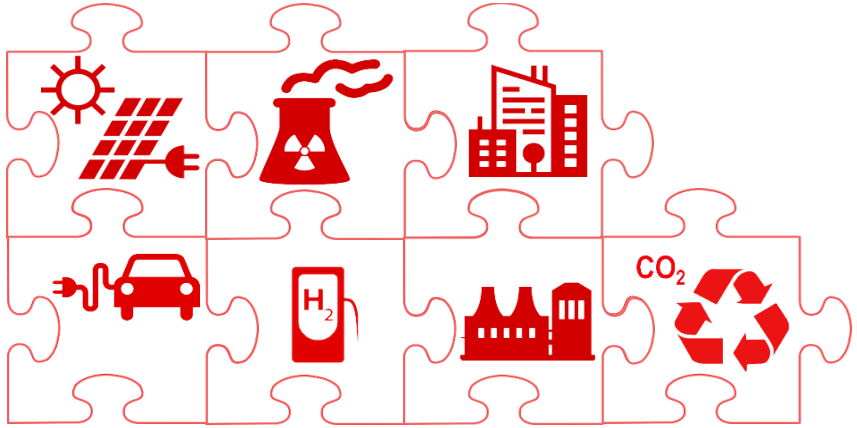


Energy R&D for a sustainable future : from climate challenges to responsible innovation

Heloise GOUTTE

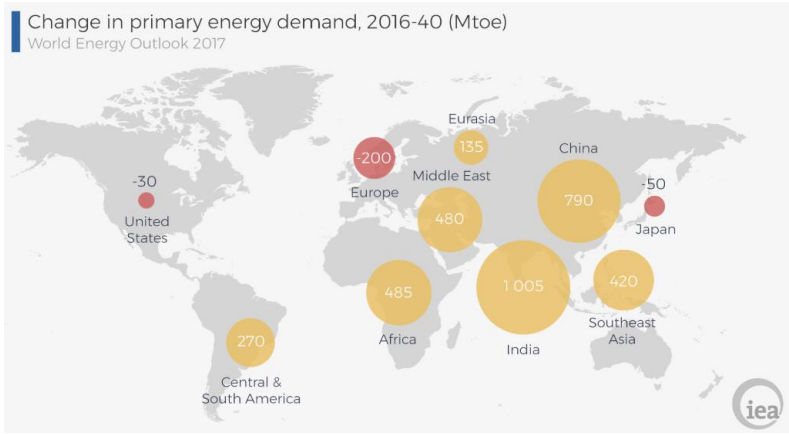
Scientific Director of Energy

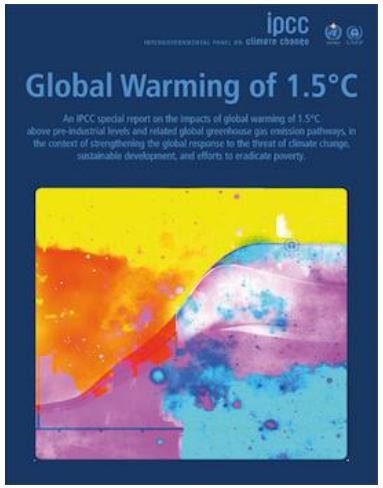
Heloise.goutte@cea.fr

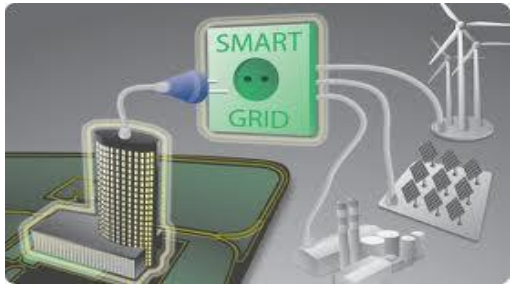
The energy world in deep evolution

… a transformation not just a transition

- **Climate** urgency
- **Geopolitical** instability
- Energy **sovereignty** challenges
- Growing **energy needs**
- Technological **innovation** and disruption
- **Industrial sector** transformation
- Evolving roles of stakeholders (territories, « **prosumers** »)

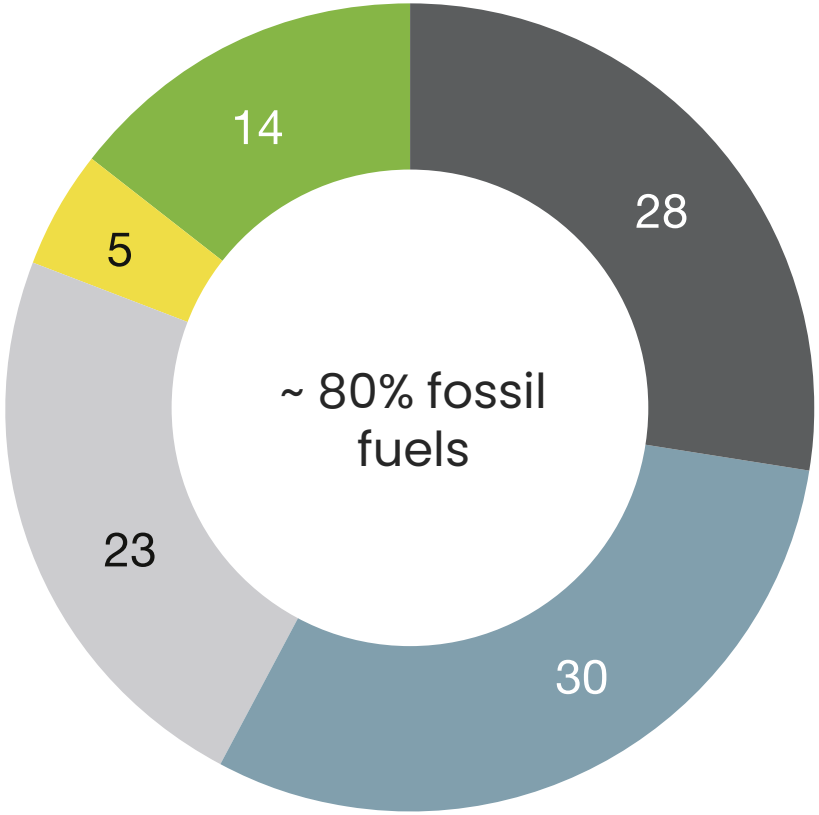






Far from Net Zero…

Global primary energy consumption by source (%)



- Coal
- Oil
- Natural gas
- Nuclear
- Renewable energies and waste

IEA 2025 and OPEC 2025

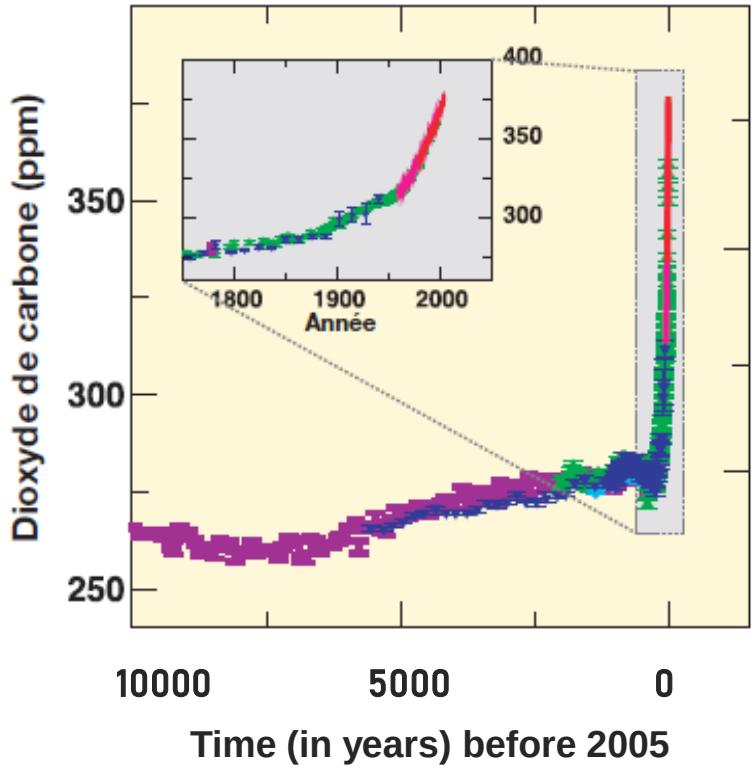
World coal, oil and natural gas consumtion hit a record in 2024

Chiffres 2022
Chiffres clés du climat, édition 2024, ministères territoires écologie logement

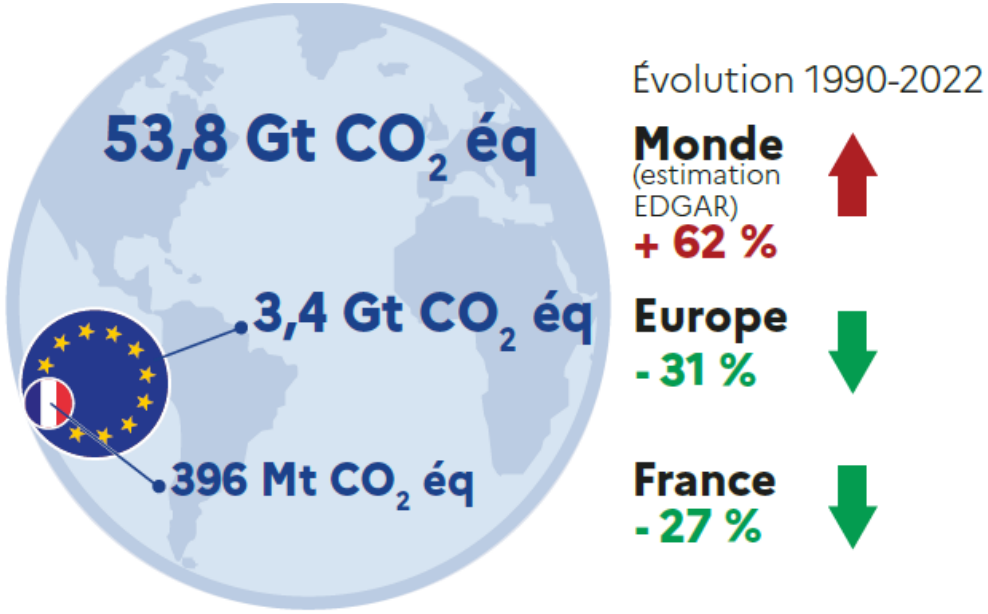
https://www.iea.org/world/energy-mix

Greenhouse gazes

Highest concentration of CO_2 in the atmosphere in 2 million years

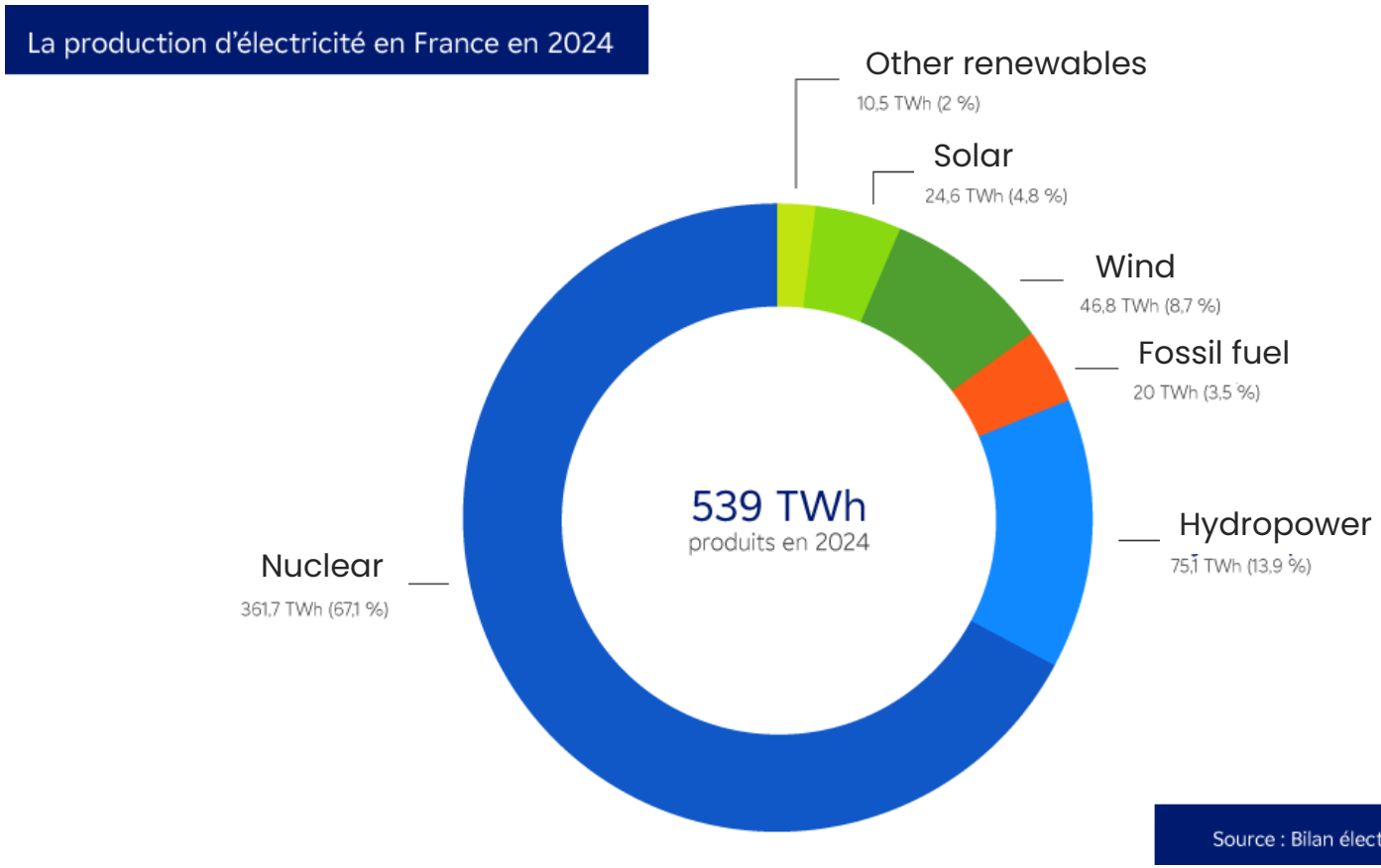


Source: IPCC WG1 report



France: 1% of global emissions
EU : 6,1% of global emissions

Low-carbon electricity in France



Consumption 447 TWh

Export - import balance 89 TWh

→ **Record : No. 1 exporting country in the EU**

% fossil fuel production : lowest level since 1950

% renewable energy production : 29%
→ record high

Our carbon footprint

Source : SDES-Insee

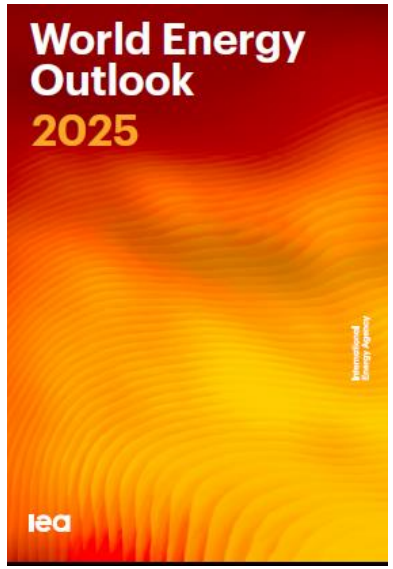
Carbon footprint of the French in 2021

9,8 t
Per capita

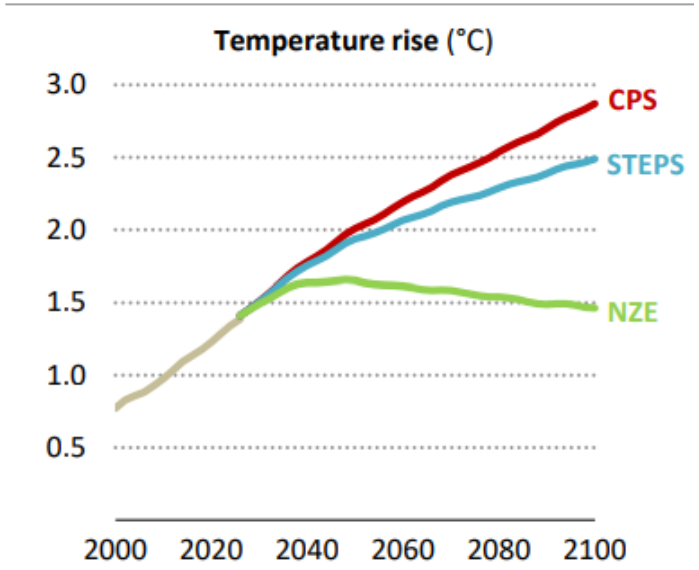
55 %
of the carbon footprint is associated with imports

→ Decarbonization must go beyond electricity (transport, industry, buildings ...)

And now ?



Global warming



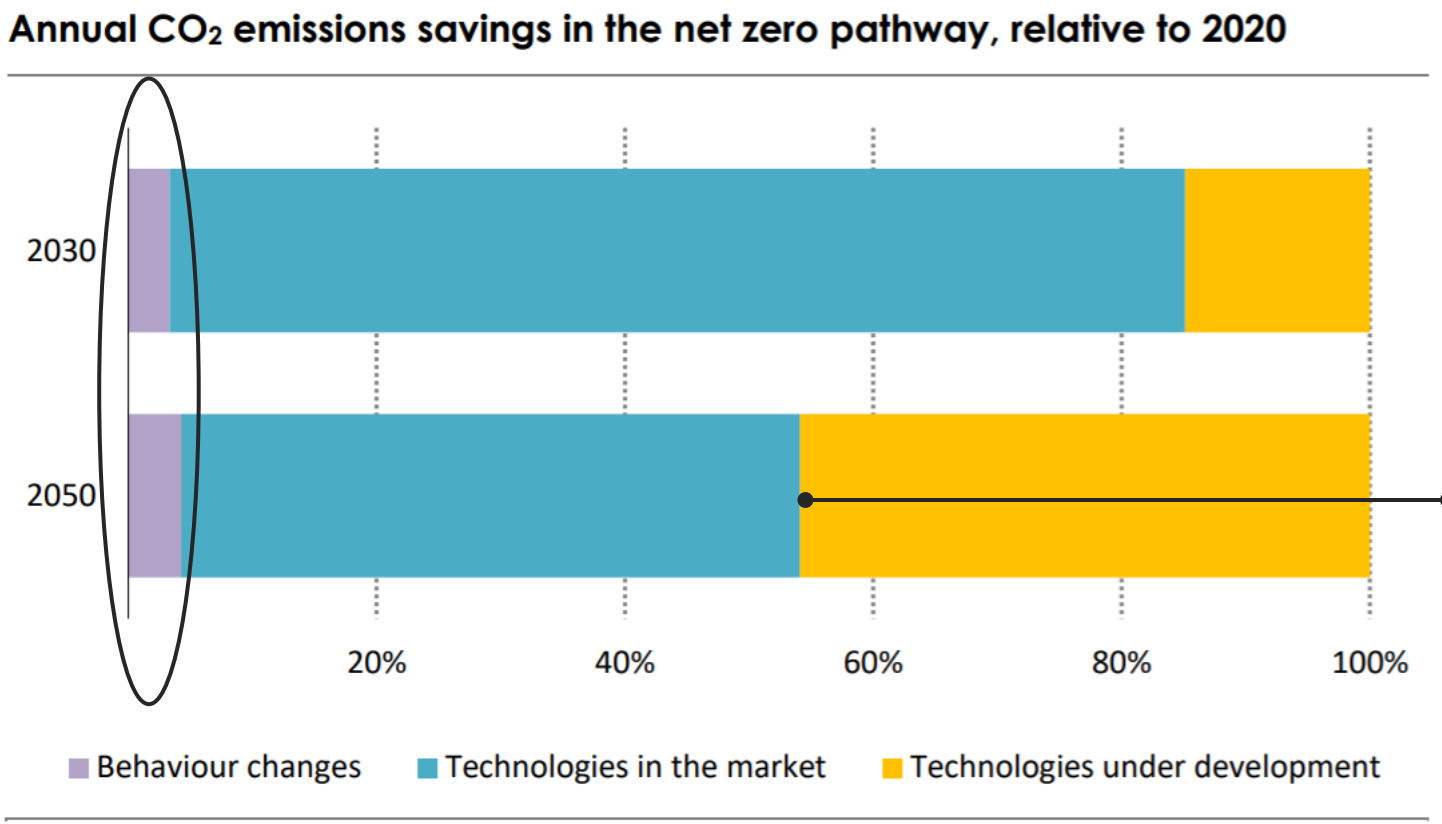
The average temperature rise reaches 2.9 °C in 2100 in the CPS, 2.5 °C in the STEPS, and in the NZE Scenario it peaks at around 1.65 °C in 2050 and falls below 1.5 °C in 2100

CPS : Current Policies Scenario
STEPS : Stated Policies Scenario
NZE : Net Zero Emissions by 2050

- CPS 2025 scenario = +2,9°C in 2100,
- CPS 2019 scenario = +4°C

https://www.iea.org/reports/world-energy-outlook-2025

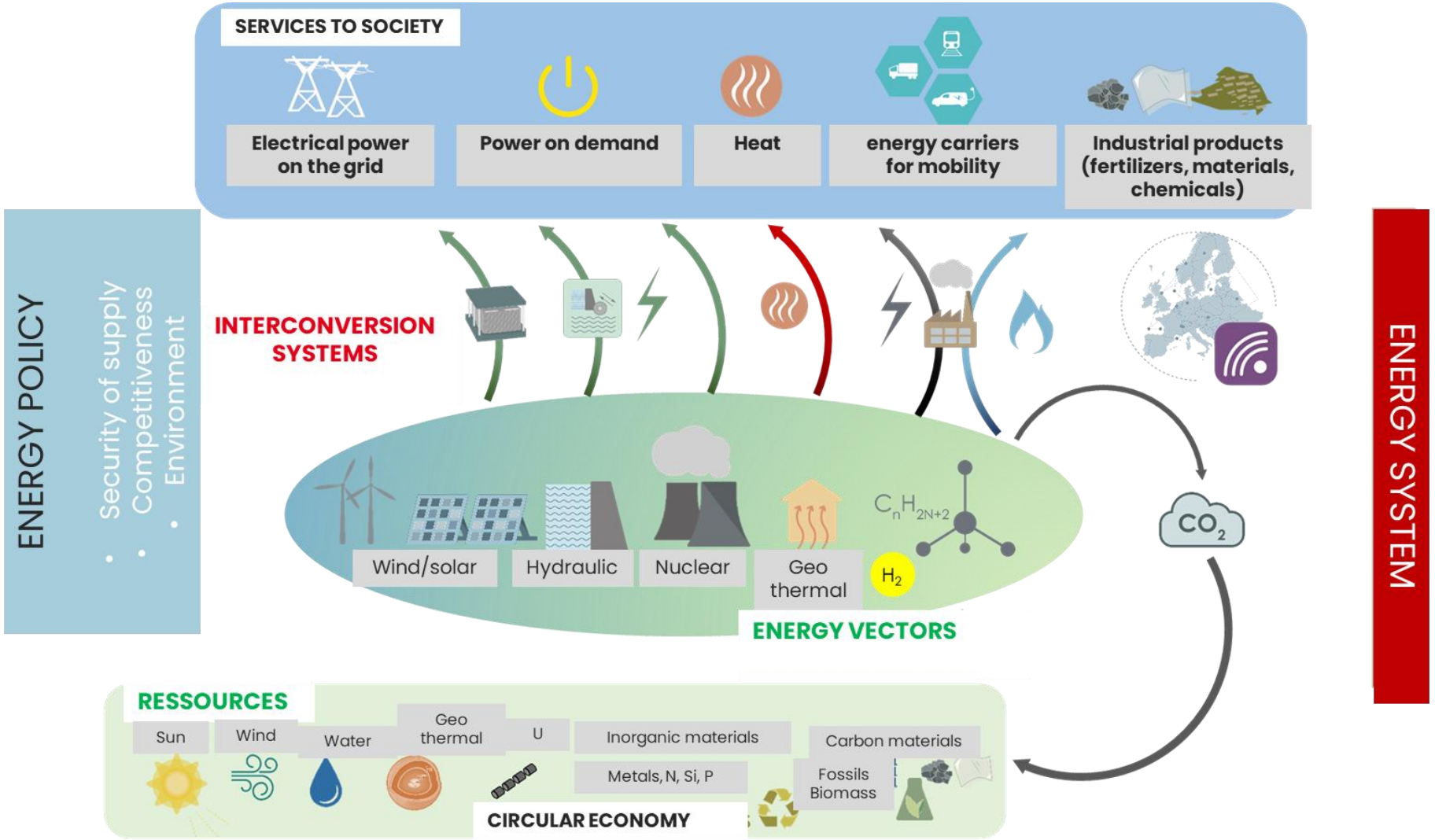
Towards carbon neutrality



Net Zero by 2050 - A Roadmap for the Global Energy Sector – IEA, May 21

45% of the innovations needed to achieve carbon neutrality have yet to be developed

An integrated vision of the energy system



Four key pillars of CEA R&D

Production

Decarbonized energy **production** (nuclear, renewable)

System

Flexibility tools **&** multi-vector energy **storage**

Smart Grids & demand **management**

Energy **conversion** (incl. efficiency, sobriety)

Ressources

Circular economy & advanced materials

Circular carbon economy

Energy mix

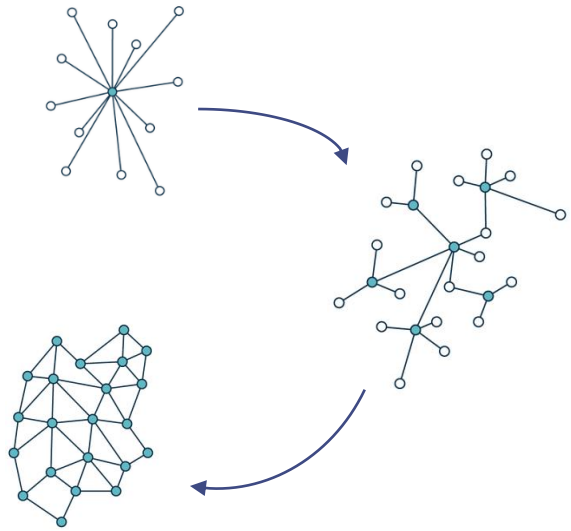
Energy **scenarios & socio-technical-economic** analysis

Energy transition : key findings and R&D pathways

No single option can provide a short- or medium-term solution in terms of energy source or energy vectors

One dependency should not be exchanged for another (materials …)

We need to manage the growing complexity of networks



Two key levers

Energy efficiency
Improving the performance of processes, equipment, and buildings

Sobriety
Reduced consumption, based on a change in lifestyles (at both individual and collective levels)

Electrification is a major part of the solution.
But it cannot cover all needs, notably in heavy mobility and industrial sectors.

Effective storage methods will be essential (daily, seasonal…)

CEA Nuclear R&D Roadmap

Supporting the industry and **managing** our historical activities

Anticipating and meeting future industrial needs

Preparing for tomorrow (new nuclear and new use cases)

Exploring the future (reinvented nuclear)

Nuclear power plant operating fleet and nuclear fuel cycle plants

Nuclear fuels and long term operation

SMR / AMR and fuel cycle

Gen IV reactors / AMR and advanced fuel cycle, fusion

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Integrating nuclear energy into a local system

SMR/AMR : new uses and local energy hubs

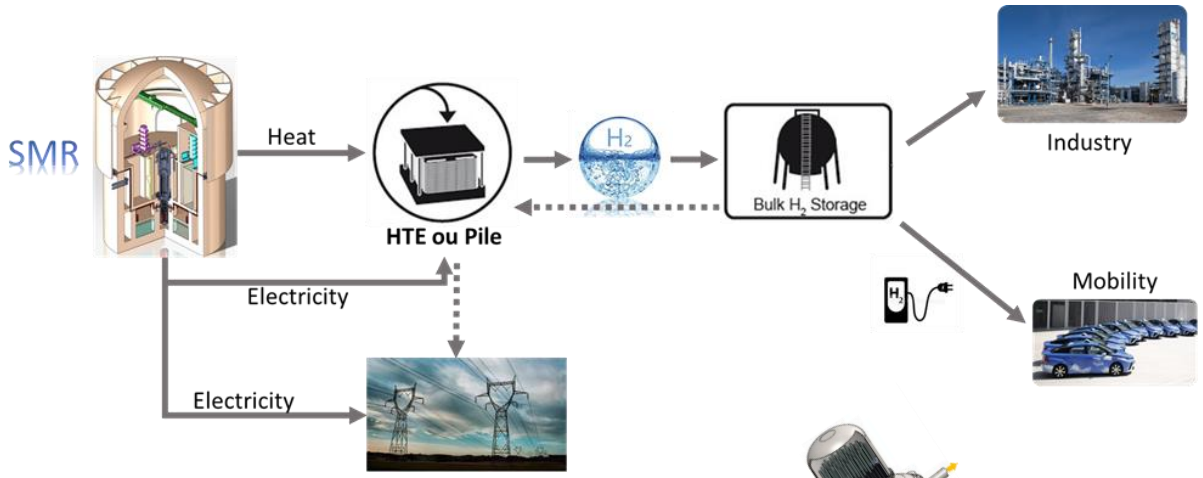
P-unitaire :
EPR : **1650 MWe**
SMR/AMR = **1/10** EPR
MMR = **1/100** EPR

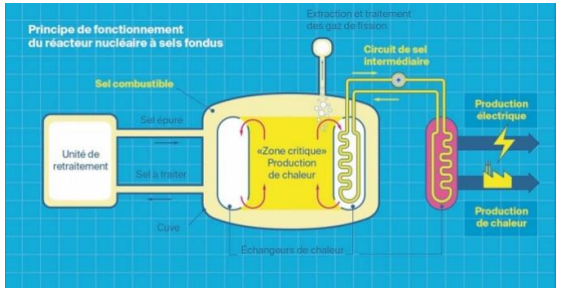
The integration of nuclear energy at the local level addresses several challenges related to the energy transition

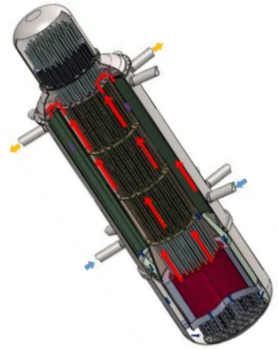
- Limited **grid hosting capacity** for large power plants
- Electricity supply to **isolated sites**
- Local electricity production to **balance** intermittent generation and avoid network reinforcement
- Coal plan **replacement**

SMR and AMR enable new applications for decarbonizing other sectors

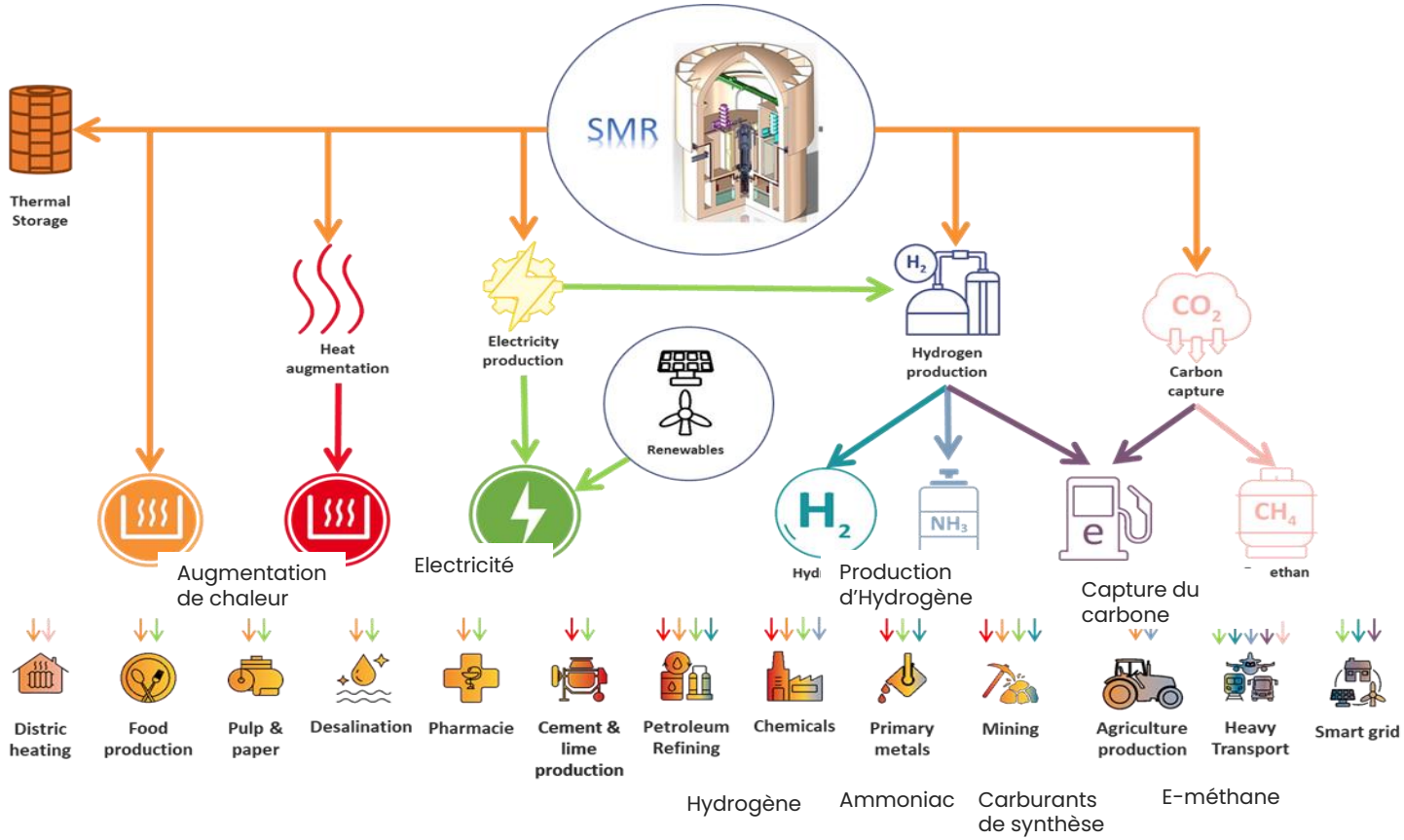
- **Heat and cogeneration** for energy-intensive industries
- **Urban heating** or cooling networks







Nuclear2X

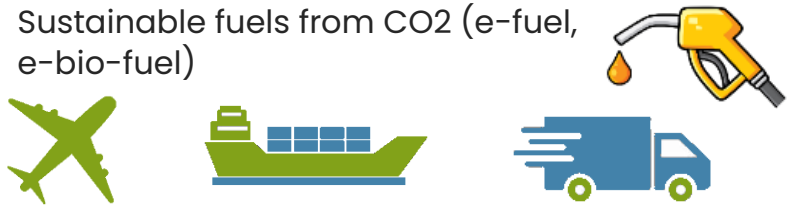


▸ ❸ Production of fuels and synthetic molecules (e-fuel)

1G/2G biofuels will not meet the demand (biomass ressources)

Long-distance transport cannot be ensured by electrification and hydrogen.

- Sustainable fuels from CO2 (e-fuel, e-bio-fuel)

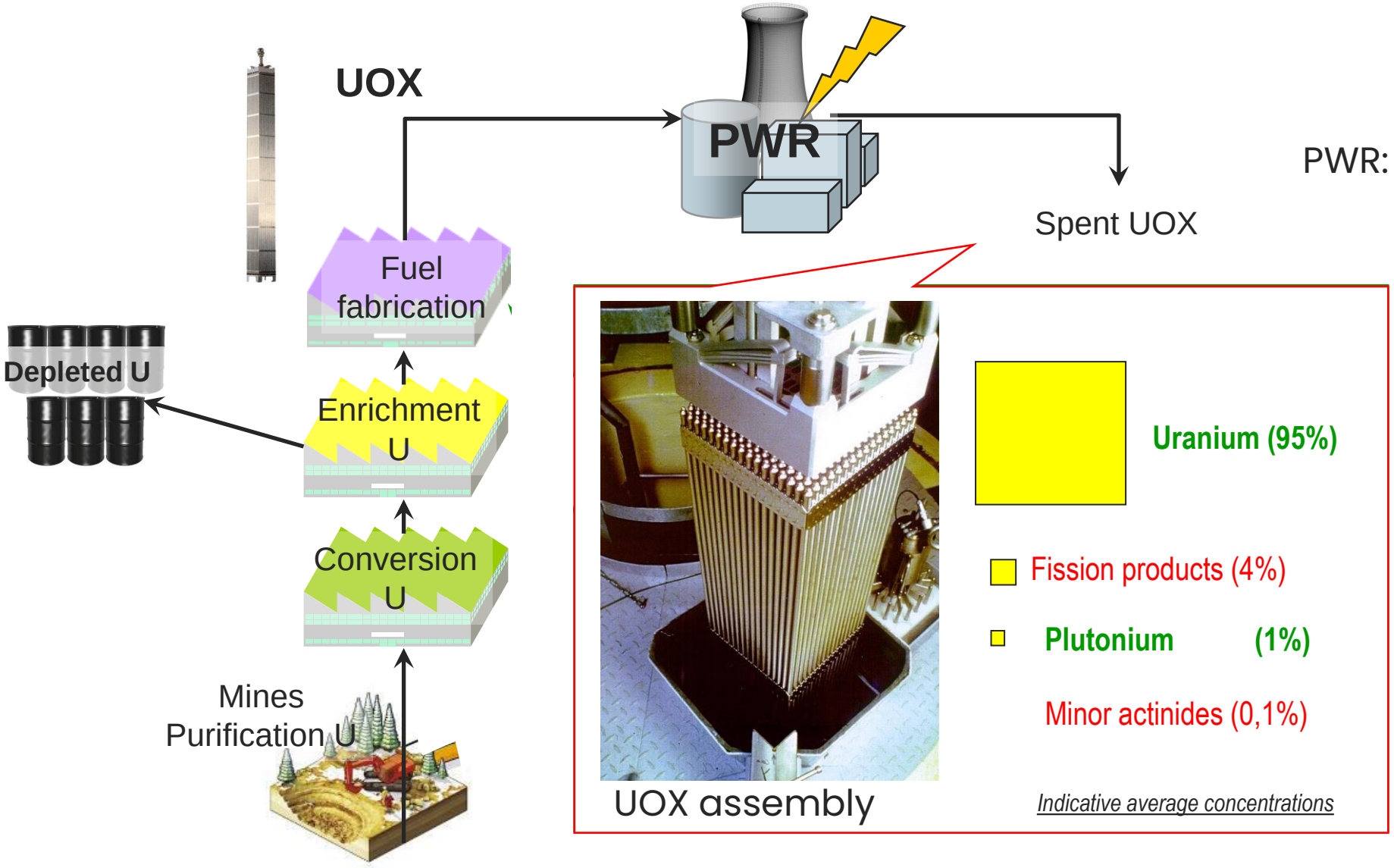


- Synthetic molecules (methane, methanol, ethylene) from CO2

▸ ❶ High / very high temperature heat

▸ ❷ Hydrogen production

The open fuel cycle



UOX assembly

Uranium (95%)

Fission products (4%)

Plutonium (1%)

Minor actinides (0,1%)

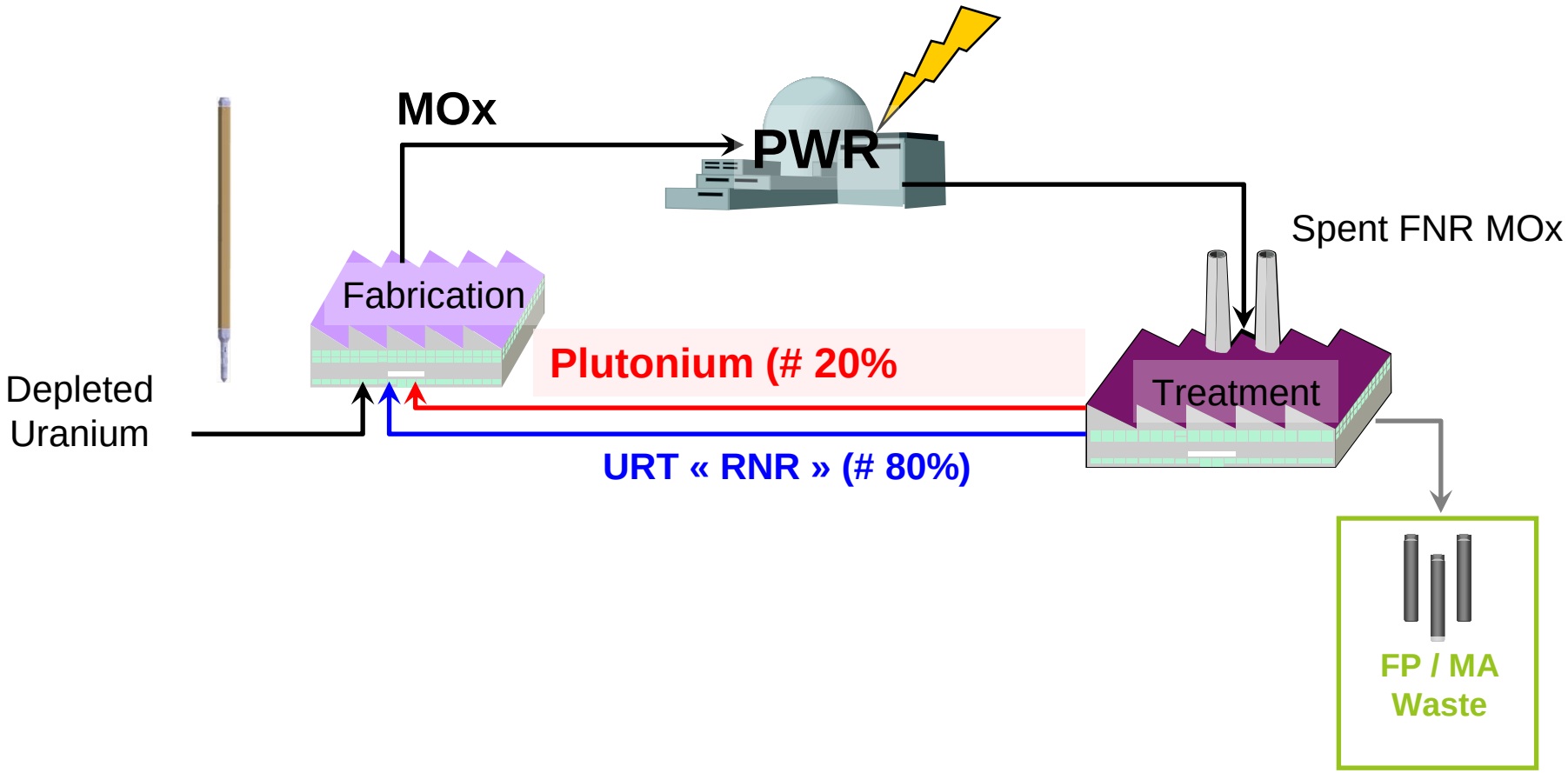
Indicative average concentrations

PWR: pressurized water reactor

Without treatment, the back end of the cycle is limited to the **transport and storage** of spent fuel assemblies, before ultimate geological disposal.

Closure of the fuel cycle

= multi-recycling in fast neutron reactors (Gen 4)



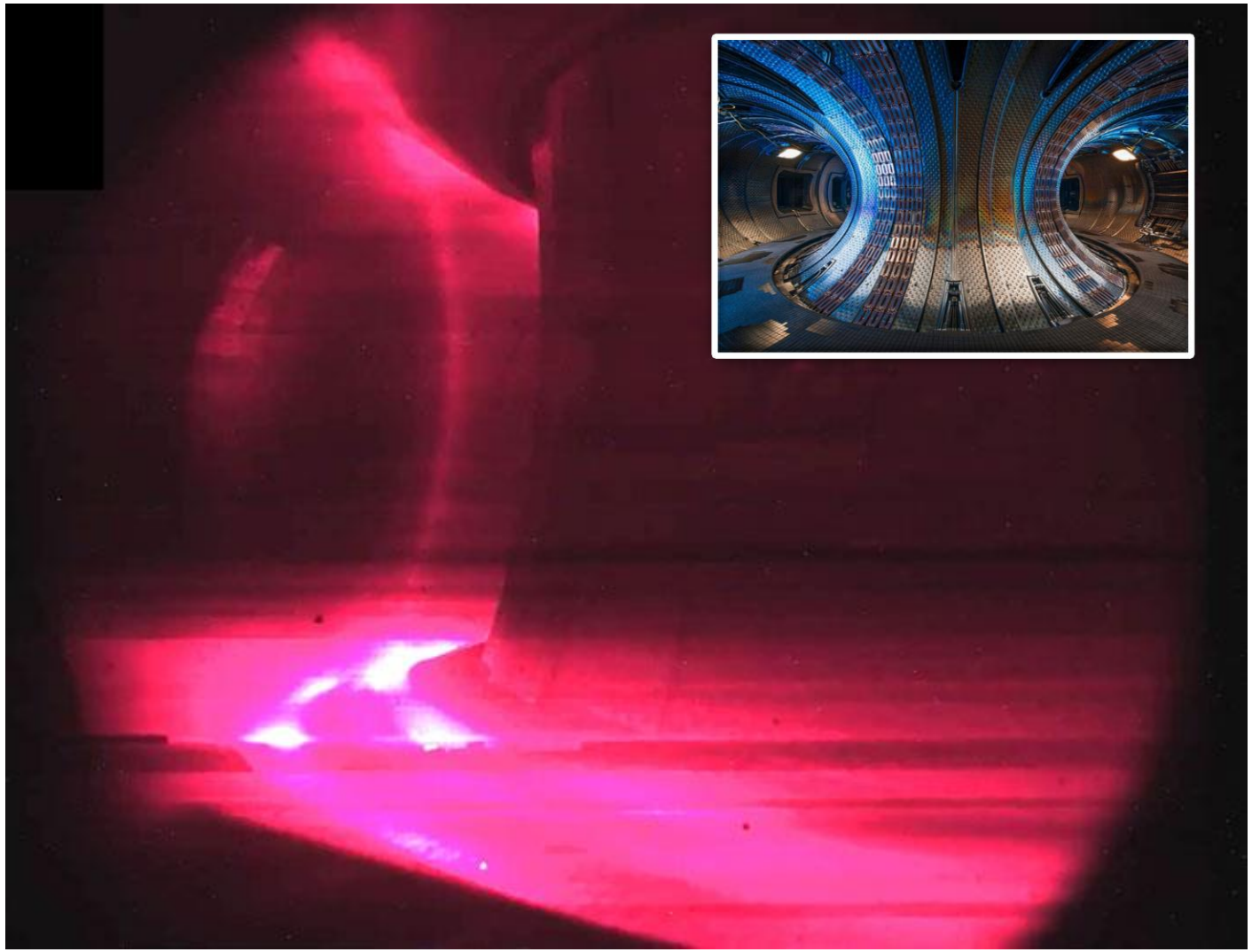
In the long term, **reduced reliance on natural uranium** and increased sovereignty through the stored inventory of depleted uranium from previous generations

Fusion

- **1,337 seconds !**

That was how long WEST, a tokamak run from the CEA Cadarache site in southern France, was able to maintain a plasma for. This was a 25% improvement on the previous record time achieved with EAST, in China, a few weeks before.

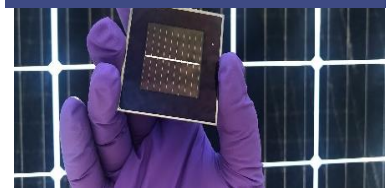
February 12th, 2025



The plasma record reached a temperature of 50 million degrees. © CEA

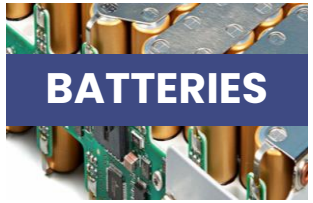
CEA R&D roadmap for new energy system

Photovoltaic



- **High-performance** and durable PV
- High efficiency cells
- PV **integration** ('everywhere') and network compatibility ('grid friendly')
- Advanced materials

BATTERIES



- **Intelligent** and **eco-designed** high-performance batteries
- Increased **durability** and security
- New generation materials
- Intelligent management systems

H2 & E-FUEL

- H2 electrolysis & co-electrolysis with CO2
- Fuel cell (mobility)
- Hyperbar storage (mobility) and LOHC
- Materials for storage and transport
- E-fuels & sustainable synthetic fuels

GRIDS

- *Multi-vector and interconnected smart grids*
- *System modeling and management*
- *Thermal energy management, coupling and storage*
- *Power electronics*

… integrating a circular economy approach

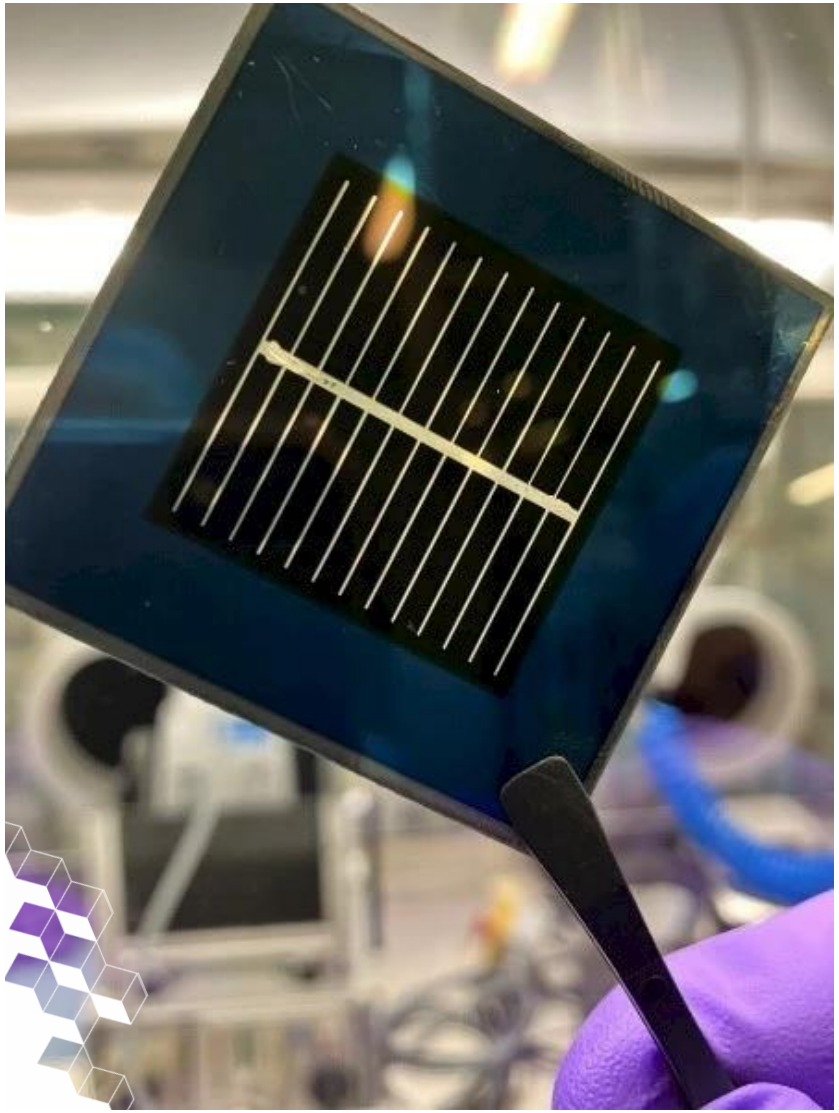
- **Energy saving and sustainability of technologies**
- **Sobriety:** manufacturing with less material consumption
- **Life cycle assessment** and eco-design
- **Recycling**
- **Reduce** the use of strategic materials

Highlight : photovoltaic cell

- **CEA and 3SUN break a new record for photovoltaic cell efficiency !**

  As part of the joint development program between CEA and 3SUN on tandem perovskite-on-silicon **solar cell** technology, a new milestone has been achieved, setting a new **efficiency record of 30.8%** *(certified)*

January 28th, 2025



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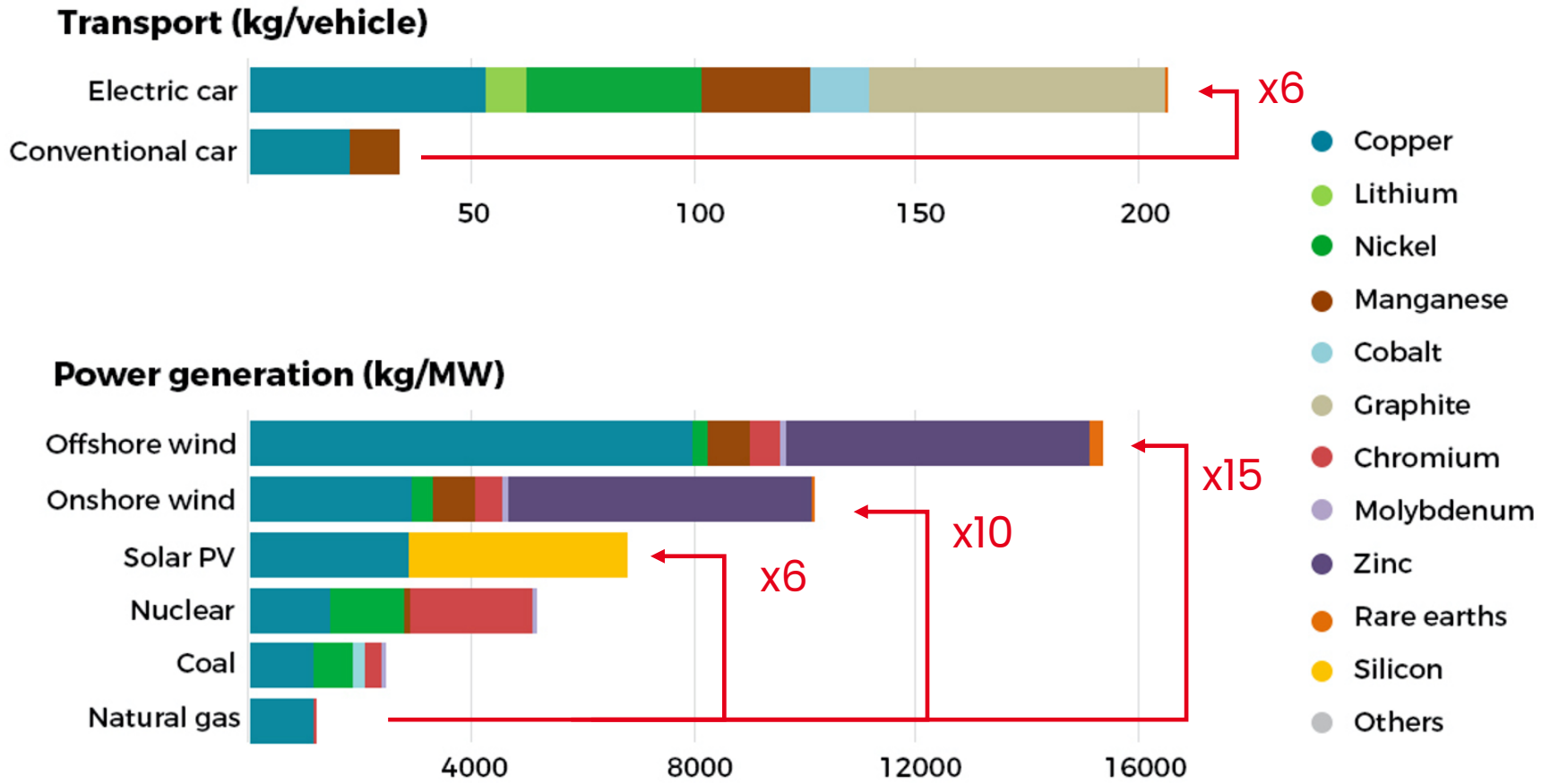
The energy transition is material-intensive



Minerals used in a selection of energy transition technologies and fossil fuels

Source : IEA 2021

→ On the road to Net Zero Emission (NZE), the circular economy is a necessity!

A European resource strategy

2024 :Critical Raw Materials Act

By 2030, Europe wants to:

- Increase and diversify the supply chains of strategic materials
- Enhance material circularity with over **>25%** of demand fulfilled through recycling
- **Support research into resource efficiency and substitution of critical materials, energy efficiency of processes, limitation of water consumption, etc.**

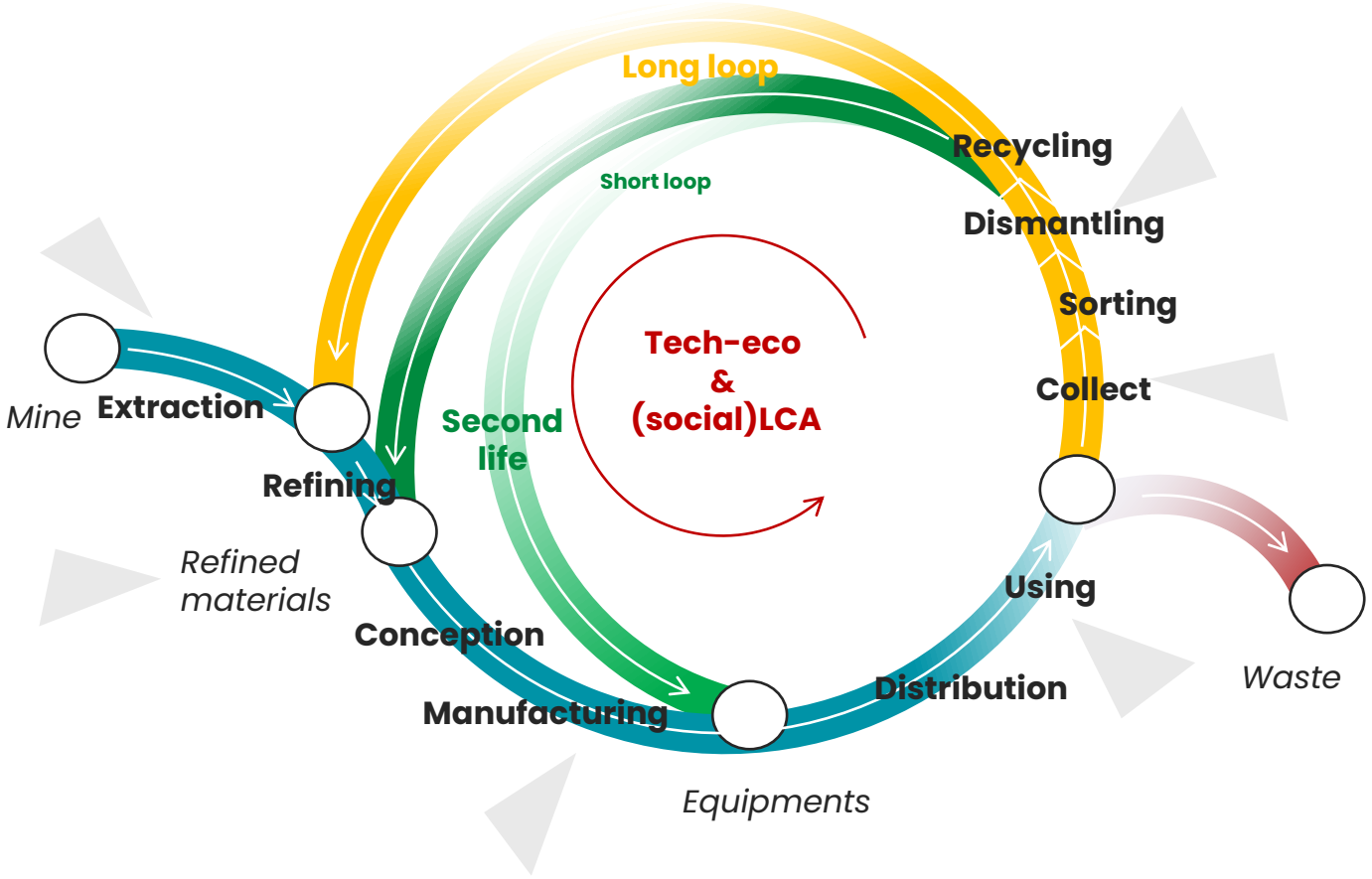
2025 :RESourceEU

Commission européenne - Communiqué de presse

Commission adopts RESourceEU to secure raw materials, reduce dependencies and boost competitiveness

Building on the critical raw Materials Act, the initiative provides financing and concrete tools (for instance to promote projects on critical raw materials in Europe and beyond)

Circular economy of materials for low carbon energy systems

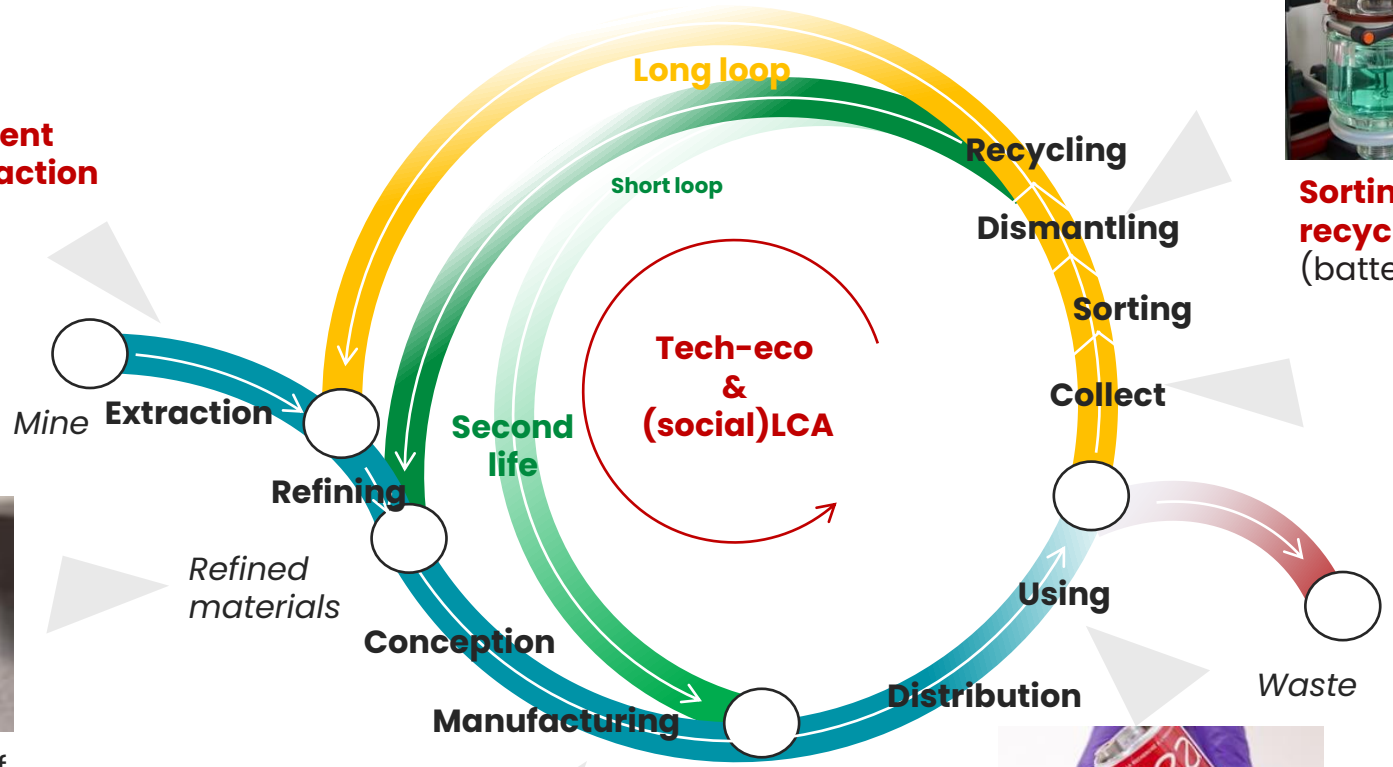


Circular economy of materials for low carbon energy systems

Clean (effluent) and **efficient** (yield, water, energy) **extraction** of raw materials (mine)

Reduction or **substitution** of **critical materials** (RE for magnets, …)

Material-saving **Manufacturing processes**



Sorting, dismantling and **recycling** (batteries, PV, magnets…)

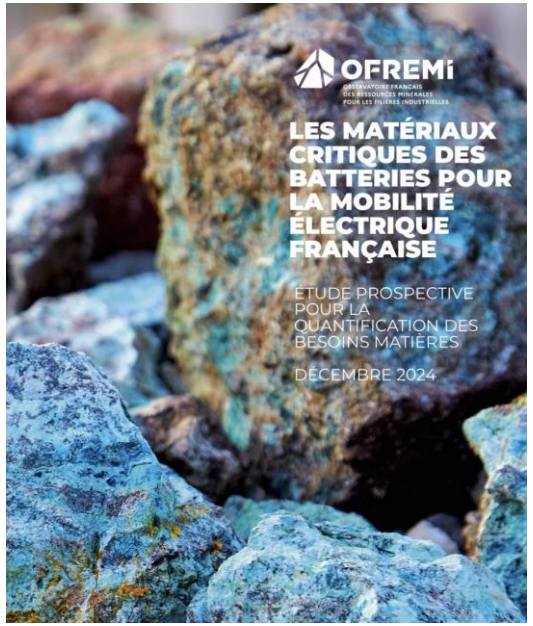
Second life
Instrumentation of batteries, PV, electrolyzers fuel cell, PE for diagnostic

Increased lifespan
Battery, PV, Electrolyzer, fuel-cell, Power Electronics instrumentation for predictive maintenance

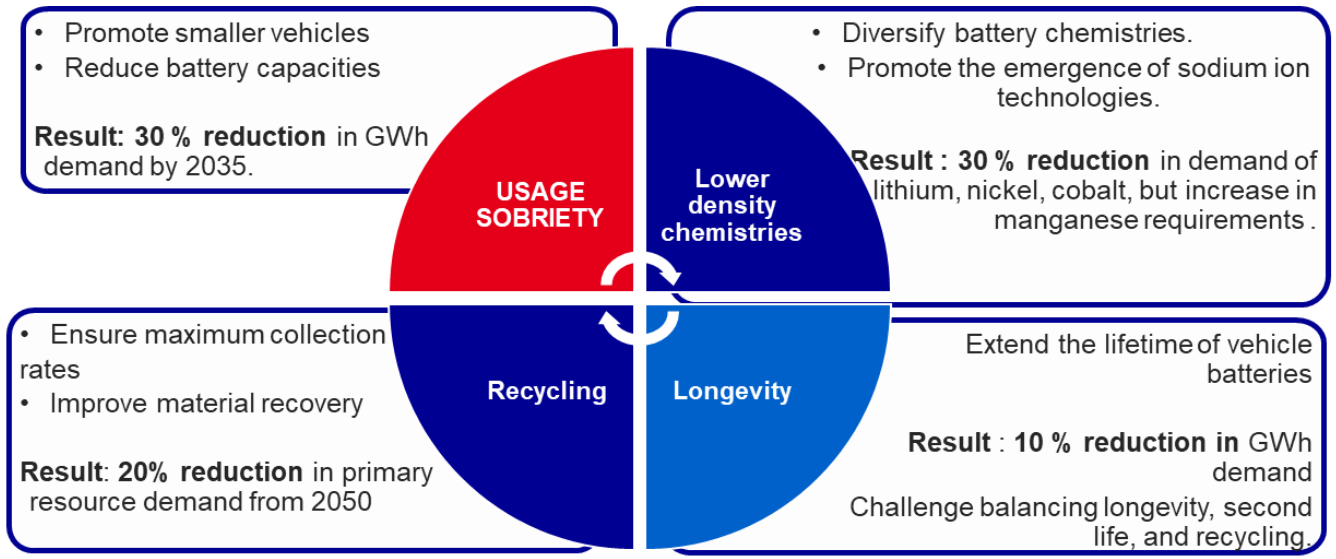
Assessing critical mineral challenges and opportunities of industrial value chains

OFREMI
OBSERVATOIRE FRANÇAIS
DES RESSOURCES MINÉRALES
POUR LES FILIÈRES INDUSTRIELLES

French Observatory of Mineral Resources for Industry



Main levers for reducing the need for critical materials required for French electric mobility (batteries), « Les matériaux critiques des batteries pour la mobilité électrique française », OFREMI, December 2024



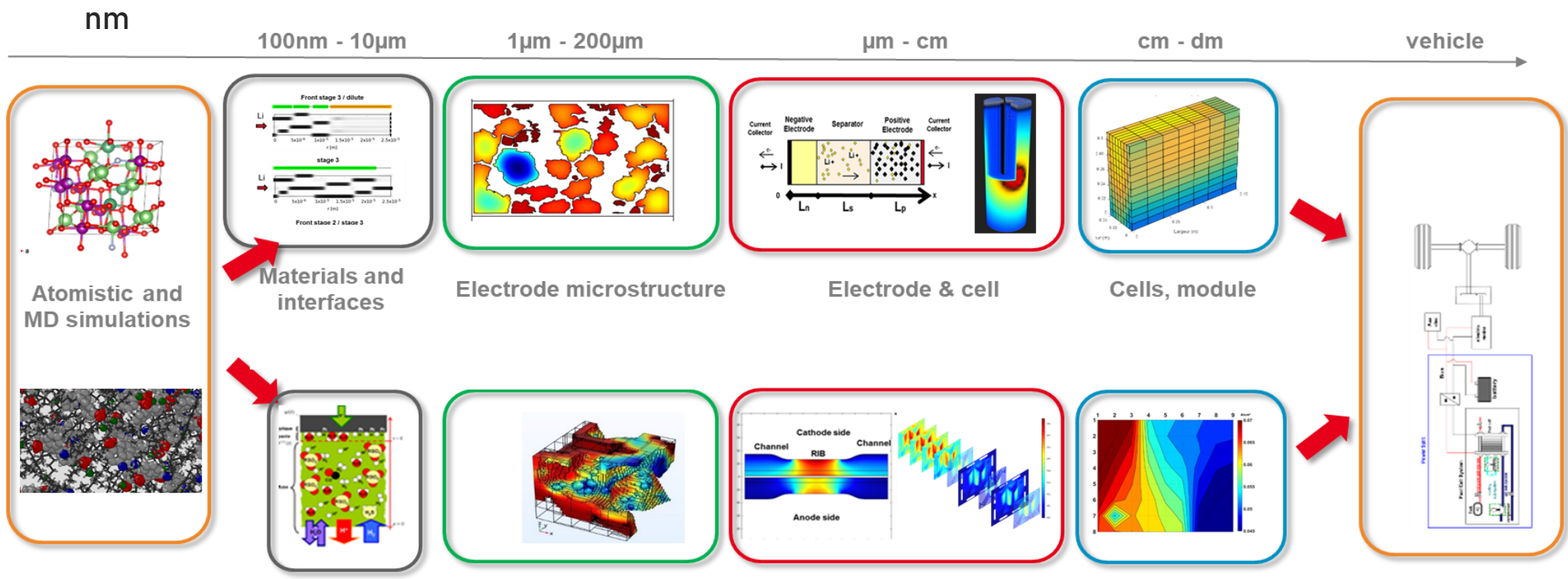
Methodological approach

"databases, experimental infrastructures and simulation"

Major challenges

- Optimal use of **high-performance computing** environments and **AI**
- Promotion of a « **Sustainable digital**» approach: improving the ratio between result quality and electrical energy consumption,
- Design and perform **experiments tailored to actual needs**, in support of simulation activities
- Maintenance and development of **experimental infrastructures**
- Development of **digital twins** for energy systems,
- Quantification of **uncertainties**

Multi-scale approach



A global approach to the value chain

From materials to use case

Technical-economic analysis and life cycle analysis (LCA)

USE CASE

Value chain

SYSTEM

MATERIALS

PROCESS

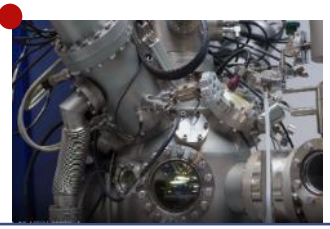
COMPONENTS

Design & optimize the properties of the targeted function in real conditions of use

Technological platforms (experiment, manufacture, industrialize)

Simulation, modeling Multi-physics, multi-scale

Characterization and advanced testing



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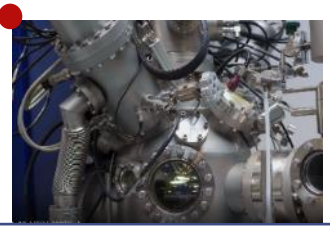
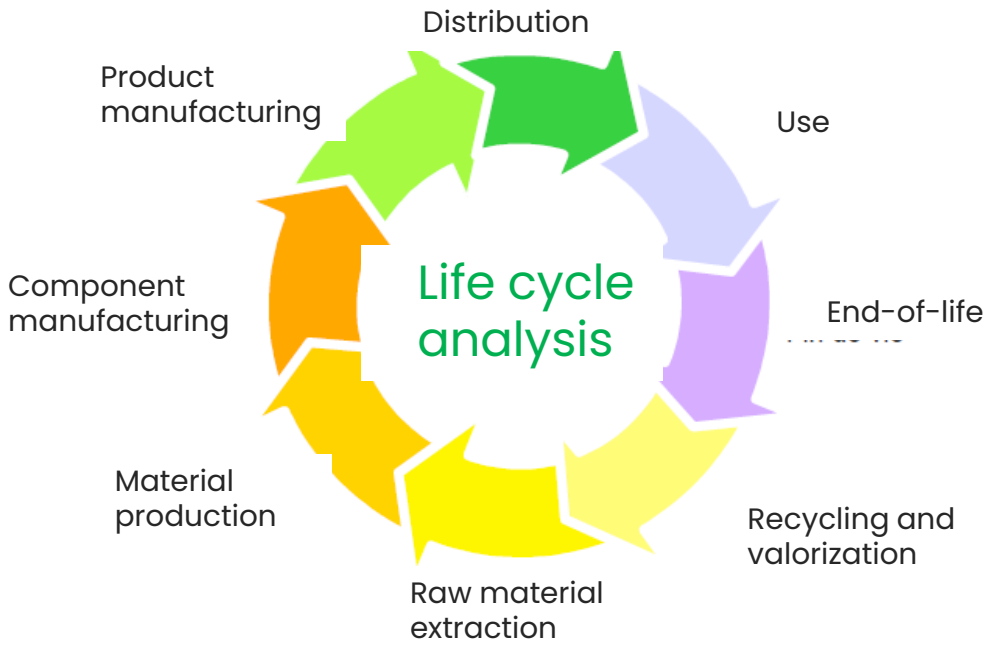


Life cycle analysis (LCA)

LCA = quantified assessment of the environmental impacts of a system throughout its life cycle



A standardized method (ISO 14040/44, etc.…), a field of scientific research and a tool widely endorsed by recent regulations

Indicateur d'impact	Acronyme	Unité	Pictogramme
Changement climatique	CC	kg CO_2 eq	
Appauvrissement de la couche d'ozone	ACO	kg CFC-11 eq	
Emissions de particules	PF	disease incidence	
Radiations ionisantes	RI	kBq U235 eq	
Formation d'ozone photochimique	FOP	kg NMVOC eq	
Acidification	A	mol H^+ eq	
Eutrophisation terrestre	ET	mol N eq	
Eutrophisation des eaux douces	EED	kg P eq	
Eutrophisation marine	EM	kg N eq	
Occupation des sols	UT	point	
Epuisement des ressources en eau	EAU	m^3 world eq	
Epuisement des ressources énergétique	ERE	MJ	
Epuisement des ressources minérales	ERM	kg Sb eq	
Toxicité humaine cancérigène	THC	CTUh	
Toxicité humaine non cancérigène	THNC	CTUh	
Ecotoxicité des eaux douces	ETED	CTUe	

Tableau 1 : Liste des 16 indicateurs d'impact environnemental préconisés par la Commission européenne dans le cadre du programme Product Environmental Footprint (PEF).

Ecodesign

Definition

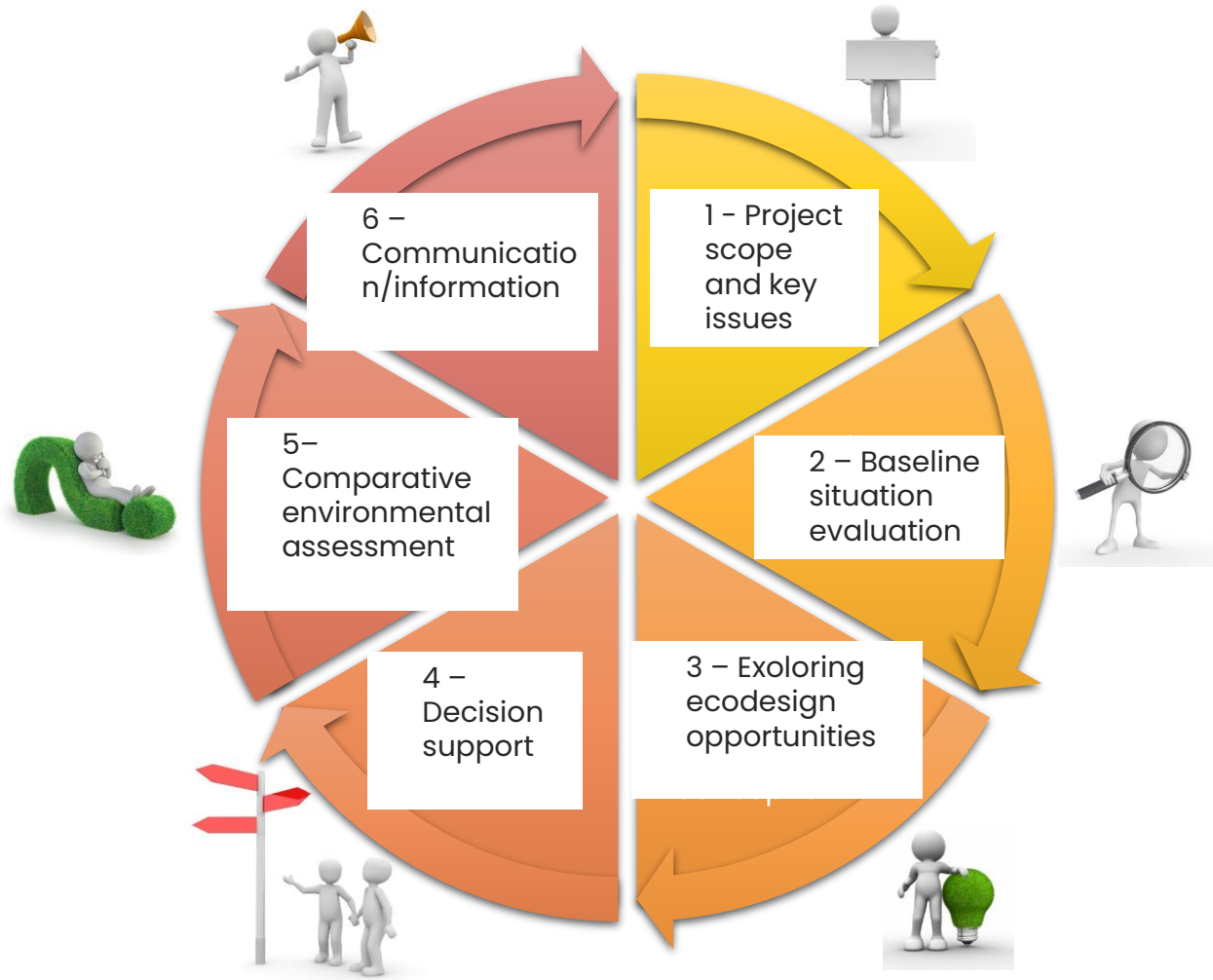
«A methodical approach that considers environmental aspects in the design and development processes with the aim of reducing negative environmental impacts throughout the life cycle of a product»

ISO 14006:2020

Tools ?

This approach relies on environmental assessment. One possible tool: Life Cycle Assessment (LCA)

Methodological approach



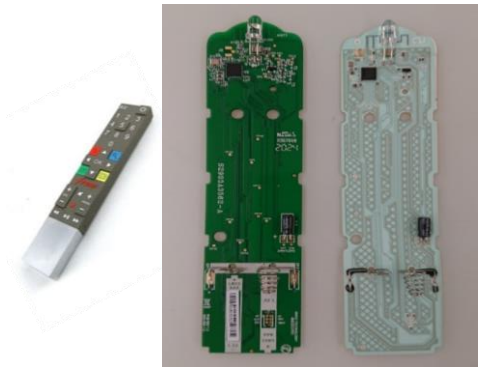
Adapted from Pôle écoconception

Low-environmental-impact polymers

Contribute to increase the **recyclability rate** of energy system's equipment by **synthesising high-performance bio-based and/or recyclable polymers and by developing resource-efficient polymer processes**

Recycling and manufacturing magnets

In Sept. 2025, CEA and Orano inaugurated a pilot line dedicated to **recycling and manufacturing high-performance permanent magnets based on rare earths.**



Conventional Printed Circuit Board (PCB) and paper-printed PCB of a remote control

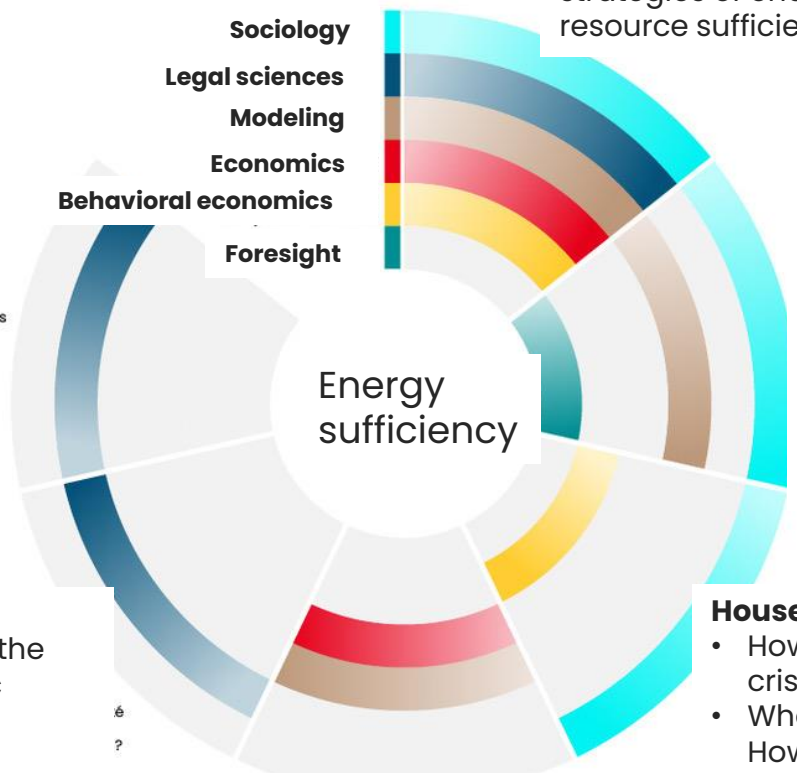
Eco-designed flexible electronics

Eco-designing **printed** and **hybrid electronics :**

- **Reduce** the environmental footprint by using **bio-based, compostable, renewable inks** and **substrates** and **optimized processes.**
- **Promote circularity** through the development of innovative **interconnection** processes

Energy sufficiency

Industry decarbonization
How can industry be decarbonized through strategies of energy and resource sufficiency ?



Regulation
- What legal frameworks are needed to promote sufficiency ?

Scenario
- How can energy demand and usage evolve
- How could demand for key resource evolve ?
- How could sufficiency reinforce sovereignty ?

Efficiency indicator
- How can we measure the effectiveness of public policies for energy sufficiency?
- In particular at the territorial level

Household perspective
- How do households respond to energy crises ?
- What are the drivers of sufficiency ? How can they be activated ??

Economic sphere
- What economic models can promote sufficiency ?
- What are the economic and environmental impacts of industrial decarbonization scenarios based on sufficiency strategies ?

Promethee : a multidisciplinary Energy Observatory Project for a Human, Economic and Ecological Transition

Sustainable development goals

- The 2030 Agenda defines 17 Sustainable Development Goals
- A global framework for **sustainable and inclusive development**
- **Energy R&D** is part of this **dynamic**
- Its support the **transition toward sustainable energy systems**

Thanks for your attention