Fuel cells:
Choice, Design and Application

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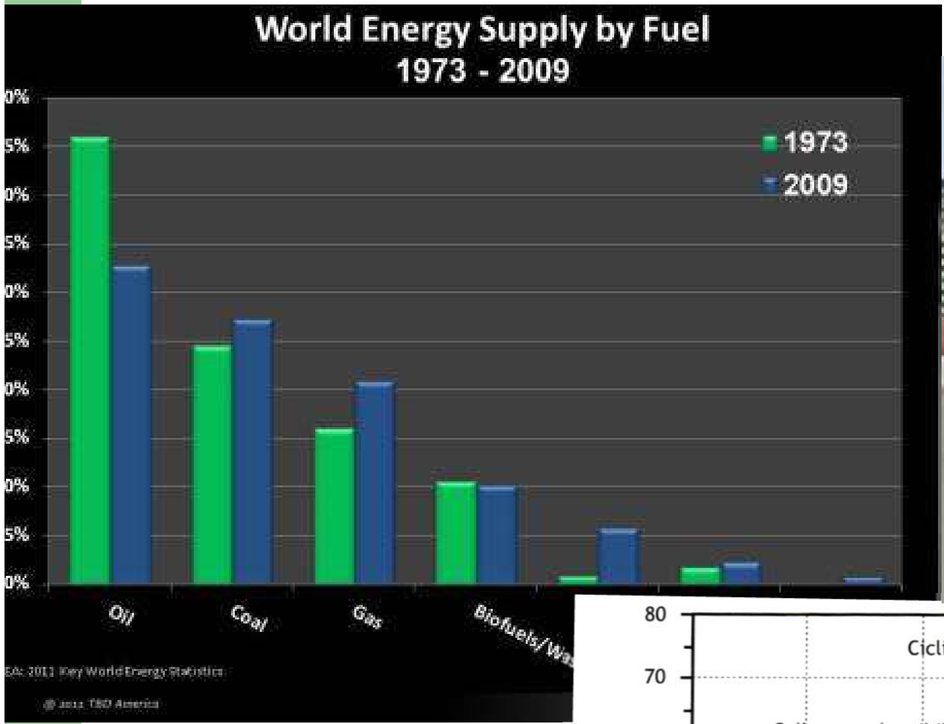
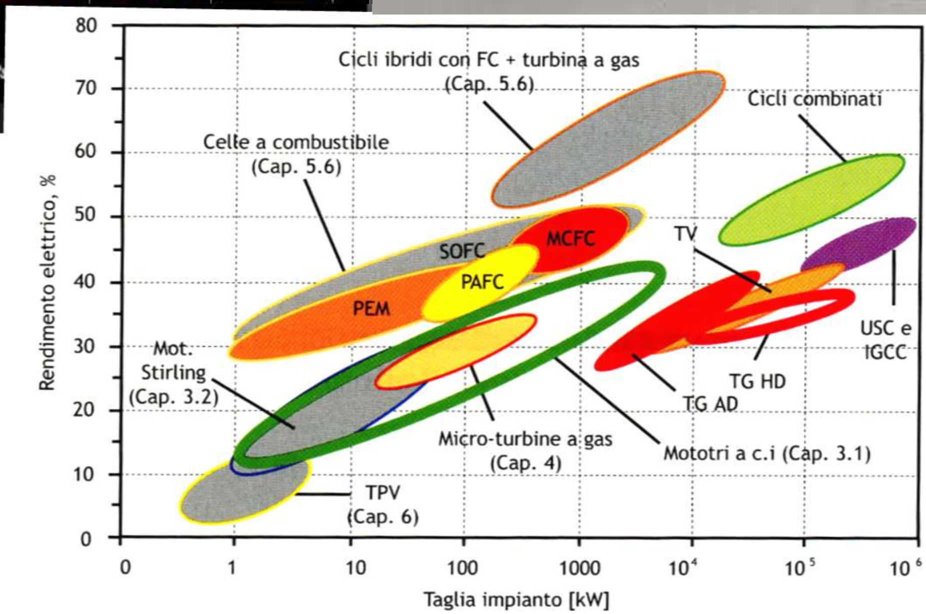
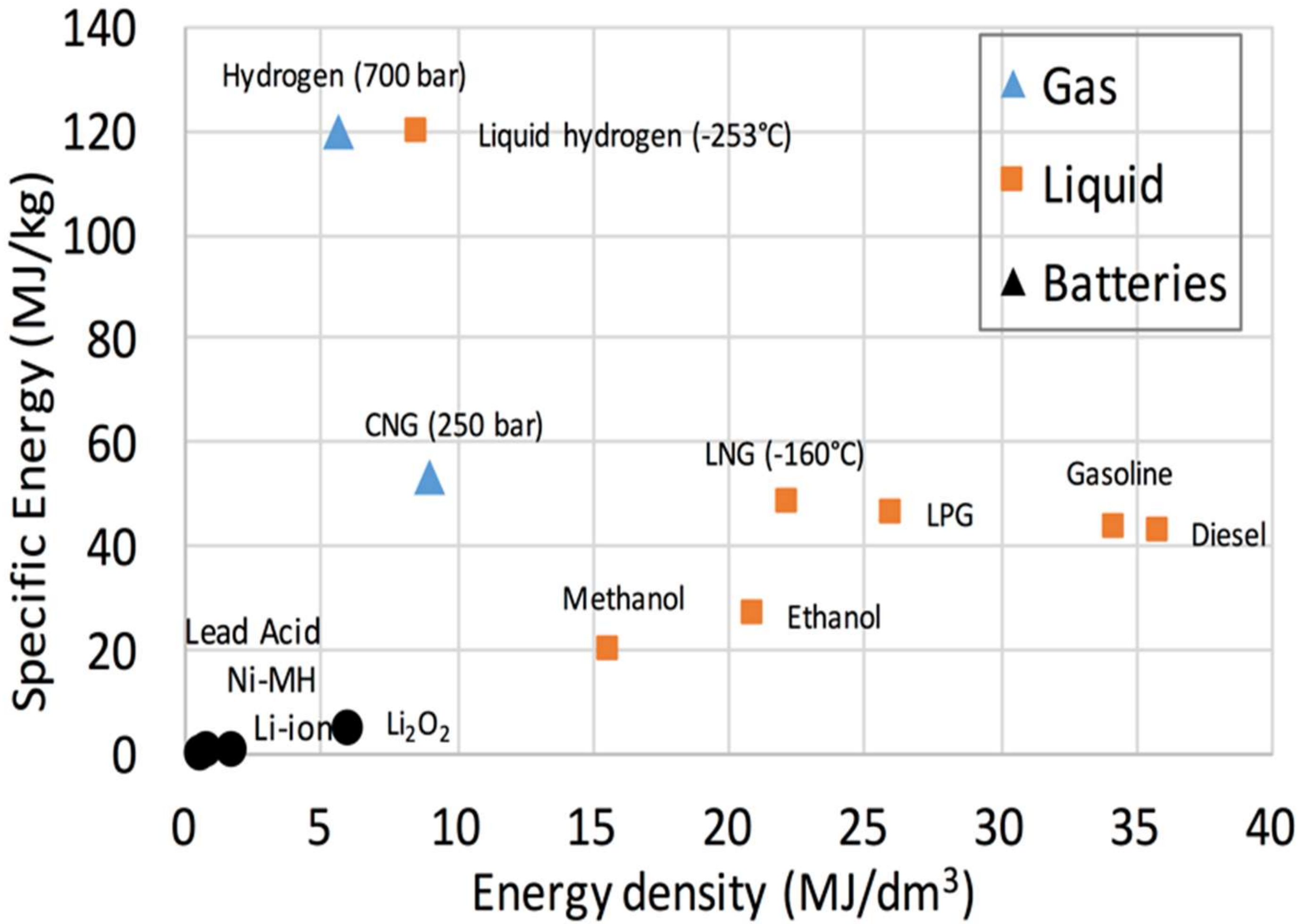
Aim of the presentation





…energy storage



Topics

- EneSysLab at a glance
- Fuel cells basic principles
- Stack design
- System design
- Fuel cells applications
- Conclusions

Objectives (today and tomorrow)

Overview on power generation (with some figures on energy demand and power conversion effficiency)

Overview on microcogeneration and in particular on fuel cells

Possible integration with renewable energy resources

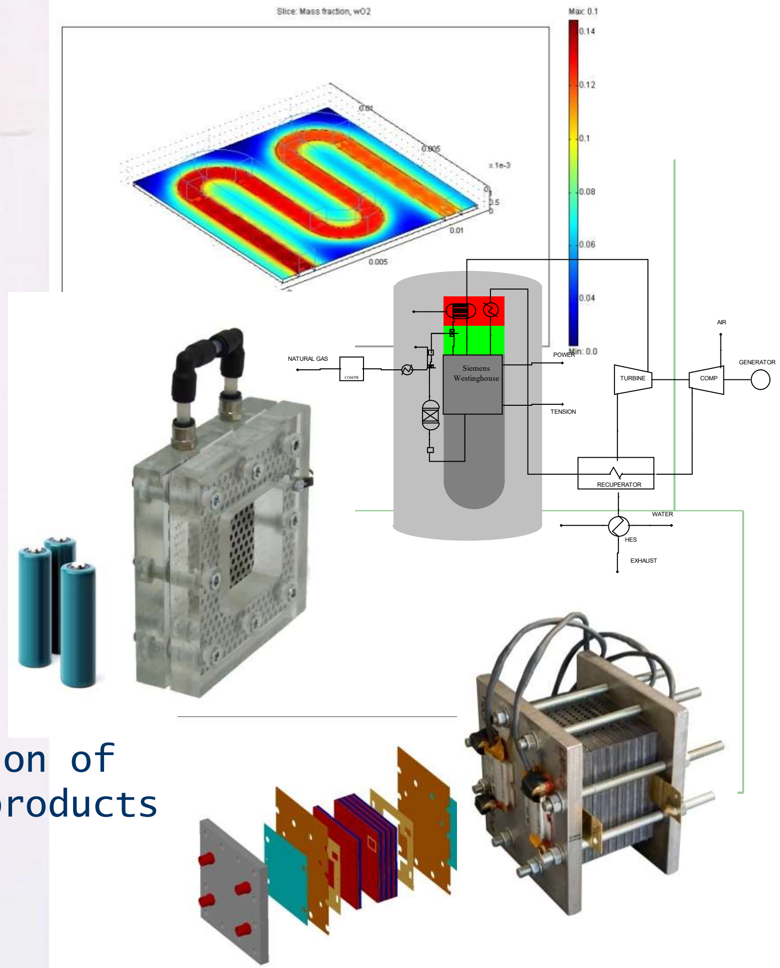
EneSys Lab
Energy System Lab

Staff

- 6 researchers
- Abt 10 external collaborators
- Abt. 10 PhD students

Activity

- Development of process simulation models
- Development thermo -fluid dynamics models
- Experimental characterization of prototypes and commercial products
- Prototypes development



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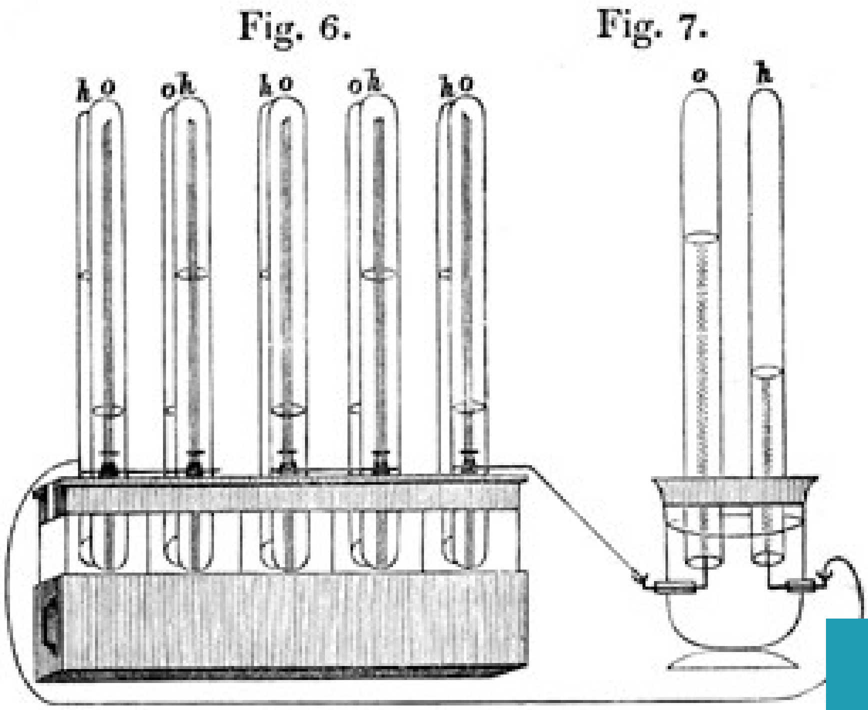
Fuel cells



…yesterday

Sir Grove 1842

…today

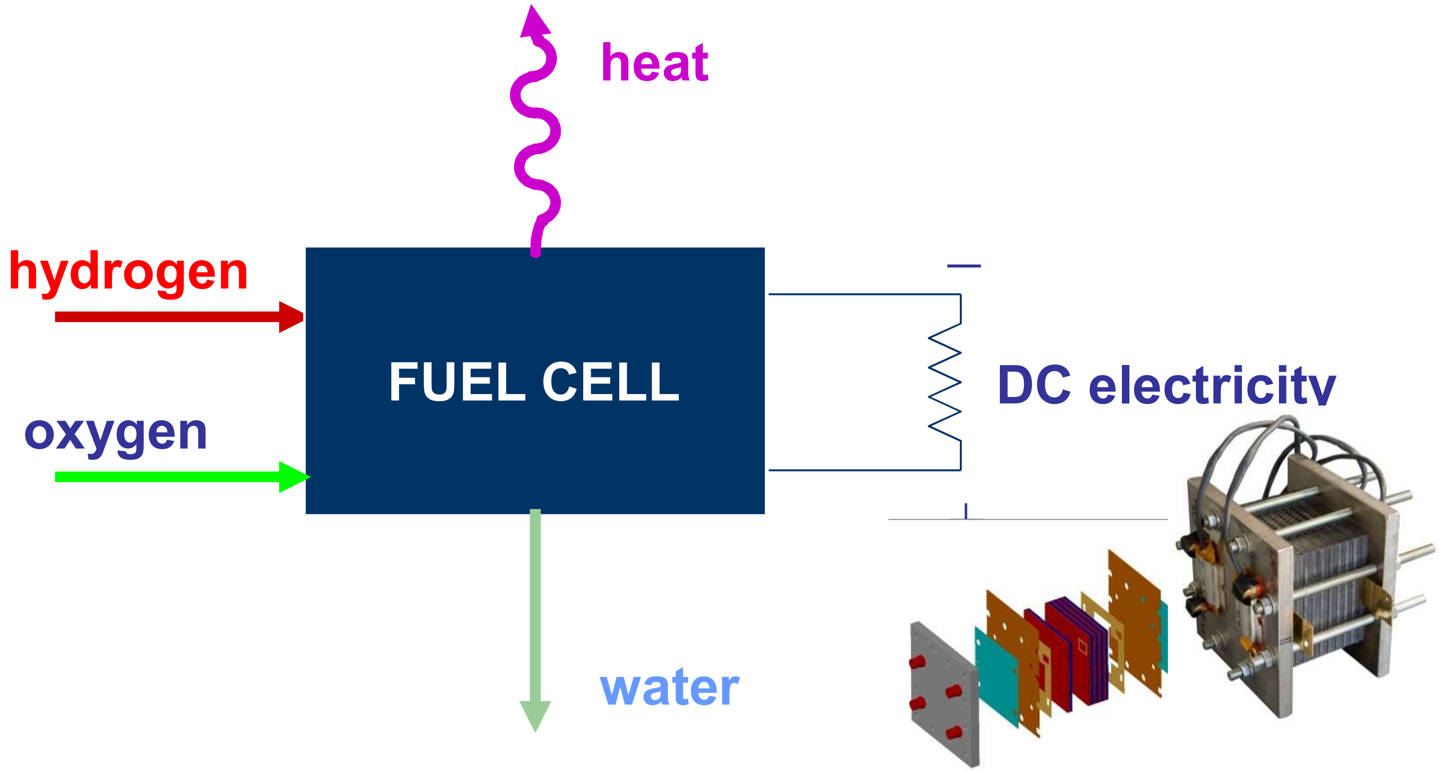
Ballard Power System

What is fuel cell?

Fuel cell is an electrochemical energy converter.

It converts chemical energy of fuel (H_2) directly into electricity.

Fuel cell is like a battery but with constant fuel and oxidant supply.



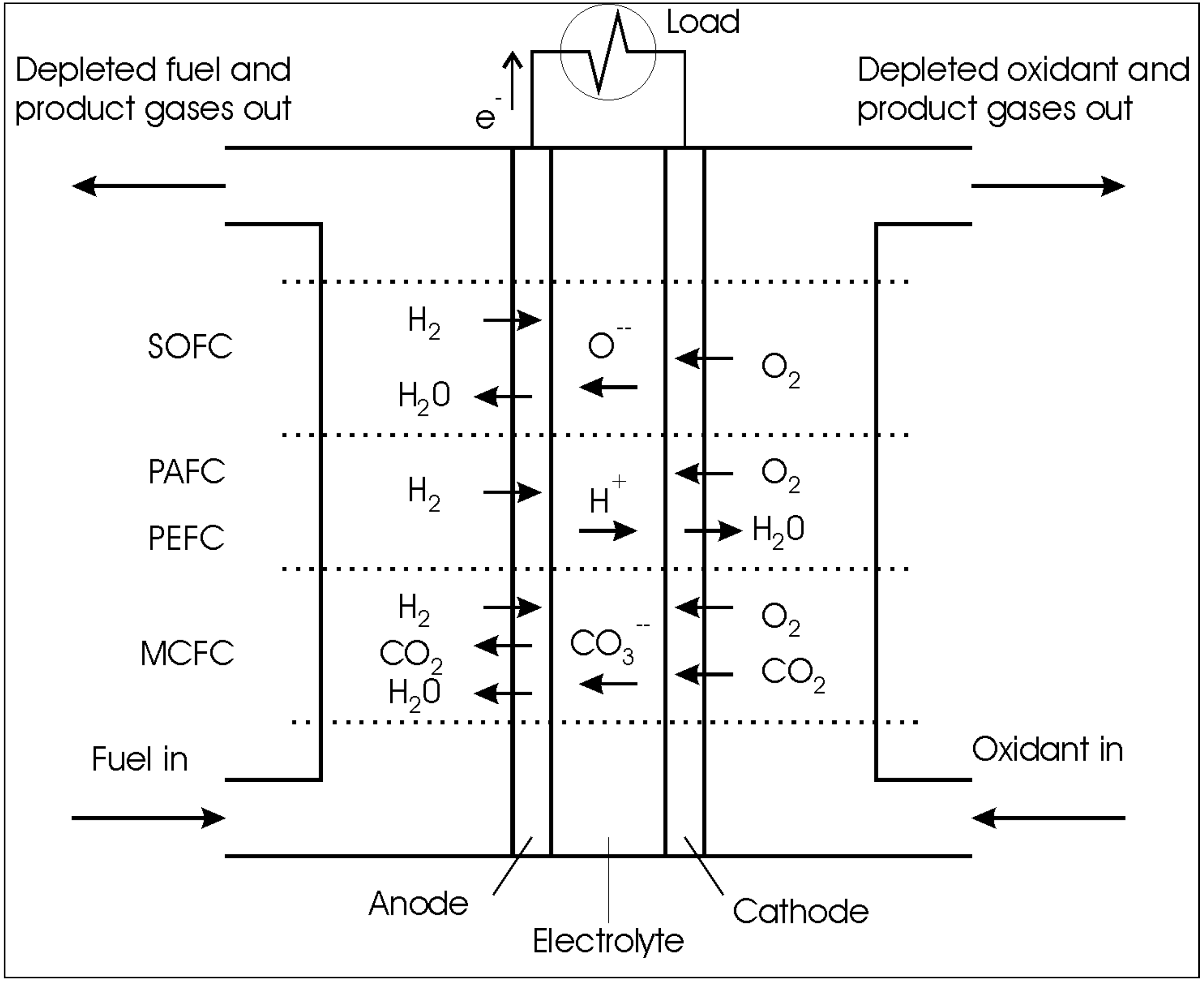
FUEL CELL TECHNOLOGIES

	PEMFC	AFC	PAFC	MCFC	SOFC	DMFC
Electrolyte	Polymer Membrane	KOH	Phosforic Acid	Molten Carbonate	Solid Oxide	Polymer Membrane
Temp. (°C)	70-80	80-100	200-220	600-650	800-1000	70-120
Corr.Den.	H	H	M	M	H	L
Reformer	External	External	External	Ext/Int	Ext/Int	Internal
Toll. CO_2	Yes	No	Yes	Yes	Yes	Si
Toll. CO	No	No	No	Yes	Yes	Si
Applications	Space. Transp. Portable	Space Transp. Portable	Dist. Generation	Generaz. MW	Gen. Distrib.-MW	Trasport.
FC Efficiecy H_2 LHV	50%	50%	50%	60%	60%	N.D.

PEMFC: Proton Exchange Membrane Fuel Cell
AFC: Alkaline Fuel Cell
PAFC: Phosforic Acid Fuel Cell

MCFC: Molten Carbonate Fuel Cell
SOFC: Solid Oxide Fuel Cell
DMFC: Direct Methanol Fuel Cell

Fuel Cell Basic Principles



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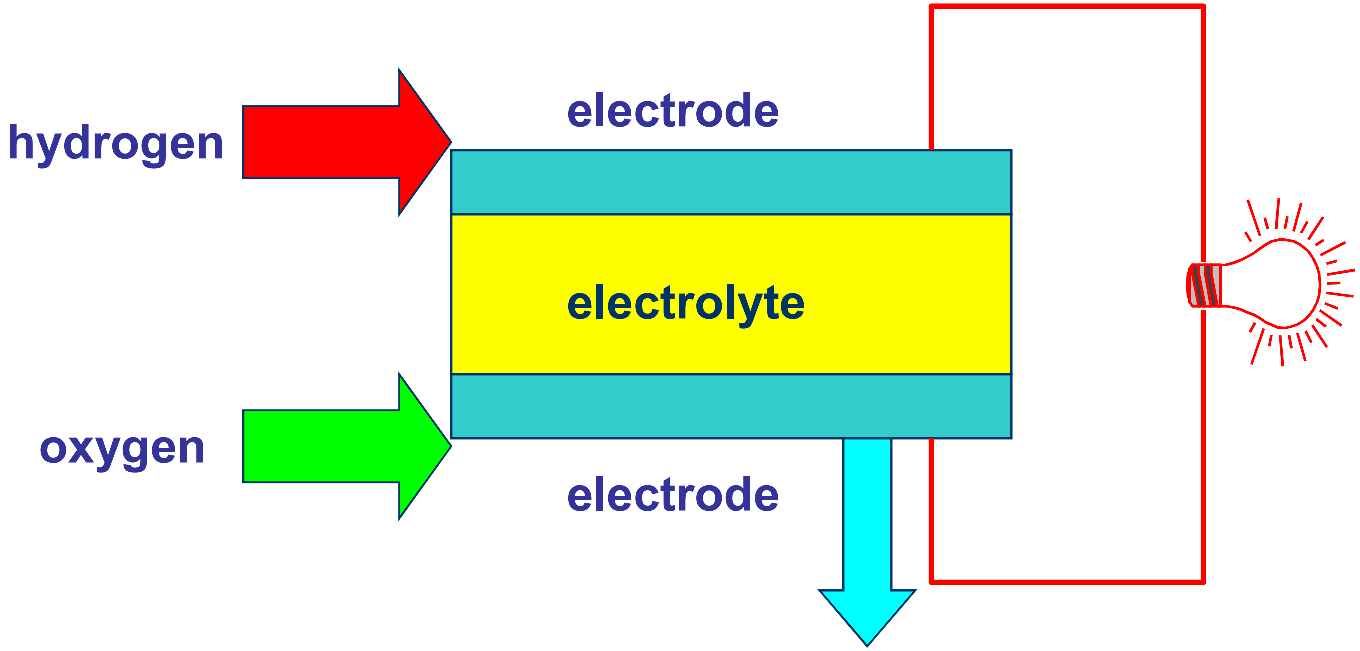
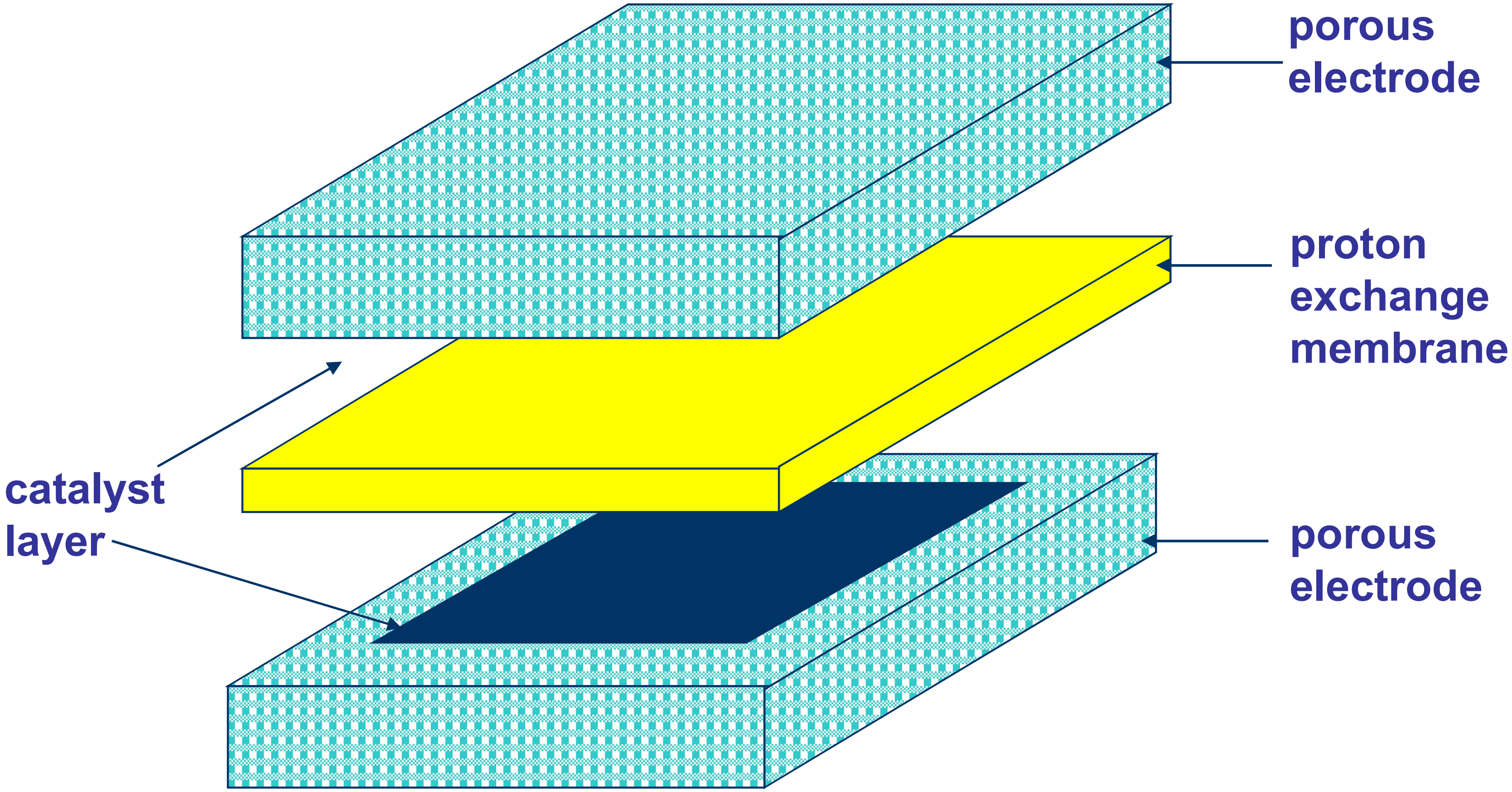
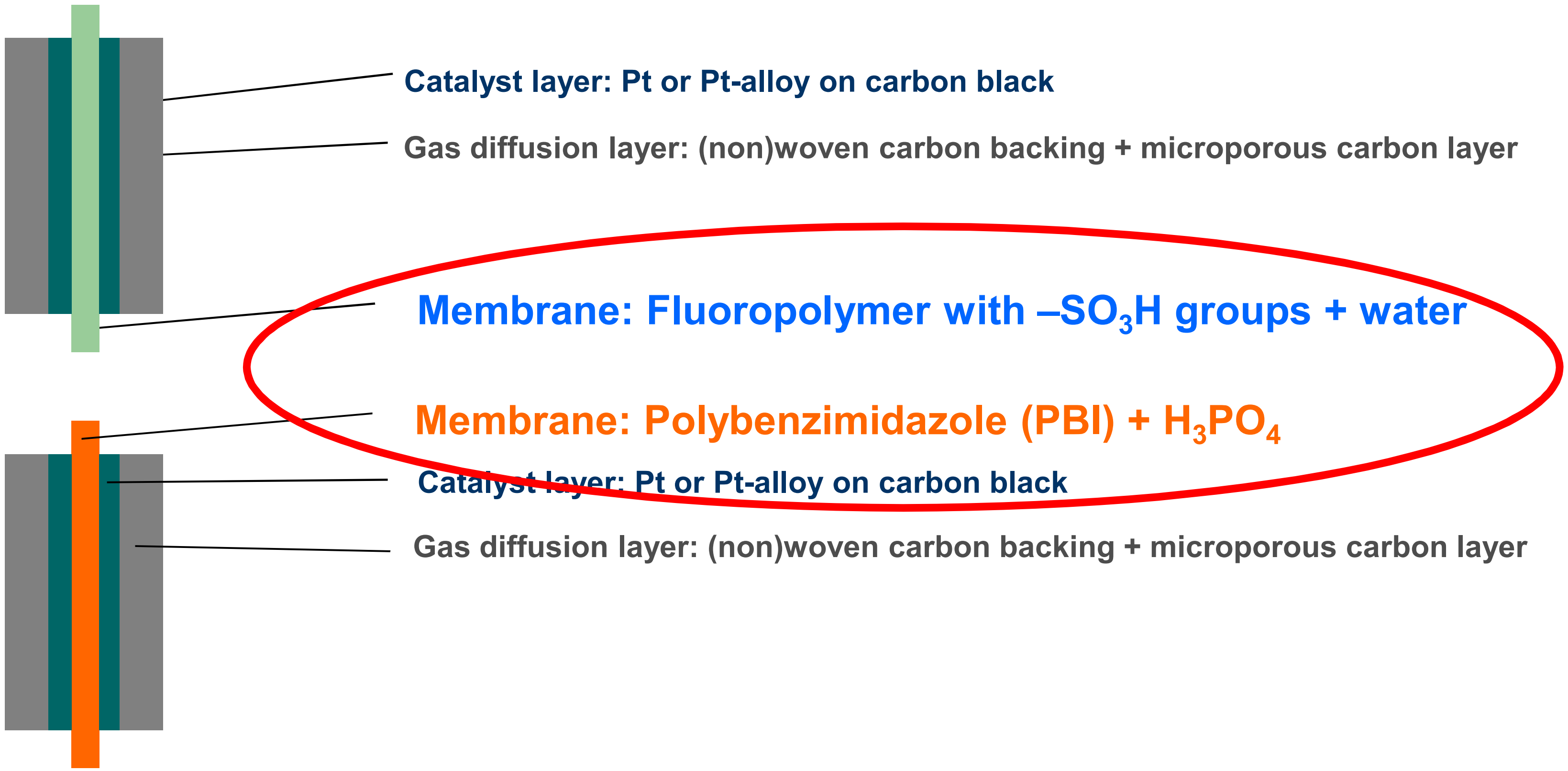


PEM Fuel Cell Basic Components



High Temperature PEM

Low temperature PEM technology:

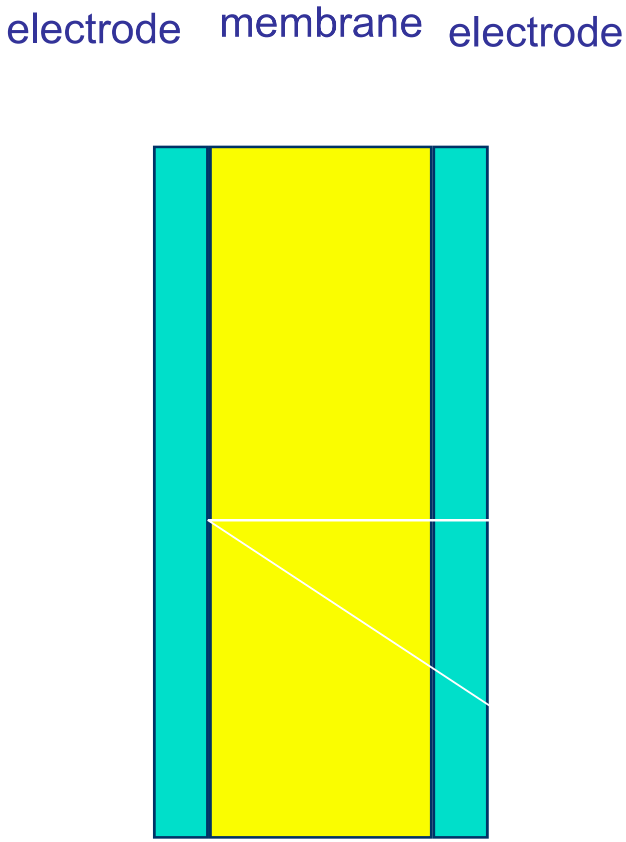


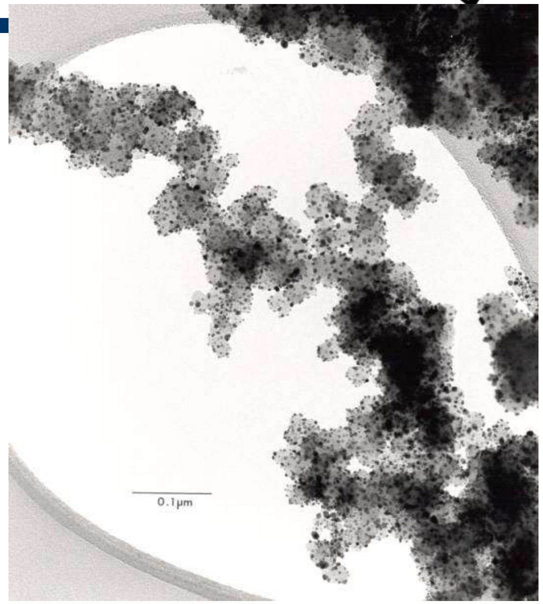
High temperature PEM technology:

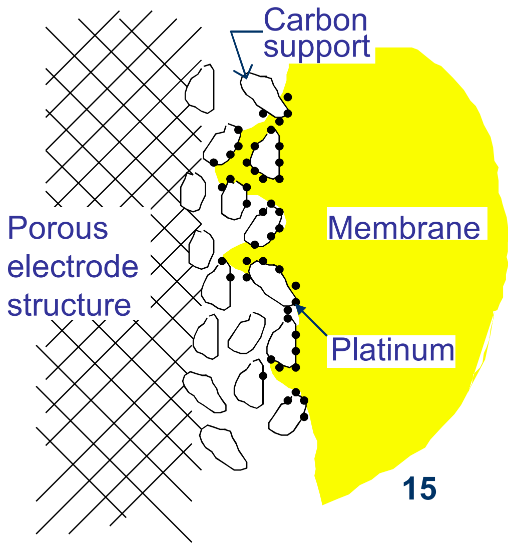
Why High -Temperature PEM Fuel Cells ?

HT PEMFC (120-180°C)	LT PEMFC (<90°C)
• Tolerance to fuel impurities – CO up to 3% (~ 1%) – H_2S up to 10 ppm – CH_3OH up to 10% • Simplified system at reformate • Independent of humidification • High chemical stability of membrane (20.000 hr) • Effective co- and tri-generation, direct use of heat possible	• Tolerance to fuel impurities – CO below 100ppm – H_2S below 0.1 ppm – CH_3OH below 1% • Hydrogen or complex reformer required • Humidification required! • Membrane stability issue • Complex co- and tri-generation

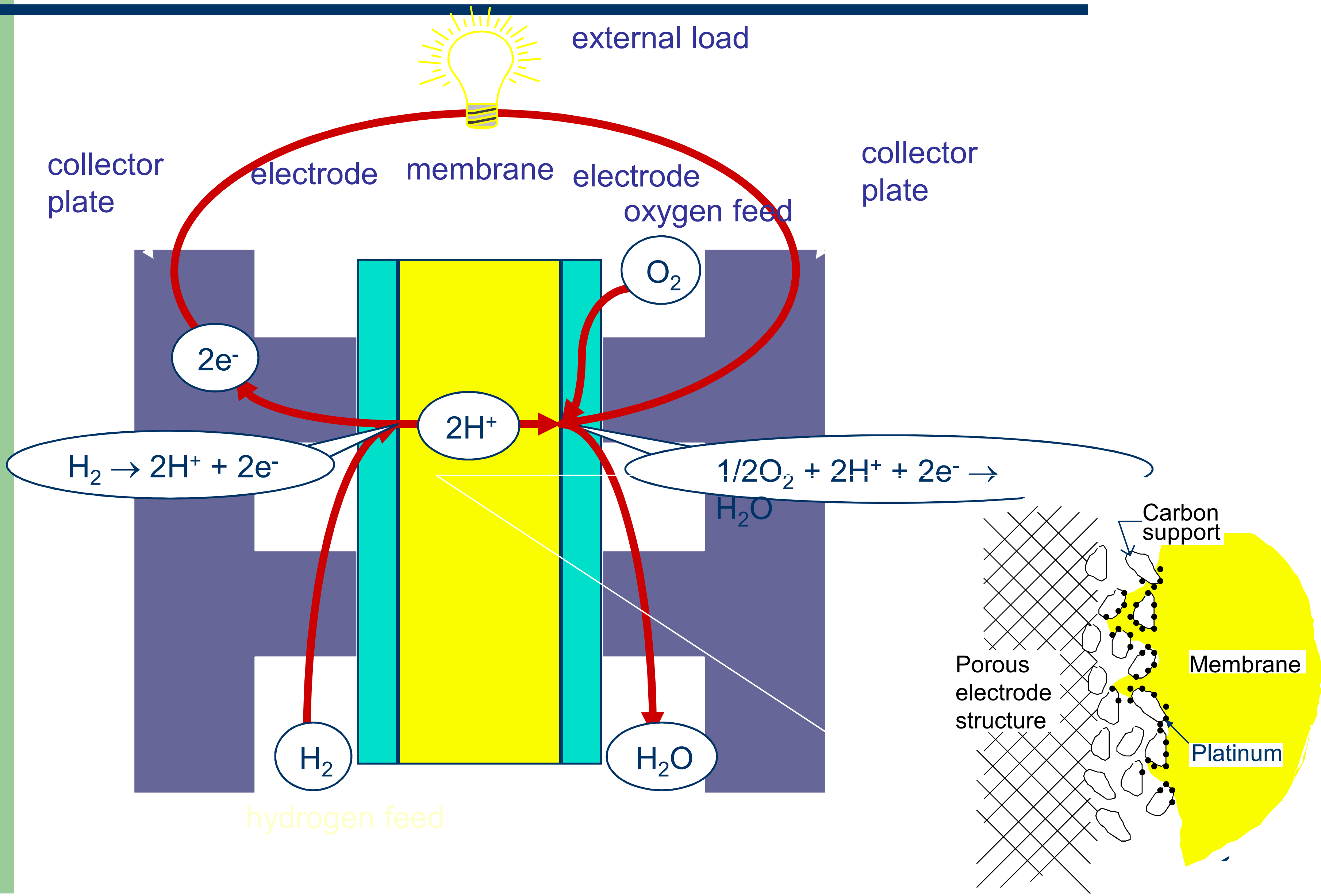
PEM Fuel Cell: How does it work?





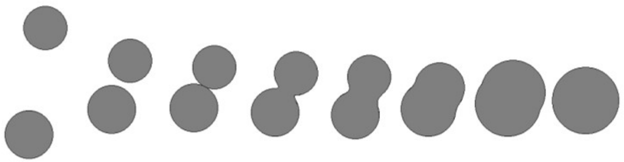


How does it work?

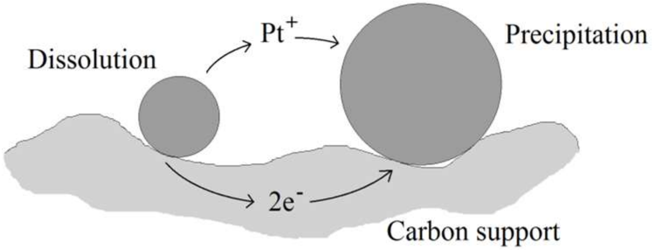


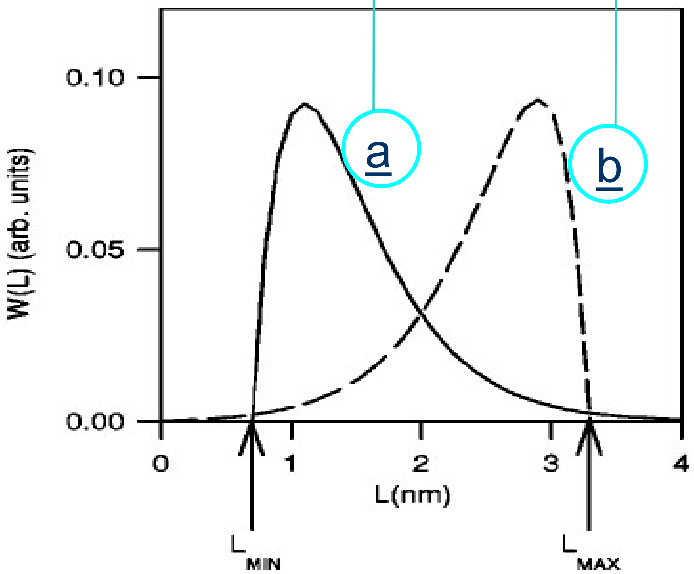
Degradation: catalyst particles growing

Coalescence



Ostwald ripening





Particles size distribution

Ascarelli method

FUEL CELL COMPONENTS - MEA

cell frame / bipolar plate

current collector /
gas diffusion layer

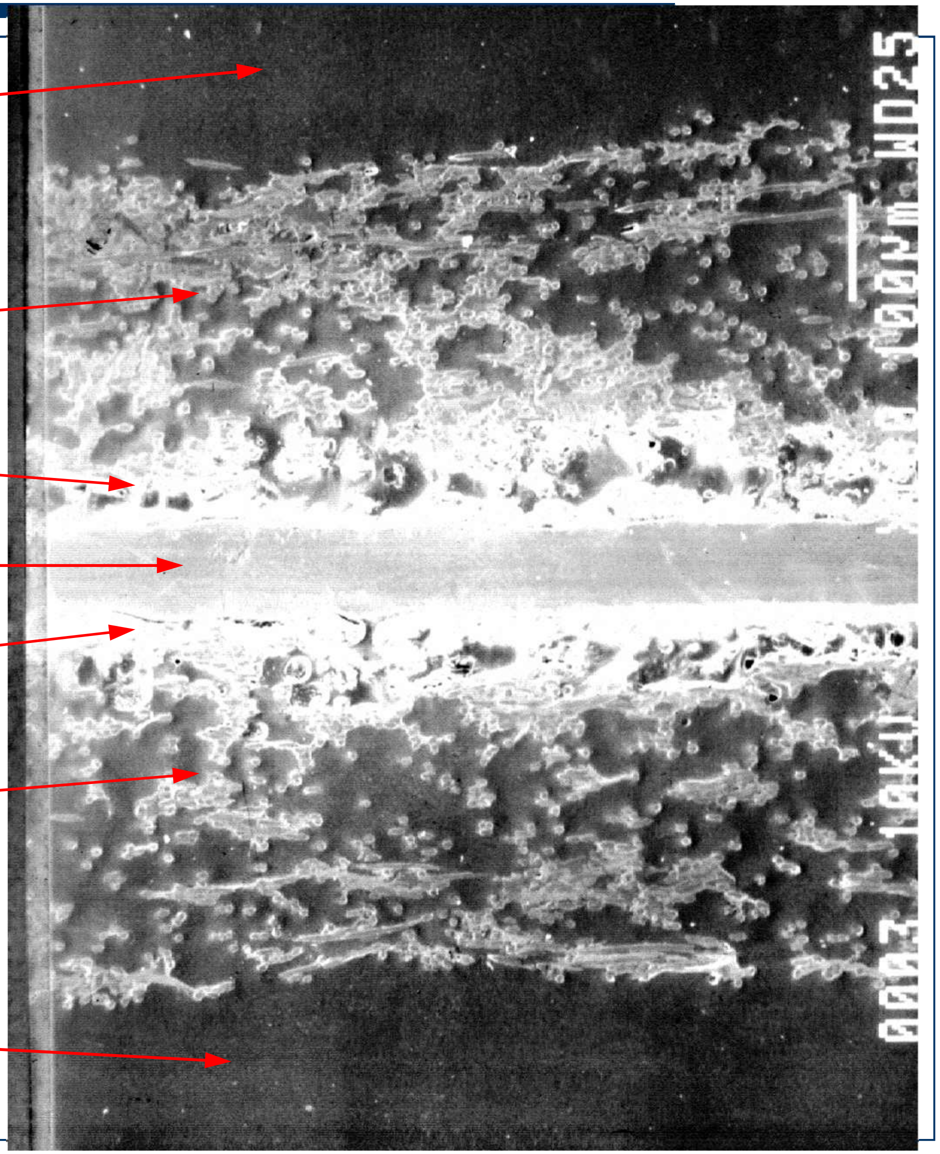
Pt-catalyst

polymer membrane

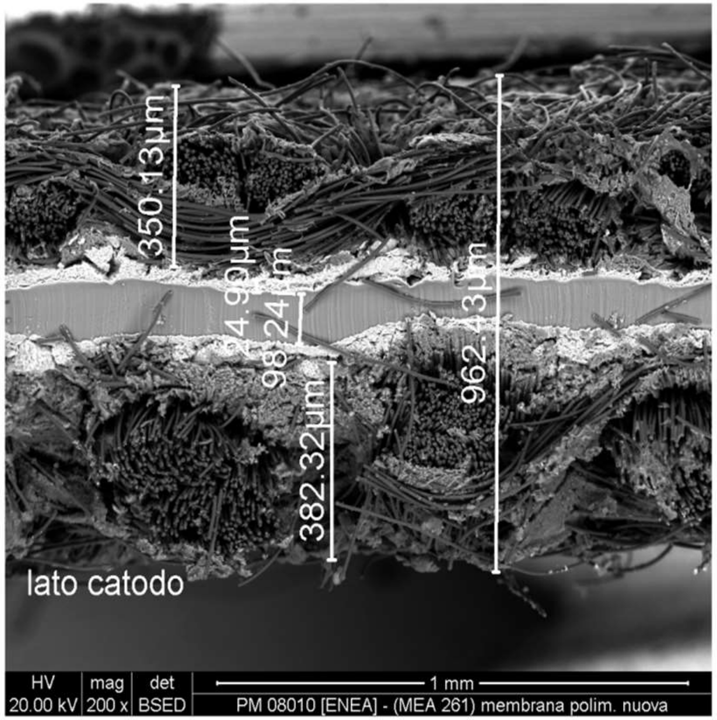
Pt-catalyst

current collector /
gas diffusion layer

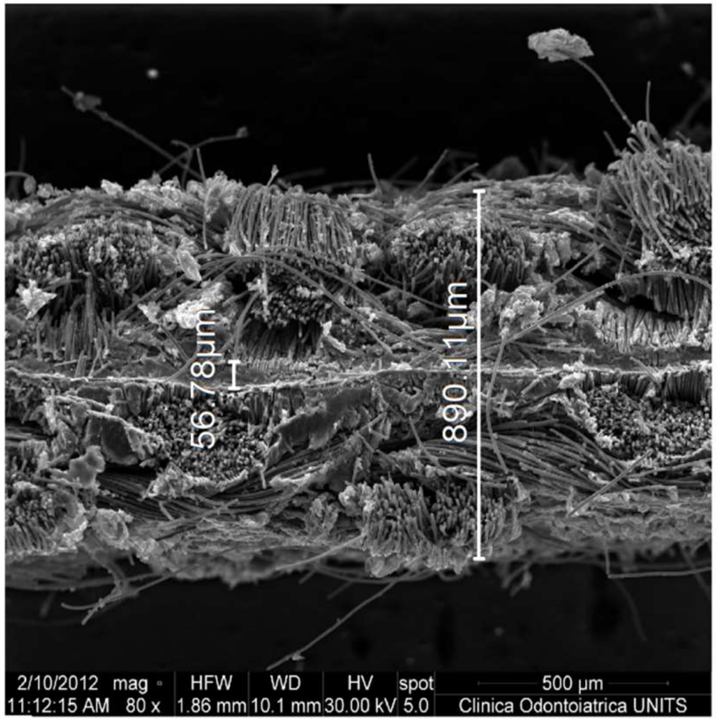
cell frame / bipolar plate



MEA deformation



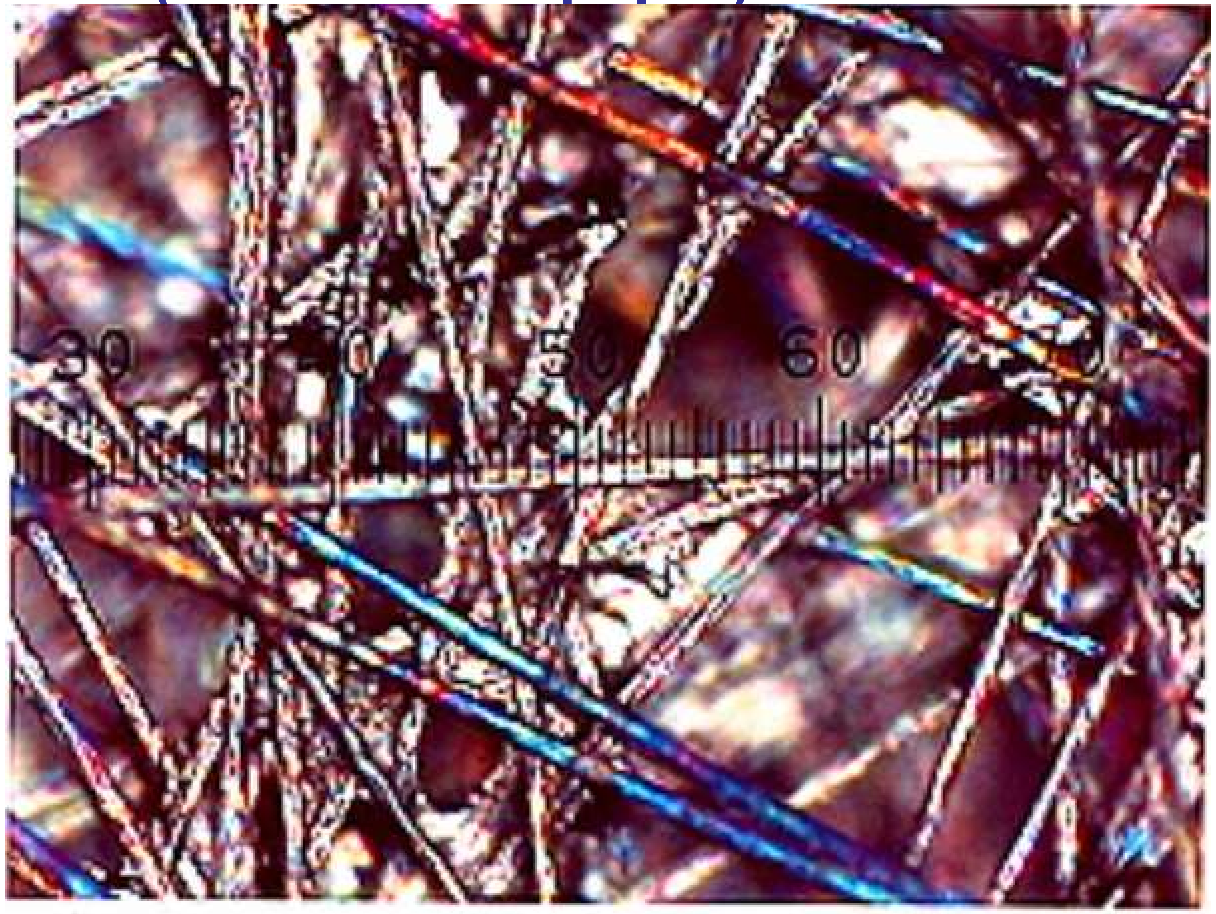
New MEA



Used MEA

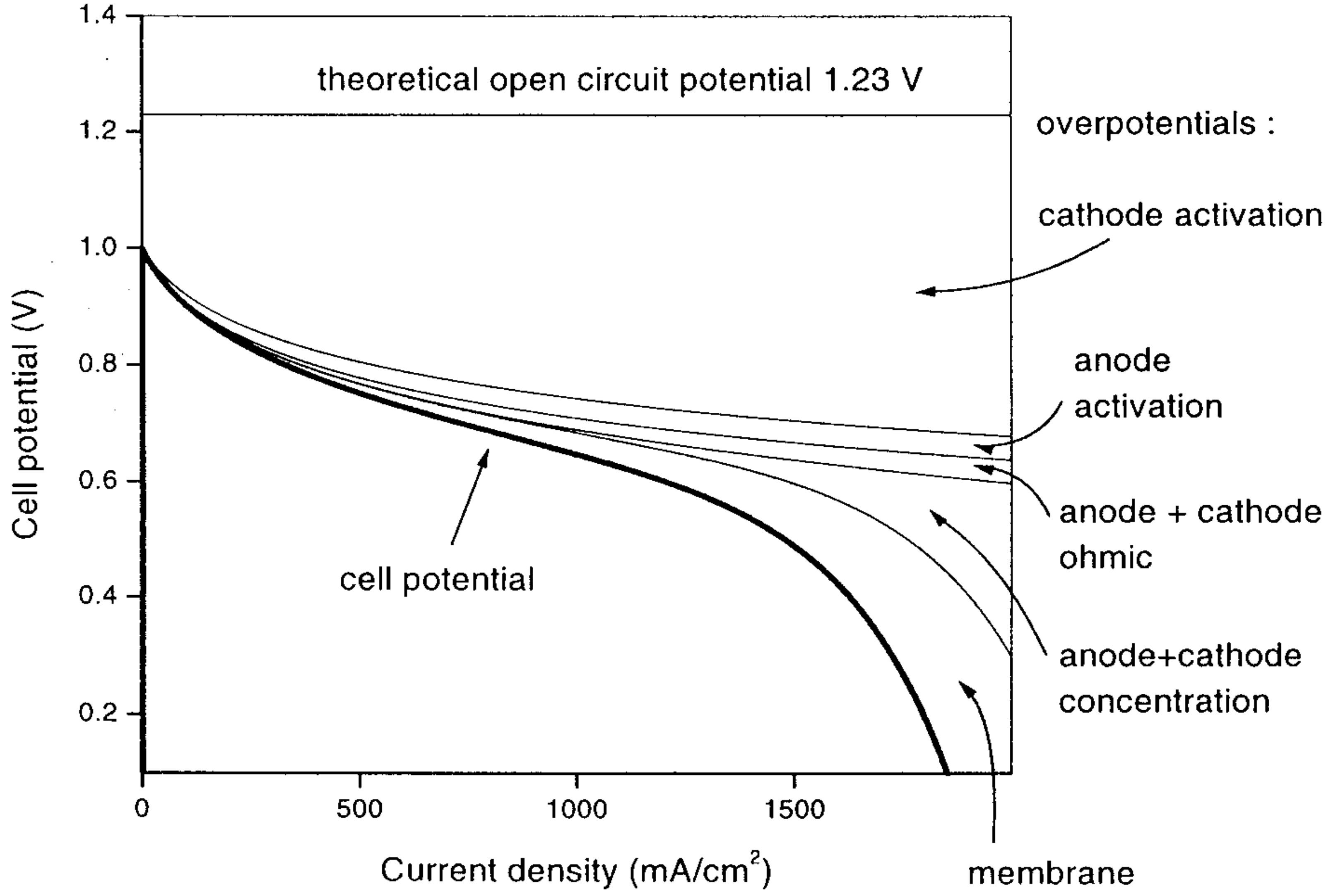
FUEL CELL COMPONENTS - GDL

Porous electrode structure
Gas diffusion layer surface
(carbon fiber paper)



80 μm

TYPES OF OVERPOTENTIALS



FUEL CELL EFFICIENCY

$$\eta = \frac{V * I}{m_c * LHV} = \left(\frac{nFE_{rev}}{LHV}\right)\left(\frac{V}{E_{rev}}\right)\left(\frac{I}{nF\gamma}\right)\left(\frac{\gamma}{m_c}\right)$$

- E_{rev}: THEORETICAL CELL VOLTAGE
- ***F***: *96439 coulomb*;
- ***n***: ELECTRONS INVOLVED IN THE REACTION;
- ***LHV***: LOWER HEATING VALUE;
- m_c: FUEL MOLAR FLOWRATE;
- ***V***: CELL VOLTAGE;
- ***I***: CURRENT INTENSITY;
- γ: USED FUEL MOLAR FLOWRATE;
- U_f: UTALIZATION FACTOR: $U_f = \gamma / m_c$.

1- **(nFE_{rev}/LHV)**. IDEAL EFFICIENCY

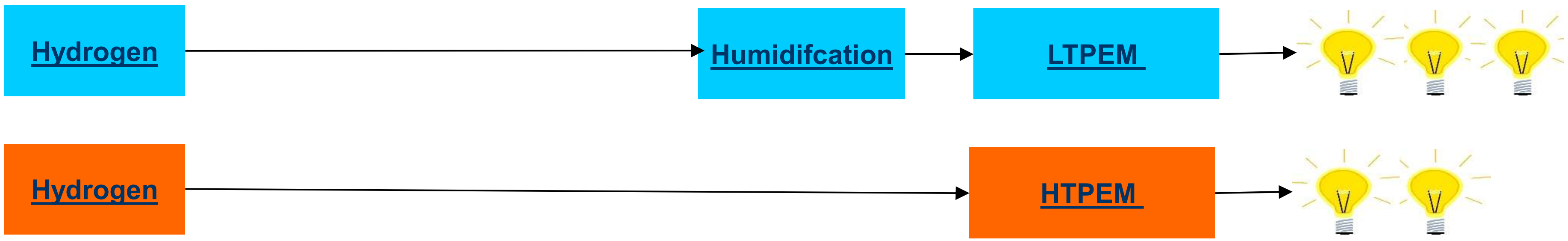
2- **(V/E_{rev})**. TAKES INTO ACCOUNT FOR ACTIVATION, OHMIC AND CONCENTRATION LOSSES

3- **($I/nF\gamma$)**. PARASSITIC LOSSES

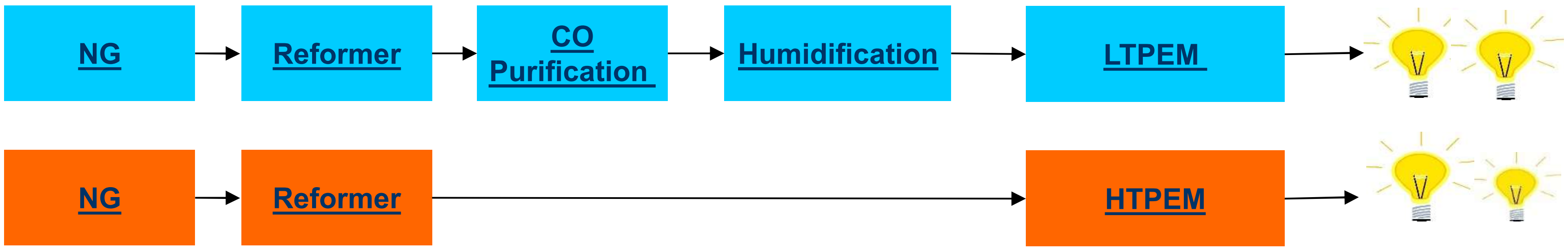
4- **(γ/m_c)**. UTILIZATION FACTOR

FUEL CELL EFFICIENCY

Hydrogen fed system



Natural gas fed system



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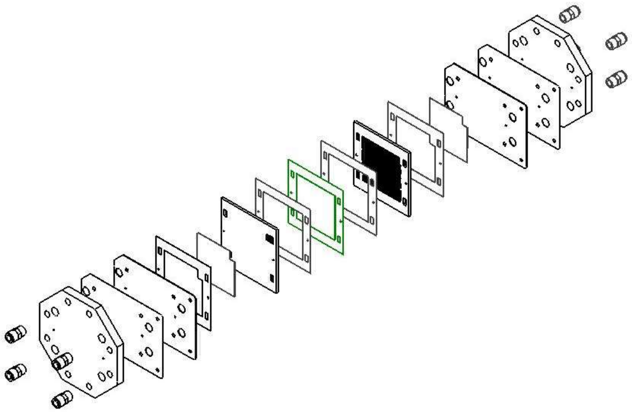
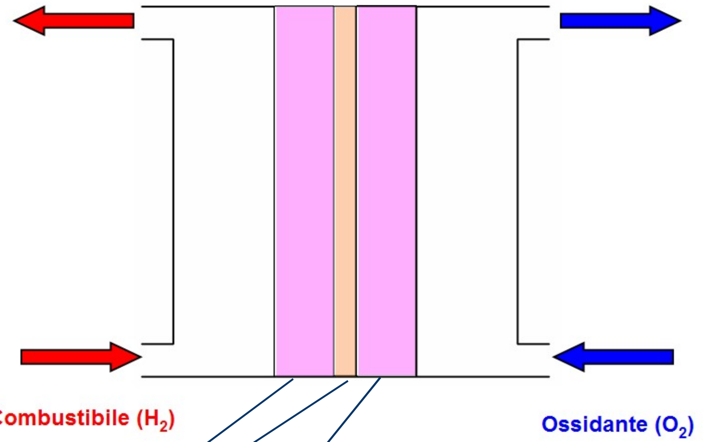
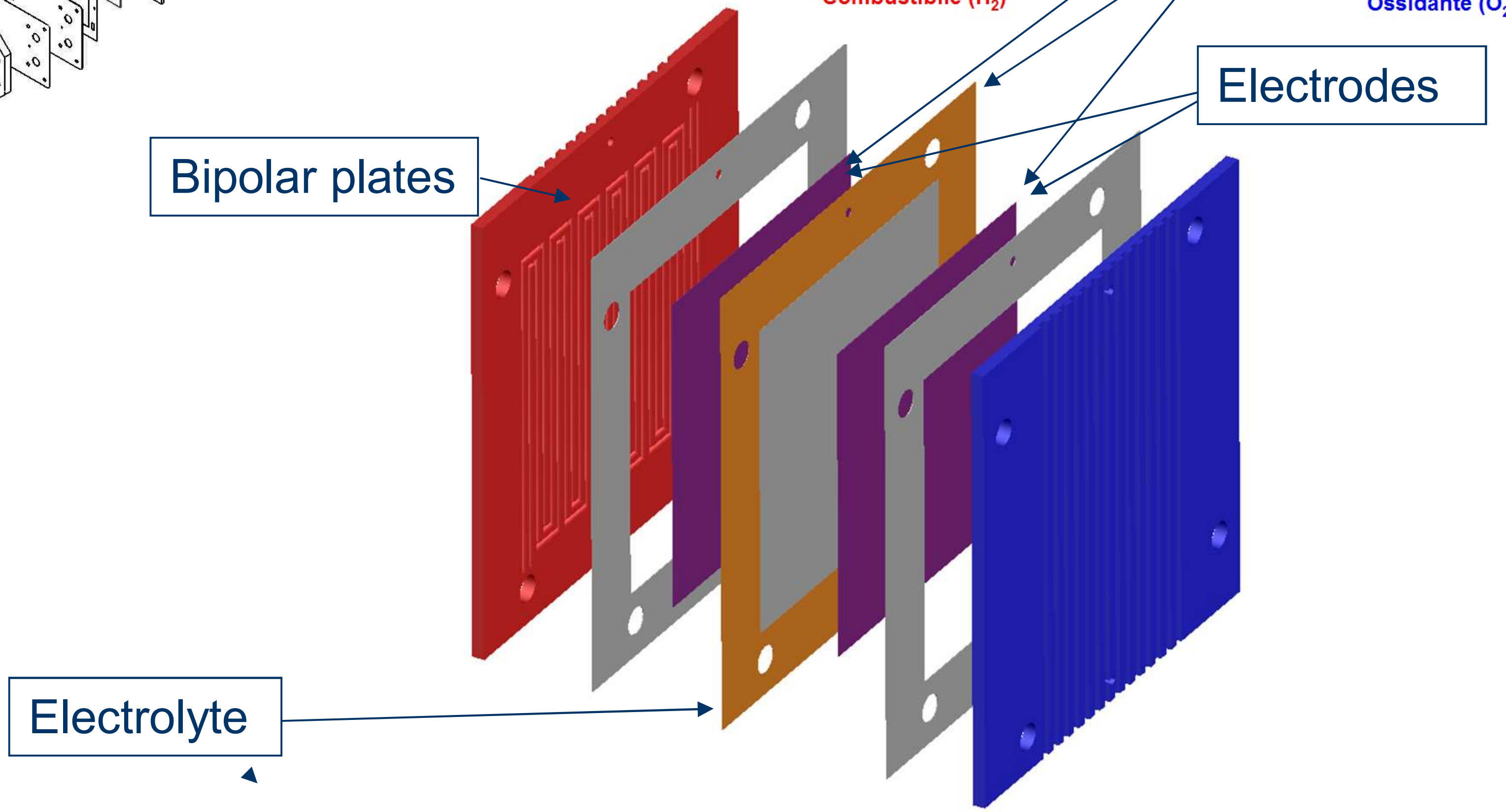
Fuel Cell Components

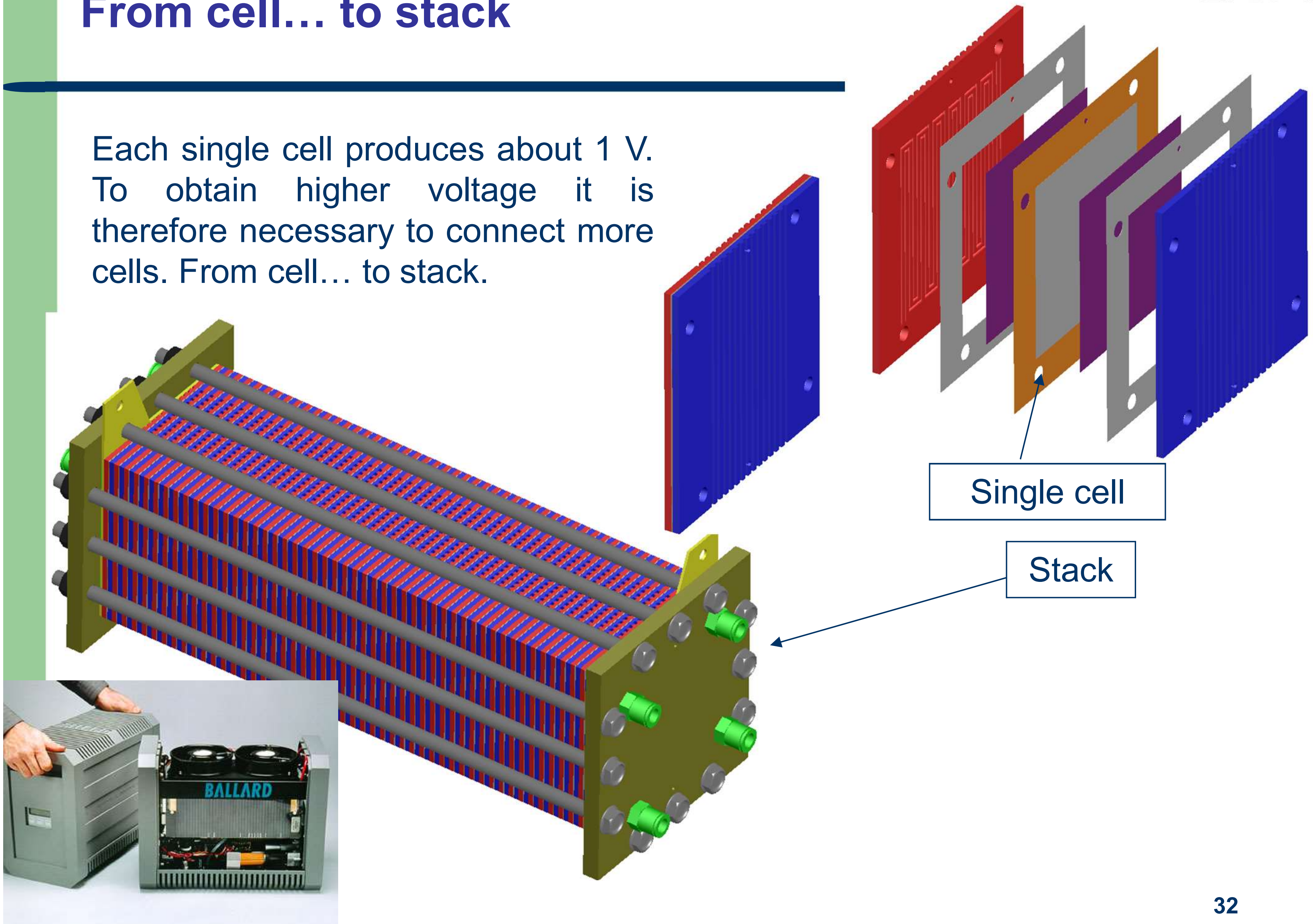






From cell… to stack

Each single cell produces about 1 V. To obtain higher voltage it is therefore necessary to connect more cells. From cell… to stack.

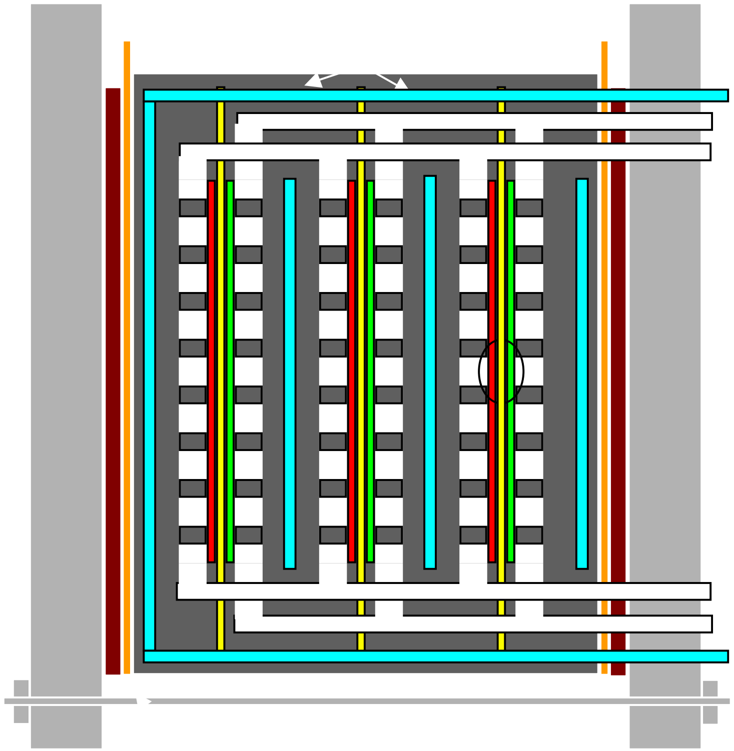


Major stack components

MEA
- Membrane
- Catalyst
- Catalyst support
- Catalyst layer
- Gas diffusion layer
- Gaskets/frames

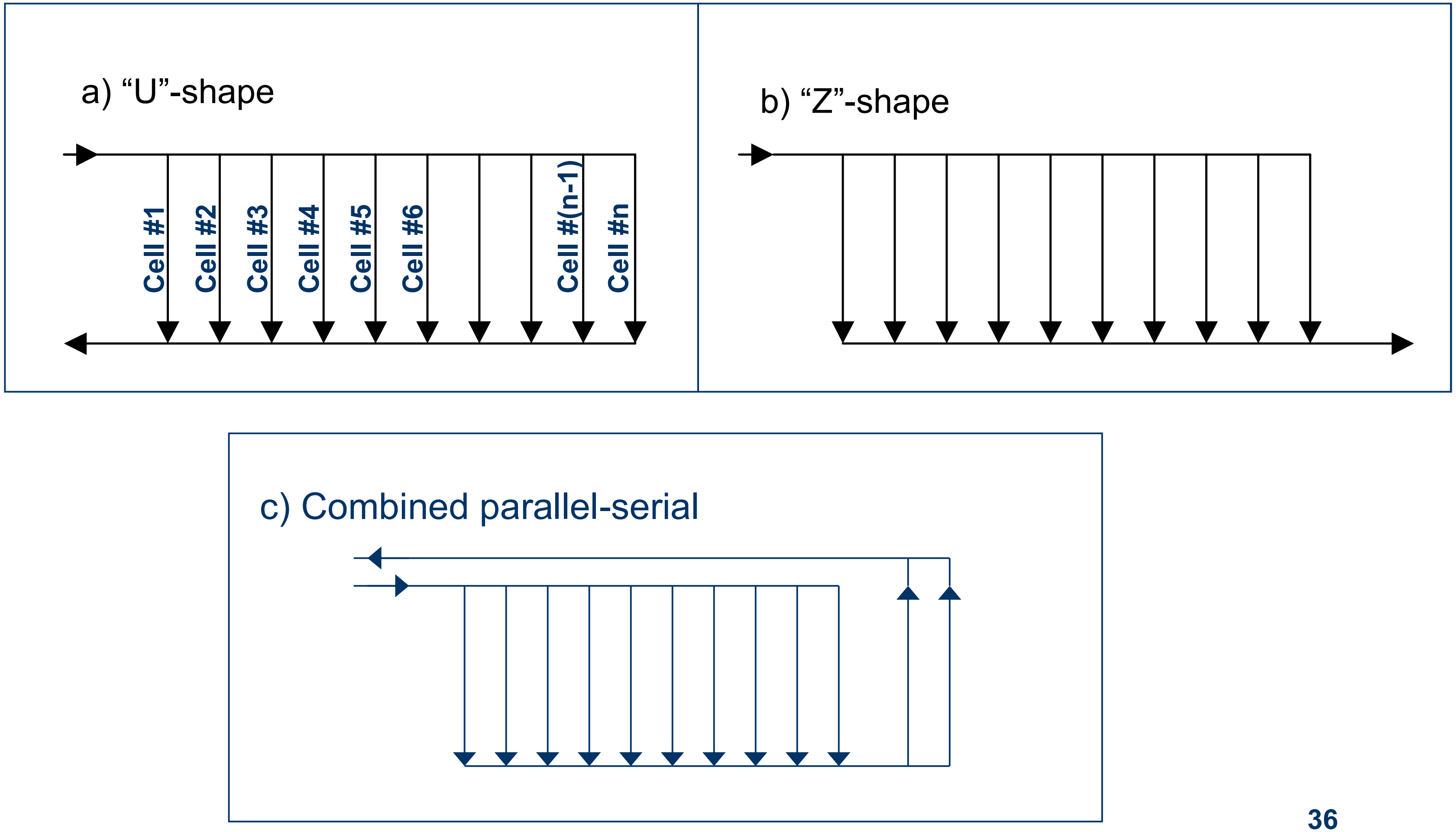
Bi-polar plate
- Flow field
- Separator/connector

- Bus plates/terminals
- End plates
- Clamping mechanism
- Fluid connections
- Manifolds
- Cooling plates/arrangements
- Humidification section (optional)



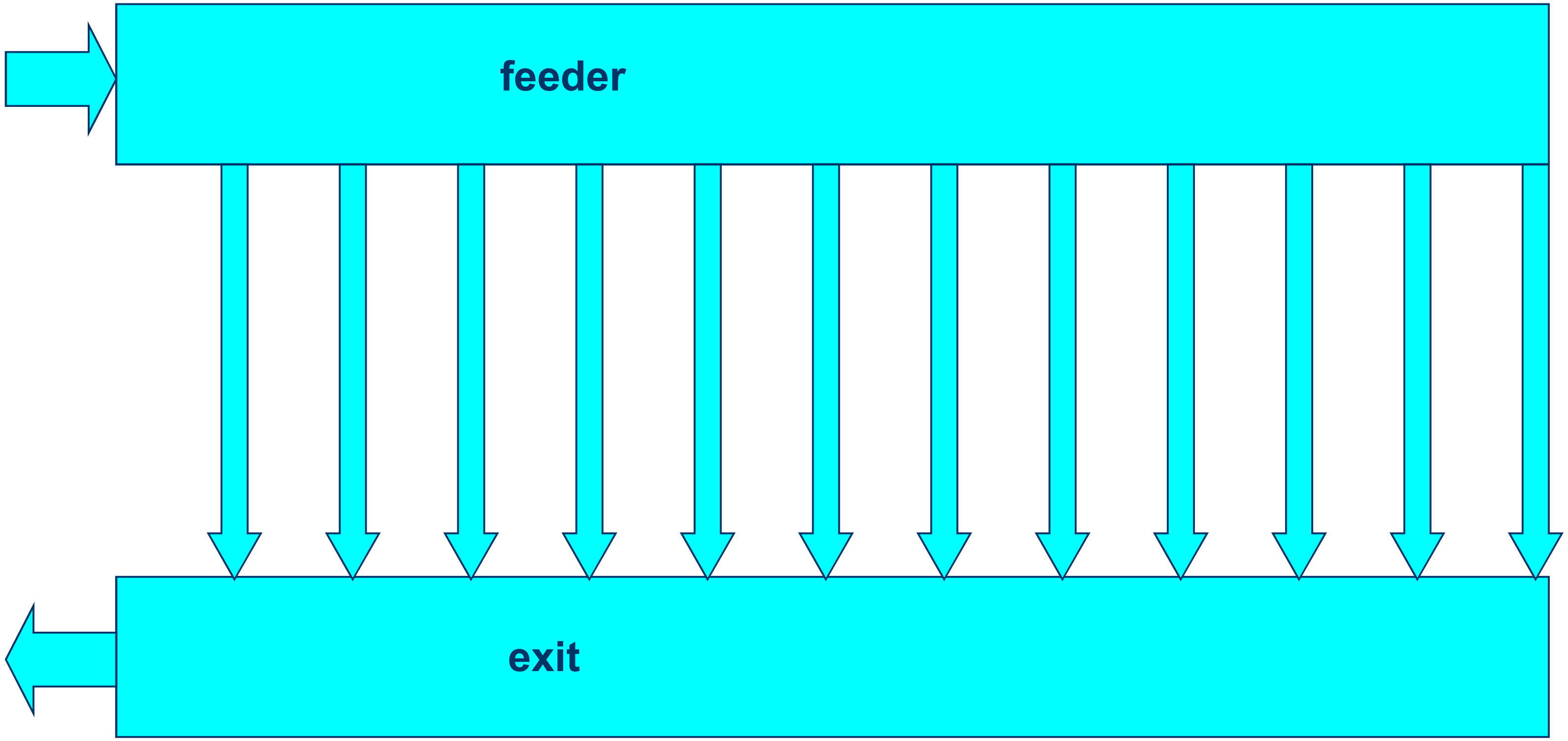
Stack design/engineering issues

- Uniform distribution of reactants to each cell

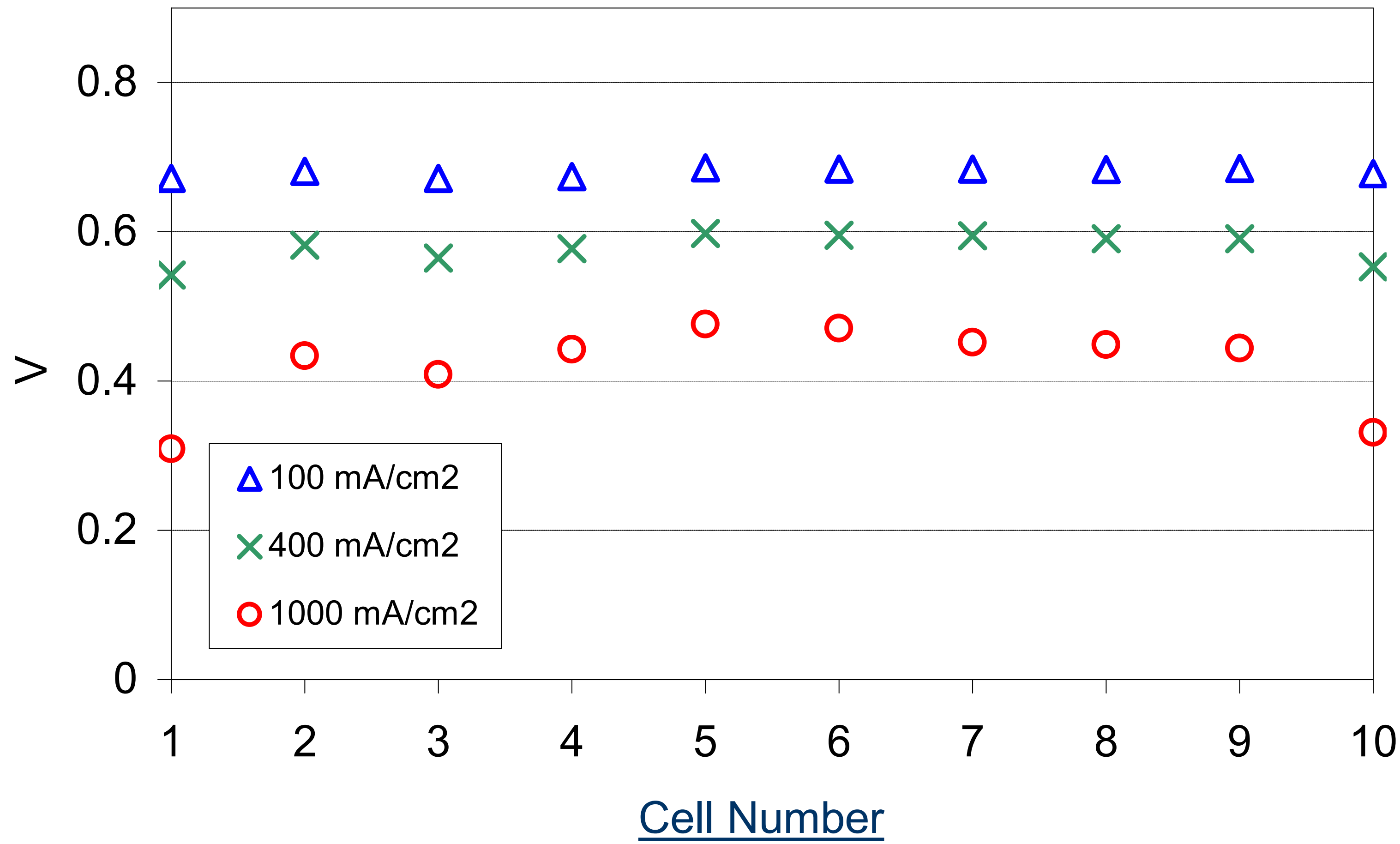


Pressure drop

$\Delta P_{feeder} << \Delta P_{cell}$

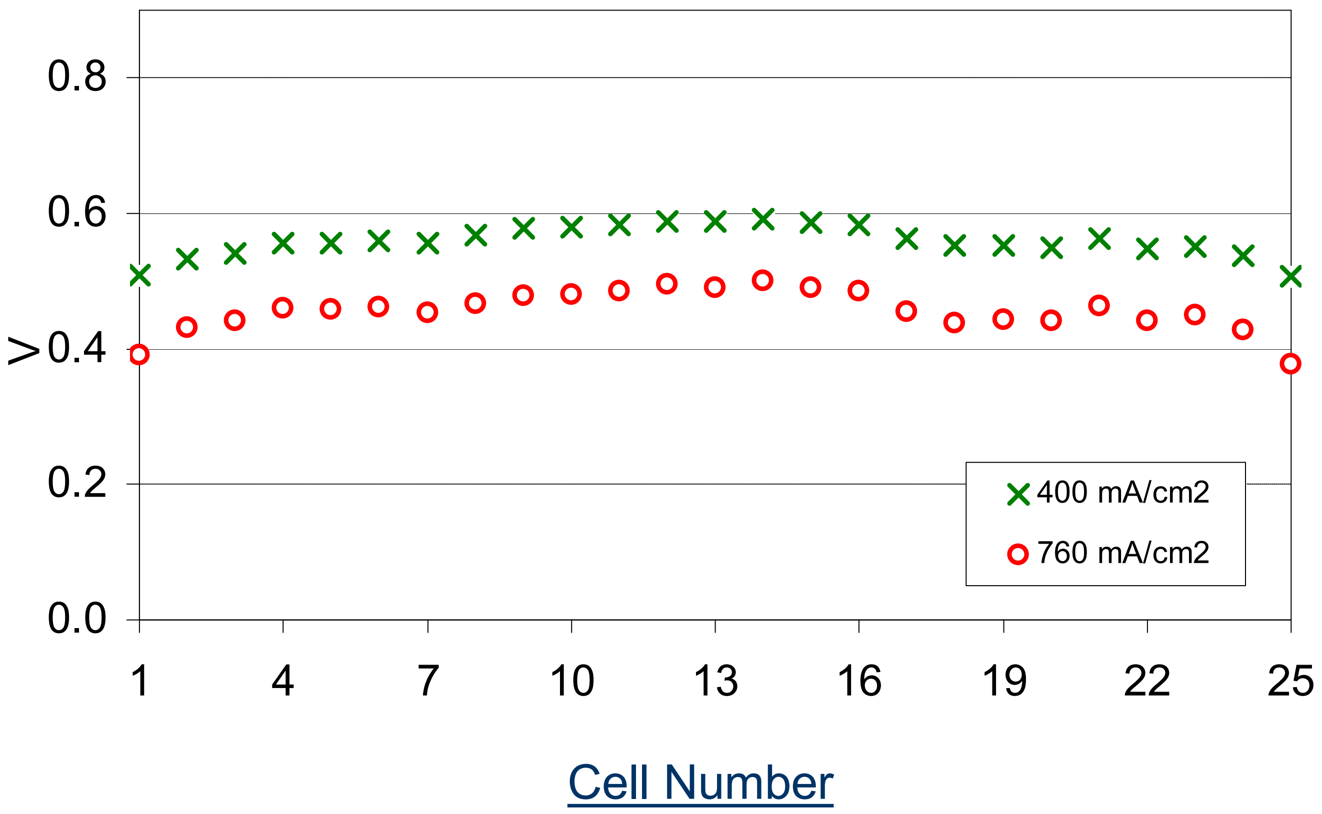


Stack Voltage Distribution



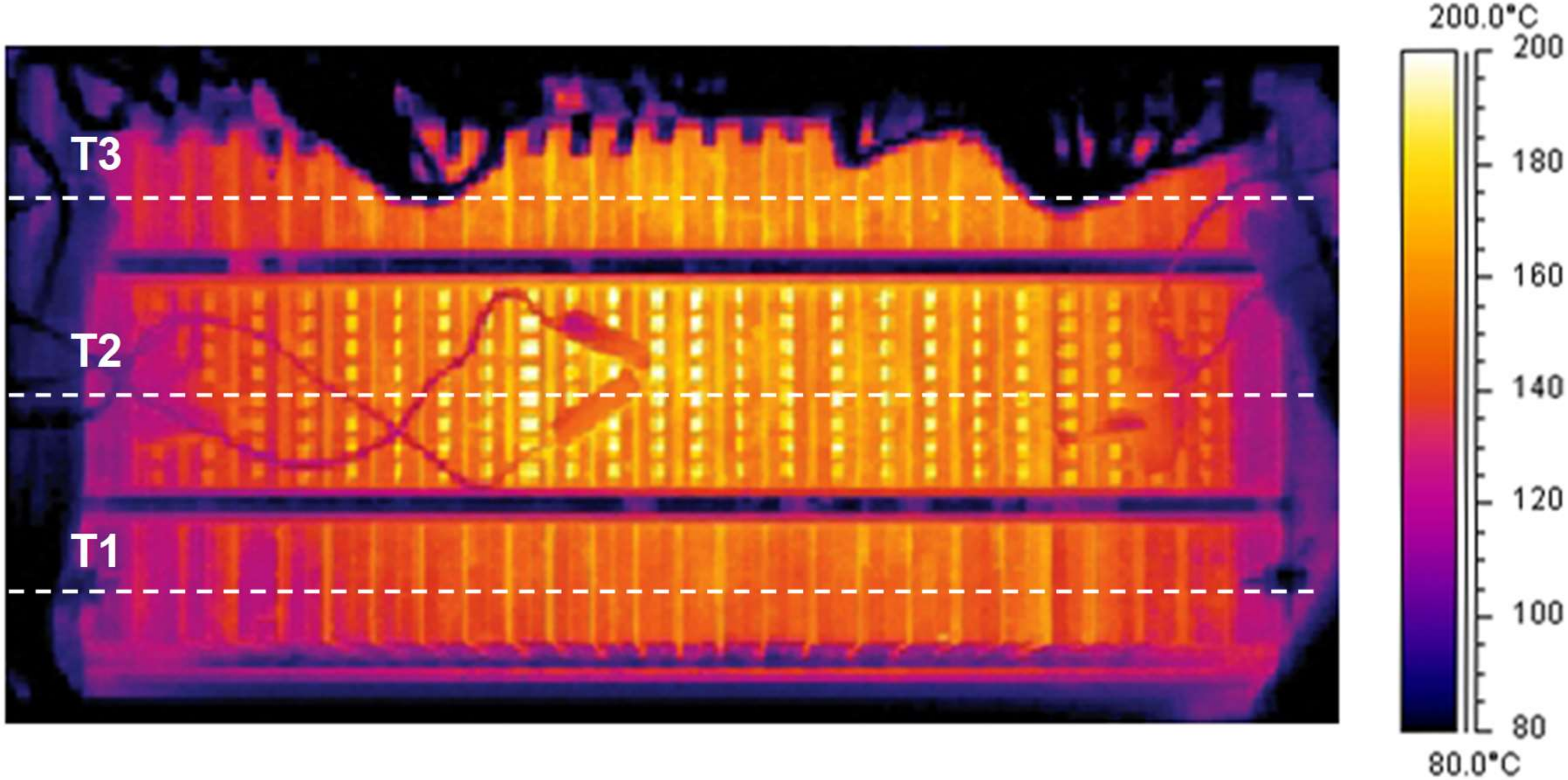
HT PEM, 160°C

Stack Voltage Distribution

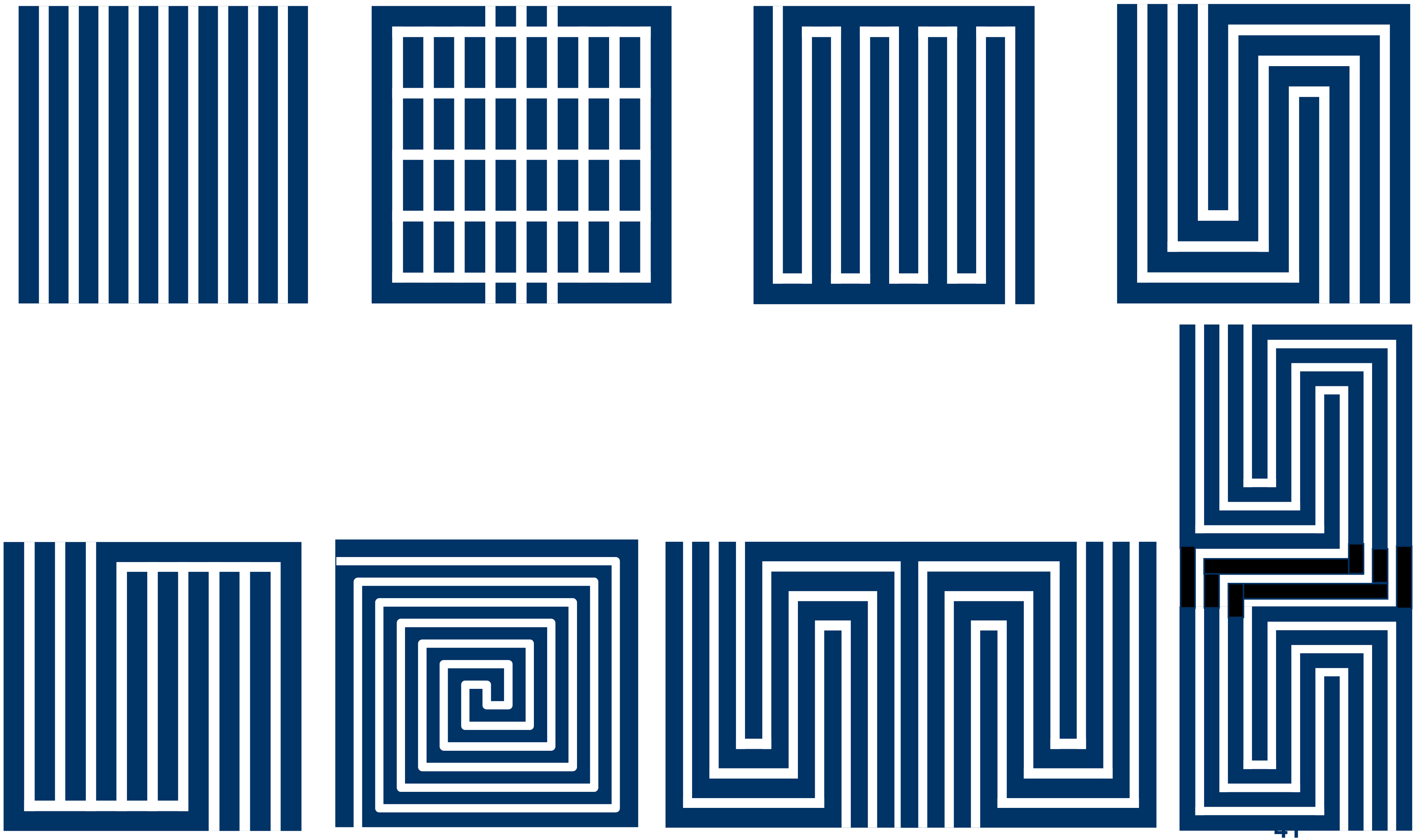


HT PEM, 160°C

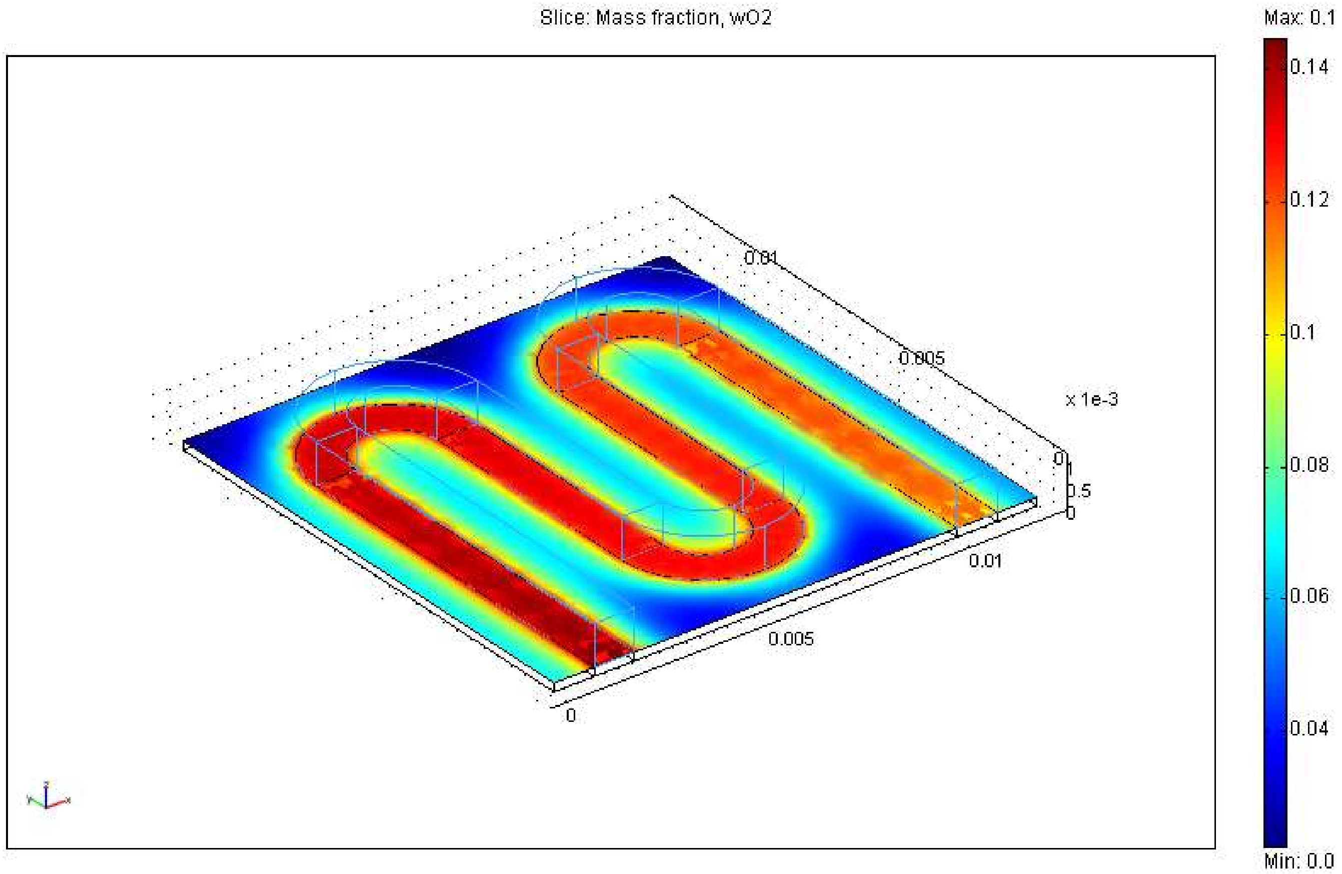
Stack Temperature Distribution



Flow field configurations



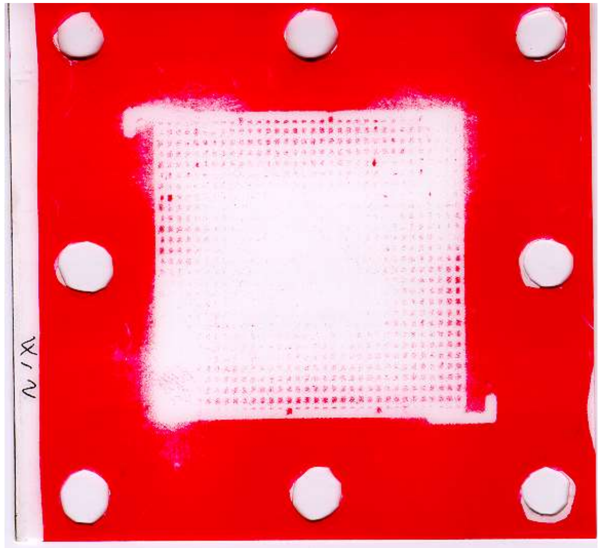
CFD can help

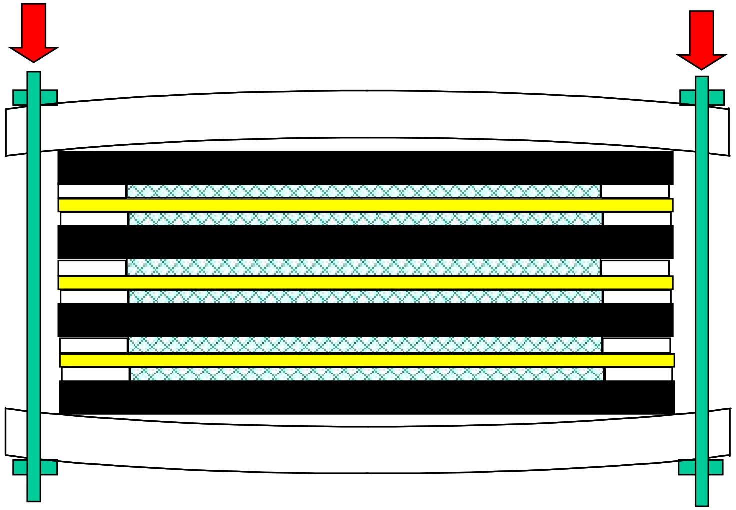


Slice: Mass fraction, wO2
Max: 0.1
0.14
0.12
0.1
0.08
0.06
0.04
Min: 0.0
0.01
0.005
x 1e-3
0
0.5
0
0.01
0.005
0

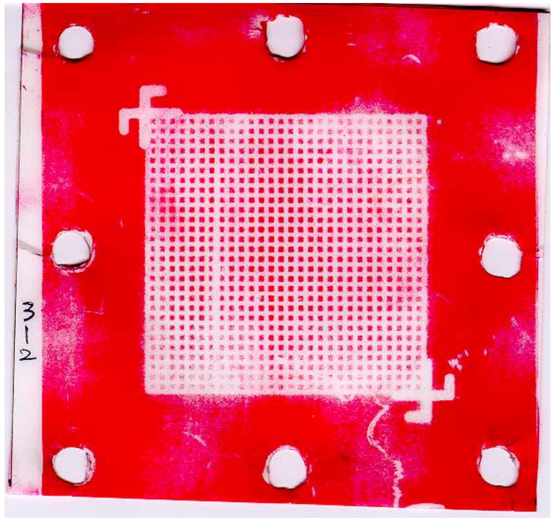
Cell/stack compression

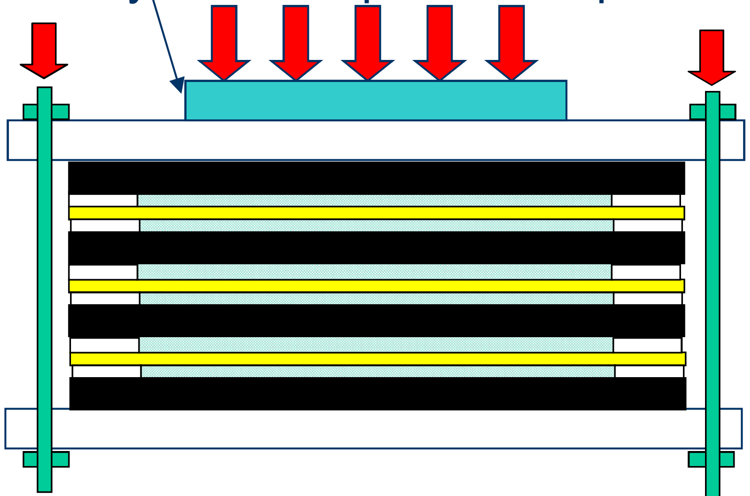
Non-uniform





Uniform





Stack design summary

- A fuel cell stack is a simple, yet complex device
- Uniformity of local conditions is essential for good design
- Understanding of operating conditions is important
- Information may be gathered through modeling/numerical simulations and experimentally
- Selection of key parameters and conditions must be made from the system perspective

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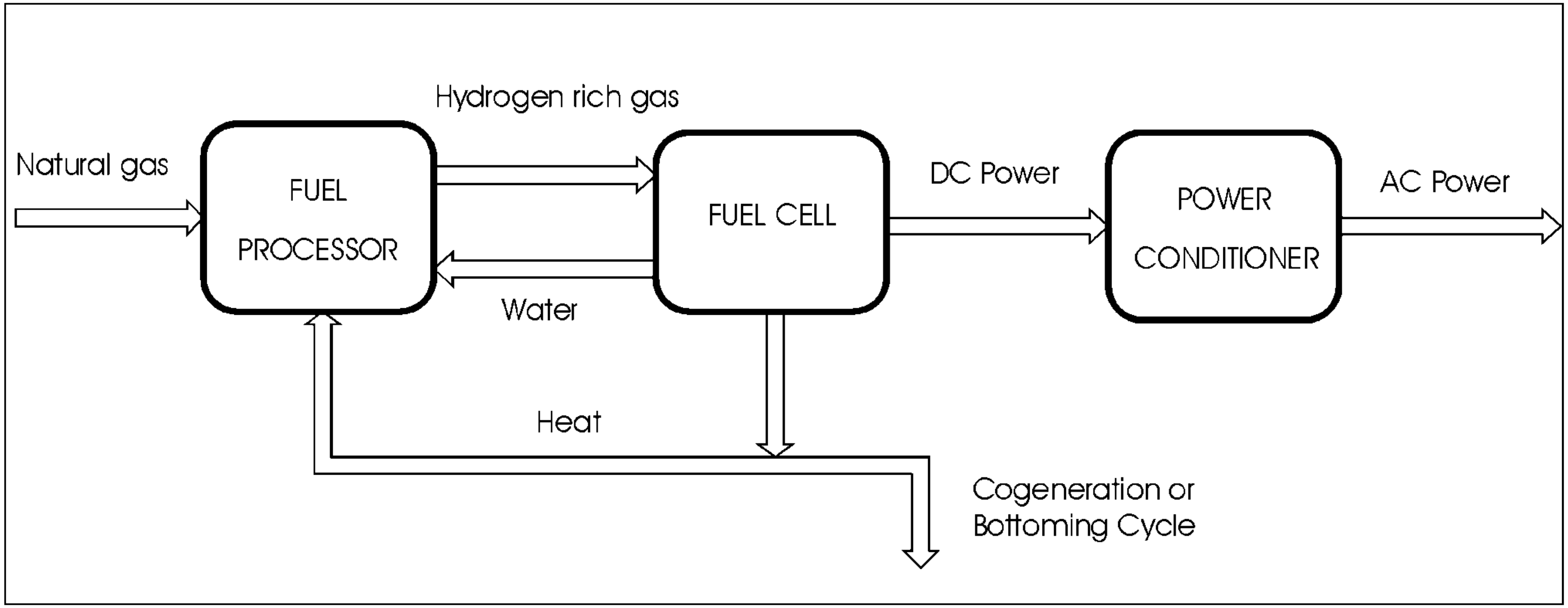
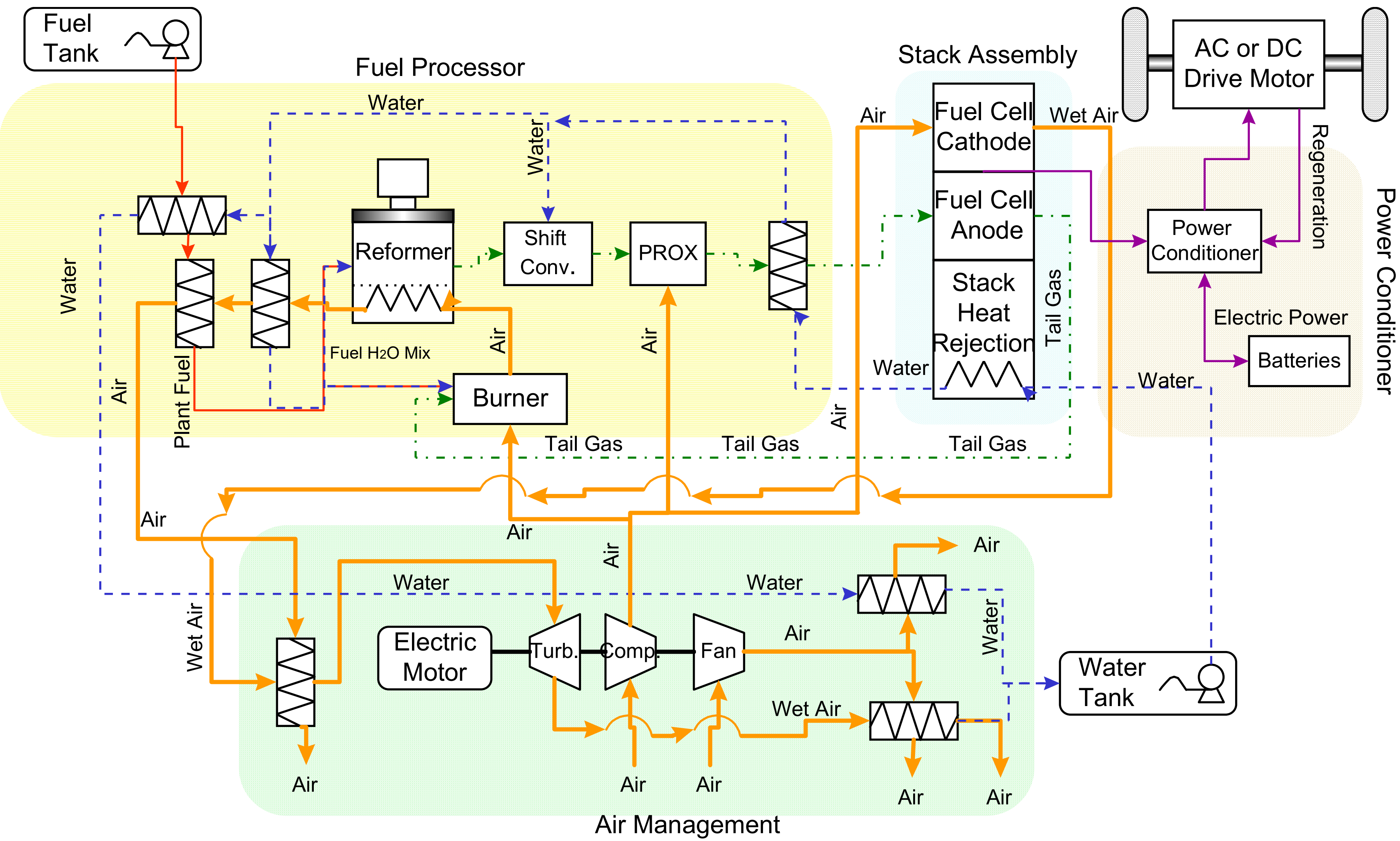
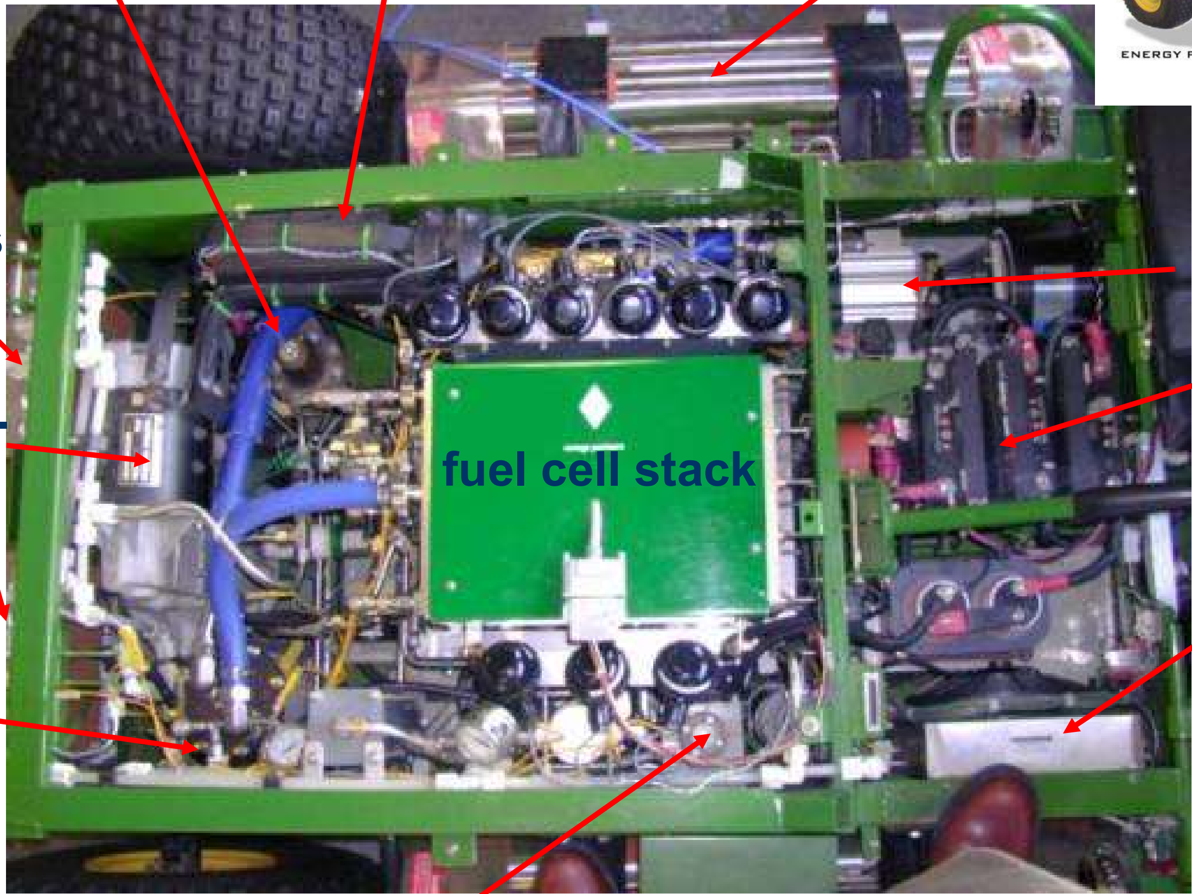
System design and integration



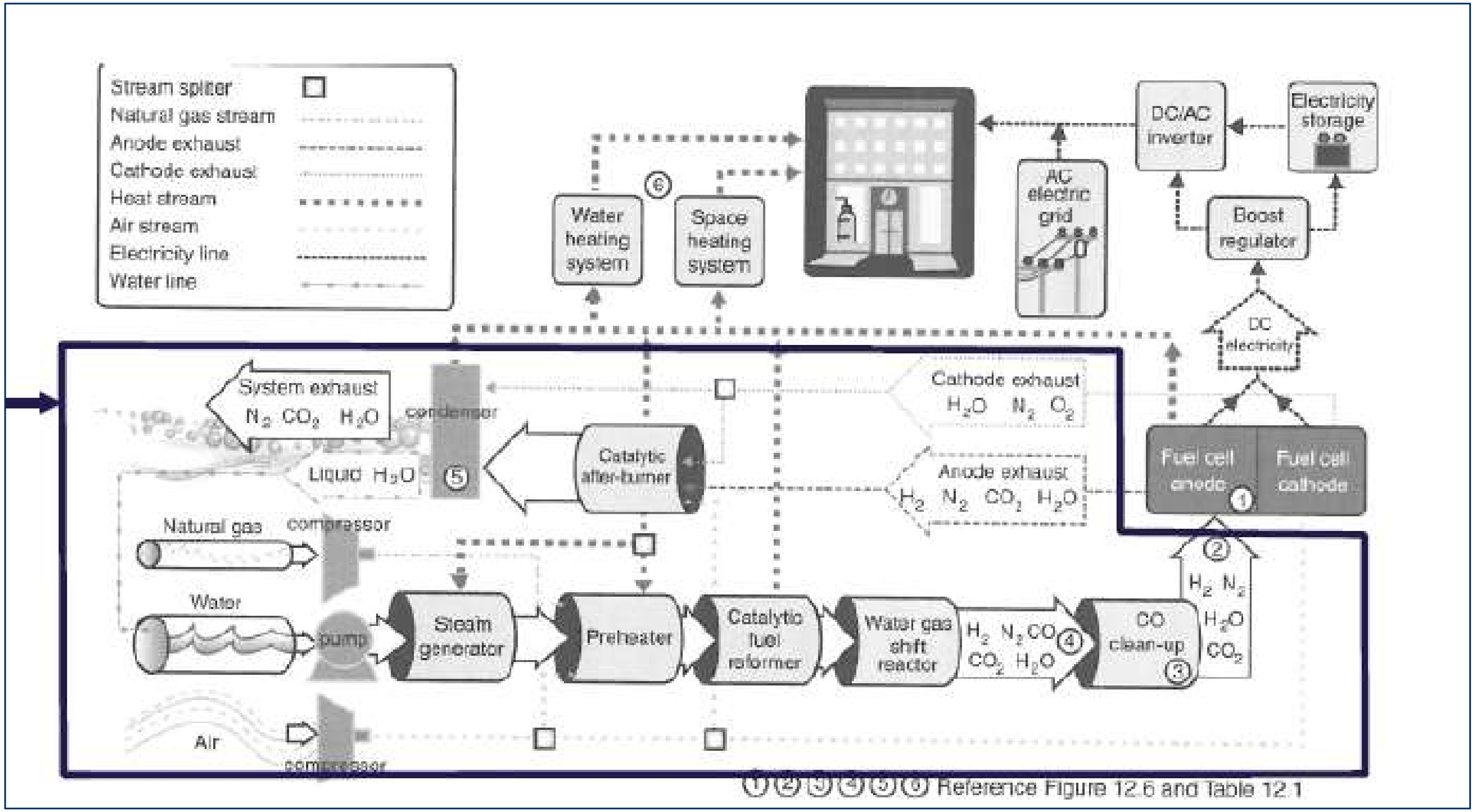
Sistem design and integration



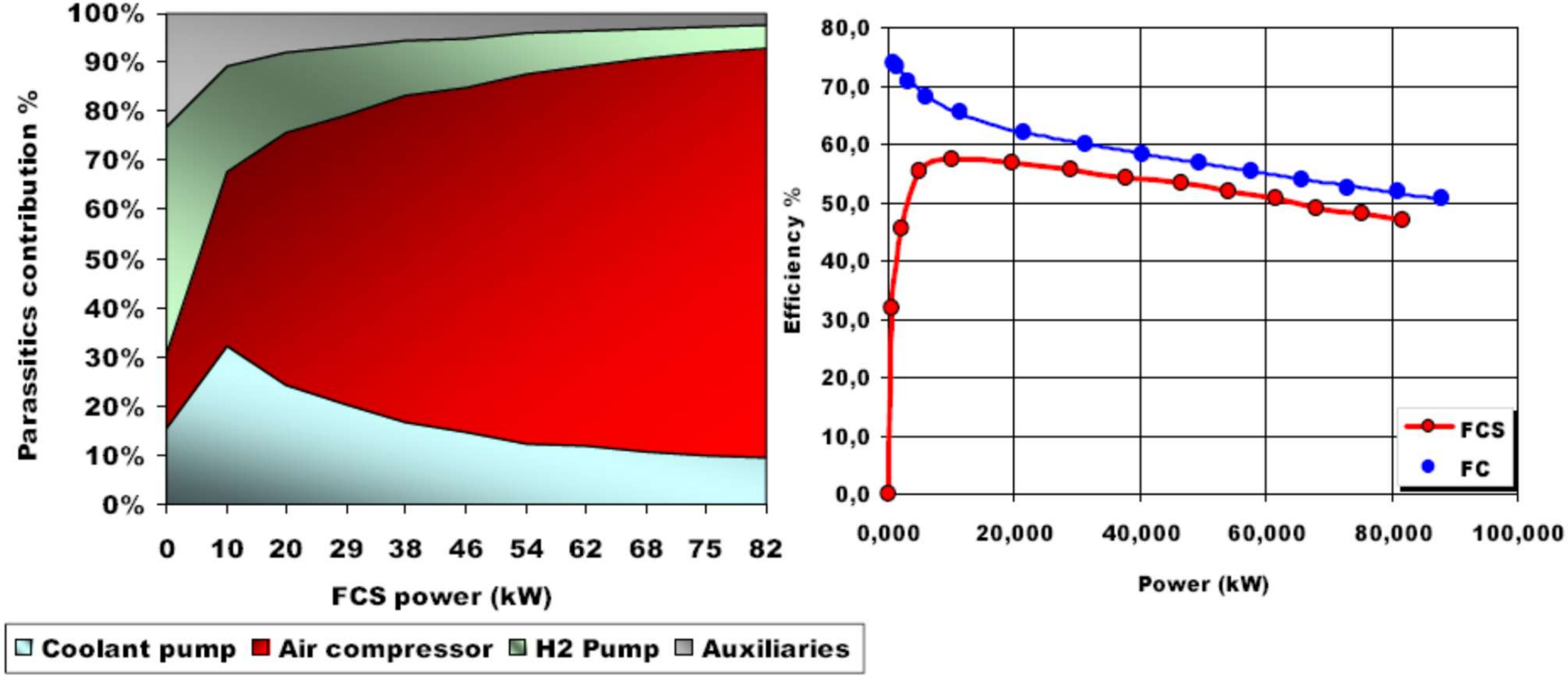
Actual fuel cell system



Schema per esercizio



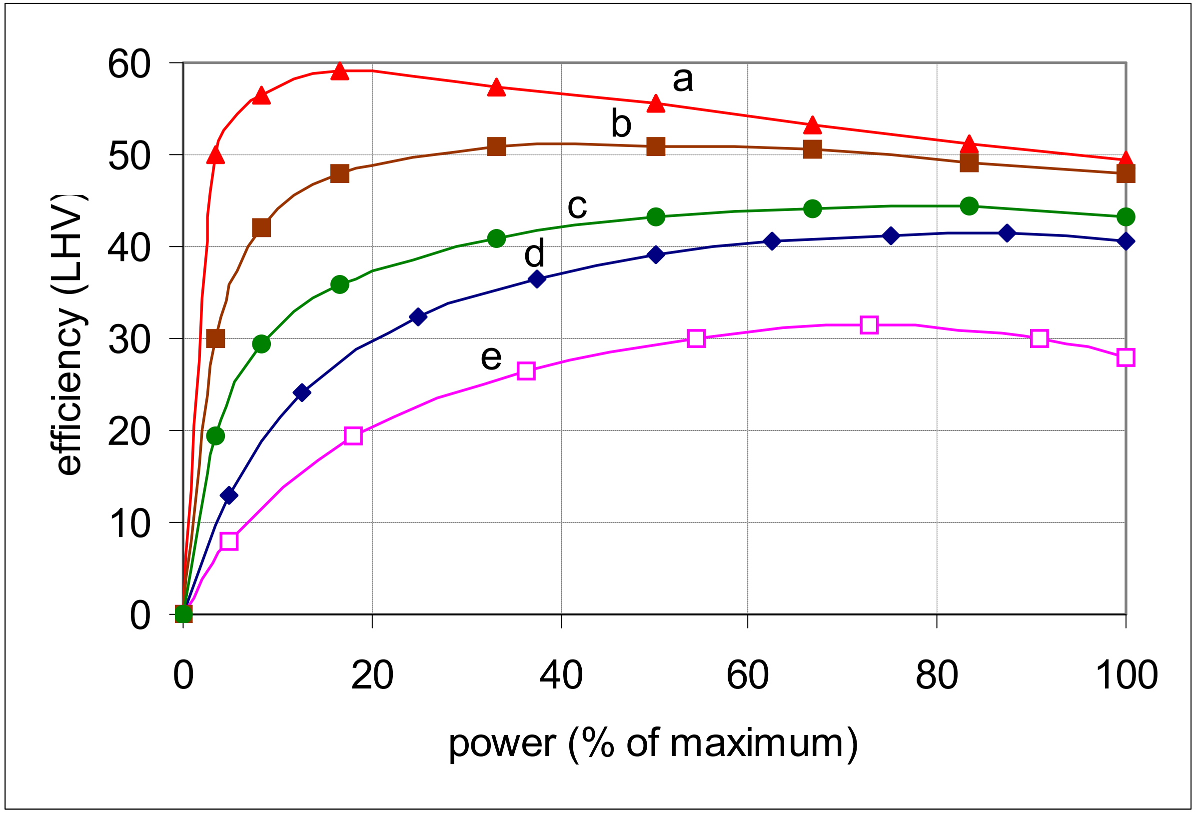
HDL 82 FCPM Efficiency Diagram



- 750 W of parasitic losses in IDLE MODE
- 6350 W of parasitic losses @ max power

NUVERA

Efficiency of fuel cell vs. ICE



a) Low pressure, low temperature fuel cell system
b) High pressure, high temperature fuel cell system
c) Fuel cell system with an on-board reformer
d) Compression-ignition engine (diesel)
e) Spark-ignition engine

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Fuel Cell applications:
Status, Challenges and Perspectives

Space	in use for decades
(Sub)marine	in use
Automotive	demonstrations
Stationary Power	demonstrations
Portable Power	military
Battery Replacement	close to commercial

Why fuel cells?

- Promise of high efficiency
- Promise of low or zero emissions
- Run on hydrogen/fuel may be produced from indigenous sources/issue of national security
- Simple/promise of low cost
- No moving parts/promise of long life
- Modular
- Quiet

Why PEM Fuel Cells?

- Simple
- Quick start-up
- Fast response
- High efficiency
- High power density (kW/kg and kW/l)
- Zero emissions

Fuel cells have already been demonstrated in every imaginable application

- Automobiles
- Buses
- Scooters
- Bicycles
- Golf carts
- Space
- Airplanes
- Locomotives
- Boats
- Underwater vehicles
- Distributed power generation
- Cogeneration
- Back-up power
- Portable power

Fuel Cells Patents

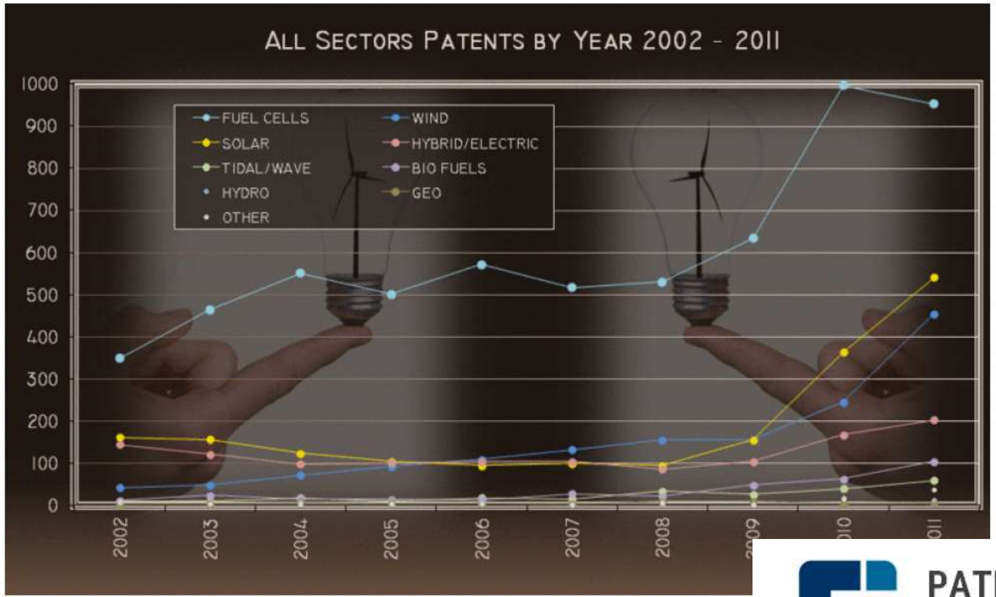
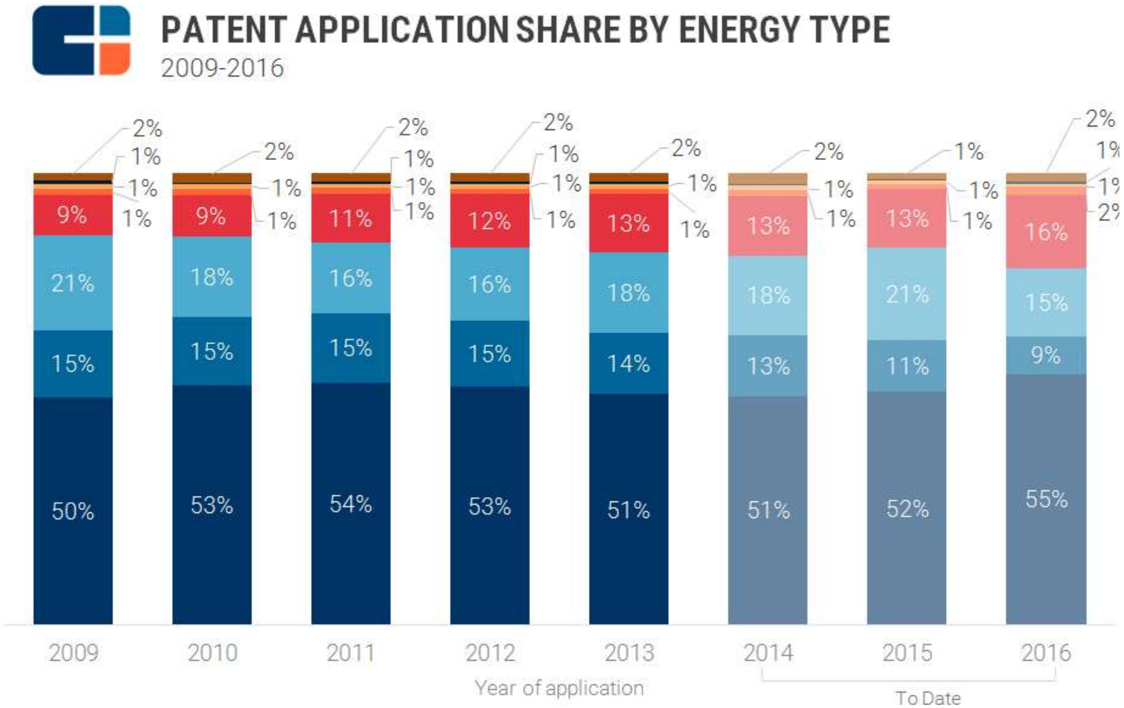


Figure 19: US Patent and Trademark Office Clean Energy Patent Awards By S
Source: Heslin Rothenberg Farley & Mesiti P.C.

DOE



Stationary power market

Table 8: Commercially Available Stationary Fuel Cells 2011			
Prime Power and mCHP			
Manufacturer	Product Name	Type	Output
Ballard	FCgen-1300	PEM	2 - 11 kW
	CLEARgen	PEM	Multiples of 500 kW
Bloom Energy	ES-5400	SOFC	100 kW
	ES-5700	SOFC	200 kW
Ceramic Fuel Cells	BlueGen	SOFC	2 kW
	Gennex	SOFC	1 kW
ClearEdge Power	ClearEdge 5	PEM	5 kW
	ClearEdge Plus	PEM	5 - 25 kW
ENEOS CellTech	ENE-FARM	PEM	250 - 700 W
FuelCell Energy	DFC 300	MCFC	300 kW
	DFC 1500	MCFC	1,400 kW
	DFC 3000	MCFC	2,800 kW
Heliocentris Fuel Cells AG	Nexa 1200	PEM	1.2 kW
Horizon	GreenHub Powerbox	PEM	500 W - 2 kW
Hydrogenics	HyPM Rack	PEM	Multiples of 10, 20, and 30 kW
	FCXR System	PEM	150 kW
Panasonic	ENE-FARM	PEM	250 - 700 W
Toshiba	ENE-FARM	PEM	250 - 700 W
UTC Power	PureCell Model 400	PAFC	400 kW

DOE

Back up and remote power market

Backup and Remote Power			
Manufacturer	Product Name	Type	Output
Altergy Systems	Freedom Power System	PEM	5 – 30 kW
Ballard	FCgen 1020A CS	PEM	1.5 – 3.6 kW
ClearEdge Power	ClearEdge CP	PEM	10 kW
Dantherm Power	DBX 2000	PEM	1.7 kW
	DBX 5000	PEM	5 kW
Horizon	H-100	PEM	100 W
	H-1000	PEM	1 kW
	H-3000	PEM	3 kW
	H-5000	PEM	5 kW
	MiniPak	PEM	100 W
Hydrogenics	HyPM XR Power Modules	PEM	4, 8, and 12 kW
IdaTech	ElectraGen H2-I	PEM	2.5 - 5 kW
	ElectraGen ME	PEM	2.5 - 5 kW
Microcell	MGEN 1000	PEM	1 kW
	MGEN 3000	PEM	3 kW
	MGEN 5000	PEM	5 kW
ReliOn	E-200	PEM	175 W
	E-1100/E-1100v	PEM	1.1 kW
	E-2500	PEM	2.5 kW
	T-1000	PEM	600 W – 1.2 kW
	T-2000	PEM	600 W – 2 kW
SFC Energy	EFOY Pro Series 600, 1600, 2200	DMFC	25, 65, and 90 W

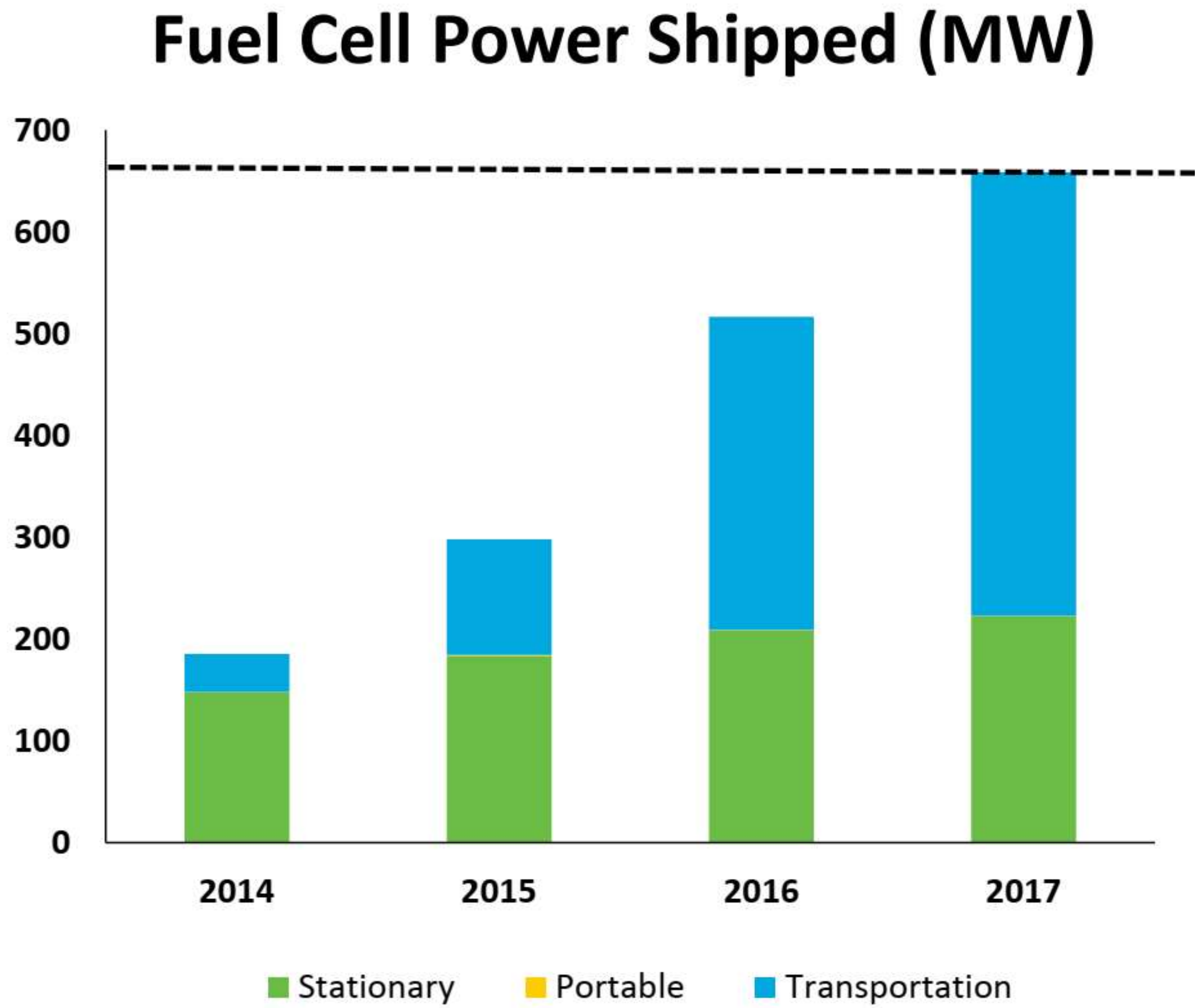
DOE

Fuel cells for transportation market

Table 15: Commercially Available Fuel Cells for Transportation 2011			
Manufacturer	**Product Name**	**Type**	**Output**
Ballard	FCvelocity-HD6	PEM	75 and 150 kW
Hydrogenics	HyPM HD Modules	PEM	4, 8, 12, 16, 33, and 100 kW
Nuvera	Andromeda Fuel Cell Stack	PEM	100 kW
	HDL-82 Power Module	PEM	82 kW
UTC Power	PureMotion 120	PEM	120 kW

DOE

MW of Fuel cells shipped



[DOE]

Fuel cell costs

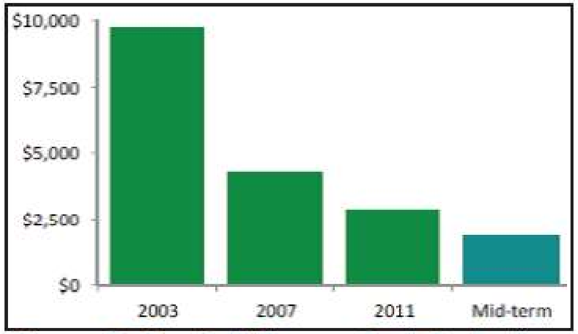
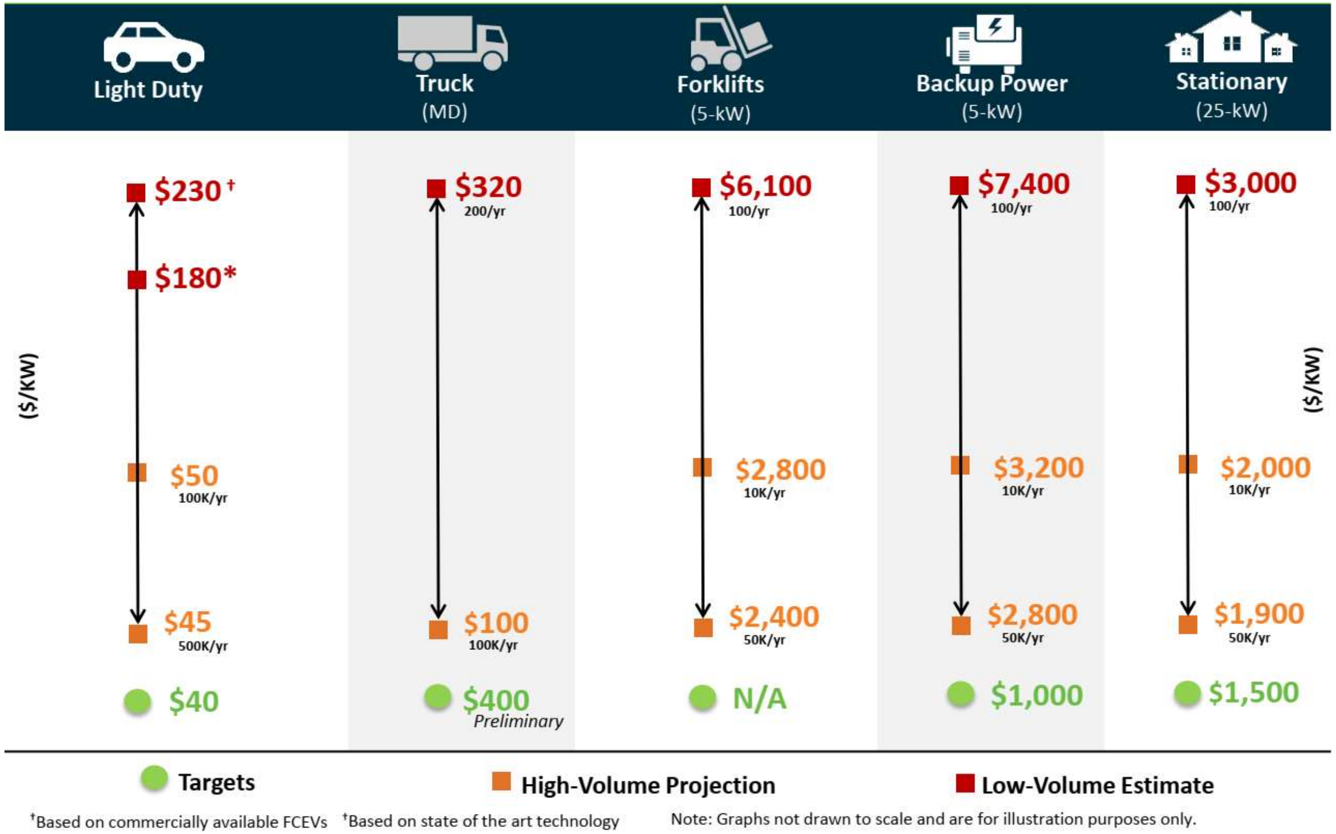


Figure 3: FuelCell Energy Cost Reduction.
Source: FuelCell Energy.

DOE



Fuel Cell Powered Fork Lifts – Ideal Niche Market

Fuel Cell Powered Fork Lifts
Ideal Niche Market

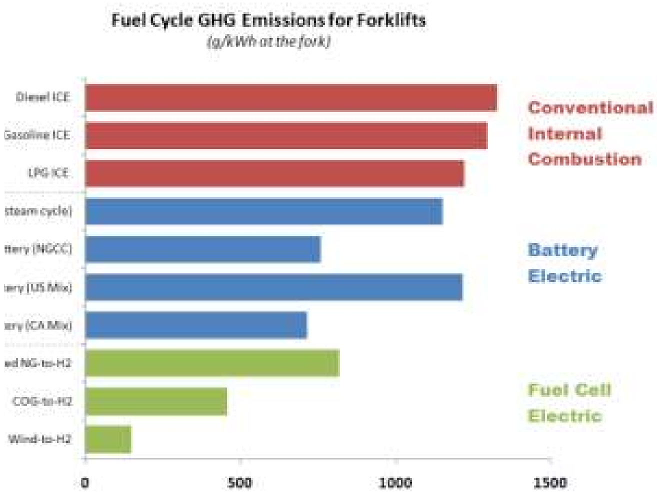
The Case for Forklifts*

Compared to conventional forklifts, fuel cell forklifts have:

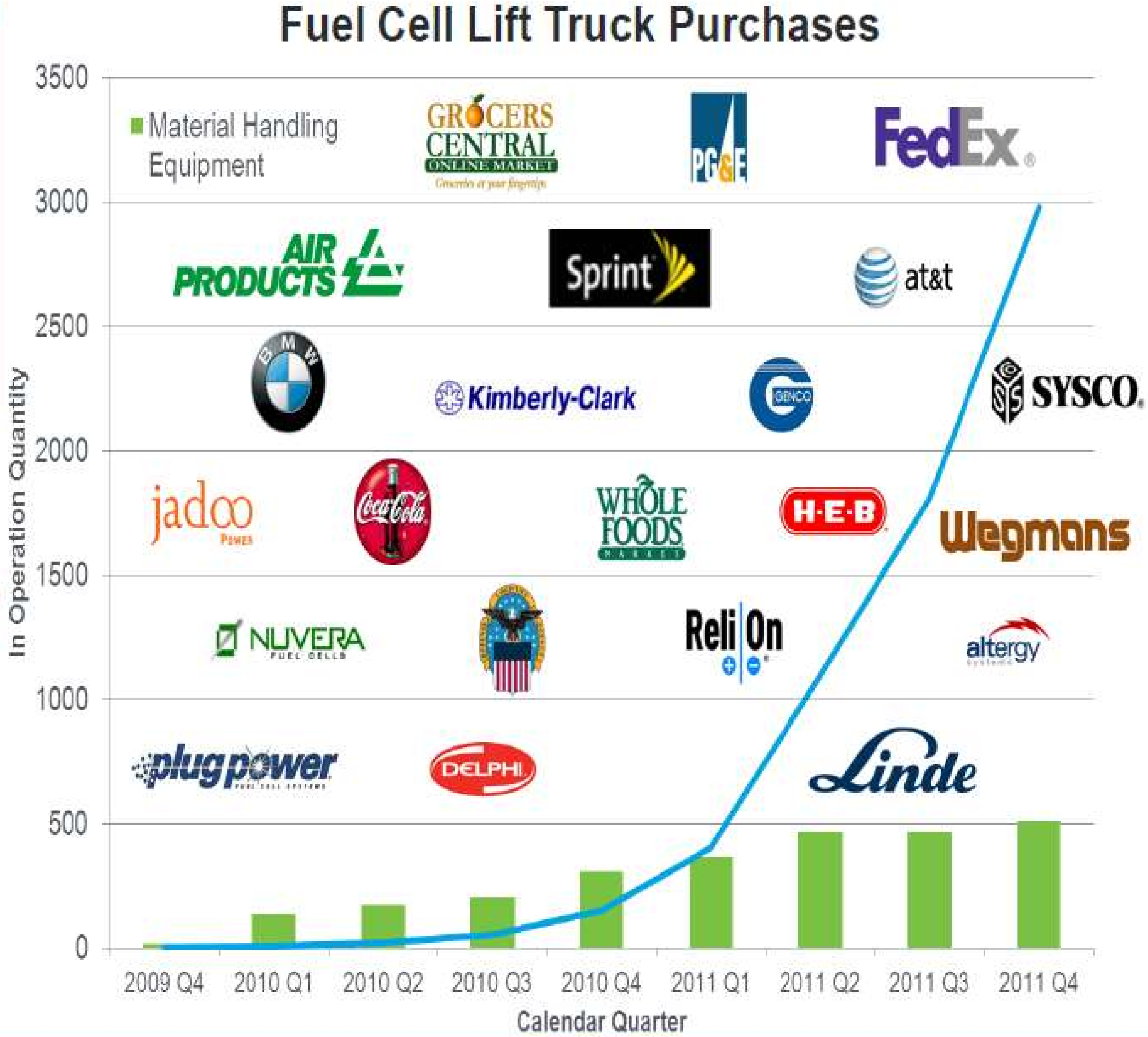
1.5 X lower maintenance cost

8 X lower refueling labor cost

2 X lower net present value of total system cost



*Preliminary Analysis



Fuel Cell Technologies Program Source: US DOE 2/14/2012 eere.energy.gov

Nuvera Fuel Cells

Power	125	kW
Operating voltage	240-384	Volt
Transient response 10-90%	2	s
Dimension	210x550x900	mm
Weight	140	kg

Ballard Fuel Cell

PRODUCT SPECIFICATIONS

Gross Power:		**75 kW**	**150 kW**
Performance:	DC voltage	275 – 400V	550 – 800V
	Maximum current	300A	300A
Physical:	Weight (dry)	< 350 kg (<700 lbs)	< 400 kg (< 990 lbs)
	Length x width x height (without controller box)	1270 x 870 x 505 mm (50 x 34 x 20 in)	
	Volume	0.55m³ (19.6 cubic ft)	
Fuel:	Gaseous hydrogen	Commercial grade (per SAE J2719)	
Oxidant:	Air		
Coolant:	50/50 Pure Ethylene Glycol and Water		
Operating Conditions:	Temperature (nominal)	63°C (149°F)	
	Fuel pressure (minimum)	12 barg	
	Air pressure (nominal)	1.2 barg	
Additional Features:	Control interface	CANbus	
	Enclosure	IP53	

Distributed cogeneration

Panasonic

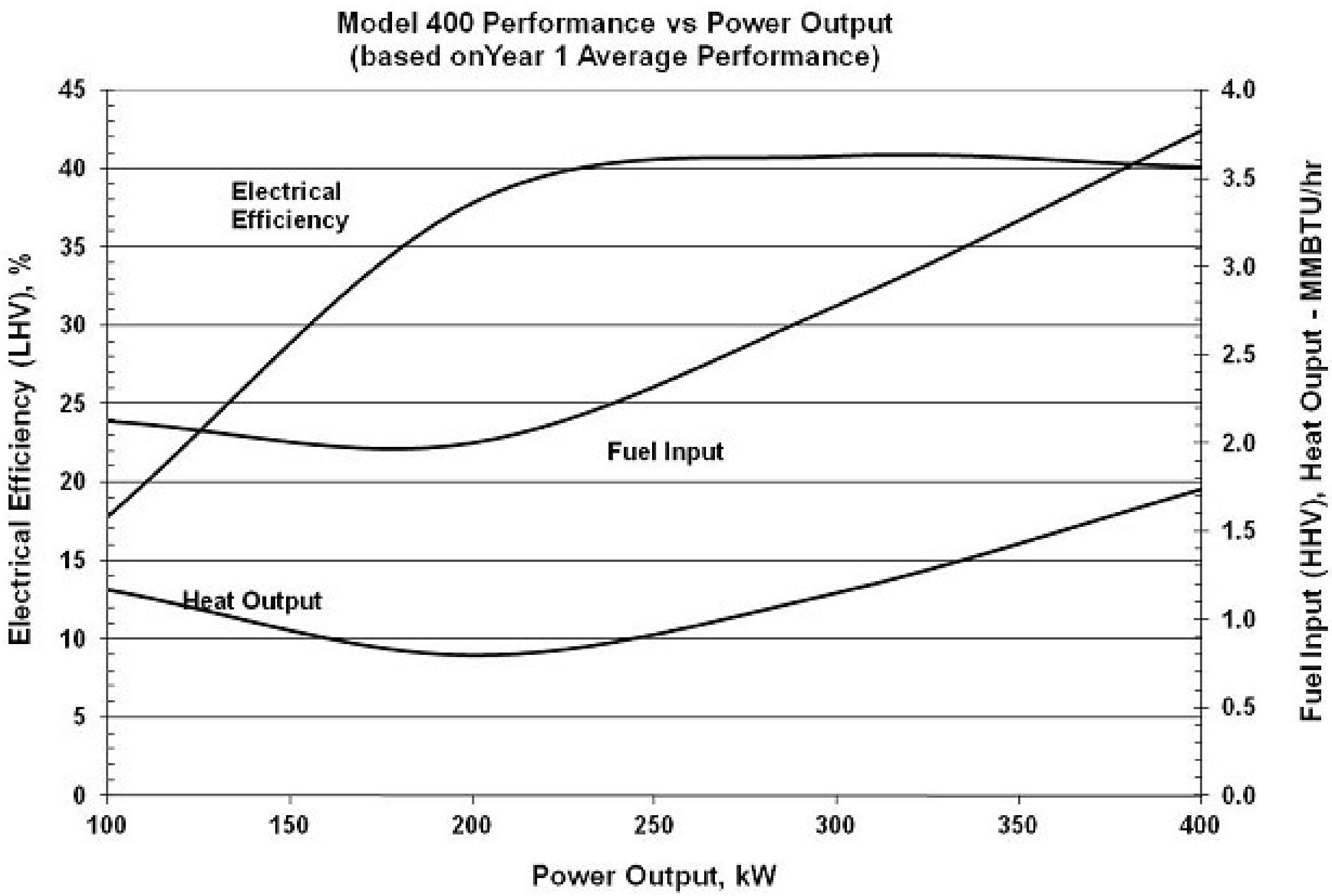
		New model	
Launch date		April 1, 2011 (scheduled)	
Performance	Electricity generation output	250W-750W	
	Rated generation efficiency	40% (LHV) 36% (HHV)	
	Rated heat recovery efficiency	50% (LHV) 45% (HHV)	
	Water tank capacity	200 liters	
Dimensions	Fuel cell unit	H1,883mm × W315mm × D480mm	
	Hot water unit	H1,883mm × W750mm × D480mm	
Weight	Fuel cell unit	100kg	
	Hot water unit	125kg	
Installation area		Approx. 2.0m2	
Recommended retail price (Including tax; not including installation)		2,761,500 yen	
Maintenance support		10 years	F

UTC Pure cell System

Fuel requirements

Model 400 Pure Cell® System			
Basic data			
Power module		Cooling module	
Dimensions [mm]	8738 x 2540 x 3023	Dimensions [mm]	4851 x 2388 x 1829
Weight [kg]	27240	Weight [kg]	1448
System			
N° of cells	PAFC, 376 x 4 stacks		
System power [kW]	400 (350 in grid independent mode)		
Output voltage [V]	480 / 60 Hz / 3 phase		
System efficiency [%]	40 BOL, 38 average 10 years, LHV		
Fuel type	Natural gas		
Fuel in [Nm^3/h]	127.43 EOL		
Fuel pressure [mbar(g)]	24.91 – 34.87		
Emissions			
NO_X [g/MWh]	9.07		
CO [g/MWh]	9.07		
CO_2 [kg/MWh]	499		
SO_X [g/MWh]	Negligible		
PM [g/MWh]	Negligible		
VOCs [g/MWh]	9.07		
Water consumption	None (up to 29 °C ambient)		
Water discharge	None (normal operating conditions)		
Noise	< 65 dBA @ 10 m		
Ambient operating temperature [°C]	From -29 to 45		

UTC Pure 400

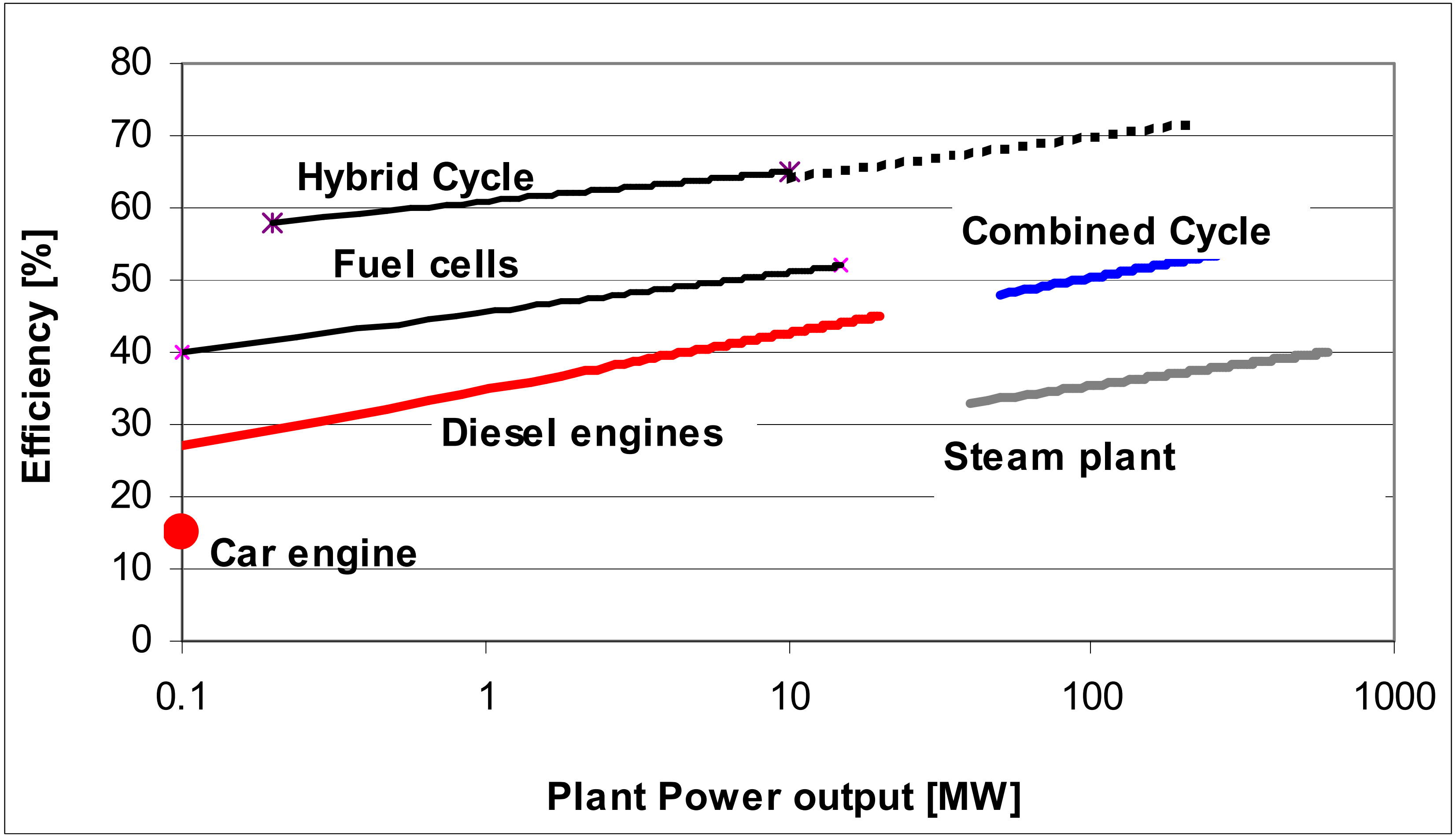


Model 400 Performance vs Power Output
(based onYear 1 Average Performance)
Electrical Efficiency
Fuel Input
Heat Output
Electrical Efficiency (LHV), %
Fuel Input (HHV), Heat Ouput - MMBTU/hr
Power Output, kW
0
5
10
15
20
25
30
35
40
45
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
100
150
200
250
300
350
400

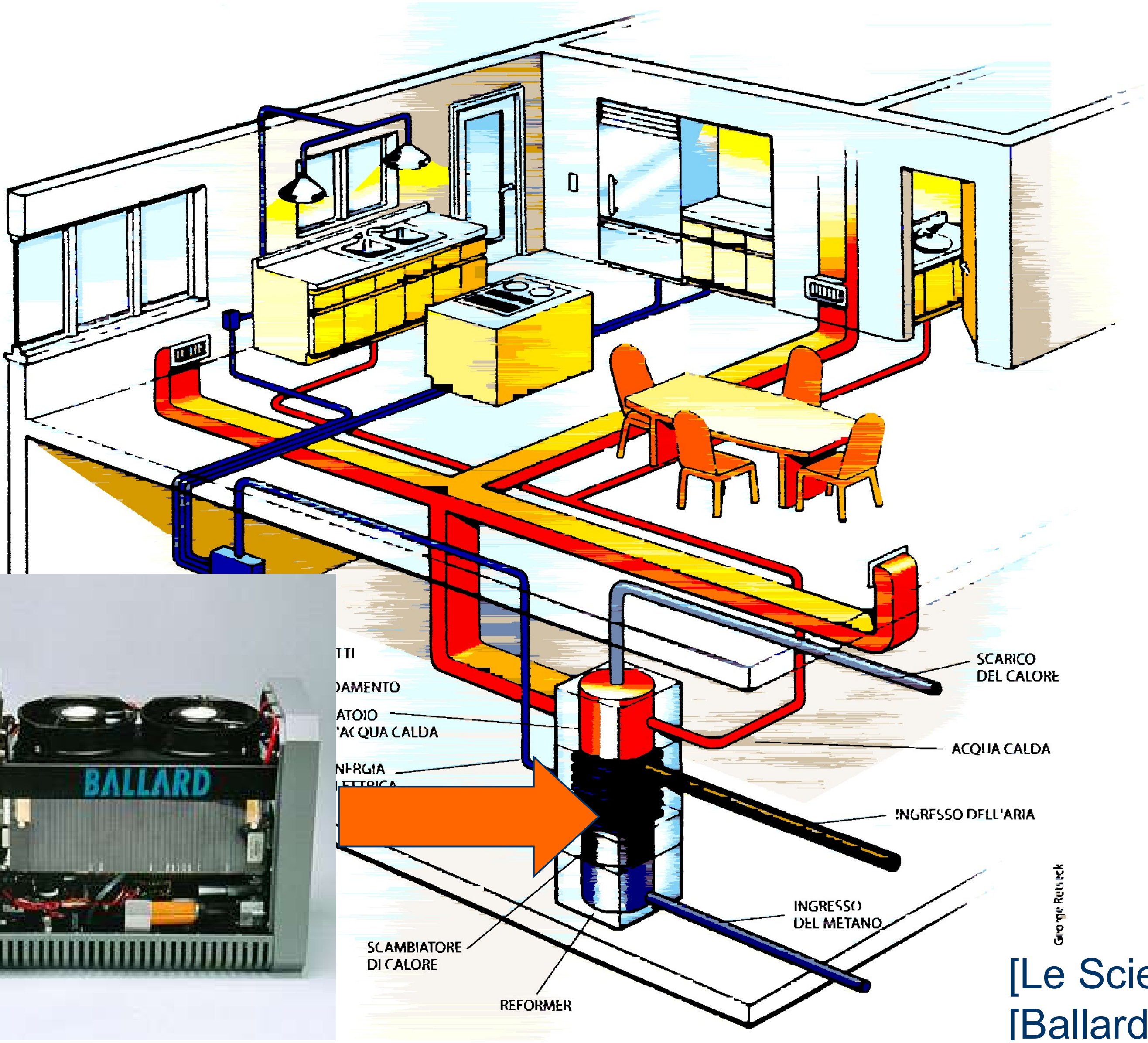
Topics

- EneSysLab at a glance
- Fuel cells basic principles
- Stack design
- System design
- Fuel cells applications
- Conclusion

POWER PLANTS EFFICIENCIES



DOMESTIC COGENERATION



[Le Scienze]
[Ballard]

Conclusions

- Fuel cells are:
  - versatile (many possible applications)
  - efficient
  - clean (when use hydrogen as fuel)
  - modular
- Fuel cells are close to commercialization
  - niche market opportunities
- Few technical challenges, but no show-stoppers
- Fuel cells are only a part of a bigger system –
  - Difficulties in market penetration of individual technologies
- Fuel cells may be the enabling technology to pave the road toward hydrogen economy