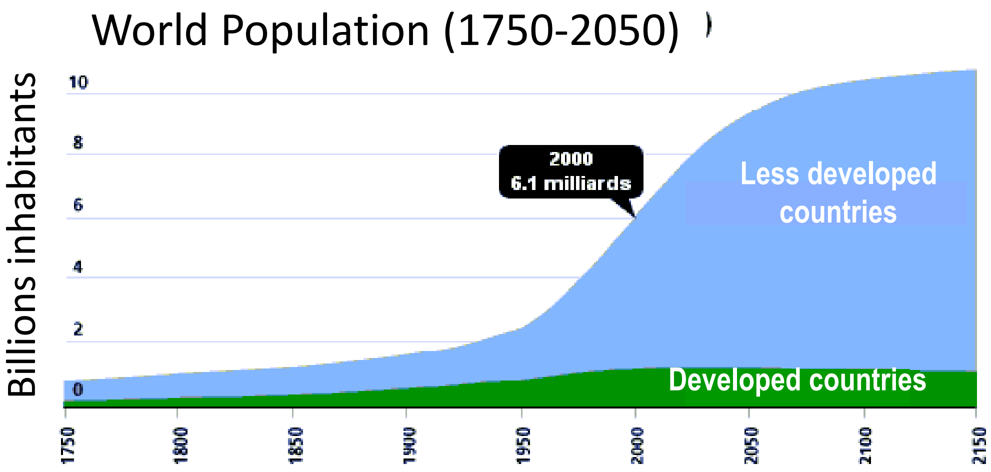
Past

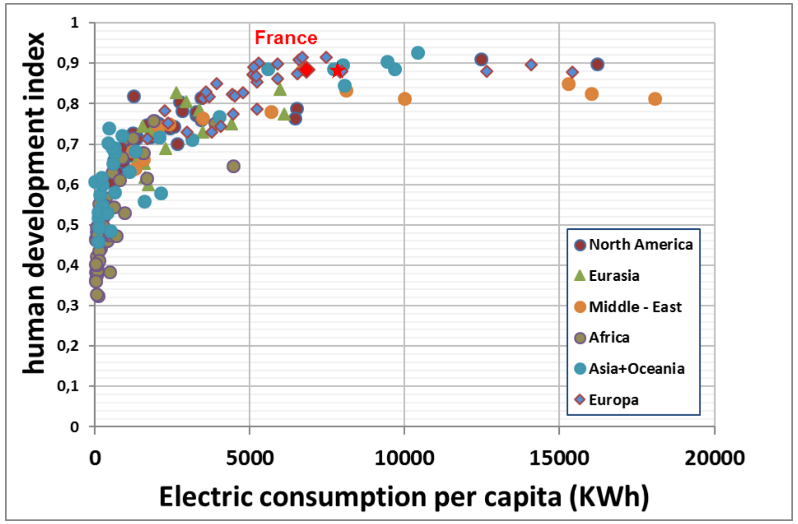


❶ Increase the energy production

Future

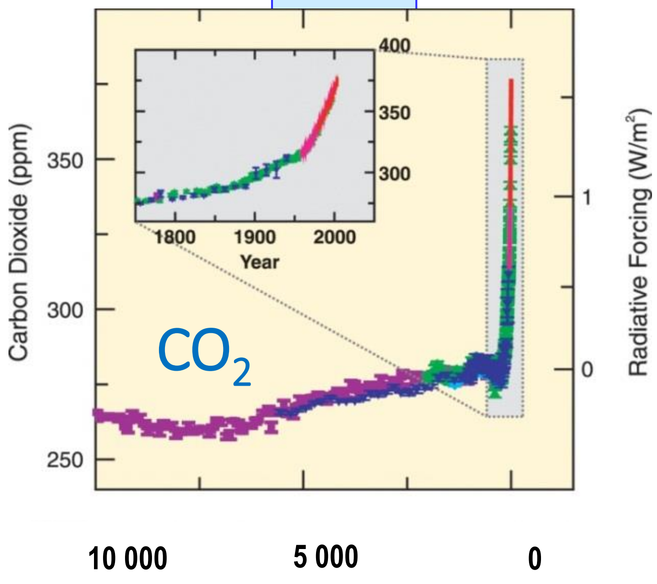






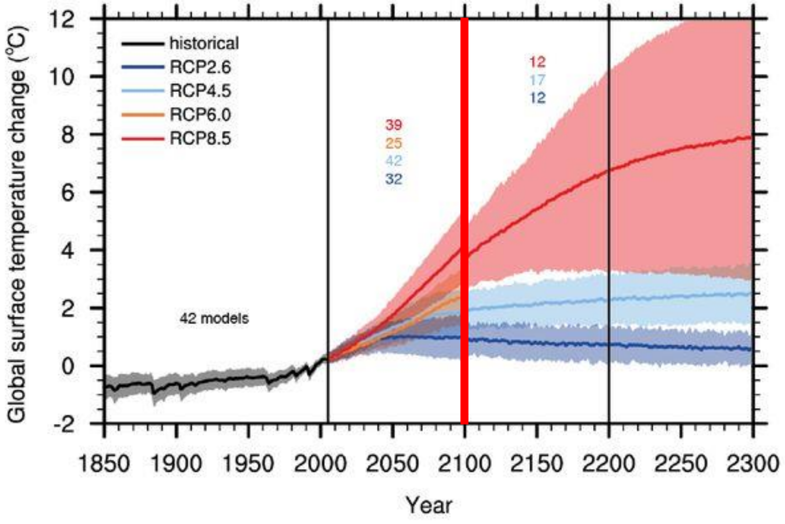
The Energy Transition (2/3)

Past

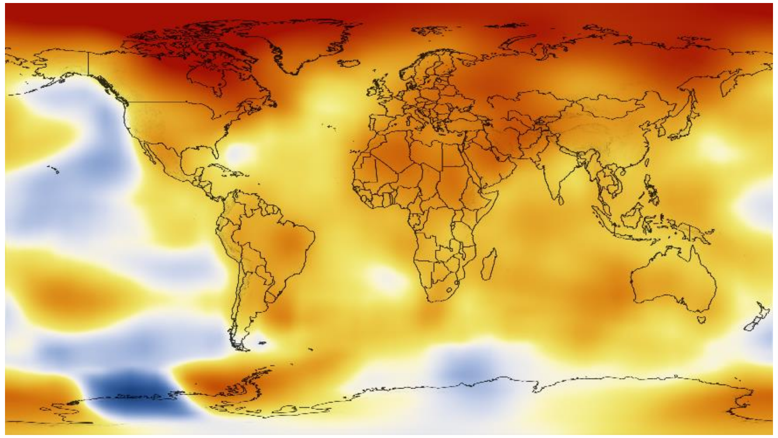


❷ Mitigate the climate change

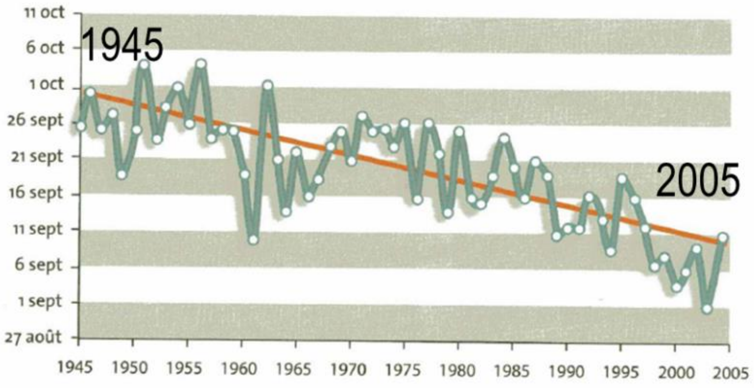
Future



Global temperatures anomaly



Date of grapes picking in Chateauneuf-du-Pape (Avignon, France)

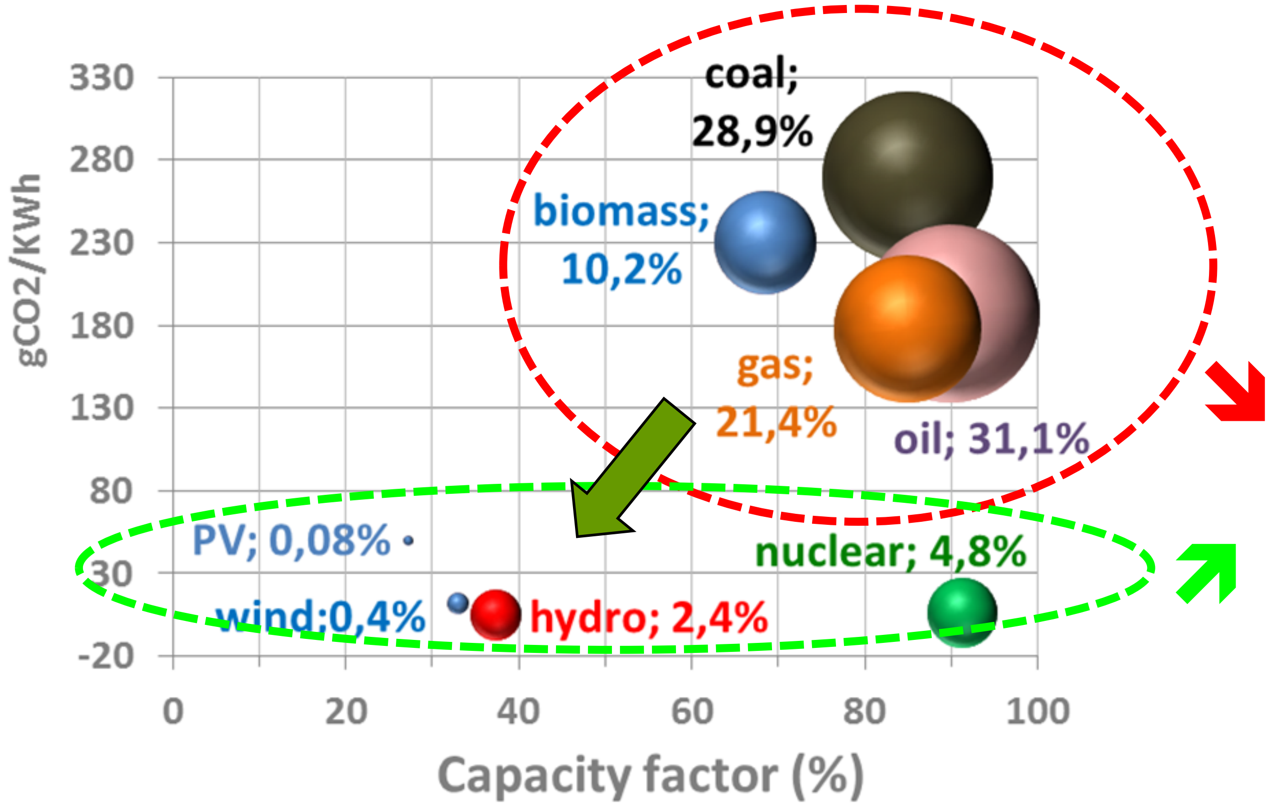


Melting of glaciers

The Energy Transition (3/3)

❶ **Increase the energy production**

❷ **Mitigate the climate change**



Energy transition

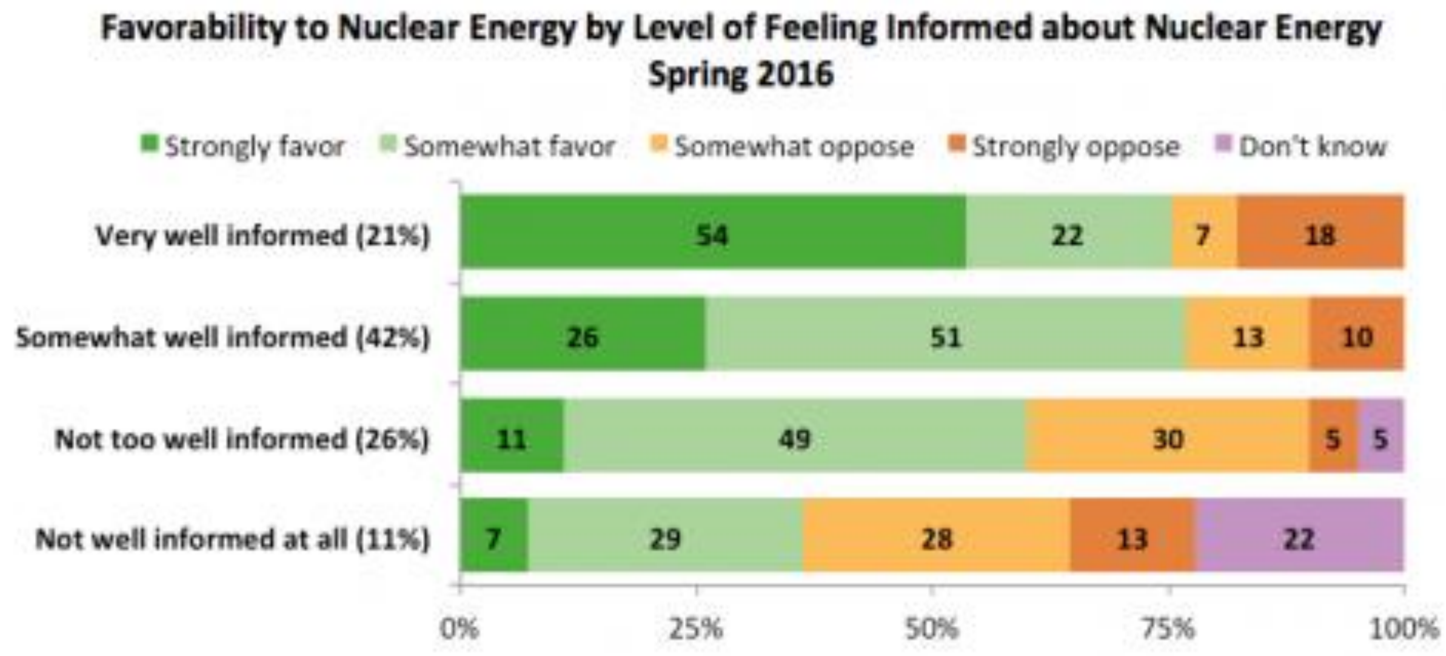
- ❶ ➚ **Energy efficienty**
- ❷ ➘ **fossil energies ⬄ ➚ renewable energies + nuclear energy**

Nuclear energy is promising …

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 …



Bisconti Research opinion survey for the Nuclear Energy Institute (NEI), 2016

Due to lack of knowledge, nuclear energy is seriously questioned …

The sole technical approach is not sufficient ➔ need for a more global and 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

❶ How to improve environmental footprint?

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

➔ Can nuclear energy be sustainable and how?

Baseline for technology development

❸ How to improve affordability?

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

Equity, reducing risks, democratic choice

❷ How to improve acceptability?

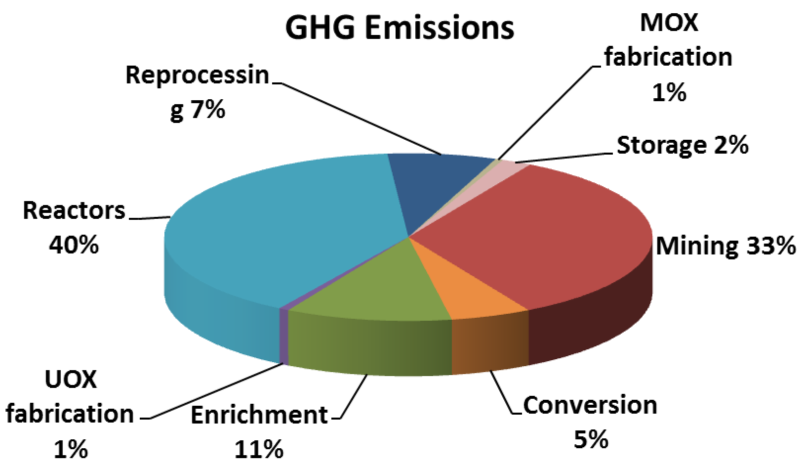
- *Highest level of safety and reliability*
- *Consensual choice of the society*
- *Promote the international stability*

Main trends will be depicted in the following

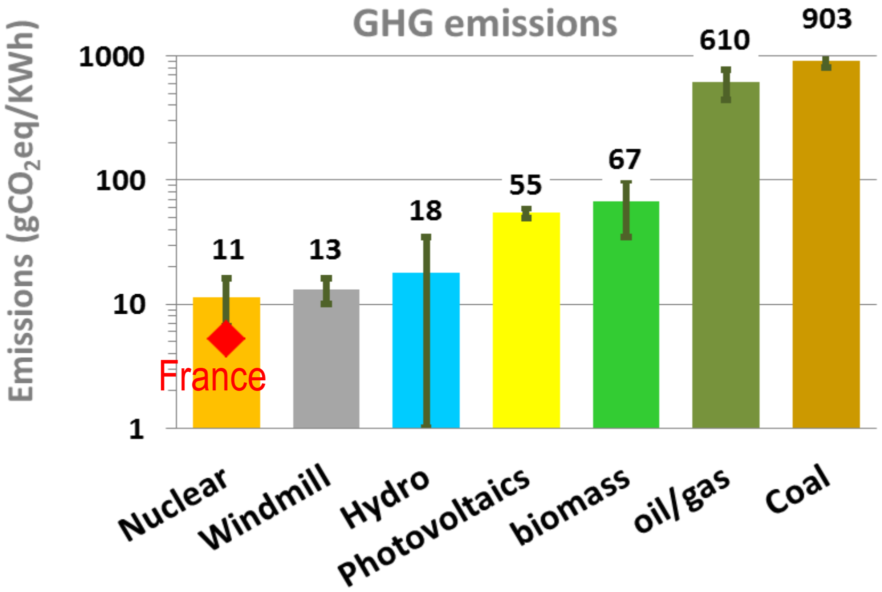
Chap.I: Environmental drivers

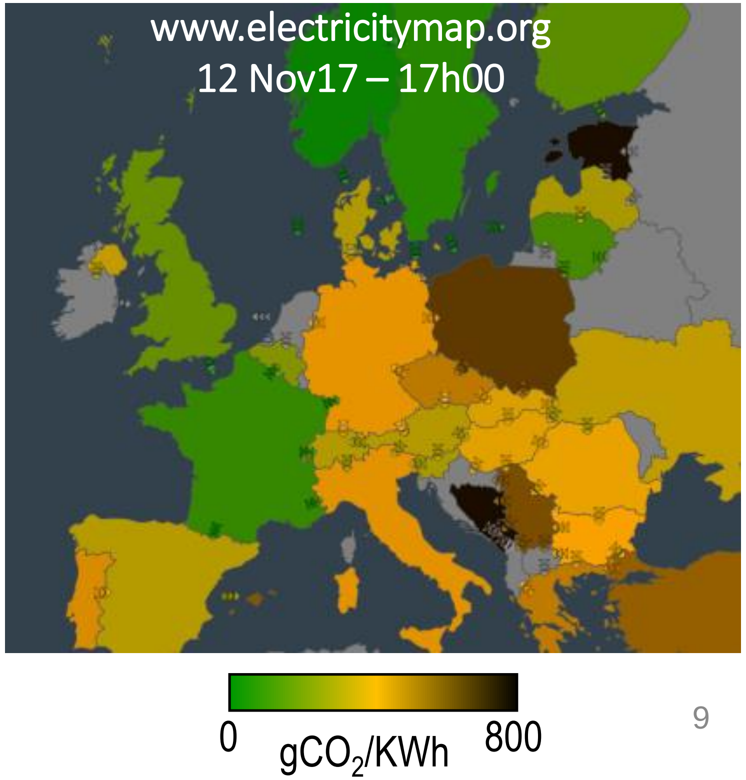
❶ Reduce GHG emissions

- Nuclear is already very beneficial
  - Emissions mainly come from infrastructures
  - The longer their lifetime, the shorter their emissions



Poinssot et al., 2014

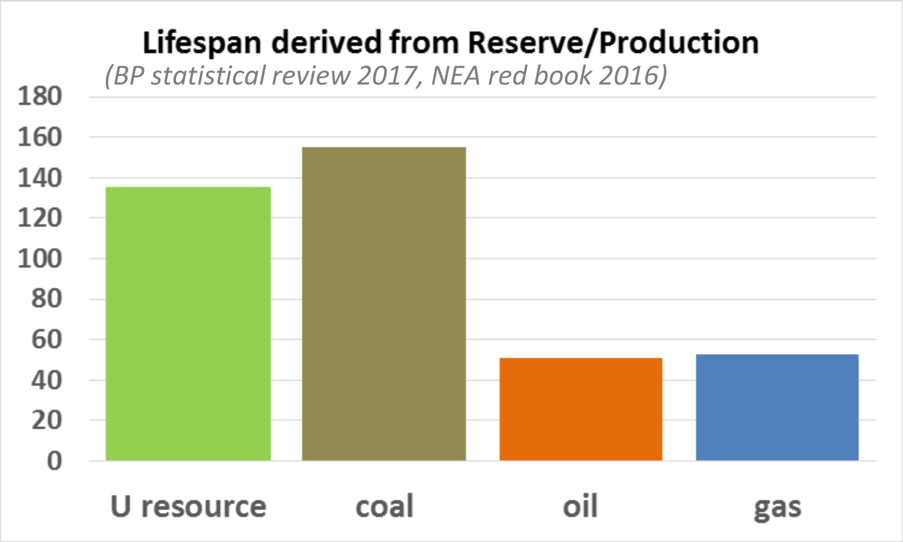


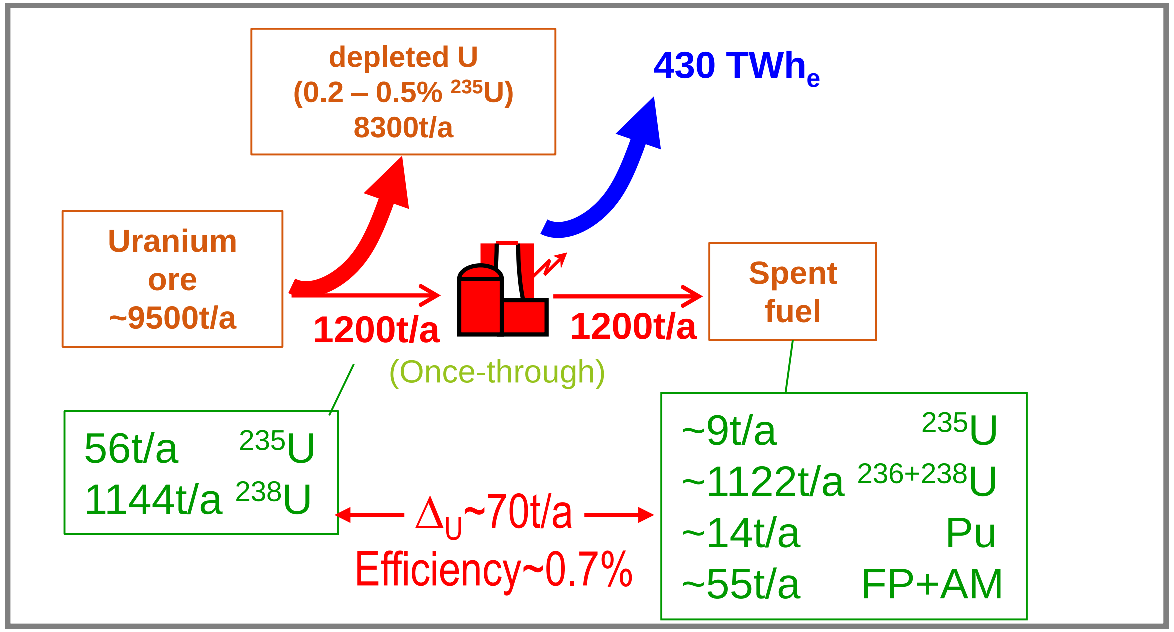


Environmental drivers

❷ **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

Saving the natural resource ⇔ recycling the actinides

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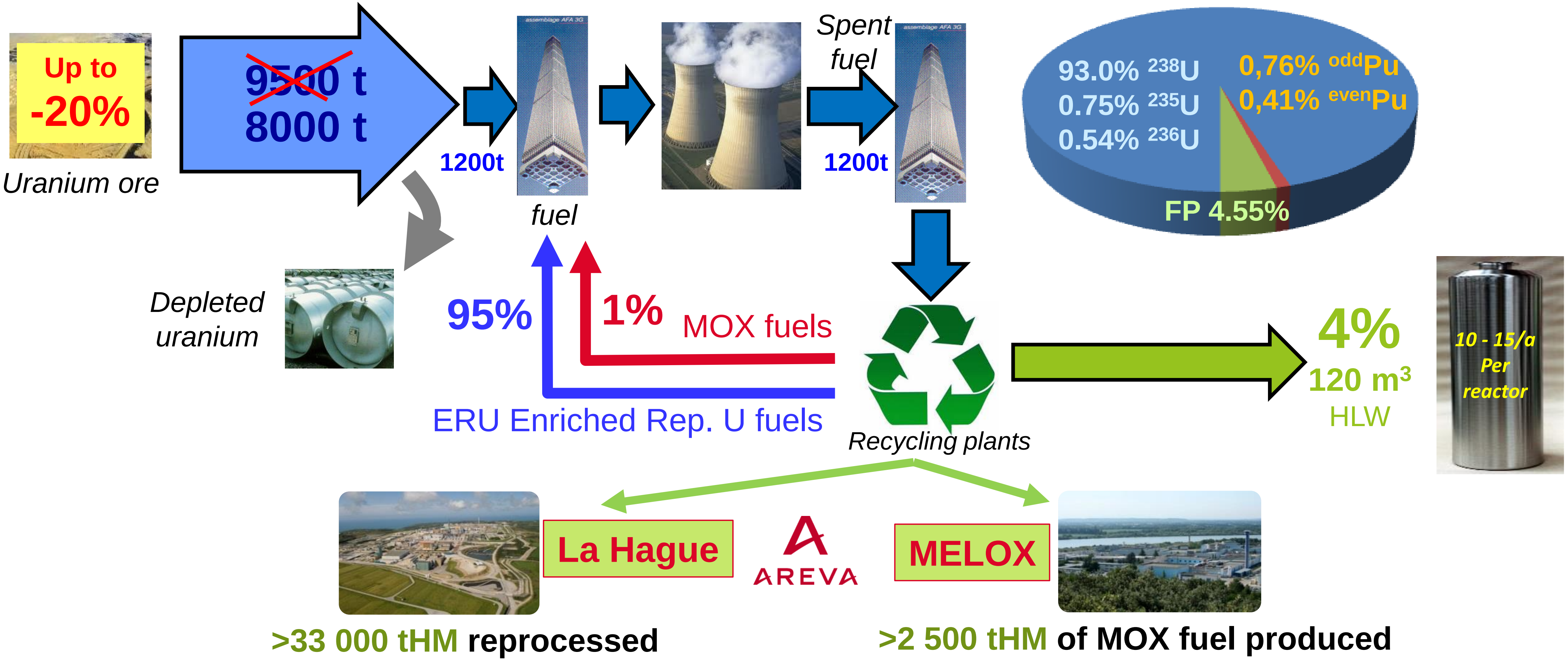


- 10 to 15% of French electricity yearly supplied by recycled materials
- ~1500t uranium ore yearly preserved
- No significant spent nuclear fuel interim storage ⇔ significant reduction of risk

The basis of spent nuclear fuel recycling processes: the PUREX approach

The Plutonium Uranium Reduction Extraction Process

PUREX

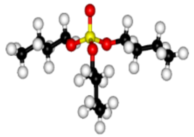
Anderson & Asprey, Univ.Chicago, 1947
US Patent 2924506
Glen Seaborg's Metallurgical Laboratory

Spent nuclear fuels

❶ Dissolution in nitric acid

Metallic waste

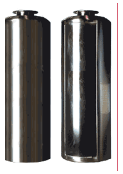
Extractant



❷ Separation of elements to be recycled

Fission products
Minor actinides

Conditioning by vitrification

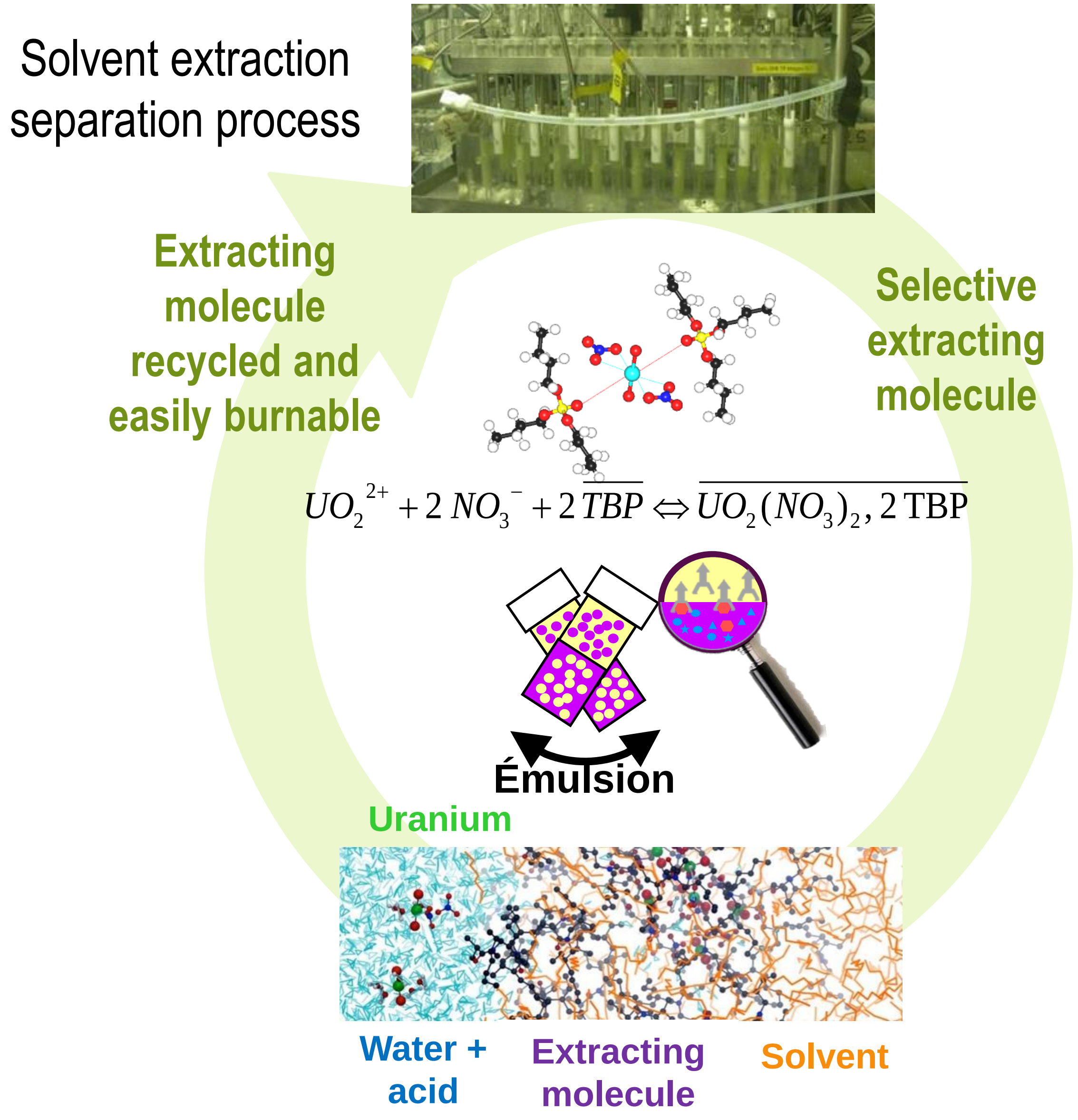


Vitrified waste

Uranium
Plutonium

❸Conversion Fabrication

The high achievements of the PUREX process

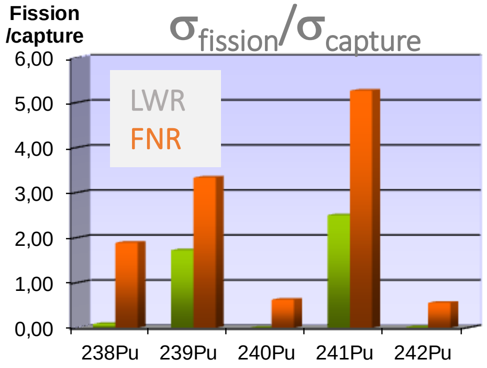


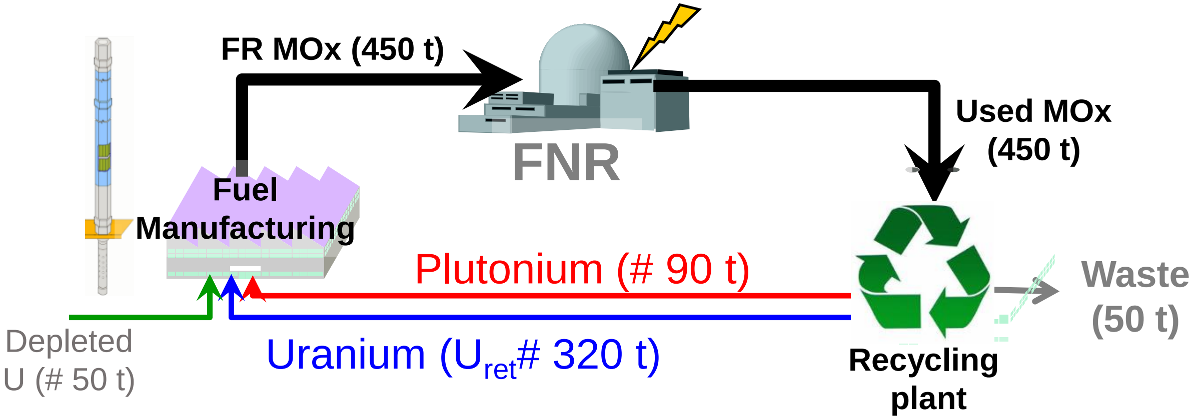
➢ PUREX separation process

- Based on the
  - selective U(VI) and Pu(IV) extraction by tri-n-butyl phosphate (TBP)
  - U/Pu separation based on Pu(IV) reduction by U(IV) and hydrazinium nitrate
- High yields of recovery (**>99.9%**) and purification versus MA and fission products (**DF > 10^7**)
  - Capacity to produce Pu nuclear-grade for MOX fuel fabrication, and clean U for ERU fuels
- Continuous and robust process
- Demonstrated to produce low amount of secondary waste thanks to extractant recycling
- Capacity to treat various types of irradiated fuels (UOX, MOX, RTR…)
- Relative low supply and operating cost

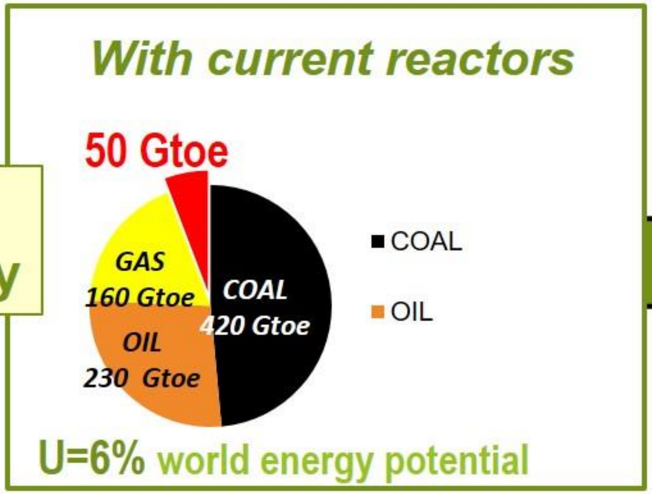
Improving further resource preservation ➔ Pu-multirecycling for transforming ^{238}U

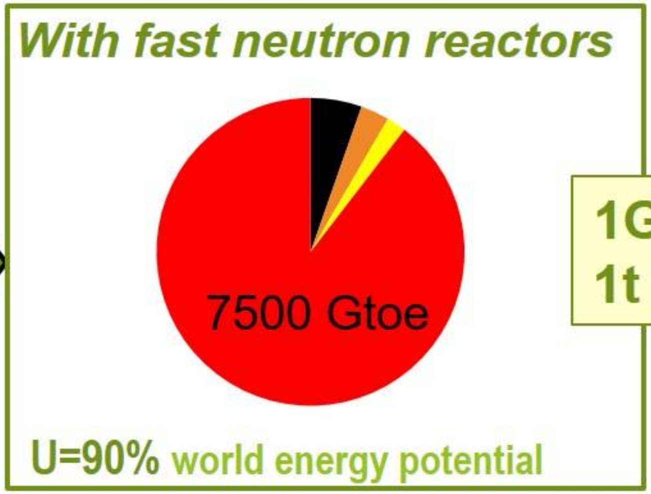
Multirecycling limited by ^{2n}Pu buildup ⟹ **GEN4 systems using fast neutron**





1GWe ~ 150t U_{nat}/y





1GWe ~ 1t U_{nat}/y

Very significant improvement of natural uranium efficiency

The beneficial long-term impact of recycling (1/2)

With recycling

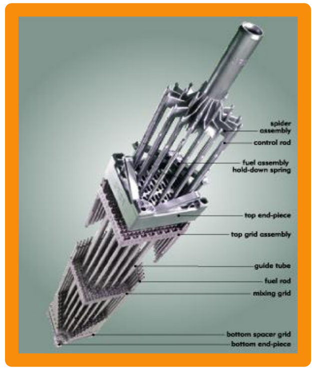
Tailored for confining

❸ Reduce waste impact

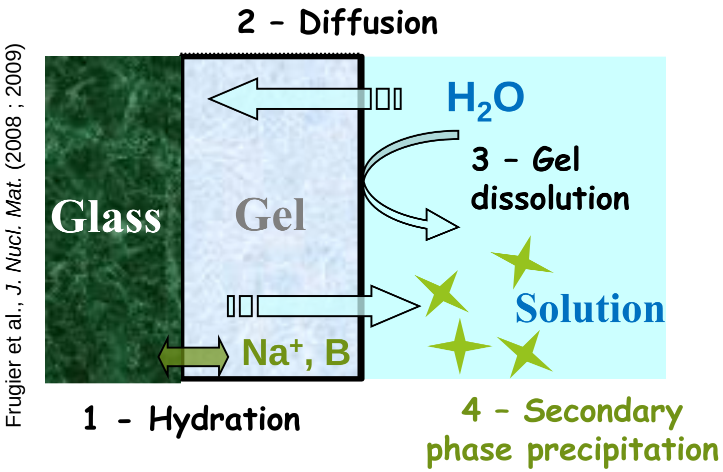
❶ A much higher durability

- Better long-term confinement properties
- Higher robustness to changing environmental condition

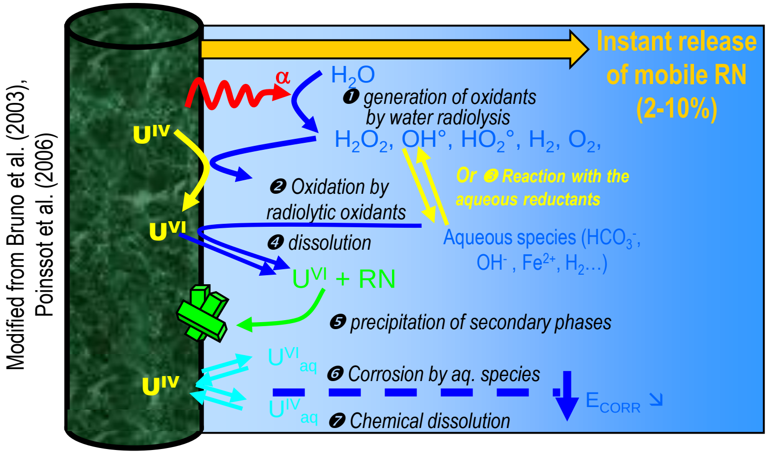
Without recycling



Tailored for producing KWh



slow RN release due to low alteration rate, potential resuming with secondary phases

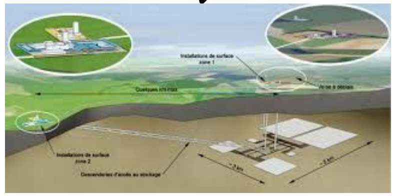


Early release of RN which increases with time, strong influence of redox conditions

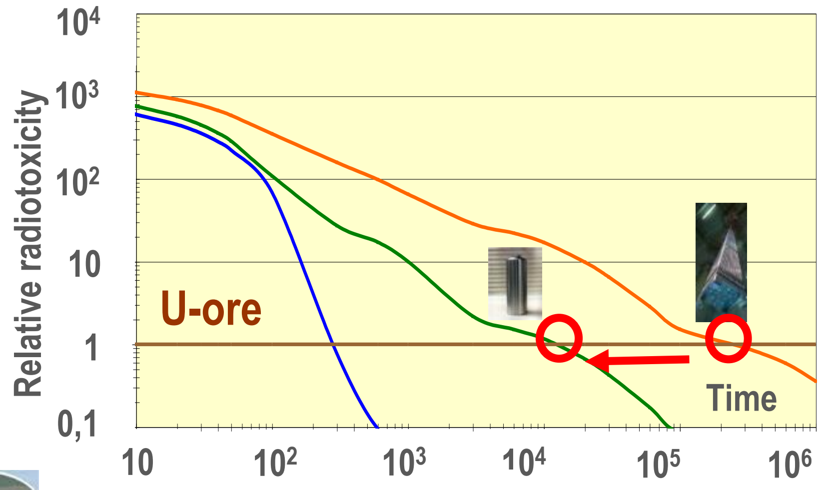
The beneficial long-term impact of recycling (2/2)

With recycling

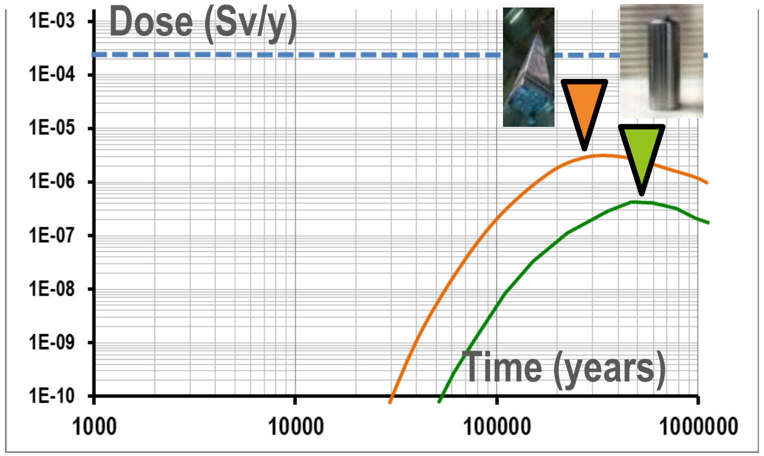
Tailored for confining



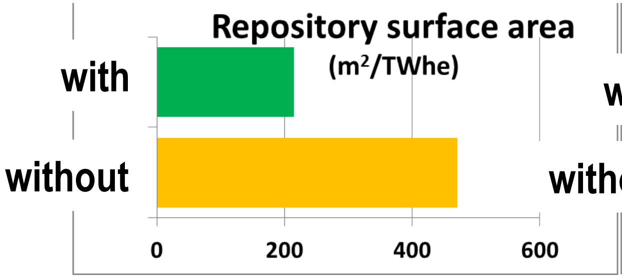
❷ Long-term toxicity ↘

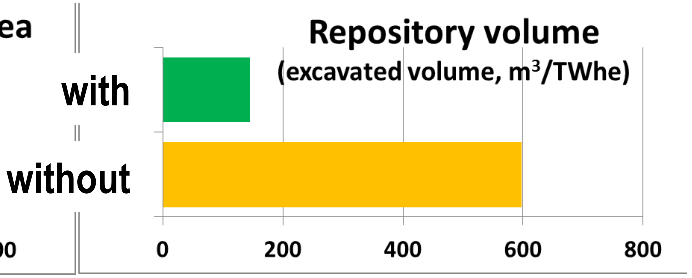


❸ Confinement performances ↗

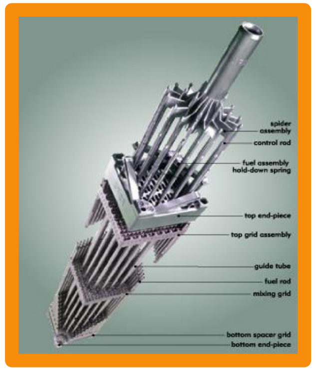


❹ Preserve repository resource

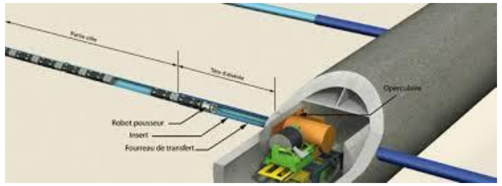




Without recycling



Tailored for producing KWh



Improve the environmental footprint

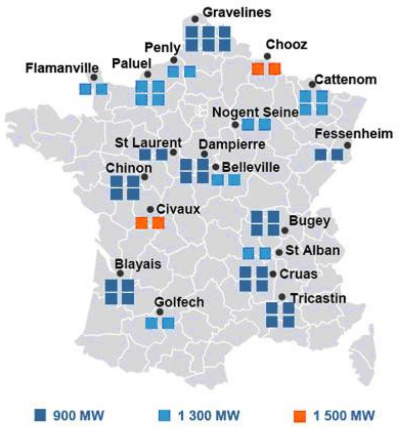
❹ Reduce environmental footprint

❶ Life Cycle Assessment

- From cradle to grave
- A dedicated tool "Nuclear Energy Life Cycle Assessment Simulation" (NELCAS) has been developed *(Poinssot et al., 2014)*

❷ French case

- Whole fuel cycle available, including recycling activities
- Large database thanks to TSN annual environmental reports



- Design
- Feed-back
- Extrapolation

→

- Construction
- Deconstruction
- Transport

- Annual TSN reports
- Feedback

→

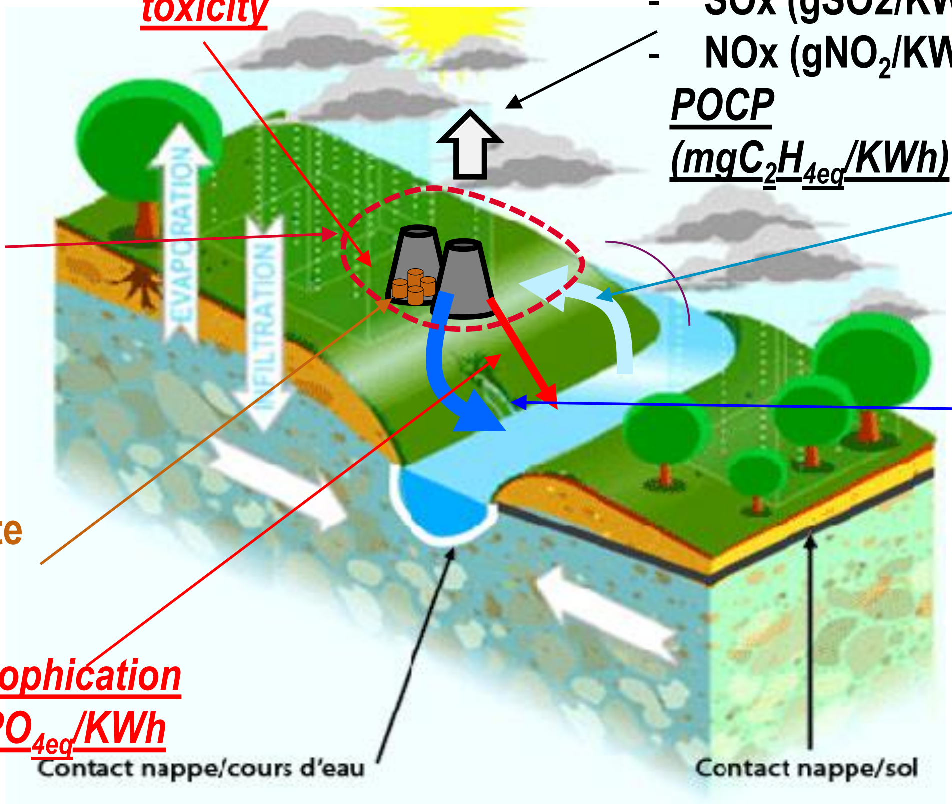
- Energy and materials streams
- Release / Withdr.

→ **NELCAS** → **Relevant environmental indicators**

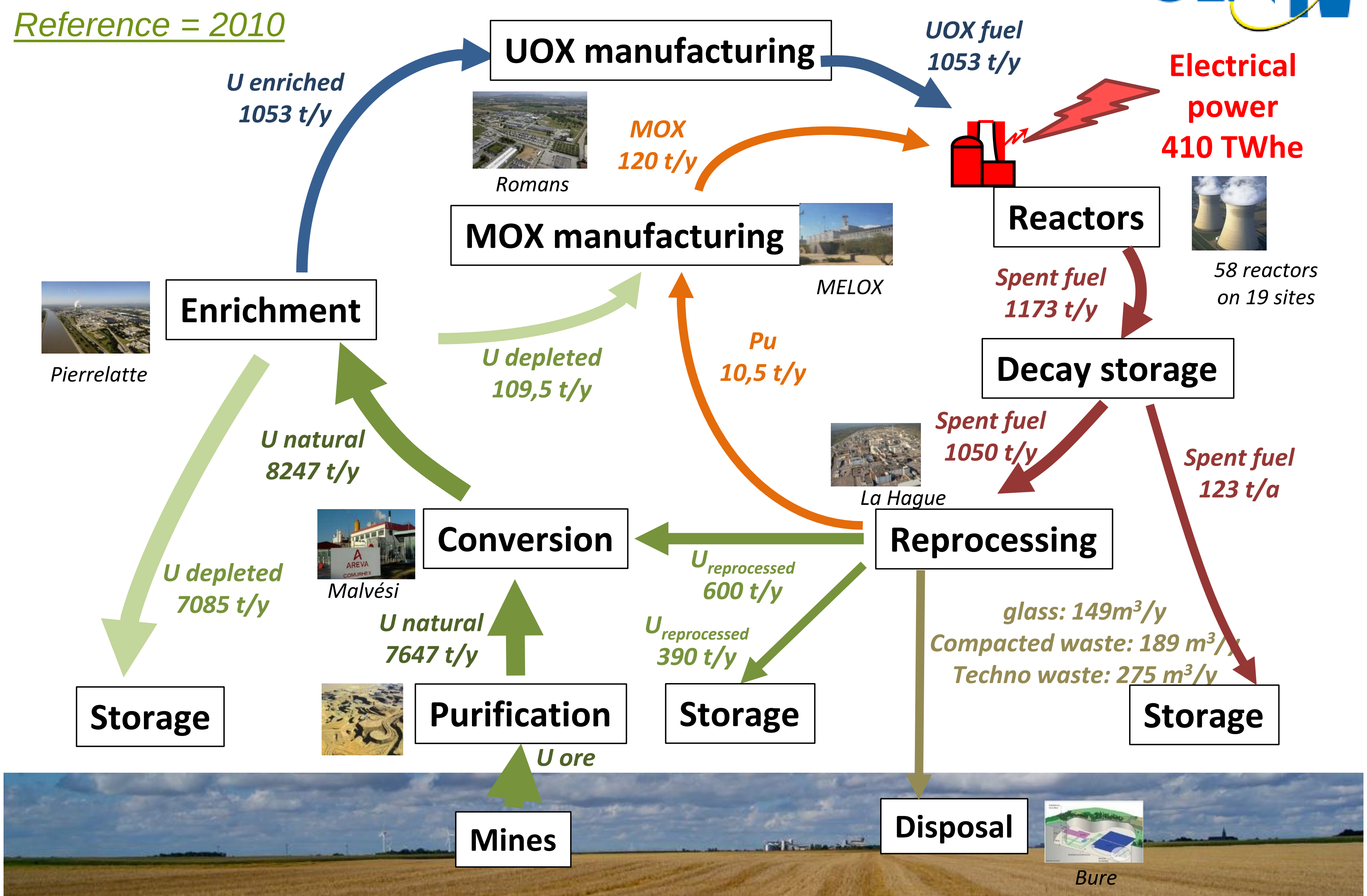
(Poinssot et al., Energy, 2014)

Selection of key environmental indicators

- Generic indicators used in any LCA study
- Maximum potential impact indicators (*underlined*)

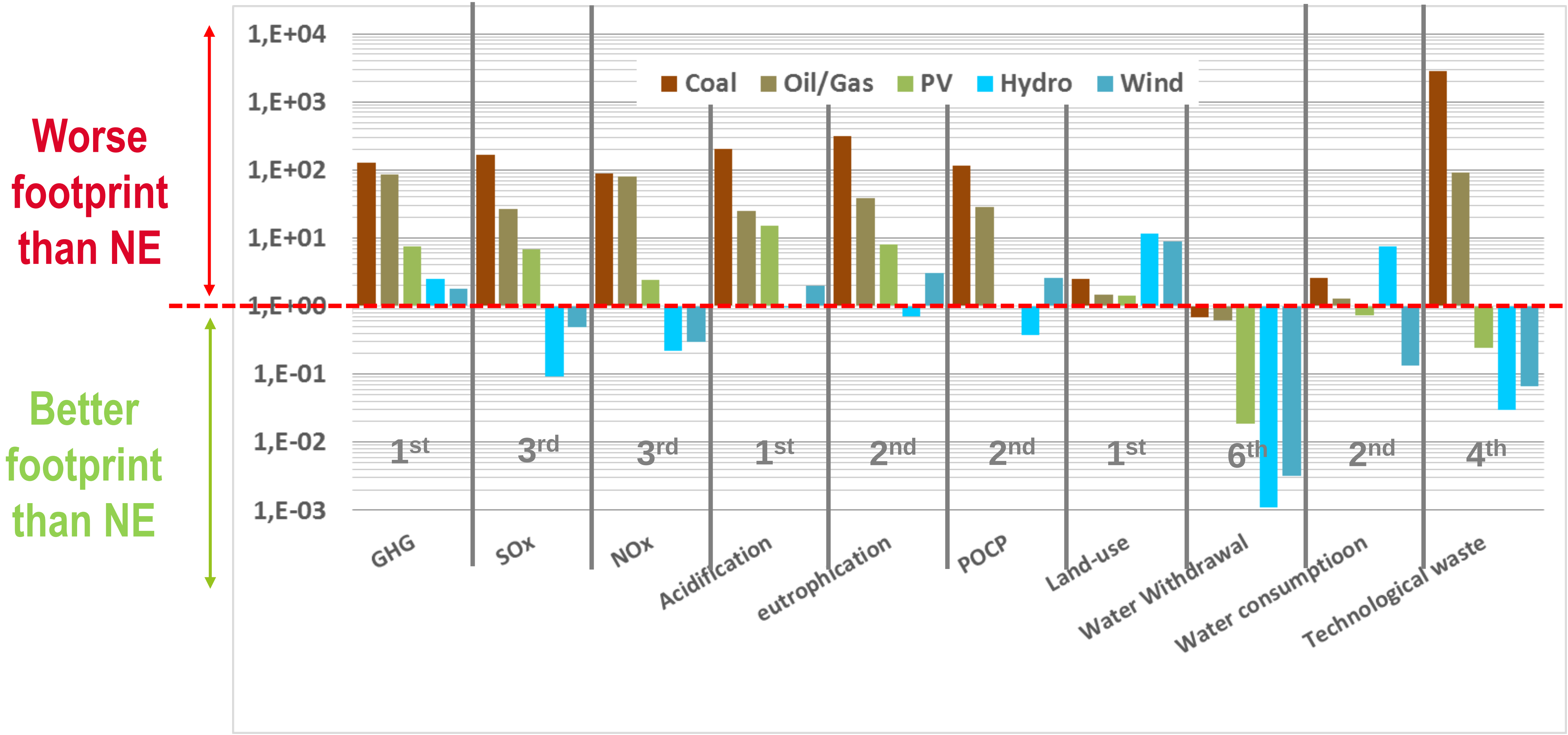


The French reference fuel cycle



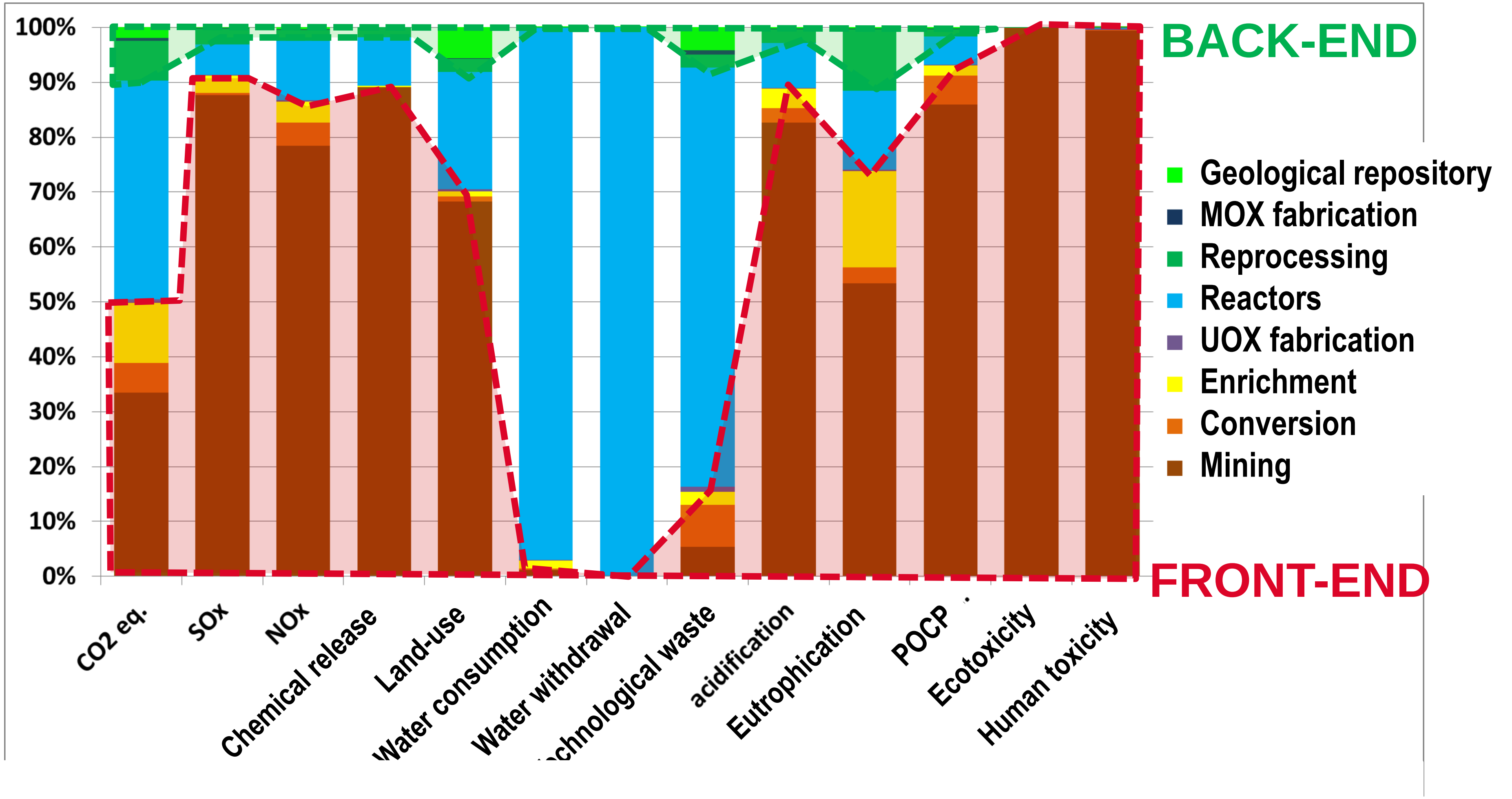
Results for the current fuel cycle

Environmental indicators normalised to the value calculated by NELCAS for the nuclear energy



Nuclear energy is within the top-3 for most of the indicators

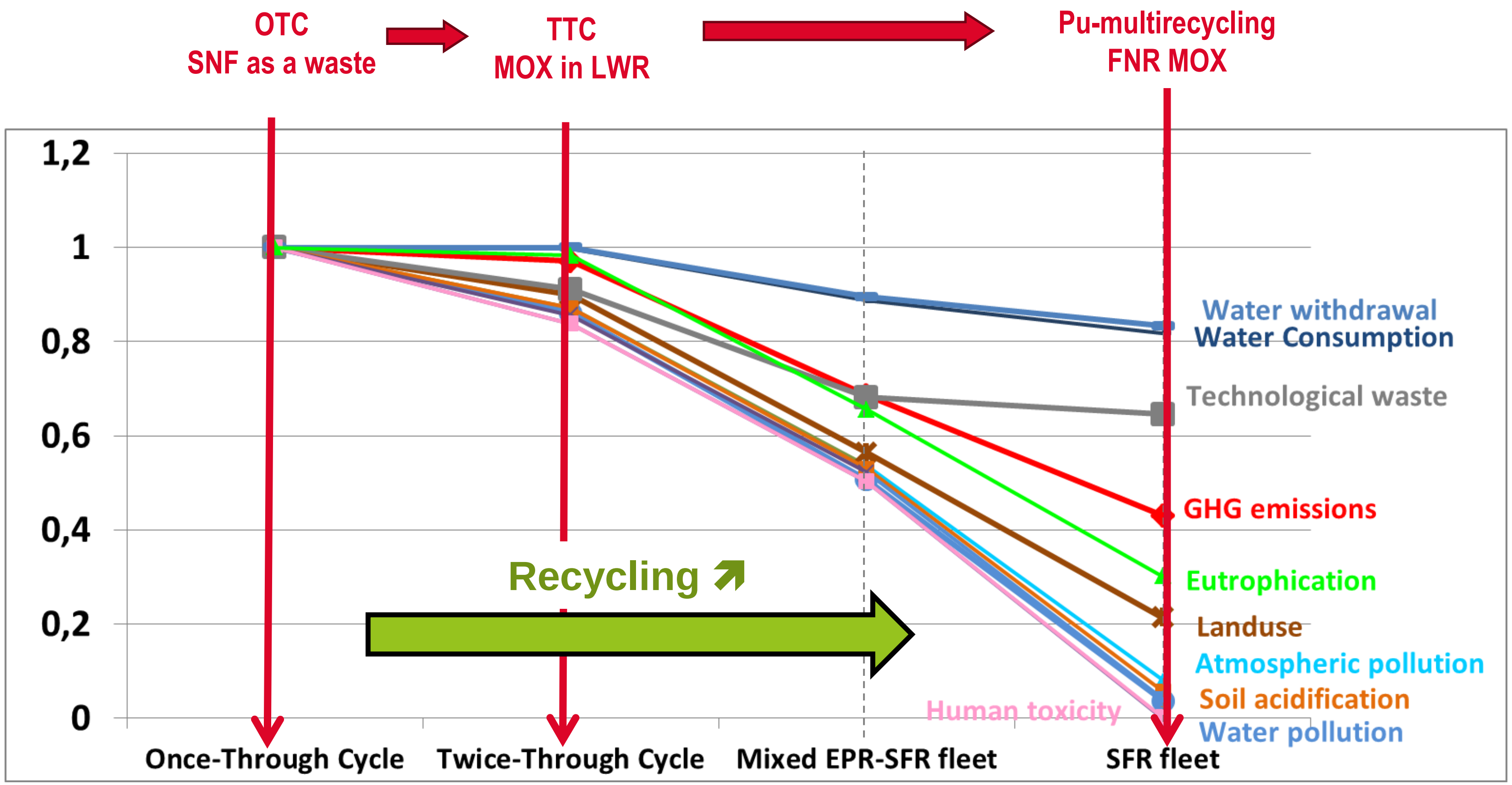
Contribution of the different fuel cycle steps to the overall footprint



- Impact of front-end activities >> impact of back-end activities
- ➘ Environmental footprint ⇔ reducing front-end impact or significance

Reducing the front-end significance thanks to actinides recycling

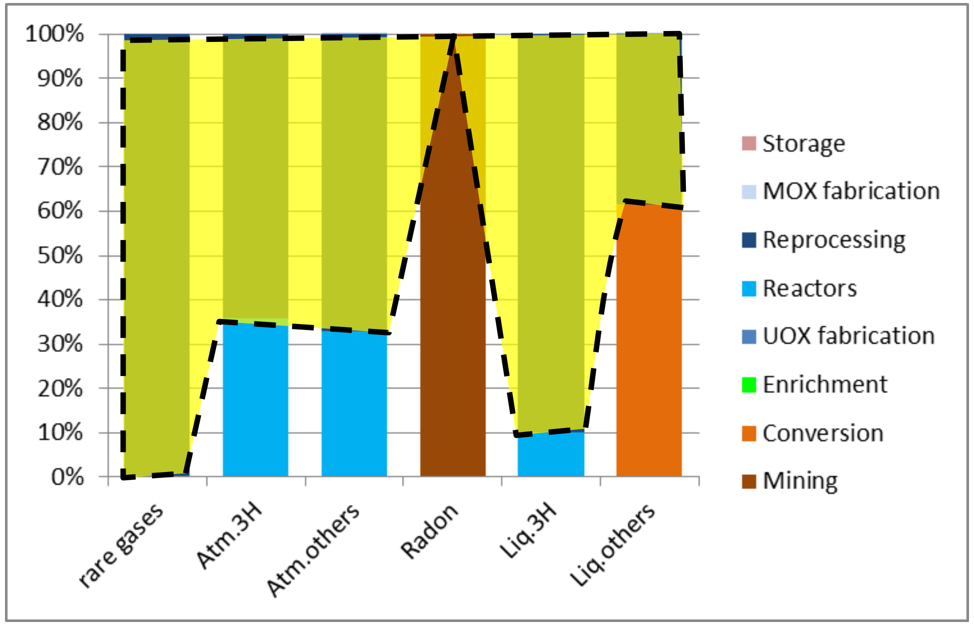
Data from Poinssot et al. (2014) & Serp et al. (2017)



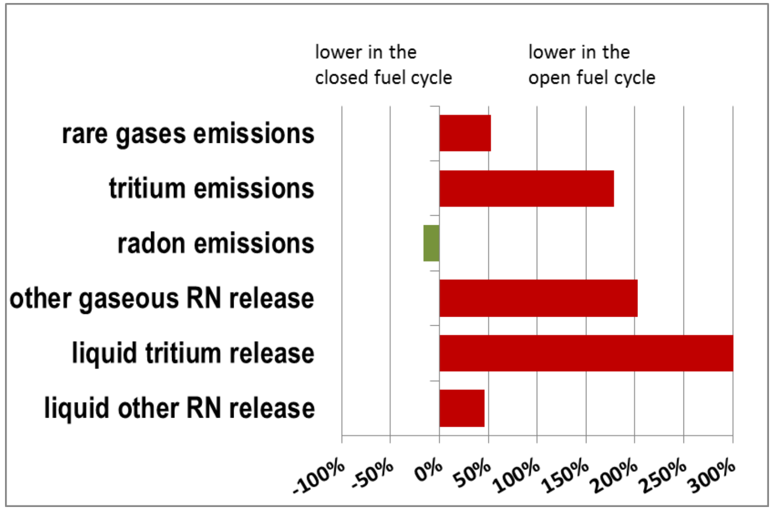
Much higher impact of front-end than back-end activities

Recycling yields to improving the footprint

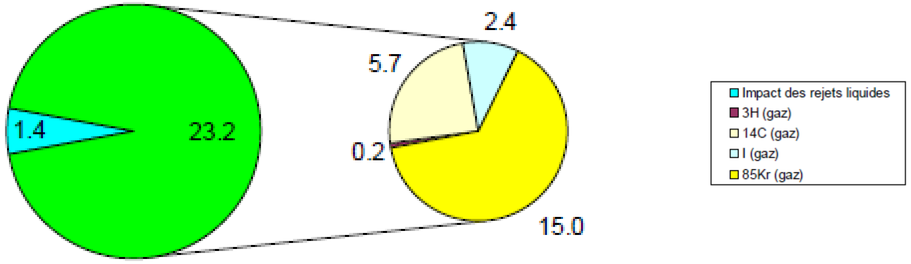
What about the radioactive release?



Evolution of the radioactive release with the recycling implementation



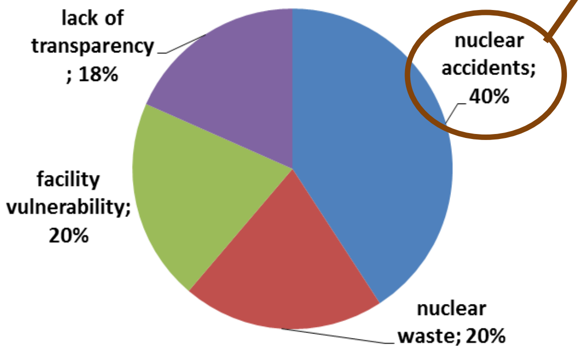
- Recycling is a significant contributor to radioactive releases
- Increased releases due to the recycling plants:
  - Atmospheric releases: ^{85}Kr, ^{14}C, ^{129}I
  - Liquid releases: mainly ^{3}H
- However, their actual impact is demonstrated to be negligible:
  - 17-24 µSv/yr for the most exposed population
  - ~**1% natural radioactivity**



Total 24,7 µSv (agriculteur)

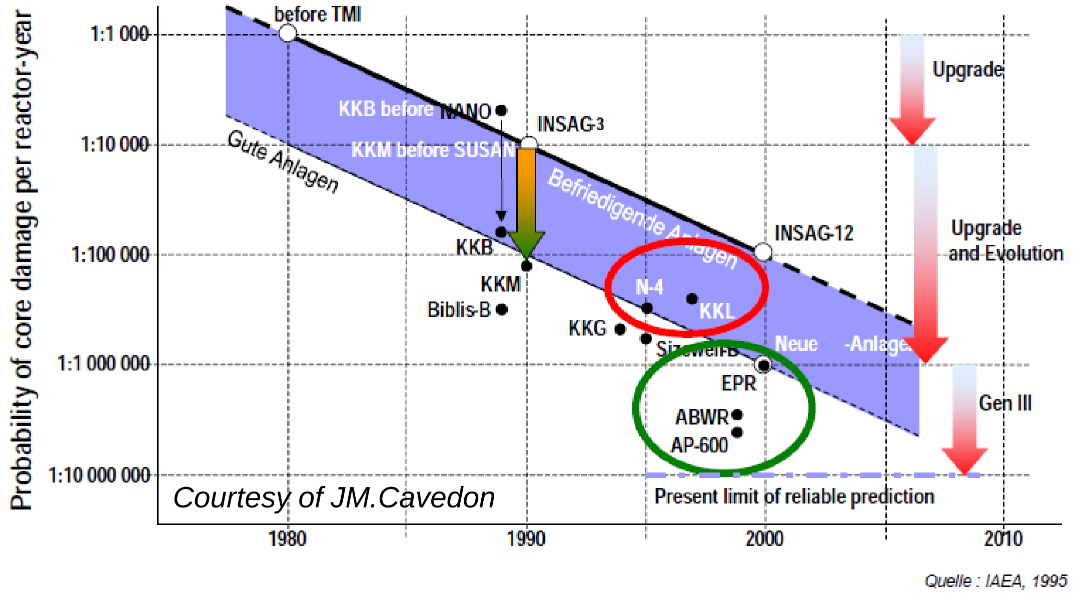
Chap.II: Societal drivers

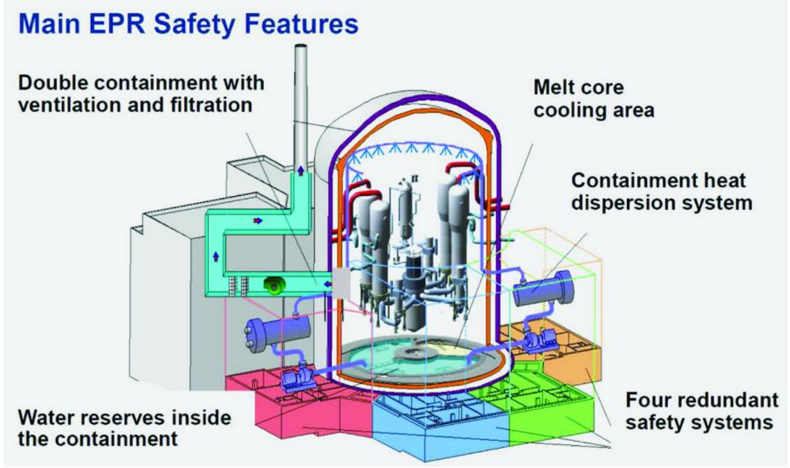
Opinion survey (IRSN, 2014)



➊ **Improve safety**

- Independent and skilled safety authorities
- Safety of reactors: towards GEN3
  - Decrease of core fusion probabiliy
  - Avoid any RN release preventing the population evacuation:
  - Example of EPR



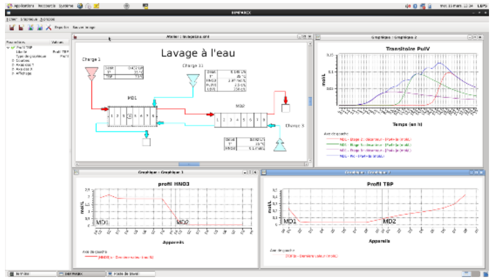


Towards a phenomenological and robust approach of processes

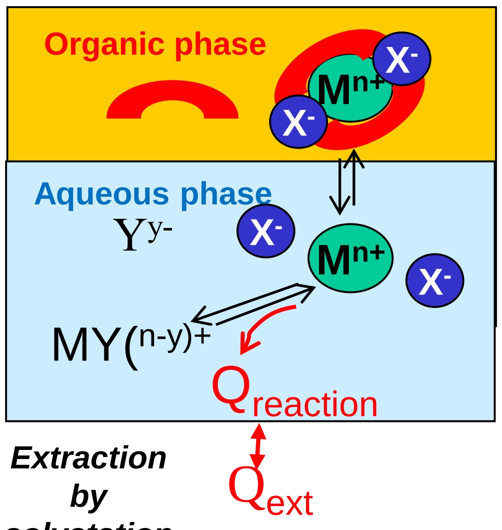
Safety of the process

❶ From empirical correlations to predictive phenomenological simulations

❷ From procedure-based to simulation-based piloting



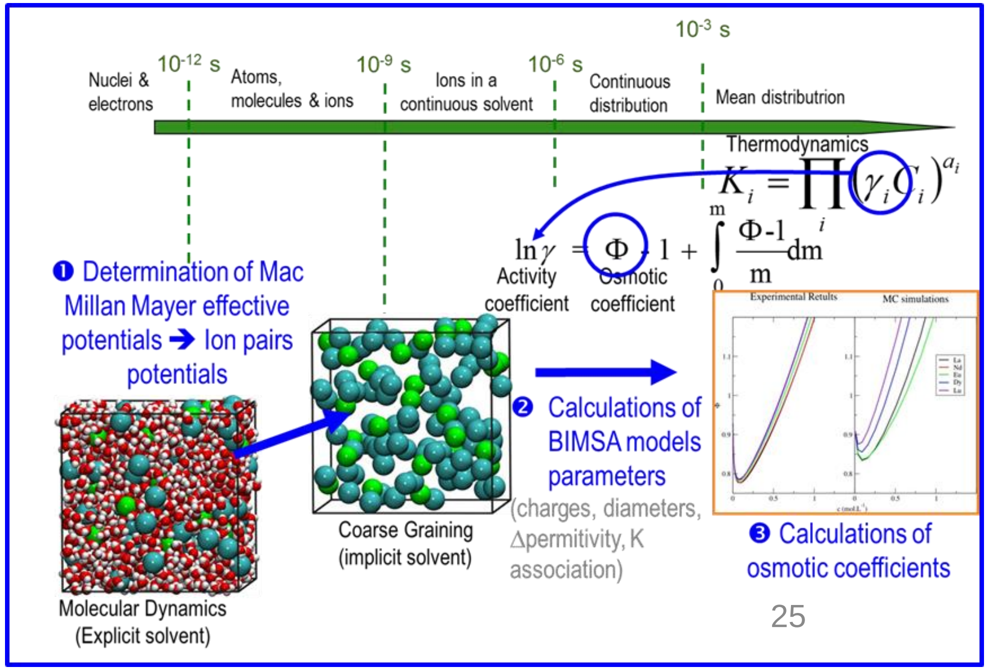
$M^{m+} + m\,X^{-} + n\,L \leftrightarrows MX_mL_n$



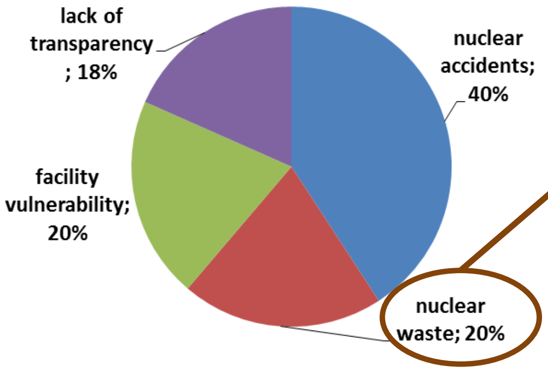
Extraction by solvatation

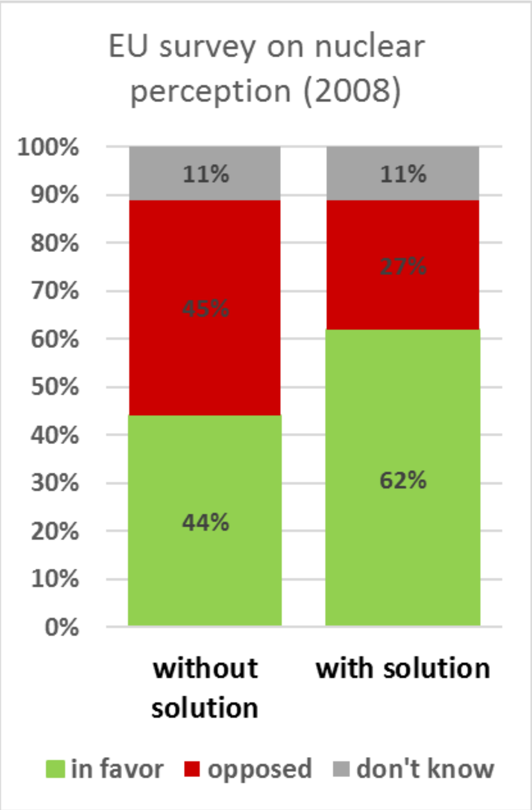
- Need for predictive simulation codes (eg. PAREX, © CEA)
  - Thermodynamic description of reactions
  - Kinetics rate
  - Heat exchanges
  - Simplified hydrodynamics

Multi-scale approach



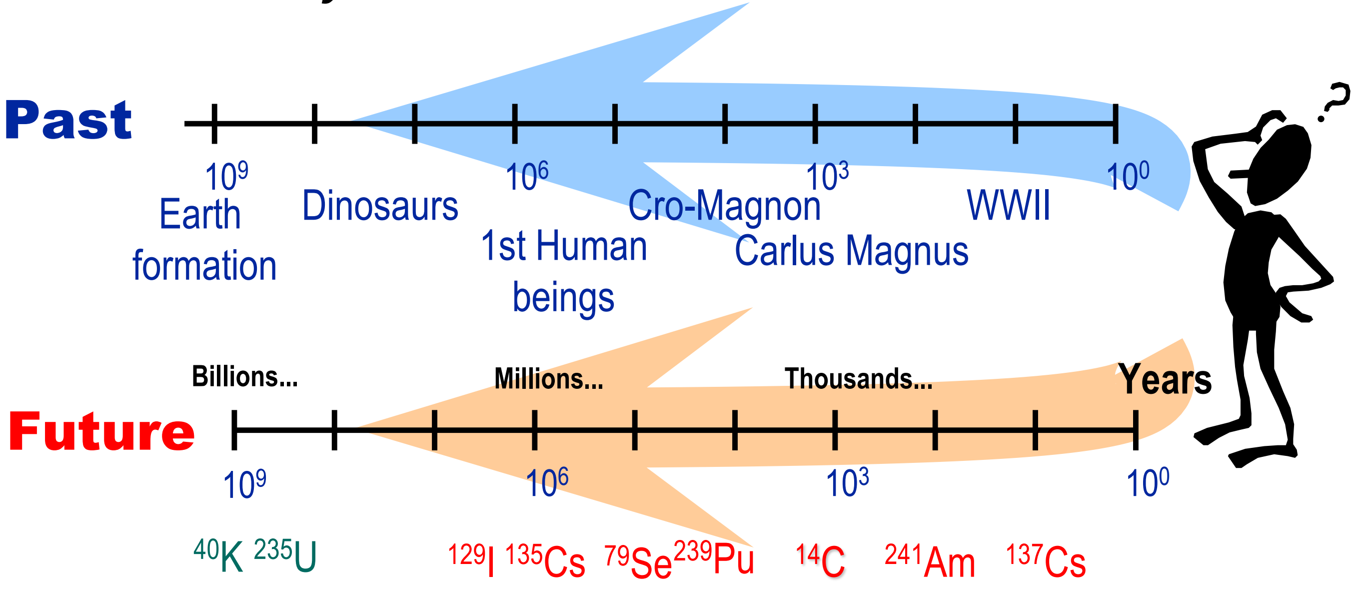
Improve waste management



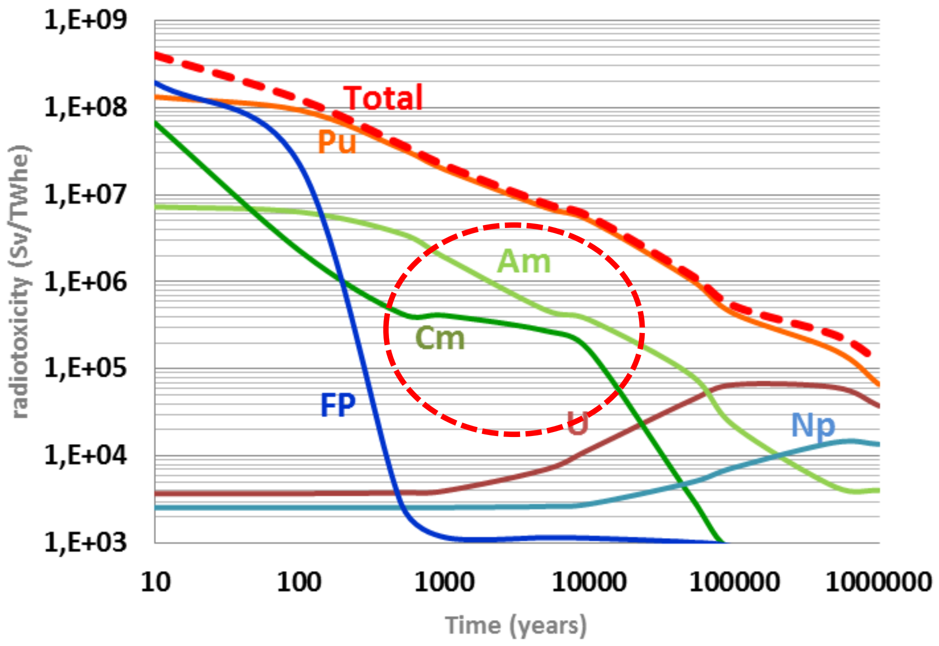


❷ Improve waste management

- Waste is severely questioned by public opinion
  - Nuclear waste seen as Achille's heel of nuclear energy, mainly due to very long lifetime
  - Main concern = waste lifetime. Any reduction could help to improve acceptability. *Could we reduce waste lifetime back within Human History?*

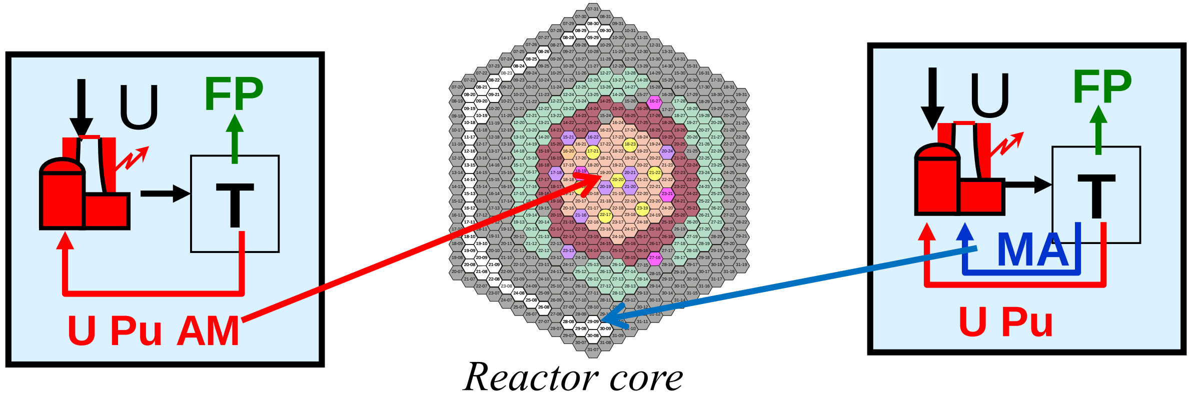


Recycling the minor actinides, a potential contribution for decreasing the waste burden



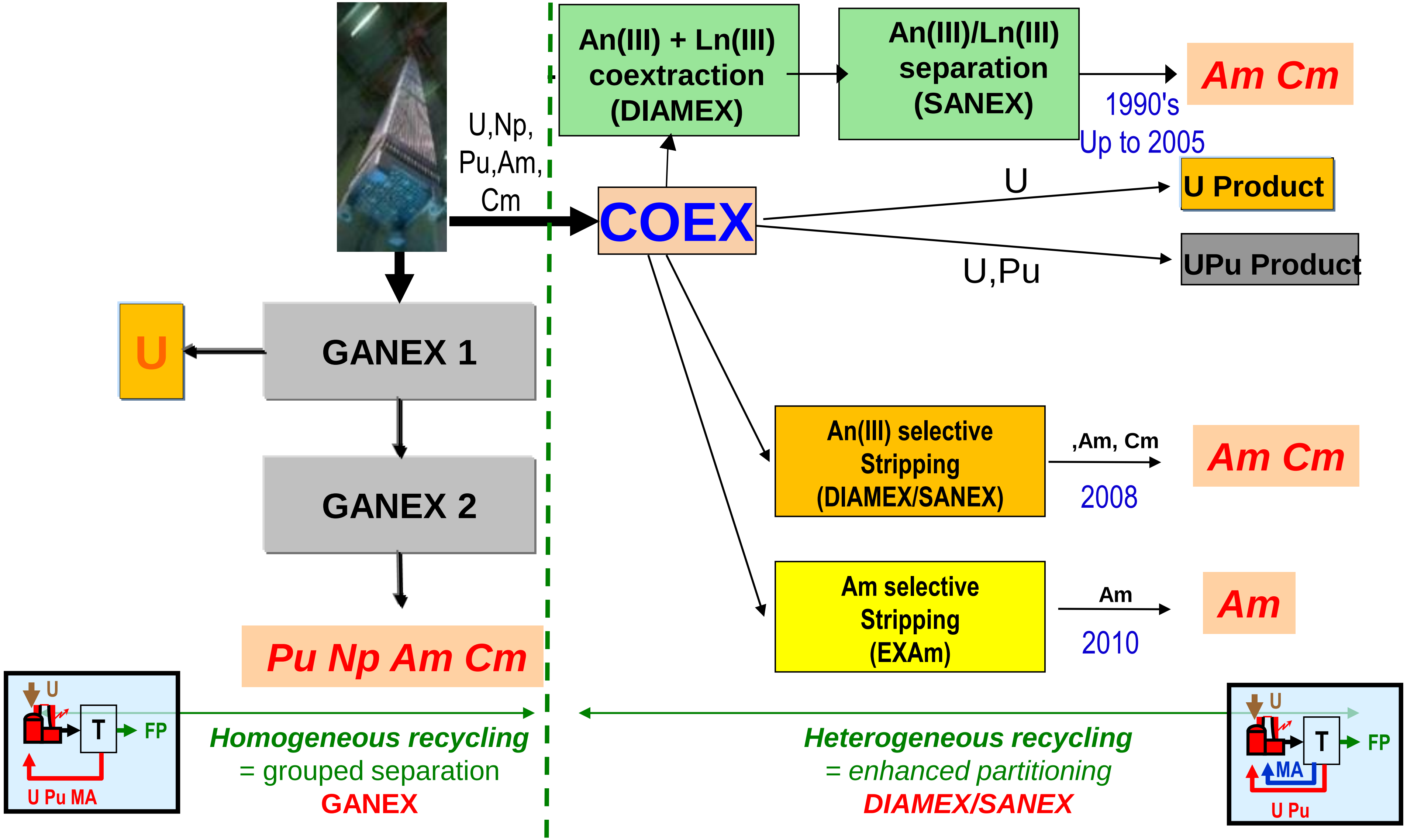
- Beyond plutonium, waste toxicity dominated by minor actinides MA (Am+Cm)
  - Recycling MA ⇔ decrease waste lifetime and toxicity
  - ↘ activity ⇔ ↘ heatpower → denser repository → repository preservation!
- In a long term nuclear energy system, MA could subsequently be transmuted in FNR
- ADS is also an alternative if no FNR is available

Homogeneous recycling
→ grouped recycling → GANEX processes

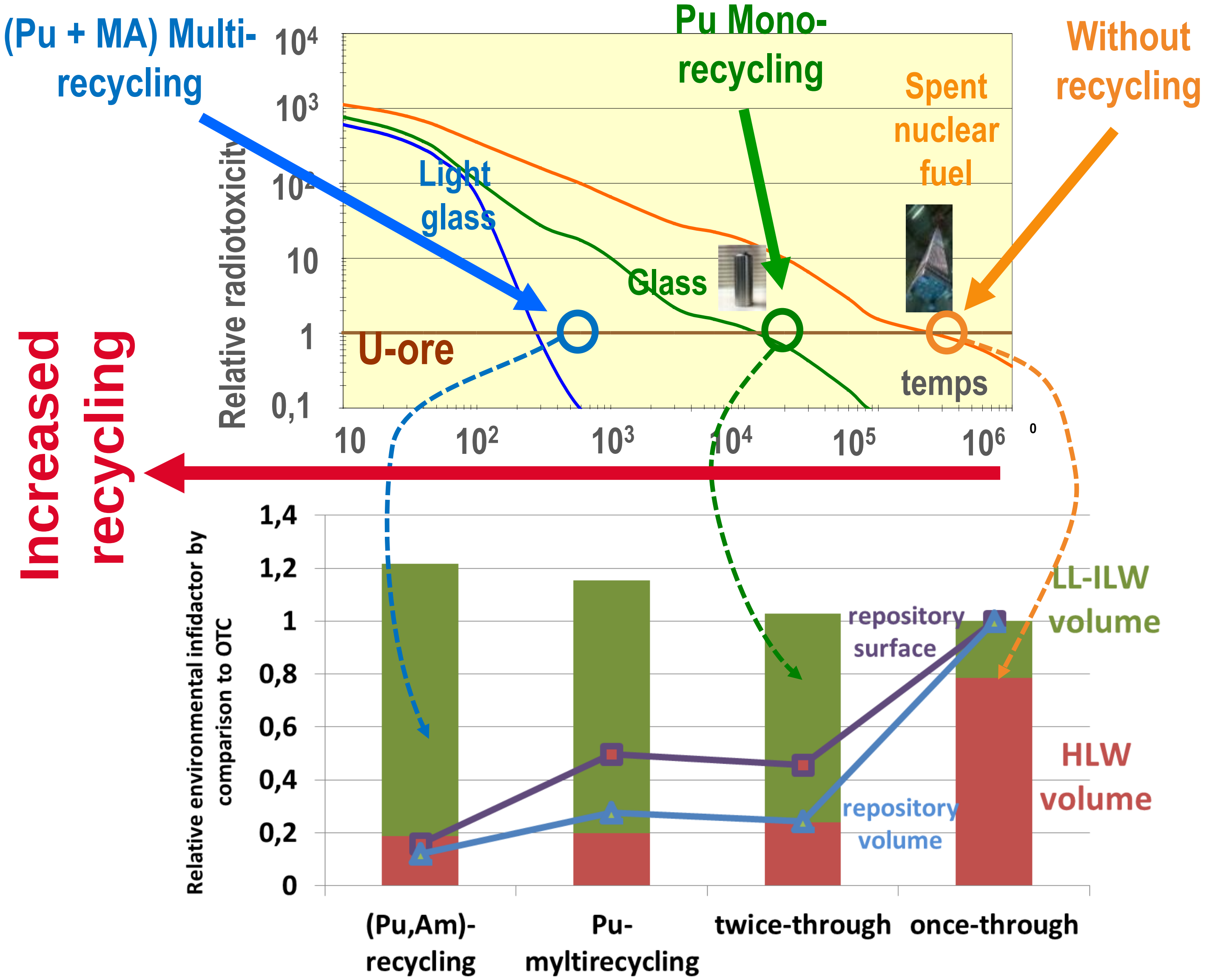


Heterogeneous recycling
→ enhanced partitioning → DIAMEX/SANEX processes

The rationale of the various processes



Synthesis on the beneficial impact of recycling on waste management



❶ **waste toxicity and lifetime reduced**

❷ **Very strong reduction of HLW volume**

❸ **Preservation of repository resource**

Surface ↘ ⇔ *lifespan* ↗

Volume ↘ ⇔ *cost* ↘

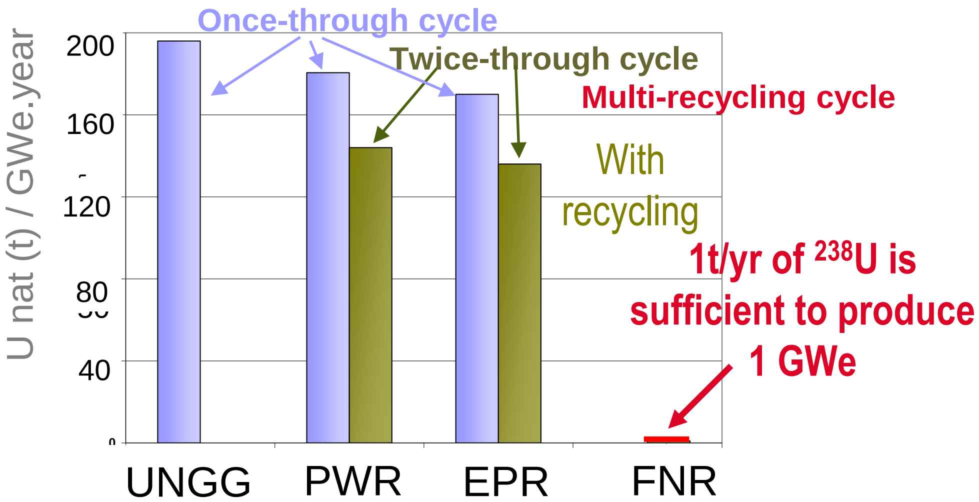
Chap.III: economic drivers

Economic optimization is already at the root of R&D for industry

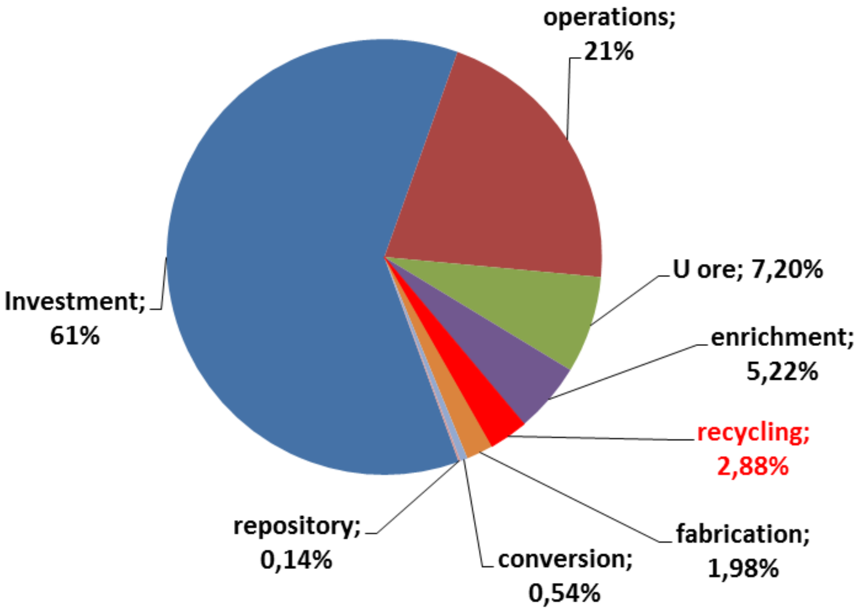
❶ Stable & predictable cost

❷ Ensure affordable costs

- Recycling decreases the dependence to U market (price, availability, volatility …)
  - Possibility of using U_{rep} and U_{dep} available stockpile with FNR
  - Significant extension of U reserve

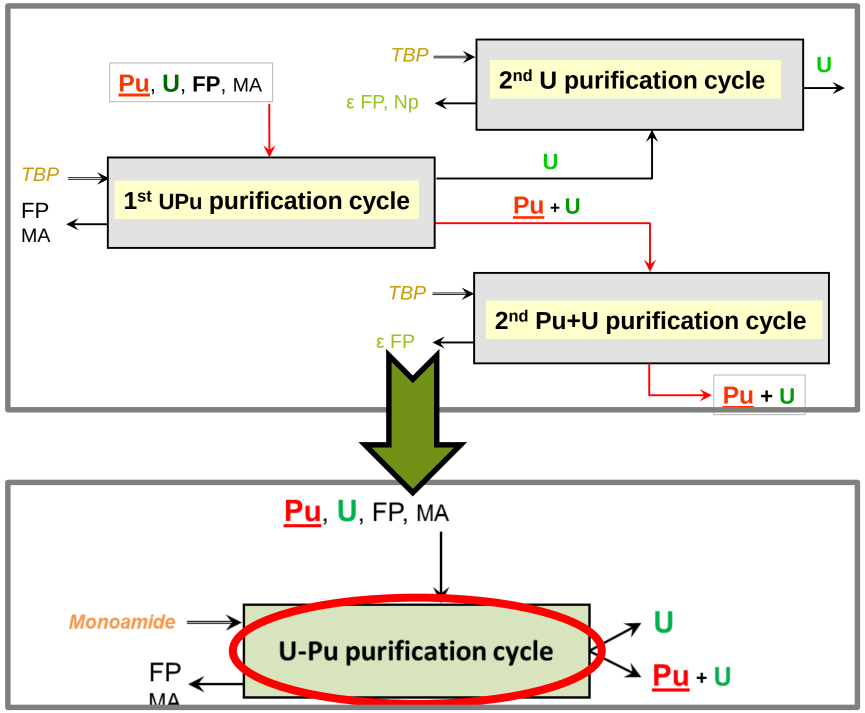


- Back-end of the fuel cycle has a limited influence on the KWh cost



Towards advanced more cost-effective separation processes

❸ Towards simpler processes



- Nuclear industry is young and complex ➔ rooms for improvements …
- Ex. for recycling: development of a simpler U/Pu L/L separation process liable for treating Pu-rich fuels
  - Typically, single-cycle + redox-free
  - Objectives: capability to treat LWR and FNR MOX fuels without dilution with UOX
    - Avoid any use of redox reagents for U/Pu separation
    - Maintain a high level of safety for Pu multirecycling conditions
  - Capacity to reach the requested performance in a single workshop instead of 3 ➔ significant investment and operation costs savings

The rationale of future NFC in view of sustainability

1980 | 2050 | 2100

Dates are purely indicative

TOWARDS INCREASING SUSTAINABILITY

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

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

Gen.IV ***…+ MA recycling***

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

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

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

Breakthrough = reactors

Breakthrough = cycles

<u>Main incentives</u>
- 1st step towards U resource saving
- Efficient waste conditioning

<u>Main incentives</u>
- Major resource saving
- Energetic independence
- Economic stability

<u>Main incentives</u>
- Decrease of waste burden,
- Optimisation of the repository
- Public acceptance

Conclusion

- Sustainability is an efficient framework for deriving a robust roadmap for future nuclear fuel systems
  - implies considering non-technical societal wishes in the overall balance
  - Overall trade-off between economic, environmental and societal drivers
  - Require indicators or figures or merit for enlightening the respective benefit

- Low GHG
- Low footprint
- Ability to preserve natural resource
- ↘ waste volume, toxicity and lifetime
- Overall footprint greatly improved by recycling

- Base-load electricity production
- Long-term predictable cost thanks to recycling
- Recycling cost limited
- Process simplification

- Improved safety by design
- Phenomenological approaches
- ↘ waste burden by actinides recycling

Sylvanes Abbey (France)

Actinides recycling is the keystone of any sustainable nuclear fuel cycle

With my warmful thanks to my colleagues and friends

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Upcoming webinars

24 January 2018	Design, Safety Features and Progress of the HTR-PM	Prof. Yujie Dong, INET, Tsinghua University, China
21 February 2018	Gen IV Reators' Materials and their Challenges	Dr. Stu Maloy, LANL, USA
21 March 2018	SCK•CEN's R&D on MYRRHA	Prof. Dr. H.C. Hamid AÏT ABDERRAHIM, SCK-CEN, Belgium