Innovative nuclear at the CEA: SMRs and Gen4 reactors activities

June 29th, 2026

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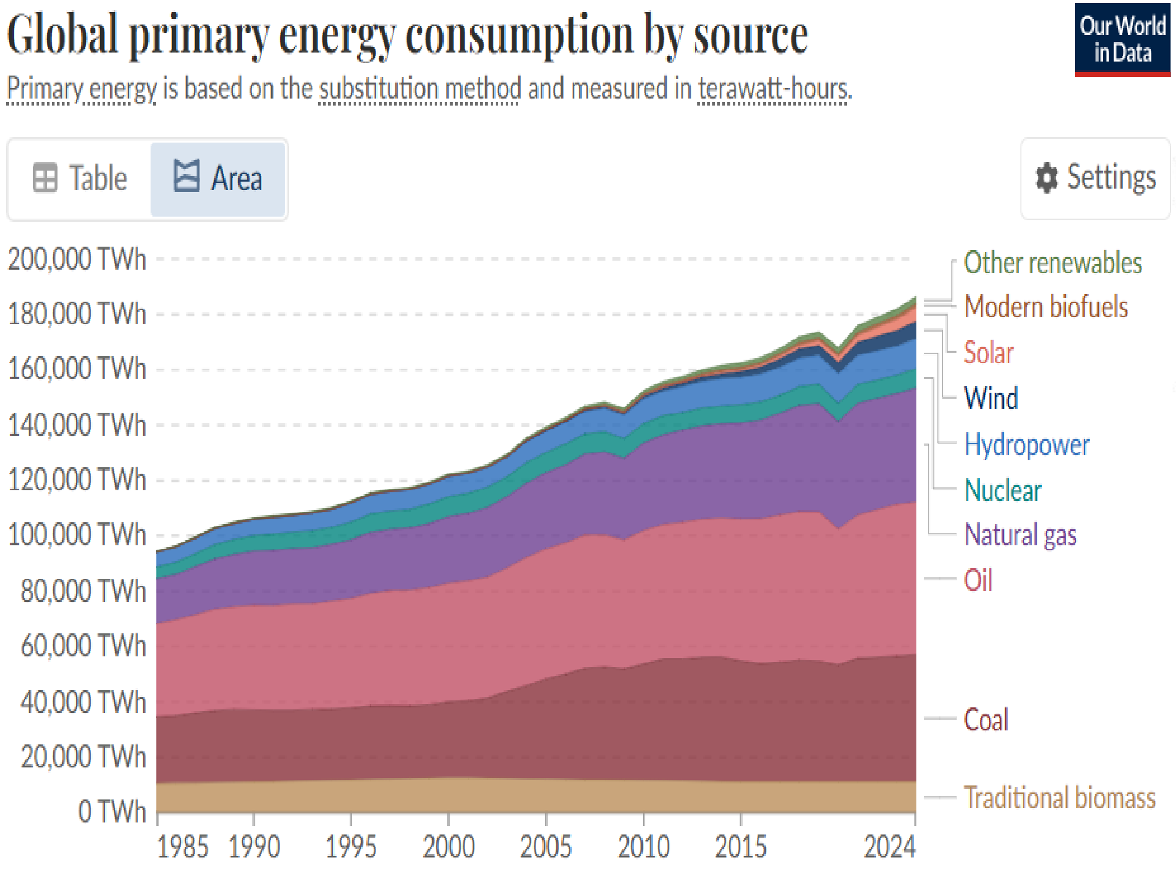
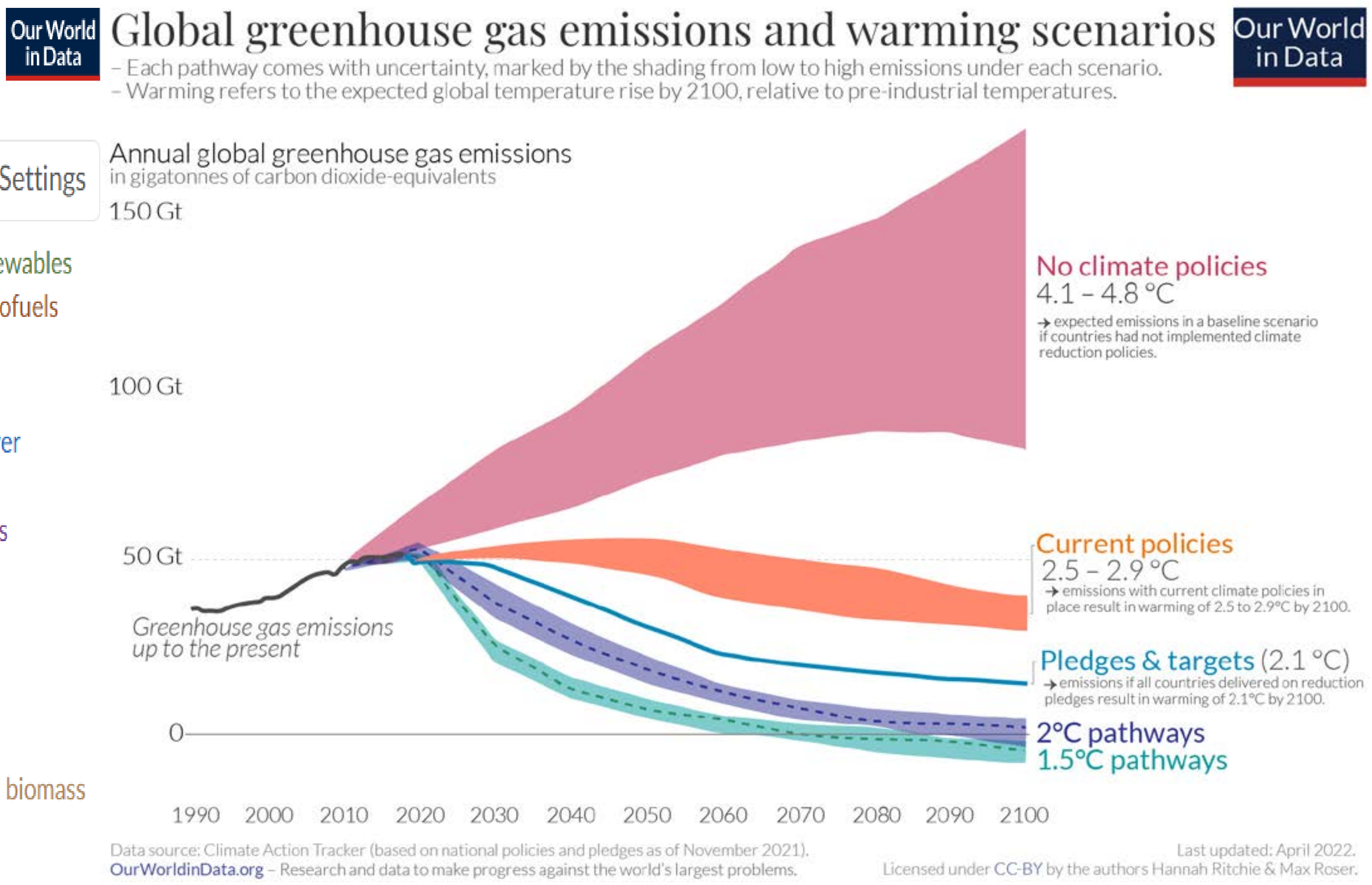
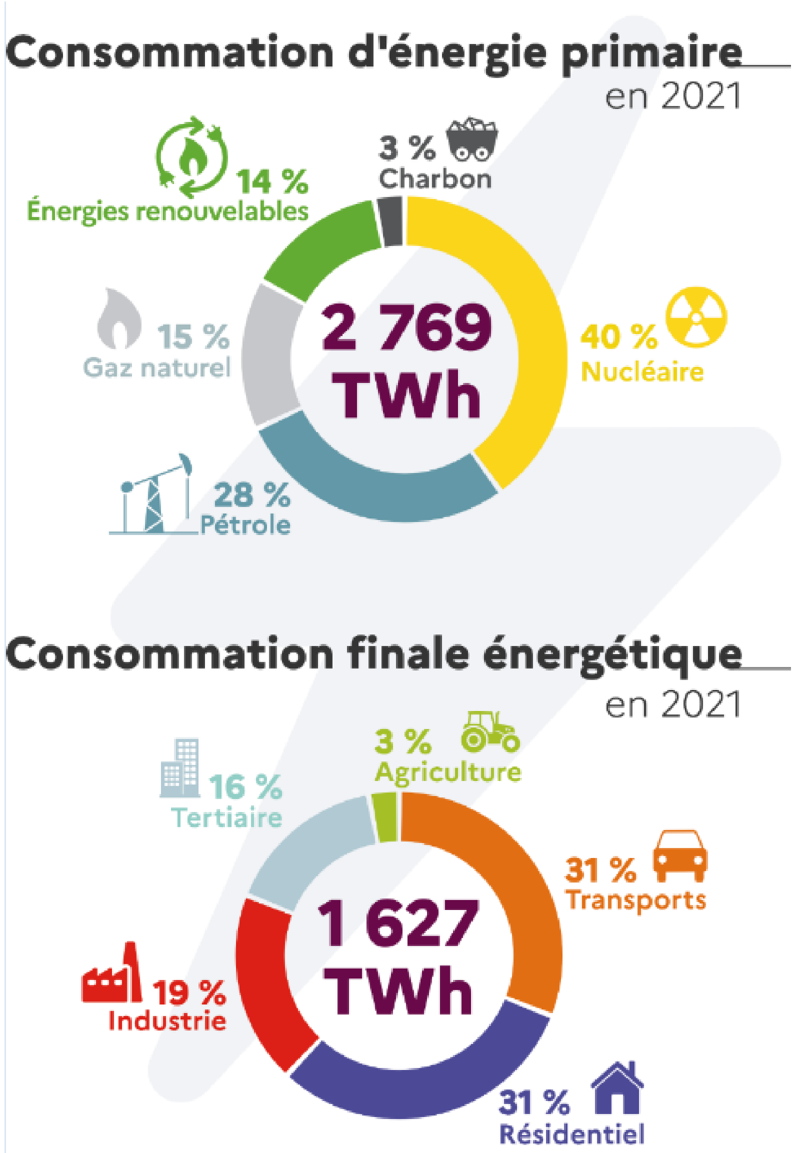
CEA energy division, head of “4th Gen Reactors and Innovative Nuclear” program

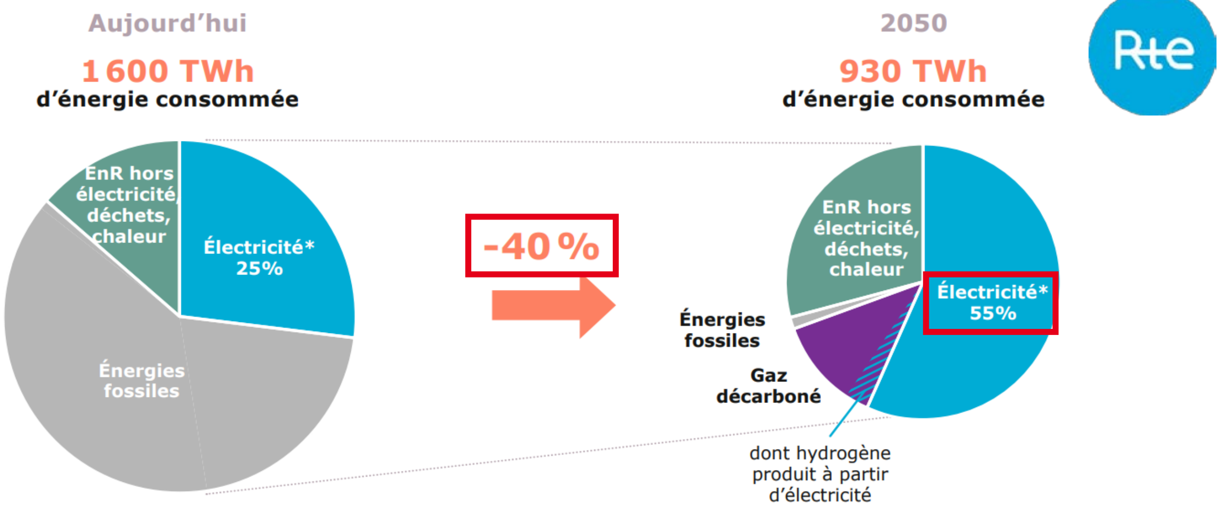
Foreword: Energy is vital and we still depend a lot on fossil fuels… with consequences



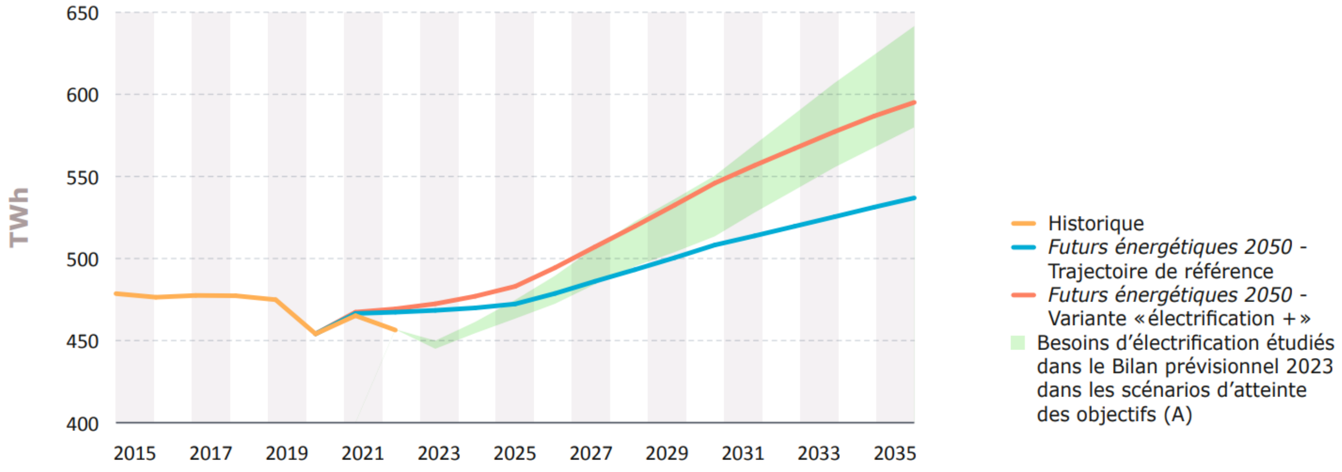


Foreword: reaching net zero for France?





* Consommation finale d'électricité (hors pertes, hors consommation issue du secteur de l'énergie et hors consommation pour la production d'hydrogène)



https://assets.rte-france.com/prod/public/2023-11/Bilan-previsionnel-2023-chapitre2-consommation.pdf

French Multiannual Energy Programme (PPE3)

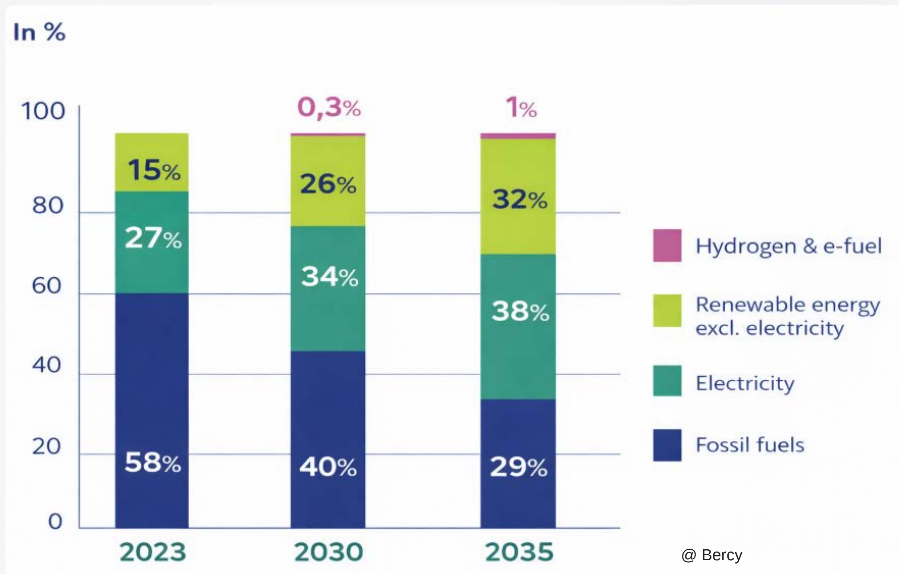
PPE provides the **Energy Policy strategic direction** for the next 10 years:

- It is designed to address a **triple challenge**: geopolitical, economic, and climate-related.
- It has **one objective**: reduce, in the final energy consumption, the share of fossil fuels to 30% by 2035, compared with 60% today

2025	→	2030	→	2035
60% fossil fuels – 40% low-carbon energy		40% fossil fuels – 60% low-carbon energy		30% fossil fuels – 70% low-carbon energy

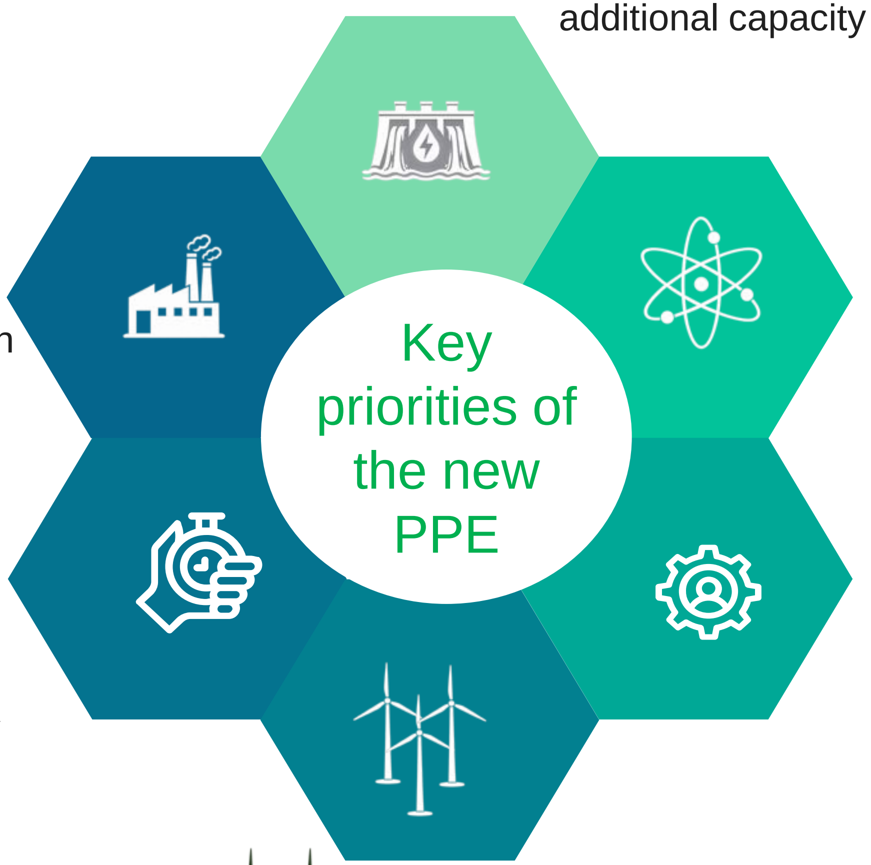
PPE3 addresses these challenges through tow keys areas:

- Reducing our dependence on fossil fuels,
- Investing in more efficient energy consumption.



French Multiannual Energy Programme (PPE3)

Hydropower expansion: +11% generation capacity between 2023 and 2035, including +1.7 GW additional capacity at dam facilities.



Major push for decarbonized energy carriers: renewable heat, biomethane, sustainable fuels, and hydrogen increasing from 220 TWh in 2023 to at least 460 TWh in 2035.

Nuclear **revival confirmed:** lifetime extensions to 50–60 years, +6 EPR2 reactors, 420 TWh nuclear generation target by 2035, and development of the back end of the fuel cycle.

Ambitious targets for onshore renewables:

- **Onshore wind:** 35–40 GW by 2035 (vs 22 GW in 2023)
- **Solar PV:** 55–90 GW by 2035 (vs 19 GW in 2023)

Initial deployment pace maintained through repowering of existing wind farms and continued solar and wind development, with public support capped at PPE2 levels until 2028

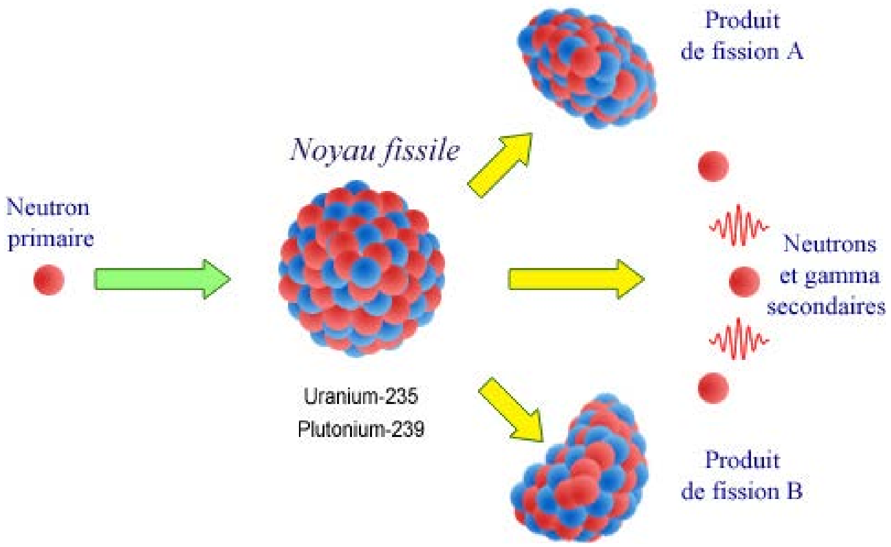
Strengthening France's industrial base: development of gigafactories and strategic industrial value chains.

Strong offshore wind ambition: from 0.8 GW in 2023 to 15 GW by 2035, supported by new tenders.

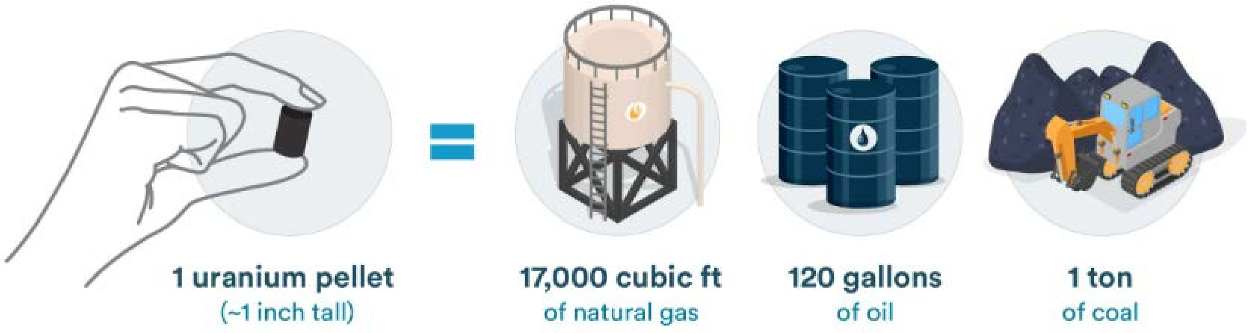
1. Context on Nuclear and SMRs

Context on nuclear: Some Physics to start

- Nuclear Power uses the **fission** of certain types of atoms to generate heat, which is then converted to electricity.

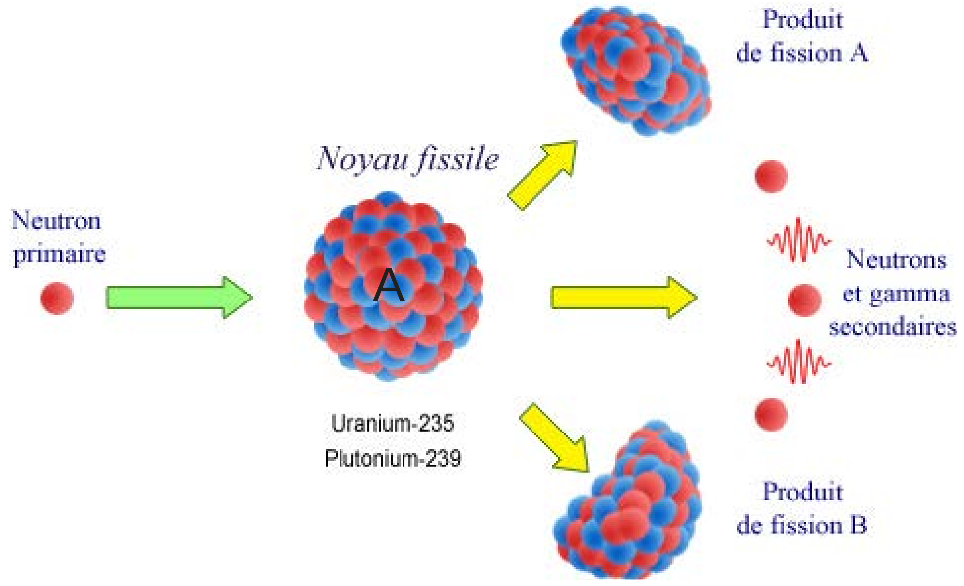


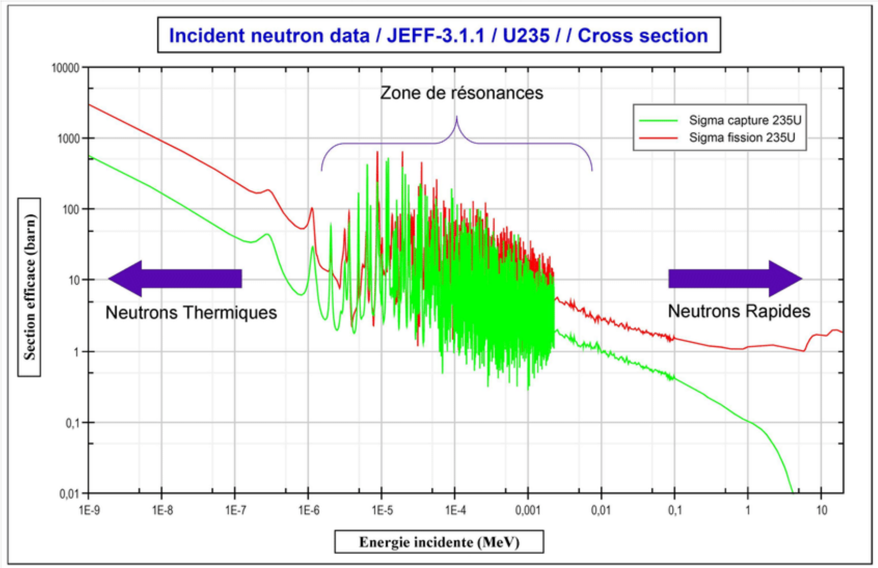
- Fission of atoms is <u>extremely</u> energetic: **1 million times** more than burning the equivalent mass of oil…



When a neutron meets a heavy nucleus...

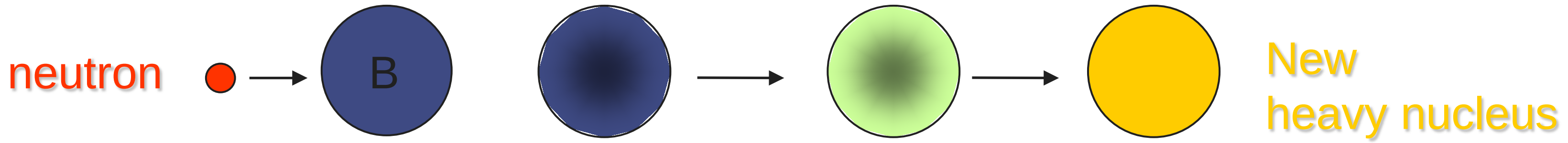
❶ Fission





Element A is <u>fissile</u> (ex. : **Uranium 235, Plutonium 239**)

❷ Capture



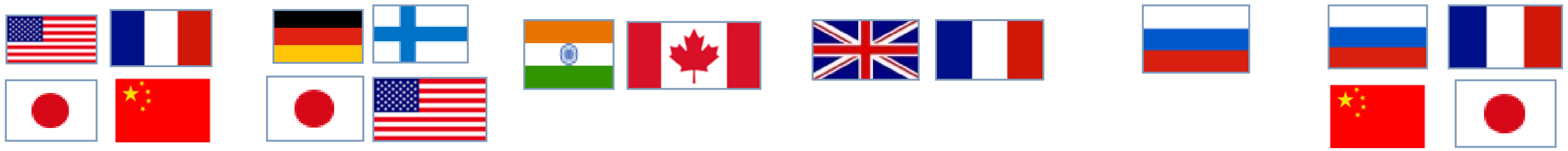
Element B is <u>fertile</u> if the newly formed nucleus is fissile (ex. : **Uranium 238 + n** transforms into **Plutonium 239** which is fissile)

A reactor core needs…

- Fissile material, always
- Moderator, sometimes
- Coolant, always

Reactor technologies

	REP (PWR)	REB (BWR)	CANDU (PHWR)	UNGG-MAGNOX - AGR	RBMK (LWGR)	RNR
Fuel type	U enr. 3%	U enr. 1,5-2%	U nat.	Unat. or U enr. 2.6%	U enr. (1.8%)	Uret or Uapp or Unat Pu
Coolant	Pressurized water	Boiling water	Heavy water	Gaz carbonique (CO_2)	Pressurized water	Sodium, Lead, Gas
Moderator	Water	Water	Heavy water	Graphite	Graphite	

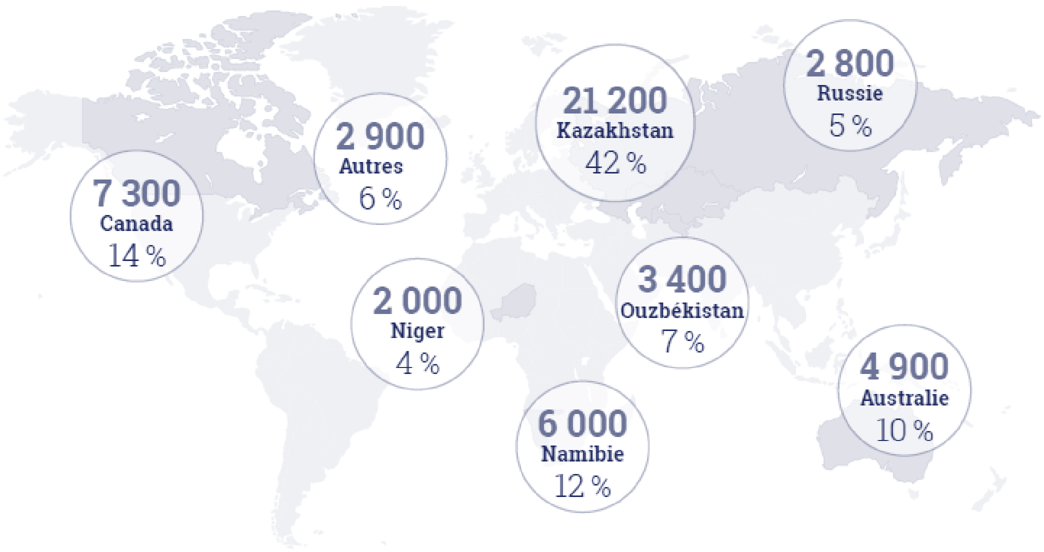


Context on nuclear: Nuclear Fuel

Nuclear fuel can be either Uranium, Plutonium (or Thorium), but:

- Only Uranium is found in the ground, Plutonium has to be generated in reactors (from Uranium atoms). The mining industry is quite concentrated worldwide.
- Uranium comes as a mix of 2 forms (U235 and U238), and some reactors require to enrich the % of U235 to use it properly. Enrichment technology is **very** sensitive (/ nuclear weapons).

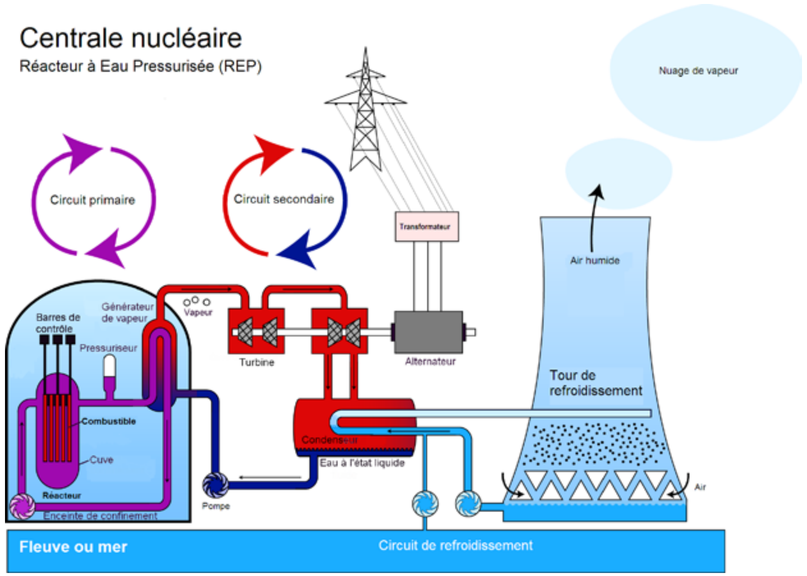
Proven Uranium ressources with mining costs under 130 USD/kg U, 2019

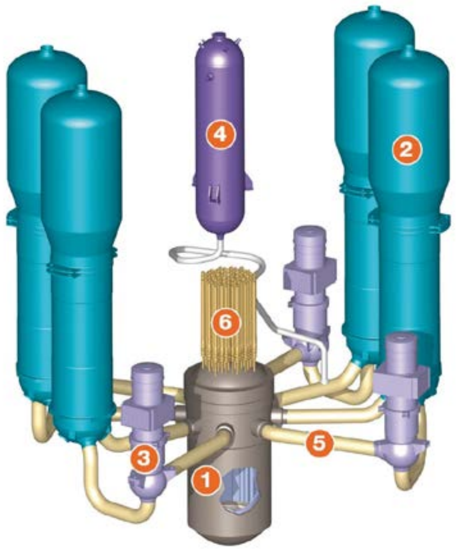


5 countries (Kazakhstan, Canada, Australia, Niger, Namibia) make up for 82% of the U production worldwide

Context on nuclear: The Existing NPP Fleet

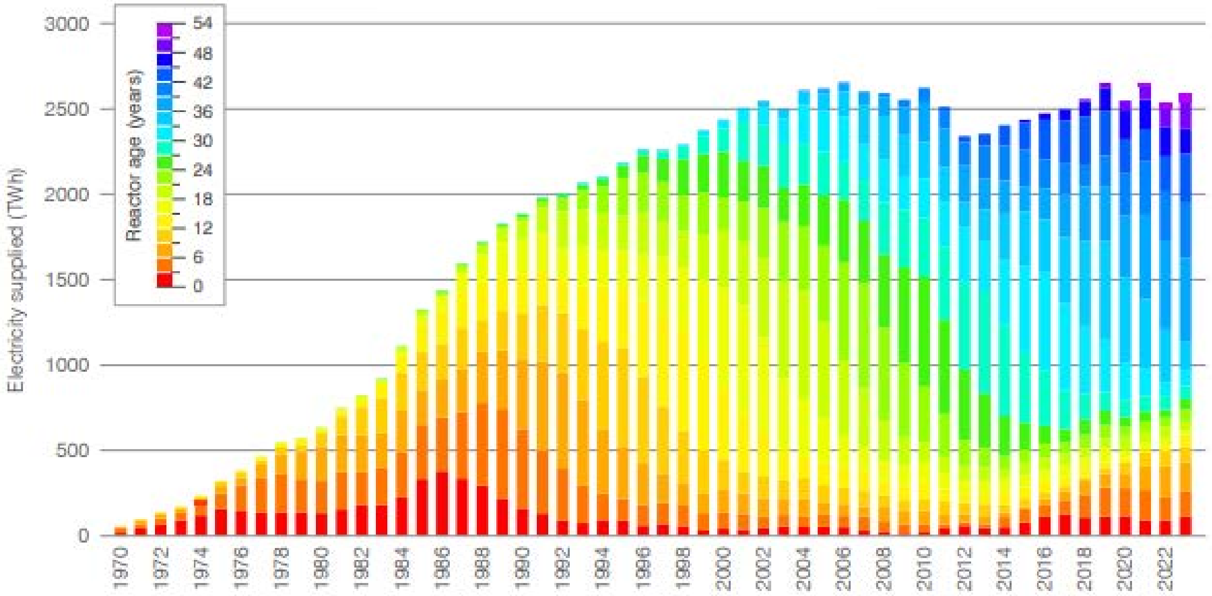
- 1 dominant technology : **Pressurized Water Reactors**





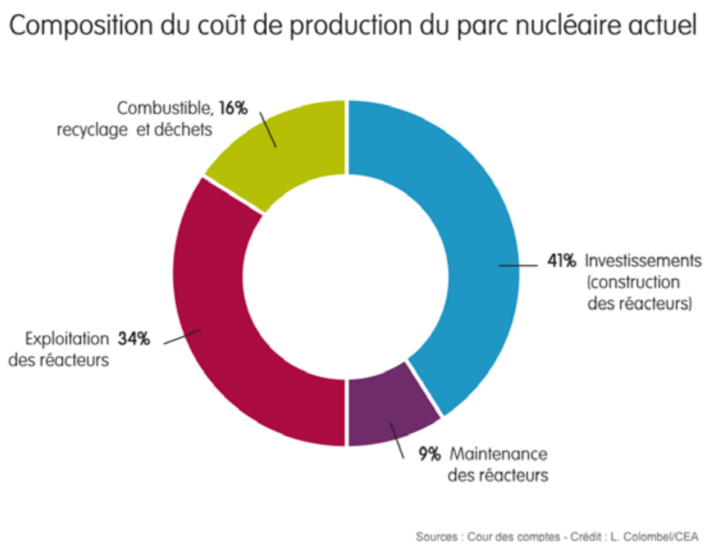
- ~440 Reactors in operation, mostly >30y old units

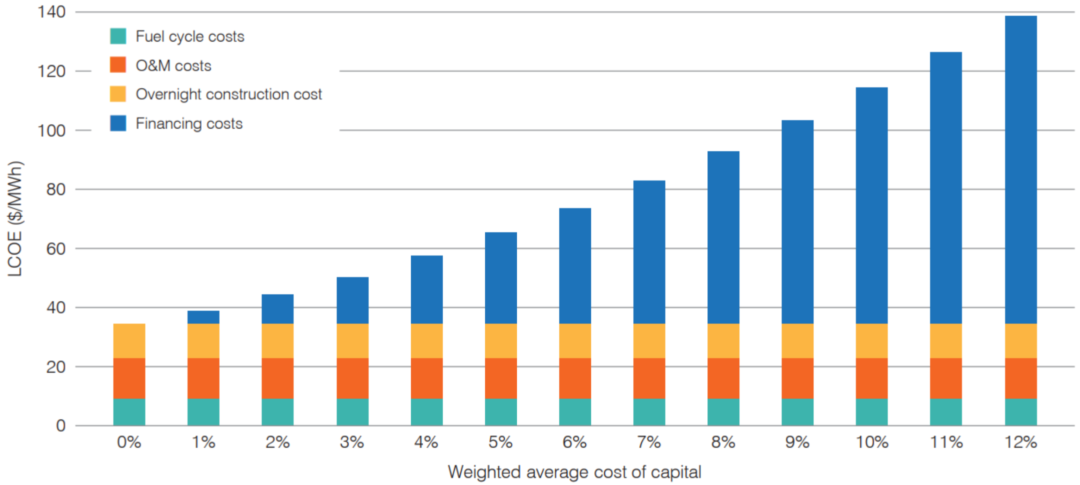
439	9%	64
OPERABLE REACTORS	SHARE OF GLOBAL ELECTRICITY GENERATION	REACTORS UNDER CONSTRUCTION
395,388 MWe	2,601,617 GWh (2023)	67,409 MWe



Context on nuclear: The Existing Fleet

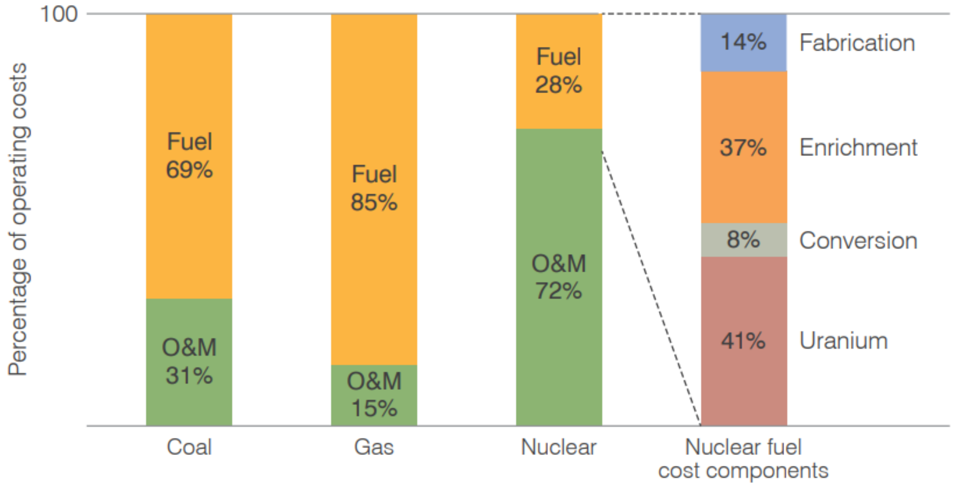
- Nuclear Energy is **very** capitalistic: construction of the plant makes up for ~40% of the final kWh cost (existing french fleet)





Note: Figures based on overnight construction cost of $4500/kWe, a capacity factor of 85%, 60-year operating lifetime and seven-year construction time. Financing costs comprise interest during construction and cost of capital.
Source: Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders, OECD Nuclear Energy Agency (2020)

- But operating costs for Nuclear are much less sensitive to varying fuel costs compared to fossil fuel plants



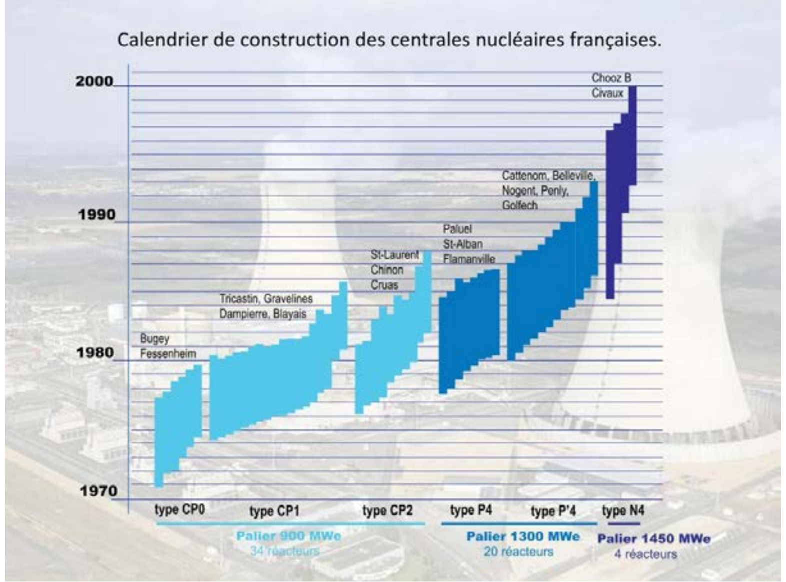
Context on nuclear: The Existing Fleet

- Economy of scale has led to increasing plant size

Fessenheim (1979) **900MWe**

EPR Flamanville (2024) **1650MWe**

- Larger units impact the duration and complexity of construction and increase siting constraints

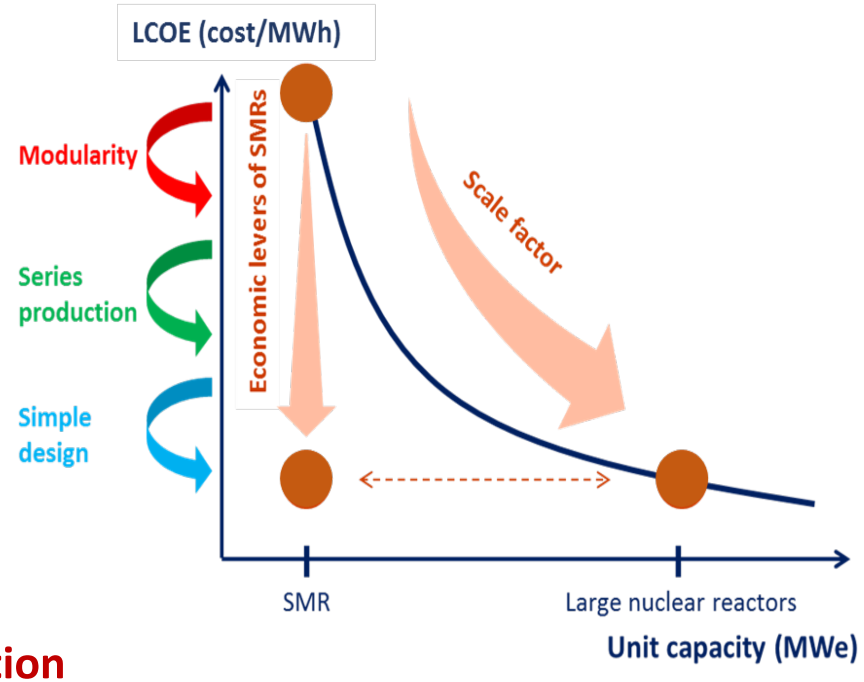


Small Modular Reactors: a different strategy

SMR is not a technology, it is an industrial and economical strategy

The Goal: compensate the scale effect with serial production, prefabrication and simplified design, and open new markets for nuclear beyond power to the grid

- **Smaller units (lower power) enabling simpler and safer design**
  - **Simplified design** (ex. passive systems for decay heat removal)
  - **Smaller footprint** and **more siting possibilies** (closer to industrial / urban areas)
- **Modular architecture, targeting economy through serial production**
  - **Prefabricated modules**, produced and tested in dedicated plants
  - **Lower constraints** on construction site
  - **Lower duration** of construction, with beneficial effects on investment costs
- **Lower investment thresholds for power generation**
  - **Lower initial investment** on the first unit
  - Income generated from first units helps financing the next units
- **Better integration on multivector grid, applications beyond power generation**
  - replacement of fossil fuel power units (~300-400MWe)
  - Heat supply for various processes (district heating, industrial heat, H2 production,…)



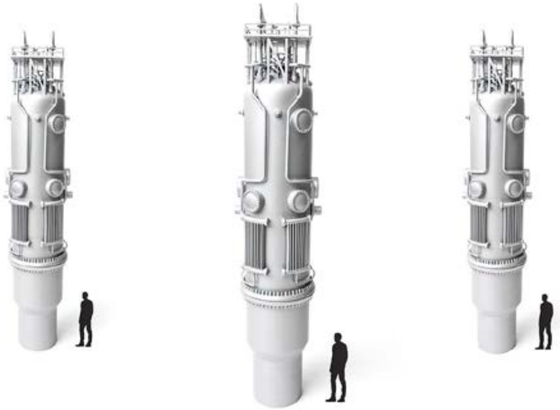
Small Modular Reactors: Small

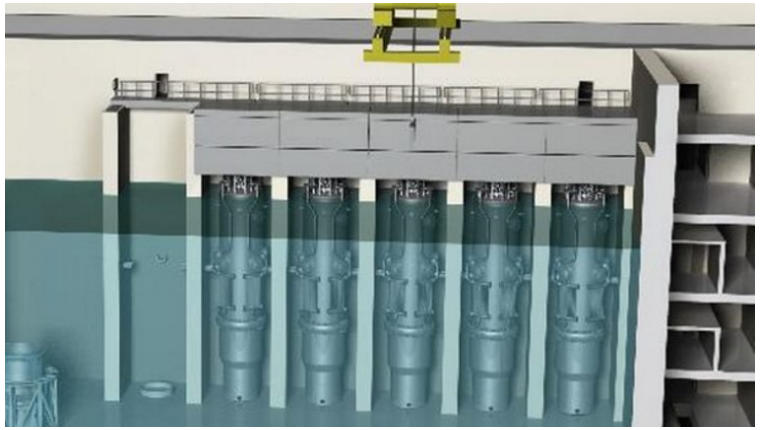
Reactor size optimum to be chosen between 2 extremes:

- **Very small units for maximal series effect, by overall more complex (=costly) systems at equivalent power level**

NUSCALE™ Power for all humankind

50MWe (➔ 77MWe in 2023)





- **Medium size units with little series effect / simplification of design, but more output/unit**

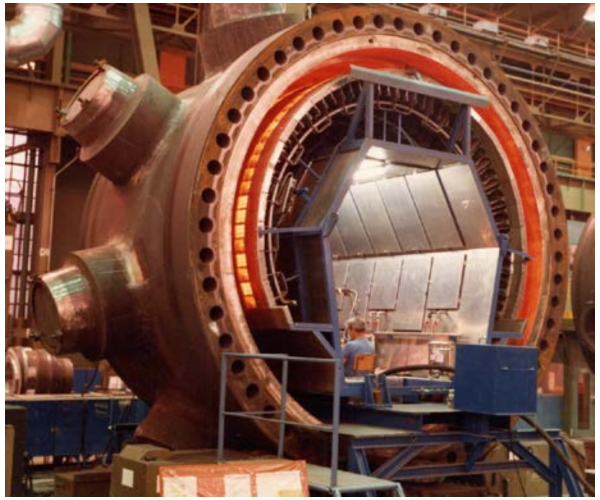
Rolls-Royce

~450MWe

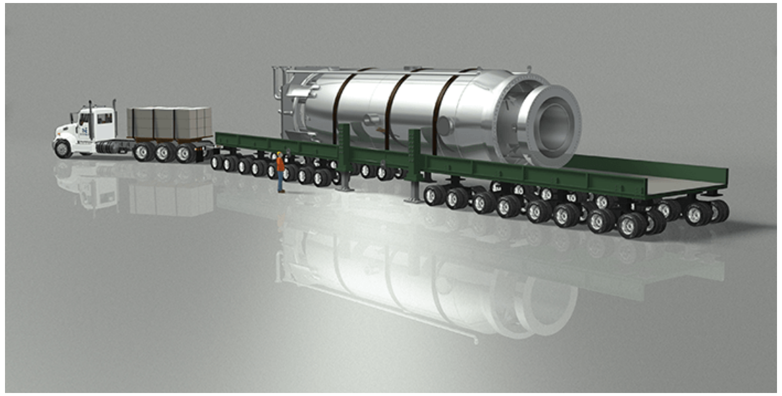
Small Modular Reactors: Modular

Setting up factories for modules construction is a big challenge

- **Transitioning from large component fabrication facilities…to serial production of standardized modules/systems**



- **Taking into account modularity from the start (design), and working on standards/licensing**



Small Modular Reactors: Reactors...

The SMR approach can be applied to different nuclear technologies

- **Current technology (Light Water Reactor) « LW SMR »**

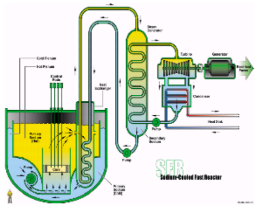
  +: Industrial fuel supply chain available
  +: Extensive feedback on safety / component fabrication
  -: Limited range of heat supply in terms of T° (~250°C max.)

  Expected Time to market for the 1st units: ~2030-2035

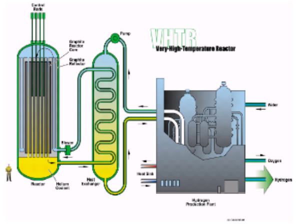
- **Innovative designs (so called « Gen IV » reactors) « AMR » (Advanced Modular Reactors)**

  +: Higher temperature heat available (up to 800°C)
  +: Better use of nuclear material (in most cases)
  - : Technological Readiness level needs to be improved
  - : less/no feedback from existing units (licensing)
  - : Fuel availability

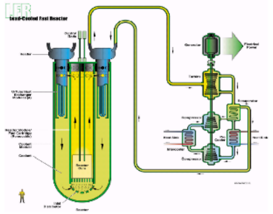
  Expected Time to market for the 1st units: ~2035-2040+



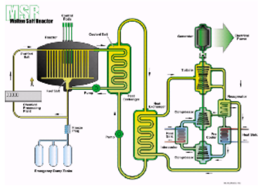
SFR
Sodium-cooled fast reactor



VHTR
Very high temperature reactor



LFR
Lead-cooled fast reactor



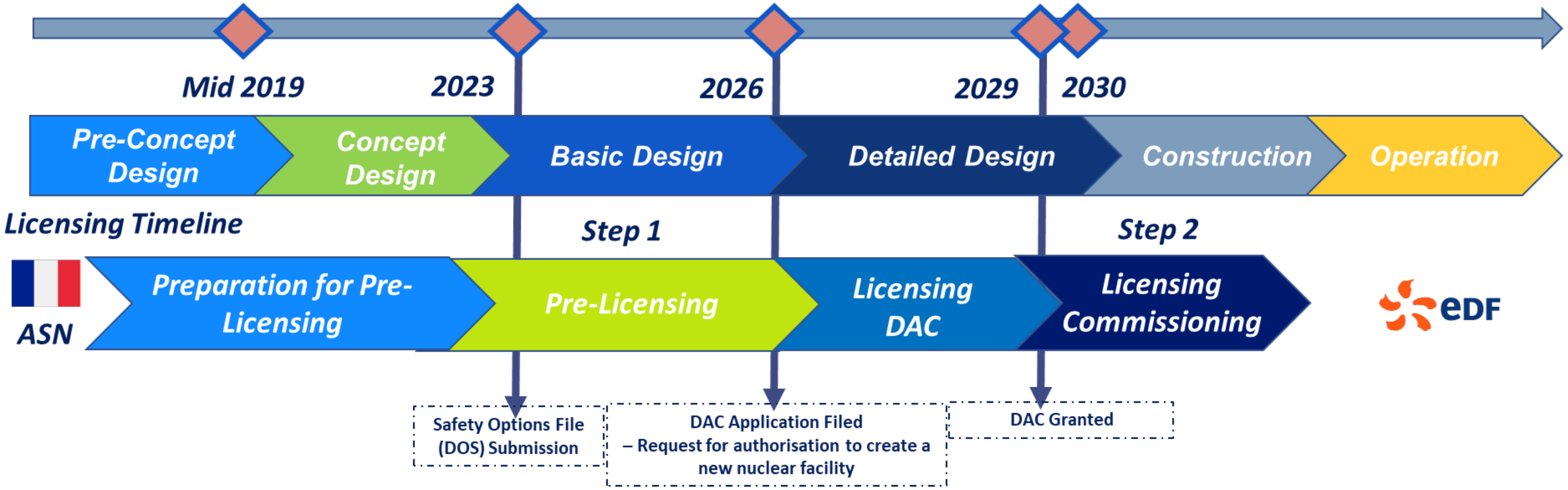
MSR
Molten salt reactor

Small Modular Reactors: Licensing

Safety is paramount to the nuclear industry, and licensing is handled at **national** level

- **Timeline for Licensing (Safety approval) is on the critical path for any new design development even for current tech.**

Timeline for the Nuward project (illustrative, prior to design change)



- **SMR need to be licensed in several countries to establish a series: <u>joint efforts required</u> from regulators**

NUWARD Joint Early Review: an initiative fostering international collaboration on safety and licensing between 6 EU regulators

Small Modular Reactors: Fuel supply

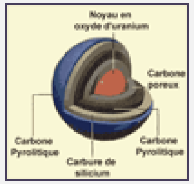
Industrial fuel fabrication facilities exist only for LW type reactors

- Fuel type depend on the reactor technology, and have various readiness levels (/technology and prod. capacities) :

Niveau de maturité technologique de la filière réacteur

Disponibilité industrielle des combustibles associés

Réacteur	Combustible	
❑ ***Réacteurs à eau légère (LWR)*** ***NUWARD** : 2* 540 MWth* ***Calogena** : réacteur piscine – 30 MWth*	C — Combustible U standard (à plaque ou à crayon) faiblement enrichi en ^{235}U (< 5 %)	Available in large quantities
RNR ❑ ***Réacteurs au sodium (SFR)*** ***HEXANA** : 2*400 MWth* ***OTRERA** : 300 MWth*	C — Combustible MOX-RNR	Tech. ready No production
❑ ***Réacteurs à haute temperature (HTR)*** ***Jimmy** : refroidi à l'helium – 20 MWth* ***Blue capsule** : refroidi au sodium - 150 MWth*	C — Combustible TRISO → Pas de capacité de production industrielle → Difficulté d'approvisionnement en uranium enrichi (entre 5 et 20 % en ^{235}U)	Tech. ready Supply issues No production
RNR ❑ ***Réacteurs au Plomb (LFR)*** ***Newcleo** : 80 MWth / 450 MWth*	C — Combustible MOX-RNR	Tech. ready No production
RNR ❑ ***Réacteurs à sels fondus (MSR)*** ***NAAREA** : 80 MWth* ***Thorizon** : 250 MWth* ***Stellaria** : 250 MWth*	C — Sels de chlorure U/Pu → pas de capacité de production industrielle → étape d'enrichissement préalable en Cl_{37}	~Lab. level



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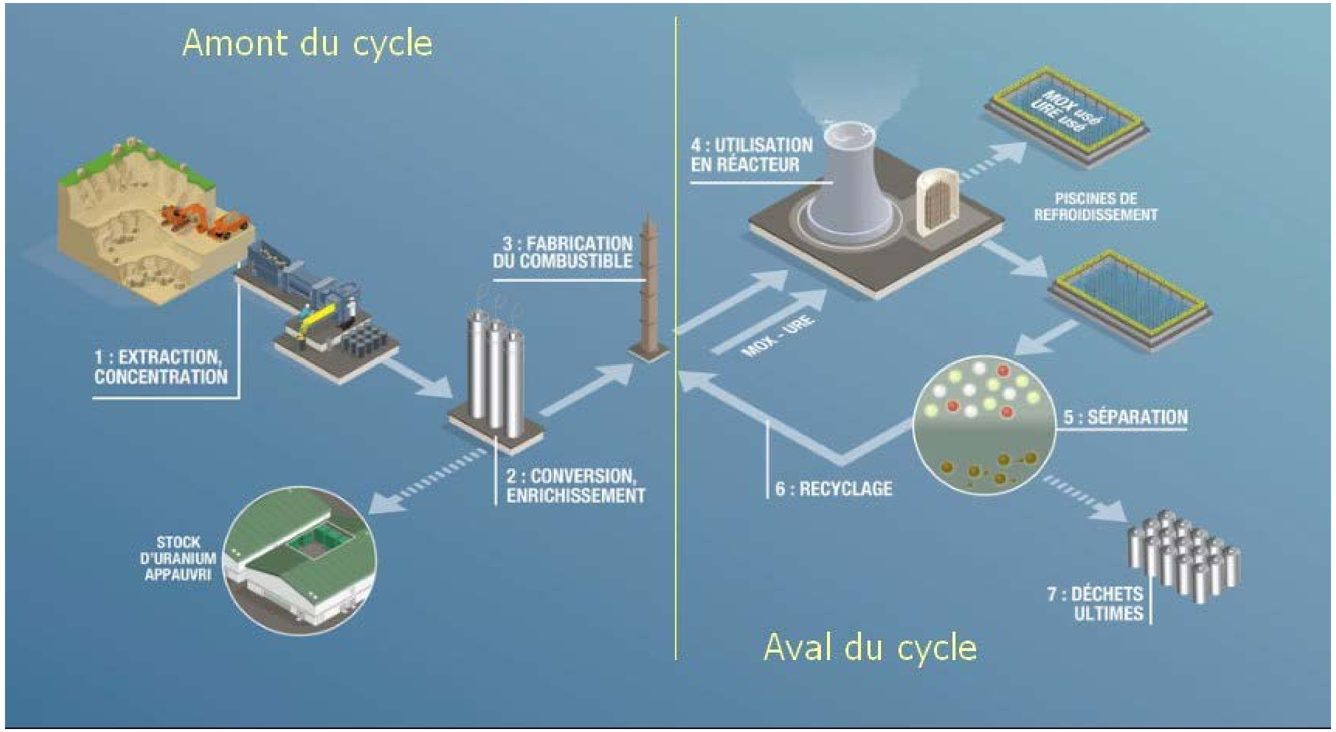
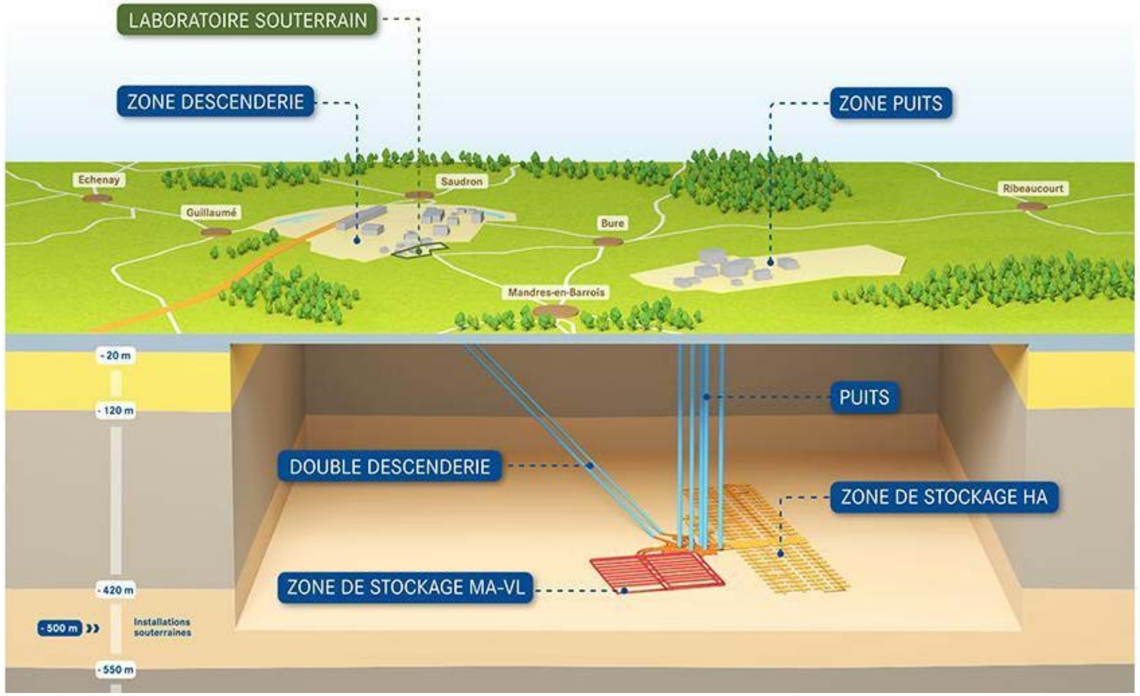
Small Modular Reactors: Nuclear Waste

Ways to handle nuclear waste have to be defined from the start

- Spent fuel type depend on the technology, and handling of the fuel cycle is a matter of the state (waste >>100 years)
- National geological repositories are qualified for some type of fuels





French program for innovative nuclear reactors

A 1 B€ public funding over 10 years to foster the French offer for small modular reactors

New reactors innovation programme (AMR with Gen4 concepts or fusion, new applications for nuclear)

- Projects granted through a competitive process (including 3 phases from concept maturation to prototyping)
- First phase closed by June 2023
- Promoting the emergence of new players (start-ups) in the French nuclear energy sector
- Leveraging public funding with private funding
- Aiming at partnerships by connecting start-ups and established market players

France 2030 Call for Projects: Innovative Nuclear Reactors

STEP 1: Supporting the creation of this new ecosystem:

- Candidates & awardess can benefit from the **support and expertise from CEA**
- The program is organised into **3 calls for projects**, each preferably dedicated to one of the three phease of the innovation continuum

Nuclear Policy Council, 17 March 2025

- Prioritize projects most likely to result in a demonstrator operational at the beginning of the **2030s**
- Establish a work program aimed at achieving the closure of the **nuclear fuel cycle**

STEP 2:

Sharing your strategic vision and expressing needs
Step1: Sumbission starting 30 May 2025

↓

Analysis of proposals by the interministerial governance of France 2030, extended to HCEA and DINN

↓

Feedback to project leaders on possible support arrangements

↓

In reference to the list of actions desired by the State and for the projects addressing them

Step 2: Supplementary dossier for evaluation of repayable advance / grant support

Nuclear Policy Council, 12 March 2026

- Additional funding provided by France 2030 for 2 SMRs: **Calogena & Jimmy**
- Continuation of the review of other applications, which will enable **additional aid to be allocated** to other projects in the coming months.

Nuclear innovation – French SMR and AMR

11 projects granted (AMR, fusion), 9 requesting a R&D support from CEA

FRANCE 2030

CALOGENA
PWR type reactor
30 MWth
District heating

HEXANA
Sodium cooled fast reactor
400 MWth / 150 MWe
Industrial heat / electricity

otrera
Sodium cooled fast reactor
110 MWe
Industrial heat / electricity

THORIZON
Molten salts reactor
250 MWth / 100 MWe
Industrial heat /electricity

STELLARIA
Molten salts reactor
250 MWth / 110 MWe
Industrial heat / electricity

naarea
Molten salts reactor
80 MWth / 40 MWe
Industrial heat / electricity

newcleo – Futurable Energy
Lead cooled fast reactor
30 or 200 MWe
Electricity, heat, radio-isotopes

BLUE CAPSULE TECHNOLOGY
HTR type Reactor
150 MWth
Industrial heat / electricity

Jimmy
HTR type reactor
15 MWth
Industrial heat

RENAISSANCE FUSION
Fusion type reactor
1 GWe
Electricity

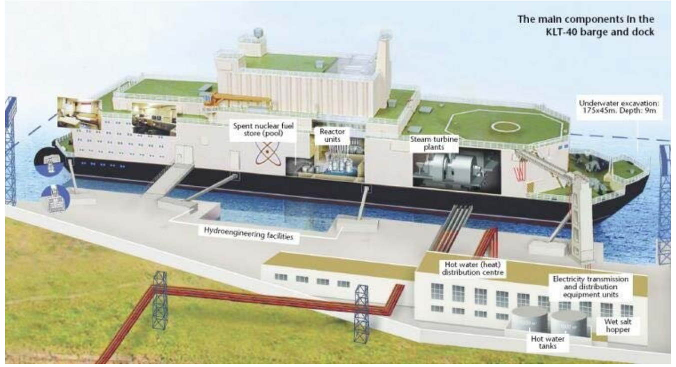
GenF
Fusion type reactor
1 GWth
Electricity

Small Modular Reactors: New Markets - Ships

Some projects target nuclear propulsion for merchant ships

- Existing nuclear ships are either military vessels or russian icebreakers derived from military tech…

- Most critical issue is not technology, but **<u>regulation</u>** (IMO) to allow nuclear merchant ship travel and port entrance
- Russia has developped a concept of « floating NPP », but with heavy restrictions on travel / conditions of operation

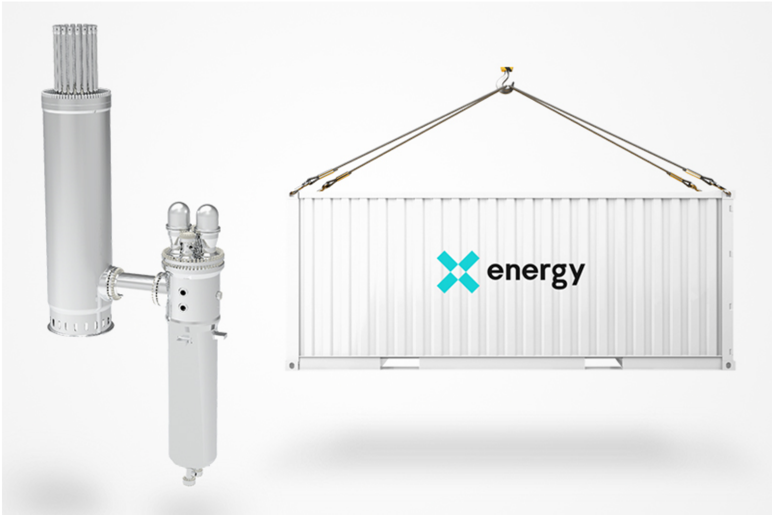


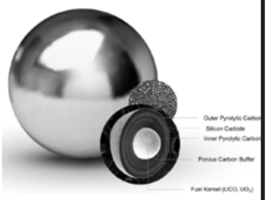
Small Modular Reactors: New Markets - MMR

Very Small Modular Reactors (called MMR « Micro Modular Reactors ») could be directly transported on site

- Interest for very remote areas (islands, mines, offshore platforms)
- Projects only with Gen IV like technologies
- Some projects being developped with both civil / military applications
- Issues with nuclear security and remote control
- Nuclear waste cannot be exported: issue?

USA : a concept led by the DOE

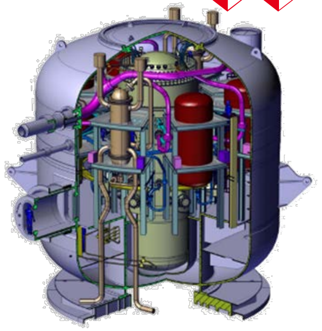




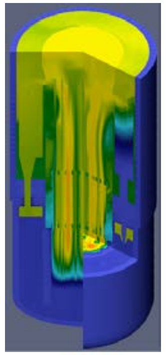
… in synergy with the DOD

P ~5MWe
4 containers
20 ft

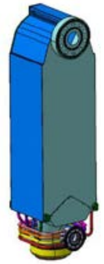
Challenges addressed by the SMR Program



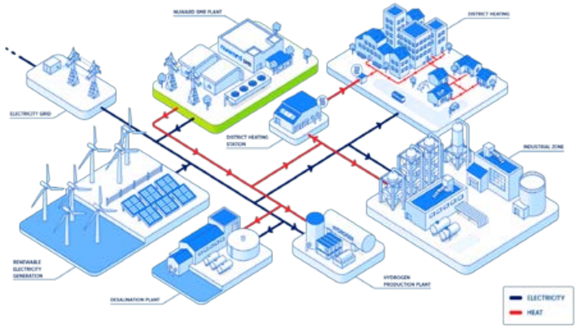
- **New designs for LW-SMRs**
  - Simplified/compact NSSS designs
  - Passive safety features



- **Safety Approaches**
  - Adaptating codes and models to new features of SMRs
  - Extending experimental databases for code qualification
  - International efforts to harmonize safety approaches of regulators



- **Industrialization**
  - Fabrication of innovative components
  - Codes and Standards



- **New applications for nuclear**
  - Technical-Economical assessment of possible use-cases
  - Energetic optimization
  - Integration of SMRs in multi-vector networks

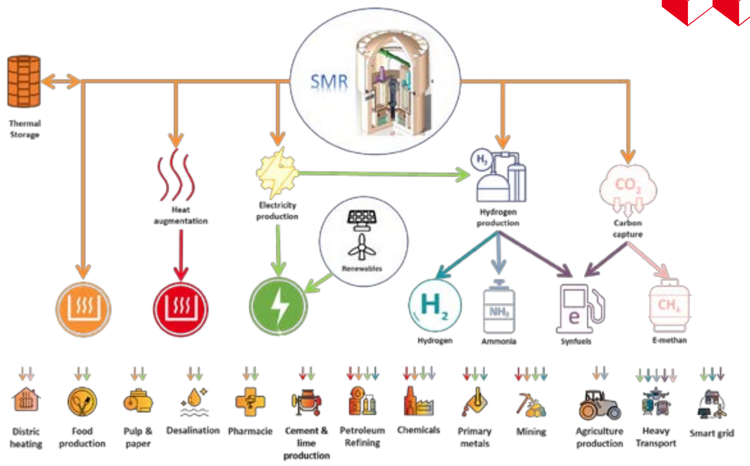
SMR Program activities : IDNES

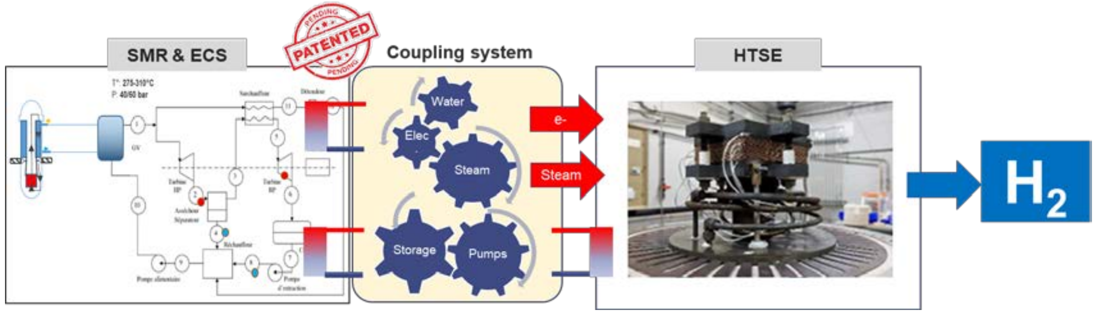
- **4 streams of research:**
  - Technical-economical studies
  - SMR-HTSE coupling for low c H2 production
  - Heat generating SMRs
  - Innovative Energy Conversion Systems

- **100% CEA Funding:**
  - IP build-up on interesting configurations / designs
  - Ability to discuss with any end-user or SMR vendor
  - Ability to foster innovation and launch new ideas

- **16 active patents developped**
  - Ability to licence to SMR vendors (NUWARD, Start-Ups)
  - Basis for technology transfert / Start-Ups creation

- **Very strong connection with other R&D Programs**
  - H2 and batteries, CO2 Cycle, Smartgrids, Gen4 reactors





Gathering Partners around International Projects

Building up upon Euratom Projects:

- ELSMOR (2019 – 2023)
- TANDEM (2022 – 2025)
- EASI-SMR (2024-2027)
- SANE (2024-2027)

Towards European Licensing of Small Modular Reactors

Participation in the SMR Industrial Alliance

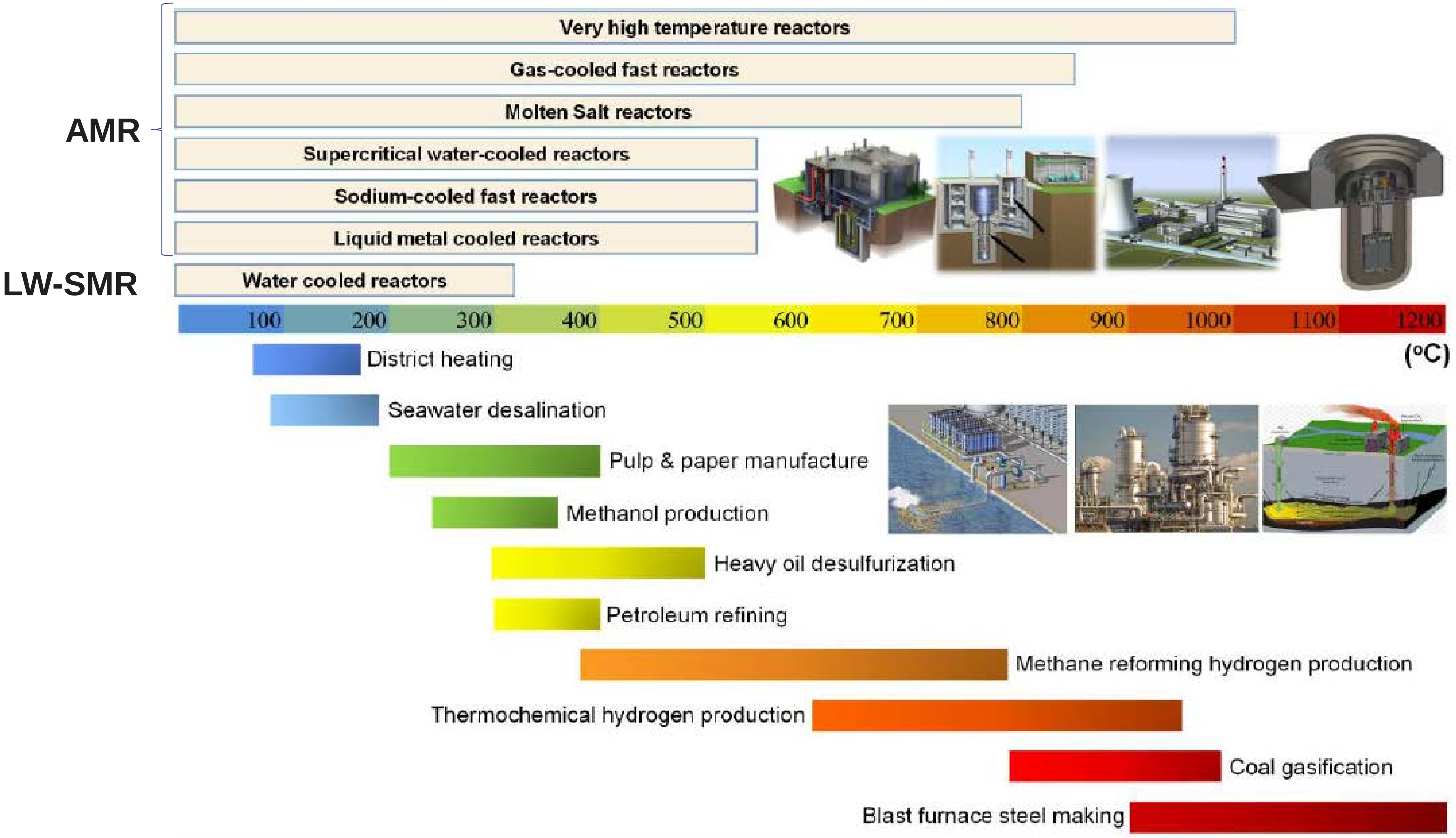
- CEA in TWG on R&D&I, Applications and Fuel cycle
- CEA associated with multiple projects

Bilateral exchanges (VTT, INL,…)

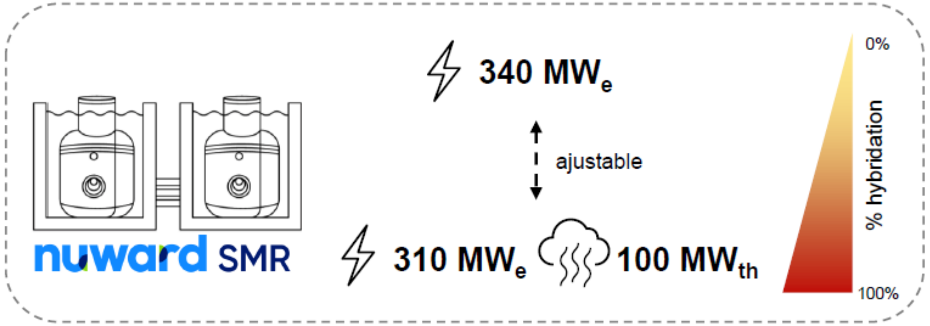
IAEA NHSI Initiative

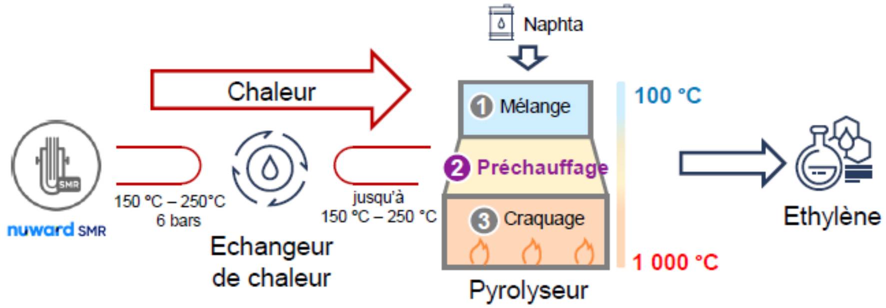
2. SMRs beyond power generation

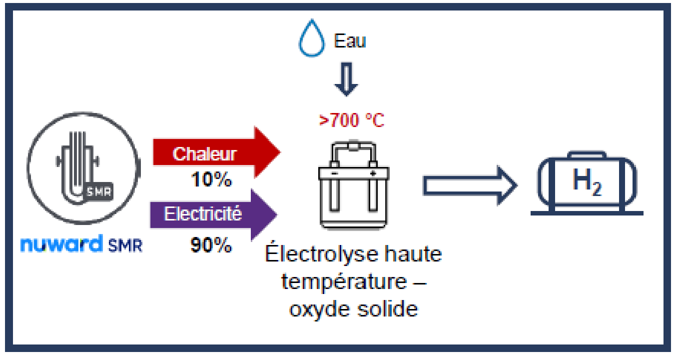
Small Modular Reactors: New Markets - Heat

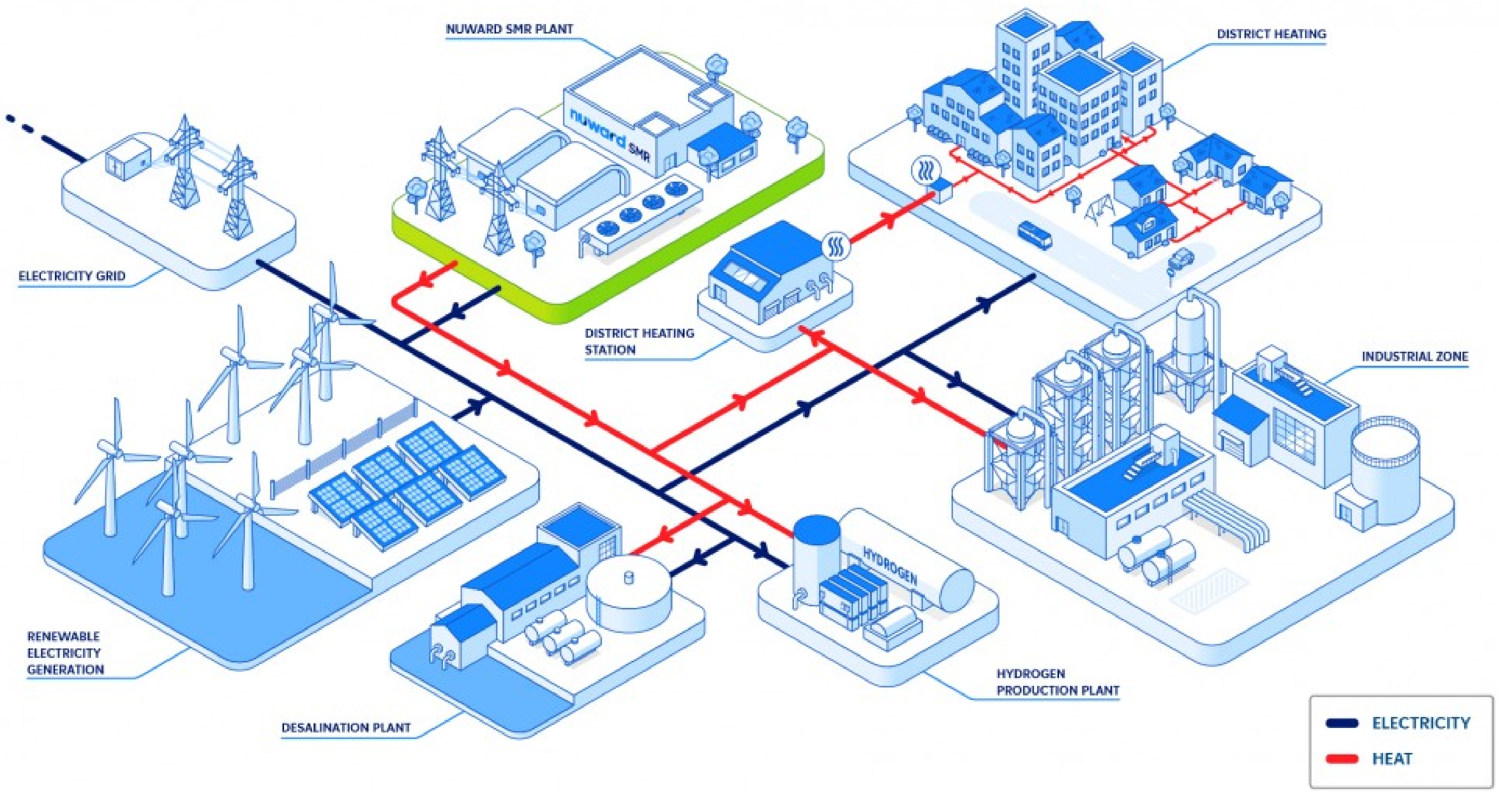


PWR cogeneration capacities

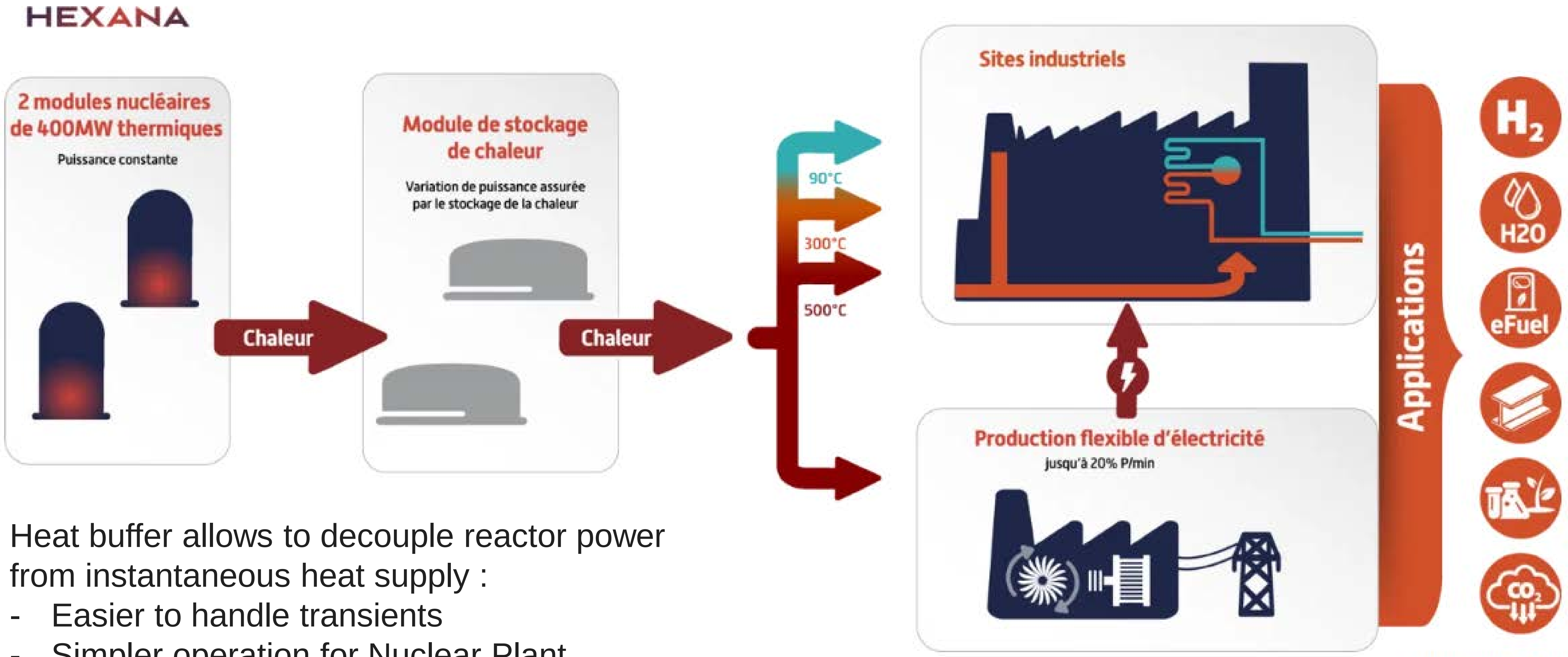








AMR design for heat and power



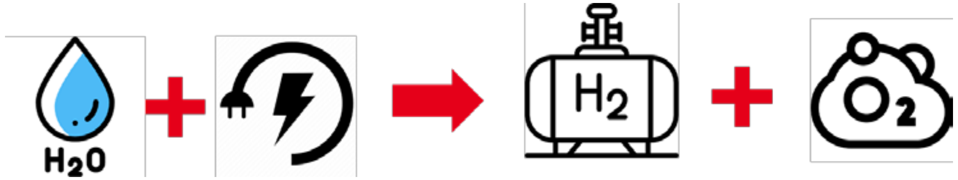
Crédit @HEXANA

Heat buffer allows to decouple reactor power from instantaneous heat supply :

- Easier to handle transients
- Simpler operation for Nuclear Plant

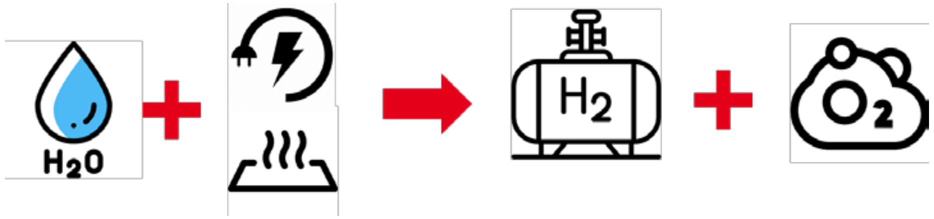
Low C H2: Electrolysis for H2 Production

Low T° Electrolysis which uses **Electricity only**



- Room T°
- 2 tech: **Alkaline** and **PEM**

High T° Electrolysis (HTSE) using **Heat** and **Electricity**

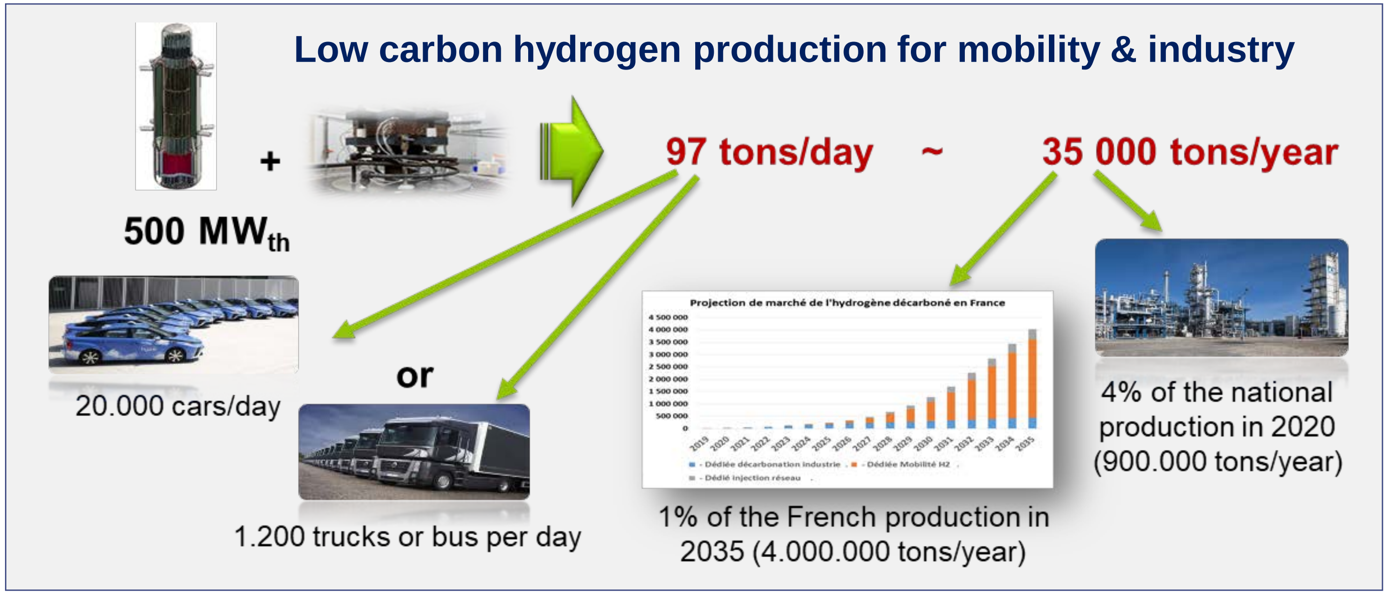


- **Higher Energy efficiency** (electricity is created from heat with 30-40% efficiency)
- **600-800°C operating T°**… but most of the heat is needed to **create steam (at <u>100°C</u>)**
- **Exothermal process:** excess heat can be used to heat up the steam (100°C -> 700°C)

➡ LW SMR can supply HTSE with 150°C heat and electricity

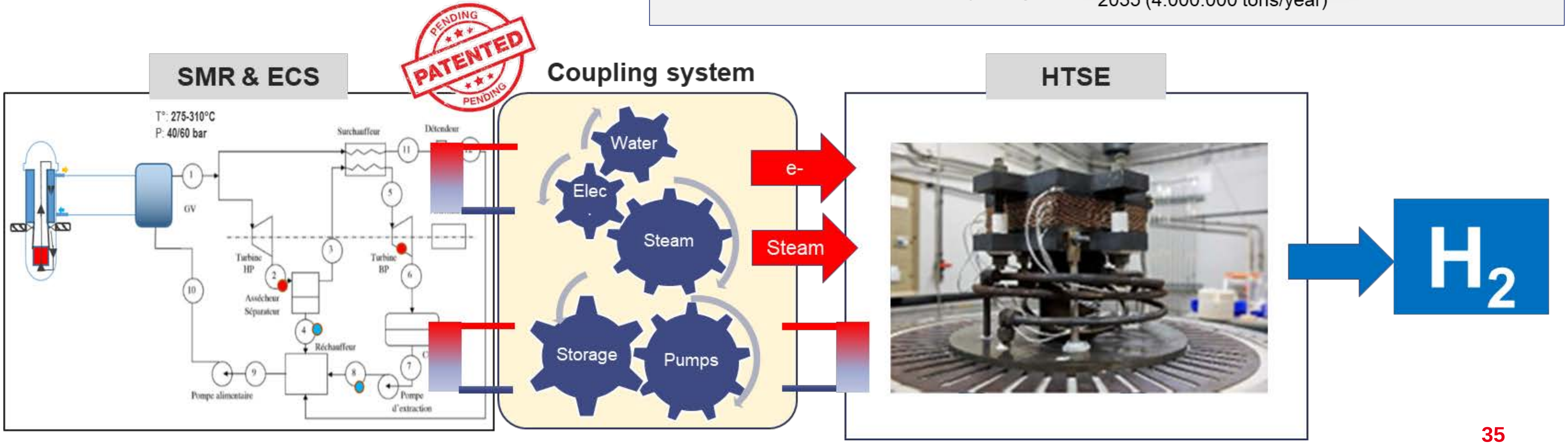
Coupling SMR-HTSE: an optimized configuration

- Low Carbon Energy supply
- Production on demand
- Optimal use of Heat and Electricity



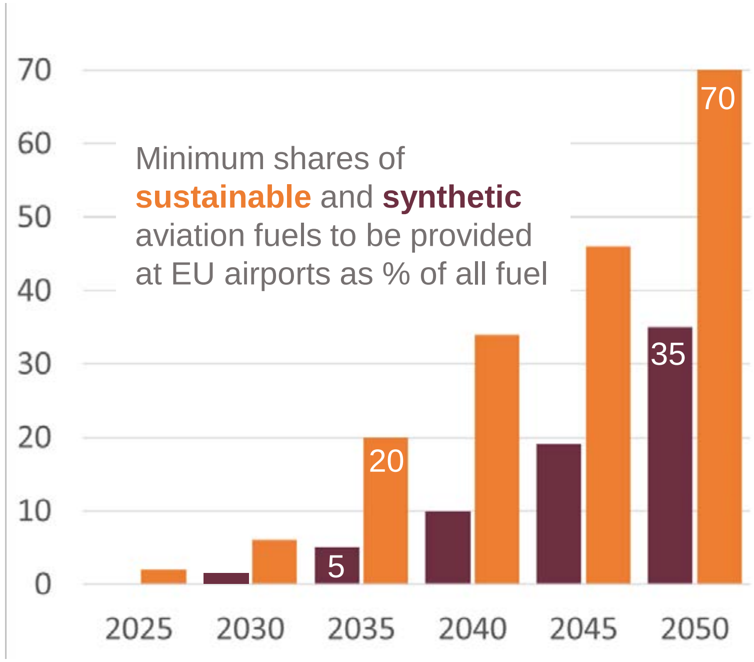
CEA expertise on:

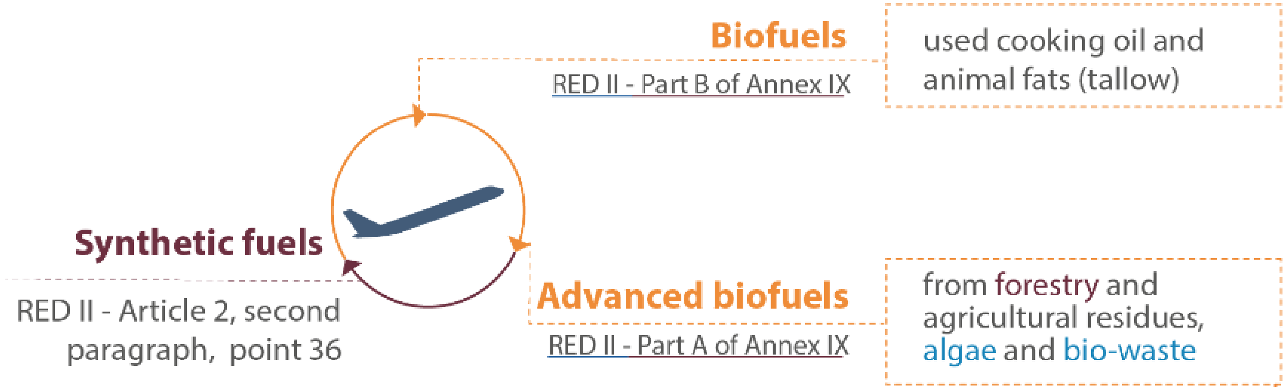
- SMRs and Energy conversion systems
- High Temperature Steam Electrolysis



E-fuels

- Long range transportation accounts for 28% of GHG emissions in the EU
- The Fit-for-55 regulation package sets a trajectory
  - For aviation



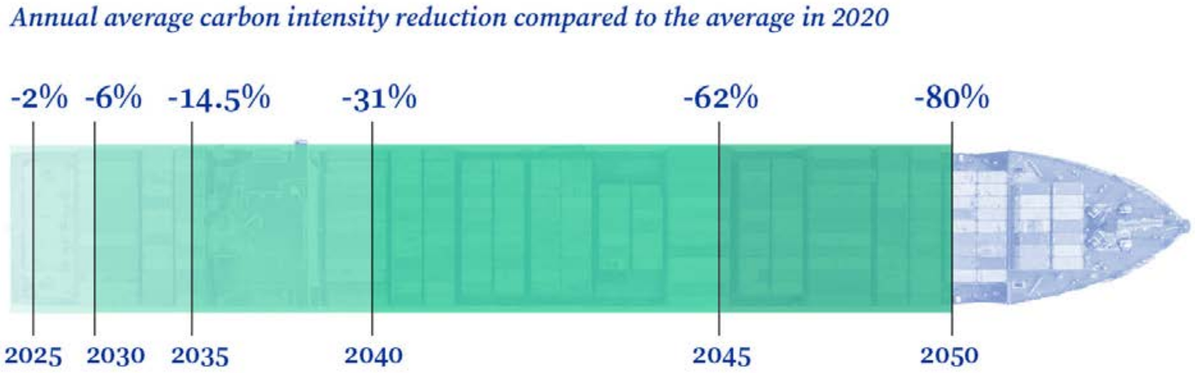


Source: Sustainable aviation fuels, EPRS, March 2022.

  - For maritime

The FuelEU maritime regulation will oblige vessels above 5 000 gross tonnes calling at European ports (with exceptions such as fishing ships):

→ to **reduce** the **greenhouse gas intensity** of the energy used on board as follows



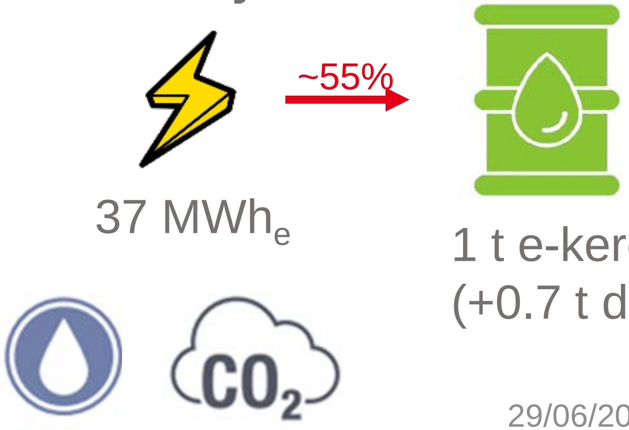
SAF: Key figures in France and in Europe

- **In France, the aviation sector**
  - **emits 21 $MtCO_2$/yr**
    - 6.8% of the total emissions
    - 83% of the sector's emissions are due to medium and long-haul flights
  - **consummes 7 Mt/yr of kerosene**
    - based on fossil oil
    - steady increase of 4%/yr
  - **For Charles de Gaulle + Orly airports**
    - 5 Mt of kerosene consummed every year

PARIS AÉROPORT

- **In Europe, the aviation sector consummes 50 Mt/yr of kerosene**

- **A massive need for low carbon electricity**



37 MWh_e

1 t e-kerosene
(+0.7 t diesel)

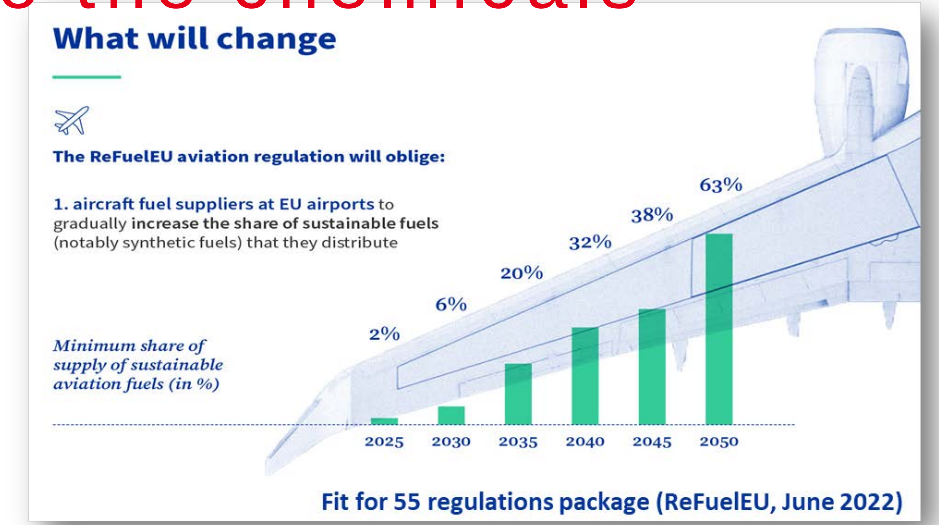
6.5 t

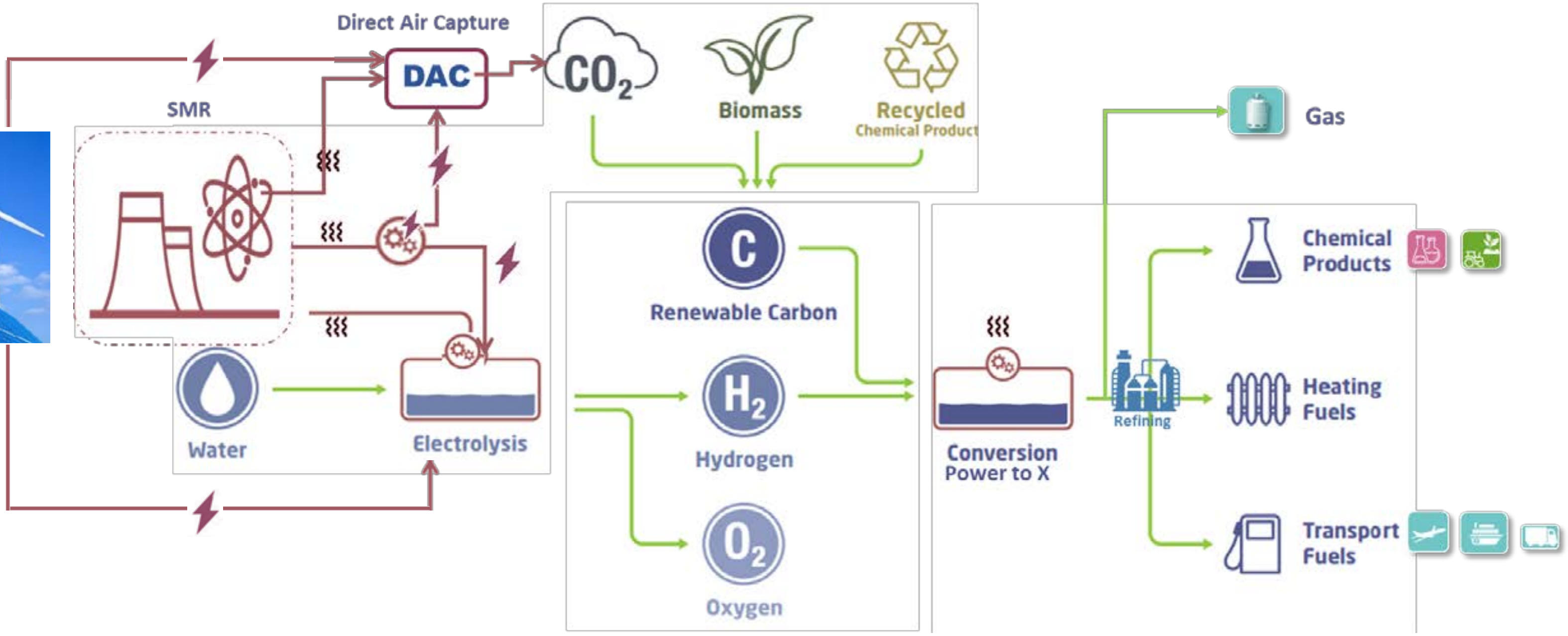
5 t

NUCLEAR to X
Integrated system from the neutron to the chemicals

Challenges:

- SAF is much more expensive -> must be compensated
- Huge amounts of low C power -> feasability to scale? Acceptability?
- Biogenic CO2 sources -> feasability to scale?





Beyond H2:
- Methan
- Methanol
- Ammonia
- E-fuels

A first generation of e-fuels utilizing low carbon H_2

- The **minimum** annual need for low carbon electricity is massive for synthetic fuels

		E-kerosene	Low carbon electricity	Low carbon H_2	Electrolyzers	CO_2 captured	REP 900MW	Windmills 8MW (45% capacity factor)
PARIS AÉROPORT	**2035** (**5%**)	**0.25 Mt**	**9.3 TWh**	**180 kt**	**1.1 GW**	**1.3 Mt**	**1.5**	**300**
PARIS AÉROPORT	2050 (35%)	1.8 Mt	65 TWh	1.3 Mt	8.0 GW	8.8 Mt	11	2100
EU	2035 (5%)	2.5 Mt	93 TWh	1.8 Mt	11 GW	13 Mt	15	3000
EU	2050 (35%)	18 Mt	650 TWh	13 Mt	80 GW	88 Mt	110	21000

x7

x10

A production cost of ca. 2 to 4 €/L depending on the hypotheses (>50 €/MWh_e, sources of CO_2, etc.)

3. Gen4 reactors

The challenges of the Generation IV systems

GenIV International Forum promotes the **sustainable development** of nuclear energy

Great challenge :

– **Best use of uranium resource,**

- Fast neutrons enable Pu self-sustaining + Uapp recovery (U238 -> Pu239 in a reactor)

->**50 to 100 times more energy** extracted from 1 kg of natural uranium

– **Reduce the production of radioactive waste,**

- Complete closure of the cycle -> feasibility (U, Pu) already demonstrated, Am transmutation/feasibility not yet established/manufacture of Am fuels

-> **Acceptability** +gain in terms of the footprint of the geological storage site

– **High safety standard and operational peformances,**

- Features at least equivalent to those of GEN III - ASTRID = substantial progress (passivity safety, SA management)

->**Acceptability** ASTRID = substantial progress (passivity, design safety)

– **Non-proliferation et nuclear security,**

– **Competitivness,**

- SFR CAPEX +30 à +50 % versus PWR !
- New market : direct use of heat in process (100% of energy used in the process, colocation)

Selection of the 6 Generation IV systems

SFR Sodium-cooled Fast Reactor System
GFR Gas-cooled Fast Reactor System
LFR Lead-cooled Fast Reactor System

} Fast Neutrons Reactors

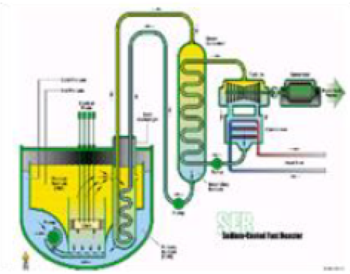
MSR Molten Salt Reactor System — Thermal or Fast neutrons ? It is open …

SCWR Supercritical Water-cooled Reactor System
VHTR (Very) High Temperature Reactor System

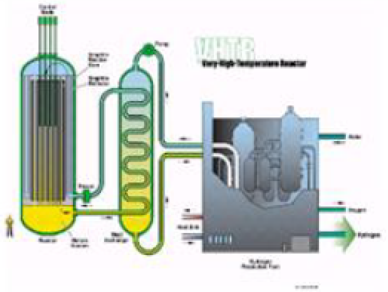
} « Thermal neutrons »
SCWR, VHTR, no gain /PWR regarding U utilization

Maturity is decreasing →

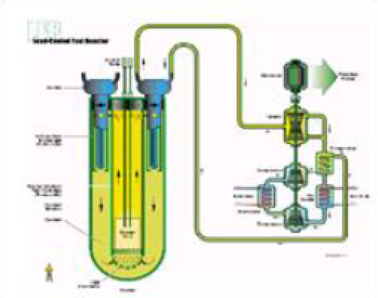
**Gen IV,
Very different
maturity levels**



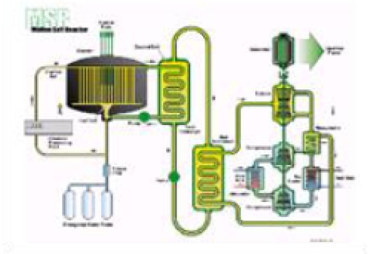
SFR
Sodium-cooled fast reactor



VHTR
Very high temperature reactor

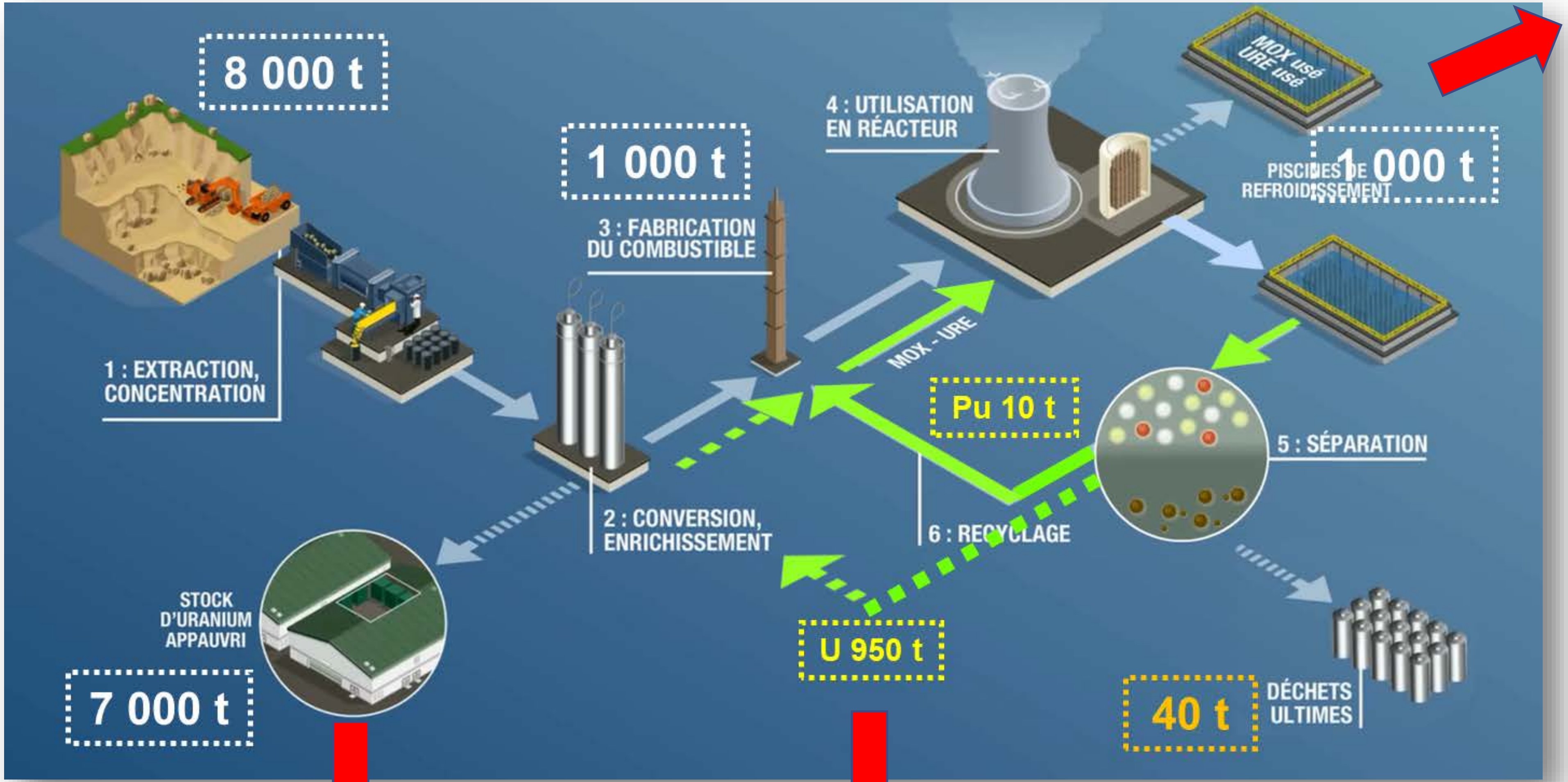


LFR
Lead-cooled fast reactor



MSR
Molten salt reactor

The current french fuel cycle



spent MOX +120 t/y
spent URE : 0-80 t/y

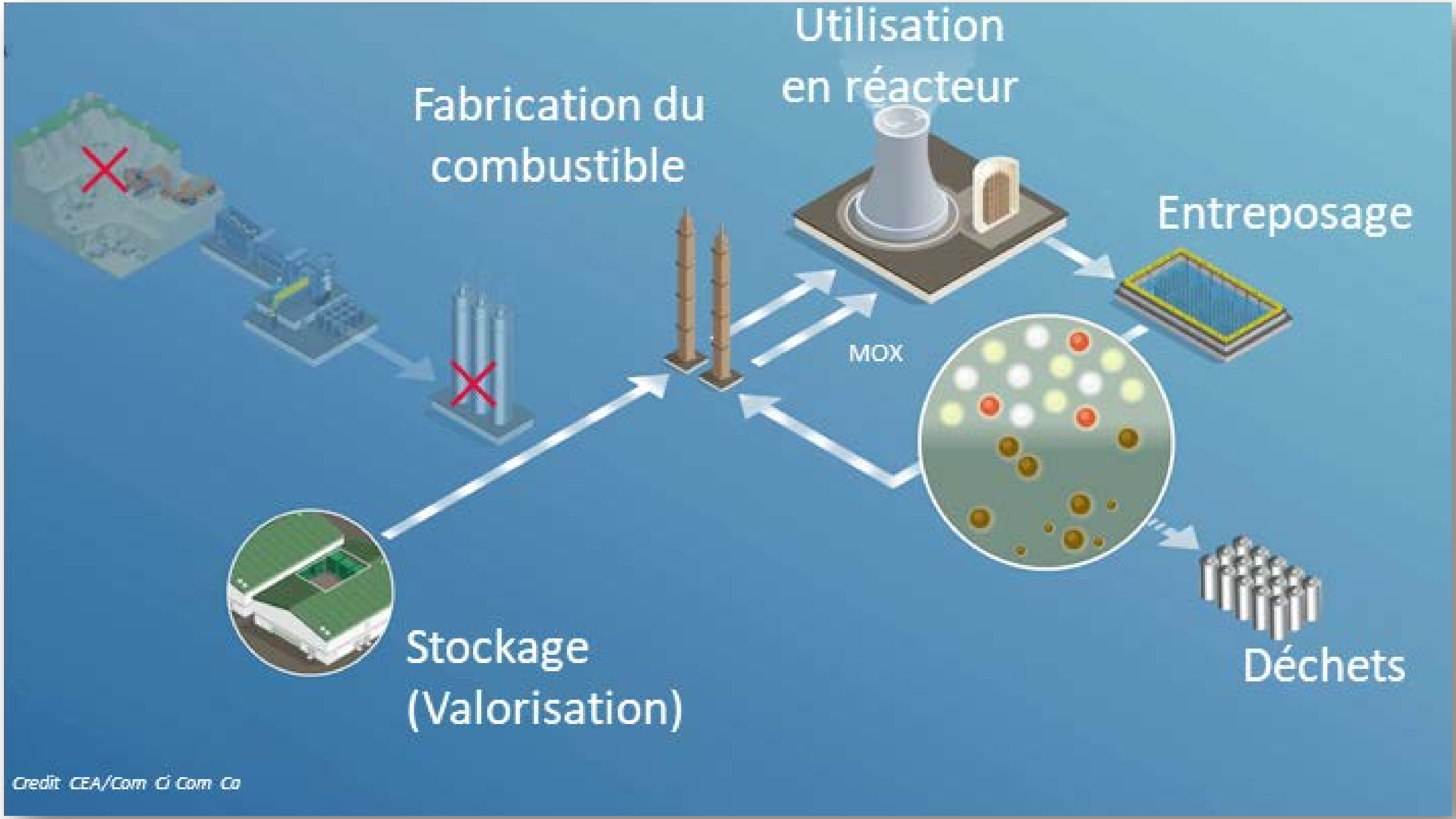
Current situation

U_{app}

URT

*Orders of magnitude for an annual output of **400 TWh/y** (approx. the output of the french fleet)*

The future cycle with Gen4 reactors



Roadmap on the french closed fuel cycle strategy

CPN 2025:

- Industrial partners (EdF, Orano, Framatome) and CEA should lay out a roadmap, combining issues/milestones for both fuel cycle facilities and SFR development to reach independency from Unat imports by the end of the century, and define the industrial organization to handle this roadmap.

- The goal is to **optimize the system as a whole** (fuel cycle facilites and reactors) with regard to the independency target, taking into consideration intermediate steps such as multirecycling in PWR with MOX, and possible synergies with AMR development.

- On the reactor side, the roadmap will include studies on the need and timeline for a **potential demonstrator** as a preliminary step for a fleet of SFRs

Roadmap on the french closed fuel cycle strategy

Building on the previous **Nuclear Policy Councils** (NPC) held since 2022, the NPC held on 12th March 2026 sets out the board **guidelines for the national nuclear policy:**

- Strong **revival of nuclear power** to ensure energy independence
- Construction of (6) **new EPR2 nuclear reactors**
- **Financing and regulation of the EPR2 program**
- Modernization of the nuclear fuel cycle: "**Aval du futur**" program (Orano)
- **Securing uranium supply**: Launch of a program to **close the nuclear fuel cycle with Gen4 installations**
- **Support for nuclear innovation**: Additional funding for small advanced reactors
- **Governance and acceleration of projects**

cea

PRESIDENCE DE LA REPUBLIQUE

Short medium, medium and long term vision

Modernization of existing facilities
Long-term continuity of existing industrial capacities

Renewal of facilities
Technological developments & innovations to adapt and improve overall industrial performance

Facilities of the 22nd century

SHORT-TERM INDUSTRIAL PROJECT

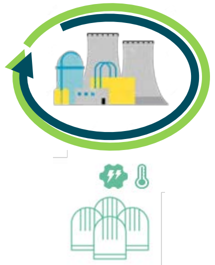
Sustain mono-recycling in current fleet of reactor:

Pursue recycling with ERU and MOX

Benefits vs open cycle:

- 20 to 25% of NatU savings
- Used fuel storage requirements divided by 4
- Very low growth in the volume of spent fuel to be stored
- High-level waste packaged safely as it is produced

MID-TERM PERSPECTIVE

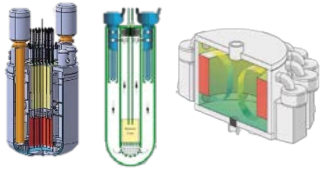


Multirecycling in future fleet of LWRs with the potential deployment of MOX-MR fuel

Adapt to new requirements for SMRs - AMRs

- Up to 40% of NatU savings
- Recycling all types of used fuel UNE, ERU, MOX
- Stabilized (or even decrease) of used fuel inventory

LONGER TERM AMBITION



Future deployment Generation IV reactors

Towards the closure of the fuel cycle:

- Increase NatU savings, beyond 40%
- Further Decrease waste volume, lifetime and toxicity level
- Complete closure of the fuel cycle with FNRs: Up to 100% savings of natural uranium

FNR/Selection of the coolant : a metal with a low melting temperature

Sodium is cheap and readily available

Specific issues posed by sodium as a heat transfer fluid are its chemical reactivity : reactivity with air ->Na fire risk +chemical reactivity with water ->heat +H2

	unité	air		helium		CO_2	eau	sodium
		1 bar, 27°C	10 bar, 227°C	60 bar, 500°C	90 bar, 900°C	60 bar, 500°C	150 bar, 300°C	1 bar, 500°C
ρ	kg/m^3	1,16	6,94	3,74	4,24	40,87	726	865
c_p	kJ/kg.K	1,01	1,02	5,19	5,19	1,19	5,60	1,30
ρc_p	$kJ/m^3.K$	1,2	7,1	19,4	22,0	48,6	4066	1125
λ	W/m.K	0,03	0,03	0,29	0,36	0,06	0,56	80
μ	10^{-5}*Pa/s	1,90	2,70	3,80	4,60	3,30	9,00	23,30
Pr	-	0,71	0,69	0,67	0,67	0,66	0,90	0,00

SFR can be operated at **high temperature** under **atmospheric pressure**

The same for LFR but in a smaller T. range

	Na	Pb	Pb_{45}/Bi_{55}
T- fusion (°C)	98	327	123
T- ébullition (°C)	883	1745	1670
Perte de charge (valeur rel.)	1	7	
ρCp (valeur rel.)	1	1.5	

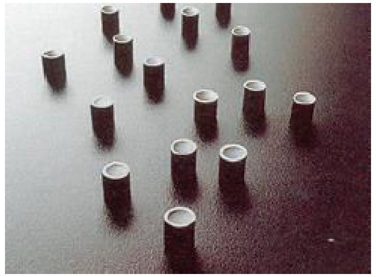
Lead - Specific problems raised by the Pb, **Pb/Bi** :

- corrosion ->PO_2 control, T. and speed limitation or coating
- Bi (very scare and costly) +production of Po (toxic and a-emitter)

FNR/Selection of the fuel type : a ceramic or a metal ?

Fissile materials

- Criteria
  - Ability to support high burn-ups ⇒ economy of fuel cycle
  - Ability to provide a high volumic power ⇒ size of the core, investment impact
- Candidate materials
  - Metal alloys of uranium UZr or uranium/plutonium: (U,Pu)Zr (US program)
  - Ceramics $(U,Pu)O_2$ / Nitride (U,Pu)N / Carbide (U,Pu)C
- Oxide $(U,Pu)O_2$ in a reference with real experience in France, Russia, Japan
  - Similarities with UO2 in PWR : physical and chemical properties
  - Manufacturing technics (powder metallurgy) and treatment (PUREX …)

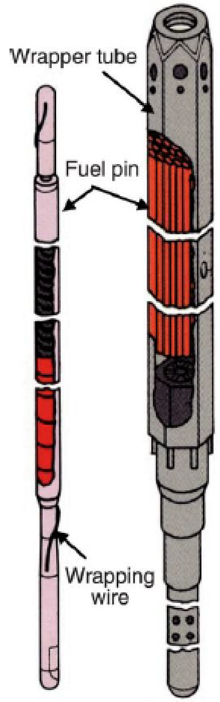


Cladding Materials

Austenitic steels – 1515Tie ->AIM1

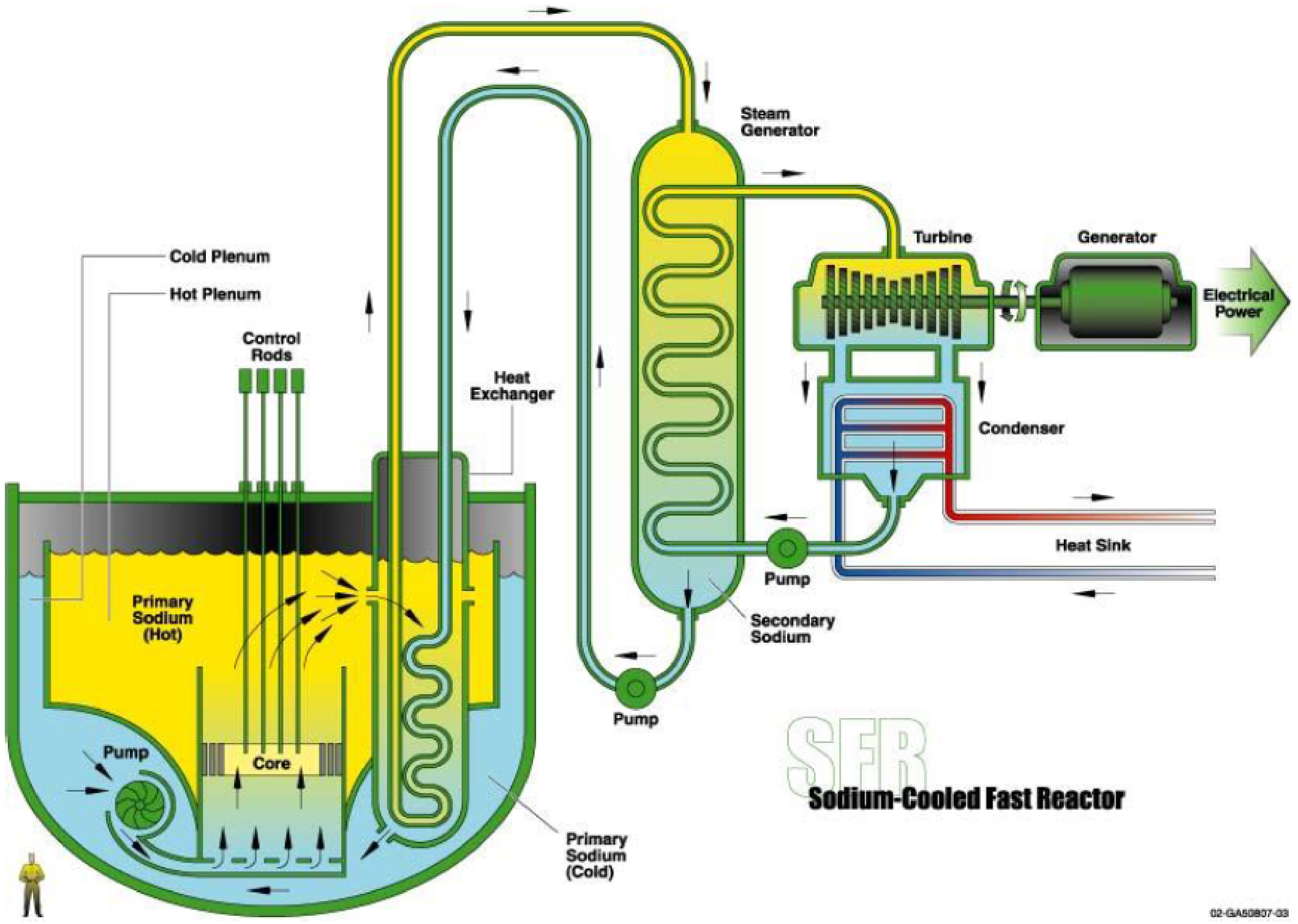
Fuel Sub-Assembly design

- Bundle - triangular mesh with a hexagonal symmetry
- Hex can envelopes the bundle enabling the coolant flow to be channeled and regulated



SFR/General architecture (pool-type) and functional diagram

- All the primary sodium is contained in a unique vessel
- All the components (pumps, IHX, control rod, instrum., etc) are entered through the top cover plate
- All structures in the primary circuit are made with austenitic stainless steels
- The cover gas above the sodium free surface is argon (no oxygen)
- Fuel transfer is made with elevators and rotating plugs (closed vessel)



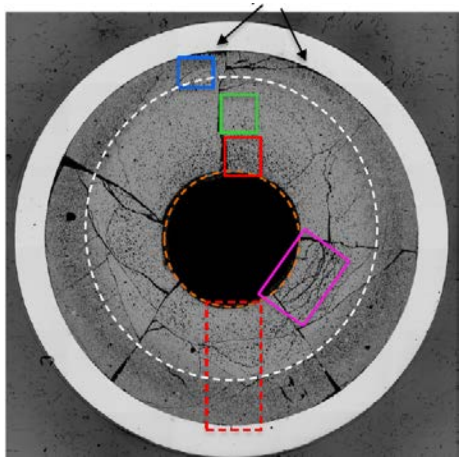
Gen4 activities

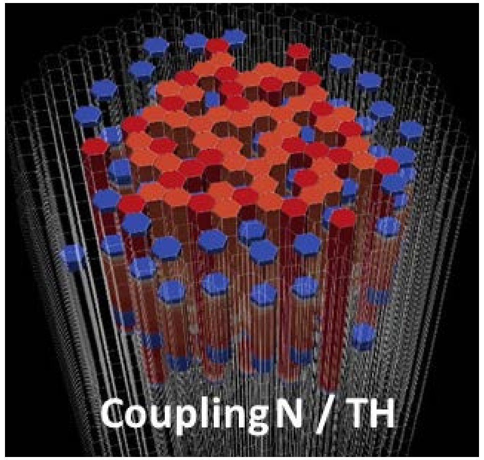
Two main topics

1. Sodium cooled fast reactor
   1. R&D program
      1. Physics
      2. Materials
      3. Sodium technologies development
      4. Innovative designs
   2. Molten Salt Reactor

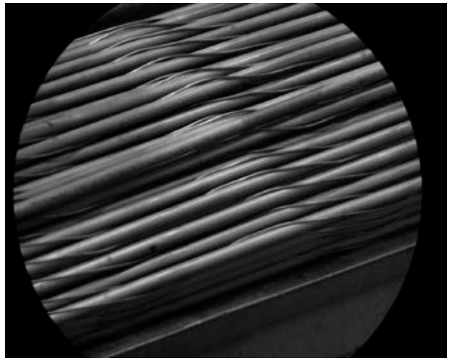
Sodium cooled fast reactor
R&D program

1. Physics
   1. Fuel modeling : GERMINAL software
   2. Neutronic modeling : Apollo3-RNR software
   3. Thermo-hydraulic modeling : CATHARE software
   4. Coupling to multi-physic modelling
   5. Severe accident modelling
   6. Chemical risk modelling
   7. Experiments in supports
2. Materials
   1. Cladding
   2. Standardization **RCC-MRx**
   3. Long term behavior includes PHENIX expertise


SFR Fuel



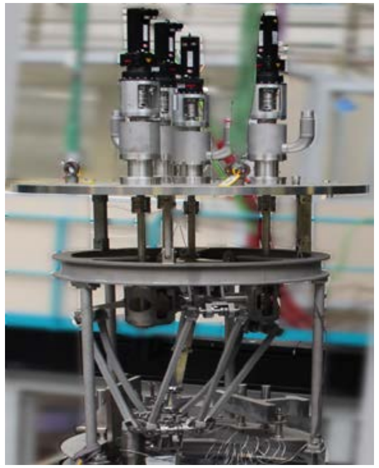
Neutronic modeling


Cladding


Long time behavior experiment

Sodium cooled fast reactor
R&D program

3. Sodium technologies development
    1. Sodium NDT
    2. Visualization in sodium environment
4. Innovative designs
    1. MOX Fuels
    2. Sensors
    3. Design studies in European projects



Sodium NDT experiment

European project ESFR SMART

Focus on the simulation software for SFR (1/2)

Neutronics codes

Apollo3-RNR + INCA pre-processor

Developed since 2013, specific VVUQ since 2019

Validation includes data from Masurca +PX +SPX +BFS

Goal : industrialisation of AP3-INCA; extension of the VVUQ

Thermal-hydraulics codes

Cathare3 RNR

Developed since 2013, specific validation 2017

Goal : extension of the VVUQ

MATHYS = multiscale coupling using Cathare3 /TrioCFD /TrioMC

Developed since 2015, specific validation 2017

MATHYS has been validated against Tall-3D (Euratom), Plandtl2/JAEA tests (2018, 2019 and 2021) and PX data

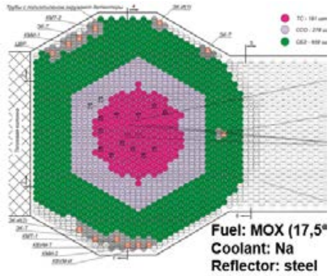
Multiphysics platform

MARCS software under development

PLANDTL2 tests

55 channels to simulate core thermal hydraulics

BFS test



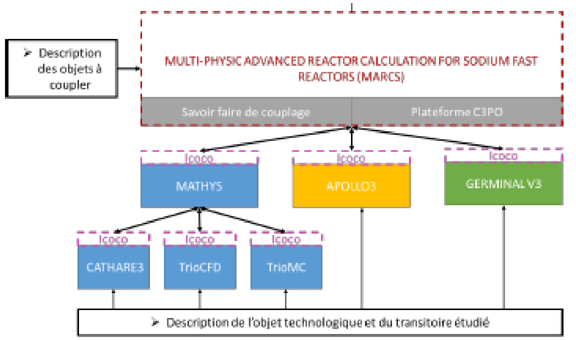
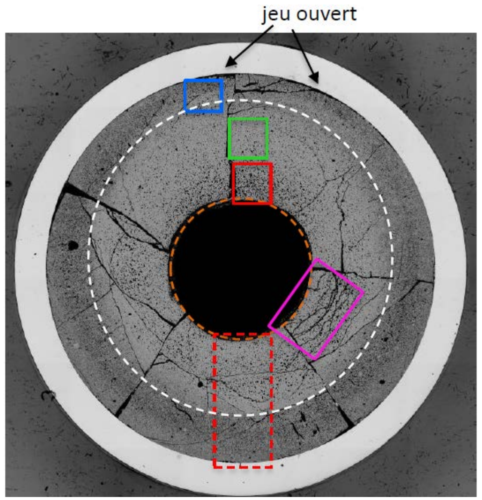


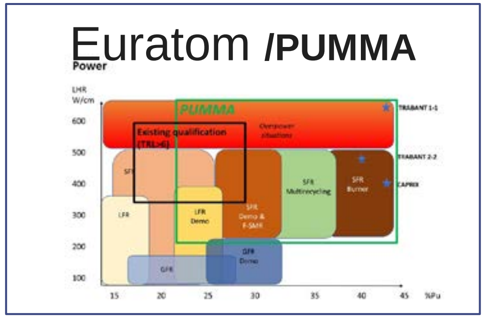
Schéma fonctionnel de l'OCS de couplage multiphysique MARCS

Focus on the simulation software for SFR (2/2)

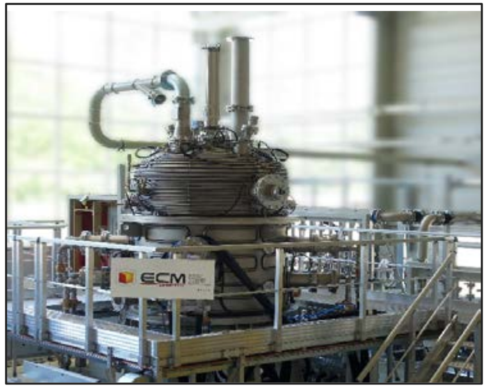
- **Fuel behavior codes**
  - **GERMINAL V3**
  - **Developed since 2017, specific VVUQ since 2021**
  - Extension of the BREF database (500+ fuel exams; +1-2 per year)
  - Additionnal validation through partnerships / EU projects
  - **New modules taking into account gas swelling at low Plin**



- **Severe accidents codes**
  - **Simmer-V – co-developed with JAEA since 2015**
  - Validation extended through CABRI data, SCARABEE and EAGLE tests
  - **SEASON code developed since 2015**
  - SAIGA program on-going at IGR (NNC)
  - + SCONE and PROCOR-Na



- **Sodium fire and Sodium/water interaction**
  - **CANOP software under development**



SFR in EU funded projects

2022 - ESFR-SMART project ended with significant results
incl. experiments in support of the design

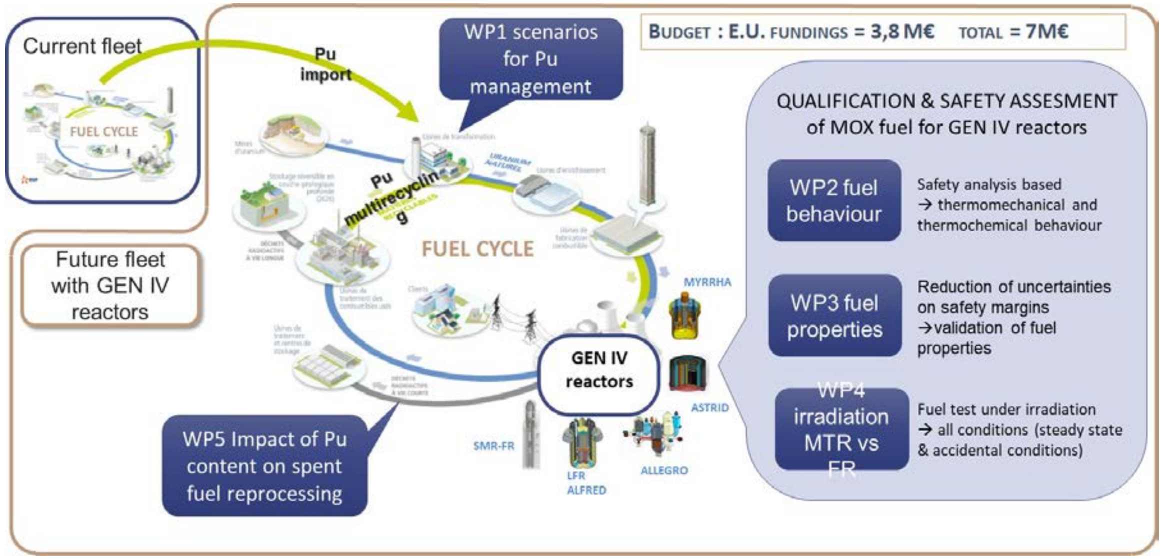
ESFR-Simple project was initiated

Kick-off meeting, October 10th-11th 2022, Aquabella hotel, Aix-en-Provence, France

Its main technical objective is to design **a flexible AMR with fast spectrum and sodium coolant** (sketch studies), also to produce additional experimental results (technological developments).

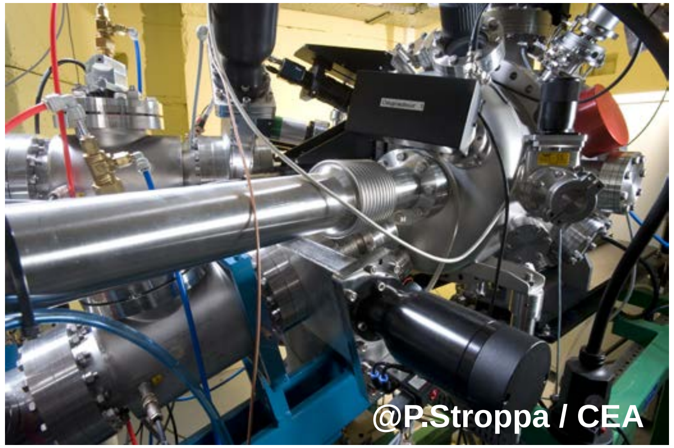
PUMMA project [2020-2024]

UPuO2 properties +in pile fuel behavior in FNR + fuel dissolution in nitric acid … incl. new experimental data



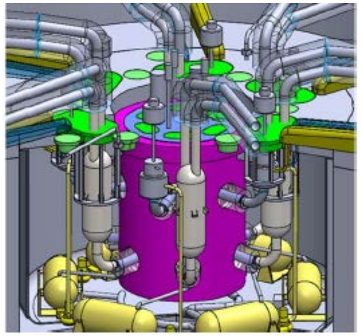
Molten Salt reactor
R&D program

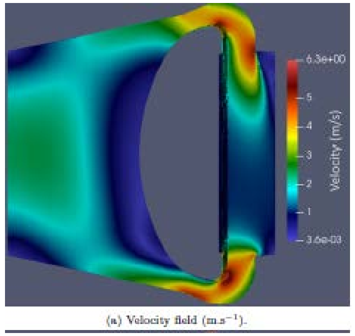
1. Innovative designs
   1. Core Designs
   2. sensors
   3. Experimental capacities
   4. Simulation codes



Ions beam Irradiations experiment


BACCHUS corrosion loop


Core Design (ISAC project)



Modelling


Experimental setups

ISAC Project on MSRs for Am transmutation

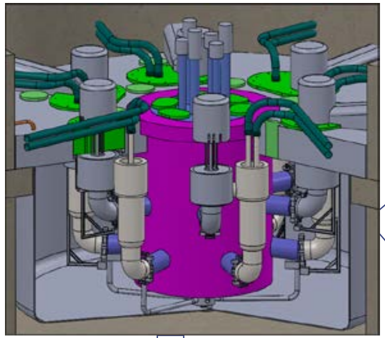
Goals of the ISAC Project:
- Feasability study on MSR concept for Minor Actinide transmutation
- Evaluate impact on final waste inventory (volume / type) and surface reduction for deep geological repository

Integral approach: reactor + fuel + deployment studies

Reactor concept : MSR fast spectrum, Pu+Am Cl salt (300MWth)

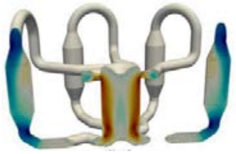
Cycle / scenarios : MSR as a backup of PWR/SFR -> a few MSRs dedicated to transmutation

DESIGN & SIMULATION



- Conceptual design (TH et core neutronics)
- Safety approach
- Maintenance
- Deployment studies
- Waste inventory evaluation

(CEA,EDF, CNRS, FRA, ORA)

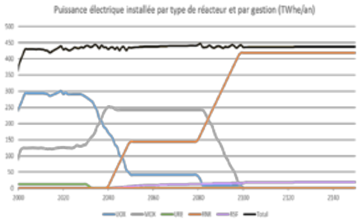


Coupled N/TH simulations

@CNRS, T. SORNAY

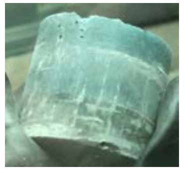
Salt compositon evolution

Scenario studies



EXPERIMENTAL PLATFORMS

Salt preparation / purification
ESOPE glovebox
Molten salt lab in JRC



Salt properties caracterisation
Am salt properties tests at MERAG (CEA Cadarache)
CNRS (Toulouse, Orsay, Orléans)

Corrosion tests in Cl salts
MESCAL Platform (CEA Saclay) and BACCHUS (Cad)
CNRS Platforms (Lille, Toulouse, Orléans)

Structural materials caracterisation
JANNuSel CEA Saclay
CNRS (Lille)

Thank you for your attention