



The hydrogen economy and the role of nuclear energy

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Outline



1. The current hydrogen industry
2. The future hydrogen industry
(the *hydrogen economy* ?)
3. Potential role of nuclear energy
 - With the current fleet
 - With new nuclear technologies
 - Examples of projects

1.

The current hydrogen industry



Uses and production methods

1. The current hydrogen industry

Introduction – a little history on hydrogen



1671

Robert Boyle
Reaction
between
iron and acid



1766-1781

Henry
Cavendish
Production of
water when
burned



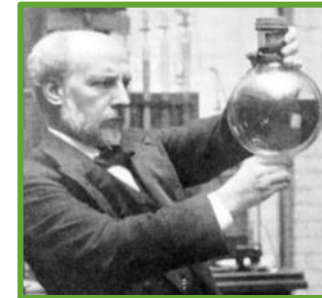
1783

Antoine
Lavoisier
calls it
« hydrogen »



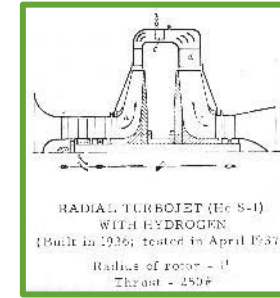
1852

First hydrogen-
lifted airship by
Henri Giffard
(1852), first
Zeppelin



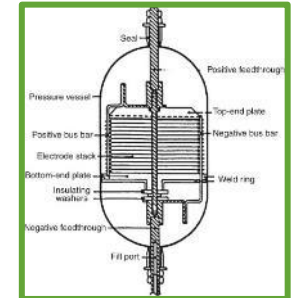
1898

Liquified by
James Dewar



1937

First hydrogen-
cooled
turbogenerator



1977

First nickel
hydrogen
battery

Hydrogen is the lightest and most abundant chemical element, but rarely found as gas on earth !

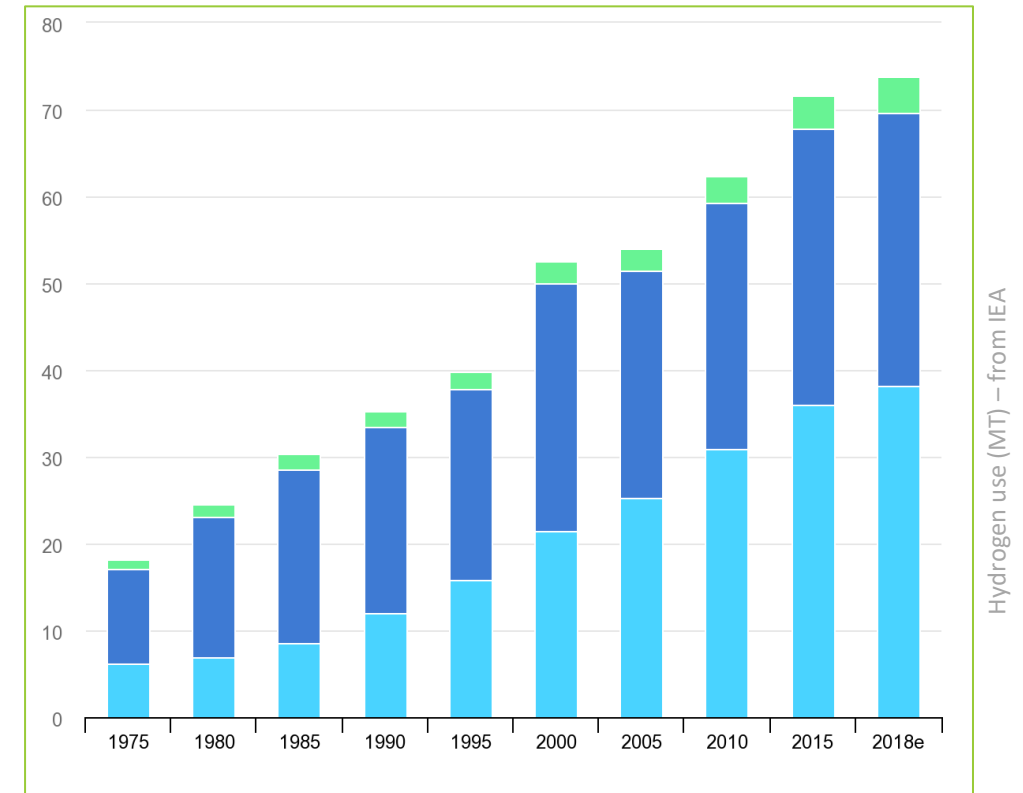
1. The current hydrogen industry

Current hydrogen uses

Global demand is rising since 1975

Main uses

- **Refineries** (hydrodesulfurization, hydrodealkylation and hydrocracking)
- **Ammonia production** (Haber-Bosch Process)
 - Fertilizers, proteins, ...
- **Others**
 - Methanol
 - Margarine
 - Semi-conductors
 - ...



Refining – Ammonia – Other

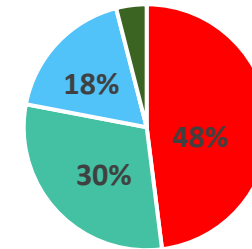
1. The current hydrogen industry

Current hydrogen production methods

- From gas through Steam Methane Reforming (**Grey hydrogen**)
 - $\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3 \text{H}_2$ (syngas production)
 - $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$ (water gas shift reaction)
- Through Steam Methane Reforming with CO_2 capture (Carbon Capture and Storage – **Blue hydrogen**)
- From coal and oil (**Brown hydrogen**)
 - Coal gasification (same principle than SMR)
 - Partial oxidation (ex. $\text{C}_{12}\text{H}_{24} + 6 \text{O}_2 \rightarrow 12 \text{CO} + 12 \text{H}_2$)
- From water through Low Temperature Electrolysis (**Green hydrogen** if electricity comes from renewables)
 - $2 \text{H}_2\text{O}(\text{l}) \rightarrow 2 \text{H}_2(\text{g}) + \text{O}_2(\text{g})$

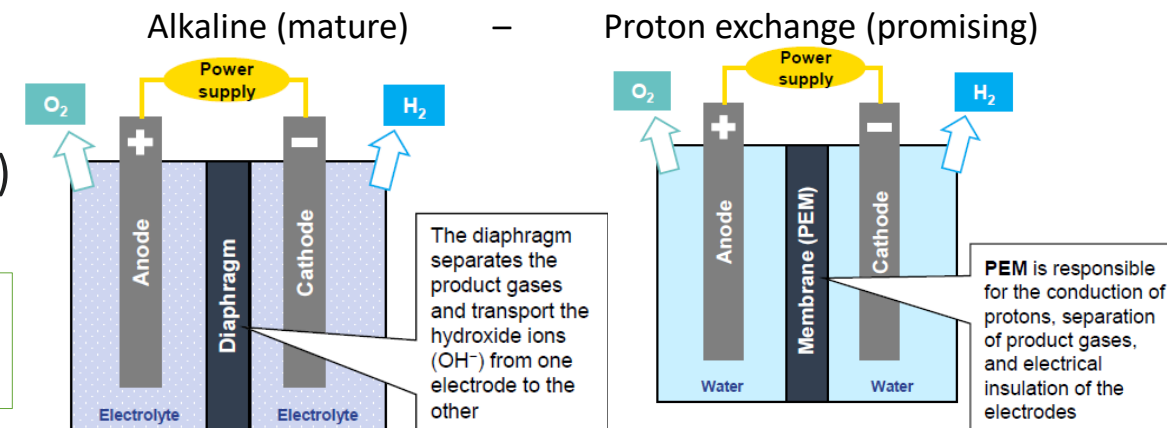
*1 kg of H_2 from methane produces > 9 kg of CO_2 !
Carbon capture is limited to 90%.*

Hydrogen Production Sources



■ Natural gas ■ Oil ■ Coal ■ Electrolysis

Source : European Mechanical Science

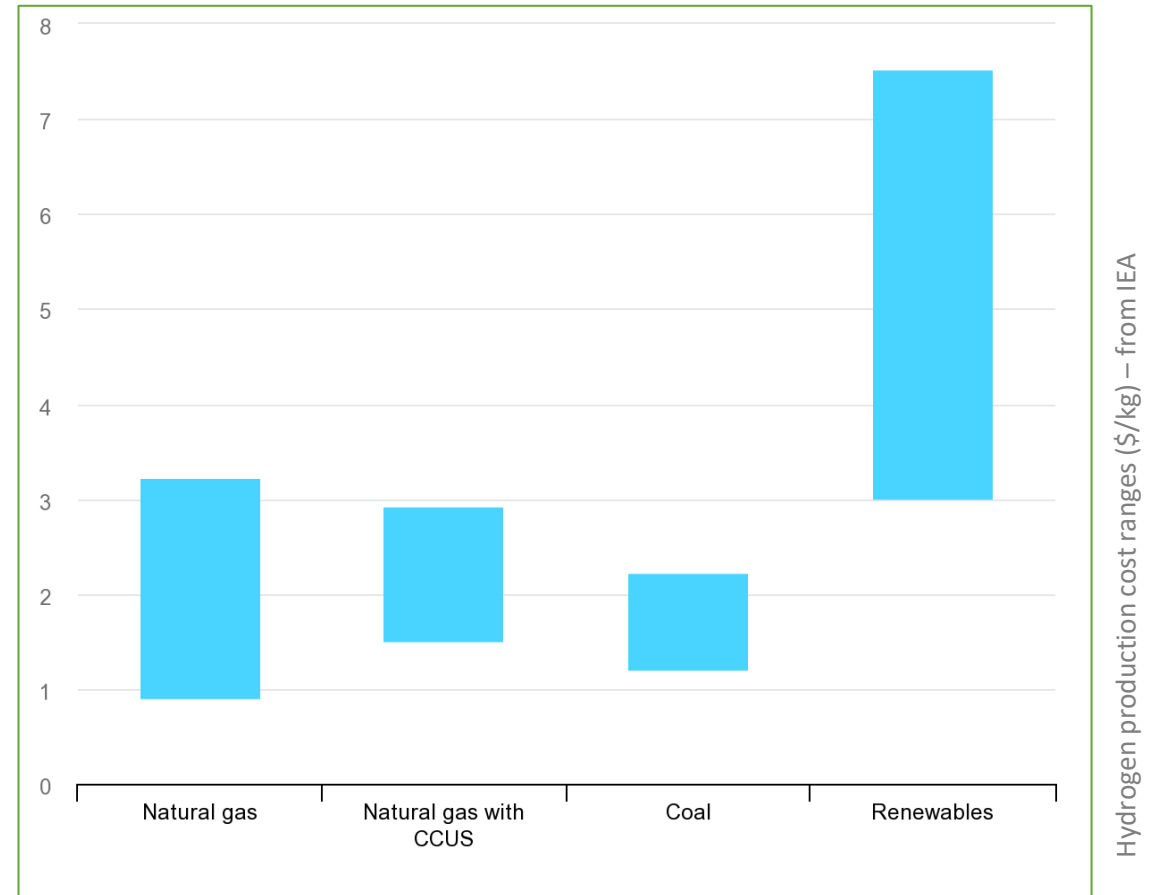


Source : ENGIE

1. The current hydrogen industry

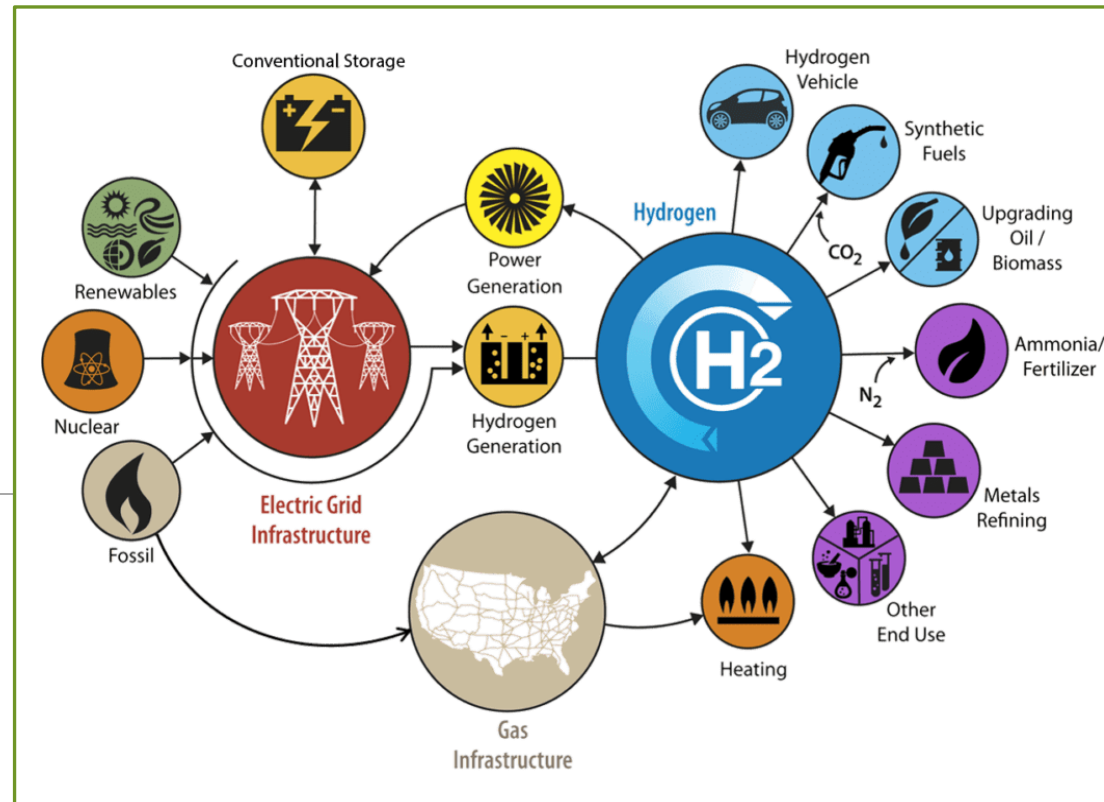
A look at the costs

- Hydrogen from fossil fuels still cheaper than from renewables, including **Blue Hydrogen**
 - Mainly driven by fuel prices
- Hydrogen from grid electricity not competitive, nor low-carbon (except in a few countries)
- **Green hydrogen** currently not competitive
 - Mainly driven by electricity prices and operating hours (load factor)
- Electrolyzer costs are expected to decrease drastically
- **Green hydrogen** costs should decrease to **2\$/kg** to be economically competitive with fossil fuels



2.

The future hydrogen industry and economy



Source : US Department of Energy

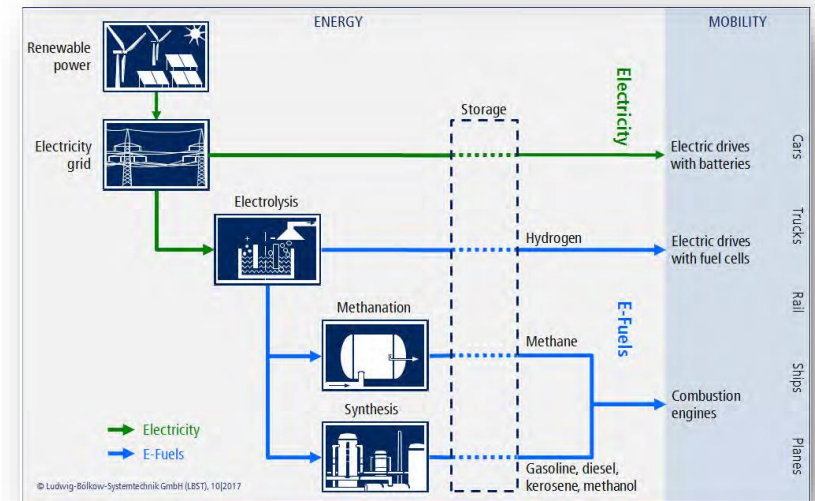
New uses and innovative production methods

2. The future hydrogen industry and economy

Potential new H₂ uses

- Hydrogen mobility (with fuel cells)
 - Competition with electric vehicles and storage issues
- Production of E-fuels (using CO₂) or ammonia to solve the storage issue (heavy transportation most promising end use)
 - Ex. Methane ($\text{CO}_2 + 4 \text{H}_2 \rightarrow \text{CH}_4 + 2 \text{H}_2\text{O}$)
 - Ammonia can be used as fuel for a combustion engine or in a fuel cell
- Heating for homes and industries
- Metal refining
 - Replacement of coke in blast furnaces or direct reduction of ore
- Flexible usage of renewable electricity (with high energy losses)
- And many other potential applications

→ **Theoretically possible to decarbonize the whole energy sector !**

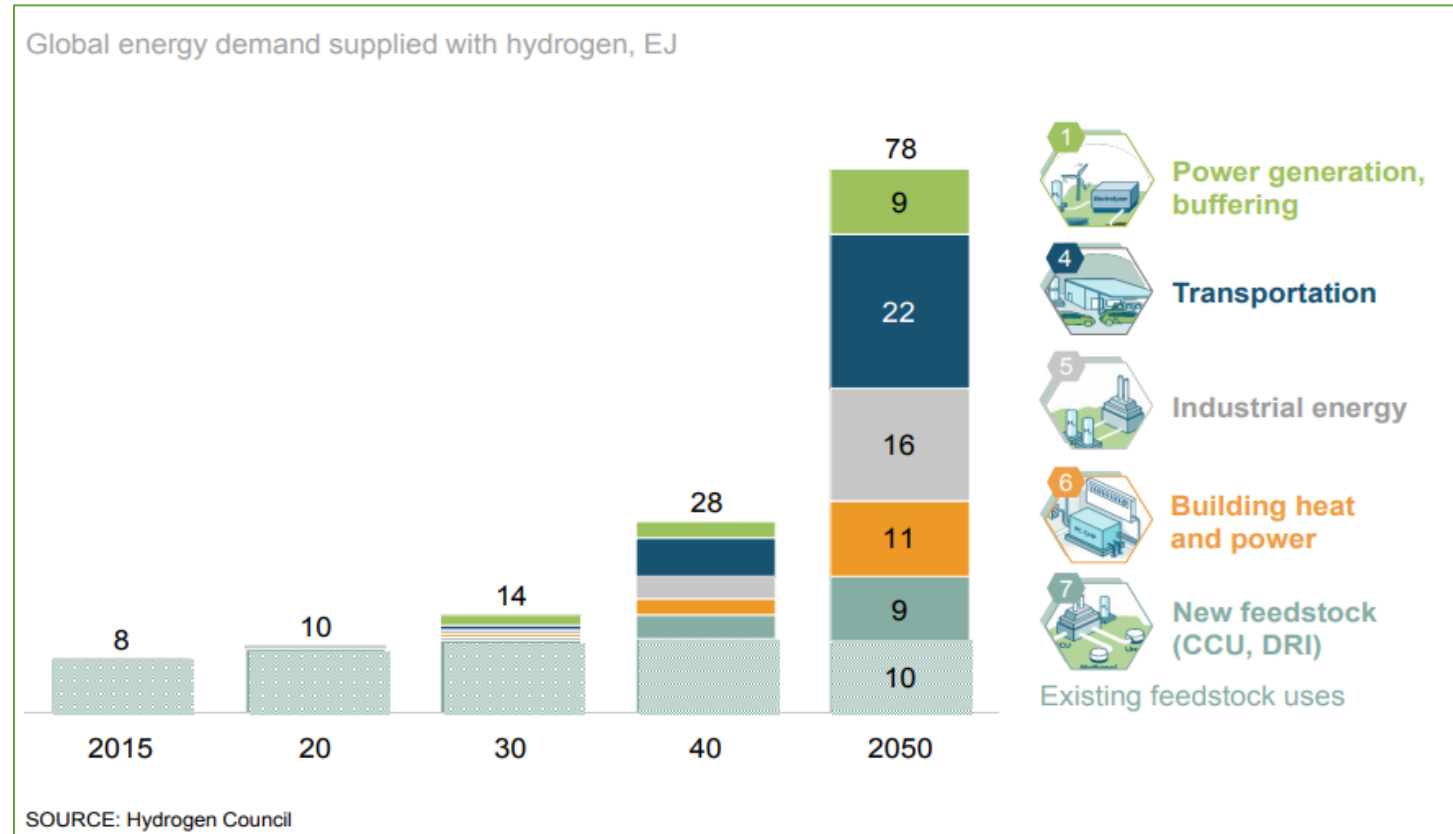


2. The future hydrogen industry and economy

Potential H₂ demand

- Current hydrogen production **80 MT/year**
- Equivalent to almost **600 GWe*** if produced by Low Temperature Electrolysis
- Demand could increase **10 fold by 2050**
- Equivalent to **6000 GWe*** !!!
- For comparison (installed capacities) :
 - Worldwide nuclear fleet = 350 GWe
 - Worldwide wind + PV fleet = 1300 GWe

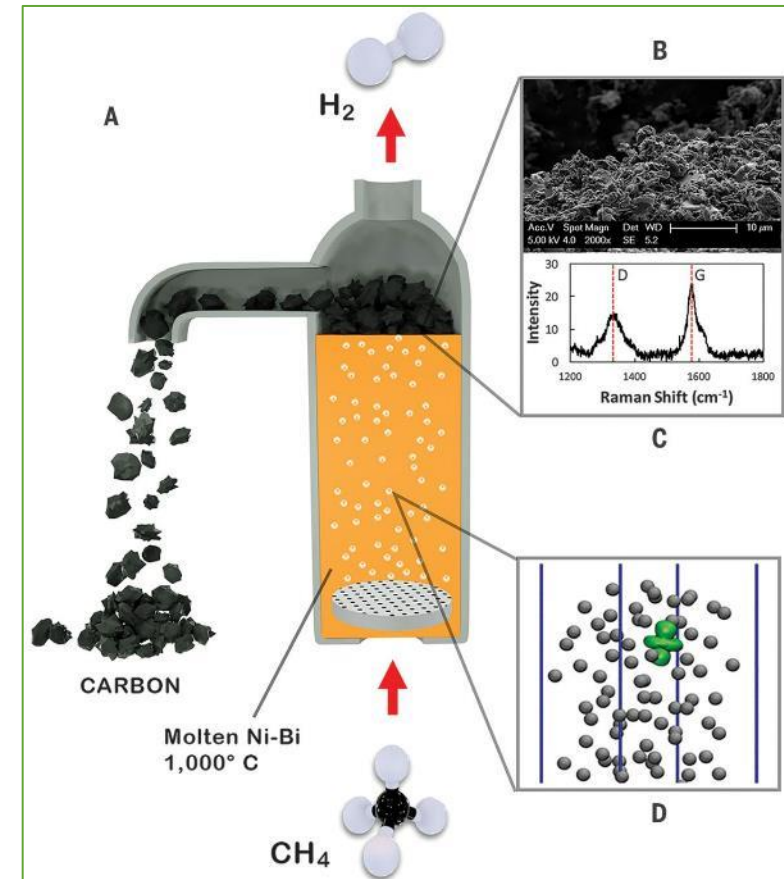
* Considering 55 kWh / kg H₂ and 85 % load factor



2. The future hydrogen industry and economy

New H₂ production methods

- The share of **green** and **blue** hydrogen will grow !
- Methane pyrolysis
 - Produces H₂ and solid carbon → no CO₂ emissions
 - Demonstration plants under development
 - Could be deployed by 2030
- Natural (native) hydrogen*
 - Continuous natural production
 - Millions of tons released each year
 - Could be a significant source in the future



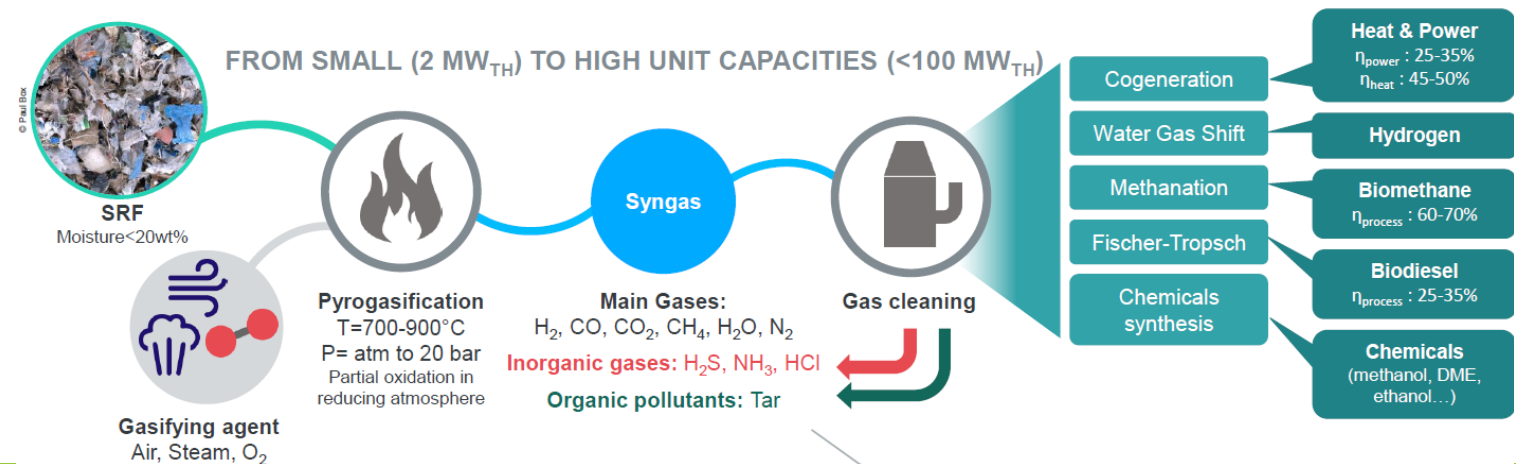
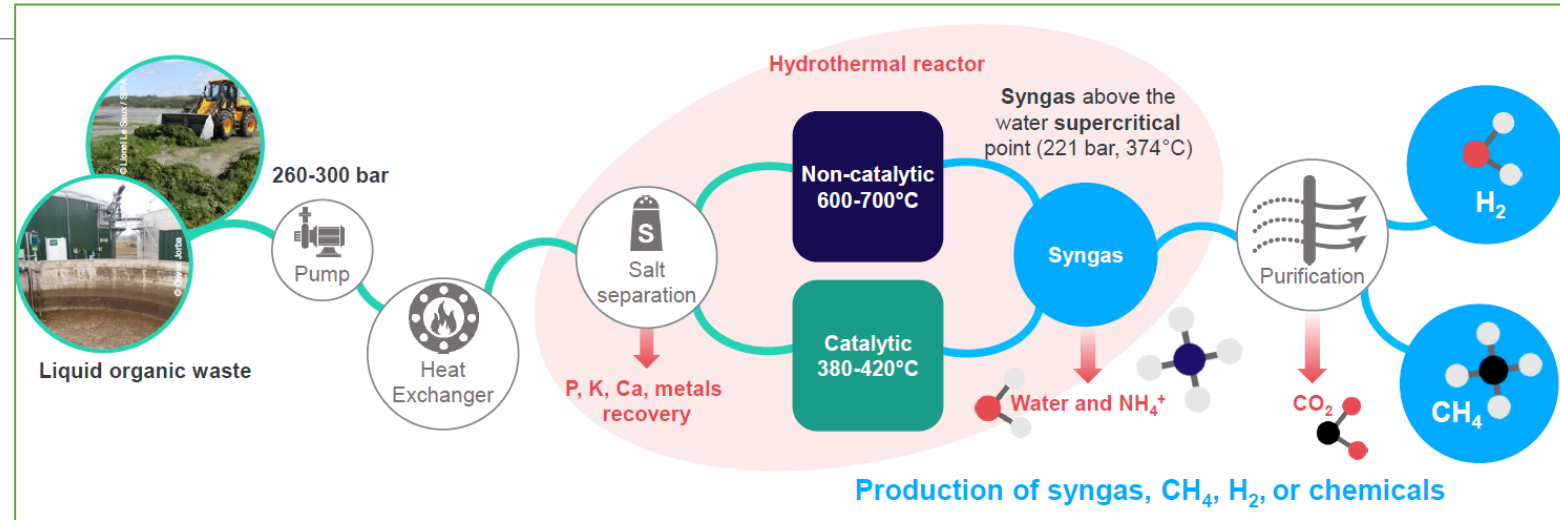
* <https://www.renewablematter.eu/articles/article/natural-hydrogen-a-geological-curiosity-or-the-primary-energy-source-for-a-low-carbon-future>

2. The future hydrogen industry and economy

New H₂ production methods

Biohydrogen using biomass, wastes

- *Hydrothermal gasification of liquid waste*
- *Pyrogasification of Solid Recovered Fuel*
- *Others (fermentation, using algae)*



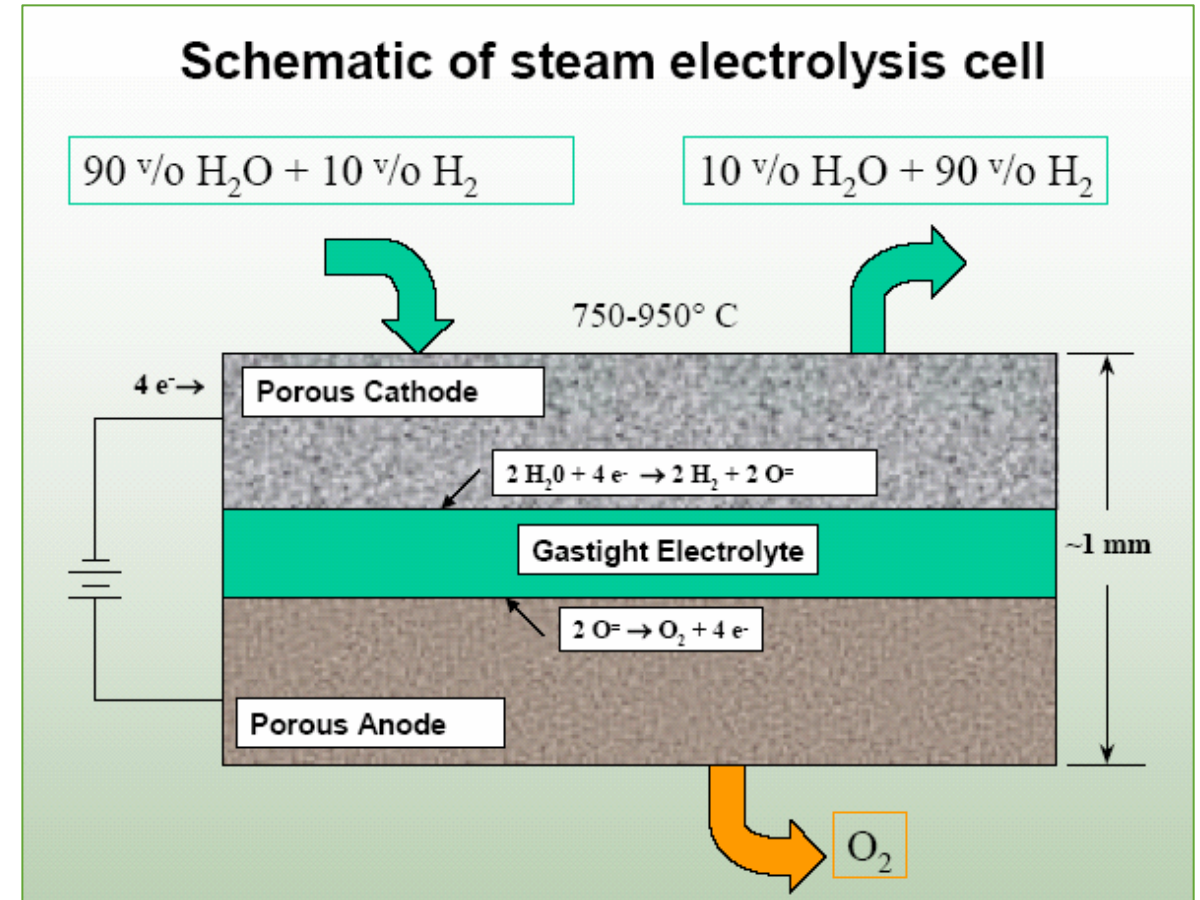
Source : ENGIE

2. The future hydrogen industry and economy

New H₂ production methods

From water

- High-temperature electrolysis
 - Uses heat (steam) and electricity
 - Greater electrical efficiency
 - Can work in both ways (electrolyzer and fuel cell)
 - Proven, but not yet mature (materials)
- Other developments (R&D stage)
 - Radiolysis
 - Thermolysis (2500°C, lower if catalysts are found)
 - Photobiological water splitting
 - Photocatalytic water splitting



2. The future hydrogen industry and economy

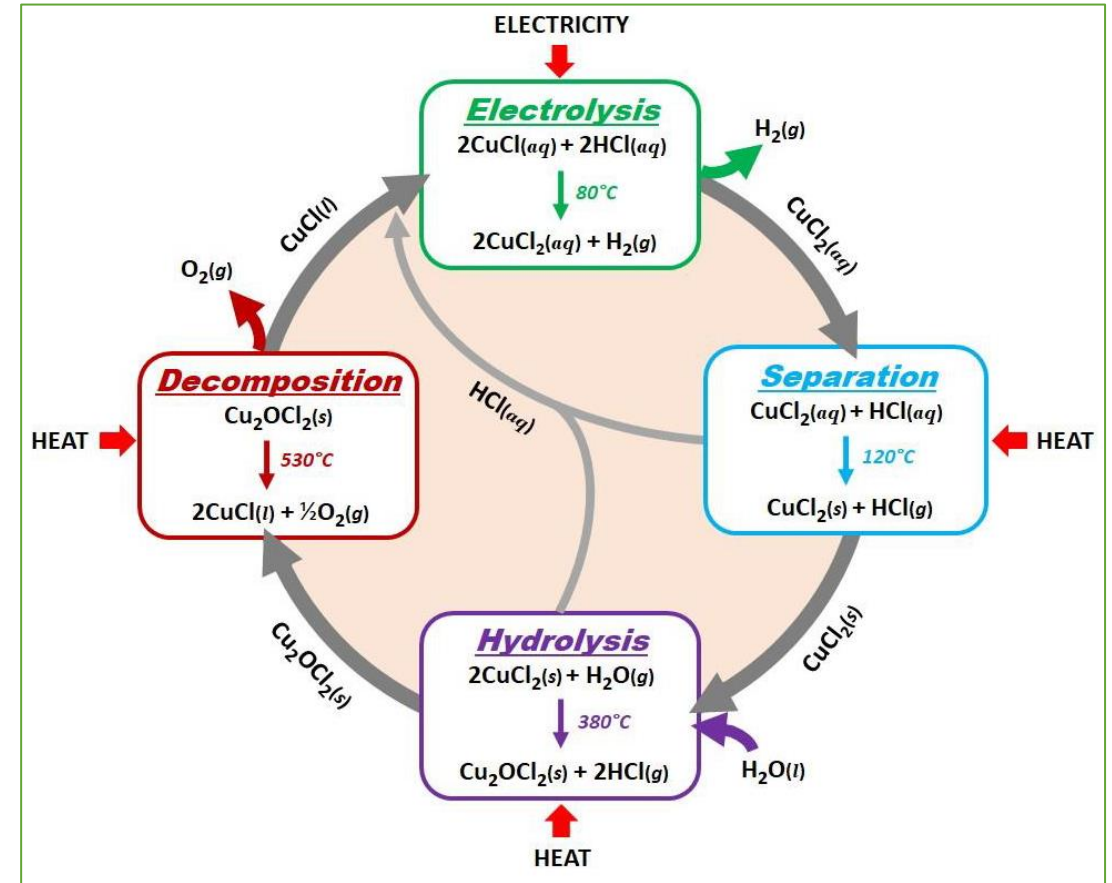
New H₂ production methods

From water

➤ Thermochemical and hybrid processes (examples)

- Sulfur-iodine cycle (see appendix)
- Hybrid sulfur cycle (see appendix)
- Hybrid copper-chlorine cycle

- Need of low-carbon heat and power
- Potential higher efficiencies than electrolysis
- Challenges for the materials



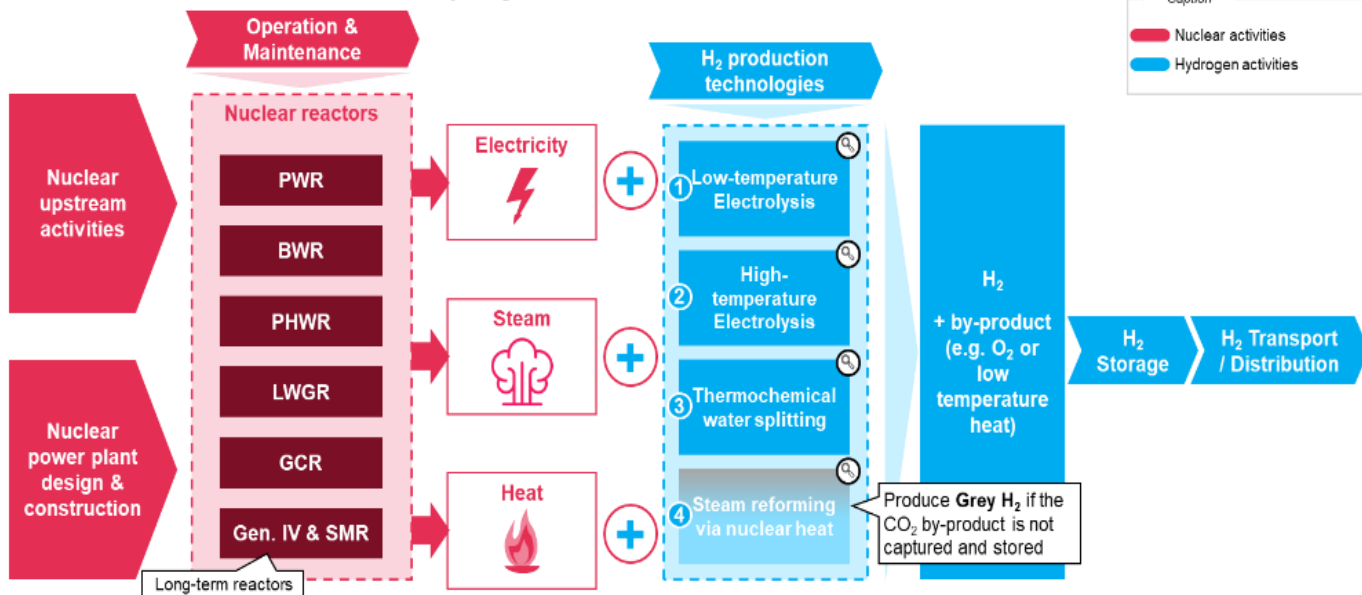
The copper-chlorine cycle
Source : Canadian Nuclear Laboratories

3.

Potential role of nuclear energy

Different nuclear technologies produce electricity, steam and heat that could be used for H₂ production

Overview of the combined nuclear and hydrogen value chain



- With the current fleet
- With new nuclear technologies
- Examples of projects

3. Potential role of nuclear energy

With the current fleet



*In France, The Netherlands and Belgium,
nuclear H₂ could be competitive with blue H₂ as from now,
according to a study by ENGIE !
Not possible in Belgium within the current framework*

- Low-temperature electrolysis is the short-term option
- 2 possibilities :
 - **Grid-supplied electrolyzers** (close to H₂ users, reduced transport costs)
 - Would produce H₂ with carbon impact proportional to that of the grid
 - Unless a traceability system is considered
 - Grid fees and taxes included in the final cost
 - **Electrolyzers on a NPP site**
 - Would provide low-carbon H₂ (0,6 kg CO₂/kg H₂*)
 - Grid fees and taxes not considered
 - Transport costs could be higher
 - Safety of the NPP has to be considered**

* Considering a value of 12 g CO₂ / kWh (IPCC value)

** See The rise of nuclear technology 2.0 - Tractebel's vision on Small Modular Reactors



3. Potential role of nuclear energy

With the current fleet

*One 1000 MWe NPP could be able to produce 135.000 T H₂ / year !
(55 kWh / kg H₂ ; load factor 85%)*

Example of France

- **National Hydrogen Strategy launched**
 - Public aid of 7B€ by 2030
 - Focusing on renewable and low carbon hydrogen produced from electrolysis
- **Grid-supplied electrolyzers**
 - Hydrogen production costs : 2,5-4,0 € / kg H₂*
 - Carbon content : 1,7 kg CO₂ / kg H₂ (with 34 g CO₂ / kWh**)
- **Electrolyzers on a NPP site**
 - Hydrogen production costs : 2,25-2,75 €/ kg H₂*

* source : Rôle de l'hydrogène dans une économie décarbonée, Académie des technologies (main assumptions : 32 €/MWh nuclear – 40-50 €/MWh market price – 500-1000 €/MW electrolyzers – 90% load factor)

** Mean value for the French electricity production in 2019 (source : RTE)



3. Potential role of nuclear energy

With the current fleet

Conclusion

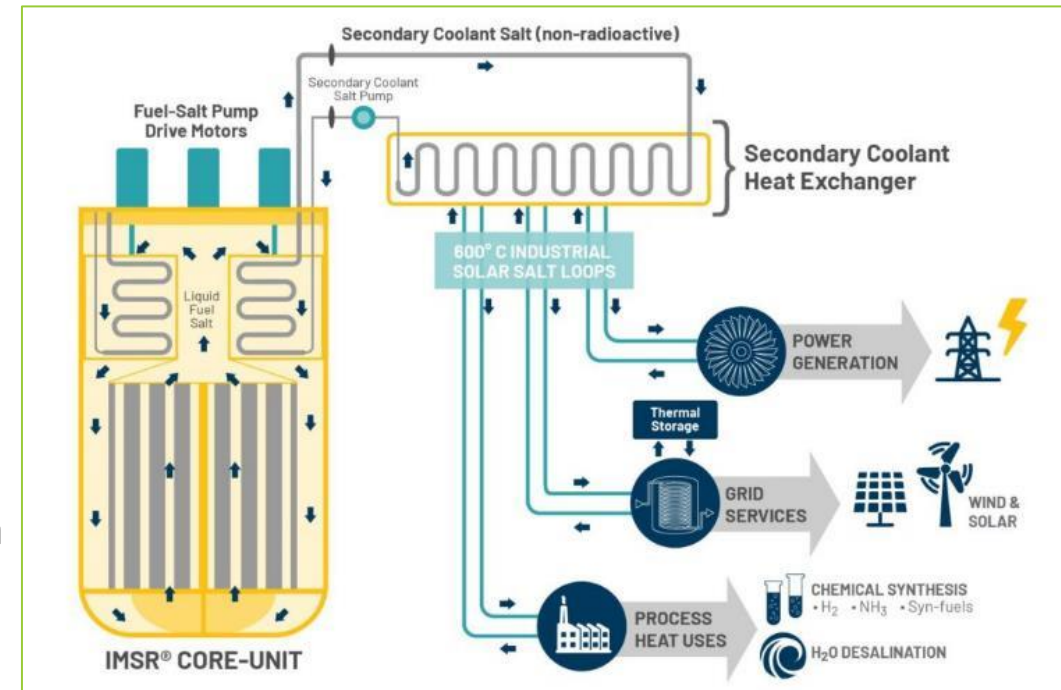
- Baseload + low carbon + affordable electricity
→ **NPPs may provide high amounts of cost-competitive hydrogen through LT electrolysis**
- **Advantages :**
 - + *Provides grid flexibility → important with an increasing share of renewables*
 - + *Capacity for massive electrolyzers production → decreasing costs and development of the H₂ economy*
 - + *Reduces dependence on imports*

3. Potential role of nuclear energy

With new nuclear technologies

- **High-Temperature Electrolysis : mid-term promising option**
 - HTE currently under development (pilot phase)
 - Could be applied with light-water reactors
 - NuScale – Small Modular Reactor designer – produced a study showing promising results*
 - Advanced reactors could probably be more efficient
- **Steam methane reforming and methane pyrolysis using nuclear heat could be options**
- **Thermochemical and hybrid cycles : long-term solution with advanced reactors ?**
 - *High temperature of advanced reactors makes it possible*
 - *With an increased safety and long-term waste solutions*
 - *But still a lot of R&D to be done (reactors and processes)*

* <https://inldigitalibrary.inl.gov/sites/sti/sti/6303857.pdf>



Terrestrial Energy's molten salt reactor would be well suited for hydrogen production

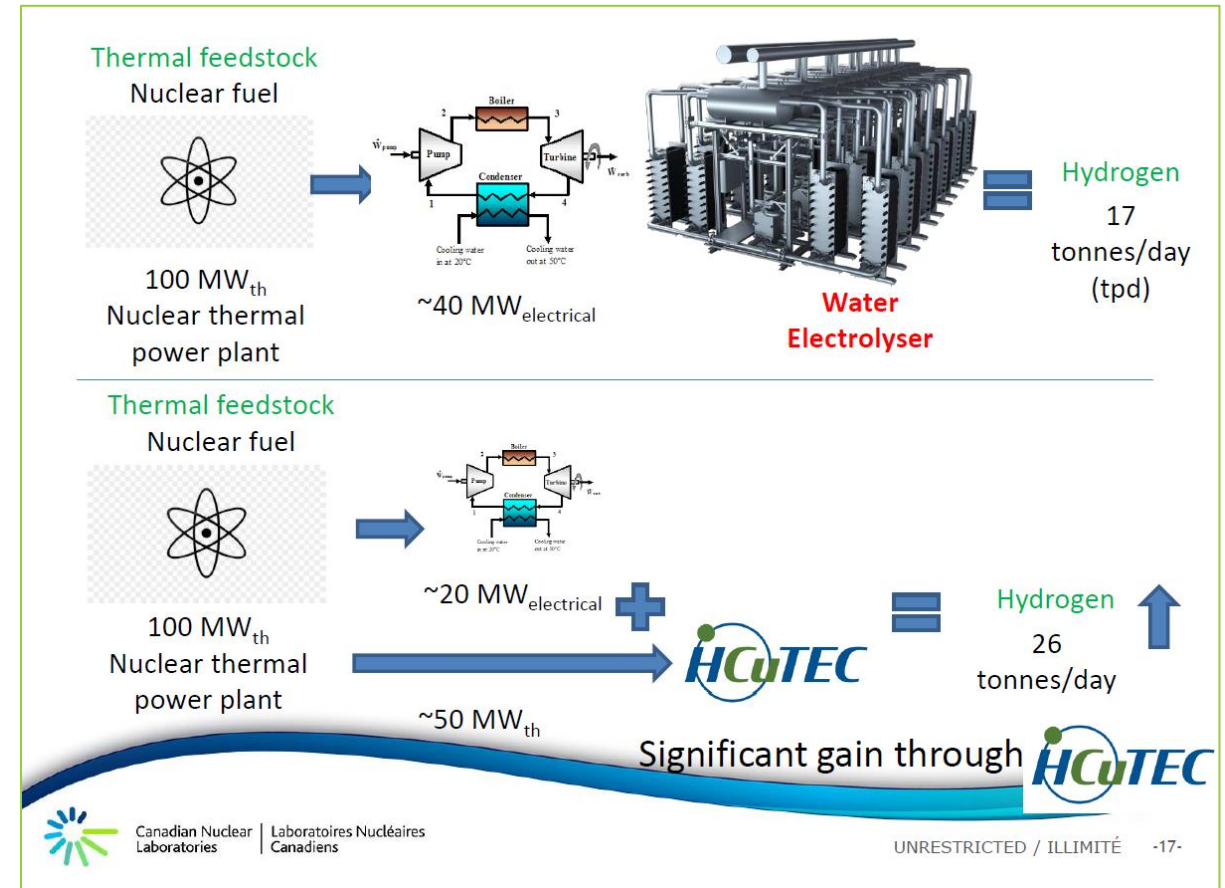
3. Potential role of nuclear energy

With new nuclear technologies

Example

Pilot plant demonstration by CNL
(at Chalk River, by 2026?)

- Using Cu-Cl cycle
- 50% gain compared to LTE



3. Potential role of nuclear energy

With new nuclear technologies

What could SMRs offer (vs. large reactors) ?

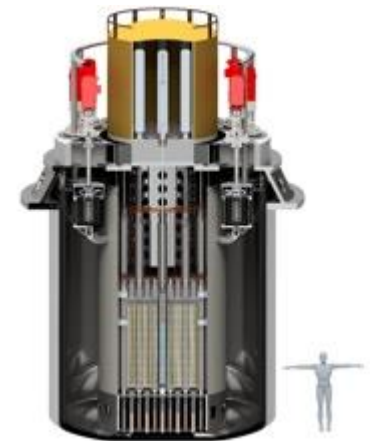
Light-water and advanced SMR's specific features

- **Reduced size + in-factory construction** : less complex, less risky → affordable for a private company
- **Flexibility and versatility** → adaptable to changing situations, to renewables-driven energy sector
- **Increased safety and lower radiological risks** → possibility to locate them close to hydrogen production sites and end-users

BWRX300 - GEH



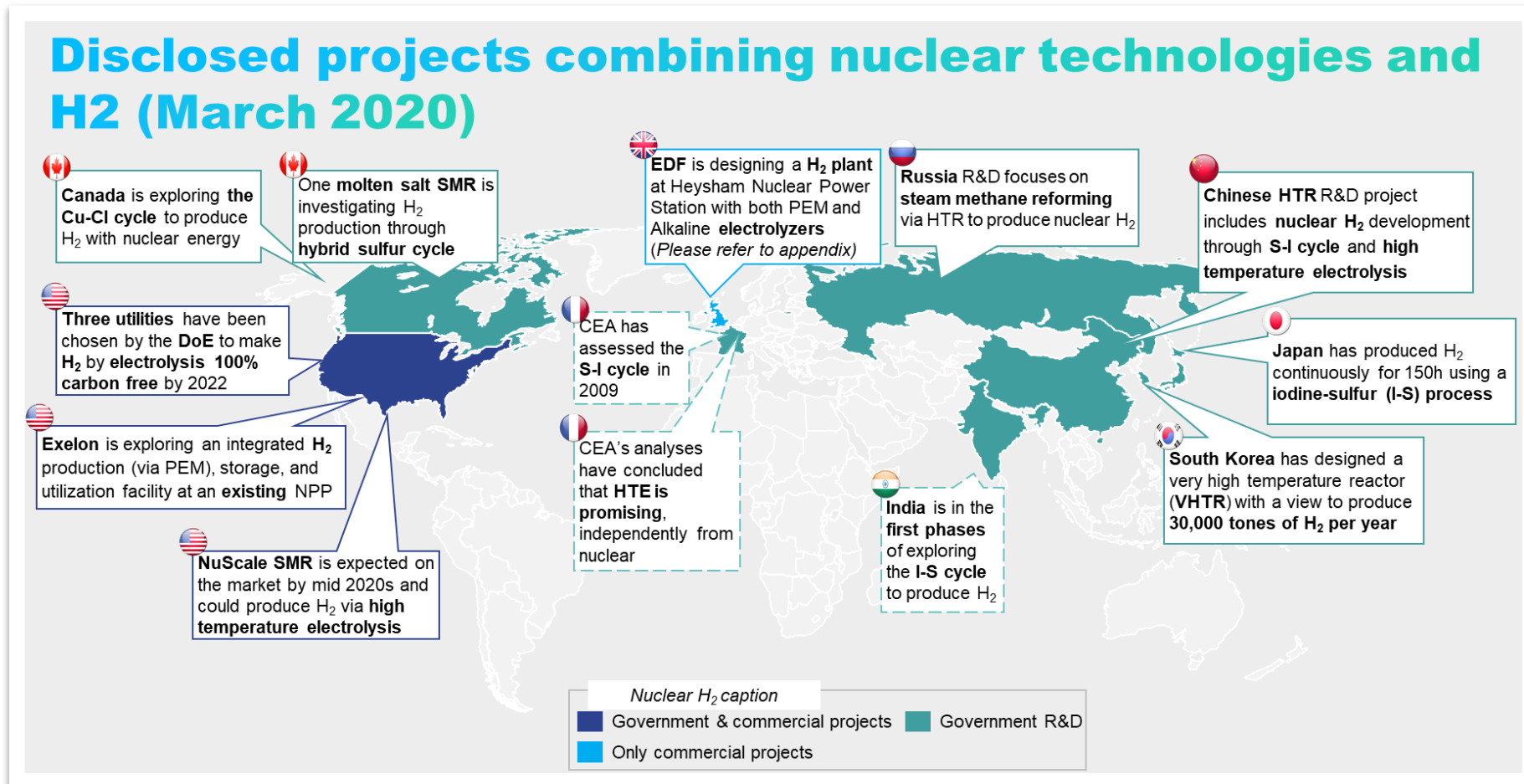
HTR-PM - INET



Sealer - LeadCold

3. Potential role of nuclear energy

Examples of projects



3. Potential role of nuclear energy

Examples of projects

EDF and CGN seek partners to develop Hydrogen and Direct Air Capture with Sizewell C

- ✓ *Hydrogen demonstrator : 2 MW (800 kg / day) – “heat assisted electrolyser” – by 2022*
- ✓ *DAC demonstrator : to remove 50 kT CO₂ by 2030 – simulating the use of 280°C steam*
- ✓ *Projects to be upgraded at the completion of Sizewell C*



NuScale + Shearwater

- ✓ *Shearwater Energy and NuScale plan UK hybrid wind-SMR energy project*
- ✓ *3 GW wind + Nuclear – including hydrogen (3000 tons/year) - Wylfa*



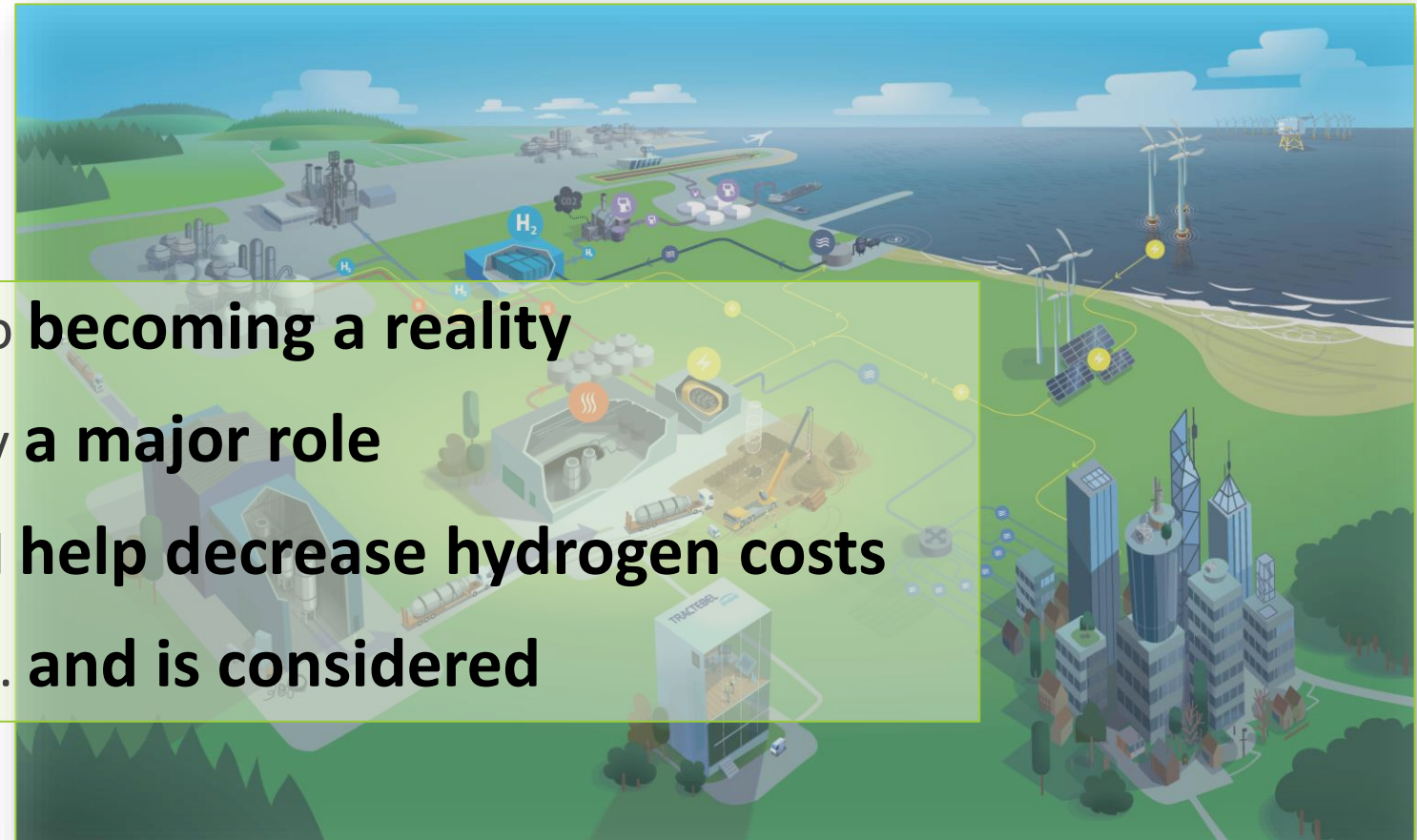
Conclusion



Conclusion

Hydrogen economy is close to **becoming a reality**
Renewables will play **a major role**
Nuclear could play a role and **help decrease hydrogen costs**
Political support is needed ... **and is considered**

<https://www.world-nuclear-news.org/Articles/EC-considers-nuclear-a-low-carbon-source-of-hydrog>



Source : Tractebel

Questions & Answers



Thank you for your attention !

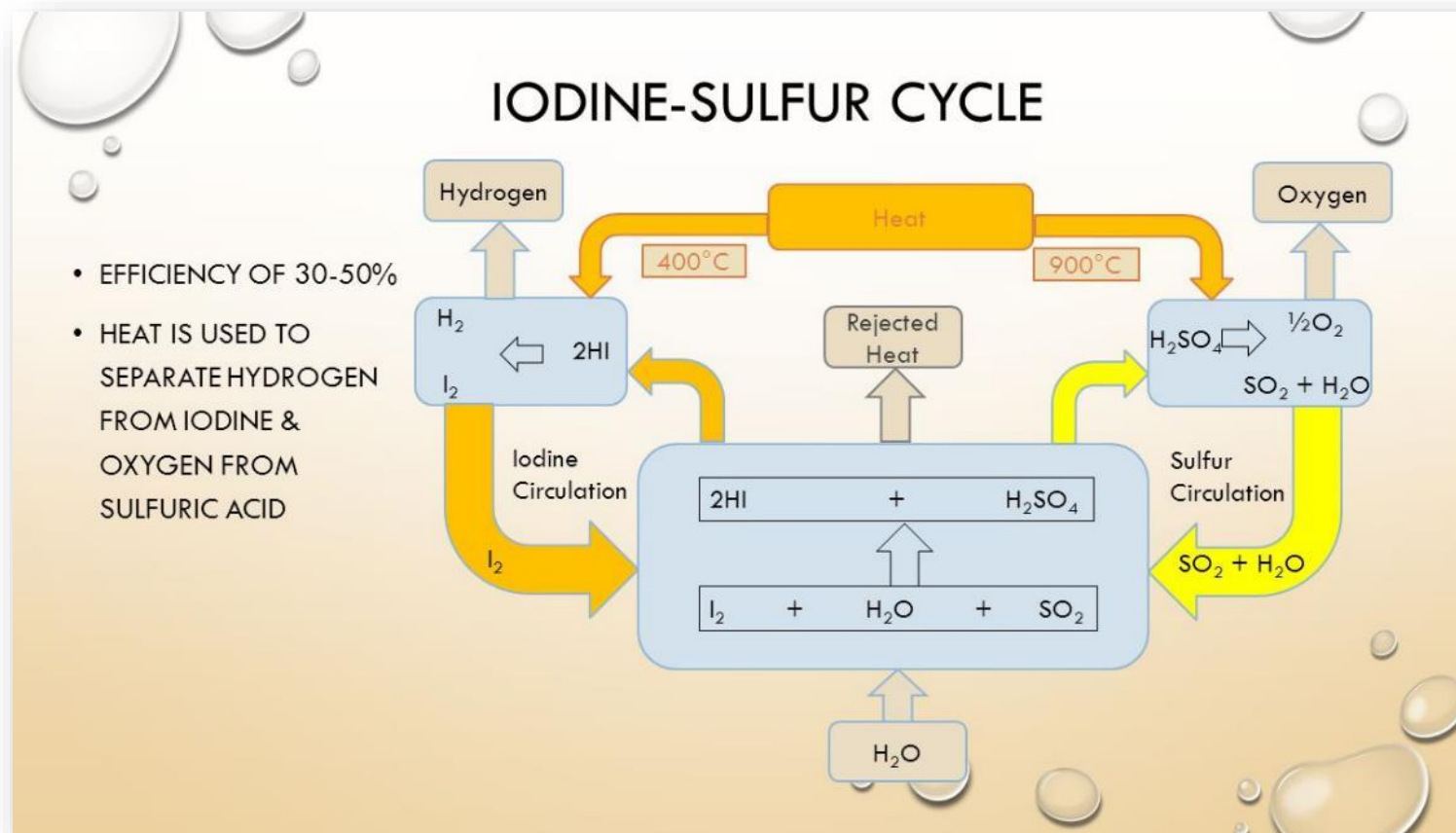
AND SPECIAL THANKS TO MY COLLEAGUES FOR THEIR SUPPORT !

TWO INTERESTING PAPERS :

[HTTPS://WWW.ENGIE.COM/EN/NEWS/REPORT-EMERGING-SUSTAINABLE-TECHNOLOGIES](https://www.engie.com/en/news/report-emerging-sustainable-technologies)

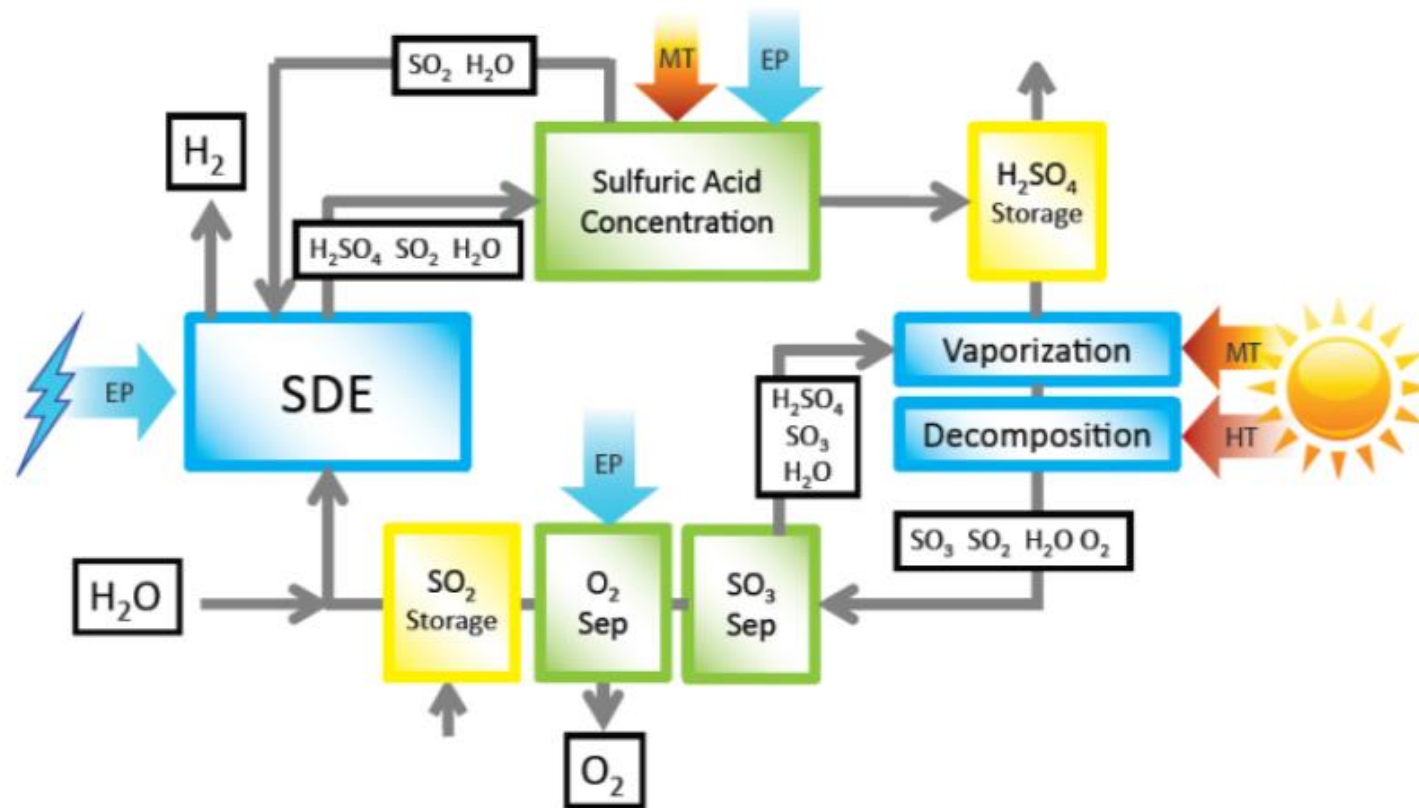
[HTTPS://TRACTEBEL-ENGIE.COM/EN/TRACTEBEL-S-VISION-ON-SMALL-MODULAR-REACTORS](https://tractebel-engie.com/en/tractebel-s-vision-on-small-modular-reactors)

Appendix Sulfur-iodine cycle (Westinghouse)



Japan has produced H_2 continuously during 150 h with the I-S cycle. Project linked with their HTTR reactor.

Appendix Sulfur Hybrid Cycle



Source : ENEA