The emerging hydrogen economy

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- Recipient, Blondel Medal 2017
- Recipient, CNRS Innovation Medal 2020

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The emerging hydrogen economy

The emerging hydrogen economy

Motivations & status

Hydrogen…

The most abundant element in the universe…

… 75% in mass and 92% in number of atoms

Very high energy density…

… 33kWh/kg

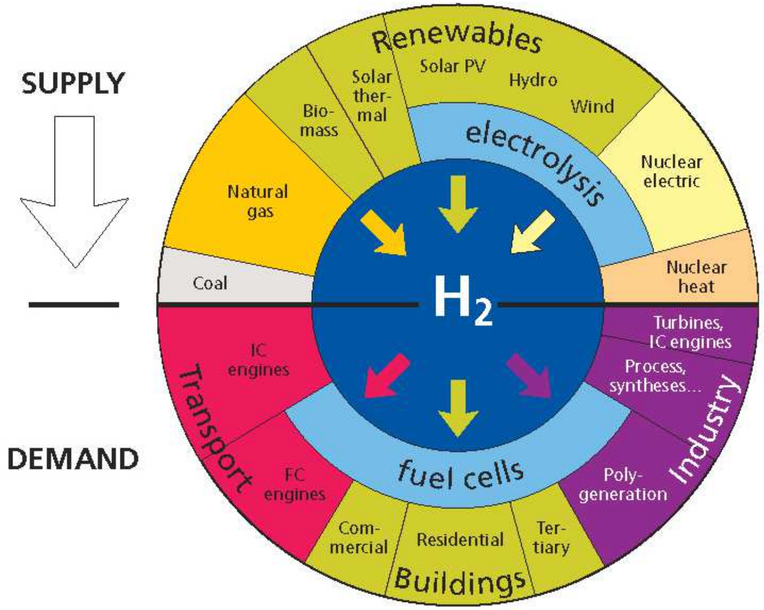
… > 3x gasoline

… > 100x electrochemical batteries

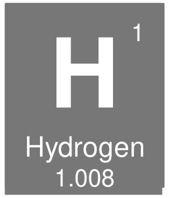
Almost never in molecular state on Earth…

… it must be produced

... energy vector (duality with electricity)



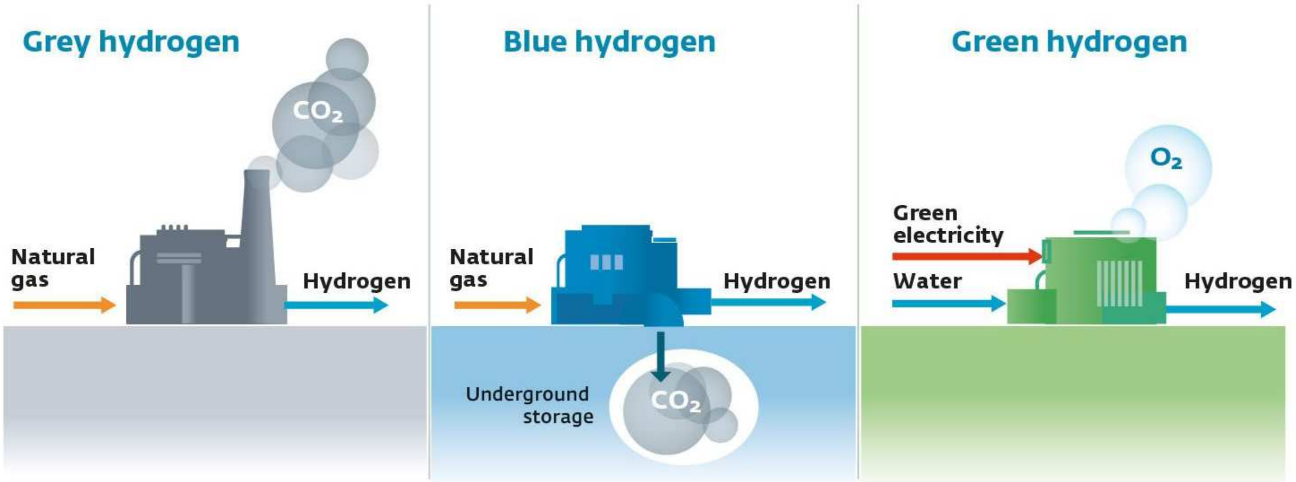
Hydrogen production



"Grey" H2 : production based on fossil fuels

"Blue" H2 : production based on fossil fuels + released CO_2 captured
or water electrolysis and electricity coming from low carbon power plants

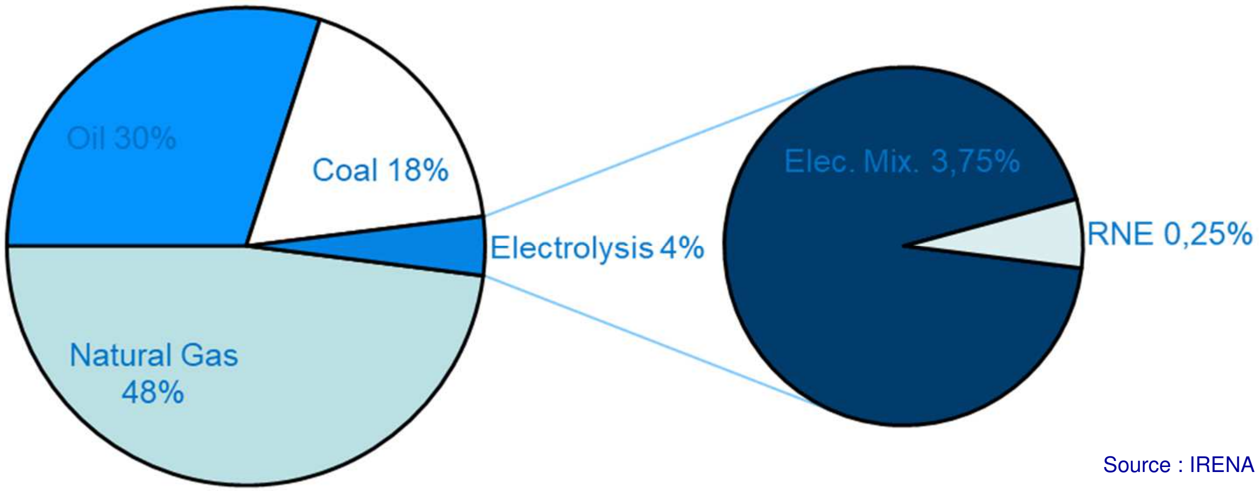
"Green" H2 : production based on water electrolysis and/or from renewables



Source : Gasunie

Hydrogen production

Hydrogen sources



Source : IRENA 2019

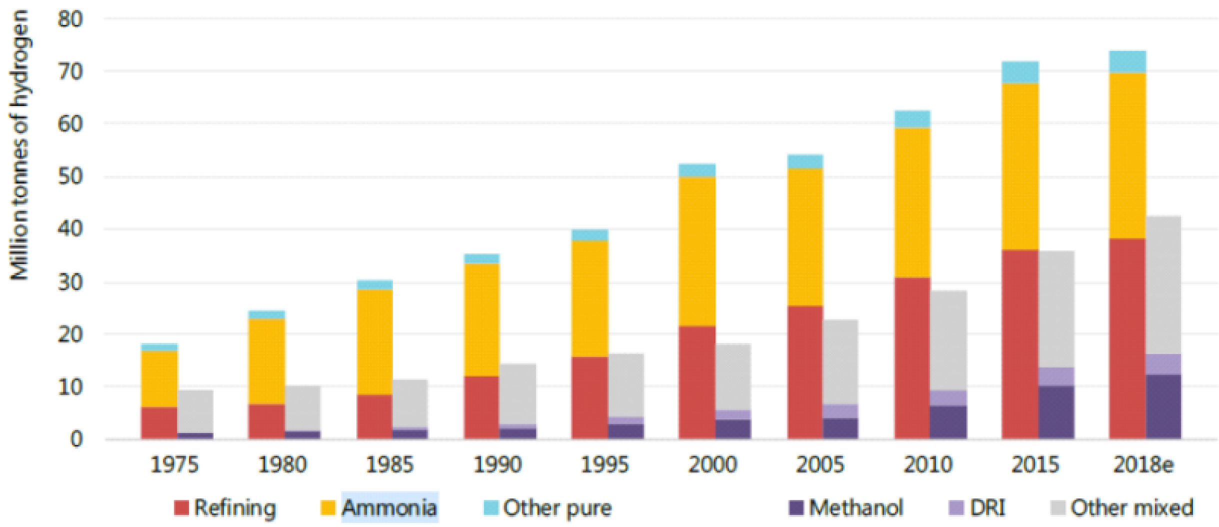
Hydrogen market in 2050

- 18% of global energy demand
- US$ 2500 billion market worth
- 30 millions of jobs around the world
- Reducing CO2 emissions by 6GT per year

Source : Petroleum Economist 2018

Hydrogen market - today

Evolution of annual global demand of H_2

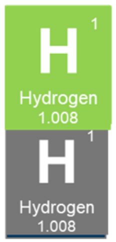


- Major usages :
  - Crude oil refining
  - Ammonia synthesis
  - Chemical industry
  - Metallurgy

Source : IEA 2019
DRI : Direct Reduction of Iron (Metallurgy)

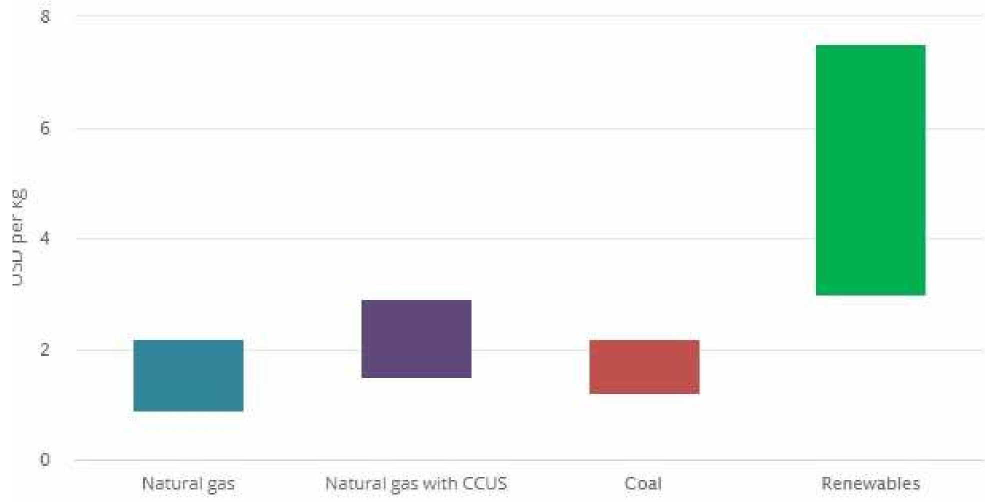
Hydrogen production costs

- Today :
  - Cost ratio of about 3 between and



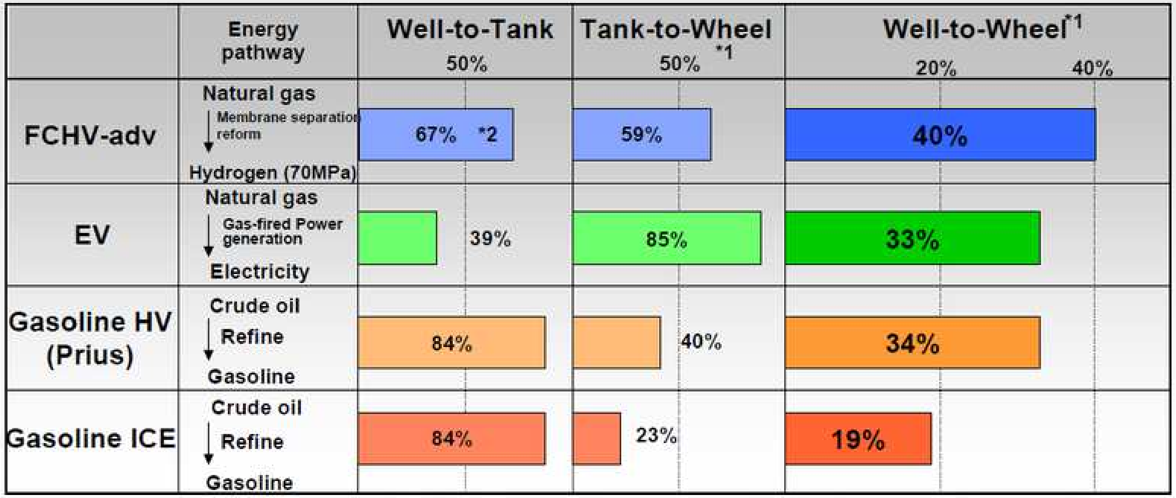
  - Cost ratio of about 2 between and

Source : IEA 2019



Towards hydrogen systems

– Switching to fuel cell ? - Transportation applications



*1 Tank-to-Wheel efficiency: measured in the Japanese 10-15 test cycle
*2 Efficiency difference between 35MPa and 70MPa: approx. 2%

(Toyota Calculation)

- **Fossil fuel ICE**
  - Low efficiency
  - Limited fossil resources
  - Pollutant emissions

- **First alternative: BEV or HEV**
  - BEV : Significant progresses BUT :
    - Long duration recharging operation
    - Limited autonomy of the electrical vehicle
    - Limited durability of the batteries
  - HEV : reduce rather than eliminate the dependency on fossil fuels…

- **Second alternative: FCEV**
  - High efficiency
  - (*Theoretical & in-situ*) pollutant emissions is zero
  - Fast recharging – high autonomy

⇨ **Interesting alternative**

\+ new application areas

Towards hydrogen systems

– **Switching to hydrogen ? – Stationary applications**

- **Increasing interest for the storage of electricity**
  - Wide use of renewables
  - Intermittency of renewables

- **First alternative: "classical" solutions**
  - Electrochemical batteries, flywheels
    - High cost, limited durability, limited energy density
    - ➔ moreover, limited ability to store electricity for long time
  - Pumped storage
    - Large scale only at specific places

- **Second alternative: hydrogen**
  - Based on the duality between electricity & hydrogen
  - Ability for long duration storage
  - Can be considered at a microgrid level and at a grid level
  - Can be coupled to refueling of FCV fleets
  - ⇨ **Interesting alternative**

The emerging hydrogen economy

Part 1 – Fuel Cell technology and PEMFC Systems

Fuel Cell technology

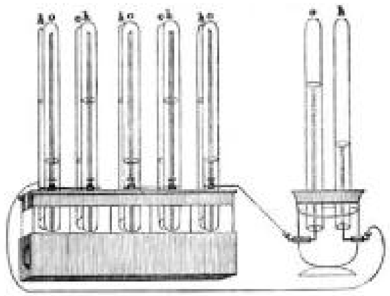
– Is Science Fiction becoming Reality ?

- **Jules Verne, 1875: "*The Mysterious Island*"**

  « … but after the European mines, […] , the American and Australian mines will for a long time yet provide for the consumption in trade. For how long a time? […] For at least two hundred and fifty or three hundred years.

  That is reassuring for us, but a bad look-out for our great-grandchildren! […] And what will they burn instead of coal? […] water decomposed into its primitive elements... "

- **Basic principle discovered and demonstrated in 1839**
  - British physicist William Grove
  - For more than a century, the priority given to the development of thermal machines and electrical batteries overshadowed this invention.



Fuel Cell technology

– Brief history

Grove (**1839**)

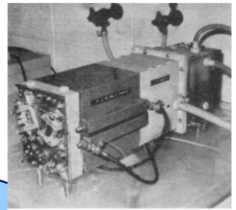
Verne (**1875**)

Allis-Chalmers (**1959**)
first fuel-cell-powered vehicle (tractor)

GM Electrovan (**1966**)

NASA – Space conquest
FCS to power the rockets of the Gemini (**1963**) and Apollo (**1968**) programs

Alsthom (**1968**)



Oil shock
- Increasing research in USA / Japan
- Research wilderness in Europe

The come-back

DC Necar 2
(**1996**)

FC Submarine
(**2005**)

PlugPower Forklift
(**2006**)

Myrte
(**2012**)

Toyota (**2015**)

Power gensets
H2SYS
(**2017**)

H2 semi-trailer
Chereau
(**2019**)

Fuel Cell technology

– Principle of a fuel cell

- **What is a Fuel Cell?**
  - US Fuel Cell Council definition, modified by FC Testing and STandardisation NETwork
    - An **electrochemical device** that continuously converts the chemical energy of a fuel and an oxidant to electrical energy (DC power), heat and other reaction products. The fuel and oxidant are typically **stored outside** of the cell and transferred into the cell as the reactants are consumed.
  - Main difference with "traditional" battery
    - Fuel is **supplied continuously** & **stored outside**
    - **Fast recharging** ability
    - **Energy** / **Power decoupling**

chemical energy → **electrical energy**

→ **thermal energy**

redox reaction
(oxidation-reduction)

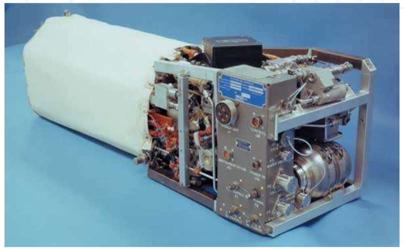
ElringKlinger PEMFC NM5

Fuel Cell technology

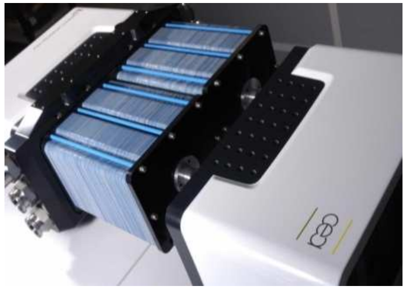
– Taxonomy of Fuel Cell

	Oper. Temp. (°C)	Power range (W)	Main application area
DMFC	20 – 90	1 – 100	Low-power portable applications (mobile phones, computers)
PEMFC	**30 – 100**	**1 – 100k**	**Transport** **Mid power stationary applications** **Heat & power co-generation (CHP)**
AFC	50 – 200	500 – 10k	Spaceships
PAFC	~220	10k – 1M	Domestic heat & power co-generation (CHP)
MCFC	~650	100k – 10M+	High-power units for CHP, maritime applications
SOFC	500 – 1000	1k – 10M+	Same as MCFC + Transport

AFC – Apollo (NASA)



PEMFC – Car Appl. (CEA)

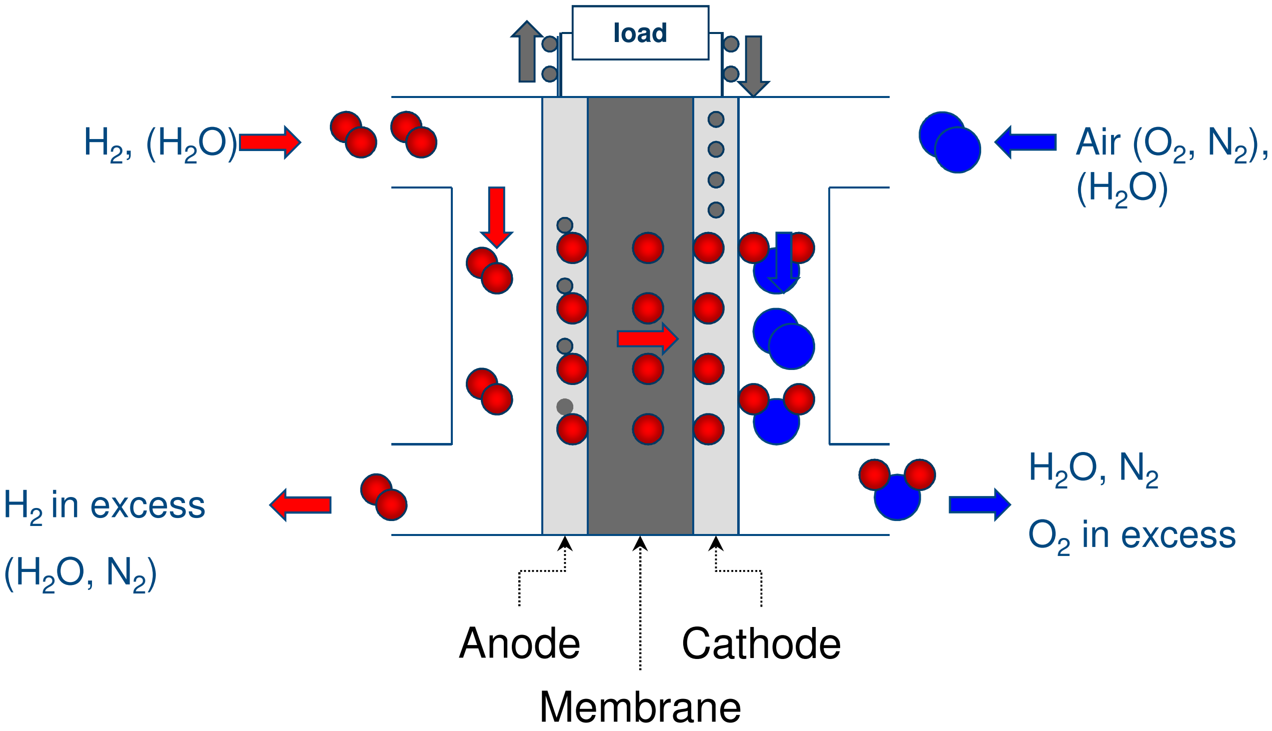


SOFC – Stat. Appl. (MSRI)

PEMFC Systems

– PEMFC – operating principle

- **Fuel / Fuel Oxidizer: H_2 (pure or reformed) / Air**



GENERAL CASE

Anode : Fuel Oxidization (Ra)

$Ra \rightarrow Oa + n.e^-$

Cathode : Reduction of fuel oxidizer Oc

$Oc + n.e^- \rightarrow Rc$

PEMFC

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

Cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Global reaction

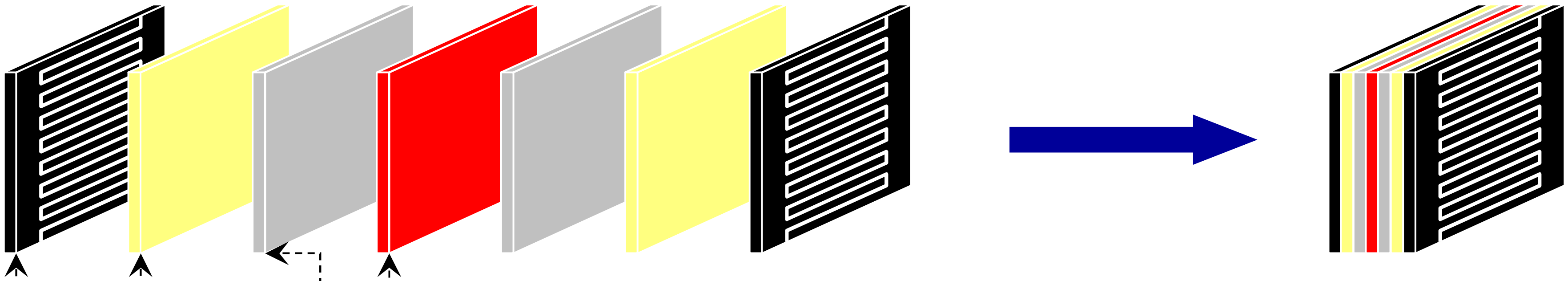
$2H_2 + O_2 \rightarrow 2H_2O$ + electricity + heat

PEMFC Systems

– **Structure**

- **Structure of a single cell**

  - PEMFC = **Polymer** Exchange **Membrane** Fuel Cell



1 Electrolyte (polymer membrane for PEMFC)

2 Electrodes with catalyst (Pt)

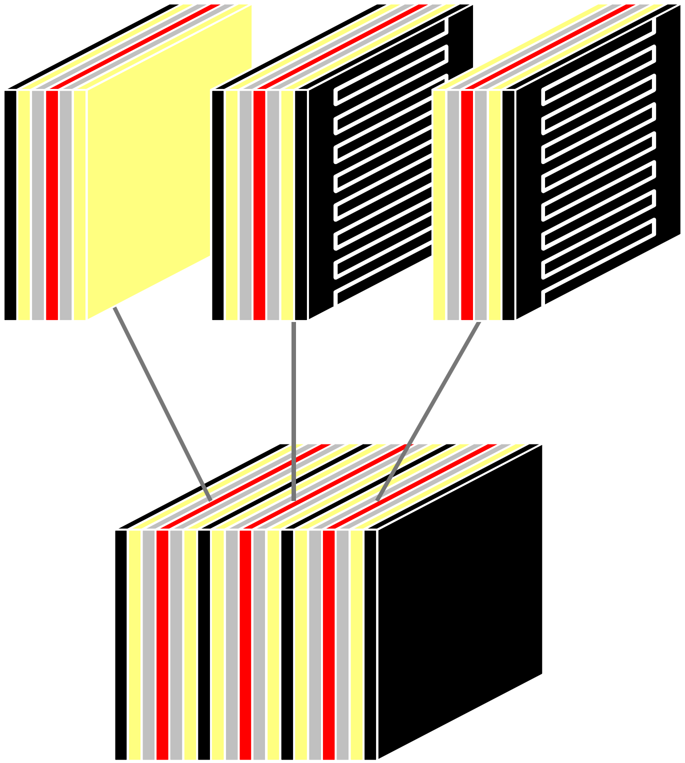
2 Gas Diffusion Layers (GDL) to supply reactants to the electrodes

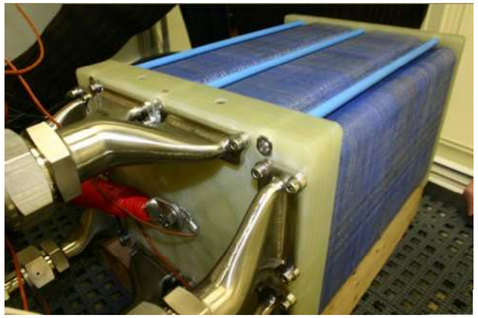
2 Bipolar Plates to supply the gas and evacuate the effluents

PEMFC Systems

– Structure

- **Structure of a stack**
  - Assembly of several cells in series ⇨ to increase the operation voltage





CEA

Pragma Ind.

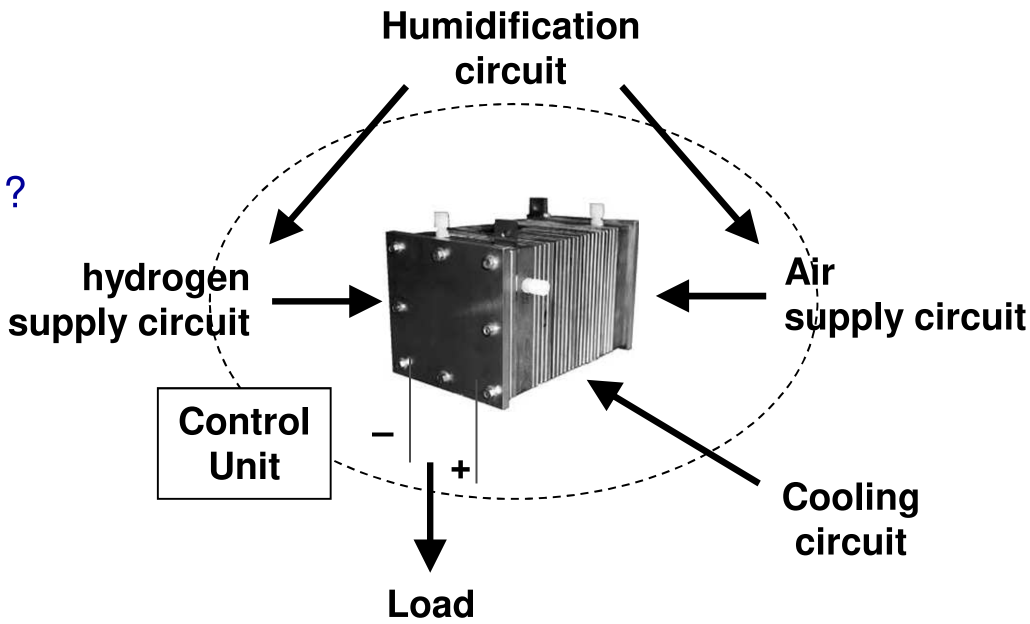
PEMFC Systems

– Whole PEMFC System

- **The stack within a whole system**
  - Stack "only" converts energy…
  - Prior to the electrochemical reaction
    - – How to supply "produce", store, and supply the hydrogen and oxygen?
  - After the electrochemical reaction
    - – How to manage the electricity generated?
    - – How to manage the heat generated?
    - – How to manage the water generated?
  - During the electrochemical reaction
    - – How to control the process?
    - – How to ensure safety of the whole system?

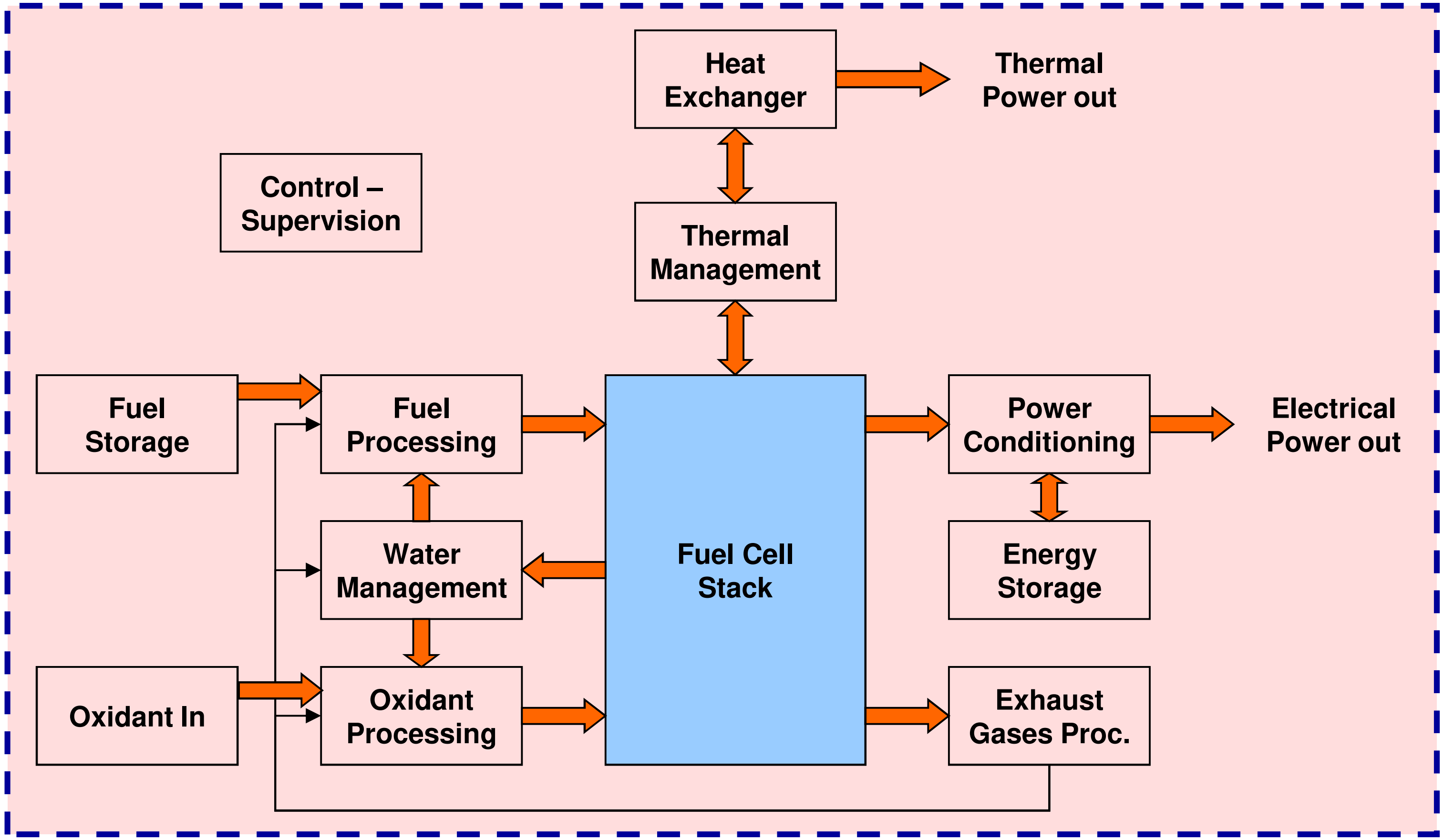
H2SYS

⇨ **FC System = Stack + Ancillaries**



Hydrogen FC Systems

– **Fuel cell stack + ancillaries + H2 storage + electrical storage**
  - **Complex multiphysics system**
  - **Scientific interdisciplinarity:**
    - Electrochemistry, but also: electrical engineering, electronics, control, signal & data treatment, artificial intelligence, industrial computer science, mechanics, thermal science, … & human and social sciences…



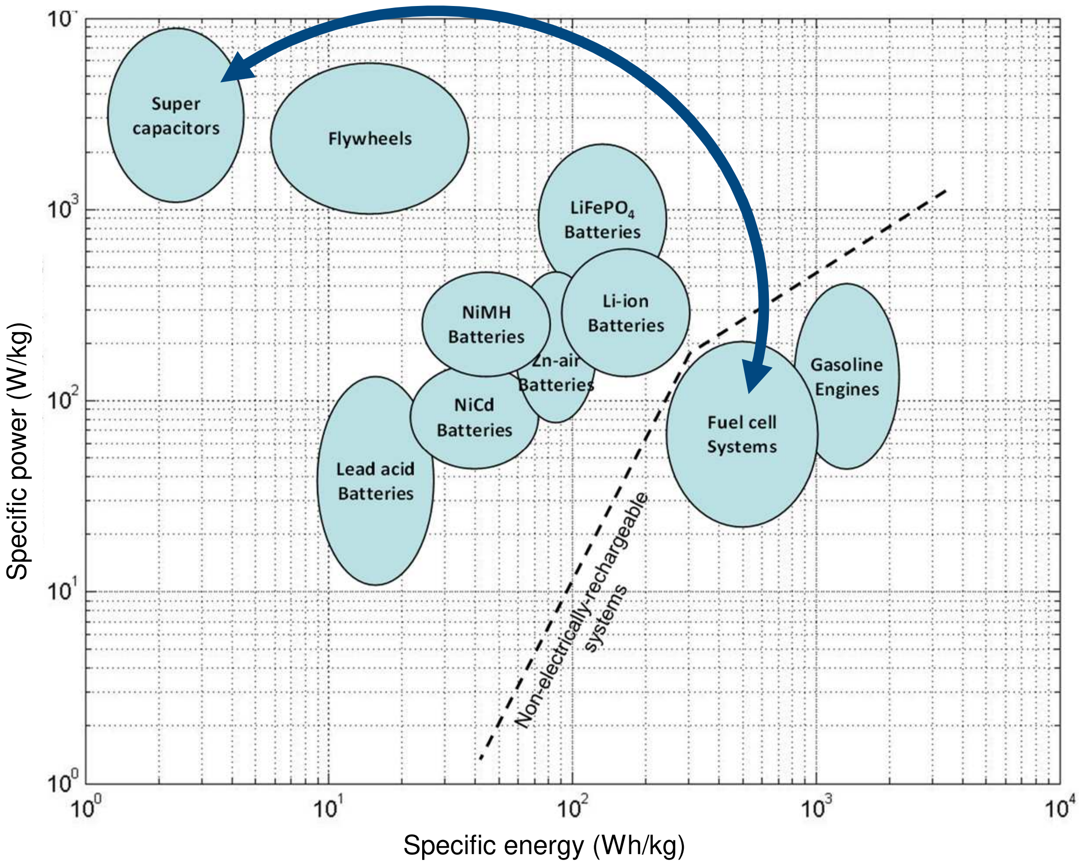
PEMFC Systems

– **Whole PEMFC System**

- **The need of electrical hybridization…**
  - FC = non electrical rechargeable system
  - FC = no possibility of recovering braking energy in transport applications
  - FC = poor dynamic systems (time constants about 100ms) ➔ smoothing energy requirements is mandatory

➔ Ragone plot…

➔ Hybridization with supercapacitors / flywheels / power batteries?



MC.Péra, D.Hissel, H.Gualous, Ch.Turpin, "Electrochemical components", Wiley, 2013.

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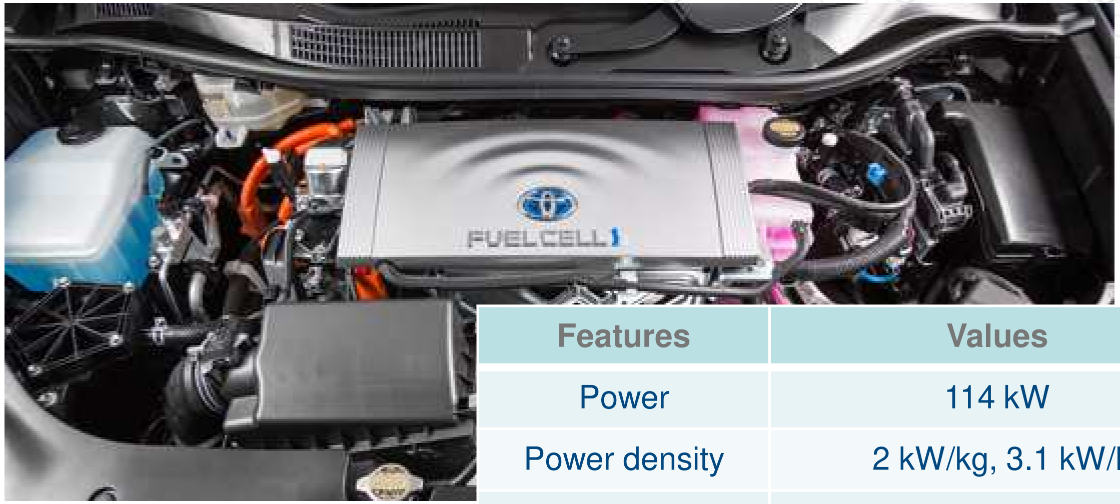
Part 2 – What are the targets for a mass market ?

Commercial applications already exist !

– **Toyota Mirai**



Features	Values
Power	114 kW
Power density	2 kW/kg, 3.1 kW/l
NiMH battery	1.6 kWh
H_2 tanks	700 bars, 10 kg
Autonomy	500 km
Price	Around €50k (or leasing)

– **And also residential applications : Panasonic µCHP system**

Features	Values
Electric Power	750 W
Thermal Power	1 kW (19kW peak)
Supply	Natural gas
Overall efficiency	ca. 90%
Electric efficiency	ca. 37%
Price	€20k

A fast growing market…

- About 20k vehicles and about 500k stationary systems sold / leased today
  - About **40%** grow in MW shipments between 2018 and 2019
- A reference to be reached to ensure a larger market : DOE

2020 Targets by Application

	Vehicles	Stationary
Fuel Cell Cost	\$40/kW \$30/kW*	\$1,000/kW** \$1,500/kW***
Durability	5,000 hrs 8,000 hrs*	80,000 hrs
Efficiency	65% 70%*	50% † 90% ‡
H_2 Storage Cost (On-Board)	\$10/kWh 1.8 kWh/L, 1.3 kWh/kg	
H_2 Cost at Pump	<\$4/gge **** <\$7/gge (early market)	

[REF] D. Papageorgopoulos, DOE Fuel Cell R&D Activities: Strategy, Advancements, and Opportunities, FDFC'2017 Conference, Stuttgart, Germany, 2017.

*** : ultimate**

**** : for natural gas**

***** : for biogas**

****** : gge = gallon gasoline equivalent = approx. 1kg H2**

Where are we today ?

– **Electric efficiency**
  - Maximal value of about **45% to 55%**

– **Durability**
  - In-situ or ex-situ tests, under transportation actual operating conditions (stop/starts, vibrations, electrical cycling, thermal cycling, humidity & pollutant conditions, …)

    ➔ **about 3500 hours for vehicle applications**

    ➔ **about 20000 hours for bus applications**

    ➔ **about 20000 hours for stationary applications**

– **Power density**
  - > 1,5 kW/l for the FC stack
  - > 1 kW/l for the fuel cell system

– **Energy density**
  - Strongly linked to the storage of H2

– **Cold start (automotive applications)**
  - From -20°C in 30 seconds without external energy

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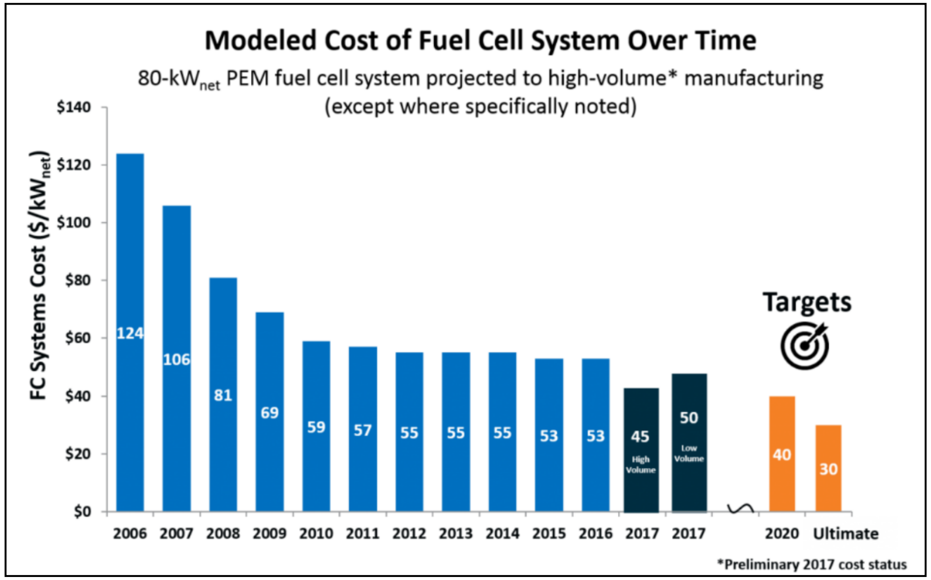
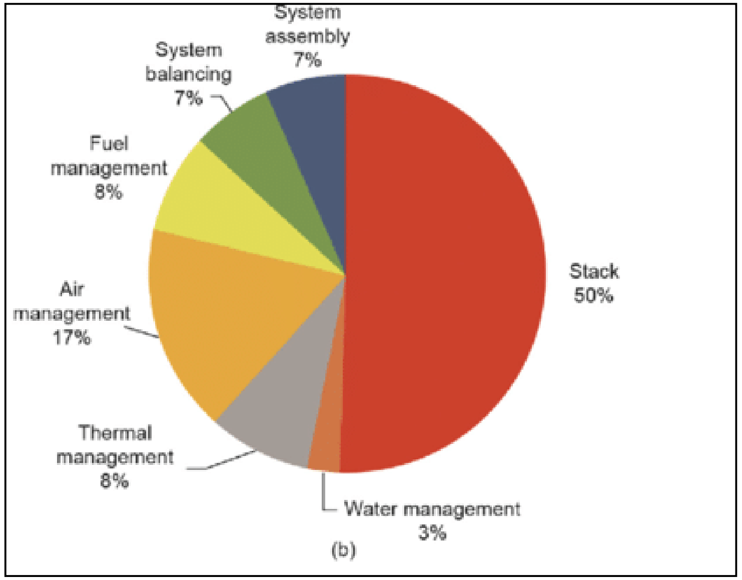
Where are we today ?

– Costs

▪ FCS costs



Projected costs for a 80kW-FCS - high-volume manufacturing (500000 units/year) – 2017's status



Costs distribution for a 80kW-FCS 2018's status

▪ H2 costs

Approx. 6 €/kg (for 80kg/day of H2 distribution)

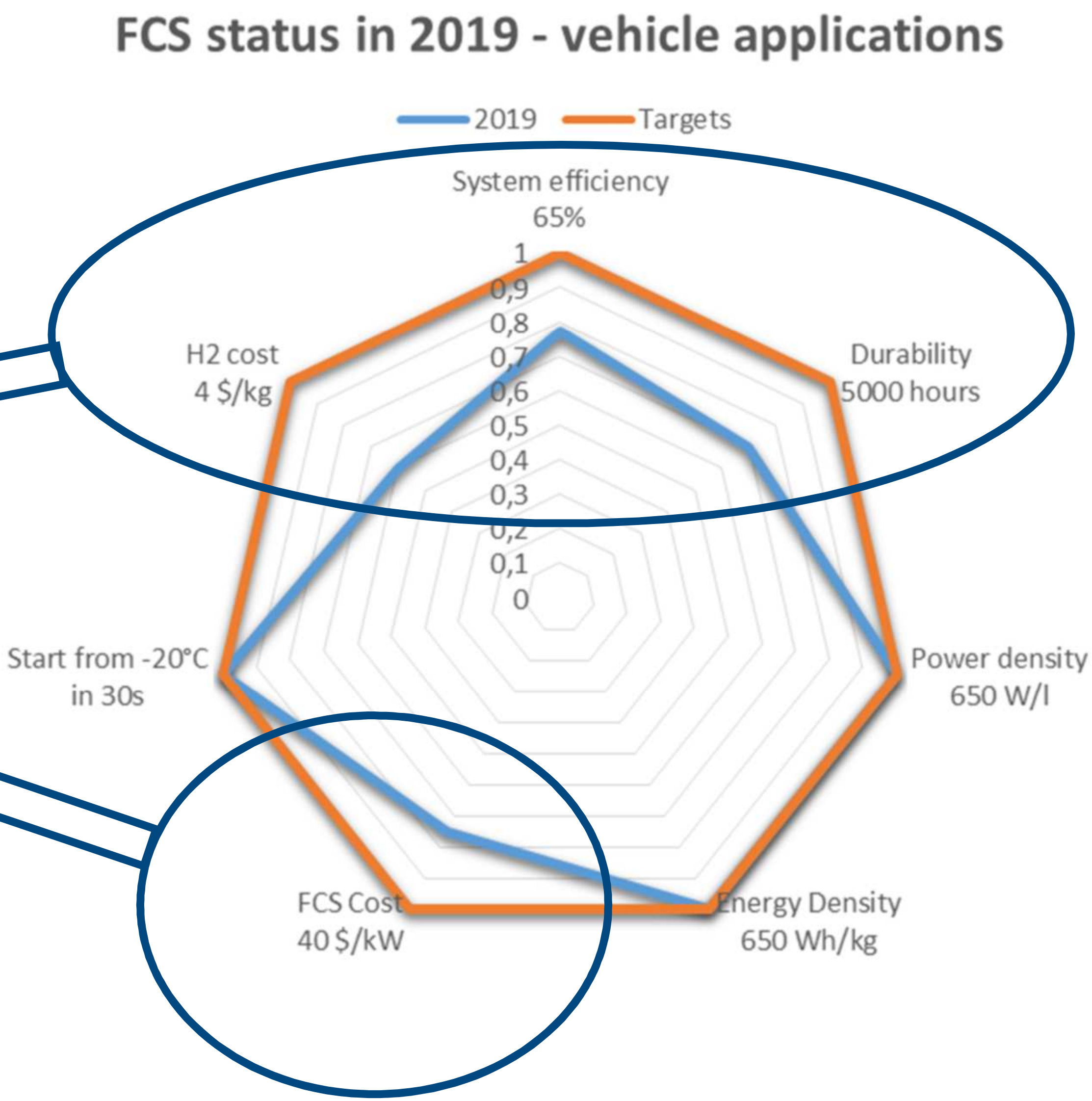
Large refueling station : approx. 1 M€

[REF] J. Wang, H. Wang, Y, Fan, Techno-economic challenges of fuel cell commercialization, Engineering, 2018.

[REF] DOE Fact of the Month for April 2018: Fuel Cell Cost Decreased by 60% since 2006, FuelCellsWorks, May 2018.

Where are we today ?

– **Radar plot regarding the DOE targets**



Research work must be performed on :
- **Efficiency**
- **Durability**
- **Costs**

The emerging hydrogen economy

Part 3 – Open issues & ongoing research actions

Where are the development headings ?

– Towards enhanced performances

▪ Scientific and technological bolts

- Fuel cell system **efficiency**
  - Increase it (elec. only) from about 45-55% to about 55-65%

- Fuel cell system **durability**
  - Ex. for PEMFC systems
    - 5000 hours are required for light vehicles (3500 hours obtained)
    - 30000 hours are required for bus & trucks
    - And up to 100000 hours for stationary applications & railways

- Public **acceptance**
  - Socio-economic aspect: hydrogen-based energy is unknown
  - Strong link with public policies

- **Cost** (whole life cycle)
  - Linked to industrial deployment

- **“Green” H_2 availability**
  - Production, storage, distribution

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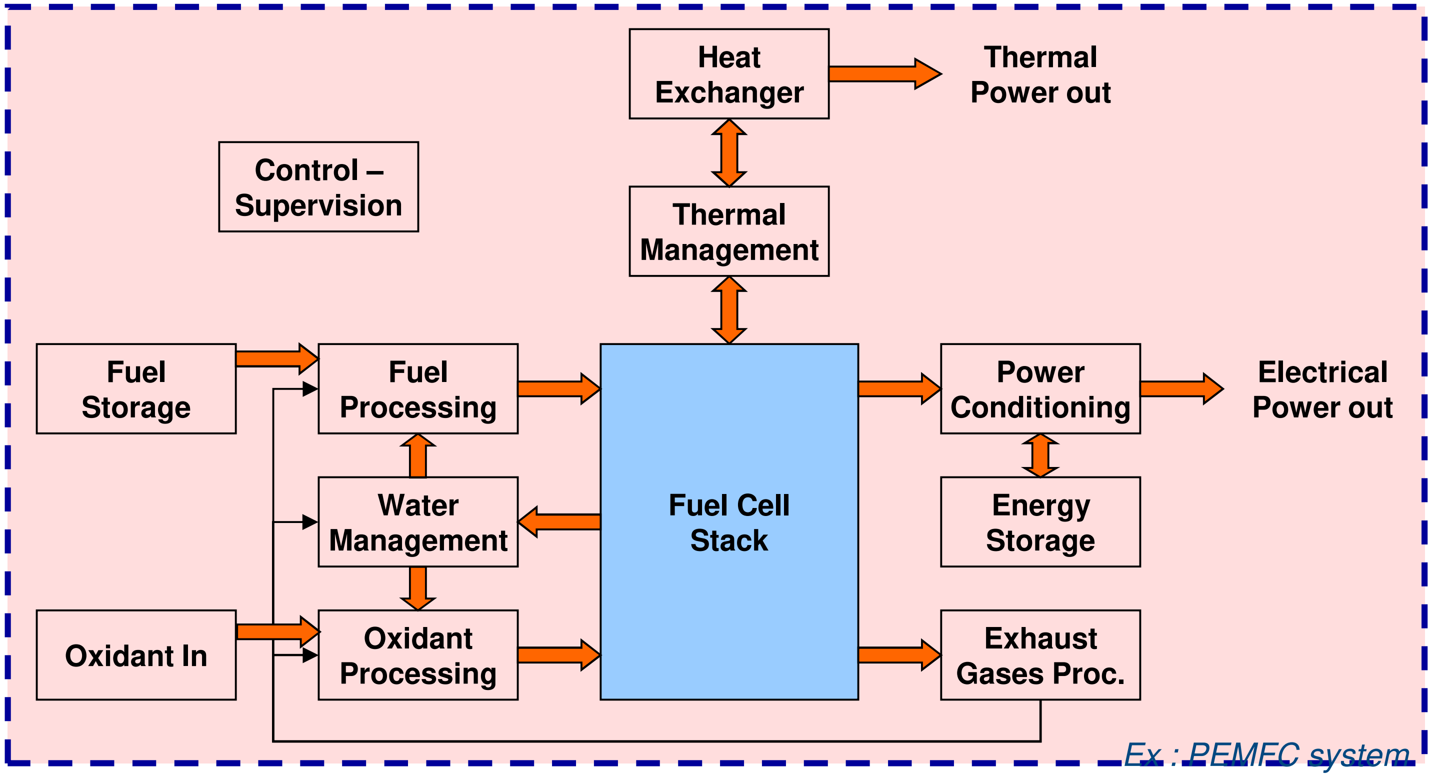
Areas of research : efficiency

- **Efficient & dedicated ancillaries are required…**
  - Specific power converters, specific air compressor, fuel storage, …
- **"Systemic" optimization of the architecture, taking care of all energy flows**
  - Electrical flows, thermal flows, gas flows…
  - Hybridization with batteries, ultracapacitors, …
- **Advanced control laws**

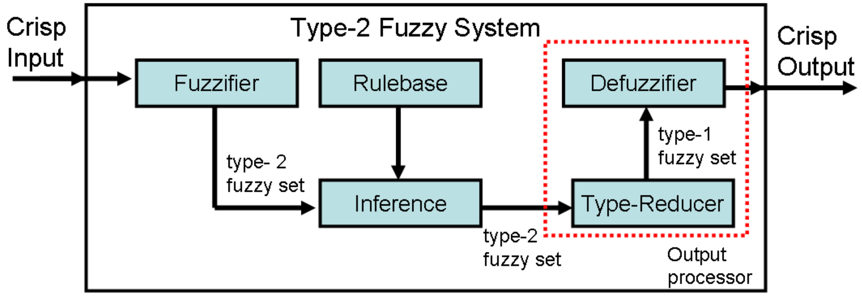


Areas of research : efficiency

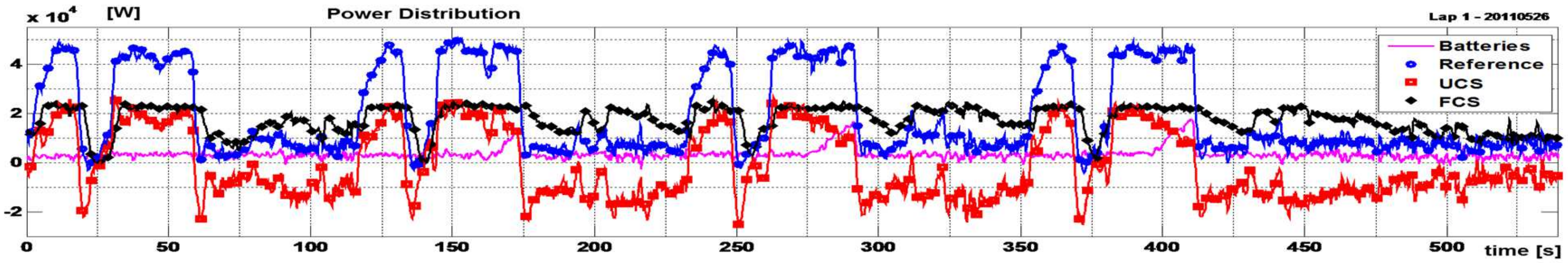
– **Optimize energy flows…**

Use of AI approaches

Propose efficient (& real-time) energy management strategies



Ex : PEMFC system



– **Optimize simultaneously the energy flows and the system architecture…**

Use of new metaheuristics

Areas of research

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Durability

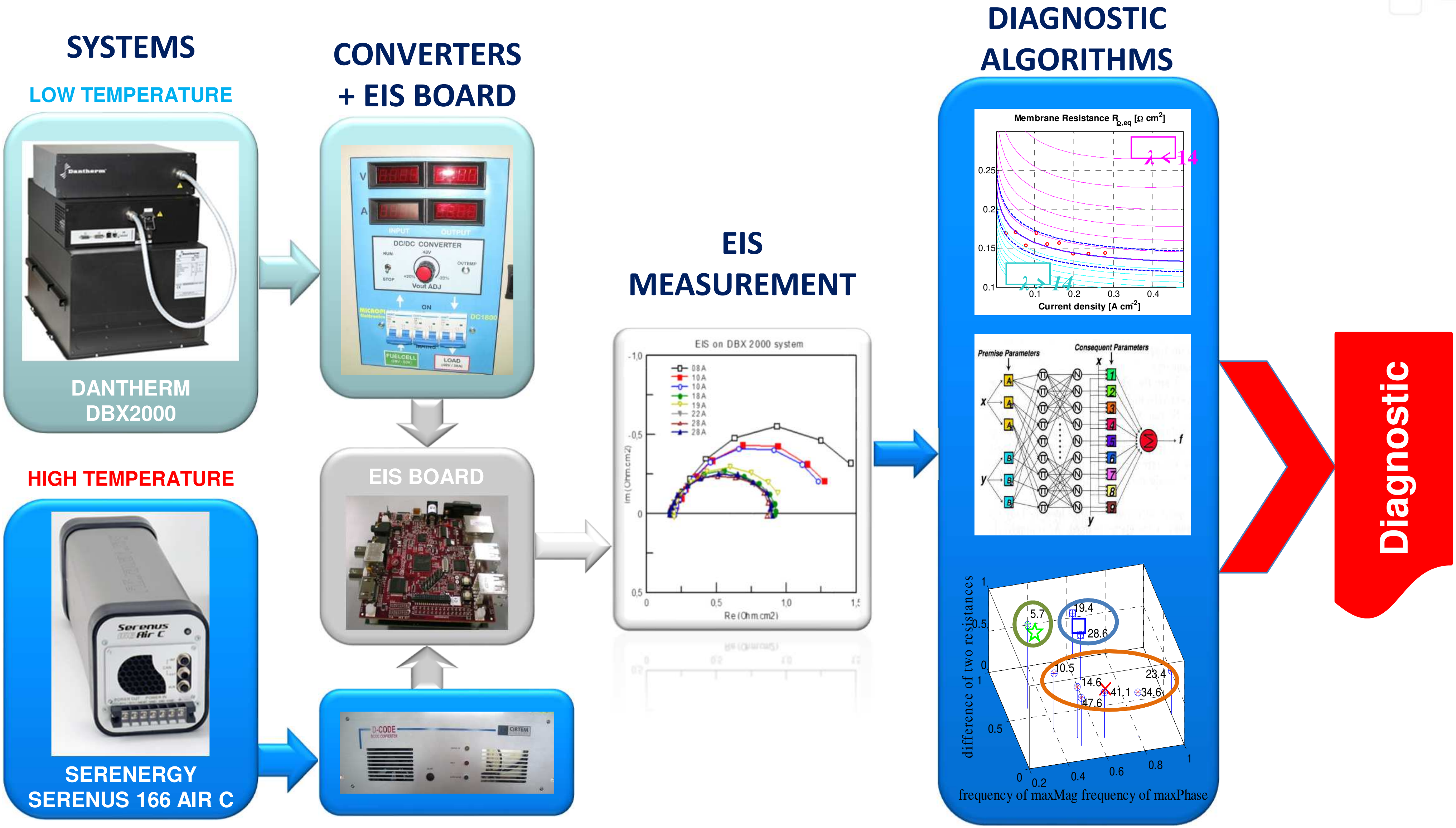
- **Objectives**
  - Increase durability of the fuel cell stack and of the fuel cell system
  - Increase efficiency of the FC system
  - Increase reliability of the FC system
  - Increase dynamic performances of the FC systems

FC STACK S.O.H.
DIAGNOSTIC / PROGNOSTIC METHODOLOGIES
ARE A KEY ISSUE !!!

- **Constraints**
  - Use of a minimal number of actual sensors
    - For complexity purpose
    - For cost purpose
    - For reliability purpose
    - For real-time control constraints

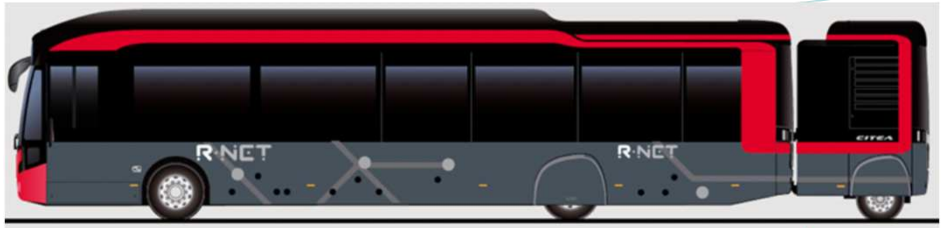
Example : signal-based FDI

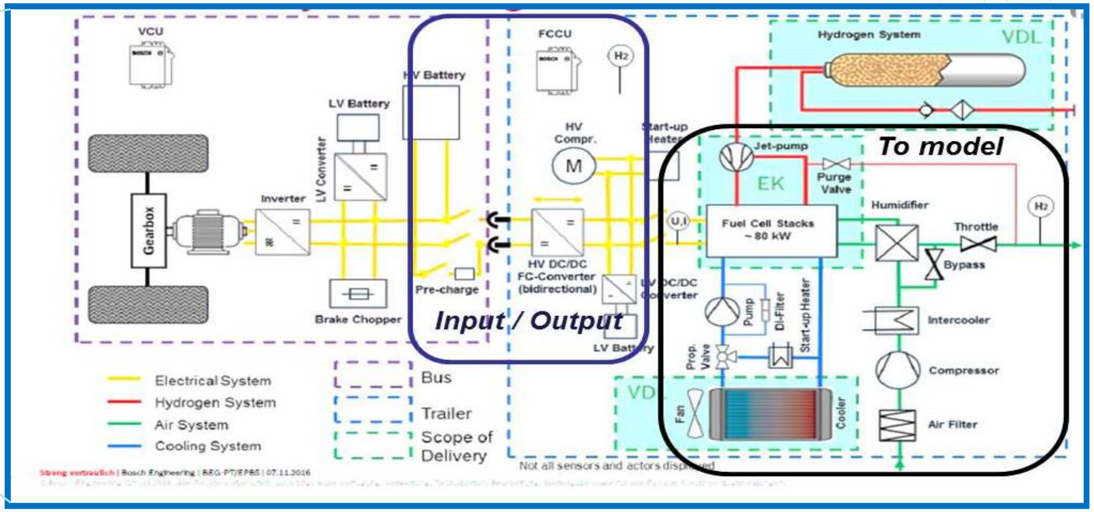
– **Example : DC-DC converter based diagnostics for PEM systems**



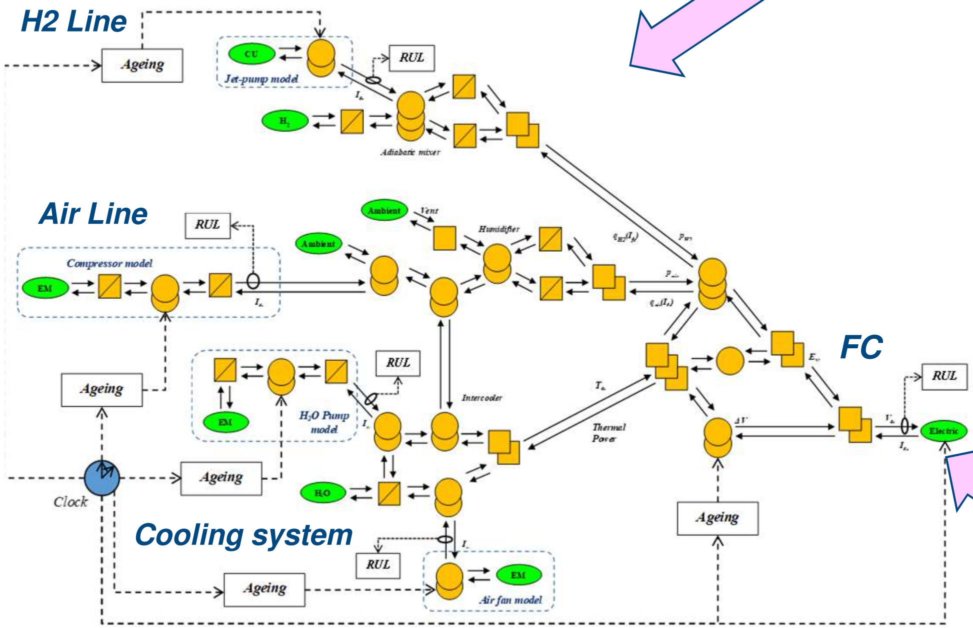
Example : on-line RUL estimation

– Example : integrated diagnostic/prognostic algorithm for embedded PEM systems





Model based prognostic algorithm

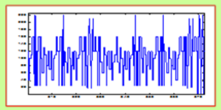


Online estimation of :

- **Performances**
- **Ageing** of the FC system
- Remaining Useful Lifetime (**RUL**)

Input

Load profile



Areas of research

– Towards enhanced performances

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Areas of research : public acceptance

- A global framework

- **Historical approach of H2 & FC**
  - Diachronic and synchronic approaches

- **Public policies**
  - Strong involvement of governments is required (funding, taxes, …)
  - Funding for innovation & for research
  - Key countries: Japan, Germany, China, Canada, USA, South Korea, France, Portugal…

- **Evaluation / mitigation of risks**
  - Normalization / standardization
  - Certification / evaluation of security issues

- **Demonstration programs**
  - Assessment of the technology in real world applications

- **Awareness on the technology**
  - Demonstration programs
  - Teaching fuel cell from lower classes

Example : Assessment in real world

Mobypost EU project – La Poste objectives

- Economic perspectives :
  - Proof of concept for the vehicle + local production of H2
  - Demonstration of economic viability of H2 for captive fleets
- Energy transition :
  - Reduce CO2 emissions and dependency to fossil fuels
  - Coupling with renewables and storage of excess production
- Social acceptance :
  - Increase postmen's security and working conditions
  - Feedback on regulatory constraints

Key numbers

- **2** demonstration territories in B-FC region
- **2** years experimental trial
- **8** European partners
- **10** FC vehicles
- **920** MM work
- **1682** postal routes covered
- **2017** (demonstration ended in…)

Example : Assessment in real world

Mobypost EU project – Main project objectives

- Taking care of postmen requirements
- Design an optimized hybrid FC powertrain
- Energy flow supervision
- Coupling with renewables (PV panels)
- Hydrogen production & storage on-site
- 1st French FCV fleet (10 vehicles, 2 H2/PV stations) testing in constrained environment (temperature, power demand)

Areas of research

– Towards enhanced performances

▪ Scientific and technological bolts

- Fuel cell system **efficiency**
  - Increase it (elec. only) from about 45-55% to about 55-65%
- Fuel cell system **durability**
  - Ex. for PEMFC systems
    - 5000 hours are required for light vehicles (3500 hours obtained)
    - 30000 hours are required for bus & trucks
    - And up to 100000 hours for stationary applications & railways

- Public **acceptance**
  - Socio-economic aspect: hydrogen-based energy is unknown
  - Strong link with public policies

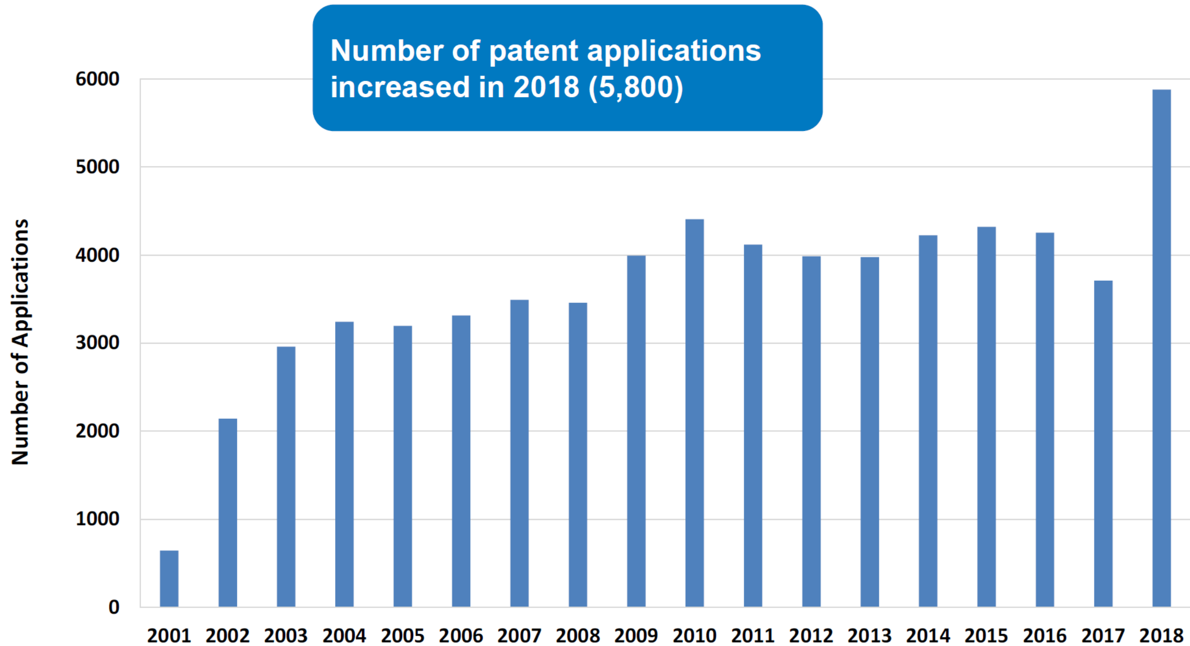
- **Cost** (whole life cycle)
  - Linked to industrial deployment

- **"Green" H_2 availability**
  - Production, storage, distribution

Areas of developments : costs

– Reduce the costs

- **A strong industrial interest** *(source Fuel Cell Industry & Patent – Overview 2015 - HGF)*
  - H2 & Fuel cells are leading to about 6000 patent applications in 2018 (+40% from 2017)
  - Key players : Honda, Toyota, Panasonic, Nissan, GM, Hyundai, Daimler, …
- **2019's prices**
  - About 500€-2000€/kW for one single FC stack – projected cost for 500000 units / year = 27€/kW
  - 50% FC stack + 50% FC ancillaries
  - About 1200€/kW for one single WE stack
- **A (small) hydrogen refueling station (700 bars) ≈ 1M€**



Pacific Northwest National Lab, USA, 2019

Areas of developments : costs

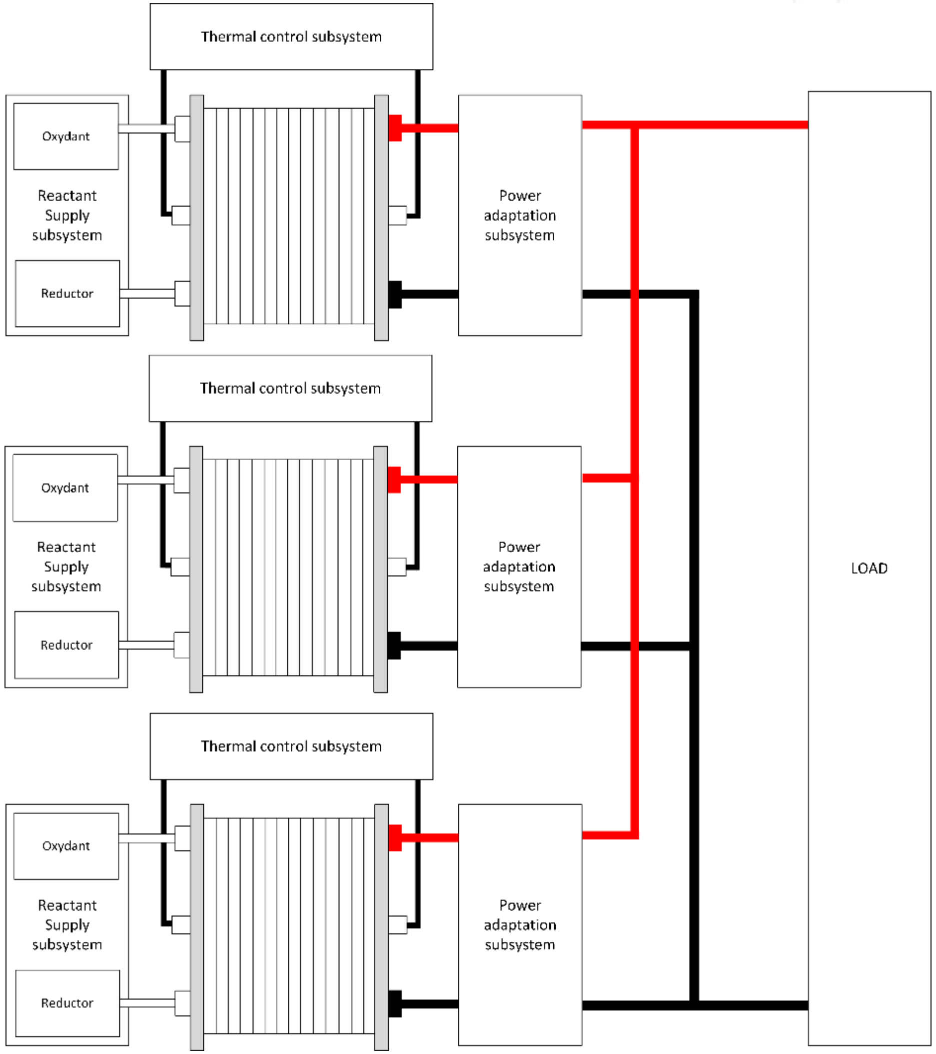
– What can be done ?

- Use of lower cost components (EME)
- **Process automation (especially for bipolar plates)**
- Design of specific ancillaries (e.g. the air compressor)
- Understand in deep the degradation mechanisms
- Optimize the whole system not only the components
- **Focus on "interesting" emerging markets** (forklifts, micro-CHP, backup power, storage of renewables, military applications (U-boats, portable, backup), aeronautic applications, …)
- **Increase modularity of FC and WE systems**

Example : Modularity of FC systems

Interests

- Ability to manage degraded mode operation
- Better performances:
  - Maximize efficiency
  - Increased lifetime
- Simplified implementation on board
- Easy scaling-up
- Modular system
  - Same FC system can address different applications (road, trucks, rail, stationary…)
  - Cost reductions



[REF] N. Marx, “Multi-stack FC systems for automotive applications”, Cotutelle PhD. Univ. Franche-Comte, Univ. Quebec Trois-Rivières, 2017.

Areas of research

– Towards enhanced performances

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Areas of developments : green H_2 availability

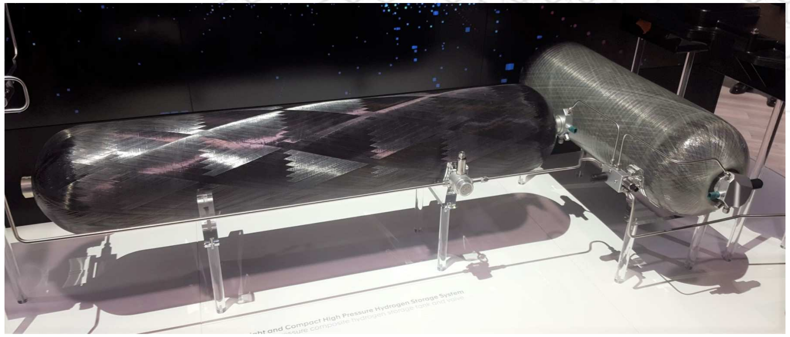
– **Increase H_2 production from renewables**
  - **Today, about 95% of H_2 is coming from fossil fuels**
    - steam reforming or partial oxidation of methane
    - coal gasification

  - **Key issue** for :
    - public acceptance
    - sustainable energy developments
    - decentralized energy production
    - coupling to biomass

Myrte Platform

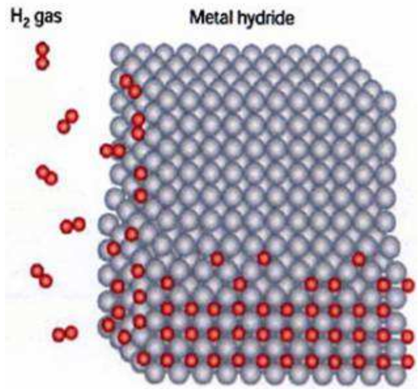
– **What can be done ?**
  - **Seasonal storage** of renewable electricity
  - **Convergence** between stationary applications & mobile applications
  - Developments of PEM & SO **electrolyzers**
  - **Exergetic optimization** of the whole electrolyzer / storage / fuel cell system
  - Development and deployment of refueling stations

Areas of developments : green H_2 availability



- **Storage of hydrogen**
  - **3 main technologies**
    - **High pressure storage** (from 30 to 700 bars)
      - Stationary and transport applications
        - Pros : durability, security, existing industrial process
        - Cons, what has to be improved : cost, manufacturing time, gravimetric density <6%
    - **Metal hydrides** ("Solid state" storage)
      - Adsorption / desorption of H2 on storage materials
        - Pros : low pressure, security, volumetric density
        - Cons, what has to be improved : mass, gravimetric density (2%), adsorption/desorption kinetics, thermal management of the whole system

Ovonic H2 storage



Areas of developments : green H_2 availability

– Storage of hydrogen

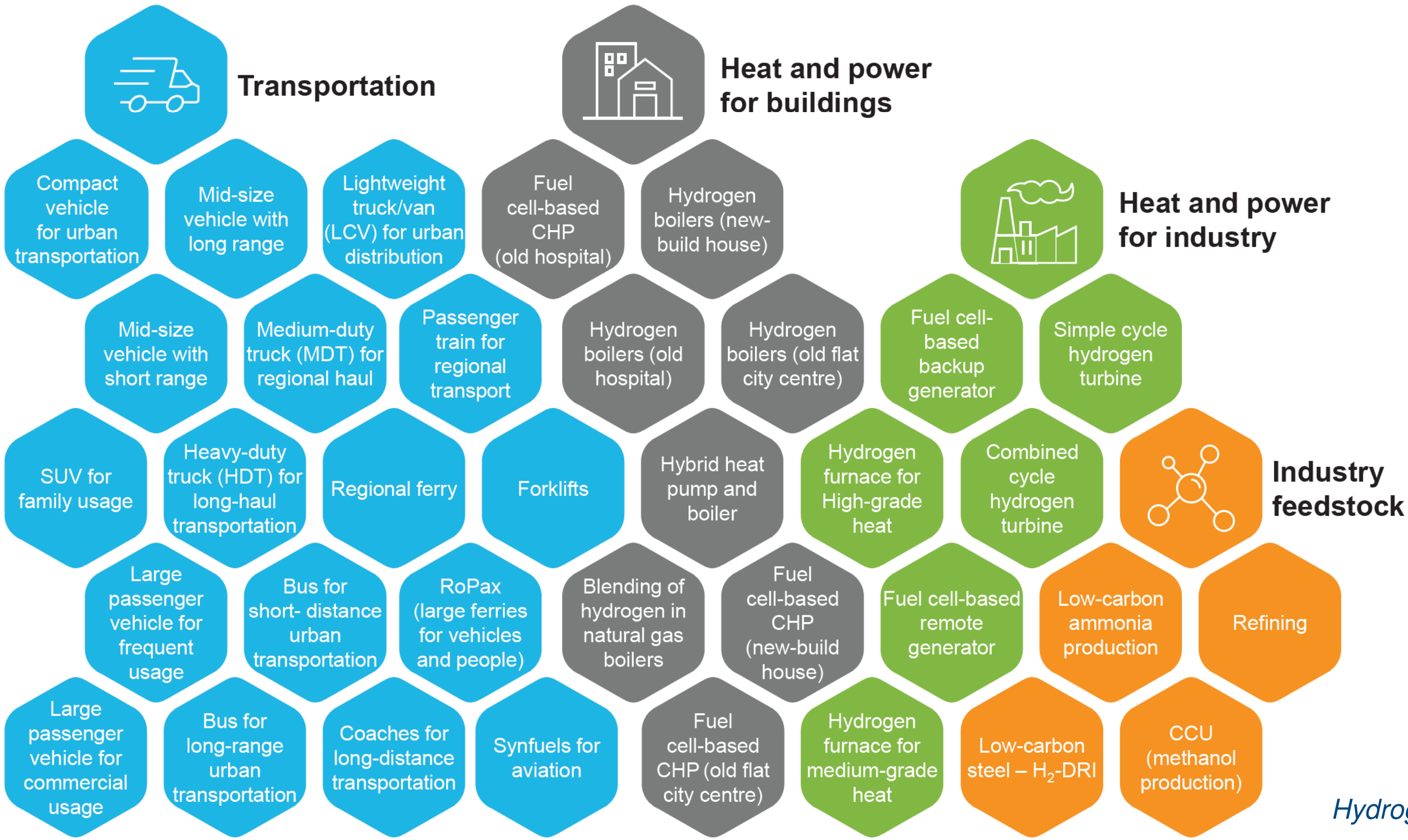
- **3 main technologies**
  - **Liquid storage**
    - Liquid hydrogen (@ -253°C)
      - Pros : presently, the best mass storage density : 15%, mastered industrial process, low pressure
      - Cons, what has to be improved : cost, limited storage time ability (24h), energy costs for liquefaction
    - Liquid Organic Hydrogen Carrier (LOHC)
      - Pros : long term storage, easy handling, existing refueling infrastructure, security
      - Cons, what has to be improved : system complexity & cost, catalysts, gravimetric density (6%)
    - Ammonia
      - Pros : long term storage, security, high gravimetric density (17%)
      - Cons, what has to be improved : toxicity, decomposition to hydrogen

The emerging hydrogen economy

Part 4 – Overview of hydrogen applications

Hydrogen applications

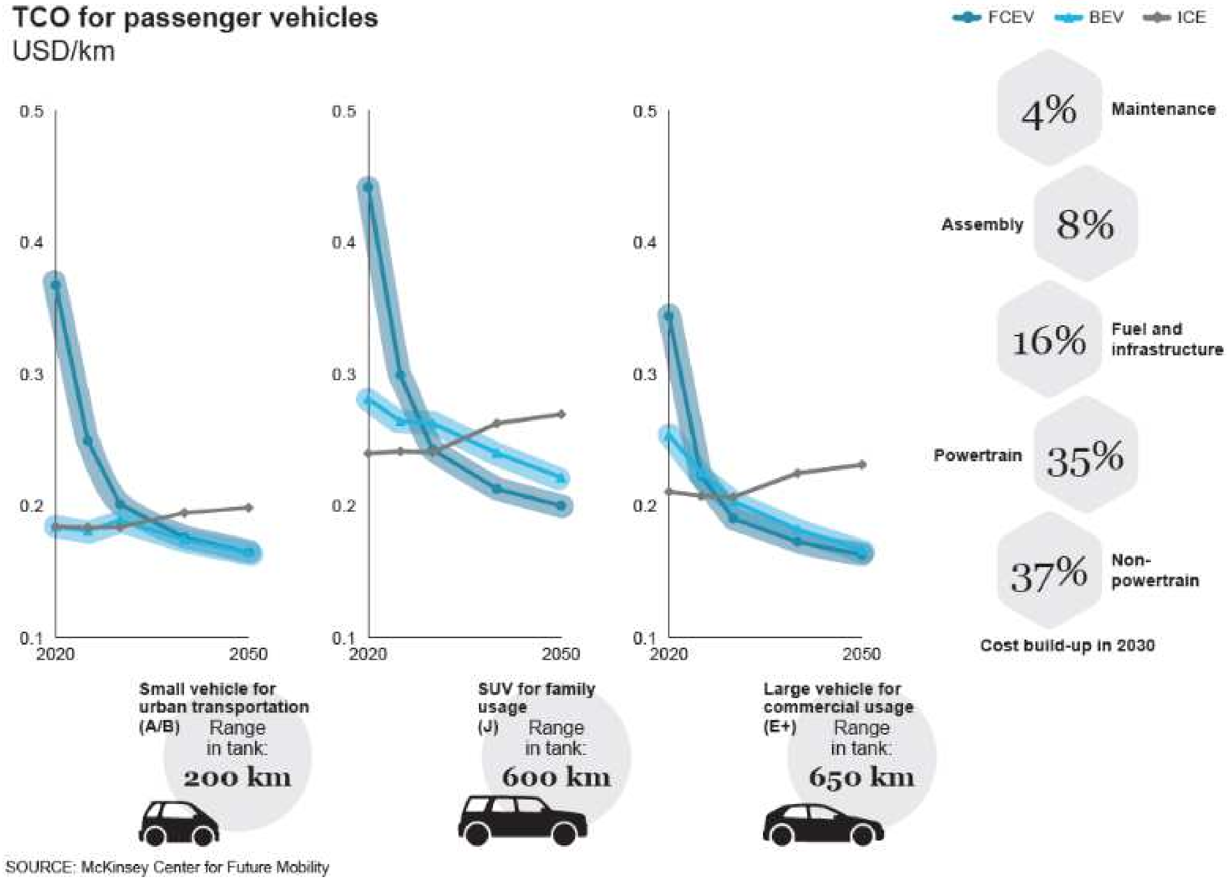
– Overview of hydrogen applications



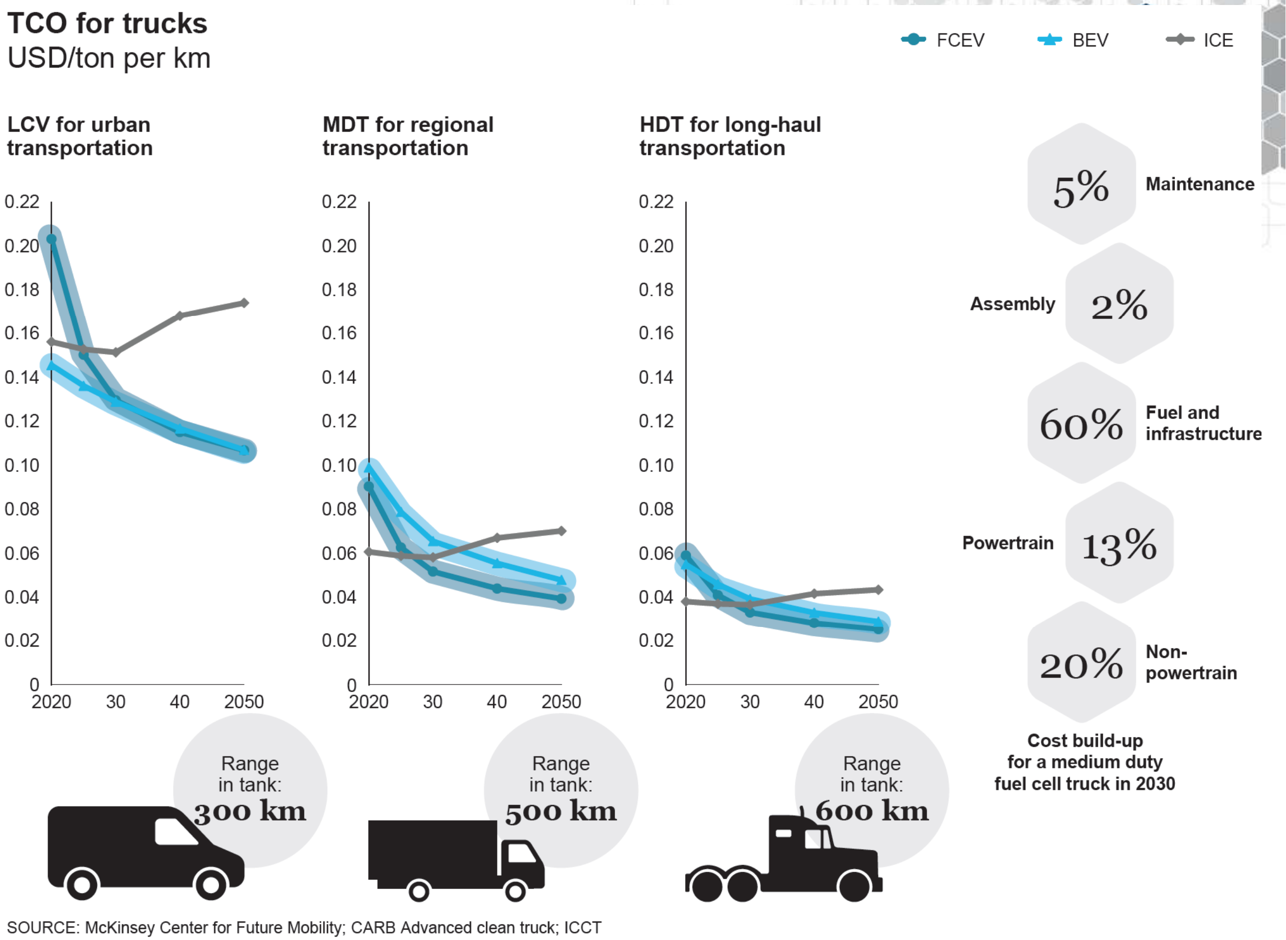
Hydrogen Council, 2020

Transportation applications

– **Passenger vehicles**
  - **About 20k vehicles around the world today**
    - France : 350 vehicles
    - World : + 7900 vehicles in 2019
  - **4 main manufacturers**
    - Toyota (Japan) – 2407 in 2019
    - Hyundai (Korea) – 4818
    - Honda (Japan) – 349
    - SAIC (China) – 300
  - **Roadmaps**
    - Hyundai : selling 700k fuel cell systems before 2030
    - China : 1M fuel cell cars commercialized before 2030
  - **FCEV can compete ICEV before 2030**
    - Major markets : SUV and large vehicles



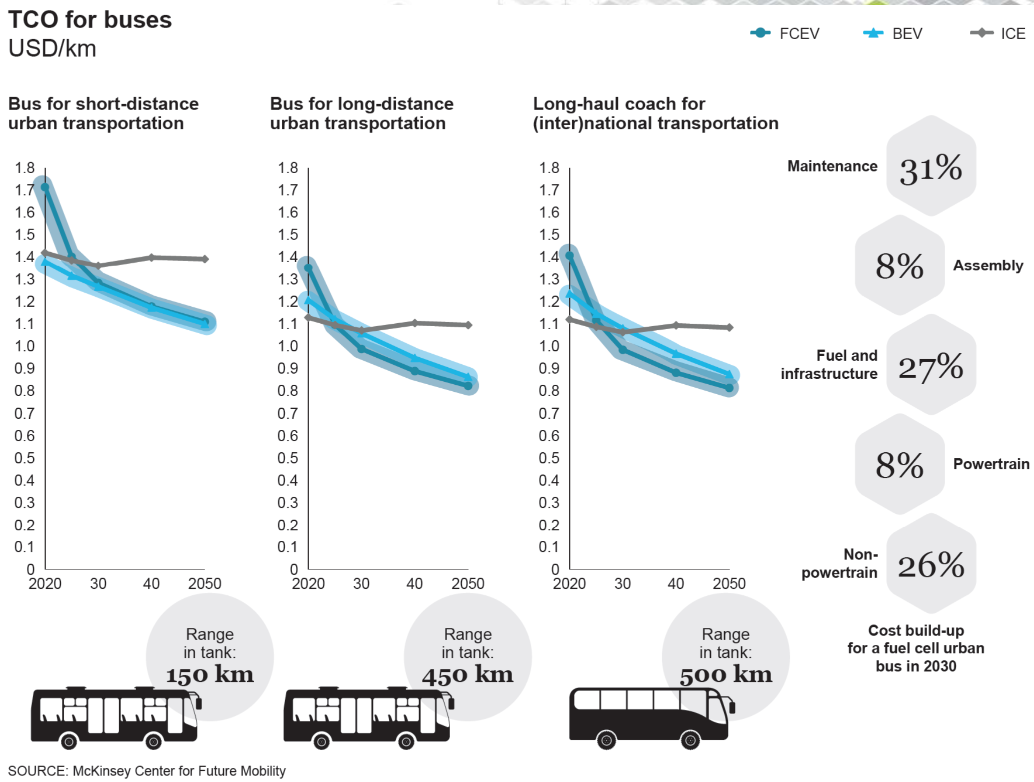
Transportation



– **Fuel cell trucks**

- **High requirements in energy and power**
  - Power : 250kW to 750kW
  - Energy : 7.5 to 16kg H2 /100km + 400km range at least
- **Main manufacturers :**
  - Hyundai (Korea) – 1600 ordered
  - Dongfeng (China) – 500 released
- **FC =** lowest-cost way to decarbonise both **the medium- and heavy-duty segments** (by 2025)

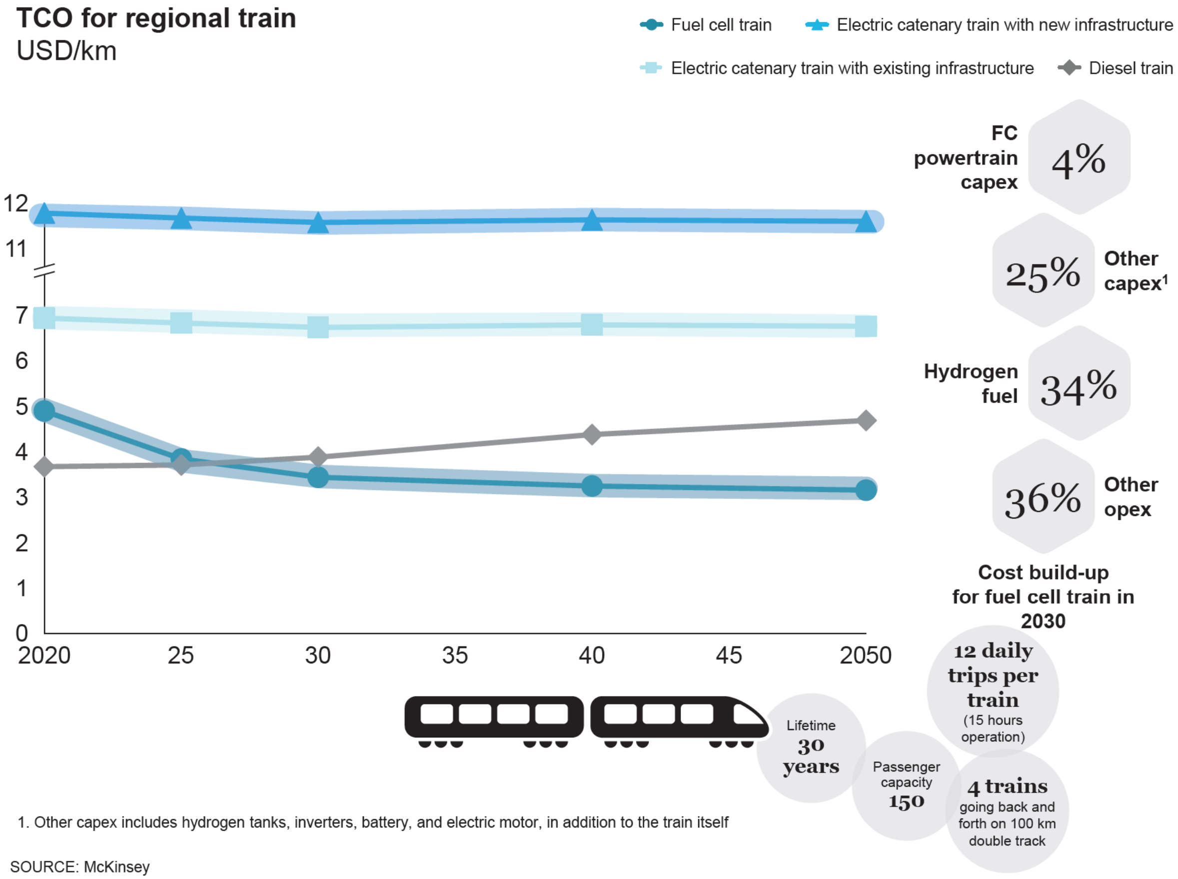
Transportation applications



– Fuel cell buses / coaches

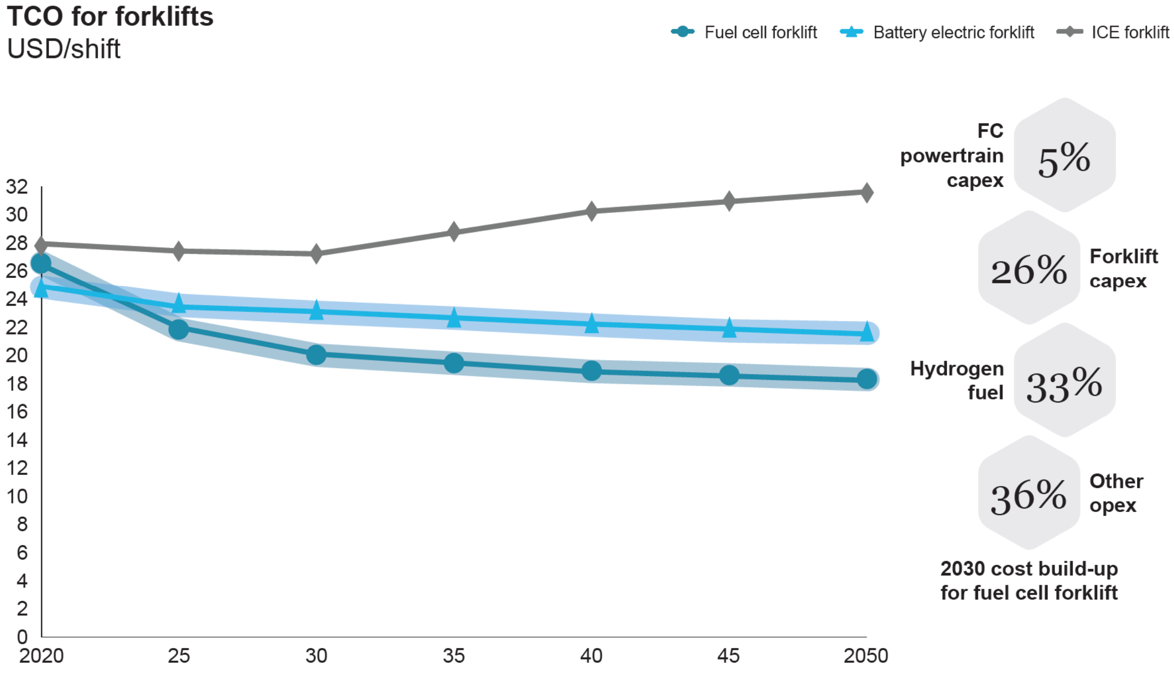
- **High requirements in energy, less in power**
  - Fuel cell : 30kW to 200kW for urban buses + battery
  - Energy : 7kg H2 /100km + 300km range at least
- **Many manufacturers involved**
  - Fast growing market
  - Volvo, Daimler, MAN, Van Hool, VDL, Hino Motors, …
- **FC =** very interesting for decarbonizing **long-range buses & coaches**. No real advantage versus battery bus in the short-range market.

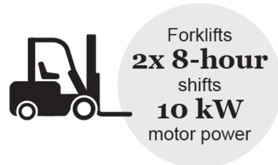
Transportation



– **Fuel cell trains**
- **Regional trains & freight locomotives**
  - 1000km max. range
  - Fuel cell : 400kW for regional passenger train
  - H2 : 350 bars, 260kg stored on board, 22-32kg H2/100km
- **Key manufacturers involved**
  - Fast growing market, many regional trains already ordered in France and Germany
  - Key players : ALSTOM, Siemens, …
- **FC** = best solution regarding TCO from 2025 for regional passenger trains…

Transport applications





– **Others**

- **Ex : Forklifts**
  - FC forklifts already outcompete the diesel and the battery in the right conditions
  - More than 30000 hydrogen forklifts already in use in the world
  - Key players: PlugPower, Hyster-Yale, …
- **Other application areas :**
  - Aeronautic applications
  - Boats
  - Garbage dumpsters
  - Off-road applications…

Heat and power applications

Mobile power gensets

Hybridized hydrogen-based power gensets

High efficiency

Zero noise

Zero pollutant emissions

Indoor & outdoor operation ability

From 1kW to 10kW electrical power

Fast refueling (30 seconds)

H2SYS

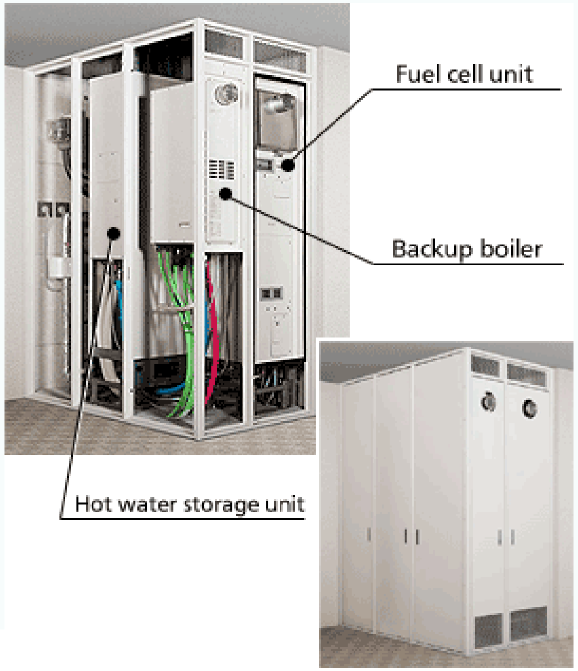
µCHP systems

Panasonic CHP Fuel Cell

Over 160000 systems sold

Features:

- 750W electrical power (rated)
- 1080W thermal power (rated)
- Fuel : city gas



Industry feedstock

– Various industry feedstock applications

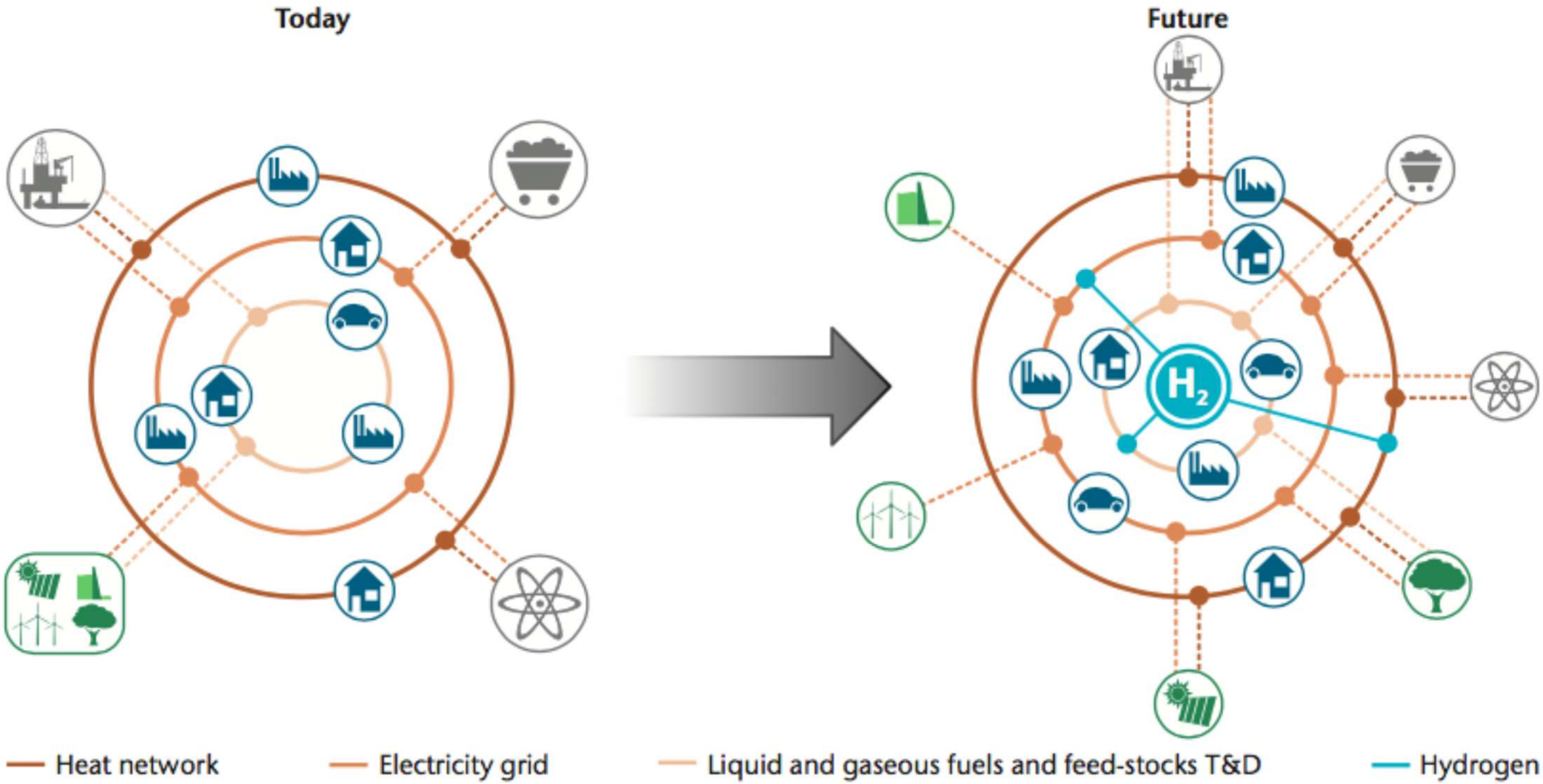
- **Ammonia production**
  - 55% of hydrogen produced in the world
  - 1MT of ammonia production requires 200kT of hydrogen (mostly grey hydrogen)
- **Refining**
  - 25% of hydrogen produced in the world
  - H_2 is used to remove sulphur from the produced fuels - hydrodesulphurisation
- **Methanol production**
  - 10% of hydrogen produced in the world
- **Low-carbon steel production**
  - 7 to 9% of world CO2 emissions (from fossil fuels) !
  - Strong need to decarbonize
  - New application area

The emerging hydrogen economy

Concluding remarks

Concluding remarks

– **H2 as the missing link of the energetic transition ?**



Concluding remarks

– **Stop stereotypes…**

- **Not enough H2 to power all vehicles !**
  - No use to power ALL vehicles… H2 must be used when & where BEV can not reach the requirements
  - Moreover, in 2017 :
    - H2 production worldwide is about 50M tons / year
    - 1 FCV will need about 150kg H2/year
    - **About 350M cars can be powered** (about 30% of the cars on road worldwide)

- **If considering H2 from water electrolysis, how many new power plants are needed ??**
  - No use to power ALL vehicles… H2 must be used when & where BEV can not reach the requirements
  - Moreover, in 2017 (France case study) :
    - In France, only 96TWh of electricity produced from hydro, windfarms, PV panels & bioenergies (approx.. 18%)
    - Considering H2 produced 100% from water electrolysis, and electricity coming only from Hydro, WF , PV & BioEnergies
    - About 40M cars in France (passengers + light duty)
    - For powering 100% of these vehicles, **we need to x4,5 (approx.) the electricity produced from renewables… or to increase by 80% the French nuclear power**

Concluding remarks

– **Reminders !**

- **Always 3 point of views**
  - **Engineer:** technological solutions
  - **Economist:** cost and ROI constraints of the solutions
  - **Consumer:** decides by him(her)self… based on the perceived value

- **Never forget the golden rule in innovation !**

  Considering industrial era, in the whole history of innovation, a substitution technology can only prevail if :

  1/ it provides (at least) the same level of perceived value than the former technology, at a 30% reduced price

  OR

  2/ it provides (at least) 30% increased perceived value, at the same price

Thanks to our research team !

Come & visit us on :

http://www.femto-st.fr

The emerging hydrogen economy

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