Hydrogen-energy systems for transportation applications

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- General Chair, IEEE Vehicular Power Propulsion Conference 2017, Belfort, France

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Hydrogen-energy systems for transportation applications

Motivations

Part 1 – Fuel Cell technology and PEMFC Systems

Part 2 – What are the targets for automotive applications ?

Part 3 – Open issues & ongoing research actions

Concluding remarks

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Hydrogen-energy systems
for transportation applications

Motivations

FC LAB Research

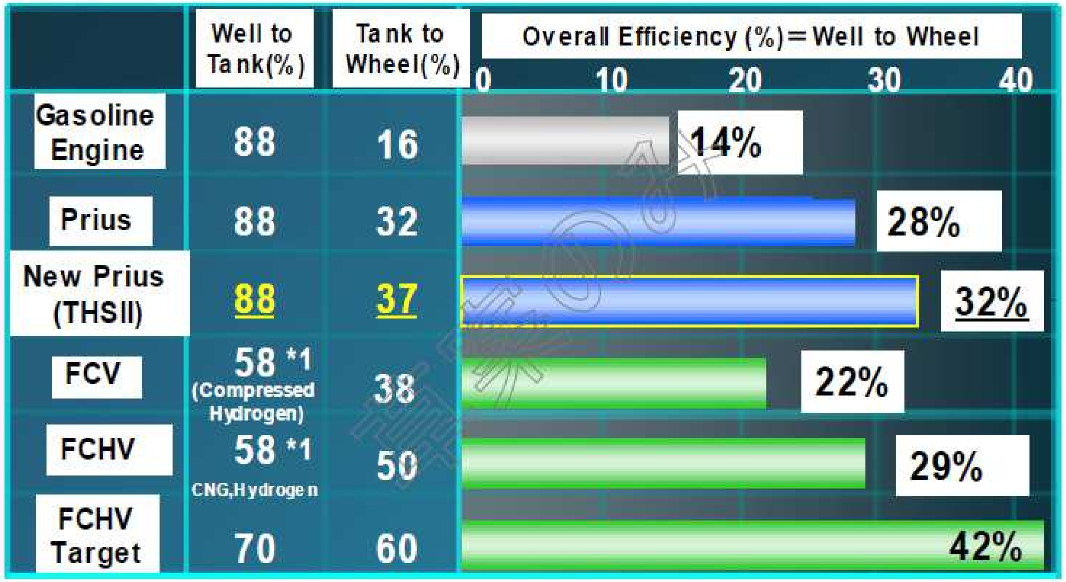
Towards FC systems

– Switching to fuel cell ? - Transportation applications

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

- **First alternative: BEV or HEV**
  - BEV : Significant progresses have been made 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: FCV / FCHV**
  - High efficiency
  - (*Theoretical & in-situ*) pollutant emissions is zero
  - Fast recharging – high autonomy
  - ⇨ **Attractive alternative**



**1 : natural gas to hydrogen*

T. Teratani, Toyota Motor Corp., Electric Propulsion Vehicles and Total Energy Management, IEEE VPPC 2012, Seoul, South Korea.

Towards FC systems

– **Switching to fuel cell ? – 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**
    - ⇨ **Attractive alternative**

Hydrogen-energy systems for transportation applications

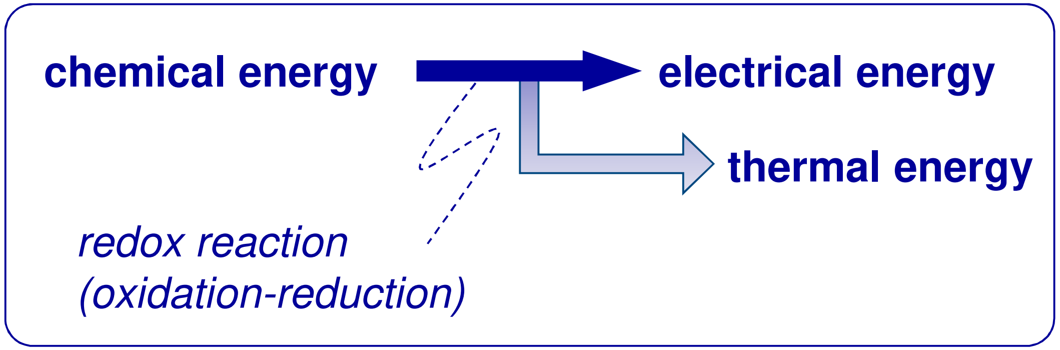
Part 1 – Fuel Cell technology and PEMFC Systems

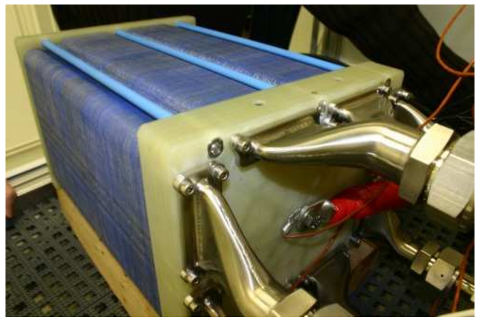
Fuel Cell technology

– 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**





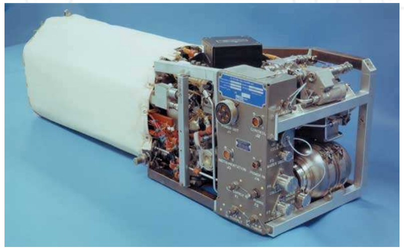
PEMFC -CEA

Fuel Cell technology

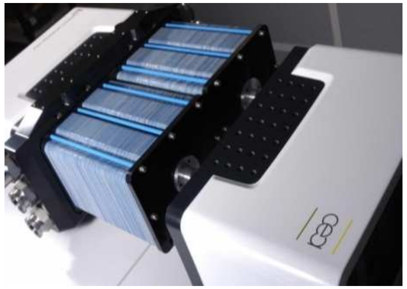
– Taxonomy of Fuel Cell

	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	**Automobile / Transport** Low-power stationary appl. (residential sector)
AFC	50 – 200	500 – 10k	Spaceships
PAFC	~220	10k – 1M	Domestic heat & electricity 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)



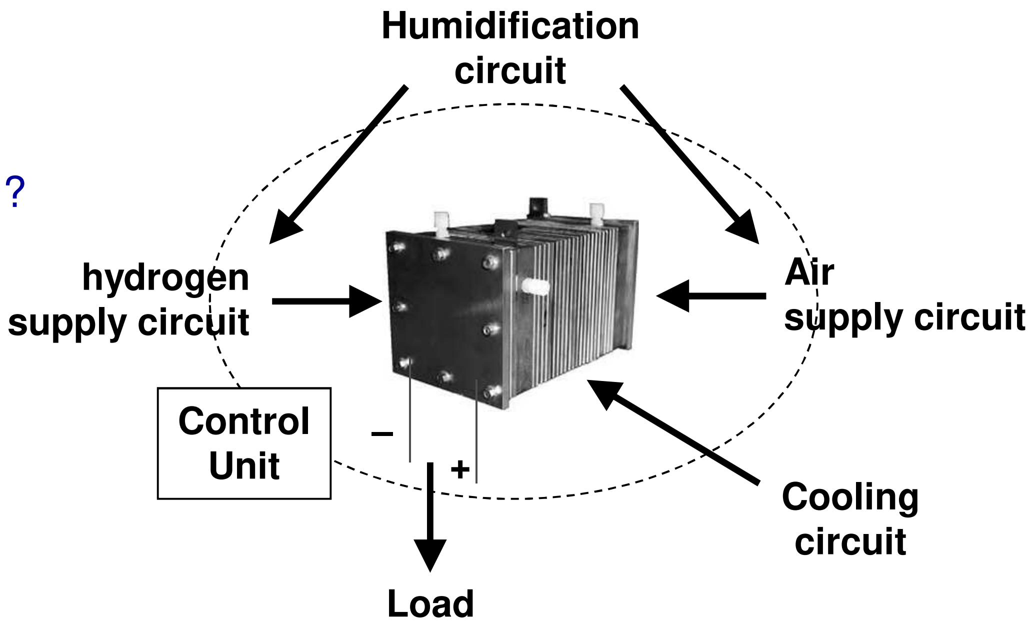
SOFC – Stat. Appl. (MSRI)

PEMFC Systems

– 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?

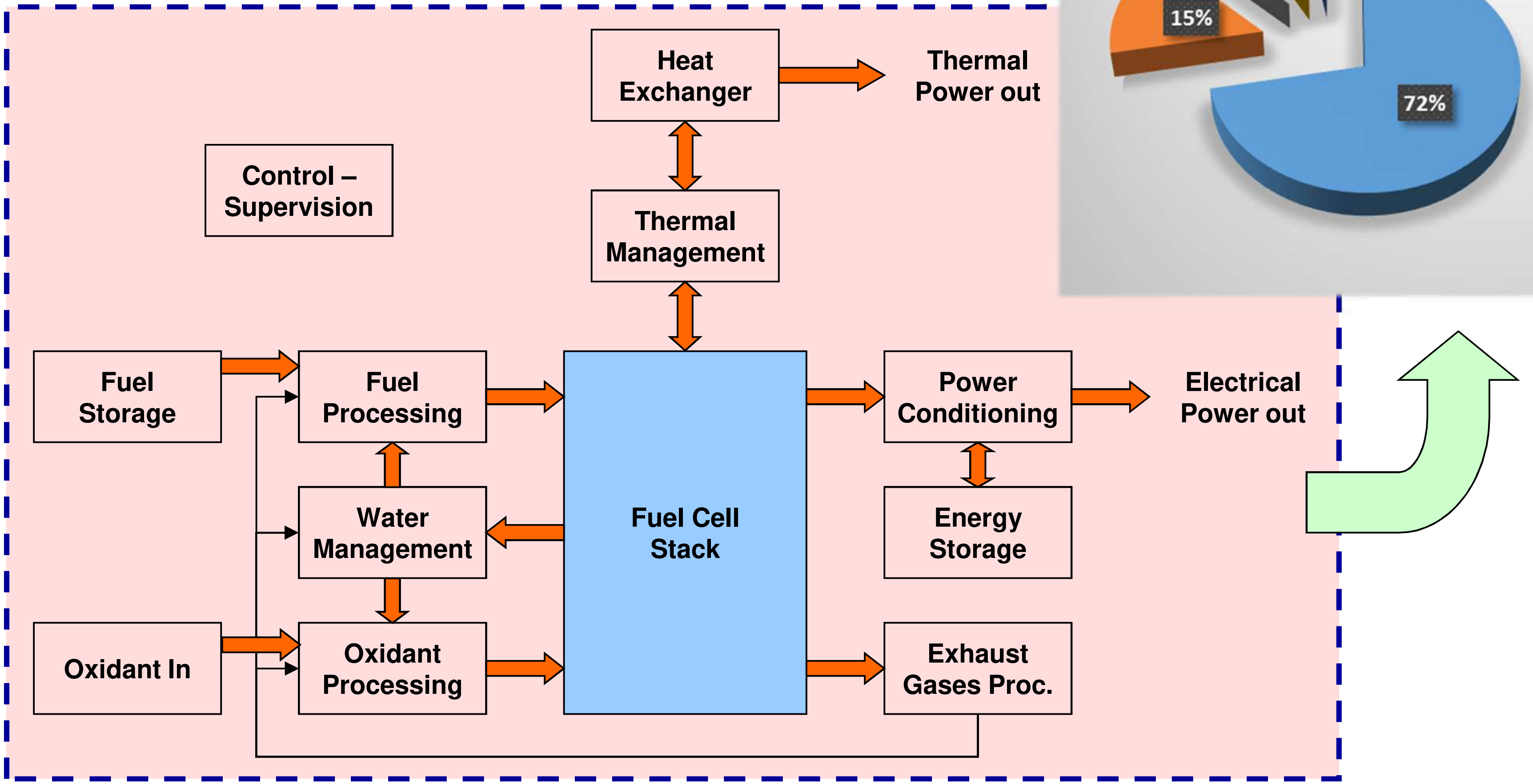
⇨ **FC System = Stack + Ancillaries**

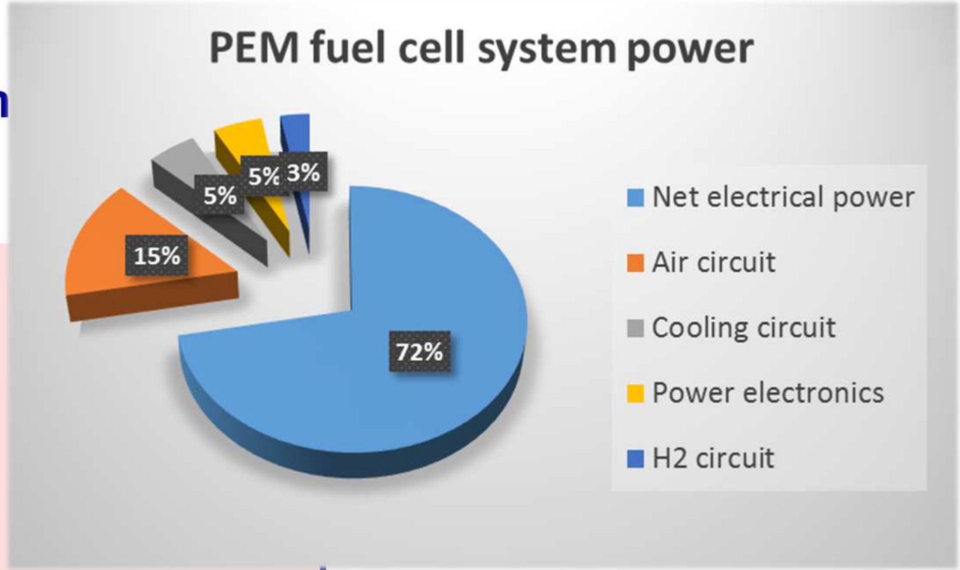


PEMFC Systems

– **Drawback from FC system's ancillaries**

- **PEMFC system: complex multiphysics system**
- **Leads to different losses (/ gross power)…**





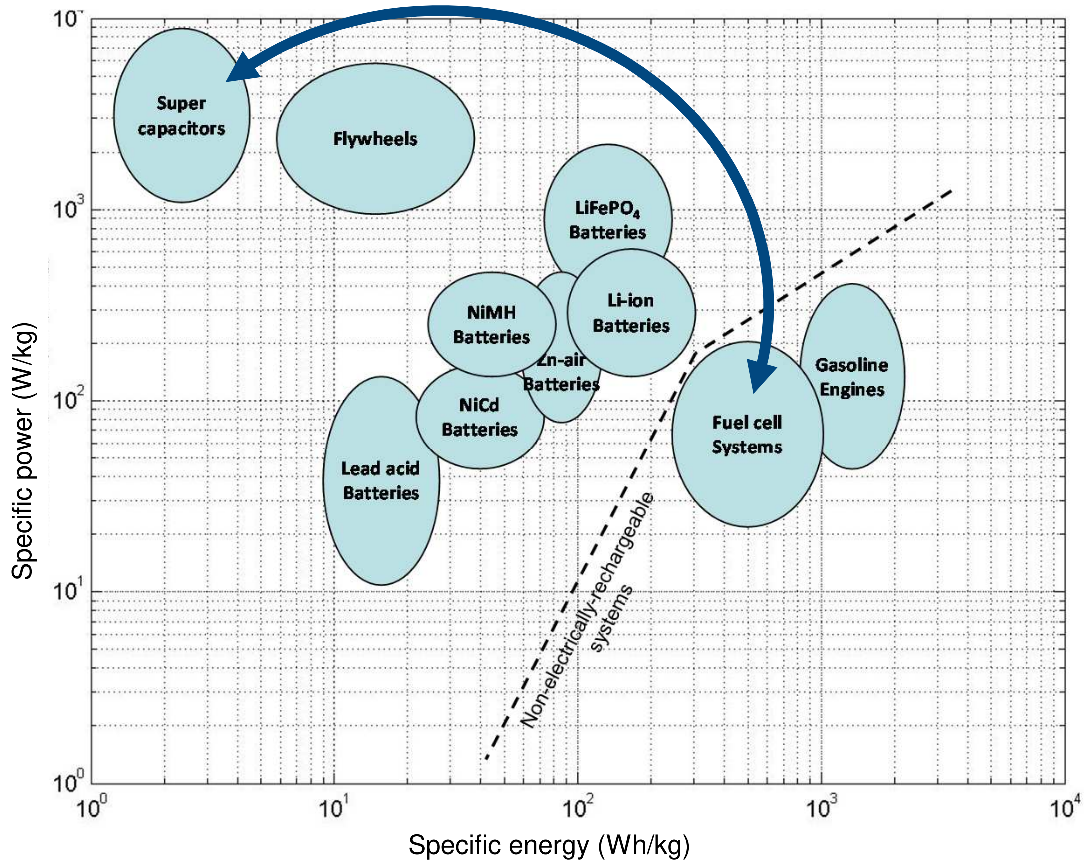
PEMFC Systems

– Whole PEMFC System

- **The need of electrical hybridization…**
  - FC = non electrical rechargeable system
  - FC = no possibility of recovering braking energy

➔ Ragone plot…

➔ Hybridization with supercapacitors / flywheels / power batteries?



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

Behavior and losses of PEMFC

– **PEMFC is a complex system**

- **Building behaviors models would be of prime importance for design, control, diagnostic, optimization… BUT**

- **FC = highly multiphysics and multiscale systems**
  - Multiphysics = electrical, mechanical, thermal engineering, electrochemistry…
  - Multiscale = from the µm to the m
  - Multiscale = different time constants are involved
    - Electrochemistry ≈ instantaneous
    - Electrical power converter ≈ 10^{-4}s
    - Membrane water hydration content ≈ 10^{0}s
    - Temperature ≈ 10^{2}s
    - Durability ≈ 10^{5}s

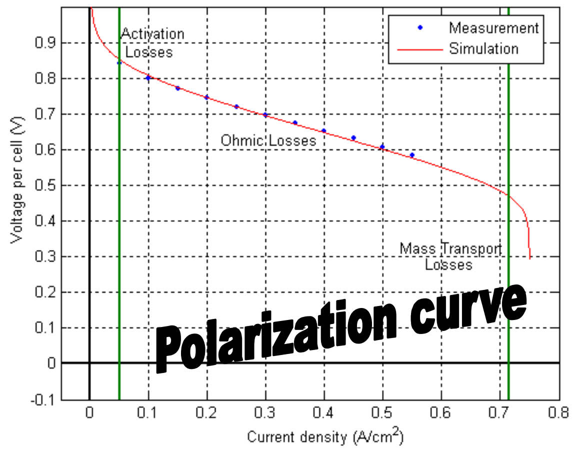
PEMFC behavior is hard to catch. Even if research increases in this area, a "complete" multiscale FC system model is still not available.

- **High difficulty to access internal parameters**
  - Specific know-how of the manufacturers
  - No sensor available

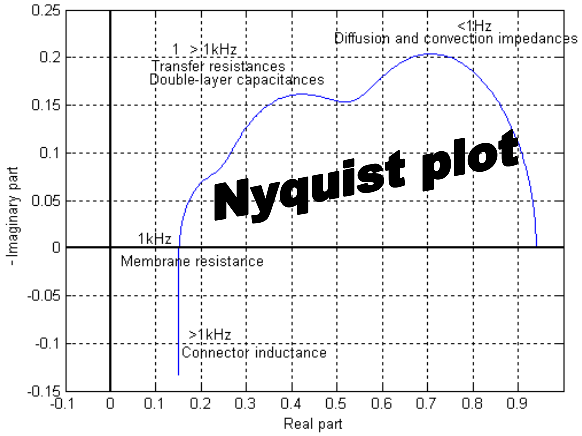
Behavior and losses of PEMFC

– **Characterization of a stack**

- **Two useful "tools"**
  - Polarization curve
    - – Enables to estimate losses
    - – Enables to estimate efficiency

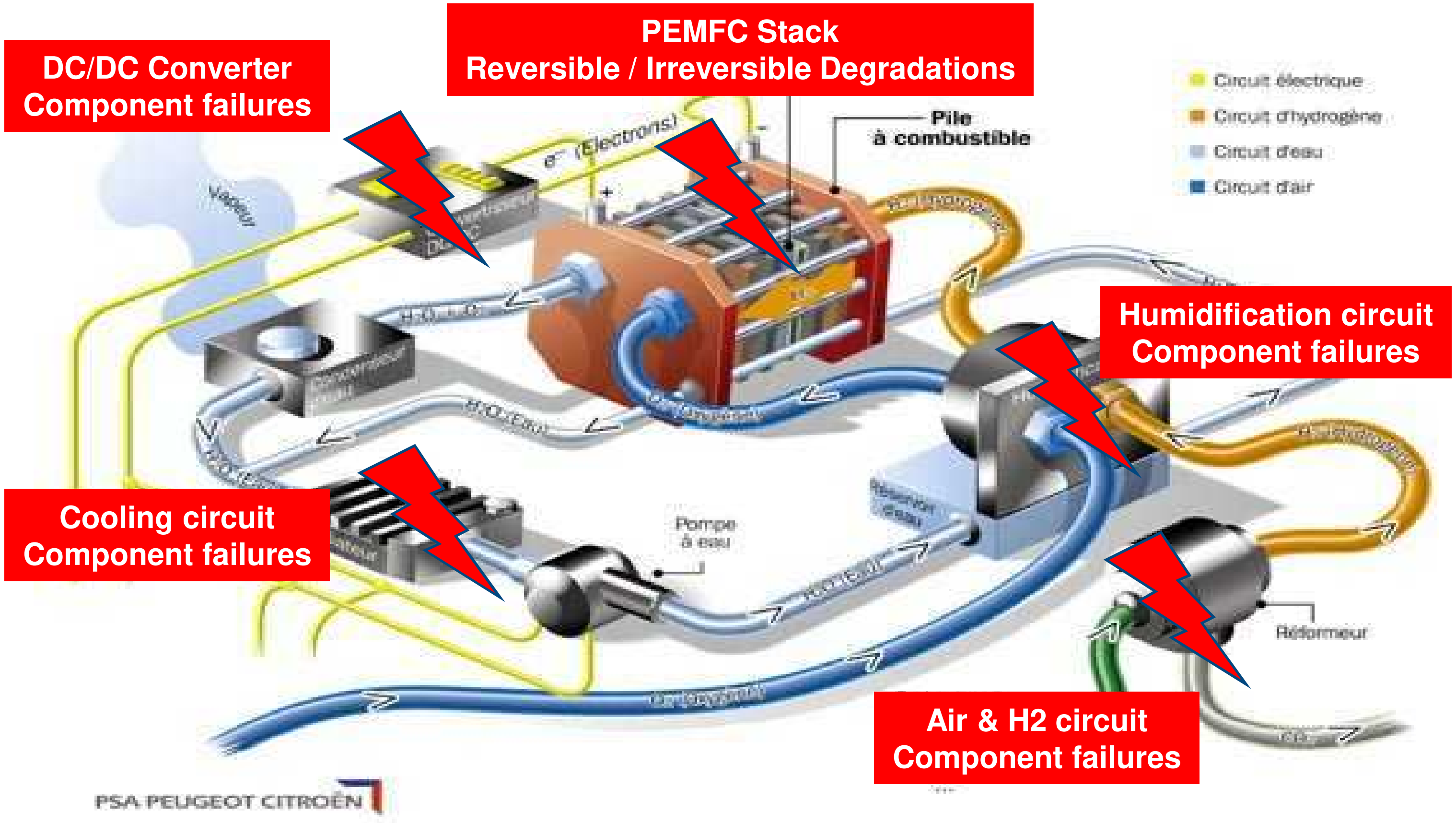


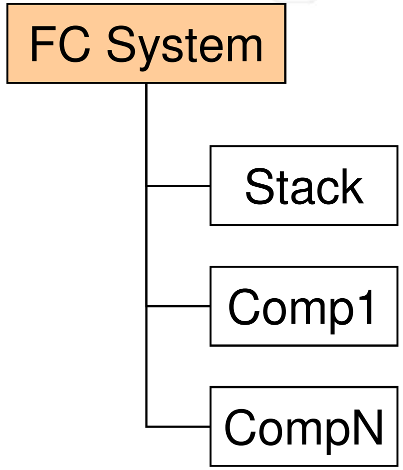
  - Electrochemical Impedance Spectroscopy
    - – Enables to build impedance spectra (Nyquist plots)
    - – Nyquist plot
      - Enables to estimate internal resistances / impedances of a fuel cell
      - Enables to depict and analyze failure / ageing mechanisms

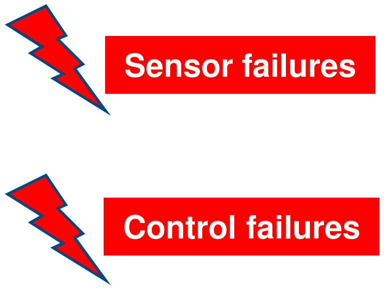


Failure mechanisms

– **Degradations/failures at system's level**







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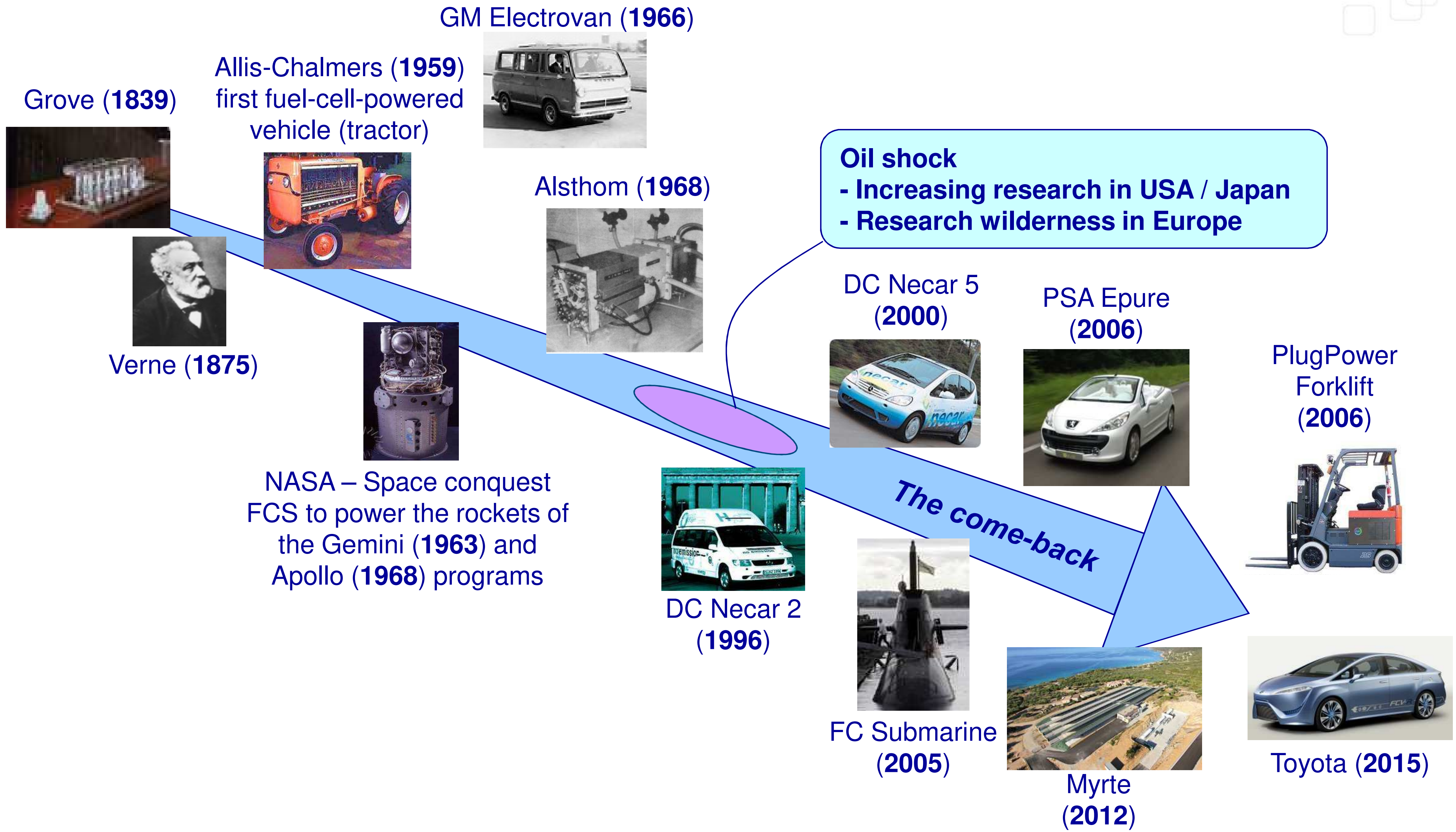
Part 2 – What are the targets for automotive applications ?

Brief history



Light duty commercial vehicles 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 $60k (or leasing)

- **And also Hyundai & Honda !**

But only few FCV sold or leased worldwide…

- **About 5000 vehicles sold / leased today**
- **A reference to be reached to ensure a larger market : DOE**

2020 Targets by Application

	Vehicle	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 ?

– **Electrical efficiency**
  - Maximal value of about **45% to 50%**

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

    ➔ **about 3000 hours**

– **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

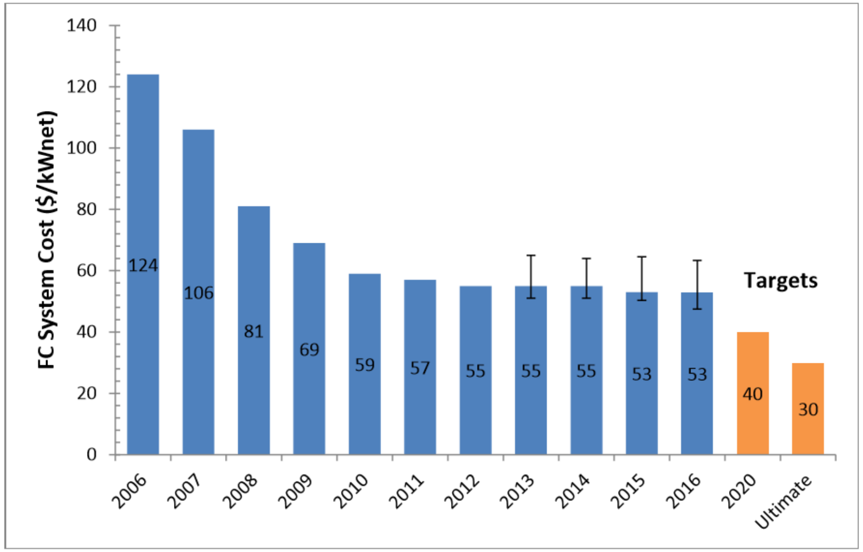
– **Cold start (automotive applications)**
  - From -20°C in 30 seconds without external energy

ElringKlinger PEMFC NM5

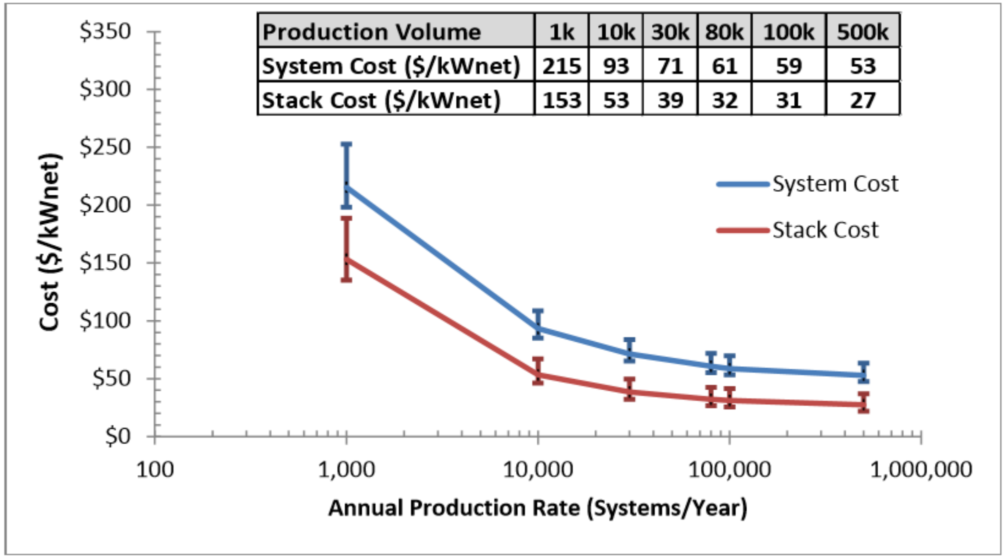
Where are we today ?

– **Costs**

- **FCS costs**



Projected costs for a 80kW-FCS - high-volume manufacturing (500000 units/year)



Projected costs for a 80kW-FC stack and 80kW-FCS (transportation) – 2016's status

- **H2 costs**

  Approx. 10 €/kg (for 80kg/day of H2 distribution)

  Large refueling station : approx. 1 M€

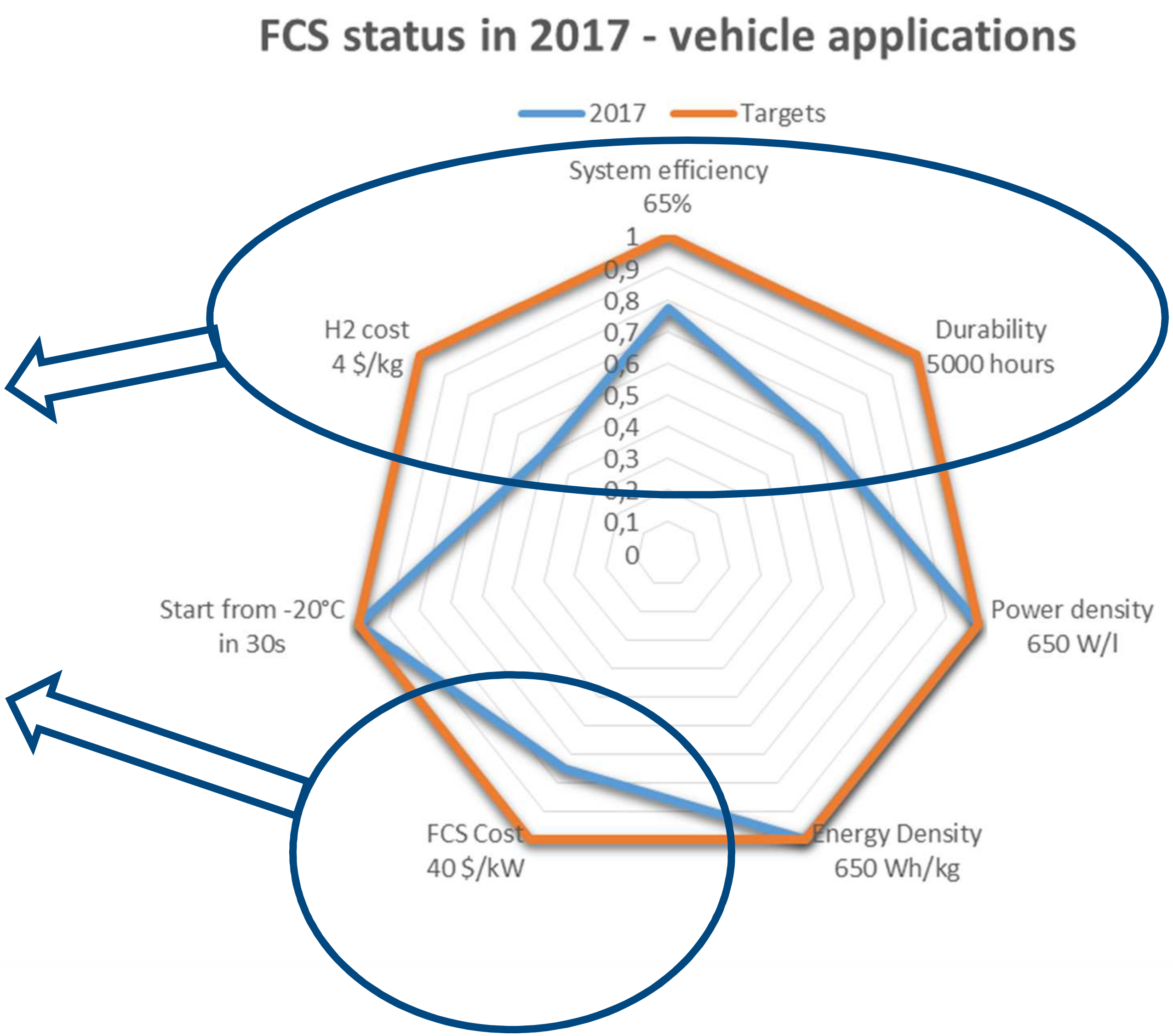
[REF] A. Wilson, J. Marcinkoski, D. Papageorgopoulos, Fuel Cell System Cost - 2016, Record #16020, DOE Hydrogen and Fuel Cells Program Record, 2016.

[REF] AFHYPAC, L'hydrogène, vecteur de la transition énergétique, Présentation au Sénat, 2014.

Where are we today ?

– **Radar plot regarding the DOE targets**

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



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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 40-45% to about 55-65%

  - Fuel cell system **durability**
    - Ex. for PEMFC systems
      - 5000 hours are required for light vehicles (3000 hours obtained)
      - 30000 hours are required for trucks
      - And up to 80000 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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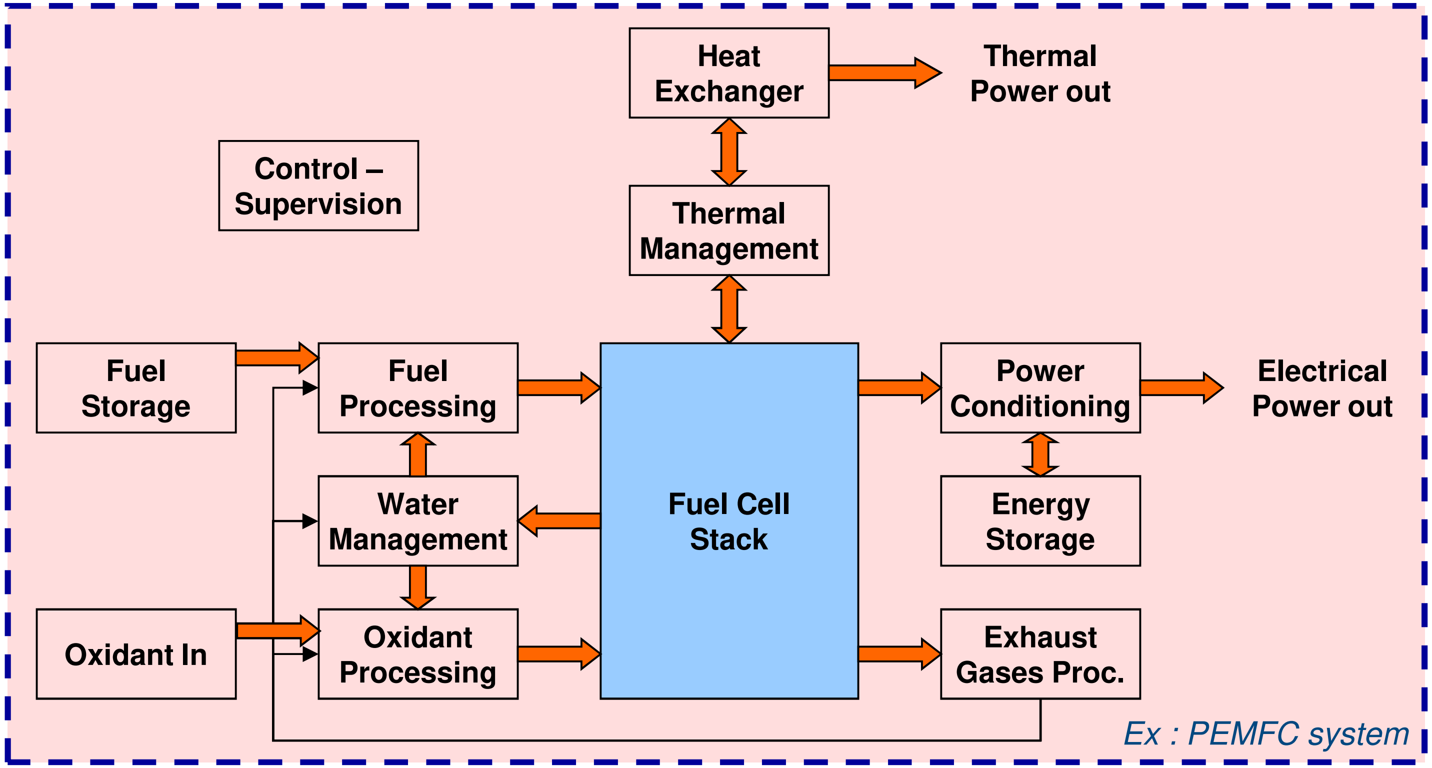
Areas of research : efficiency

– **Efficient & dedicated ancillaries are required…**
  - Specific power converters
  - Specific air compressor
  - Systems for the humidification / cooling
  - Fuel storage
  - "Systemic" optimization of the architecture, taking care of all energy flows

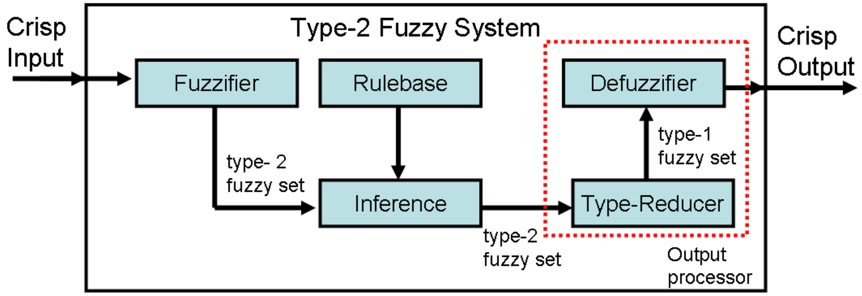


Areas of research : efficiency

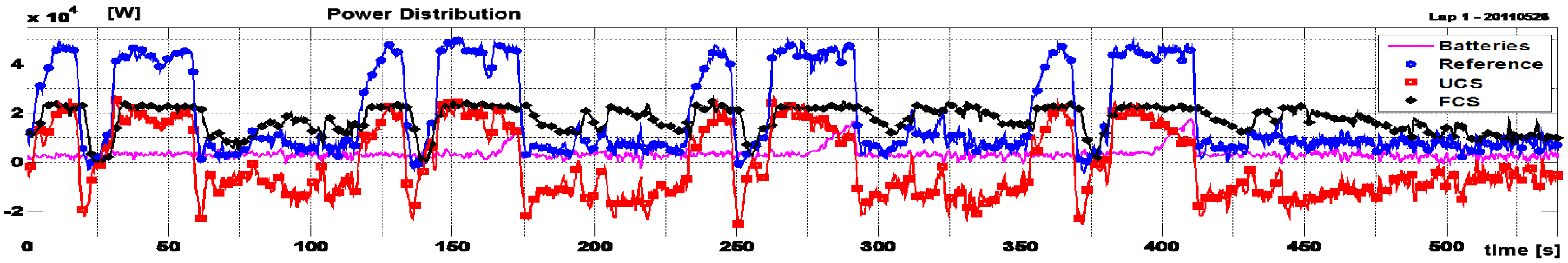
– **Optimize energy flows…**

Use of AI approaches

Propose efficient (& real-time) energy management strategies



Ex : PEMFC system



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

Use of new metaheuristics

Areas of research

– Towards enhanced performances

- **Scientific and technological bolts**
  - Fuel cell system **efficiency**
    - Increase it (elec. only) from about 30-40% to about 55-65%

  - Fuel cell system **durability**
    - Ex. for PEMFC systems
      - 5000 hours are required for light vehicles (2500-3000 hours obtained)
      - 30000 hours are required for trucks
      - And up to 100000 hours for stationary applications & railways
  - Public **acceptance**
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  - **Cost** (whole life cycle)
    - Linked to industrial deployment
  - **“Green” H_2 availability**
    - Production, storage, distribution

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 METHODOLOGIES ARE A KEY ISSUE !!!**

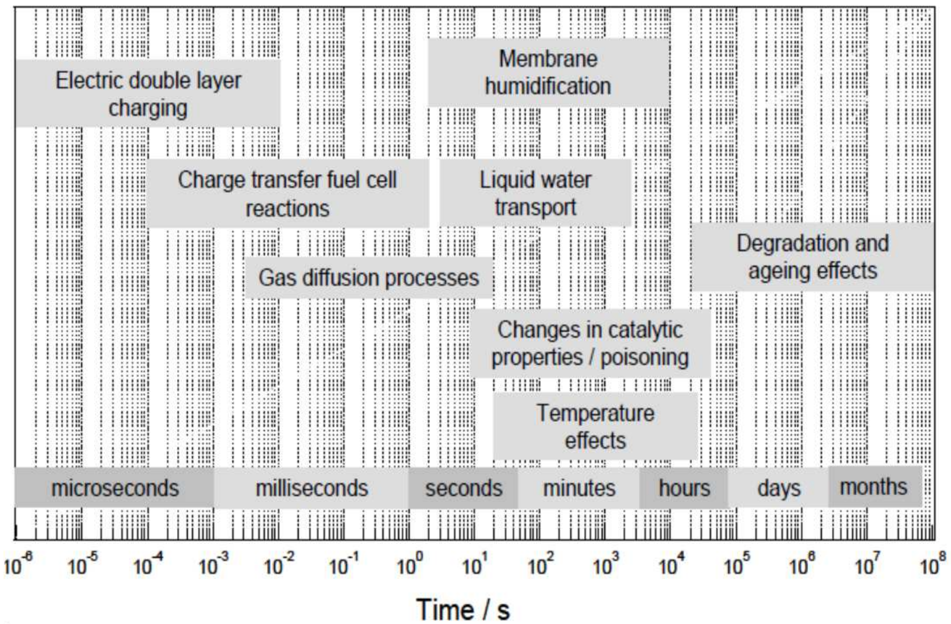
- **Constraints**
  - Use of a minimal number of actual sensors
    - For complexity purpose
    - For cost purpose
    - For reliability purpose
    - For real-time control constraints

Diagnostic of FC

- **Activities at stack / system level started approx. 2001**
- **Model-based approaches**
  - Need of an accurate behavior model, easy-coupling with control (explicit physical causality)
  - Difficulties : multi-physics and multi-scale, determination of internal parameters, large number of sensors (expensive)
- **Non model-based approaches**
  - Need of large data sets, real-time ability
  - Difficulties: requirement of large experimental dataset under both normal and target fault conditions

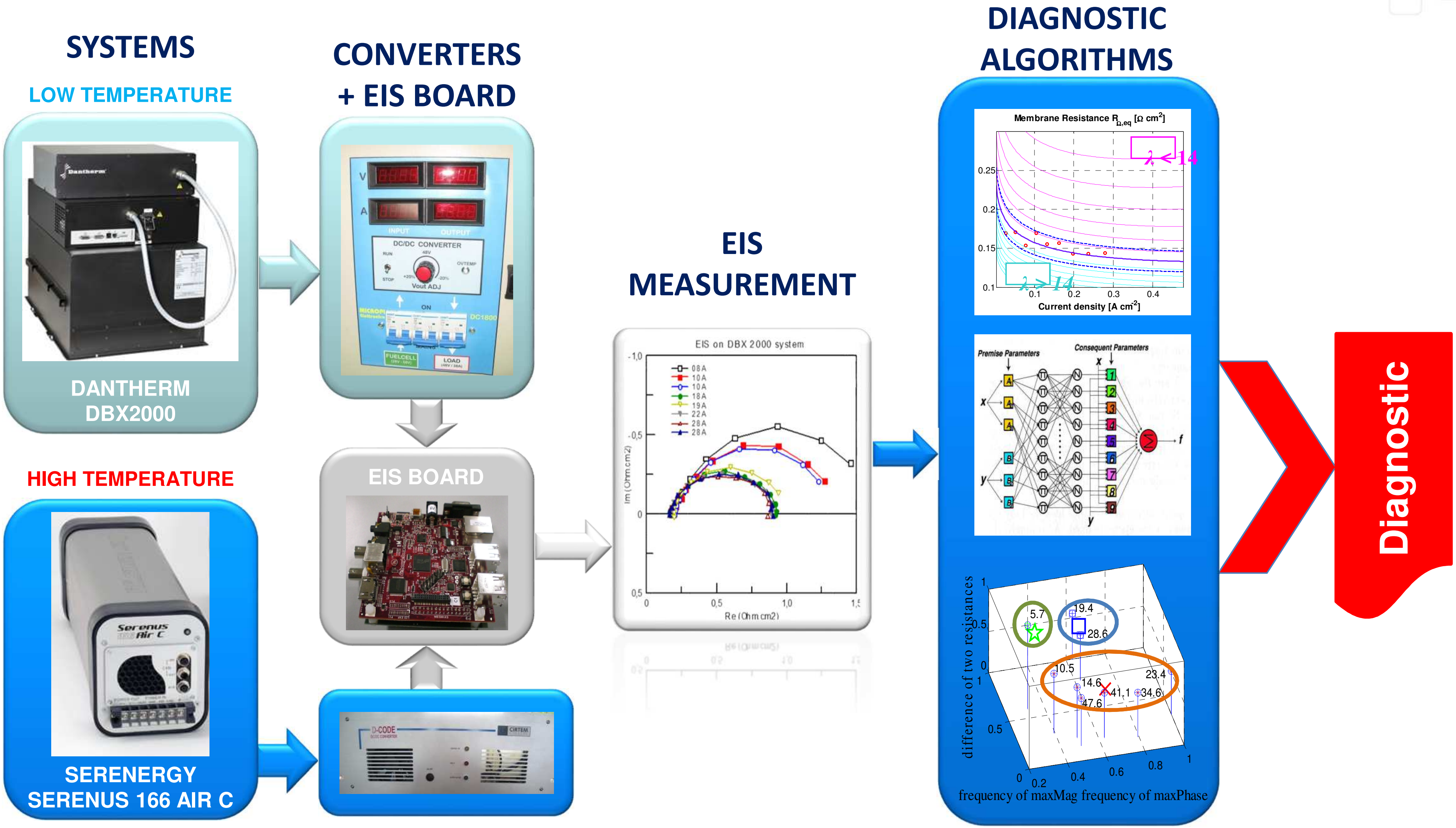
FC Specificities

- Time : from µ-scale to macro-scale (µs to years)
- Scale : from µ-scale to macro-scale (µm to m)
- Highly multi-physics (chemistry, electrochemistry, electrical engineering, thermodynamics, mechanical engineering, thermal engineering, control engineering, ...)



Example : signal-based FDI

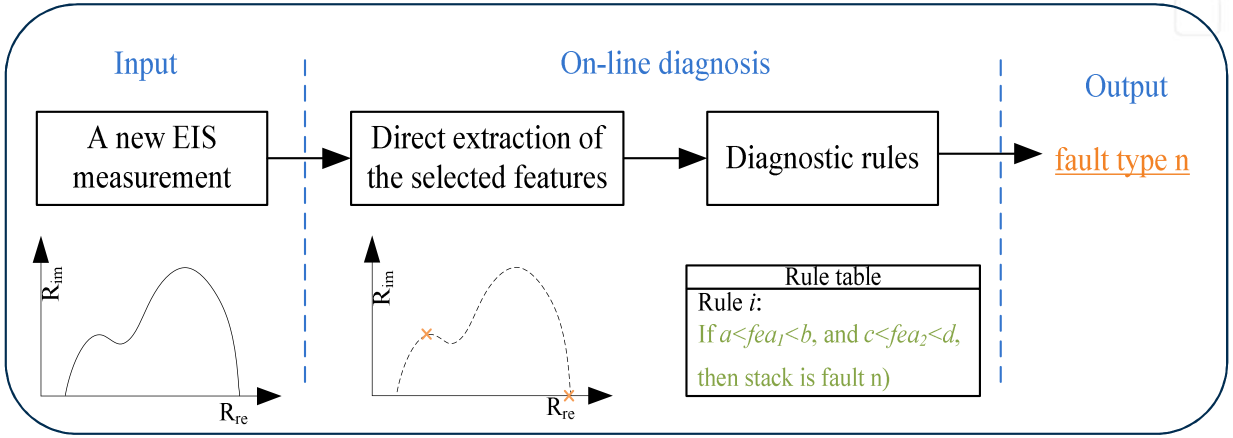
– **Example : DC-DC converter based diagnostics for PEM systems**



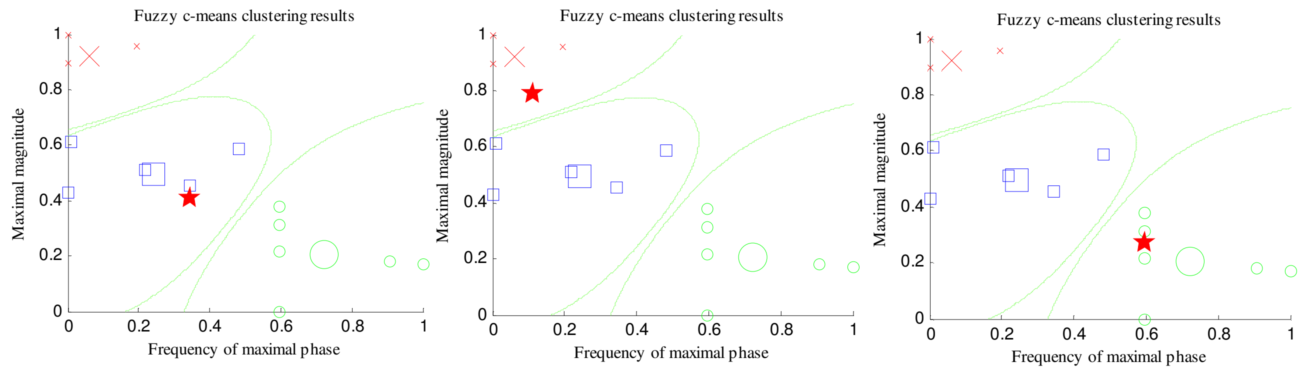
Example : signal-based FDI

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

– **Online diagnostic algorithm (Zheng et al. 2014)**



– **Online testing results based on Nexa™ stack + high voltage DC/DC converter**




```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
normal
membership degree=0.91724
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
air starvation
membership degree=0.80418
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
high air flow
membership degree=0.82023
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Training accuracy rate = 93%

Testing accuracy rate = 100%

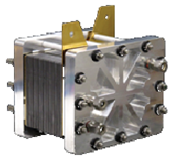
Testing of 3 new points obtained under normal, low and high flow conditions

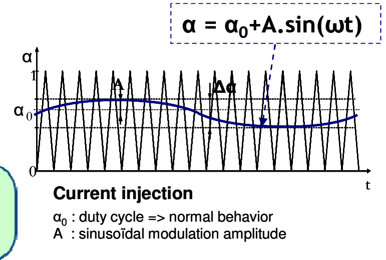
Relating activities : diagnostic to prognostic

– Already on-going works

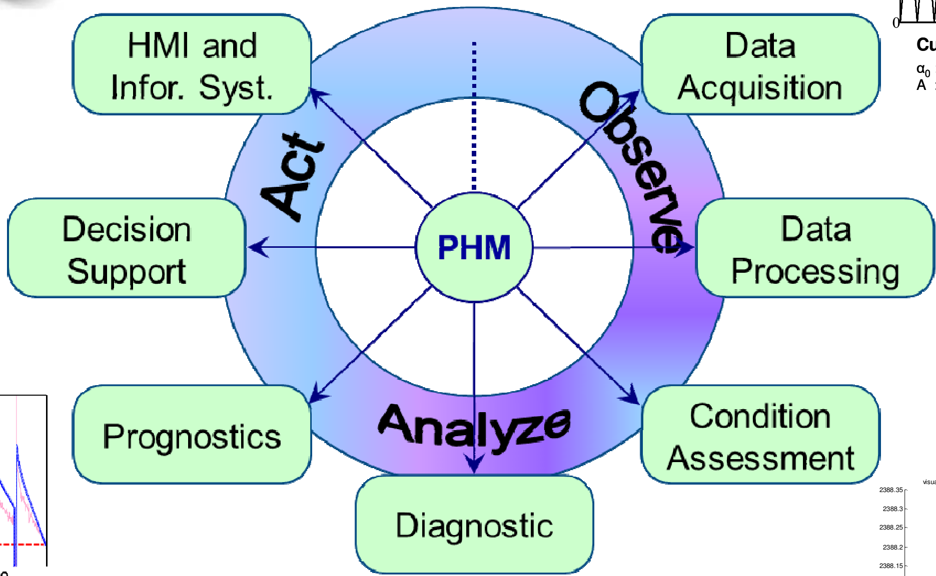
- ***taxonomy of failures***
- ***wearing mechanism analysis…***

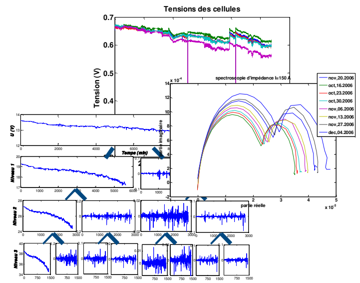
- ***residual-based control***
- ***fault-tolerant control…***

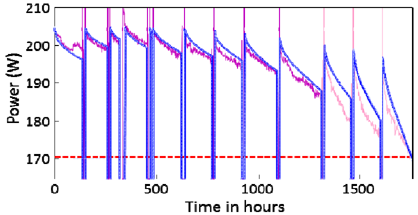




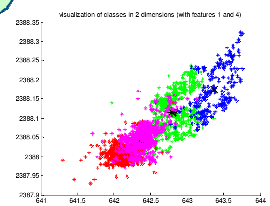
- ***T°, I, V***
- ***EIS…***



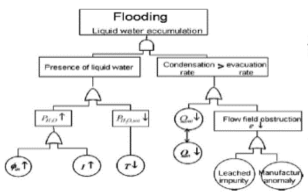


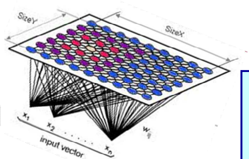


- ***polarization curves***
- ***Nyquist diagrams…***



- ***particle filtering***
- ***echo state networks…***





- ***fault tree analysis***
- ***statistical analysis***
- ***ANN models, wavelet analysis…***

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FC LAB Research

Prognostic of FC

– **A new research field, strongly coupled to industrial requirements !**
  - **Interest / issues**
    - Estimating remaining useful lifetime of FC stacks / systems under actual operating conditions
    - Durability / reliability increase of multi-stack systems
    - Issues :
      - Obtain consistent database in different operating conditions
      - AST procedures at stack / system level
      - Variability of FC stack performances (due to industrial process)
      - Prognostic under varying operating conditions
      - Definition of thresholds for RUL estimation (under varying operating conditions)
  - **Approaches currently evaluated :**
    - Kalman filters
    - Particle filters
    - Reservoir computing
    - ANFIS approaches
    - Time-evolving model-based approaches
  - **For free experimental database : see http://eng.fclab.fr/ieee-phm-2014-data-challenge/**

Areas of research

– **Towards enhanced performances**

- **Scientific and technological bolts**
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  - **Cost** (whole life cycle)
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    – Production, storage, distribution

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, Canada, USA, South Korea, France, …

- **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…)

LA POSTE | STEINBEIS-EUROPA-ZENTRUM | EIFER | Ma Hy Tec | DUCATI energia
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New Energy World JU fuel cells & hydrogen for sustainability
SEVENTH FRAMEWORK PROGRAMME

Example : Assessment in real world

Mobypost EU project – Main project objectives

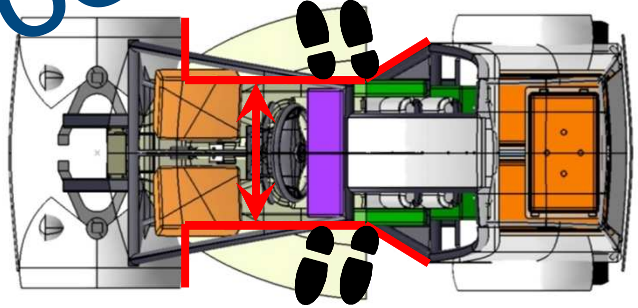
- Taking care of postmen requirements
- Design an optimized hybrid FC powertrain
- Energy flow supervision
- Coupling with renewables (PV panels)
- Hydrogen production & storage on-site
- 1st French FCV fleet (10 vehicles, 2 H2/PV stations) testing in constrained environment (temperature, power demand)

Example : Assessment in real world

Mobypost EU project – Design by postmen for postmen

A real success story !!

- Identify actual postmen requirements
- Specifications from postal delivery business
- Design and architecture validated by postmen
  - 1m width
  - 45km/h
  - 4 wheels
  - no car doors
- Most of postal routes realized without going out of the vehicle
- Increased working conditions for postmen



Areas of research

– Towards enhanced performances

▪ Scientific and technological bolts

- Fuel cell system **efficiency**
  - Increase it (elec. only) from about 40-45% to about 55-65%

- Fuel cell system **durability**
  - Ex. for PEMFC systems
    - 5000 hours are required for light vehicles (3000 hours obtained)
    - 30000 hours are required for trucks
    - And up to 80000 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 US DOE annual market report)*
  - Fuel cells receive far more patents than other renewable energy technologies (950 patents in 2011 versus 450 for photovoltaic)
- **2016's prices**
  - About 500€-2000€/kW for one single stack – projected cost for 500000 units / year = 27€/kW
  - 35% FC stack + 35% FC ancillaries + 30% electrical powertrain
- **A (small) hydrogen refueling station ≈ 1M€**

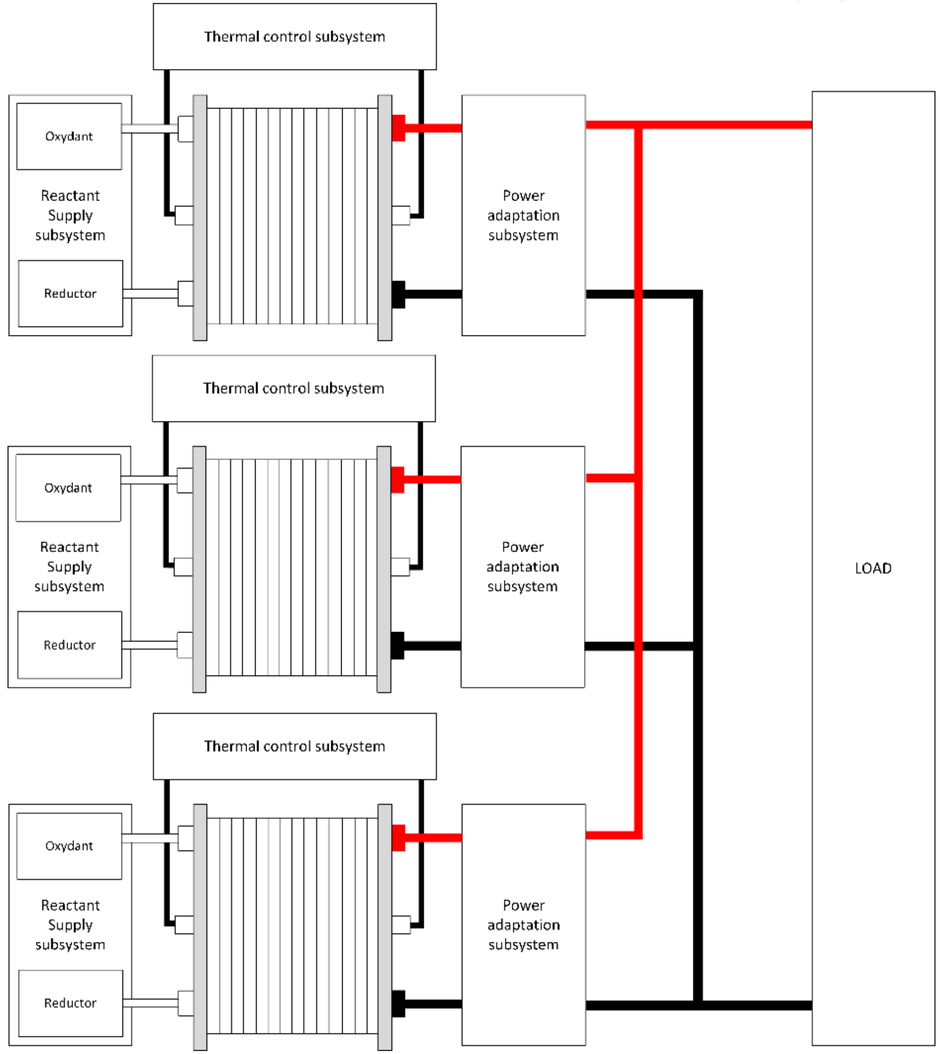
– What can be done ?

- 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 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, …)
  - 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

- **What can be done ?**
  - **Seasonal storage** of renewable electricity
  - **Convergence** between stationary applications & mobile applications
  - Developments of PEM & SO **electrolyzers**
  - Developments of new materials / solutions for hydrogen storage (increase of mass storage percentage)
  - **Exergetic optimization** of the whole electrolyzer / storage / fuel cell system
  - Development and deployment of refueling stations

Hydrogen-energy systems
for transportation applications

Concluding remarks

Concluding remarks

– The interest of H2 technology

- **H2**
  - Best candidate for next generation fuel?
  - Will play a key role in the future energy economy
  - Still issues on H2 production, public acceptance, on-board storage, distribution facilities

- **FC are promising energy converters for next generation EVs**
  - High efficiency & low noise level
  - Possibly no dependency to fossil fuels
  - Applications can be considered in transportation, mobility, micro-CHP, storage of renewables
  - Still issues at system-level :
    - Lot of interactions between the FC stack & its ancillaries
    - Limited durability under varying operating conditions
    - Reliability, Diagnostic & Prognostic
    - Dedicated ancillaries on a tiny market
    - Global optimization is required (architecture, stack, ancillaries, control, costs, efficiency, …)

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A last thing…

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Hydrogen-energy systems for transportation applications

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