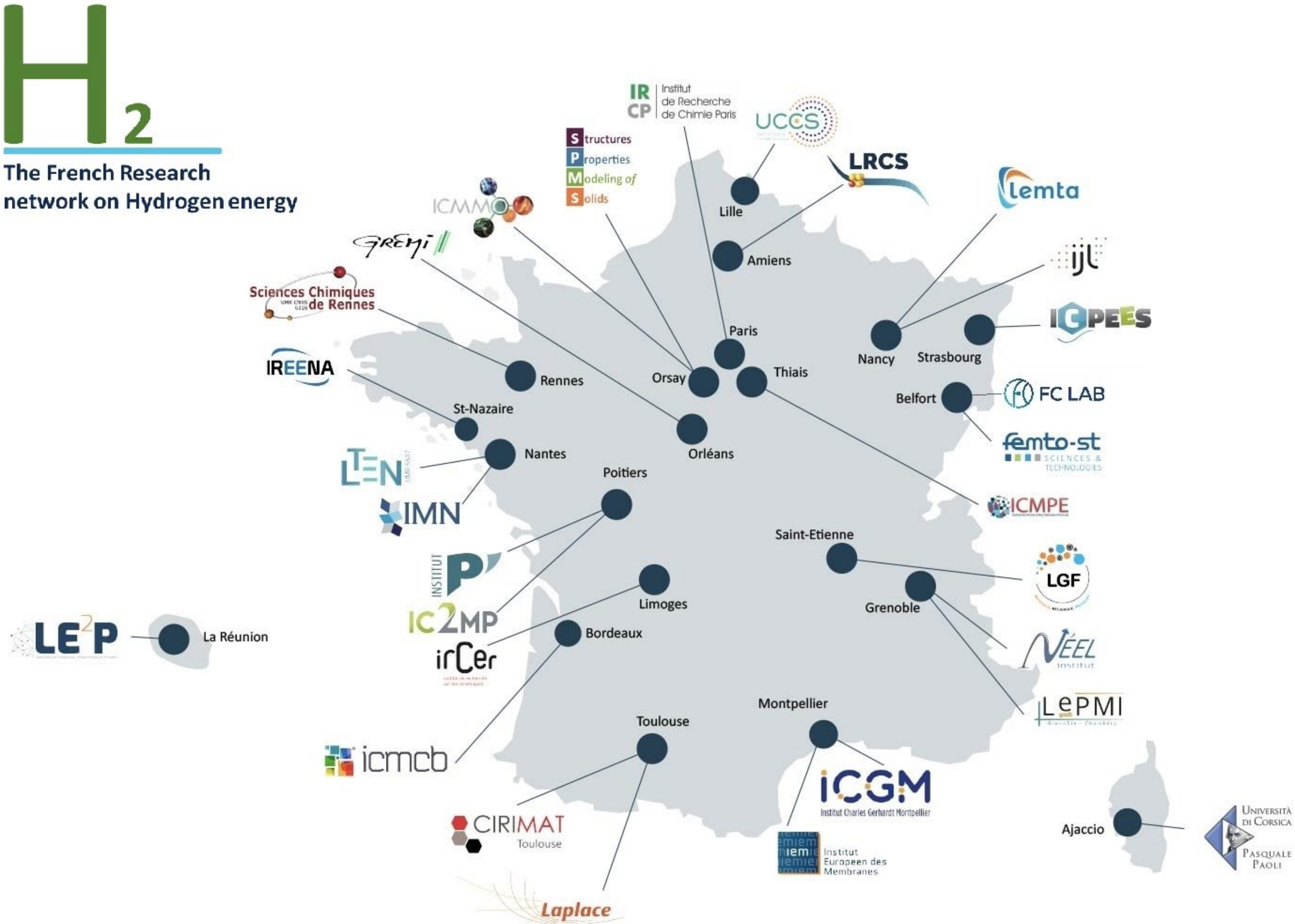
Hydrogen Conference

Cityjoule 2023

Prof. Bruno AUVITY
Laboratoire de Thermique et Energie de Nantes (CNRS-UMR 6607)
Polytech Nantes – The graduate School of Engineering of Nantes University

Member of the French Hydrogen Research Netwok – FRH2

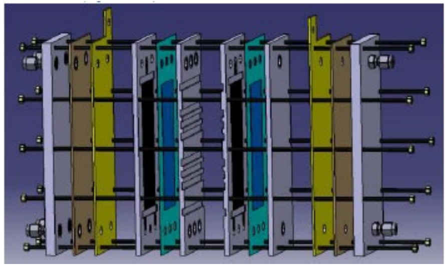


Who am I?

From the system

-Development of fuel cell power train
Under energy constraint : 2 Prototype cars Cityjoule/Polyjoule
Under technico-economic constraint: Naval propulsion + H_2 UAV

-Design of PEMFC stack
Specific design for the Shell Eco Marathon prototype cars



-Diagnostic of PEMFC stack
Based on multiphysics modelling

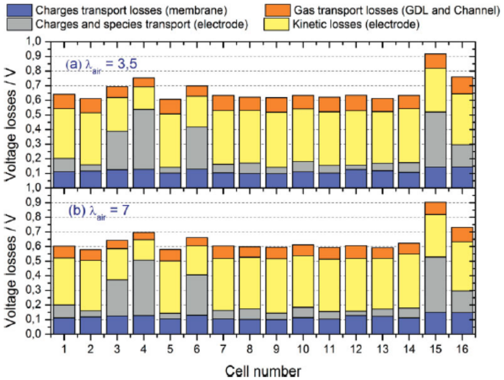
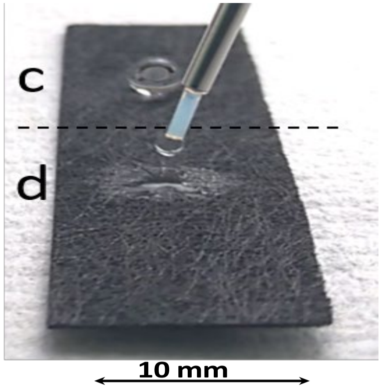
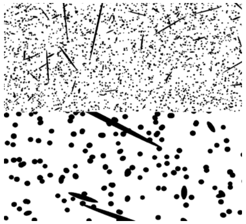


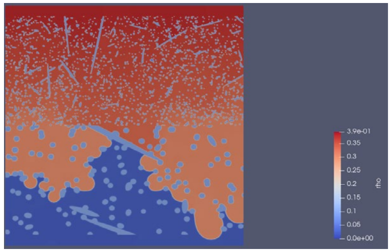
Fig. 12 Repartition of voltage losses in the 16 cells of the stack for λ_{air} = 3.5 and λ_{air} = 7 (measure m0).



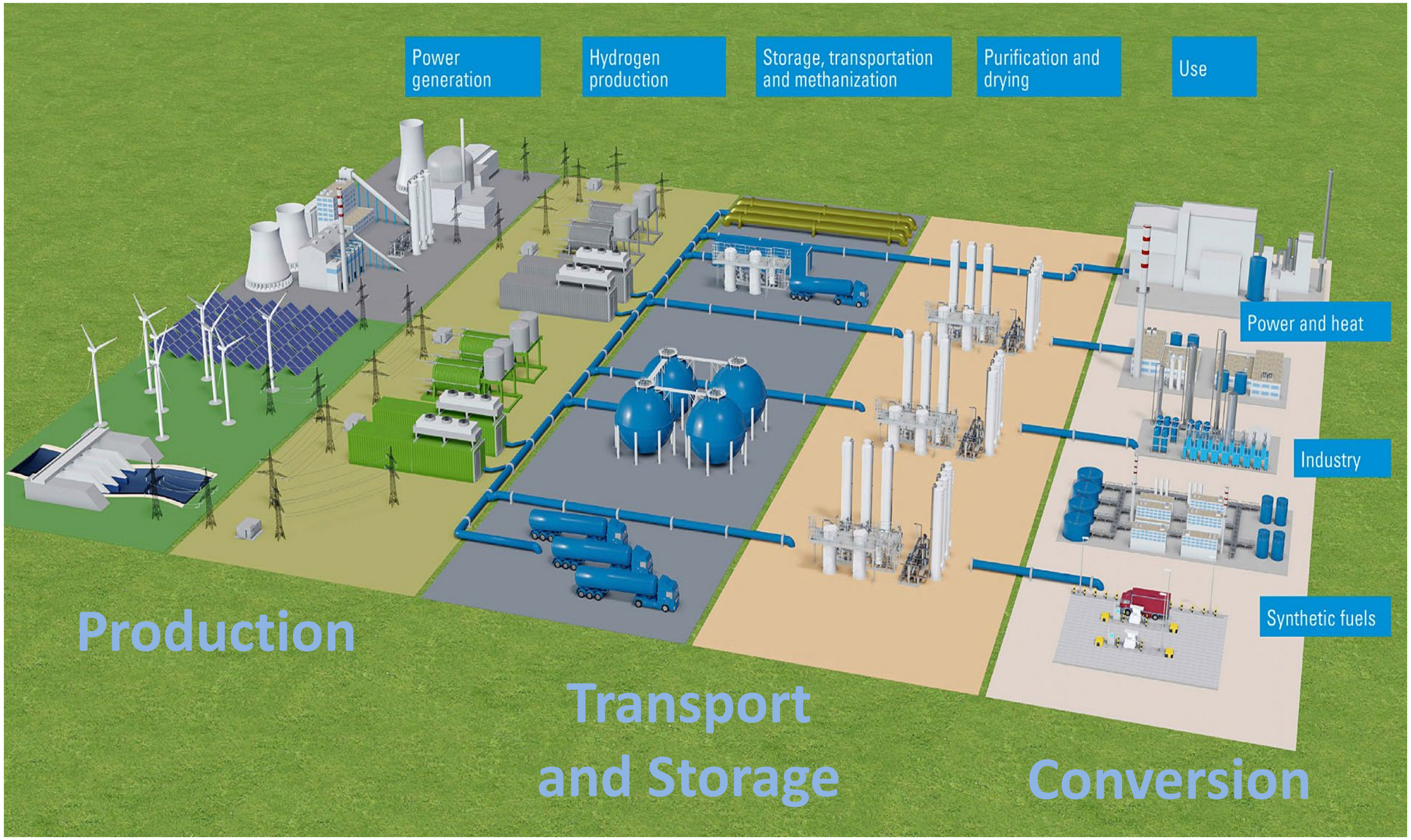
To the component

- Water management in PEMFC
Dynamic liquid water transport in GDL
Engineered Gas Diffusion Layers structure





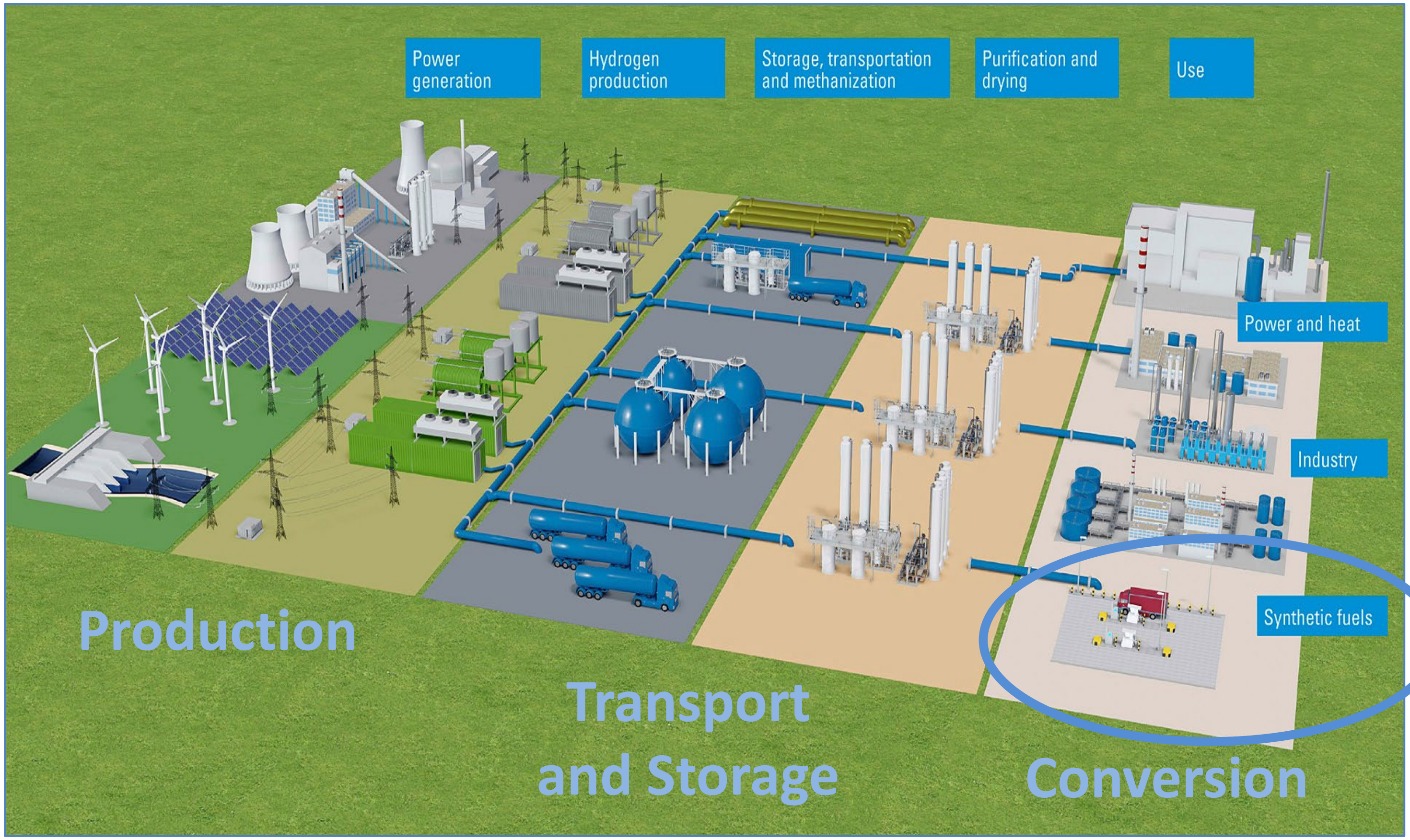
As H_2 is not naturally available, it has to be produced!



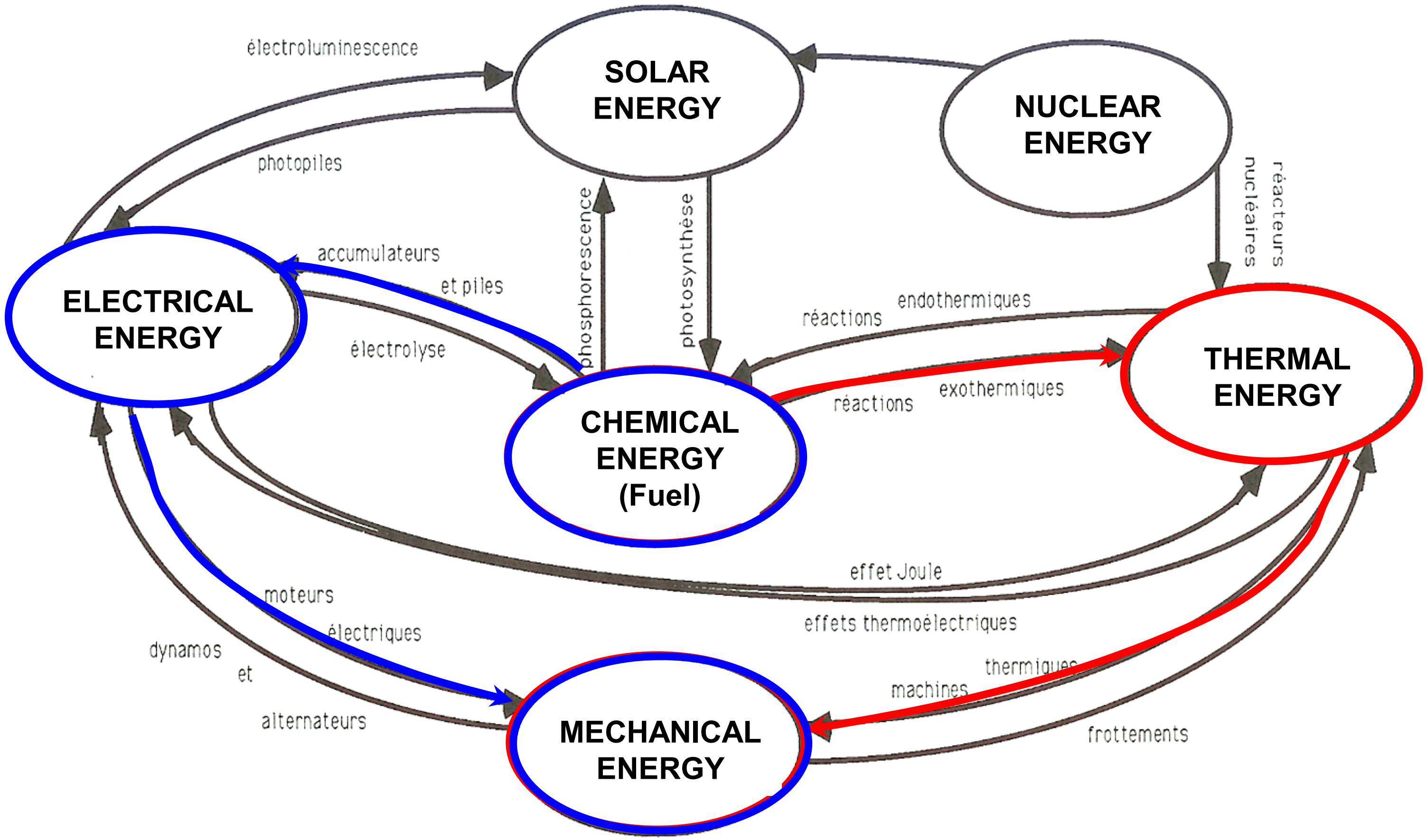
References used in the talk

- exchanges within the FRH2
- reports from Int. Energy Agency (IEA) : *World Energy Outlook 2021, Global Hydrogen Review 2021, The future of Hydrogen 2020*.

H_2 as fuel for mobility



H2 conversion for mobility

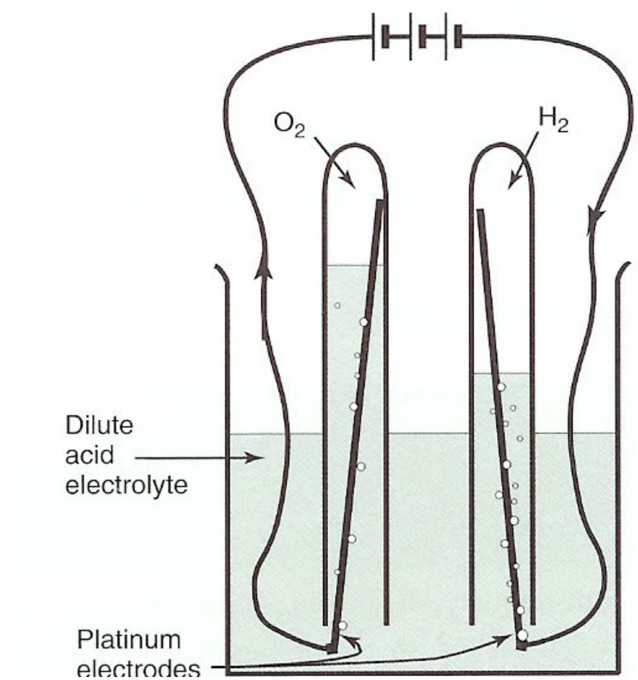


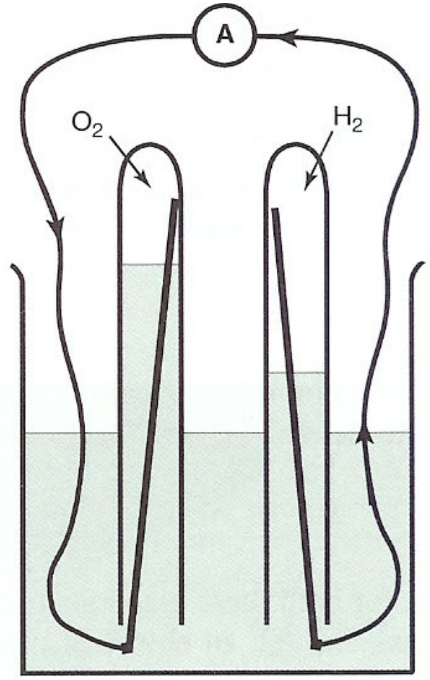
The different forms of energy and associated conversion processes

Energy flow for a conventionnal Internal Combustion Engine.
Overall Efficiency : 70% x 50% ~ 35%

Energy flow for a fuel cell power train
Overall efficiency : 60% x 85% ~ 50%

Basic principles of a fuel cell





Water electrolysis :

Anode : $2H^+ + 2e^- \longrightarrow H_2$

Cathode : $H_2O \longrightarrow \frac{1}{2}\, O_2 + 2H^+ + 2e^-$

$$H_2O \longrightarrow H_2 + \frac{1}{2}\, O_2$$

Inverse elecrolysis (fuel cell):

Anode : $H_2 \longrightarrow 2H^+ + 2e^-$

Cathode : $\frac{1}{2}\, O_2 + 2H^+ + 2e^- \longrightarrow H_2O$

$$H_2 + \frac{1}{2}\, O_2 \longrightarrow H_2O$$

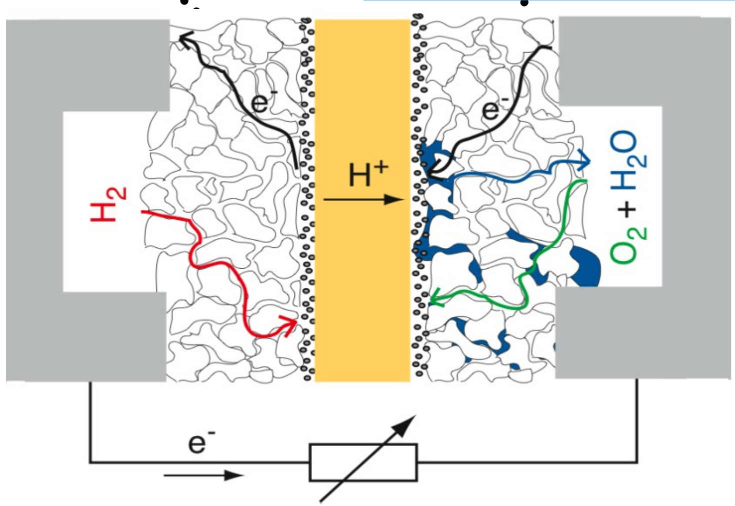
IMPORTANTE LIMITS : weak produced current because of :

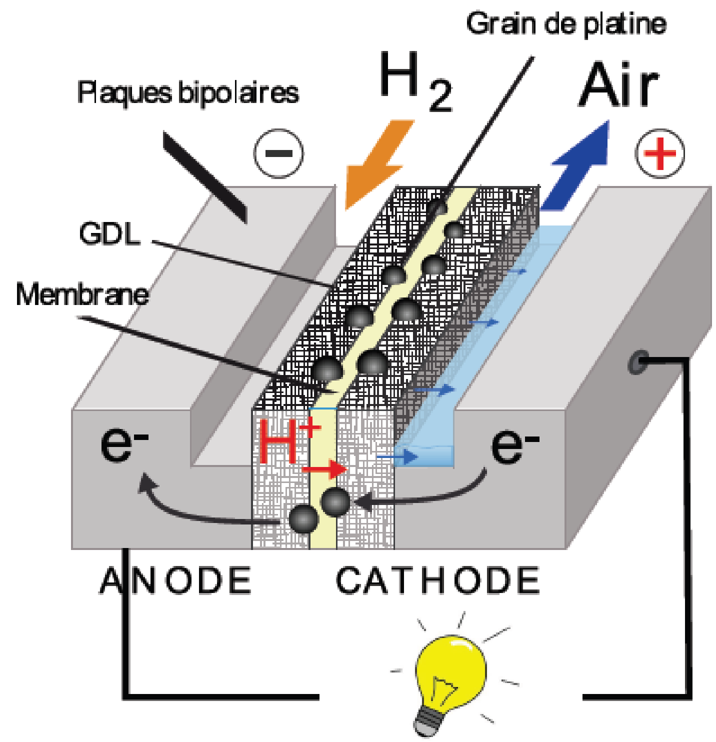
- the delicate triple contact between gas, solide and electrolyte
- the distance between the two electrodes

Scheme of a Polymer Exchange Membrane Fuel cell

$$H_2 \rightarrow 2H^+ + 2e^-$$

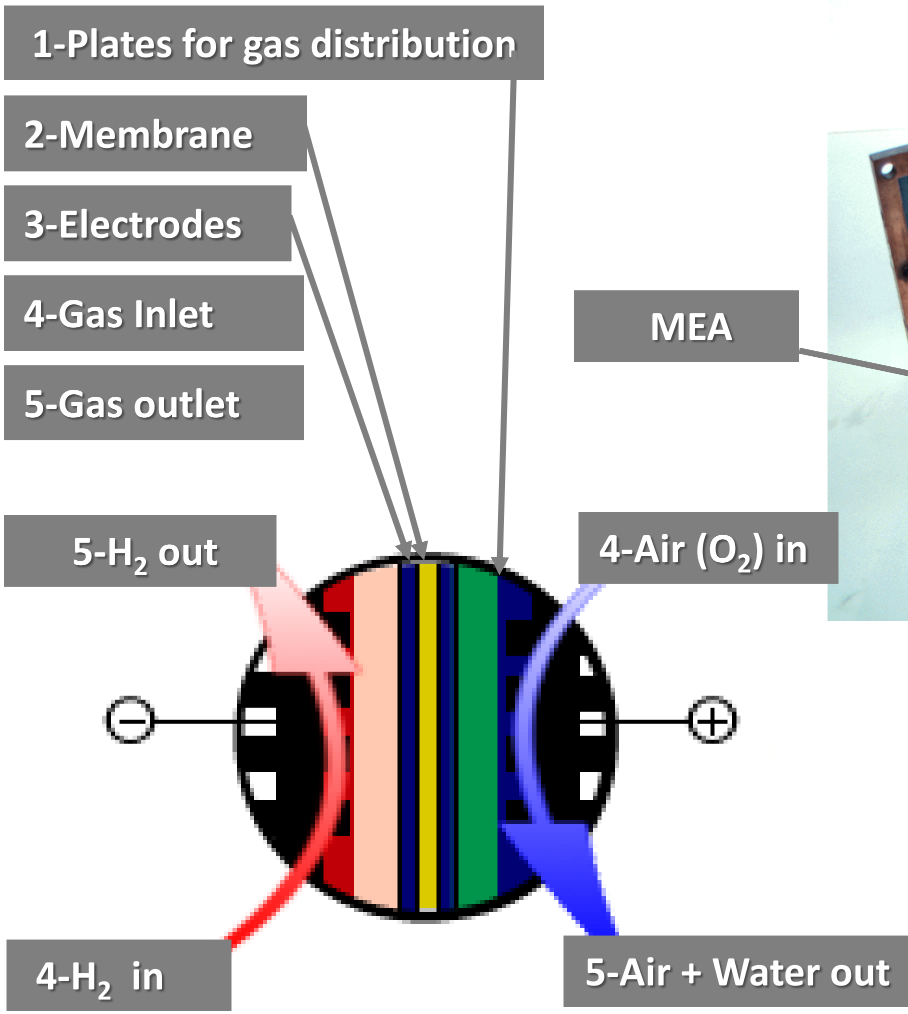
$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

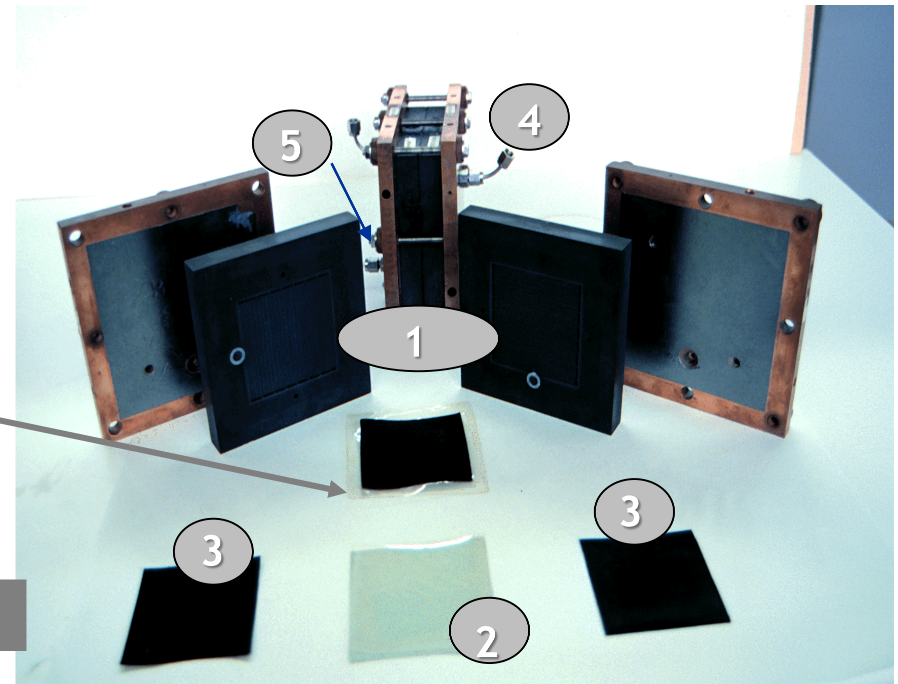




One example of PEM Fuel Cell

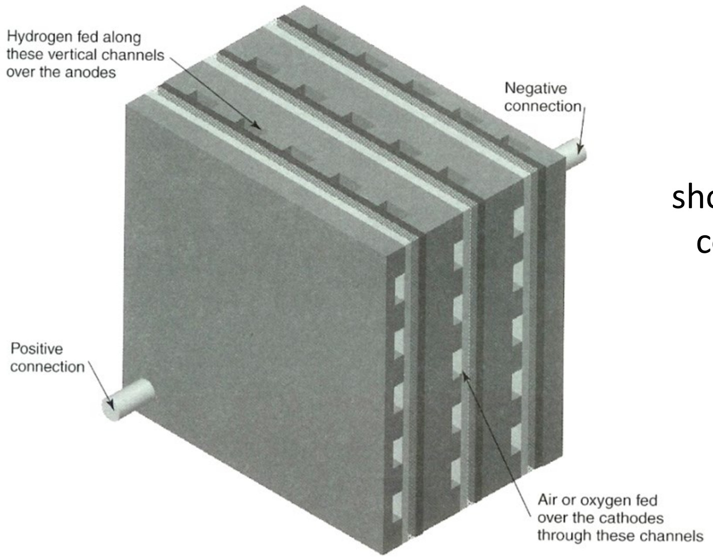
Mono cellule





The different components of a PEM Fuel Cell
(Photo CNR-ITAE, Italie)

STACKING OF CELLS – "STACK"



Stack of 3 cells
showing how bipolar plates connect cells electrically

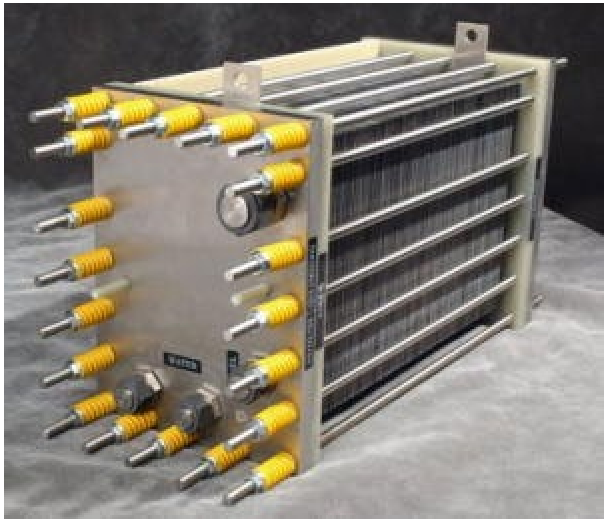
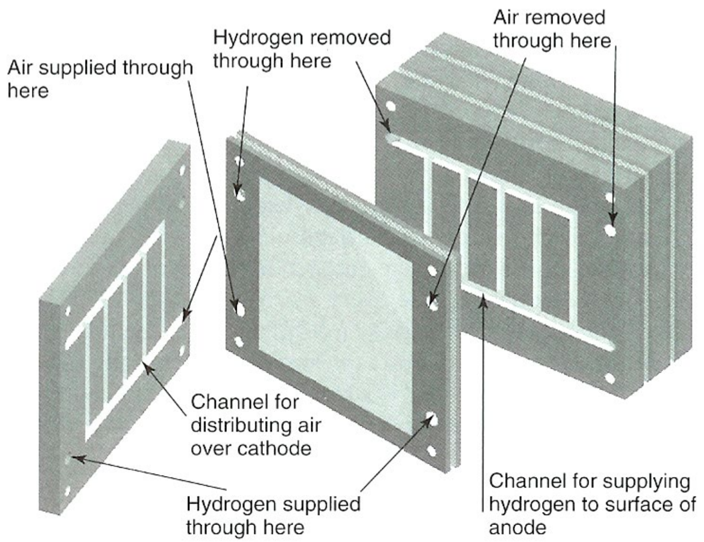
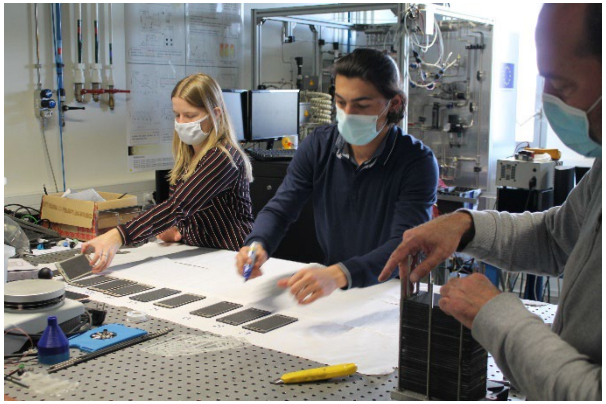


Photo by Warren Gretz courtesy of
[US Department of Energy/National Renewable Energy Laboratory (DOE/NREL)](#).

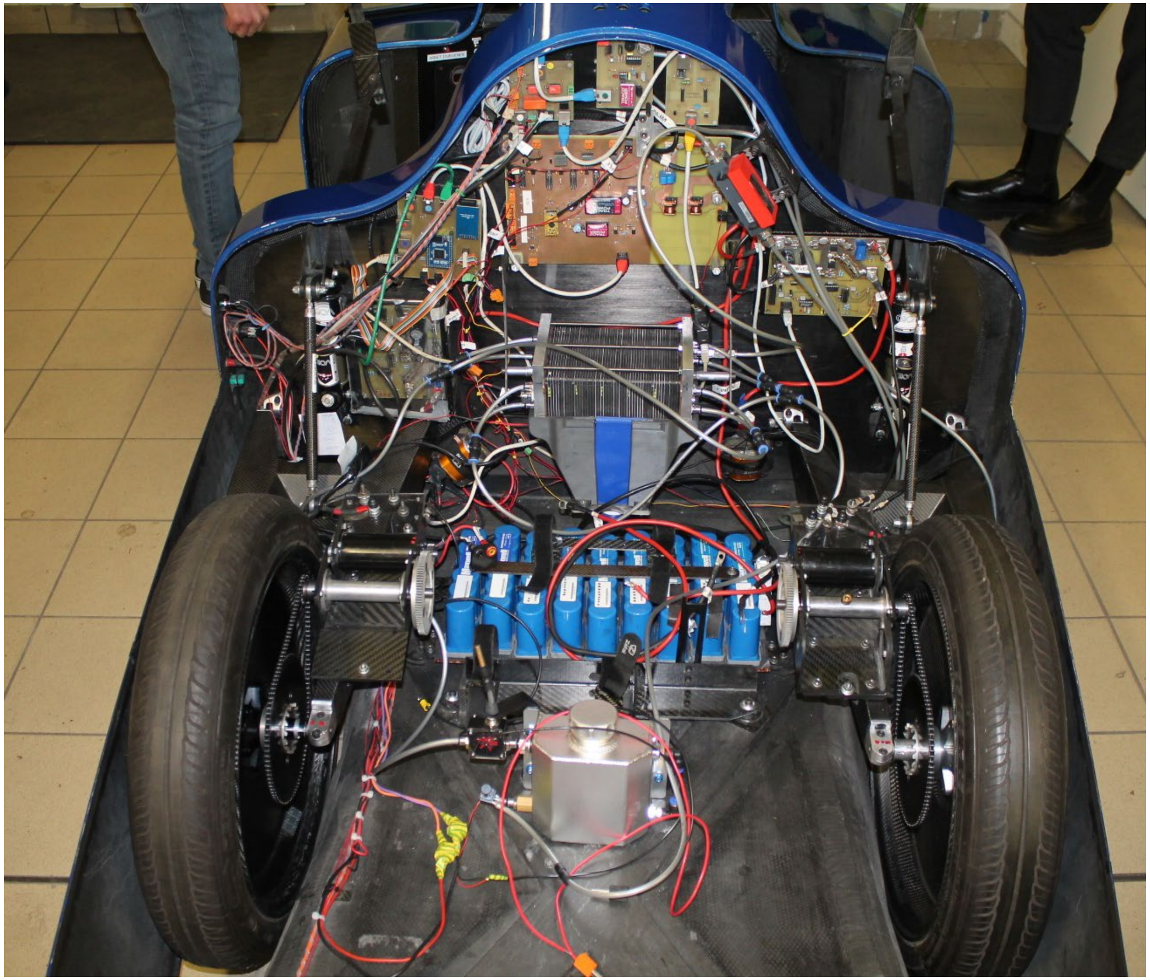


Exploded view of a stack
showing how bipolar plates distribute gas to the electrodes

FUEL CELL STACK IN A POWER TRAIN



Stack preparation by the Polyjoule team



Overall vue of the power train

First commercialisations :

Toyota Miraï since 2015

Hyundai Ix35 since 2016
(French cab company in Paris HYPE)

Some orders of magnitude

Lower Heating Value of H2 : 120 MJ/kg (to be compared to 50 MJ/kg for Natural Gas CH_4)
Or 33,3 kWh/kg
Or 3 kWh/Nm^3

To have the **same energy content as in 1 liter of gasoline** (about 10 kWh)

- With gazeous H2 at **atmospheric conditions** : **3 m^3**

- With gazeous H2 at **350 bars : 10 liters** **BUT** …. a heavy tank is needed (around 50 g H2/ kg tank)
  THEN : **7 kg for the tank**

- With **liqueous H2 (at 20 K!!)** : around **4,5 liters** **BUT** …. weight and insulation of the tank!!

Estimation of the power train weight for car
Comparison of Electric, Internal Combustion Engine and Fuel Cell Engine

Target: drive 400 kms with a car having a power of 60 kW

Internal Combustion Engine:
Data : consumption 5l/100 kms ; ICE efficiency: 35%; LHV gasoline: 42 MJ/kg;
Gasoline density: 0,72 kg/l; power density for ICE : 300 W/kg

Total weight: around **250 kg** (engine **200kg + 15 kg for gasoline** + **10 kg** for the tank)

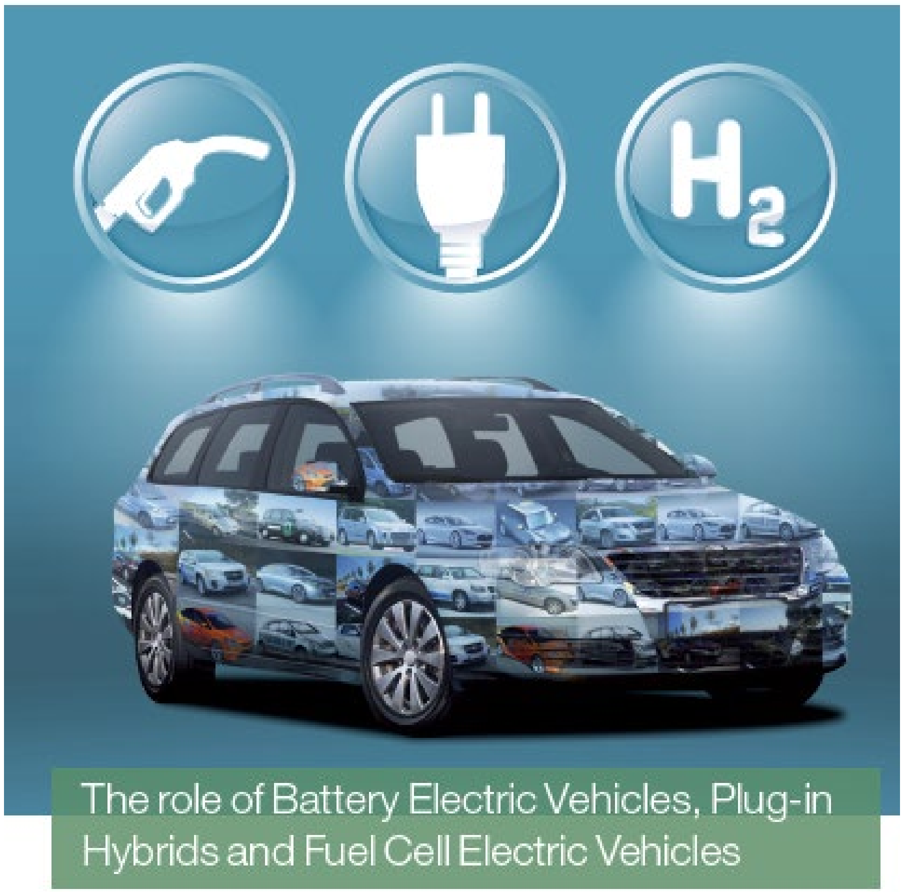
Electric vehicule :
Data : lead-acid Battery : 30 Wh/kg
Li-Ion Battery : 100 Wh/kg and 200 W/kg; Electrical motor efficiency : 90%; Electricc motor weight : 200 kg

Total weight: **2, 2 tons** (lead-acid battery); **800 kg** (Li-Ion)

Full H2 vehicule :
Data : H2 LHV: 120 MJ/kg; storage density : 0,05 kg H2/kg réservoir; Fuel cell : 200 $W_{élec}$/kg
Fuel cell efficiency : 50%; electric motor efficiency : 90%; electric motor weight : 200 kg

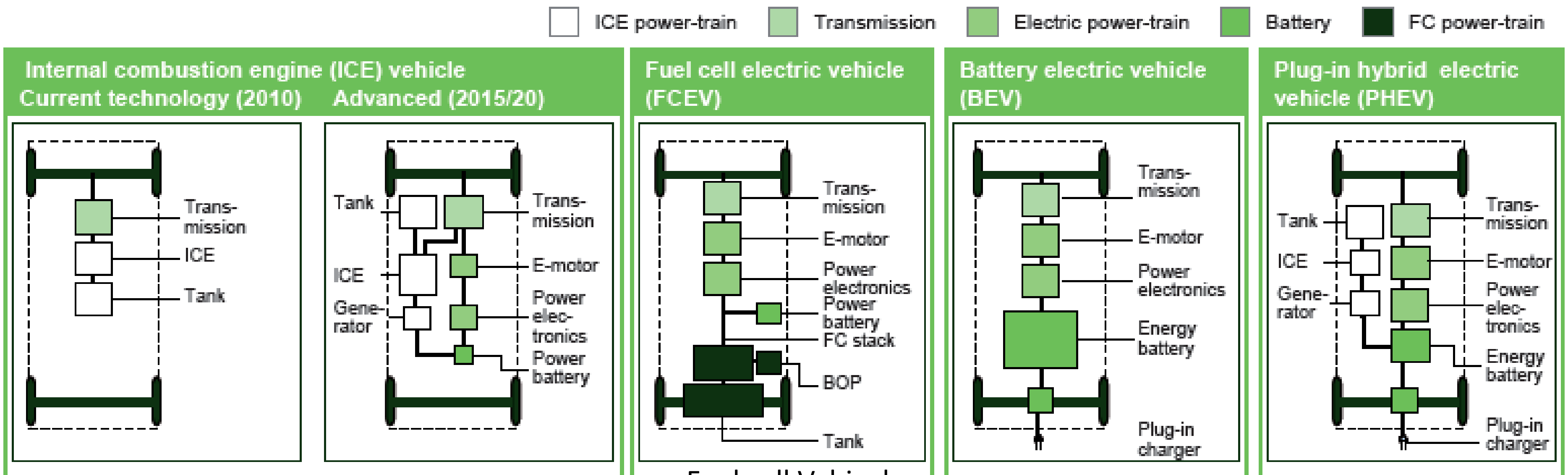
Total weight: around **500 kg** (with Fuel cell **330 kg** + H2 **4kg** + reservoir **80kg**)
Note : **4kg of H_2** need 48,1 m3 at 1 bar or **137 litres at 350 bars**

A portfolio of power-trains for Europe: a fact-based analysis



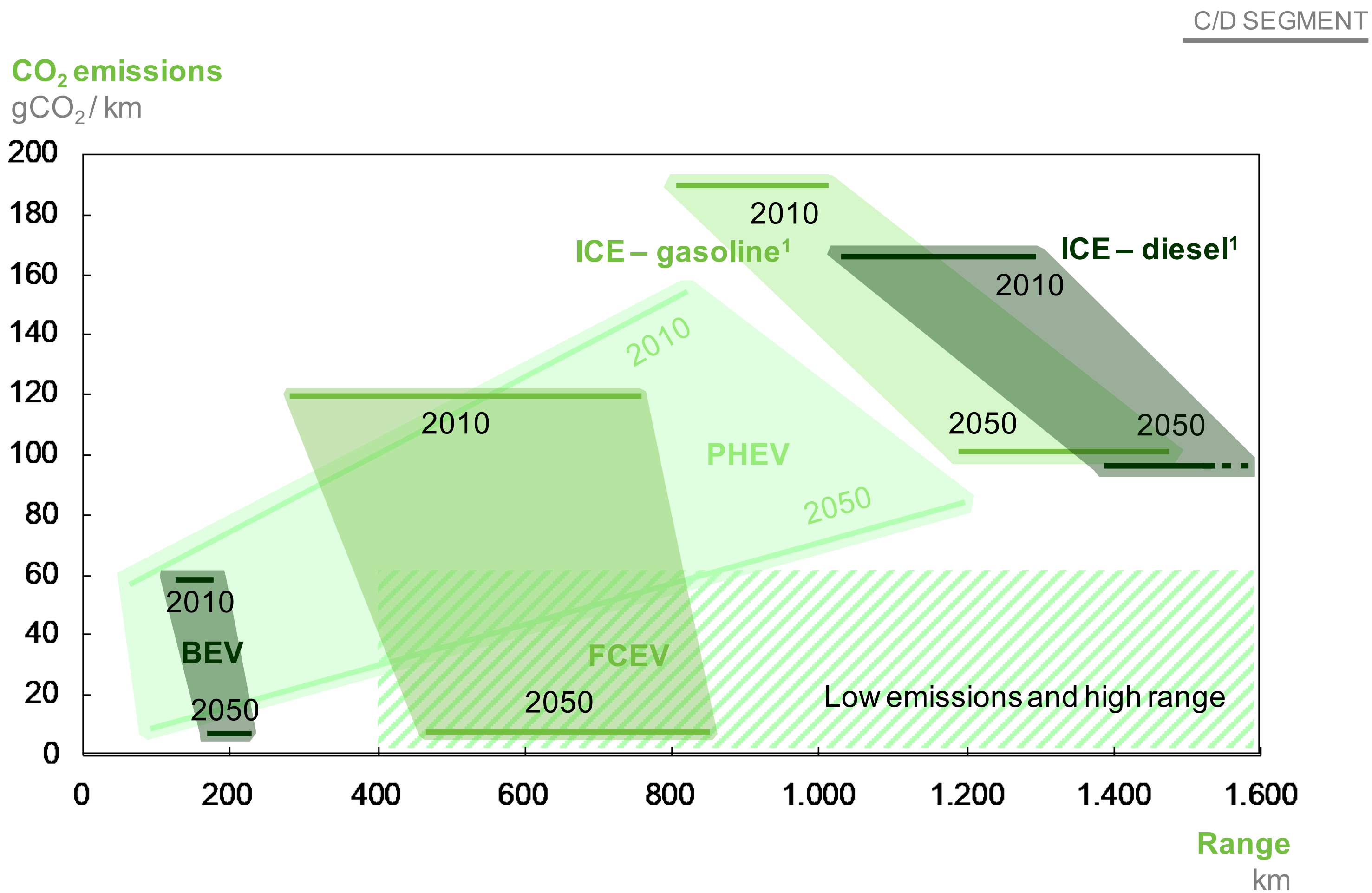
Report edited in 2015 under the initiative of FCH JU
Authored by
- 10 big car manufacturers ,
- 5 Oil and Gas companies
- 3 gas producers

H2 and fuel cell for mobility



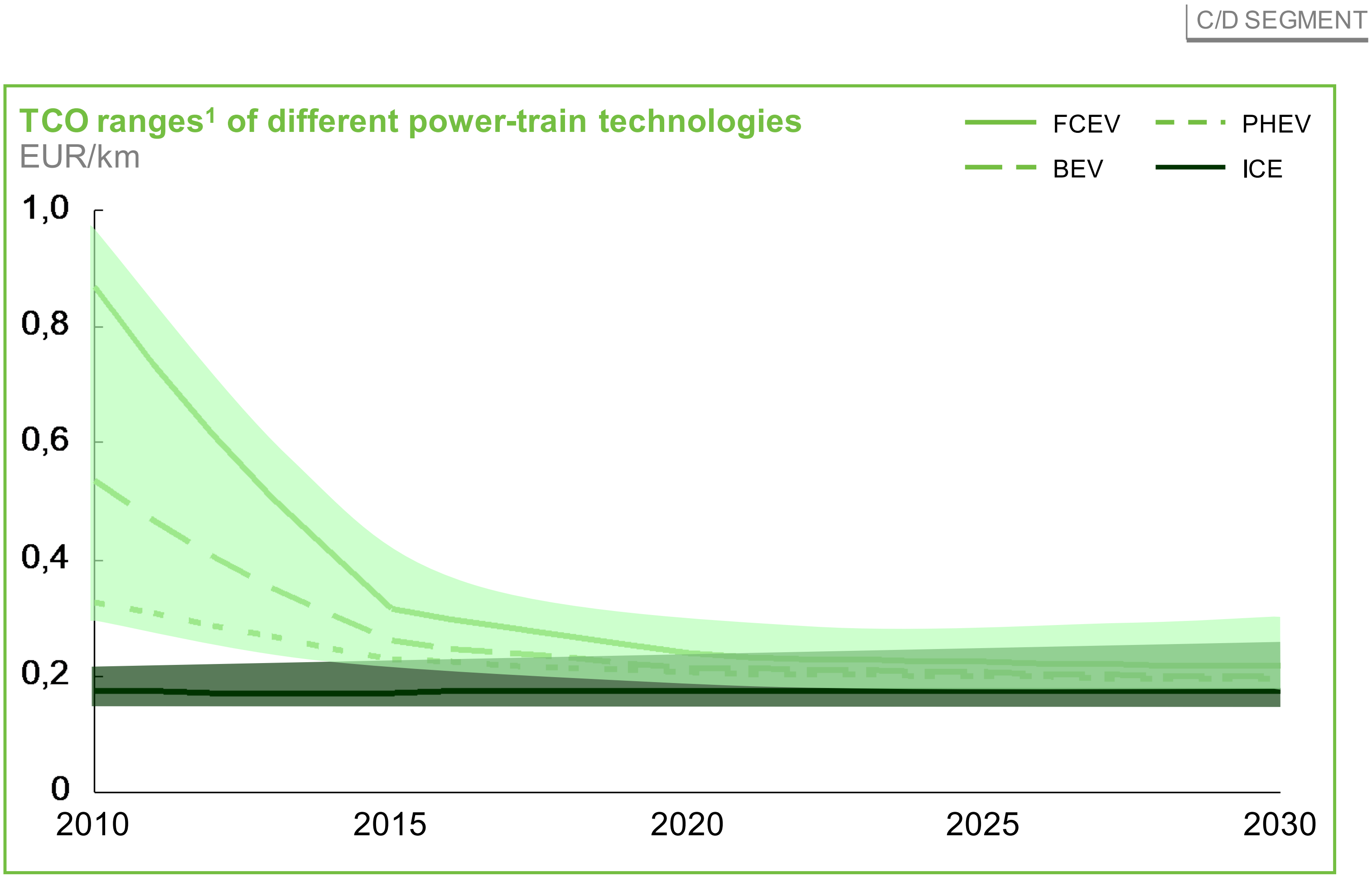
Internal Combustion Engine | Fuel cell Vehicule | Electric vehicule | Hybride vehicule

H2 and fuel cell for mobility



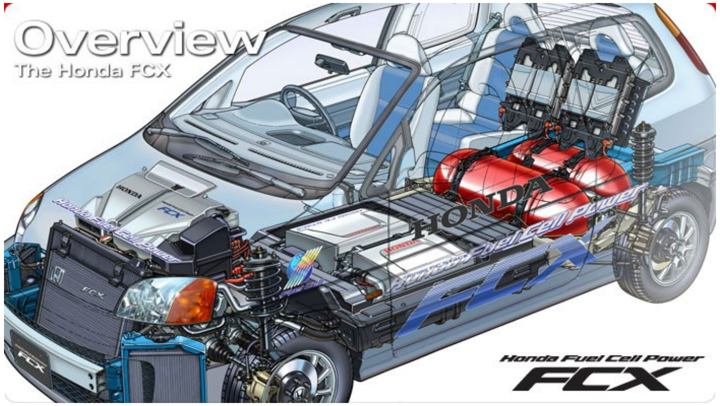
Fuel cell vehicules present a good compromise between autonomy and CO2 emissions

TCO : Total Cost of Ownership for a fuel cell vehicule

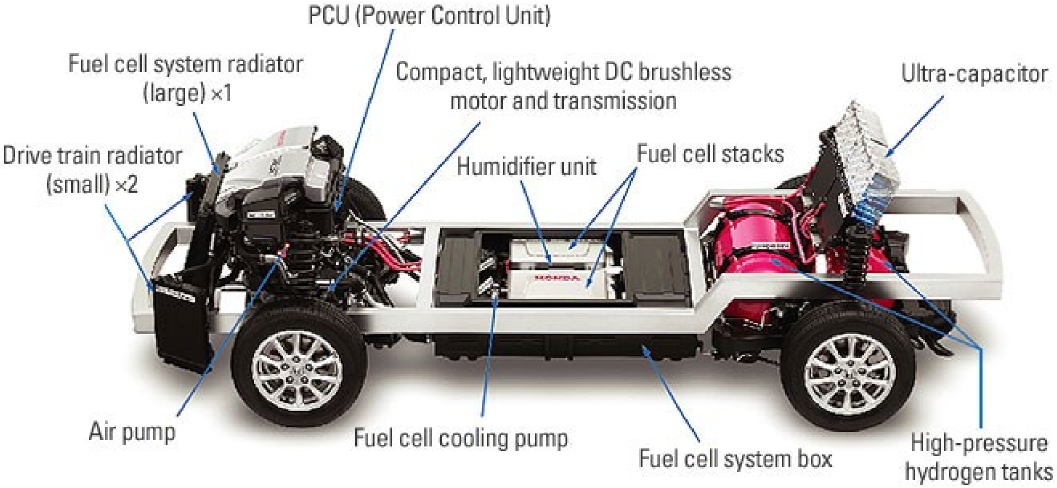


On the long term, the TCO for fuel cell will catch up with other powertrain

Captive fleet of vehicules to overcome the « chicken and egg » dilemna!



Vehicule available for rent since 2011 in California
Total max power of stacks = 86 kW
H2 storage = 156 litres under 350 bars
Autonomy = about 400 kms.



The final mile delivery with captive fleet

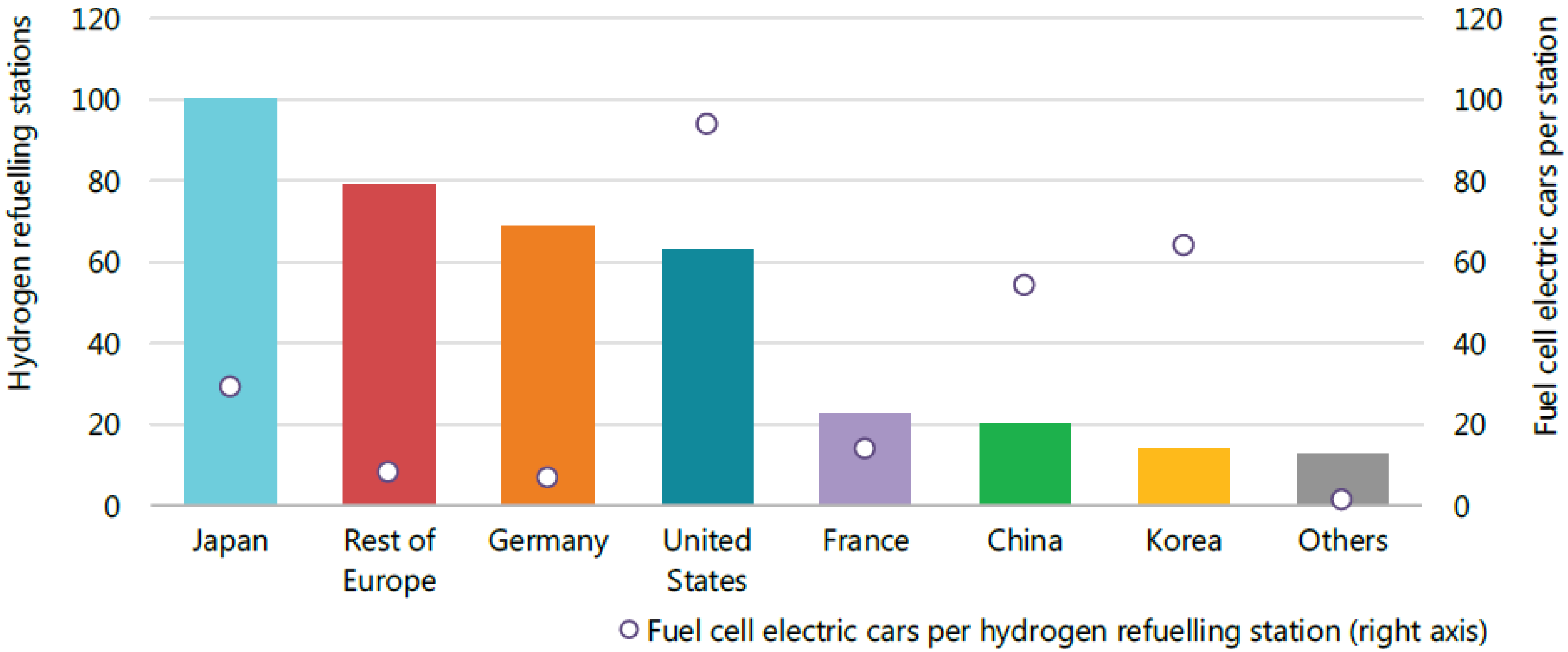
Peugeot Expert H_2- STELLANTIS
(commercialization end of 2021)

Battery capacity = 10,5 kWh (50 km range)
+ 4,4 kg H2 at 700 bar :
Target : 400 km range

Renault Master Van H_2-Tech (commercialization in 2022)
HYVIA = Renault + Plug Power

Battery capacity = 33 kWh (around 100 km range)
+ 6kg H2
Target : 500 km range

Hydrogene refuelling station and their use in 2018



The **number of H2 cars per refuelling station considerably varies between countries**,
Target : 2500 à 3000 vehicules/station

For comparison with **electric charging station**,
In average 10 electric vehicules per public stations and 1 vehicule per private station.

Gasoline/Diesel Station : between 3000-3500 vehicules/station

Zero emission public transportation in PAU

www.pau.fr

Zero emission public transportation in PAU

Comparison of an electric solution with a H2 solution based on a global analysis including operating constraints, infrastructure cost and maintenance, expected service level,….

- **For the same bus frequency, the electric solutions have the same cost (investing + operating) than H2 solution**.

BUT, **10** electric buses with battery charged on transfer bases or **14** electric buses in autonomy mode against only **8 H2 buses**.

Zero emission public transportation in PAU

8 BUS 18m Exquicity design by Pau

VANHOOL

Fuel Cell *BALLARD velocity HD* 100KW

- Consommation 9-10kg/100km
- Capacité 145 passengers
- Autonomie 350kms/j
- Disponibilié 90 %

> 520 000 kms & 2,7 Million de passagers

Atelier de maintenance dédié aux bus H2 (ATEX/ICPE)

STATION ENGIE ITM POWER

H2 Vert production electrolyser PEM @350 bars SAE-J2601/2

- 174-268 kg/j H2
- Stockage 800kg 600 bars (4 j backup)
- Remplissage “à la place” 120 to 240 kg/j
- disponibilité 98%

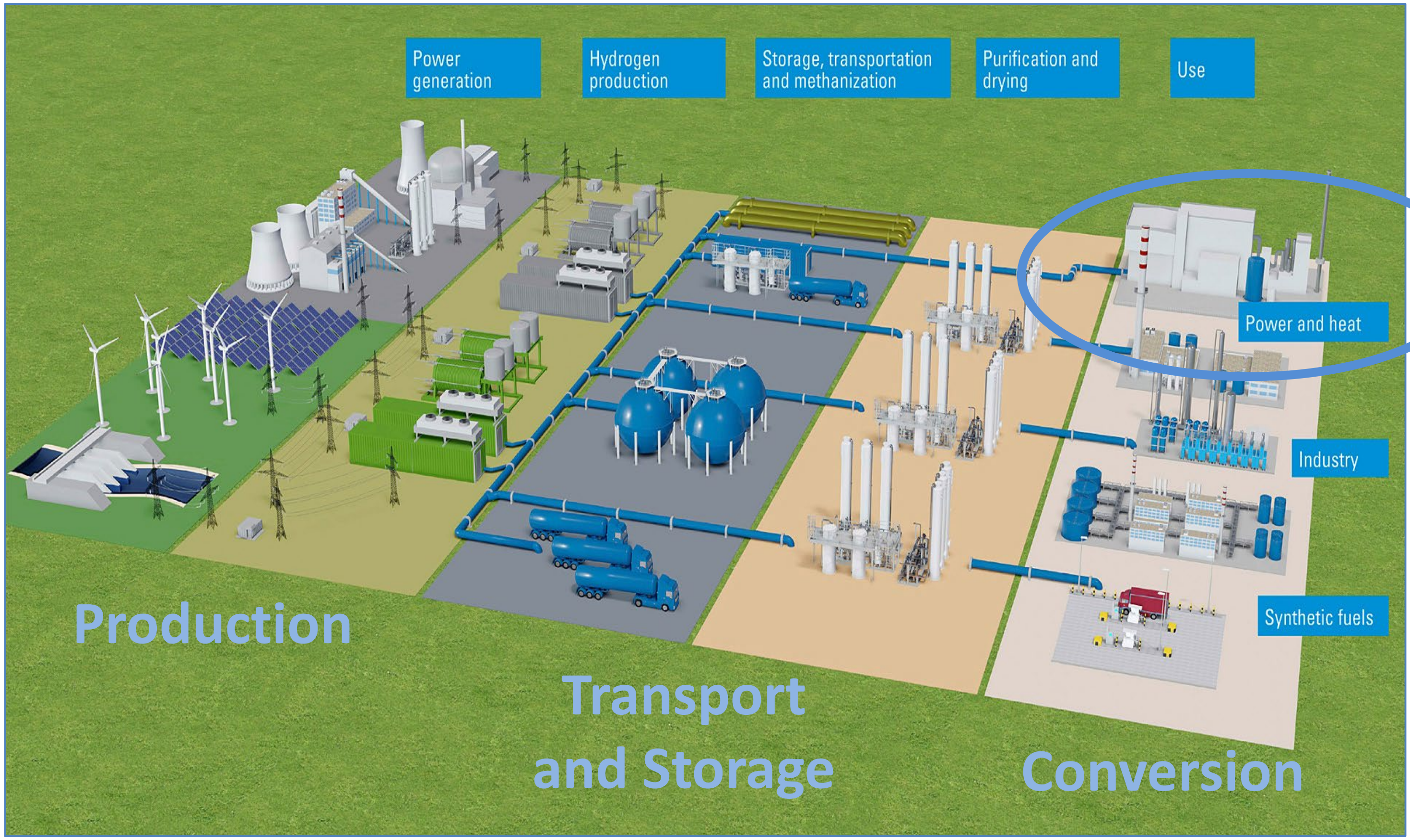
> 40T H2

FEBUS

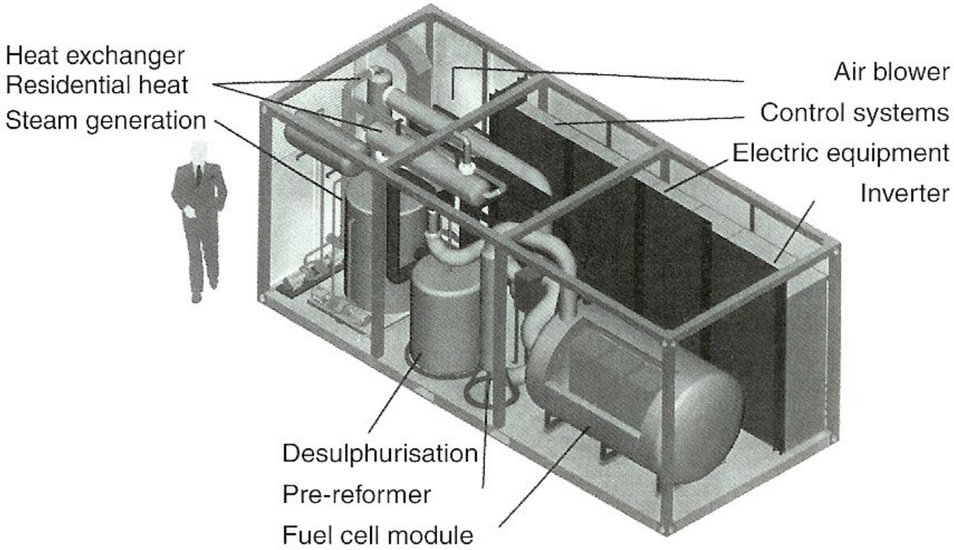
FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

PAU BÉARN PYRÉNÉES MOBILITÉS

H_2 for power



Power generation
Hydrogen production
Storage, transportation and methanization
Purification and drying
Use
Power and heat
Industry
Synthetic fuels
Production
Transport and Storage
Conversion



Combined Heat and Power 100 kW plant
With a Solid Oxyde Fuel Cell SOFC
(Siemens Power Generation)

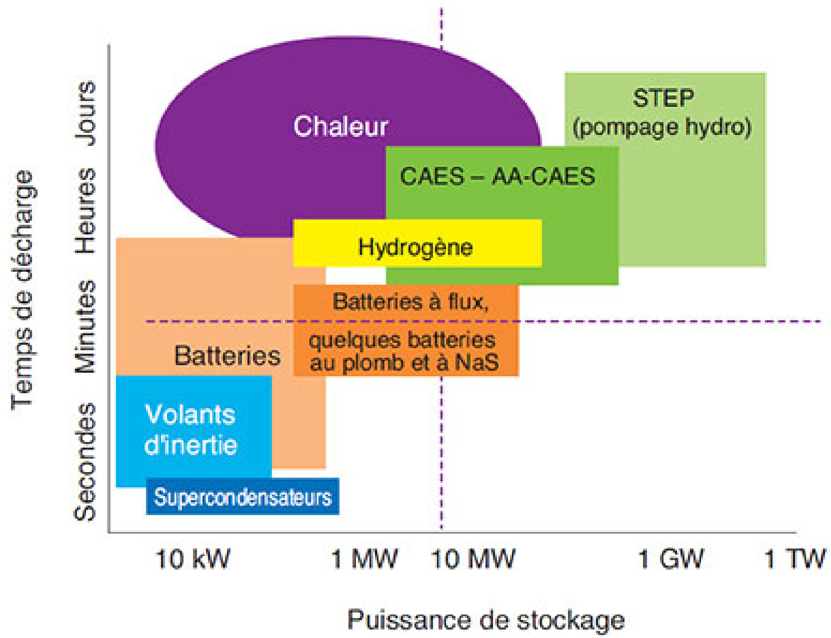
With internal reforming of Natural Gas, desulphuration unit and heat exchangers.

Combined Heat and Power 250 kW plant
With PEMFC
(Ballard Power Systems)

Operated in Berlin since 2000.

Energy comparison of electricity storage systems from renewables

Les différentes technologies de stockage en fonction de leur puissance et du temps de décharge (autonomie)



Source : IFPEN d'après diverses sources

Hypothesis:
- electrolyser consumption : 6 kWh/m3$_{NH2}$
- Fuel cell efficiency : 50%
- Isentropic efficiency of compressors : 80%
- Isentropic efficiency of turbine : 87%
- if cooled compression: isothermal efficiency 70%
- isentropique efficiency for Pumped Storage Power Station:
  80% in pump mode,
  87% in turbine mode

Energy efficiency of these different storage solutions:

-Hydrogen storage:

around 25 %

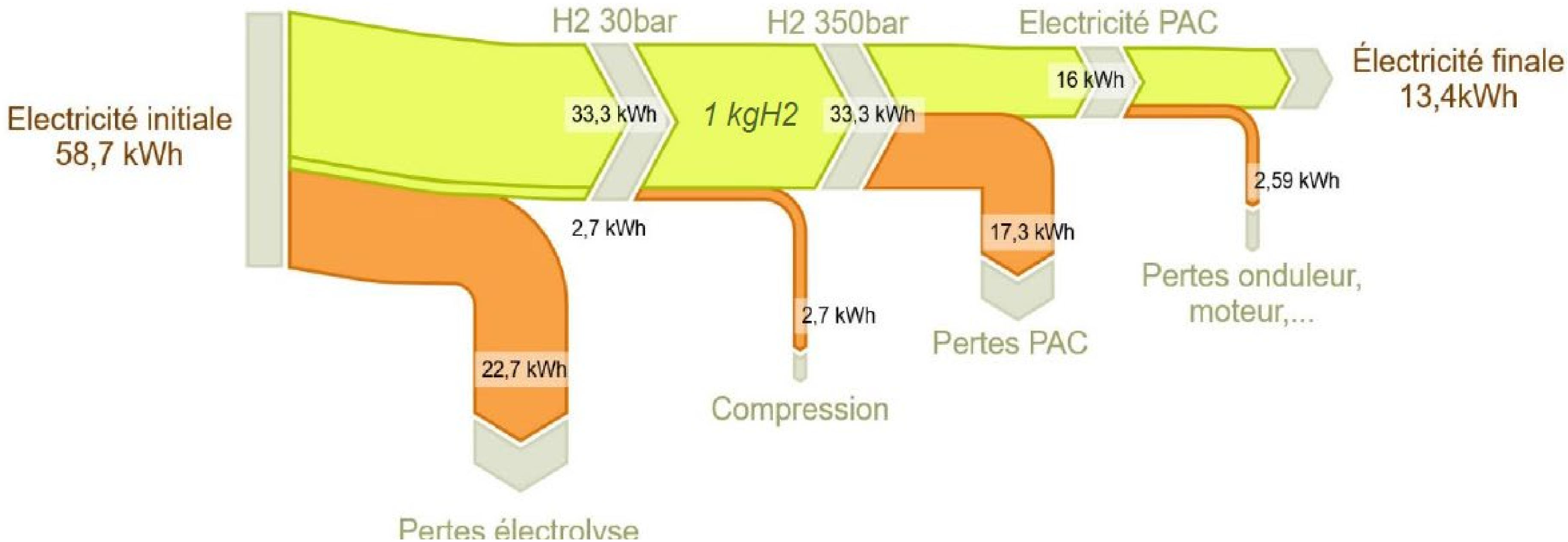
- Compressed Air Energy Storage, CAES with a 30 bar reservoir :

around 25 % or up to about **70 % with thermal storage**

- Pumped Storage Power Stations, PSPS:

70 %

Efficiency of the whole conversion process



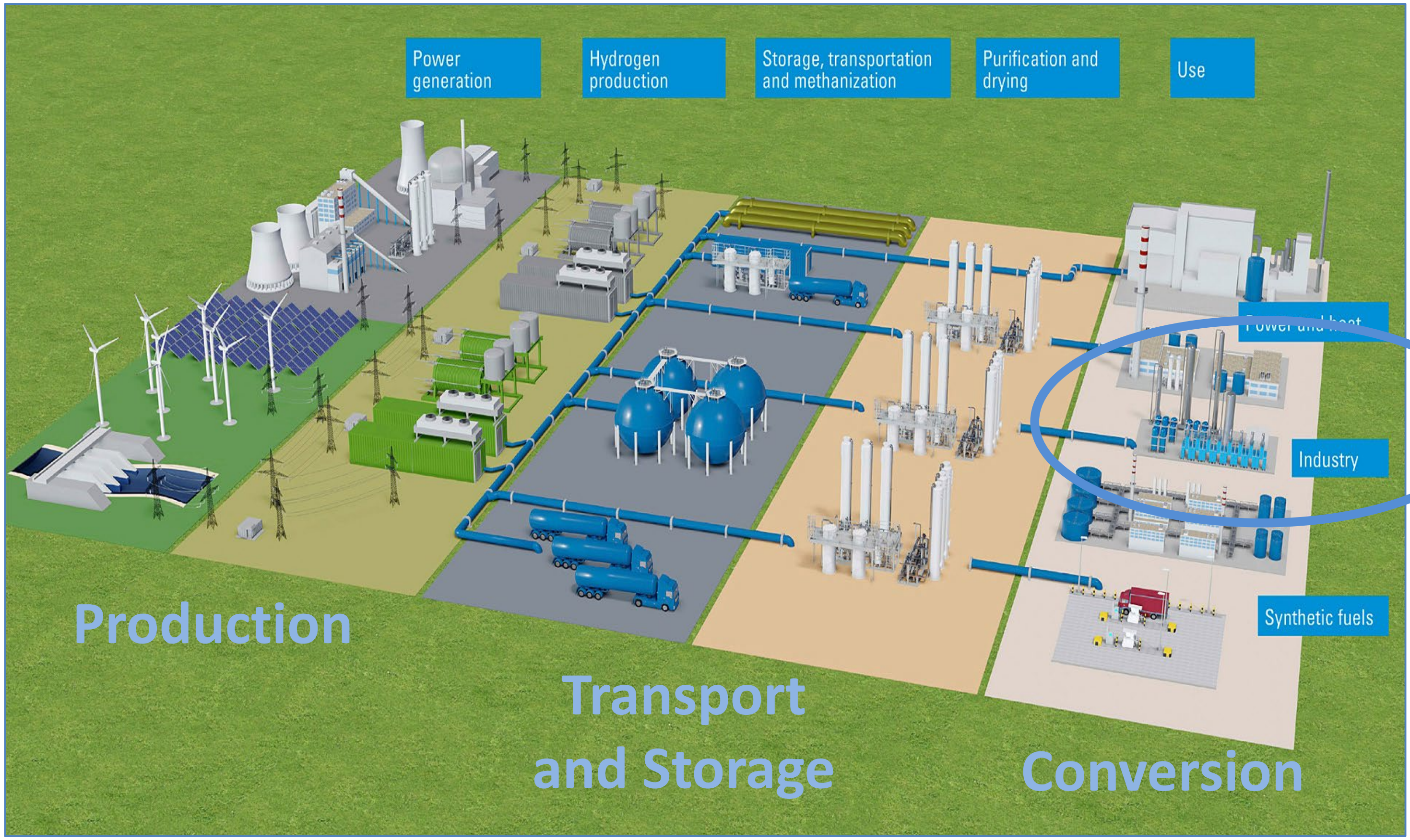
SANKEY diagram (energy flow diagram) showing the energy involved in the production of 1 kg of H2

Via hydrogen vector: from electron to electron efficiency = 23%

Via battery : $$\eta_{VEB} = \eta_{Charge} * \eta_{Décharge} * \eta_{\frac{DC}{AC}} * \eta_{Moteur} \approx 70\%$$

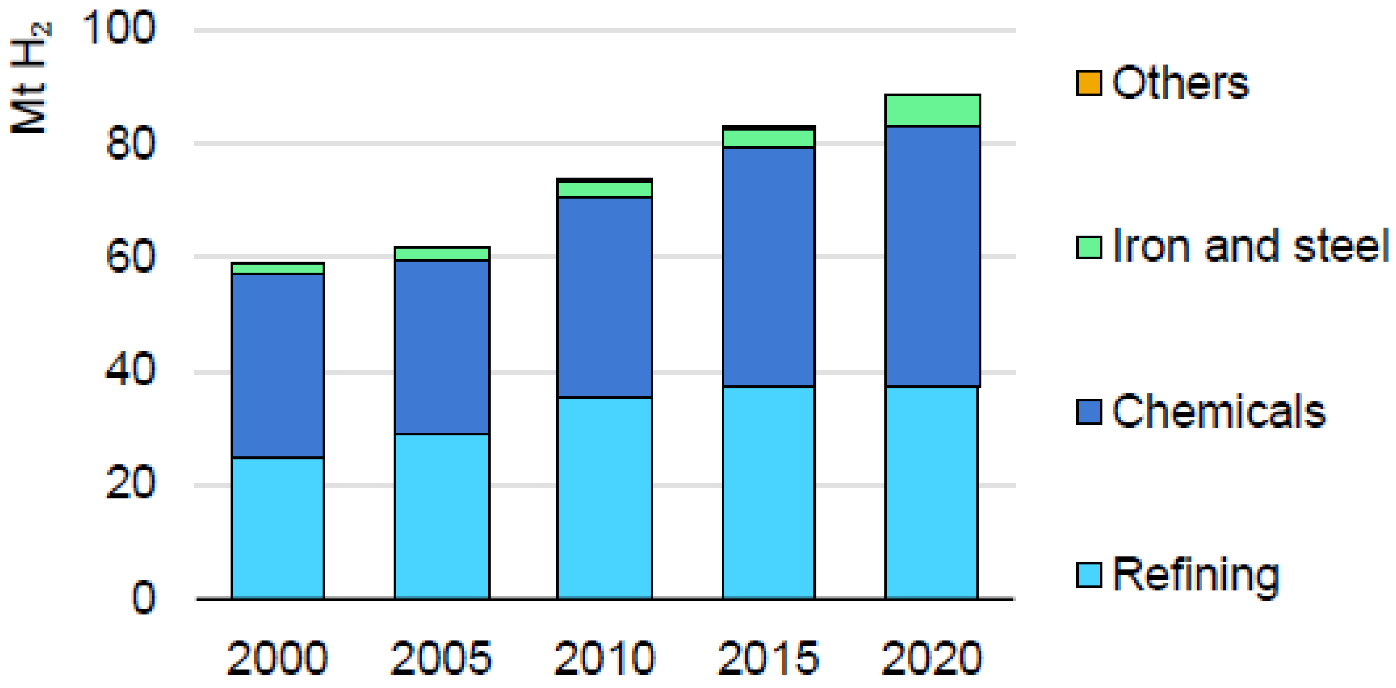
With : charging efficiency = 88%
Discharging efficiency = 93%

H_2 for Industry



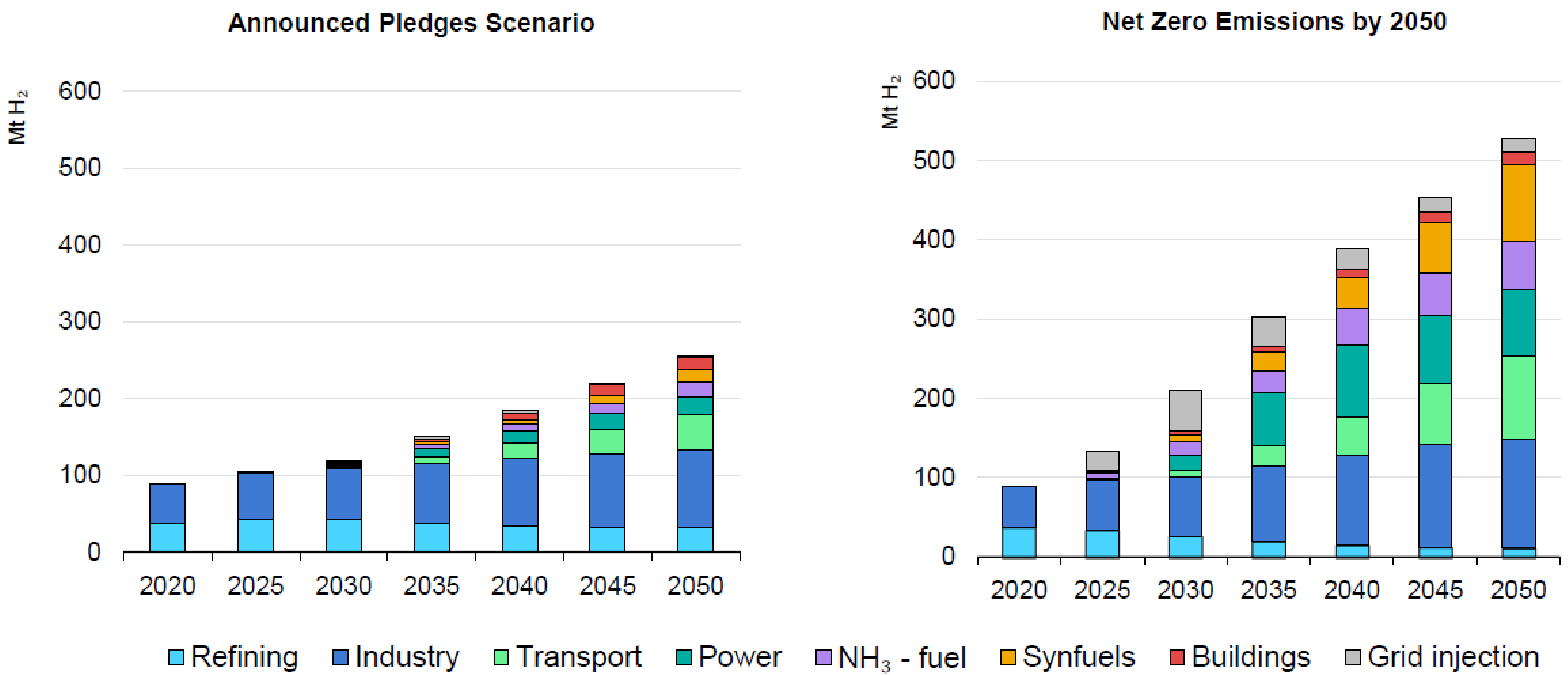
Up to now, H_2 is used in the industry sector

Hydrogen demand by sector, 2000-2020

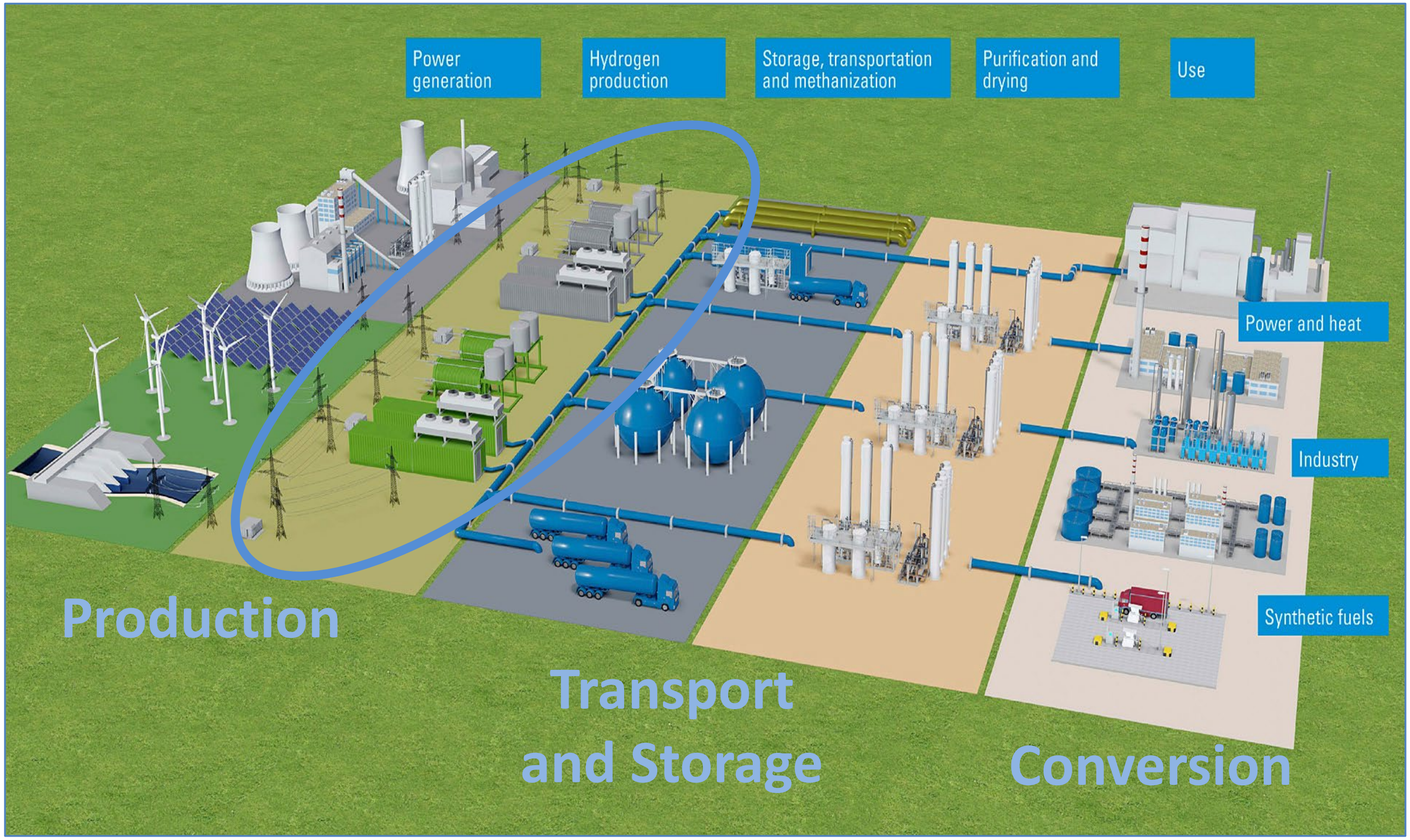


Up to now, H_2 is used in the industry sector

Government pledges suggest greater hydrogen use, but not nearly enough to the level needed to achieve net zero energy system emissions by 2050



H_2 production



H_2 Production in 2019

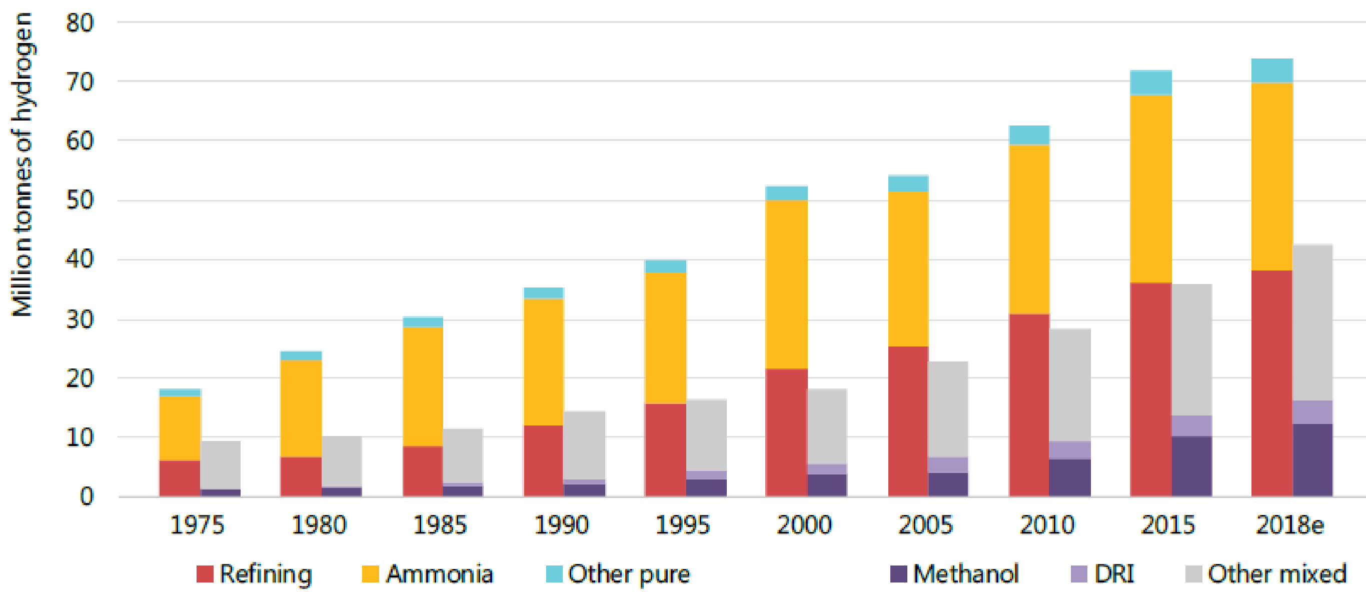
In 2019, the total production of pure H2 is of **70 Million of tonnes**

- 76% produced from Natural Gas
- 23 % produced from coal

This production is responsible for the emission of **830 MtCO2/year** (the equivalent of the summed emission of Indonesia and Great Britain)

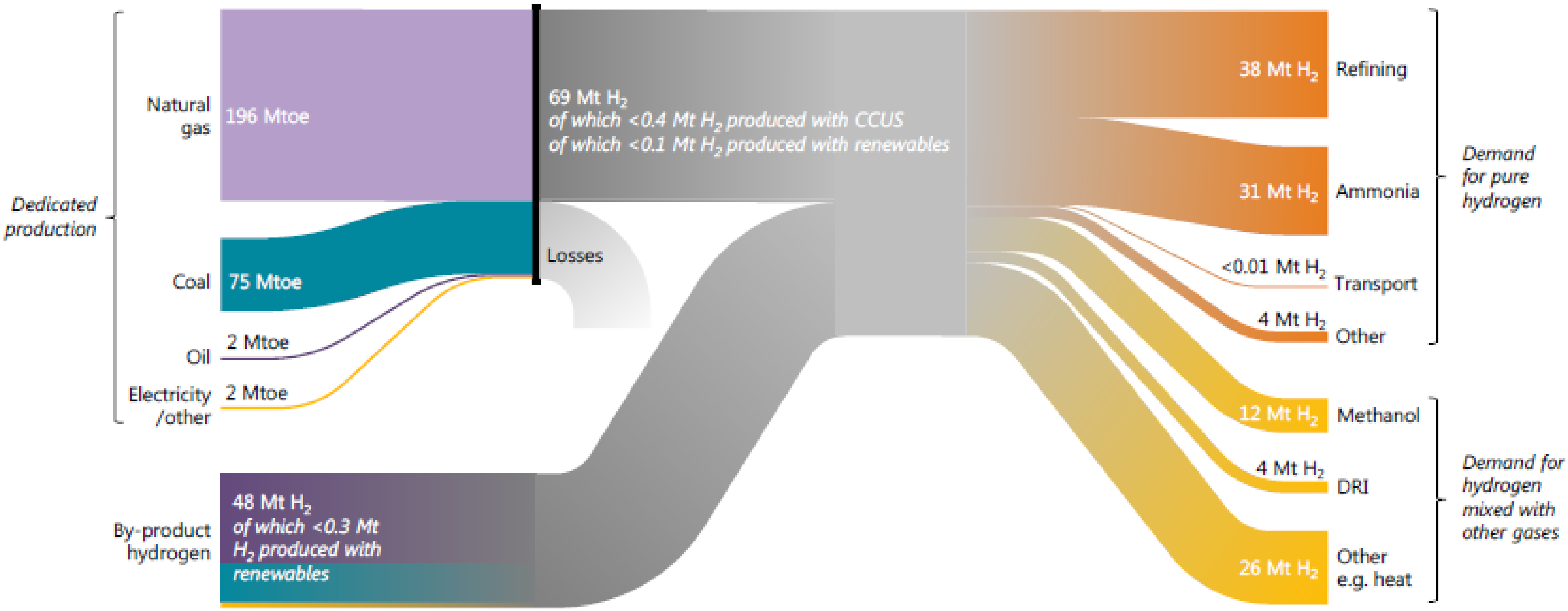
Around only **2% of H_2 is produced by water electrolysis**.

If all H_2 produced in 2019 was produced through water electrolysis , it would have consumned 360 TWh of electricty, the equivalent of the annual electricity production in Europe.



Evolution of H_2 production since 1975

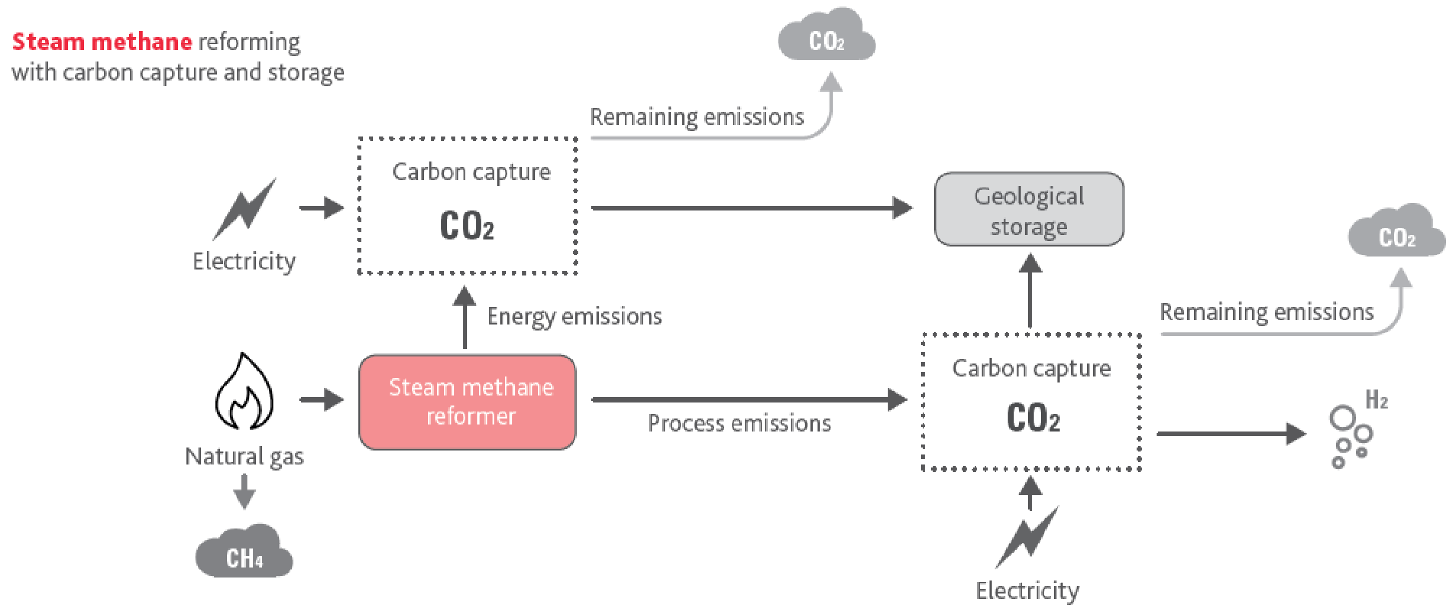
H_2 Production and consommation in 2019



In 2019, the demand in **pure H_2** is mostly driven by **oil refining** and **ammonia production** (fertilizers).

The demand in **non pure H_2** is for **methanol** production and **DRI (Direct Reduced Iron steel) production.**

Hydrogen from methane : steam reforming



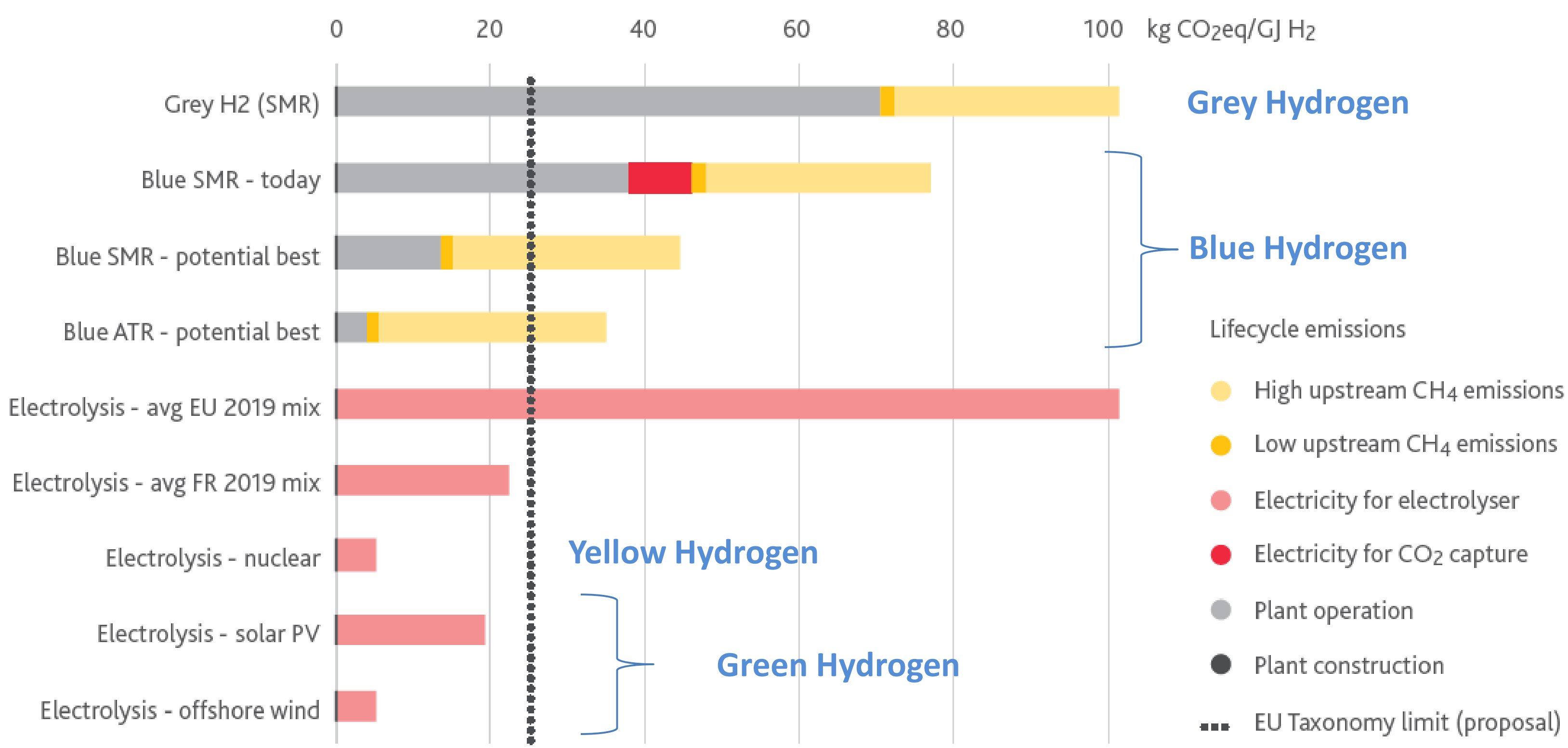
- **Natural Gas** *advantages* ⇒ - available in the ground.
 - distribution network already in place.

drawbacks ⇒ - sulphurous substances are poluttants for fuel cell catalysers

- **steam reforming reaction** neads a lot of heat energy and releases CO_2

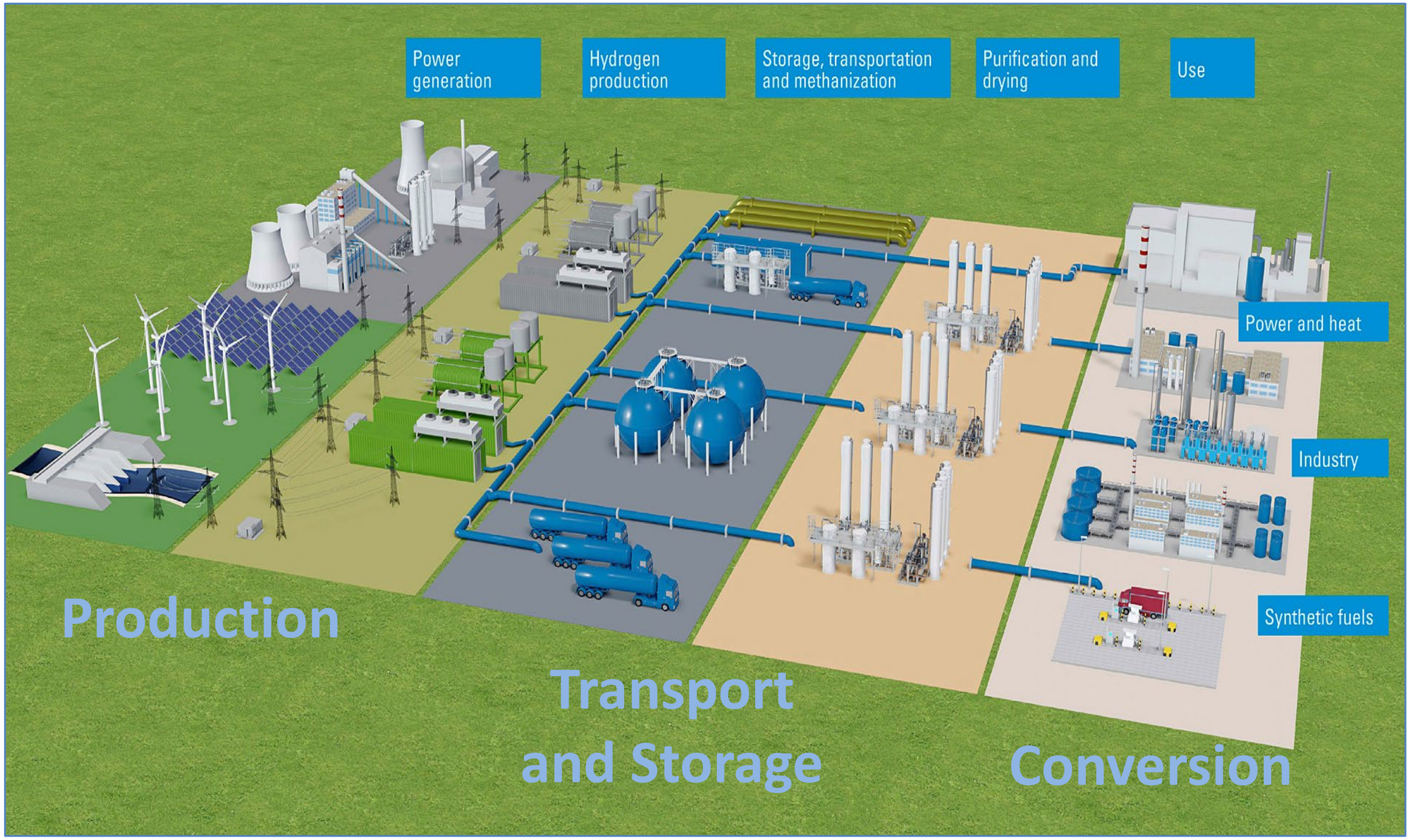
$$CH_4 + H_2O \longrightarrow CO + 3\,H_2$$
$$CO + H_2O \longrightarrow CO_2 + H_2$$

Different routes for H2 production

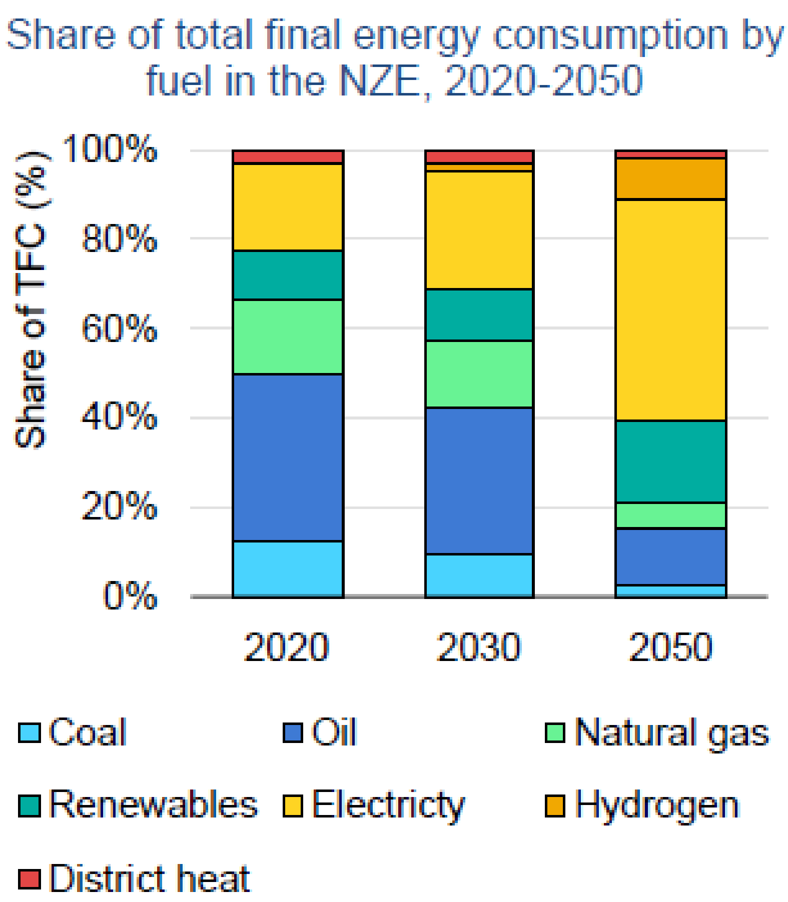


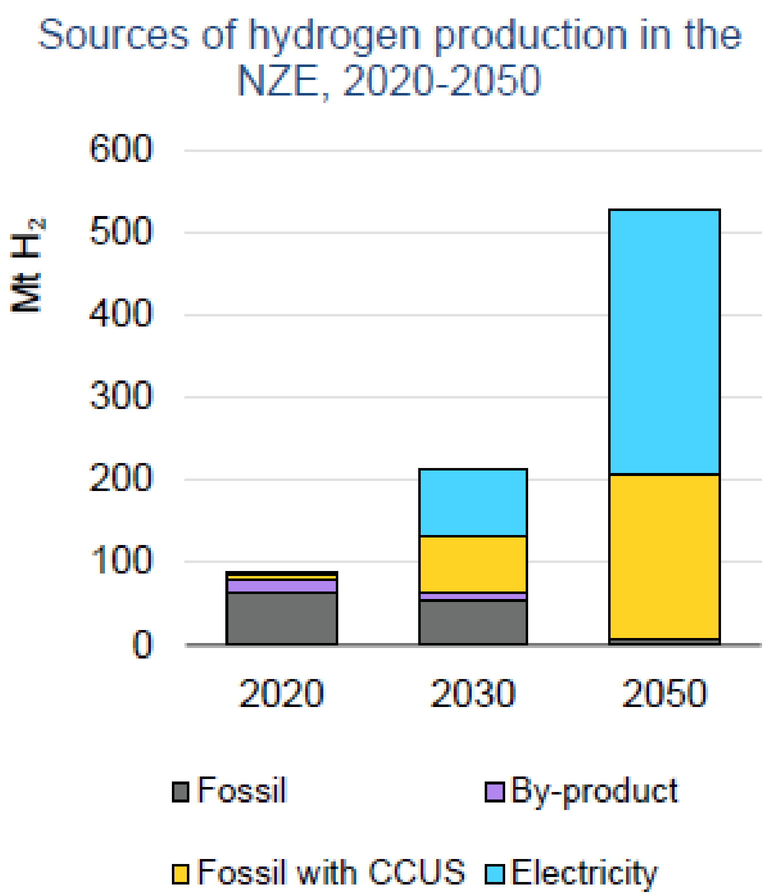
Green house gas emission during H2 production

One final word

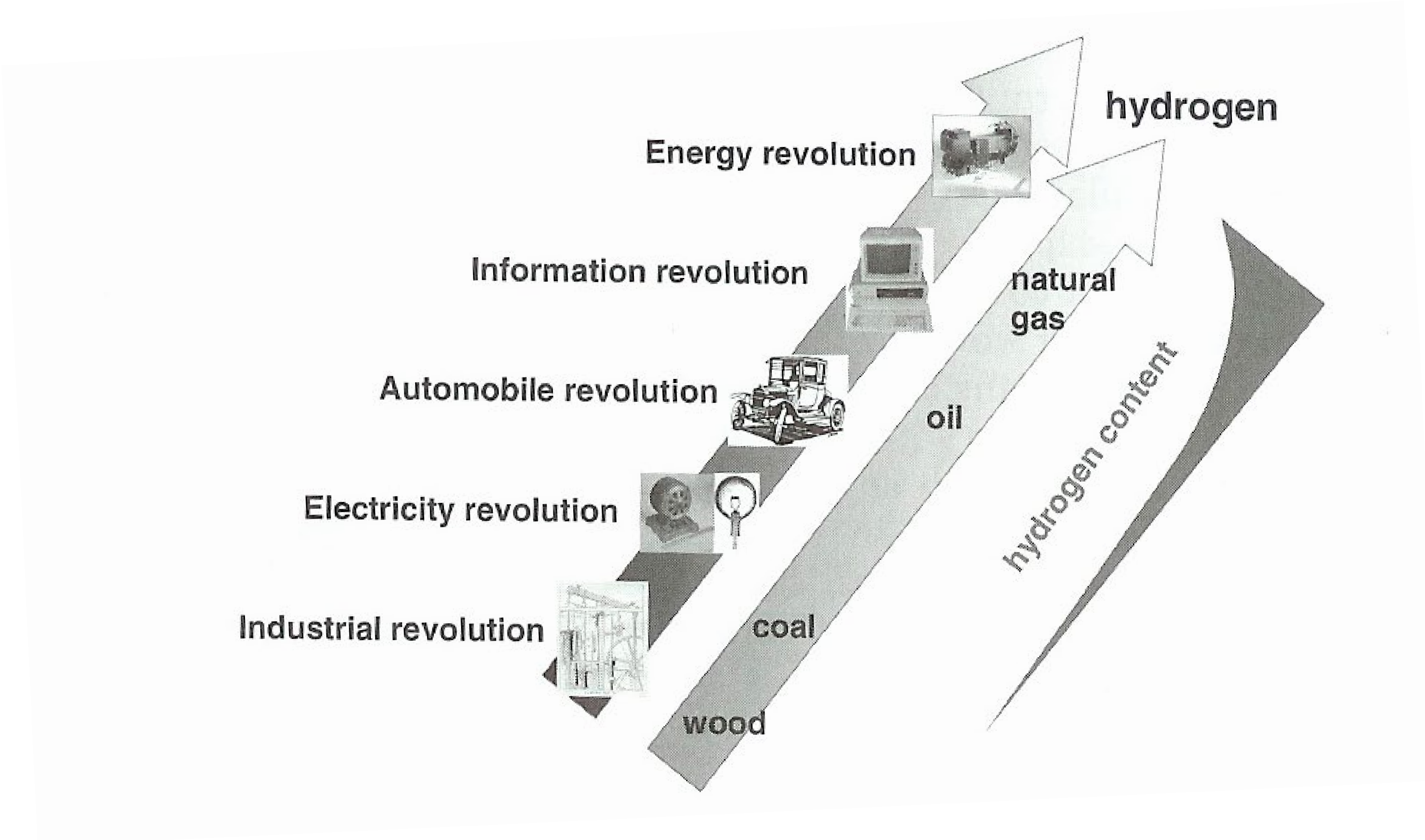


Hydrogen is an important part of the Net zero Emissions Scenario, but is only one piece of the puzzle





HYDROGEN : The flow of history ???



History of technology evolutions along with fuel history

Thank you for your attention !!

Cityjoule 2013

Prof. Bruno AUVITY
Laboratoire de Thermique et Energie de Nantes (CNRS-UMR 6607)
Polytech Nantes – The graduate School of Engineering of Nantes University