# Fuel cells:
# Choice, Design and Application

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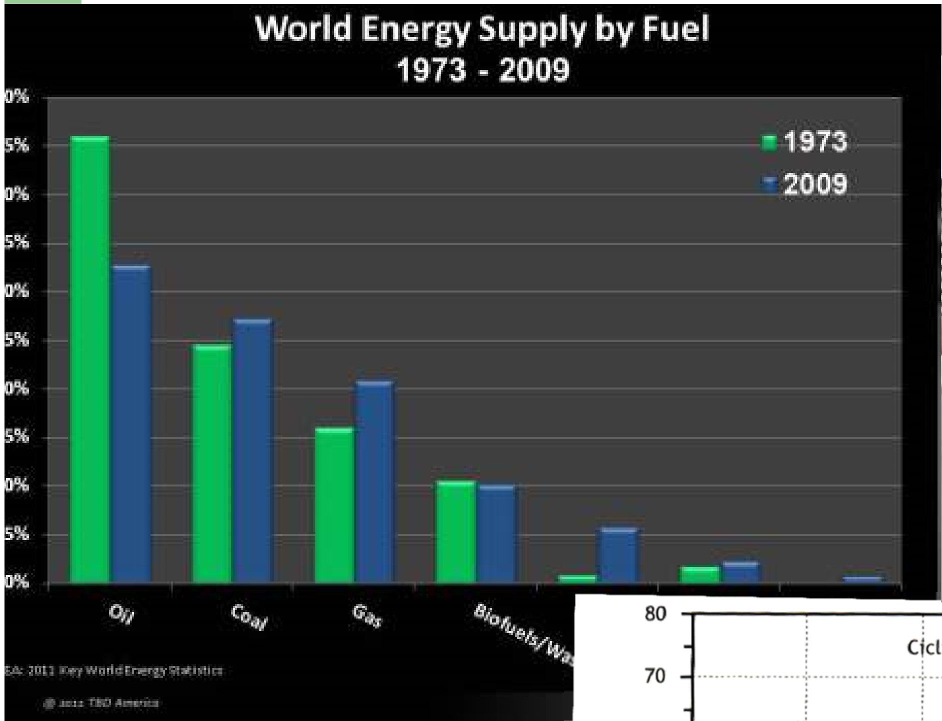
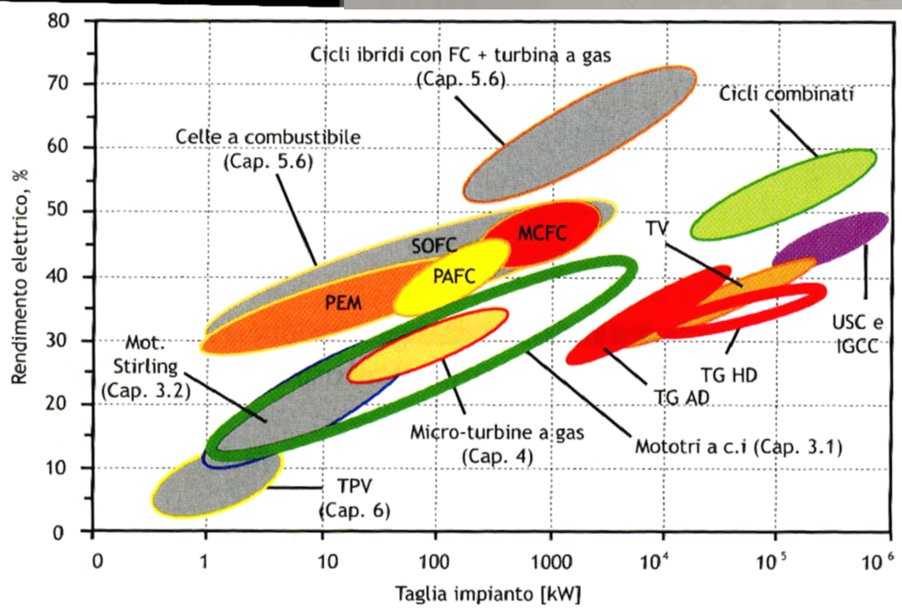
University of Trieste
- Italy -

2017 – Pordenone

# Aim of the presentation







# 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

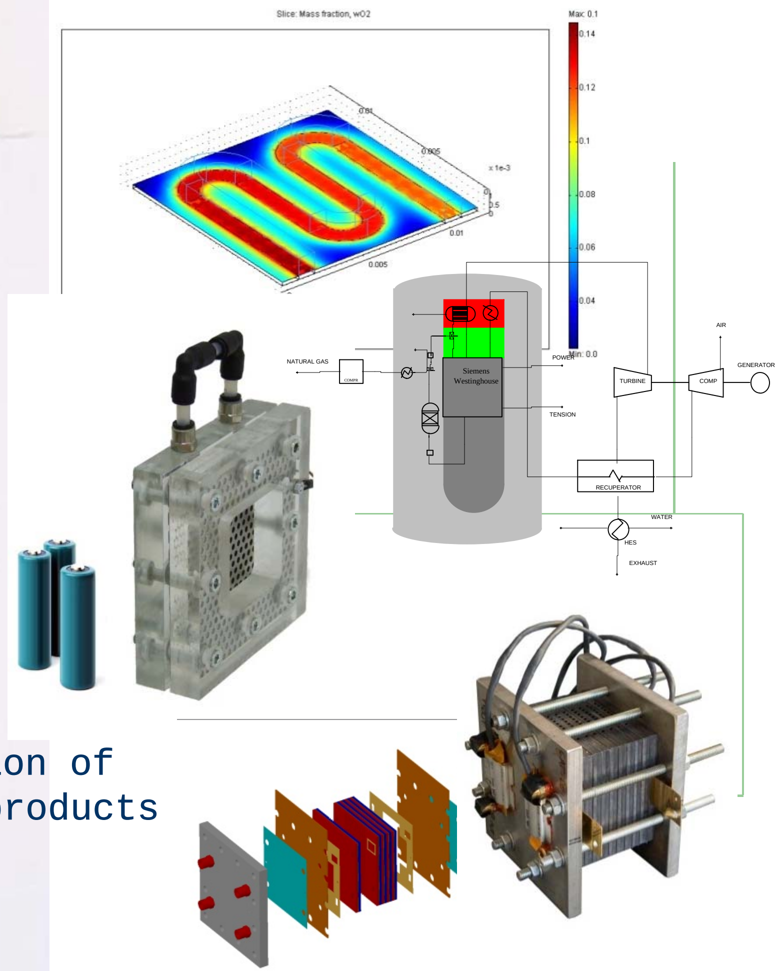
# EneSys Lab
## *Energy System Lab*

### 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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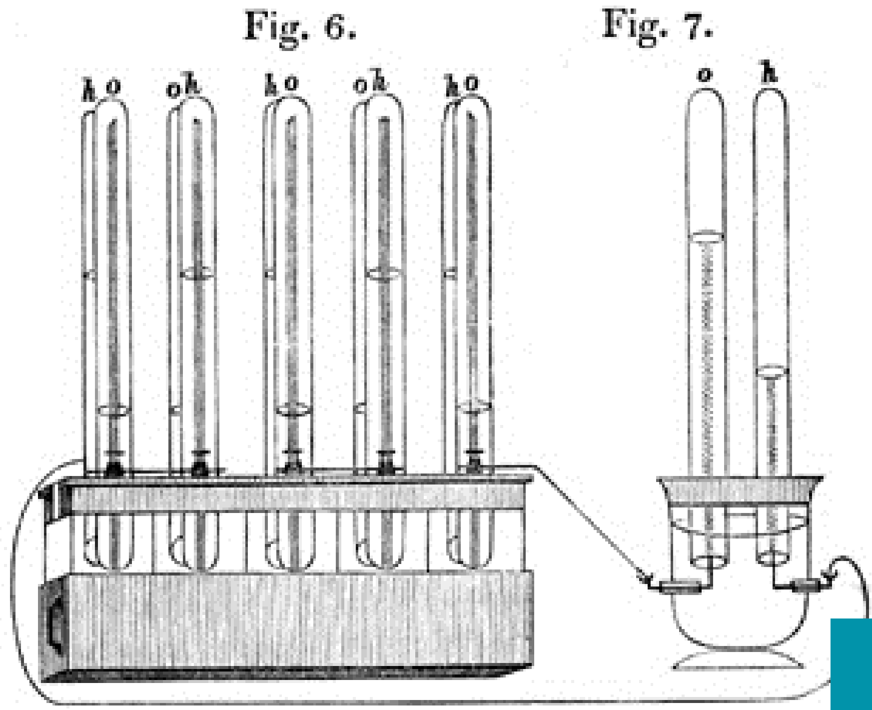
# Fuel cells




…yesterday

Sir Grove 1842


…today

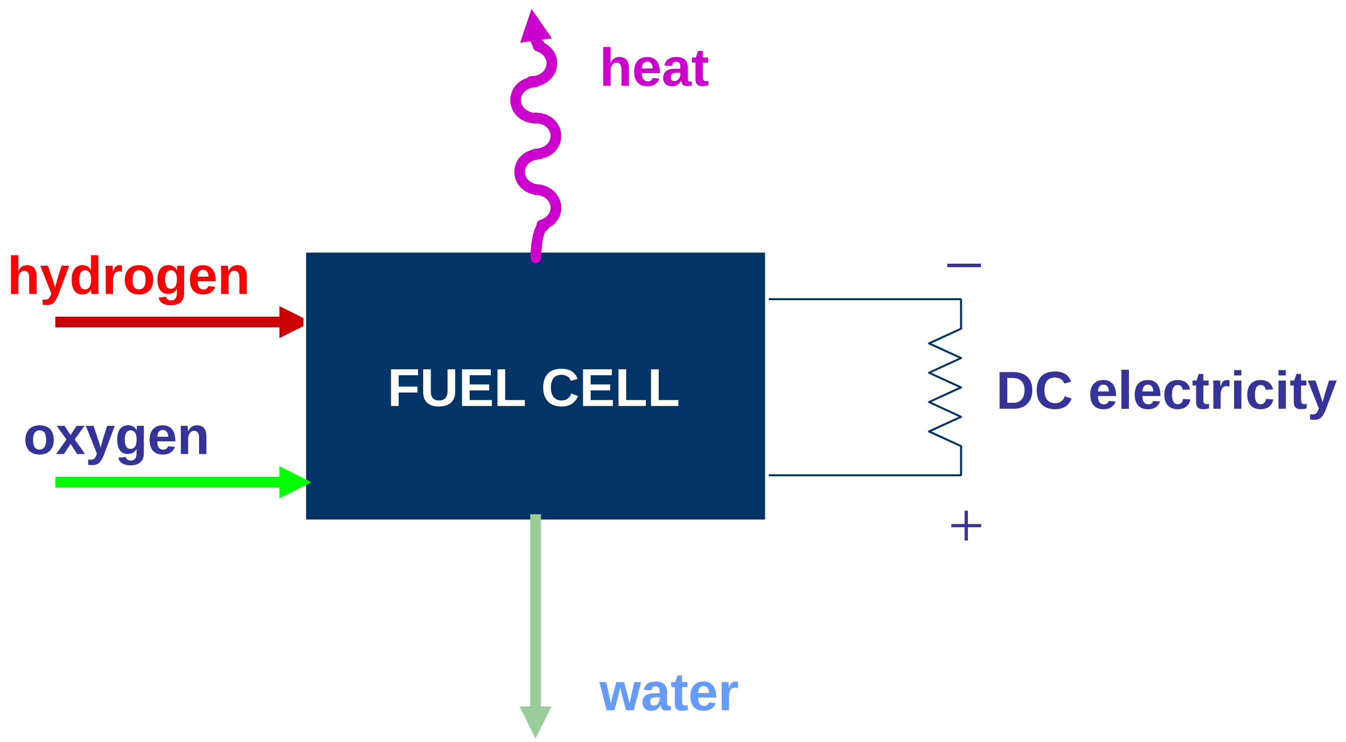
Ballard Power System

# 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.



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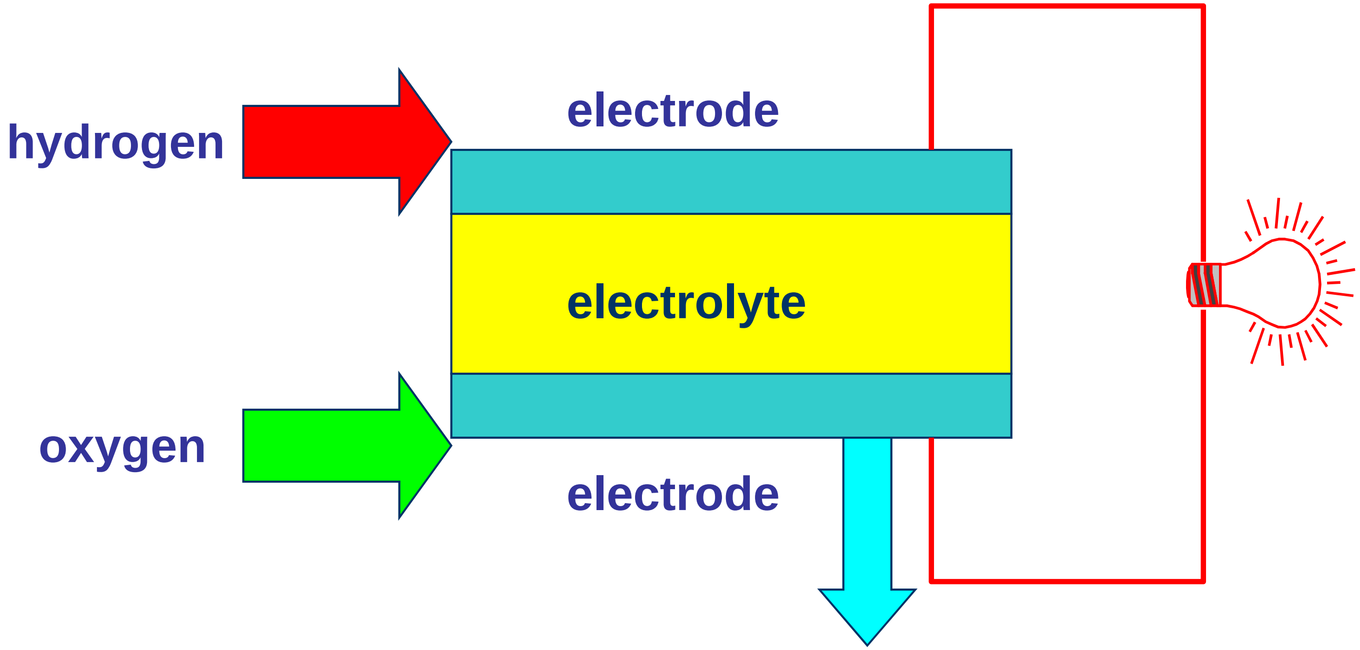
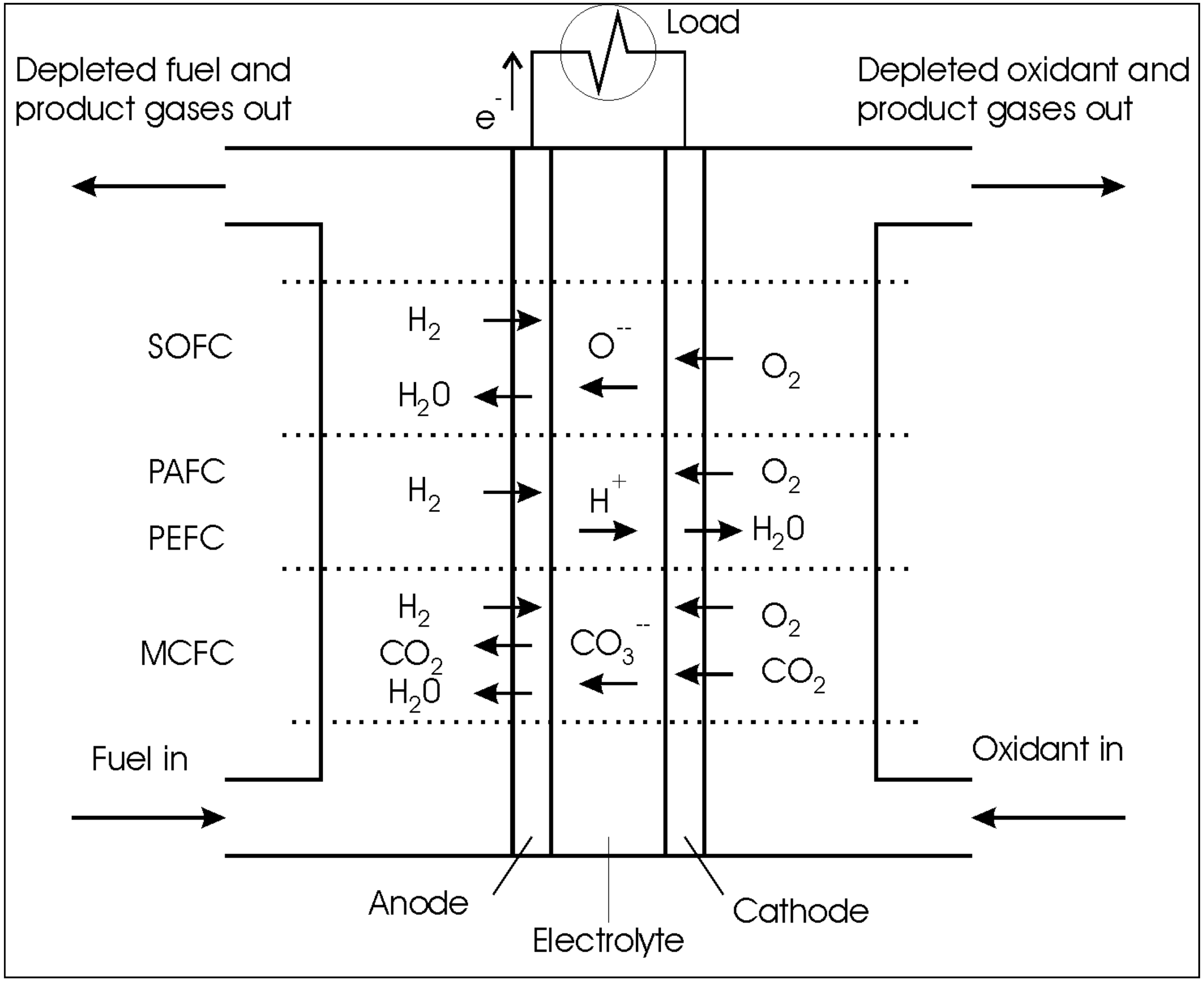


# Fuel Cell Basic Principles



# FUEL CELL TECHNOLOGIES

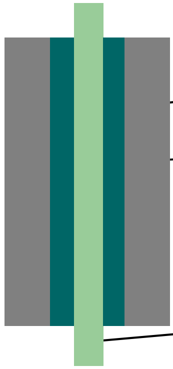
| | PEMFC | AFC | PAFC | MCFC | SOFC | DMFC |
|---|---|---|---|---|---|---|
| Electrolyte | Polymer Membrane | KOH | Phosforic Acid | Molten Carbonate | Solid Oxide | Polymer Membrane |
| Temp. (°C) | 70-80 | 80-100 | 200-220 | 600-650 | 800-1000 | 70-120 |
| Corr.Den. | H | H | M | M | H | L |
| Reformer | 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

# High Temperature PEM

## Low temperature PEM technology:

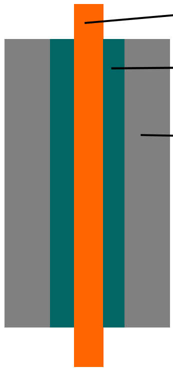


**Catalyst layer: Pt or Pt-alloy on carbon black**

**Gas diffusion layer: (non)woven carbon backing + microporous carbon layer**

**Membrane: Fluoropolymer with –$SO_3H$ groups + water**

**Membrane: Polybenzimidazole (PBI) + $H_3PO_4$**

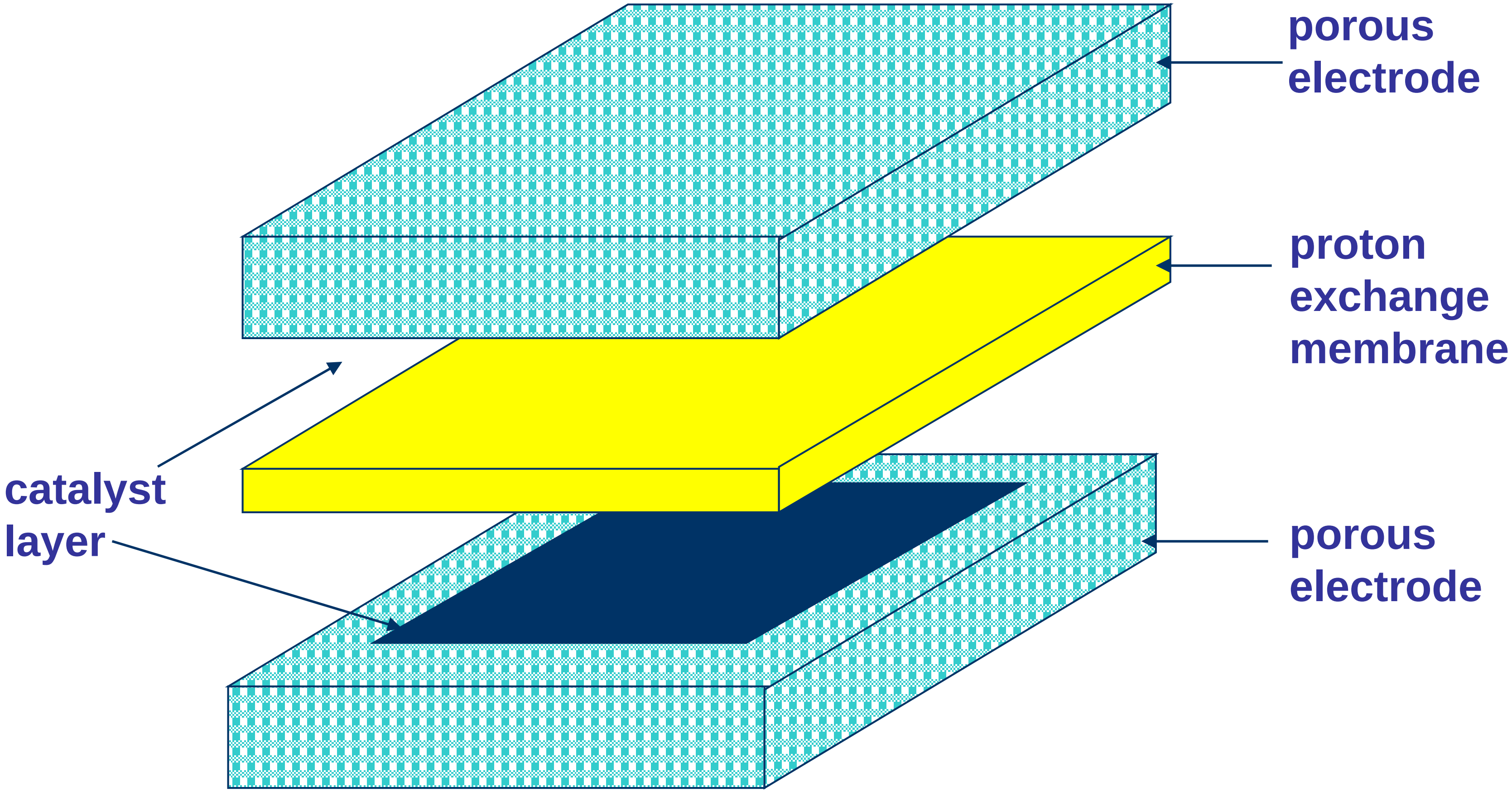


**Catalyst layer: Pt or Pt-alloy on carbon black**

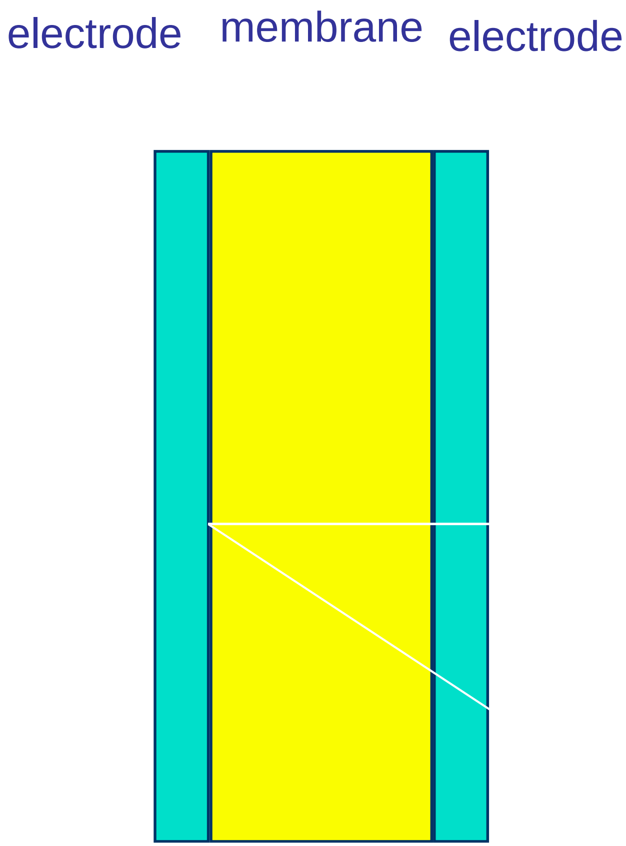
**Gas diffusion layer: (non)woven carbon backing + microporous carbon layer**

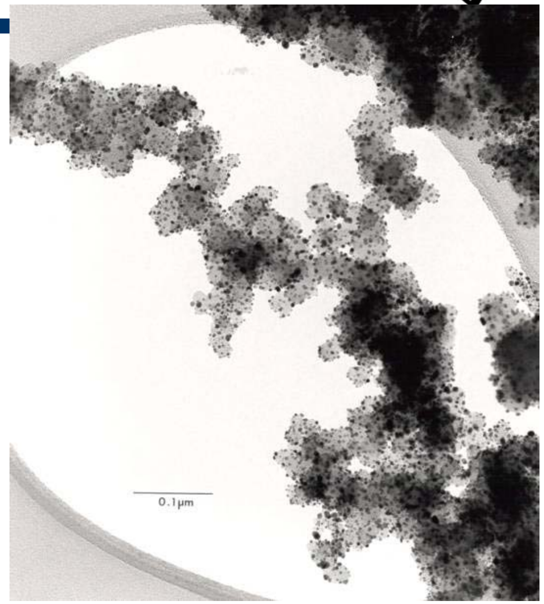
## High temperature PEM technology:

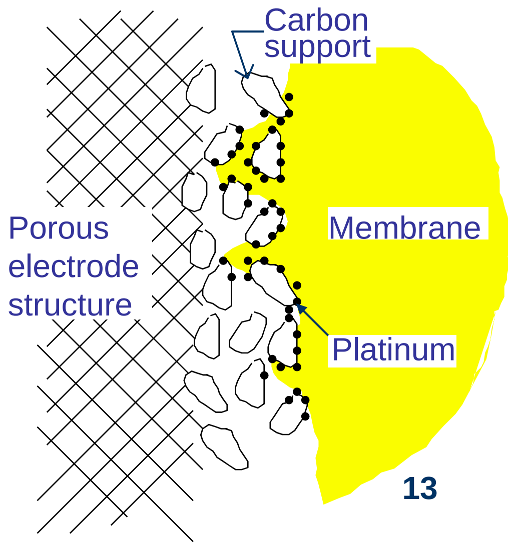
# PEM Fuel Cell Basic Components



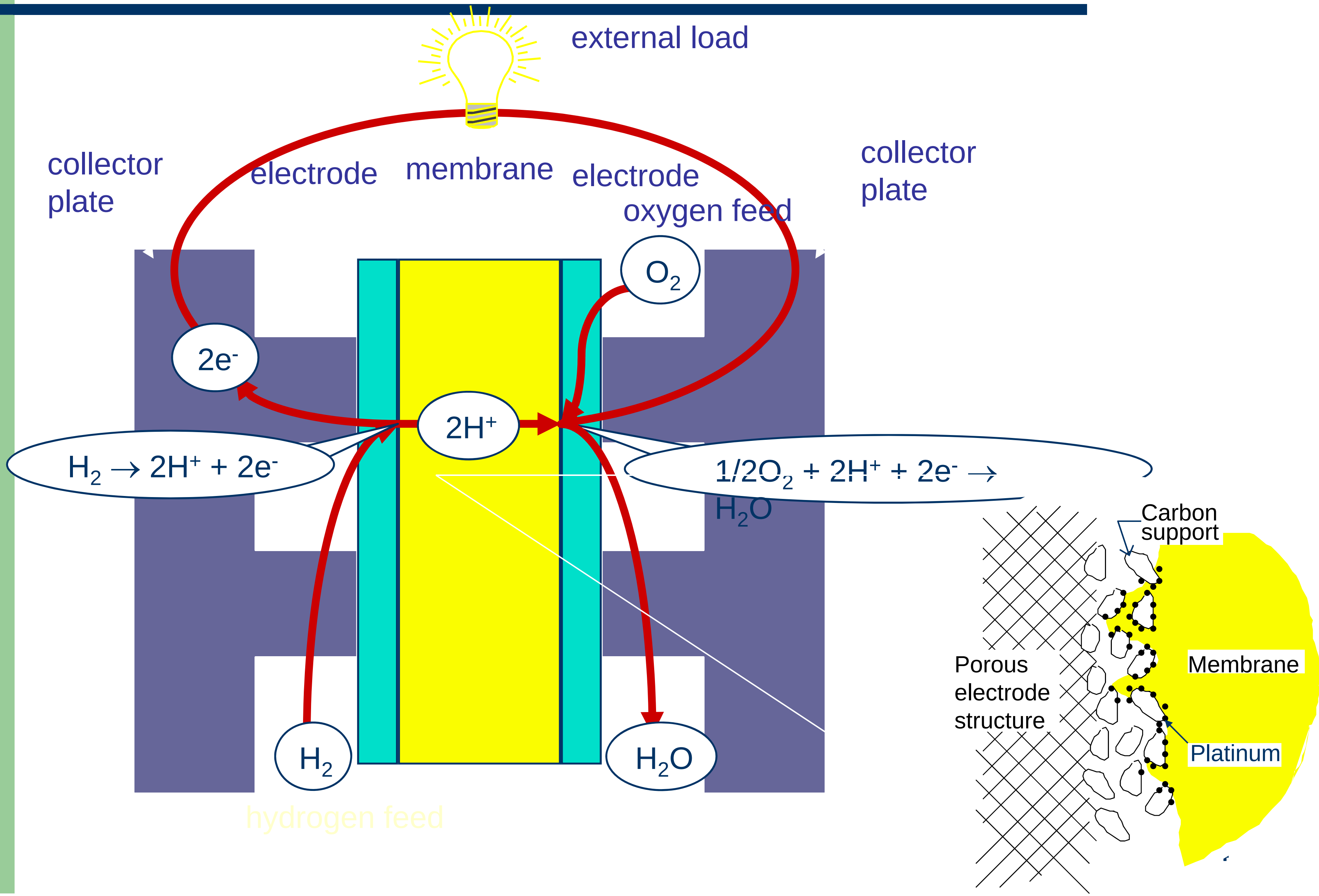
# PEM Fuel Cell: How does it work?



# How does it work?



# FUEL CELL COMPONENTS - MEA

cell frame / bipolar plate

current collector / gas diffusion layer

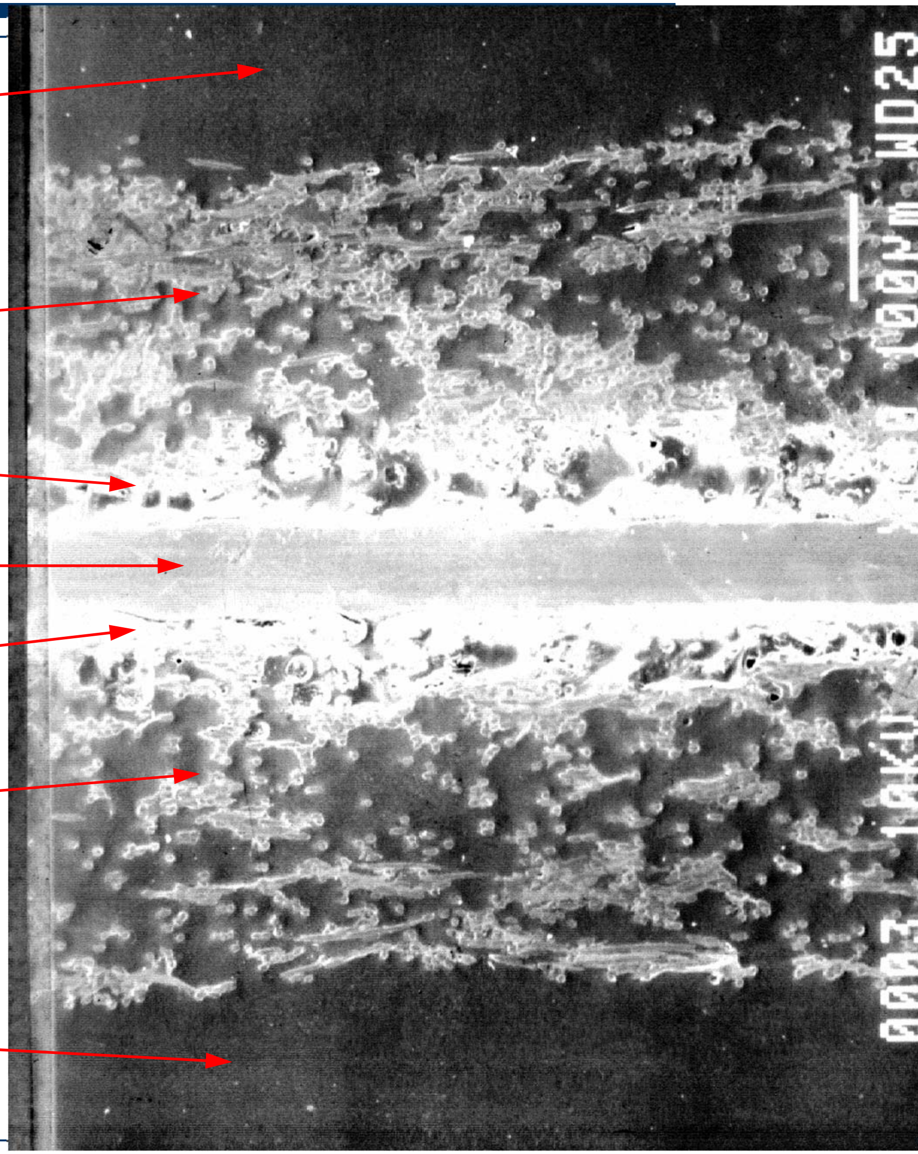
Pt-catalyst

polymer membrane

Pt-catalyst

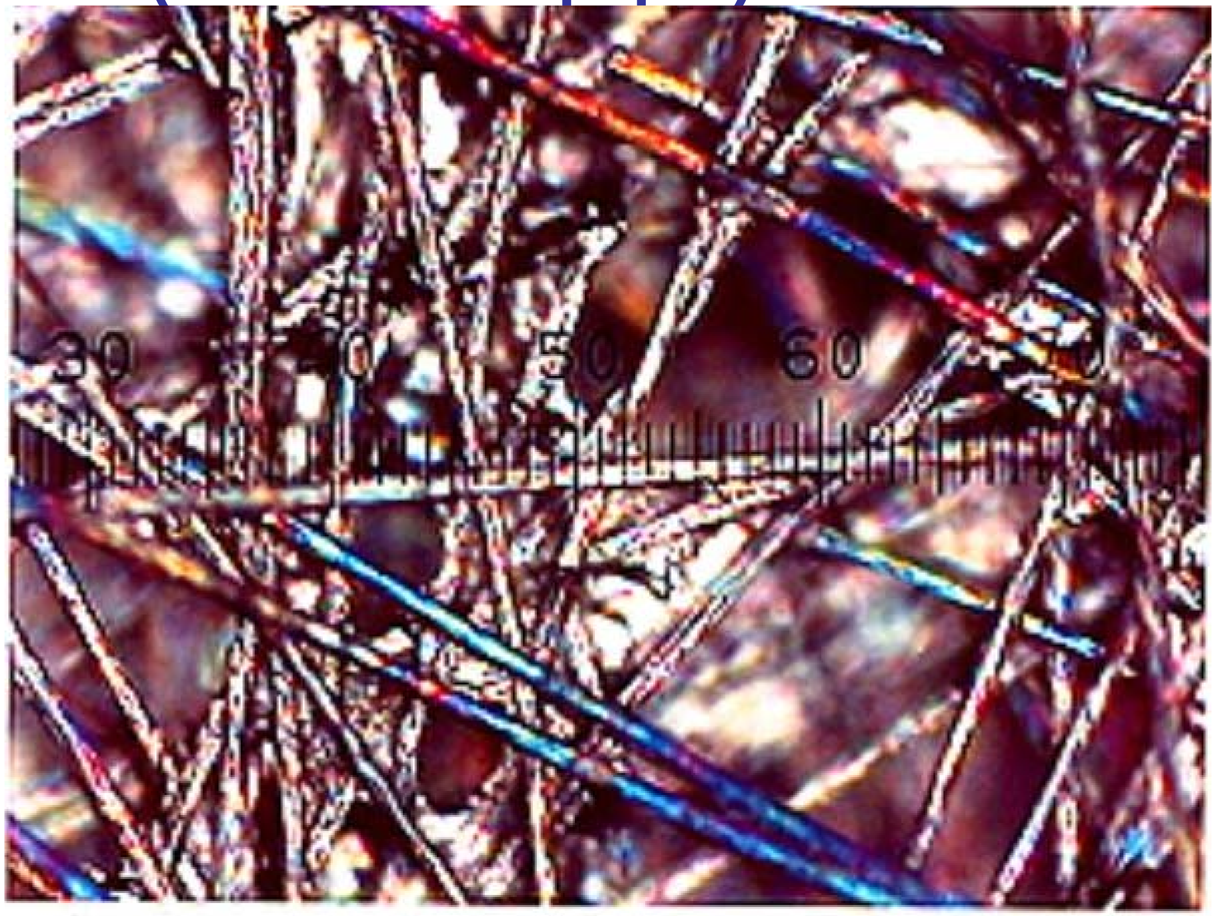
current collector / gas diffusion layer

cell frame / bipolar plate



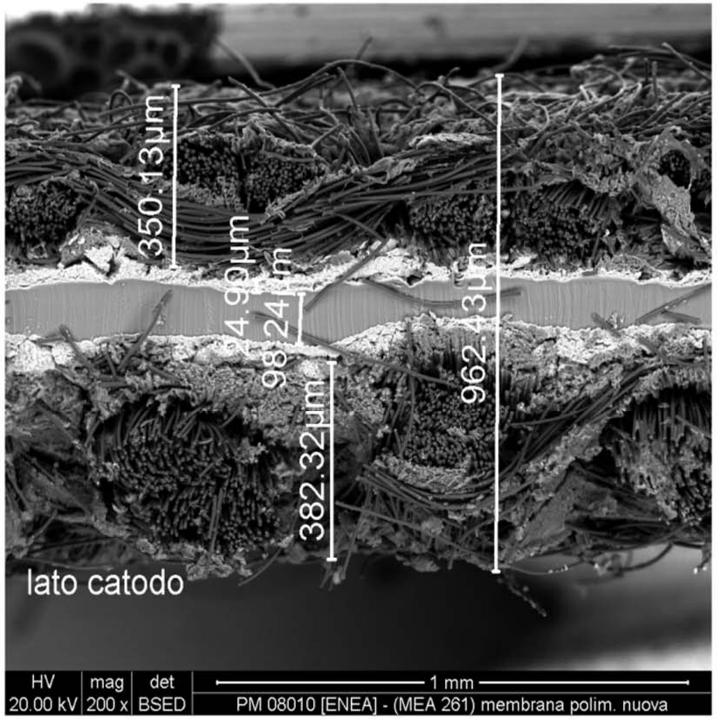
# FUEL CELL COMPONENTS - GDL

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

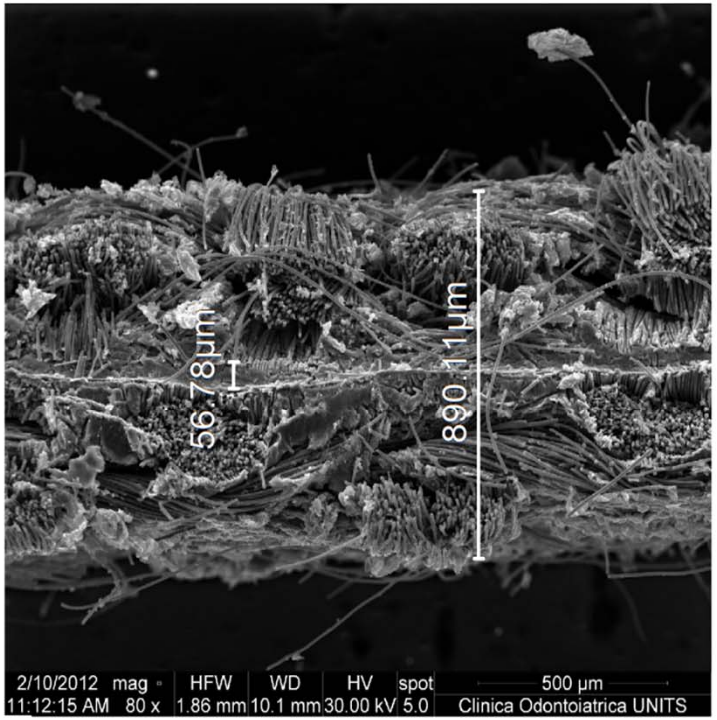



**80 μm**

# MEA deformation




*New MEA*

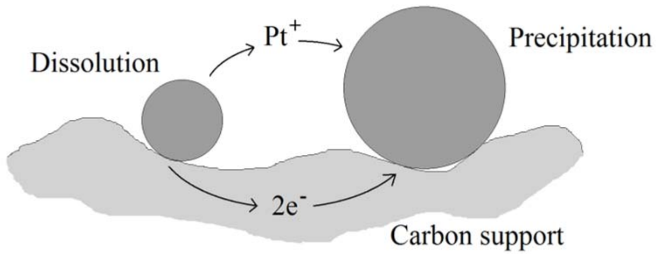


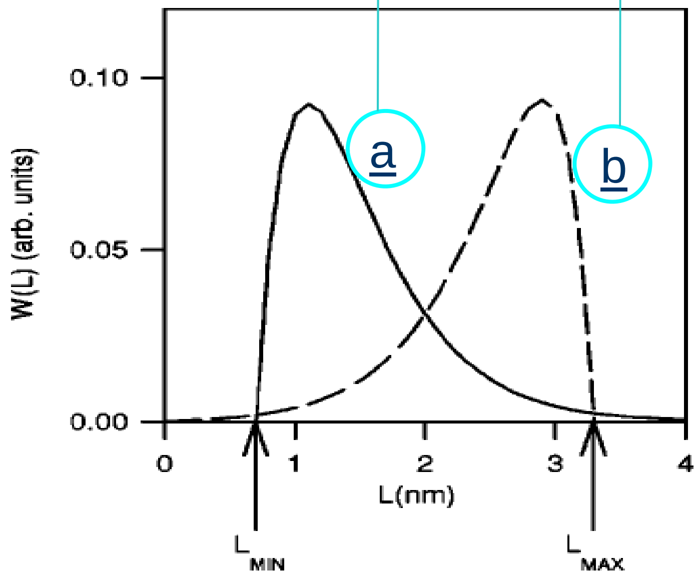

*Used MEA*

# Degradation: catalyst particles growing

## Coalescence

## Ostwald ripening

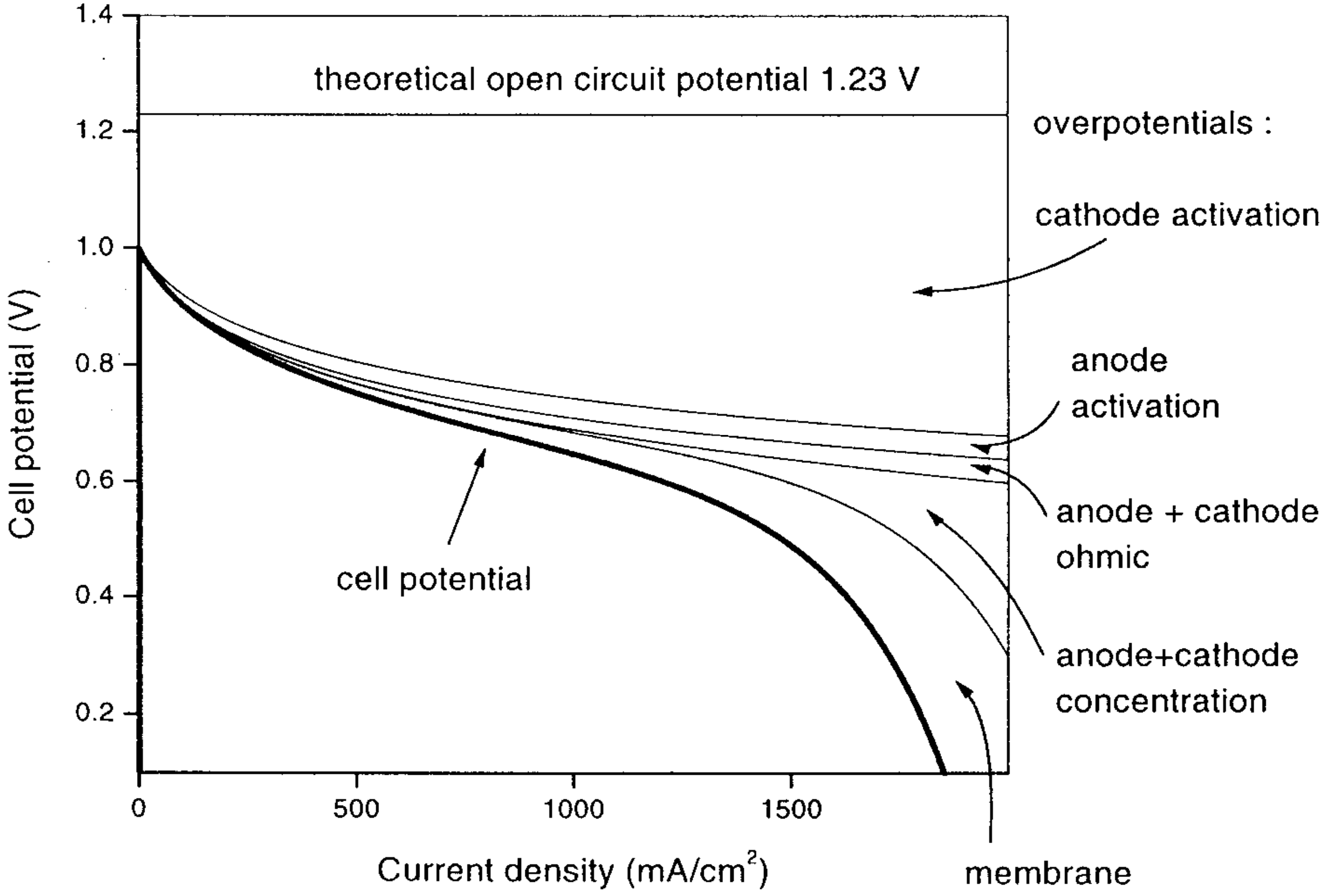



Particles size distribution

Ascarelli method

# 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;
- $\gamma$: USED FUEL MOLAR FLOWRATE;
- $U_f$: UTALIZATION FACTOR: $U_f = \gamma / m_c$.

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

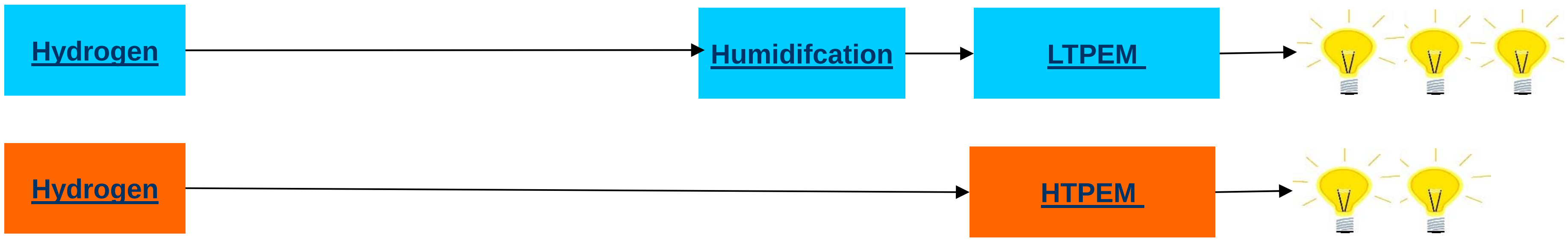
**2- ($V/E_{rev}$).** TAKES INTO ACCOUNT FOR ACTIVATION, OHMIC AND CONCENTRATION LOSSES

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

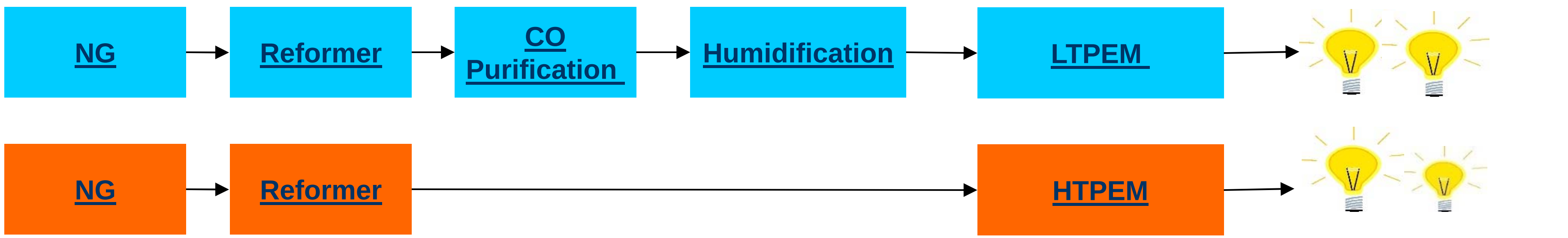
**4- ($\gamma/m_c$).** UTILIZATION FACTOR

# FUEL CELL EFFICIENCY

## Hydrogen fed system




## Natural gas fed system



# Topics

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- Stack design
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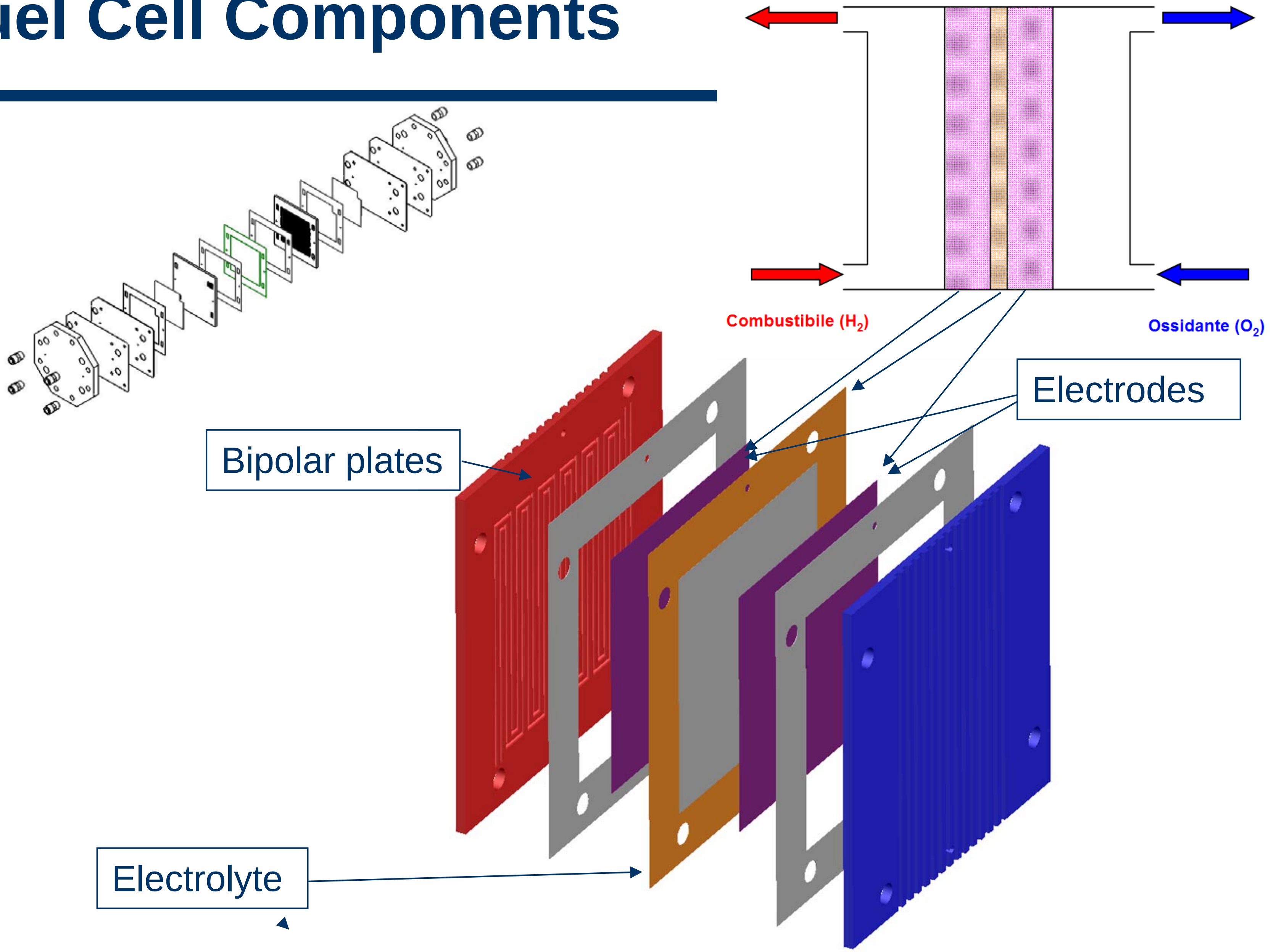
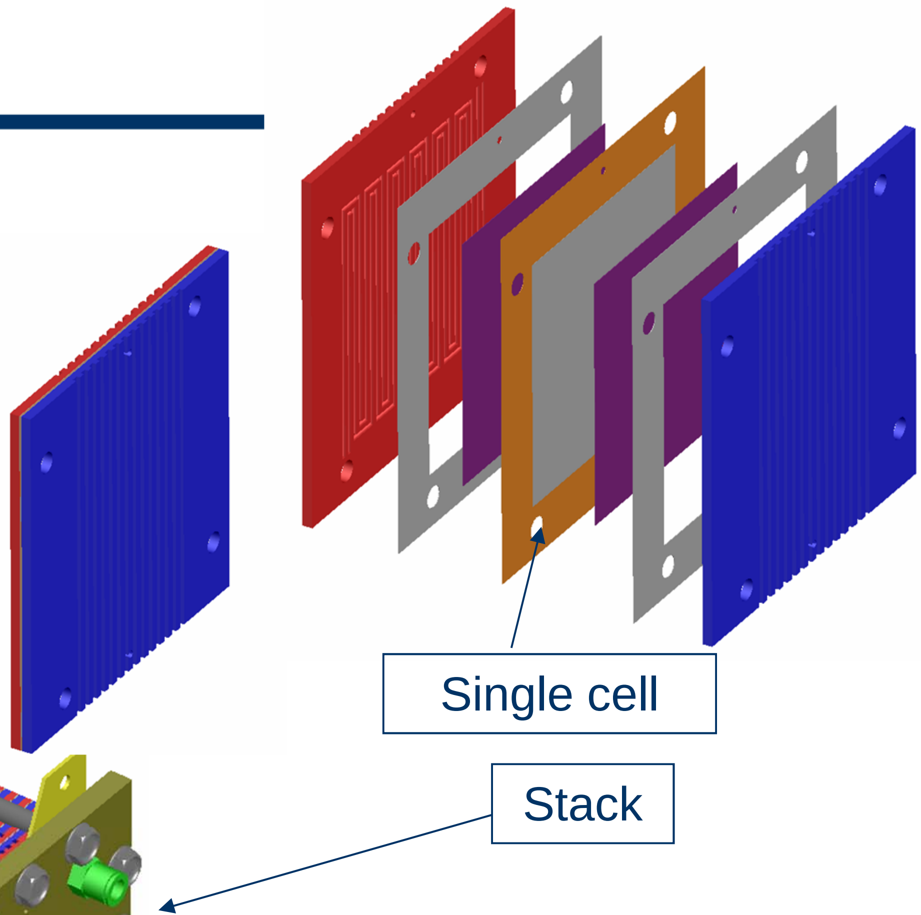
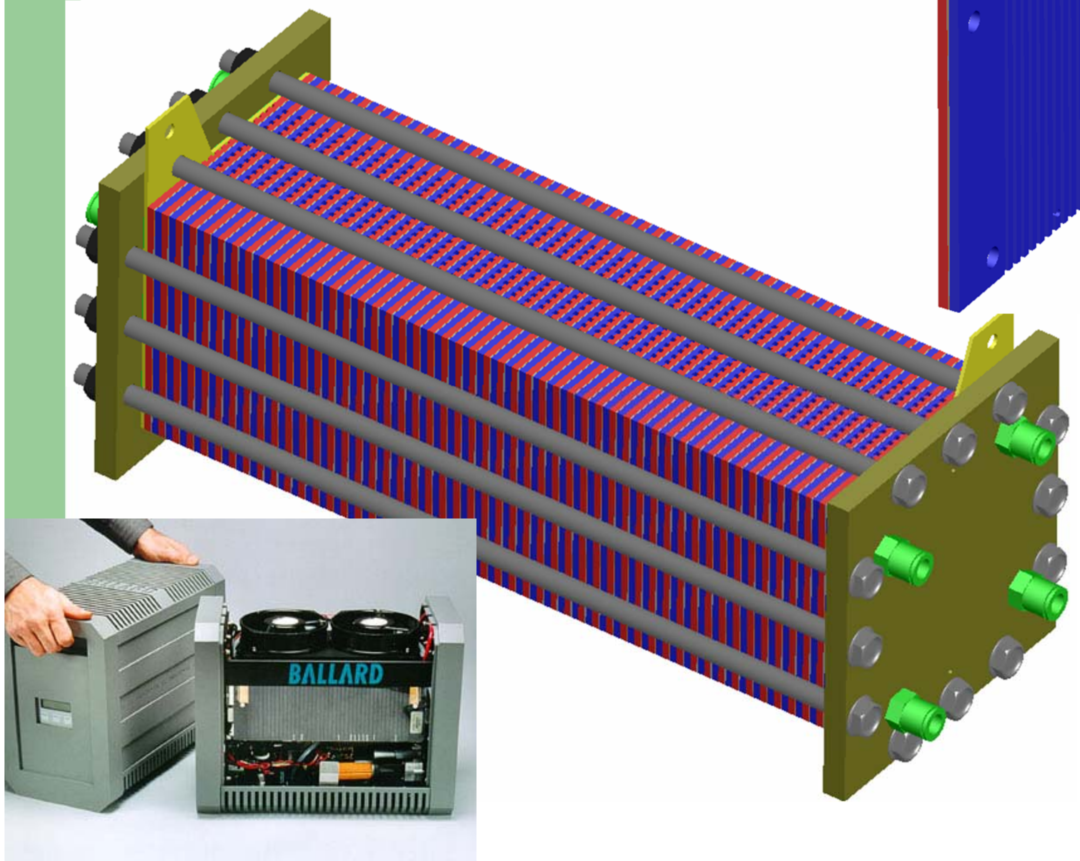
# Fuel Cell Components



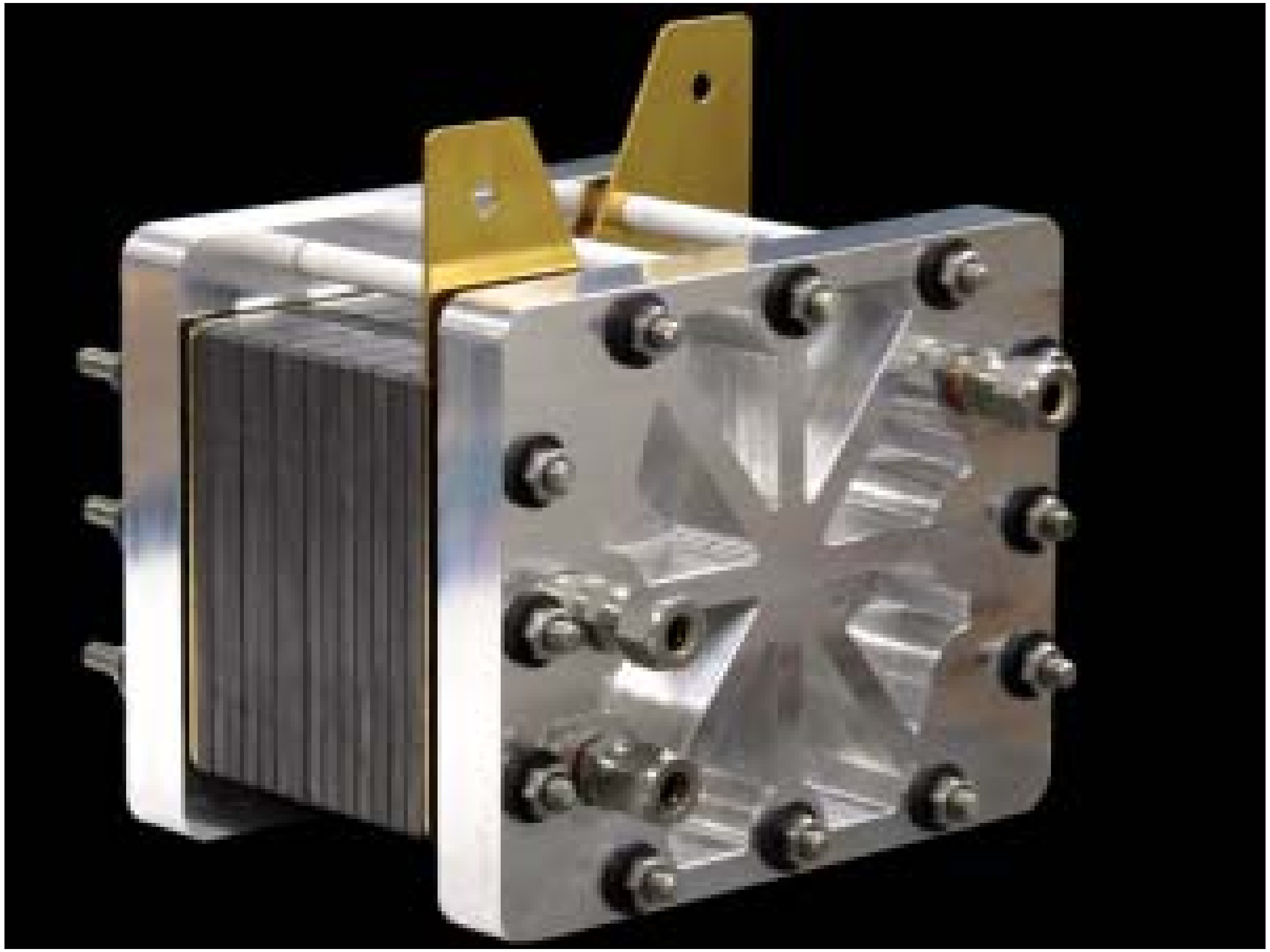
# From cell… to stack

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



# Example of Stack



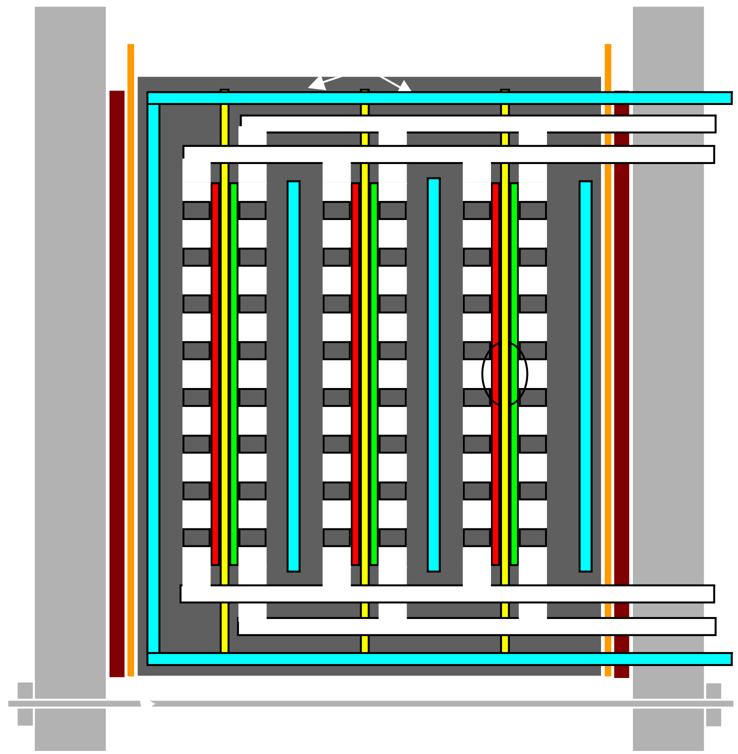
[Pragma Industries]

# Major stack components

MEA
- Membrane
- Catalyst
- Catalyst support
- Catalyst layer
- Gas diffusion layer

Bi-polar plate
- Gaskets/frames
- Flow field
- Separator/connector

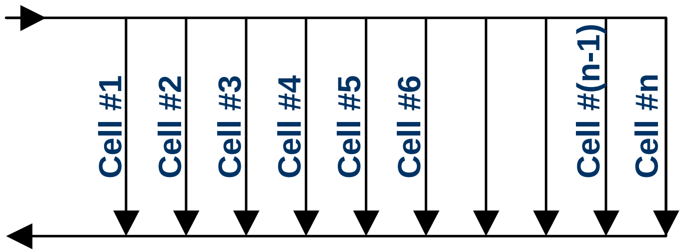
- Bus plates/terminals
- End plates
- Clamping mechanism
- Fluid connections
- Manifolds
- Cooling plates/arrangements
- Humidification section (optional)



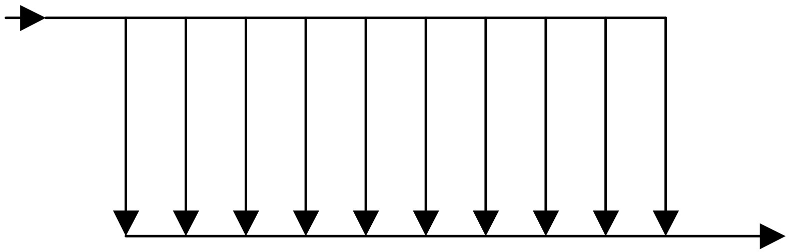
# Stack design/engineering issues

- **Uniform distribution of reactants to each cell**

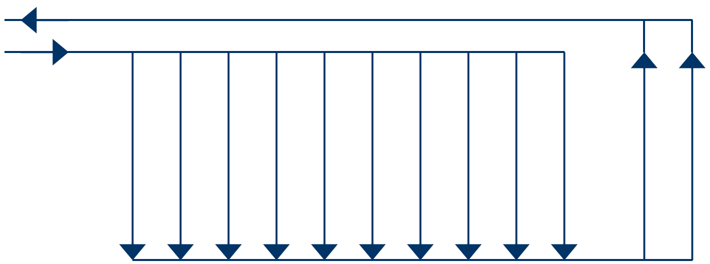
a) "U"-shape




b) "Z"-shape

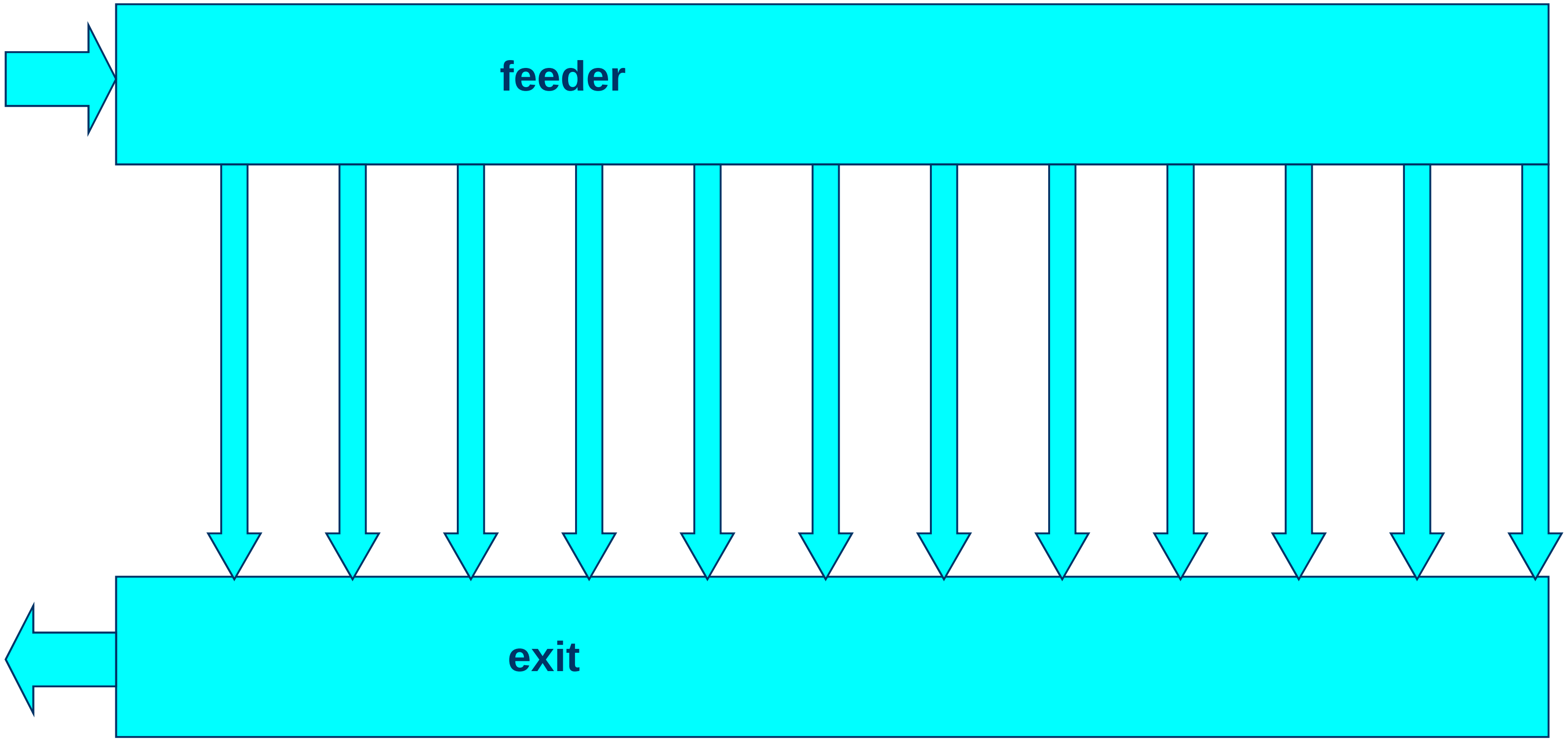


c) Combined parallel-serial

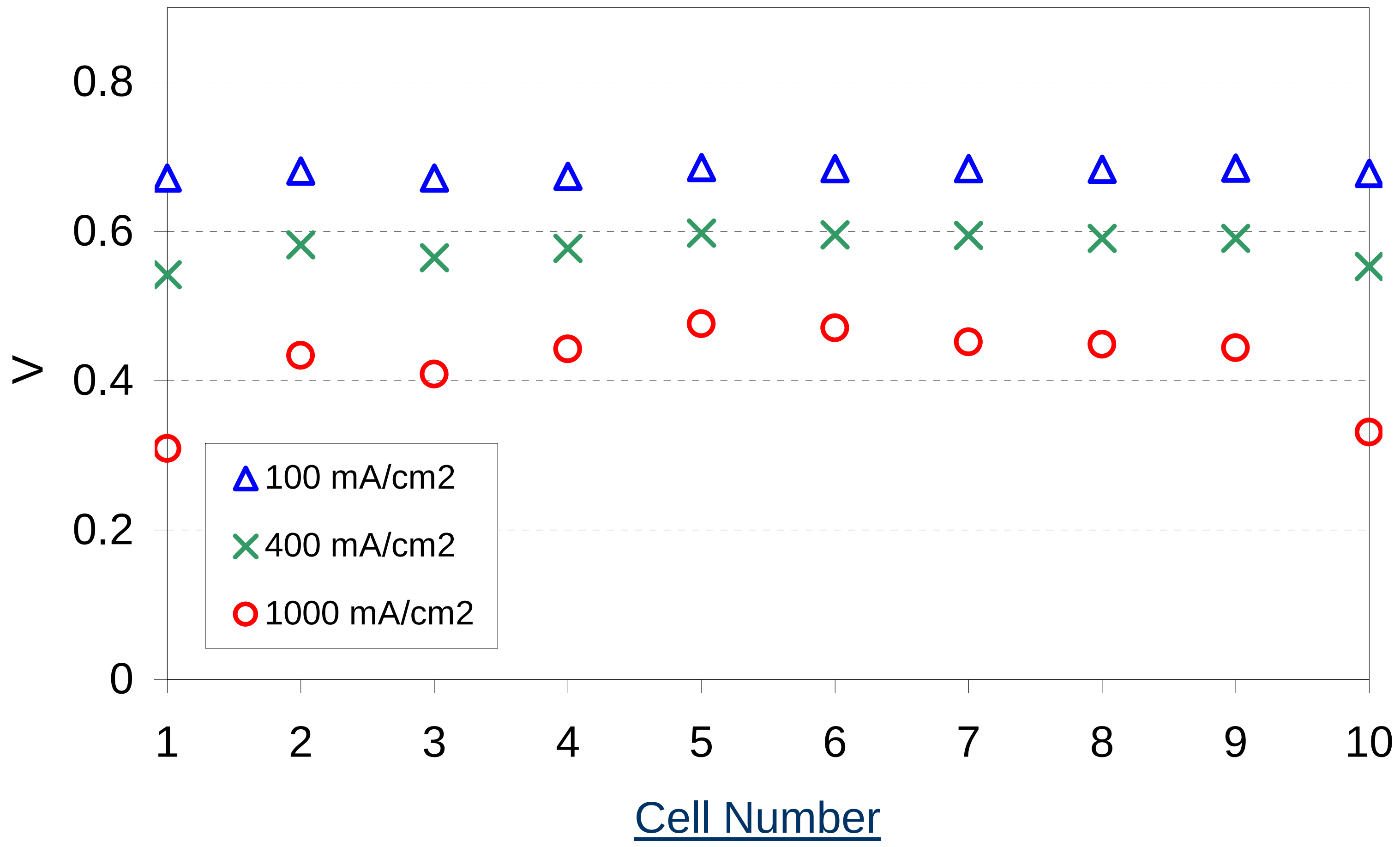


# Pressure drop

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

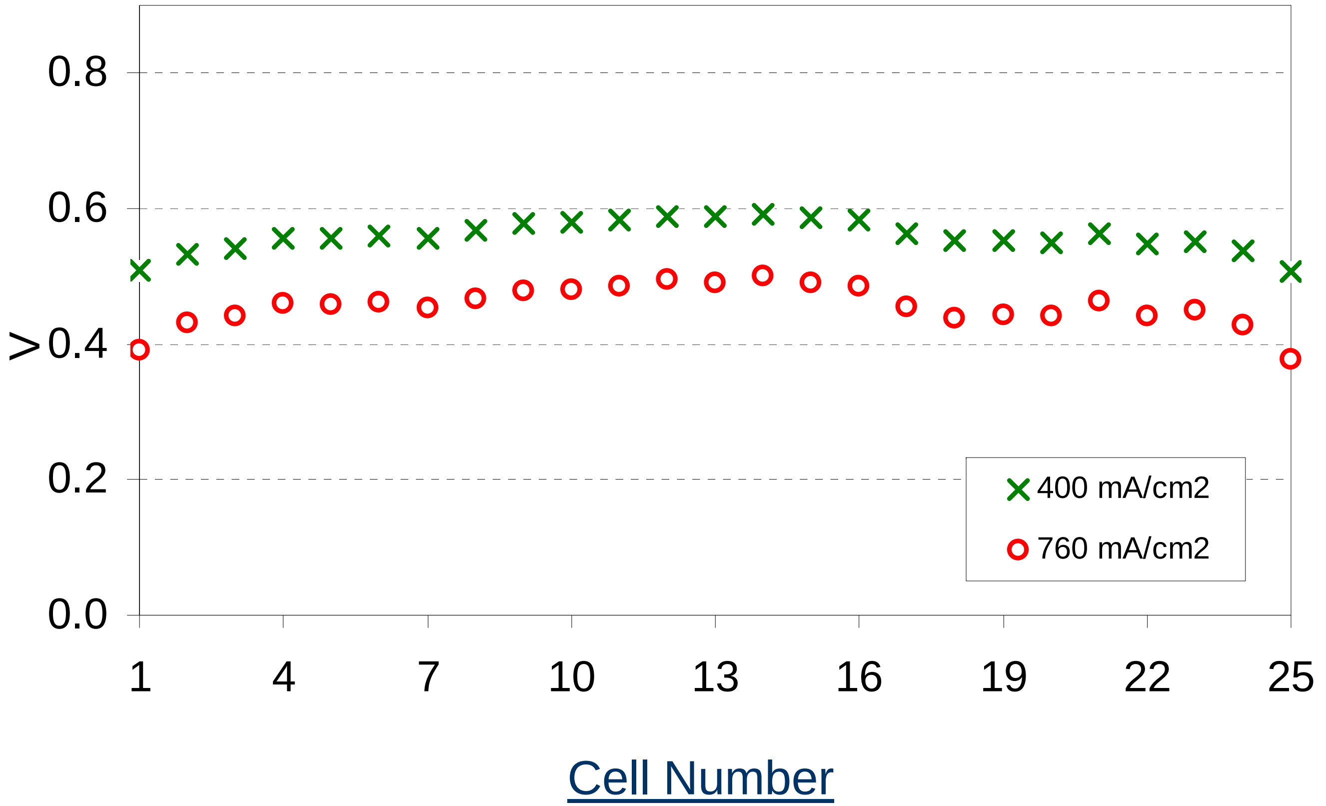


# Stack Voltage Distribution



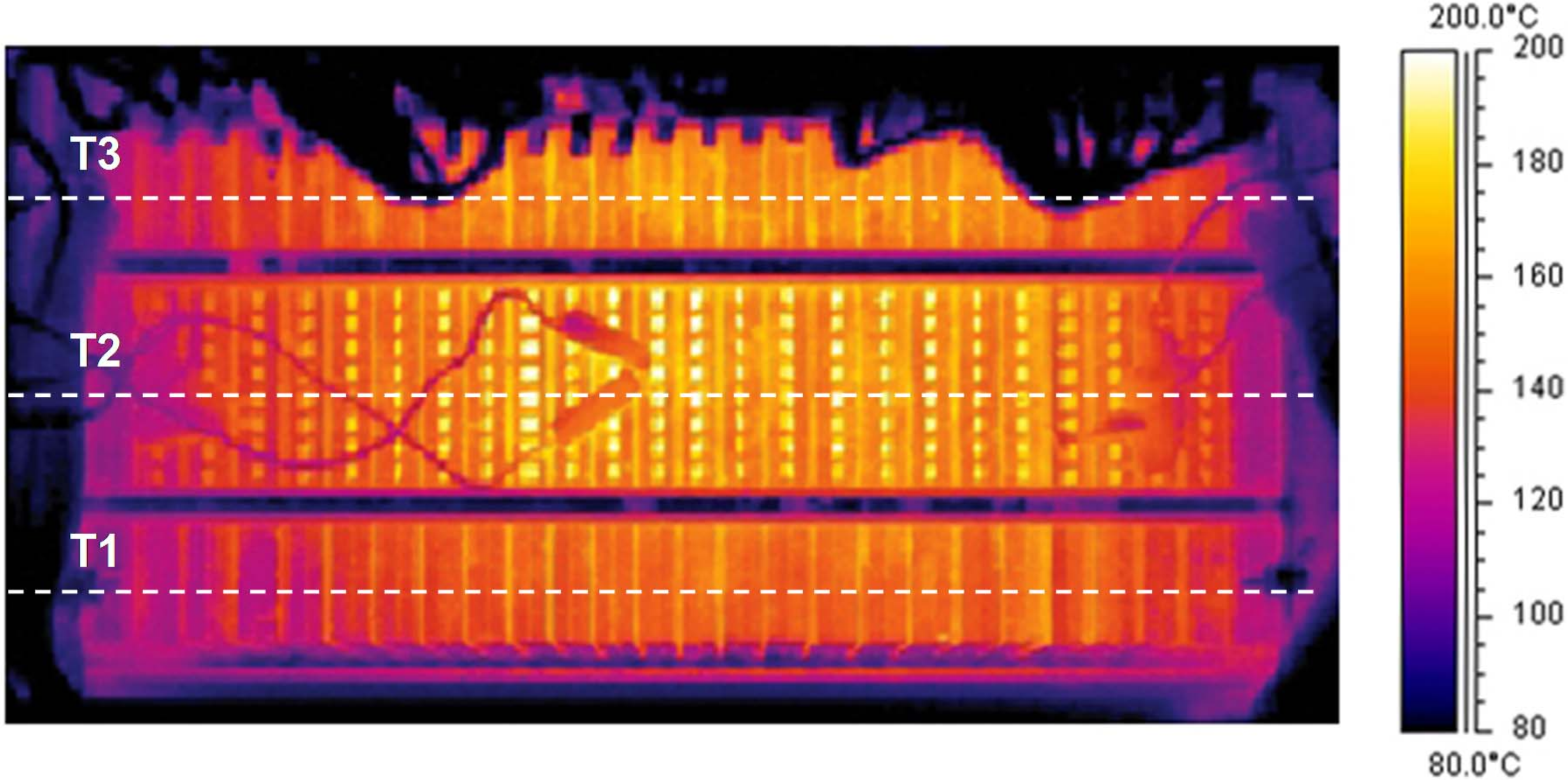

HT PEM, 160°C

# Stack Voltage Distribution

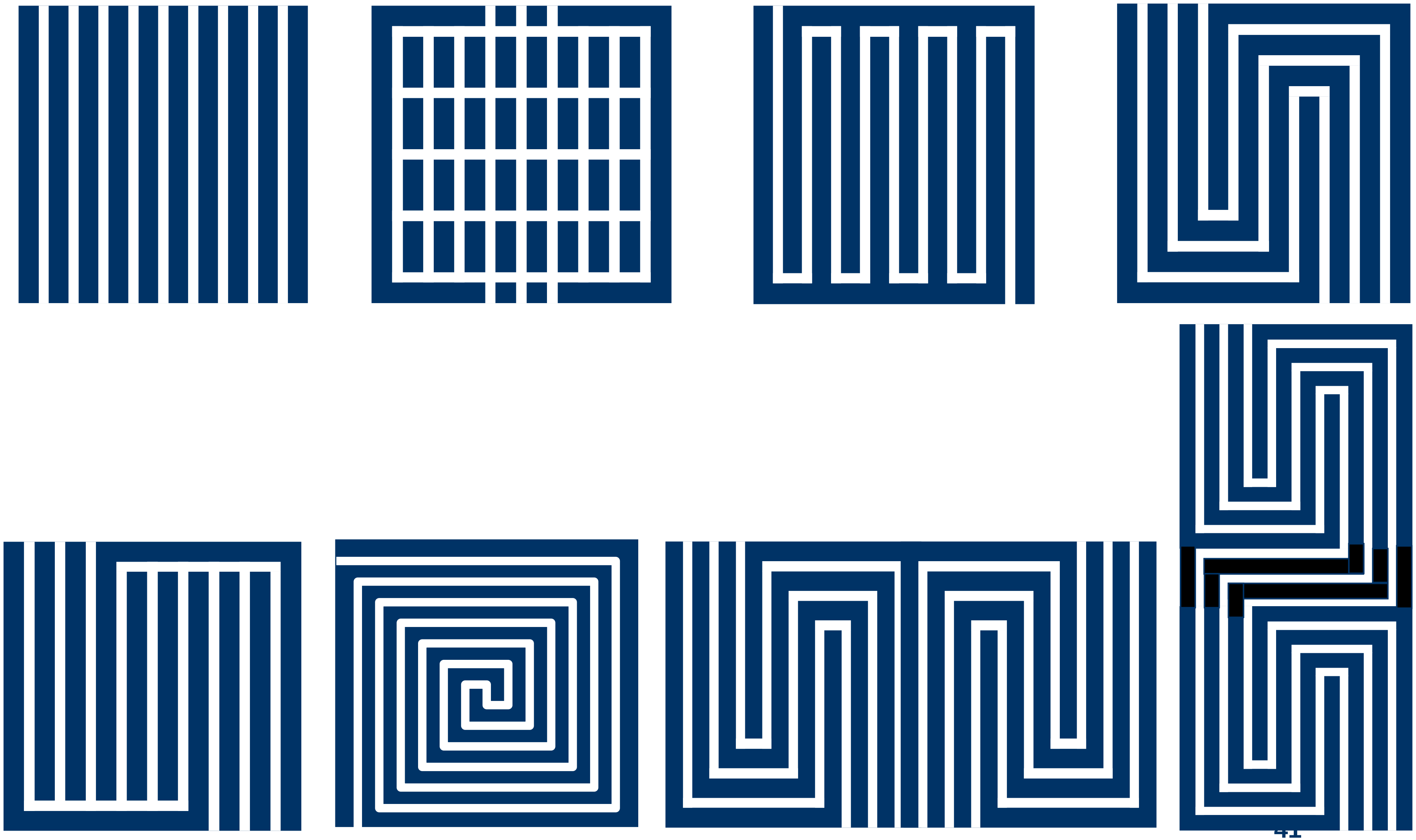



HT PEM, 160°C

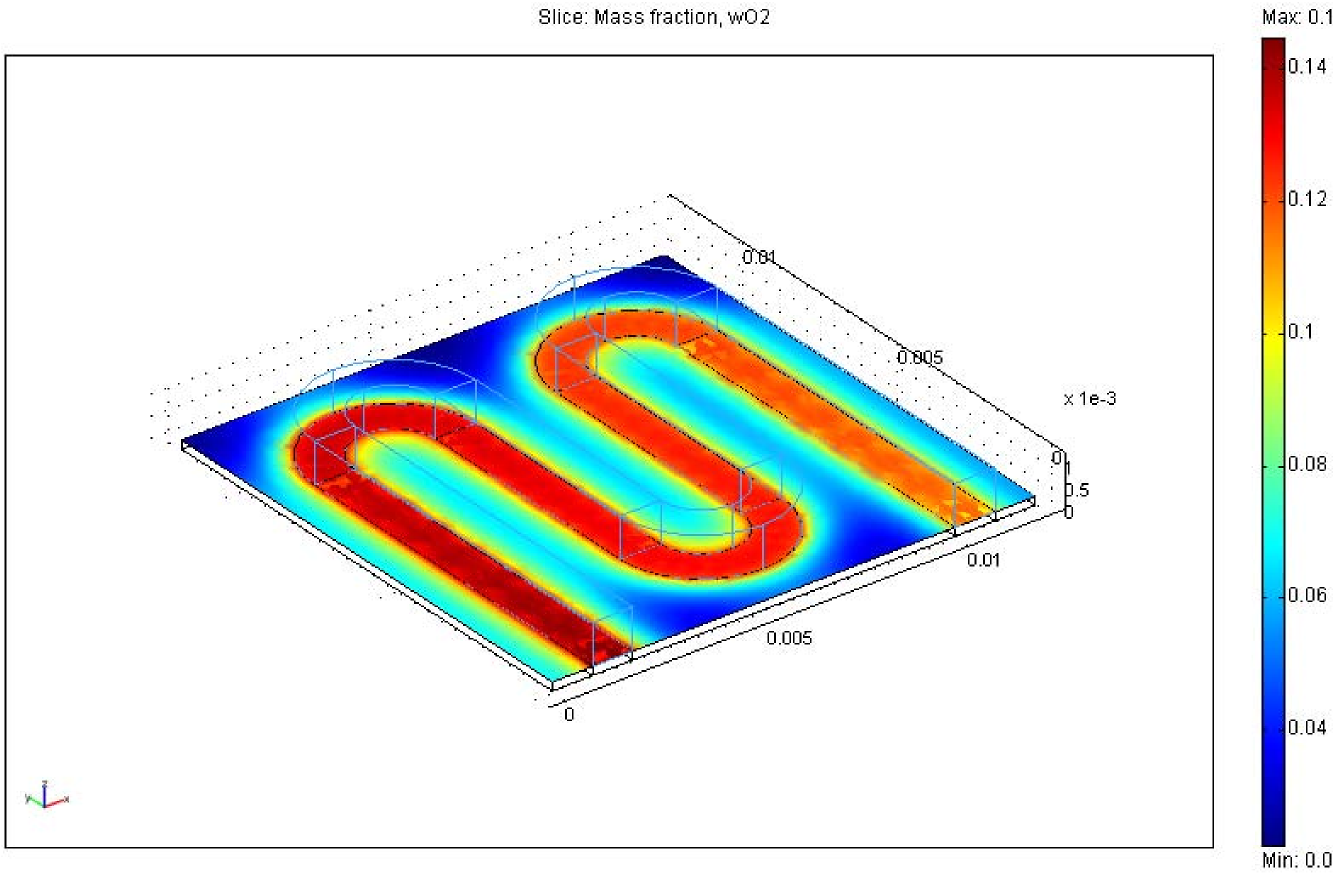
# Stack Temperature Distribution



# Flow field configurations



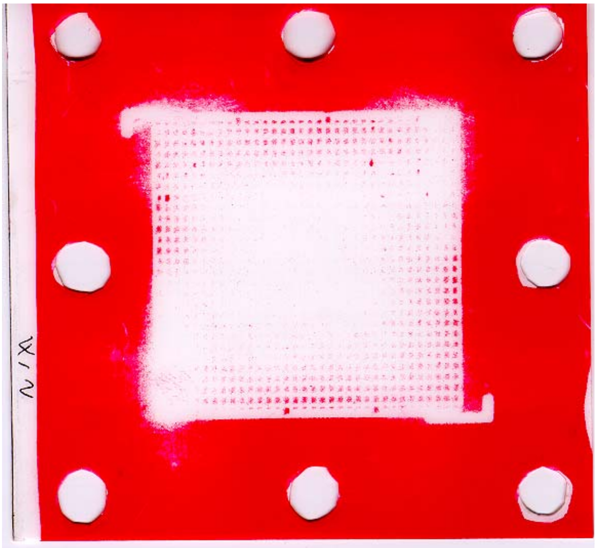
# CFD can help

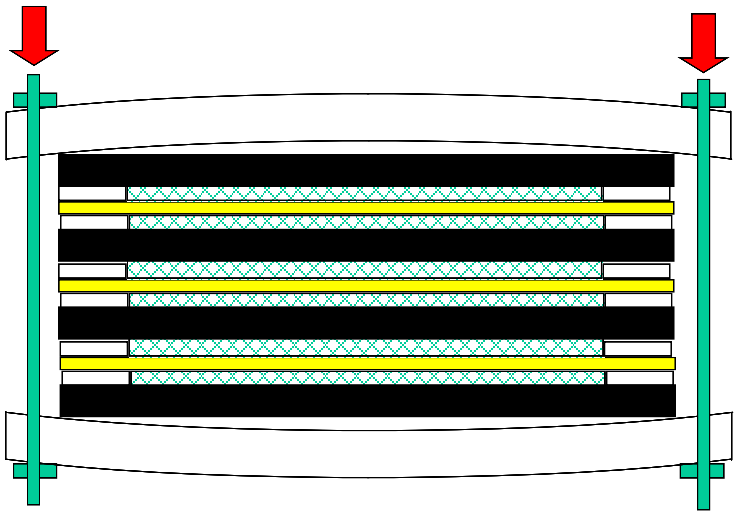


Slice: Mass fraction, wO2
Max: 0.1
0.14
0.12
0.1
0.08
0.06
0.04
Min: 0.0
0.01
0.005
x 1e-3
0
0.5
0
0.01
0.005
0

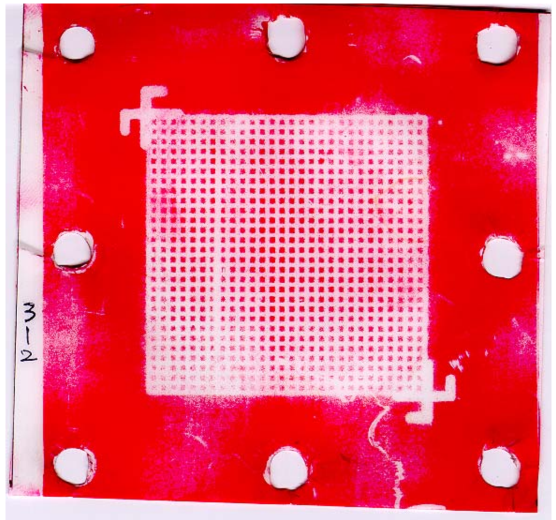
# Cell/stack compression

**Non-uniform**

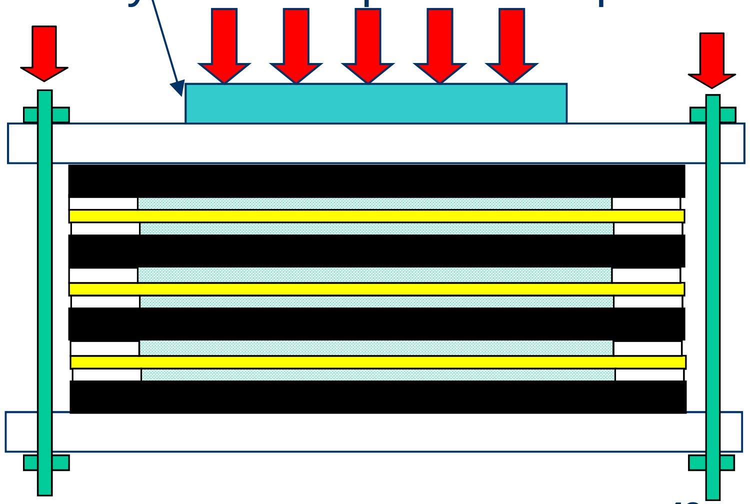




**Uniform**



Hydraulic or pneumatic piston



# 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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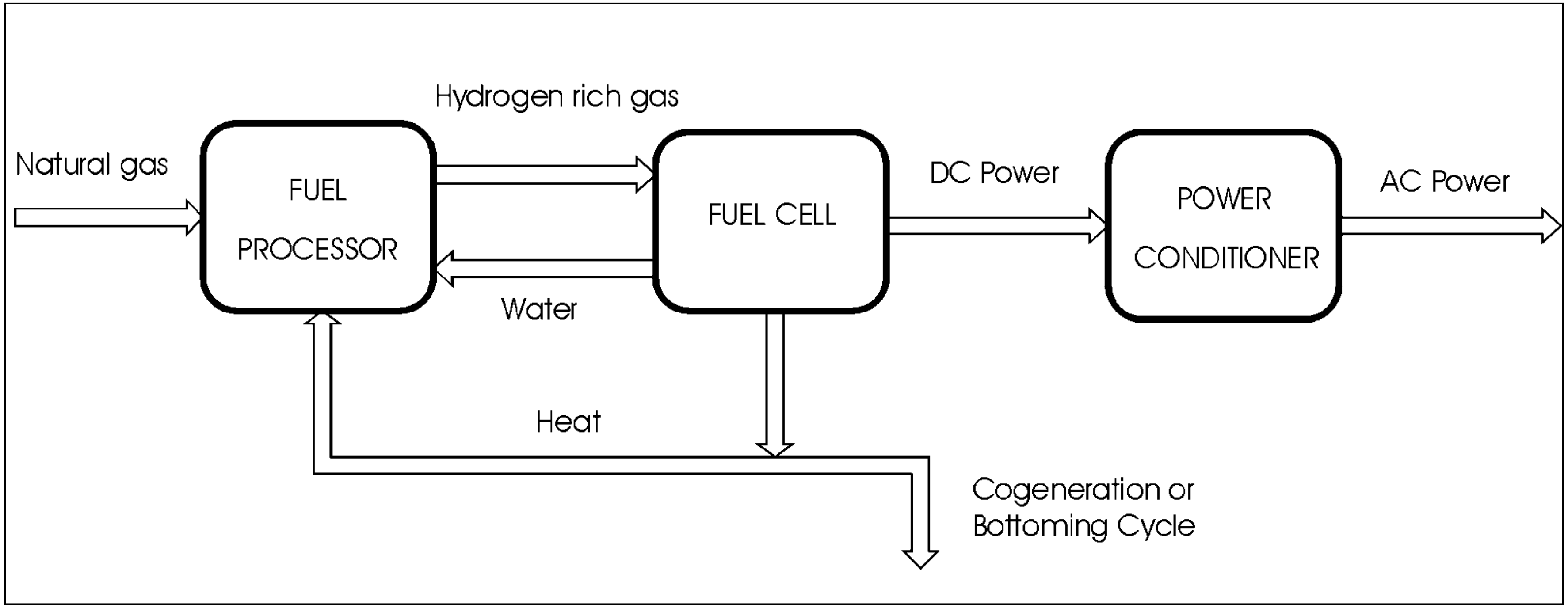
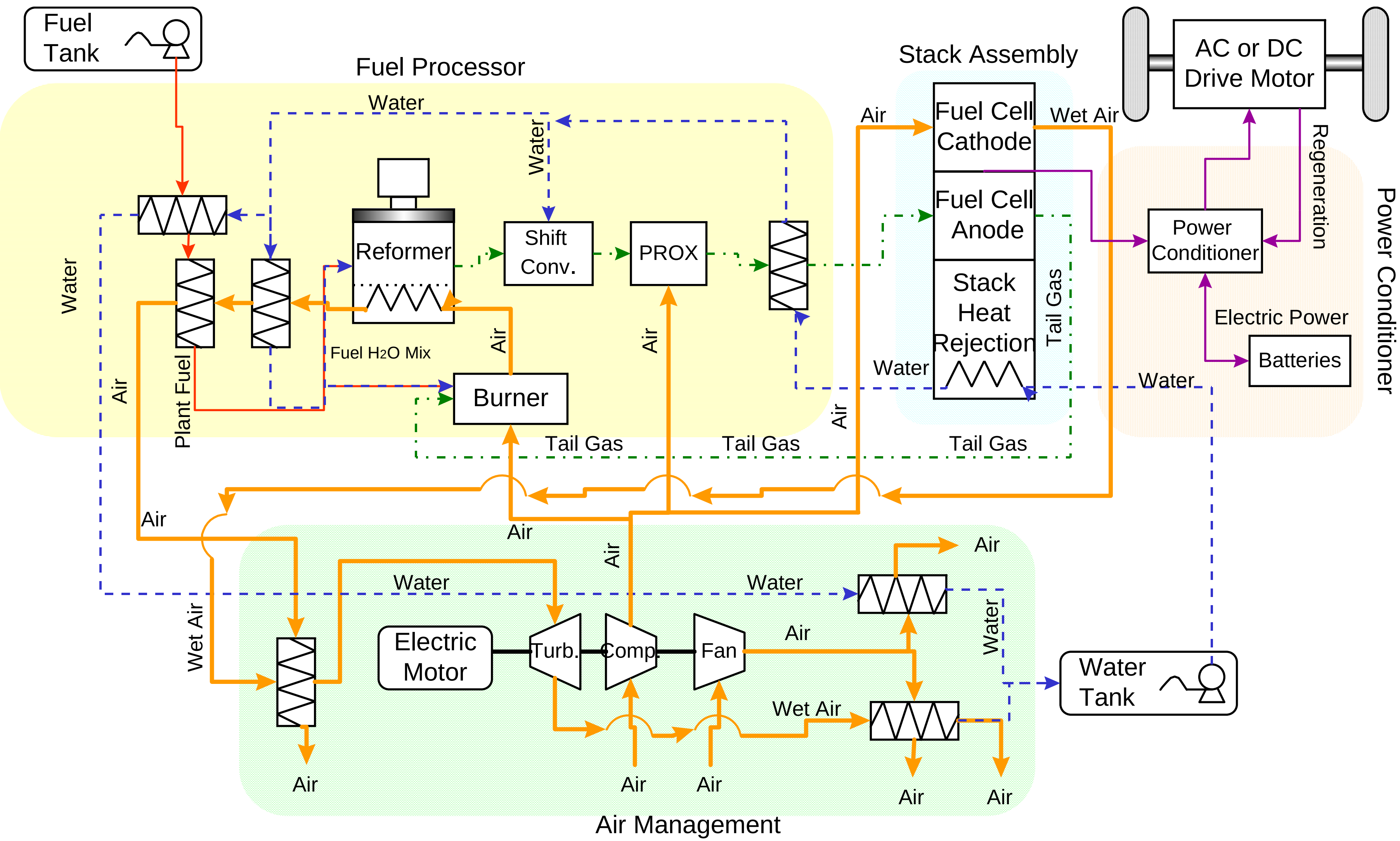
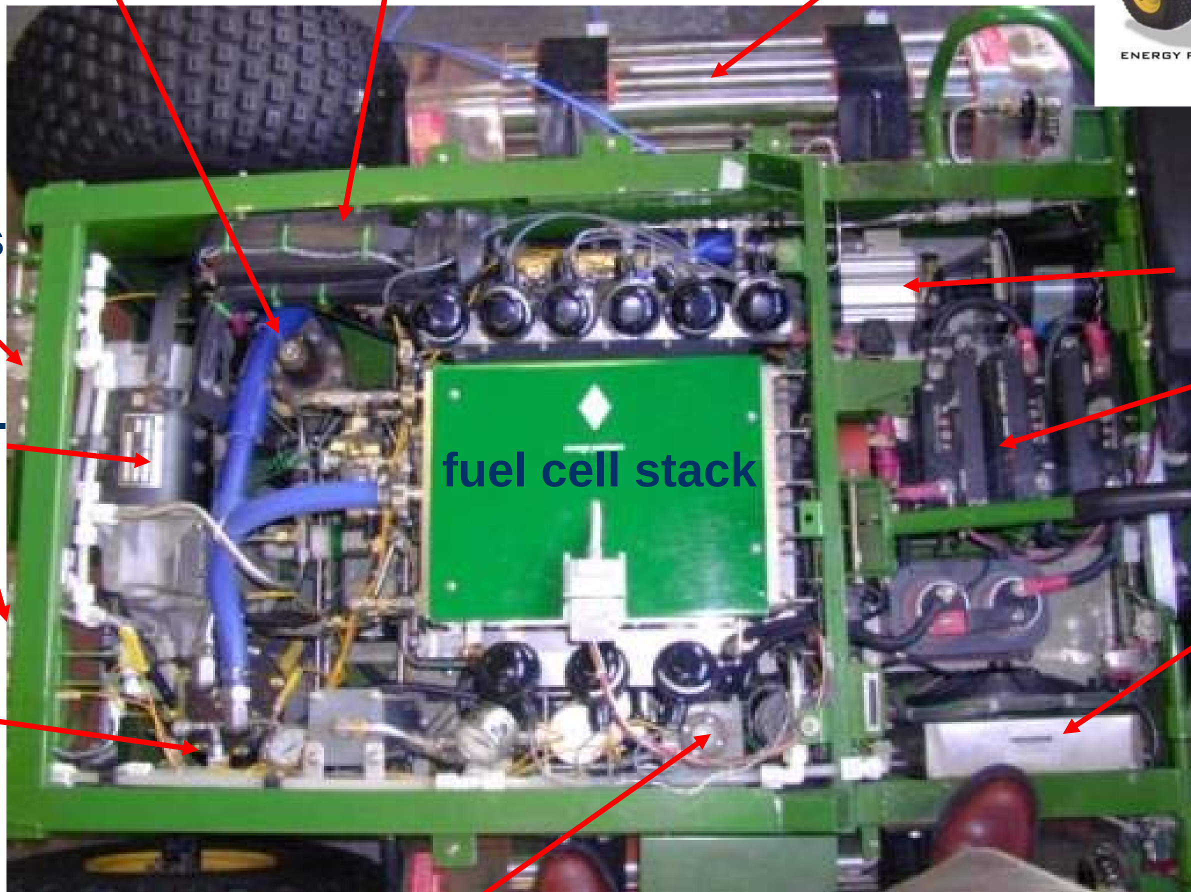
# System design and integration



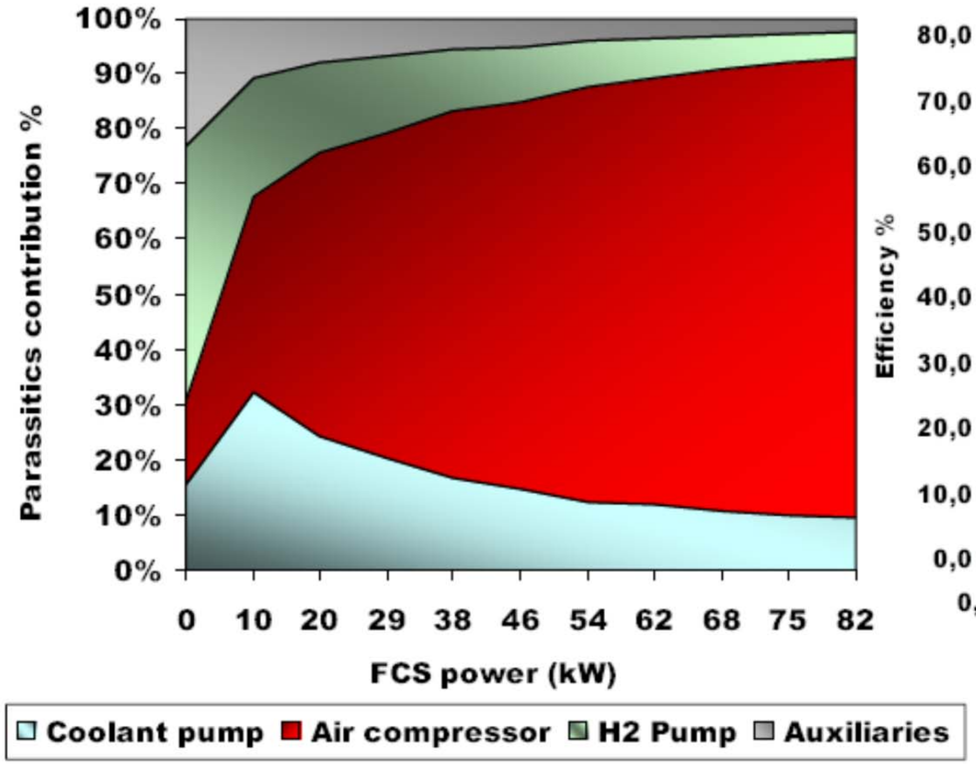
# Sistem design and integration

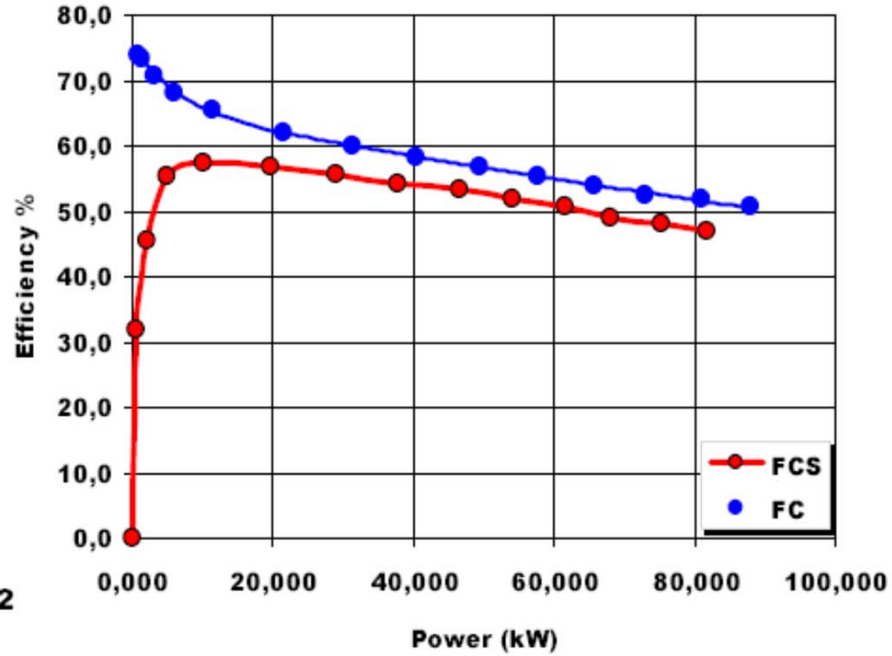


# Actual fuel cell system

# HDL 82 FCPM Efficiency Diagram




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

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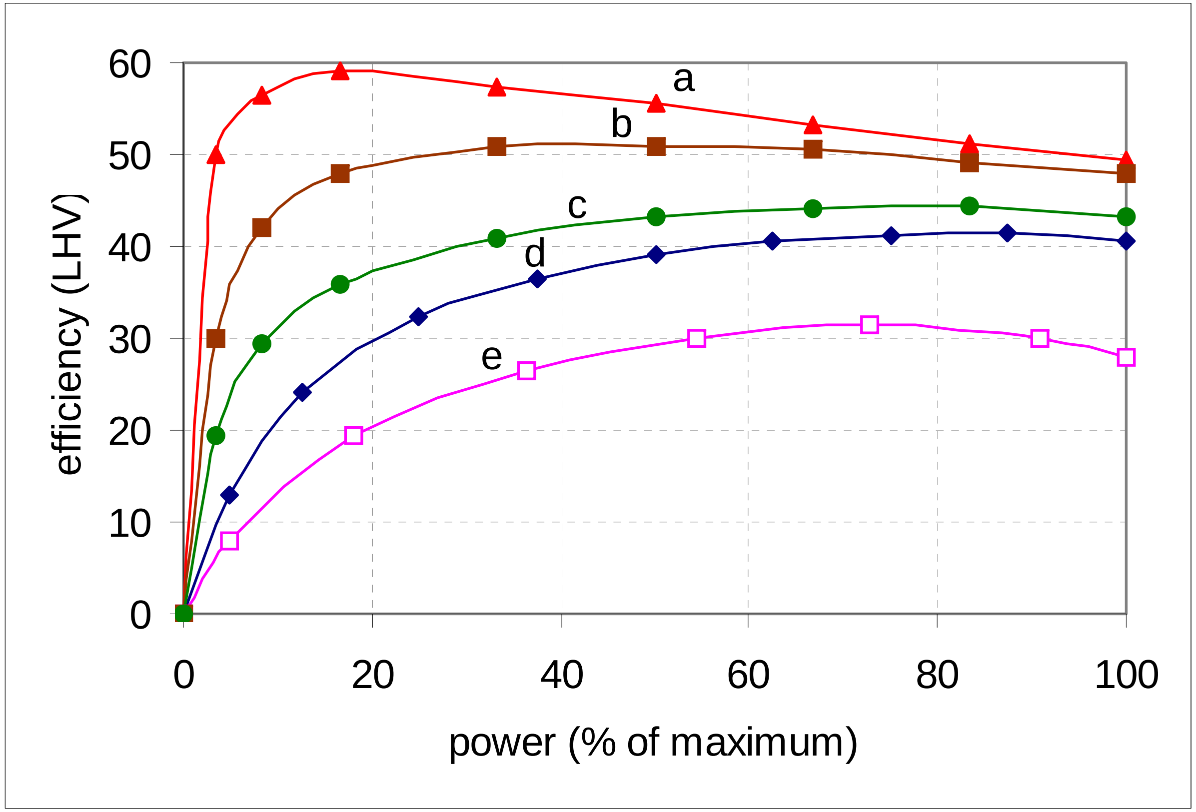
# Efficiency of fuel cell vs. ICE




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

# Topics

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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

# Patents 2002-2011

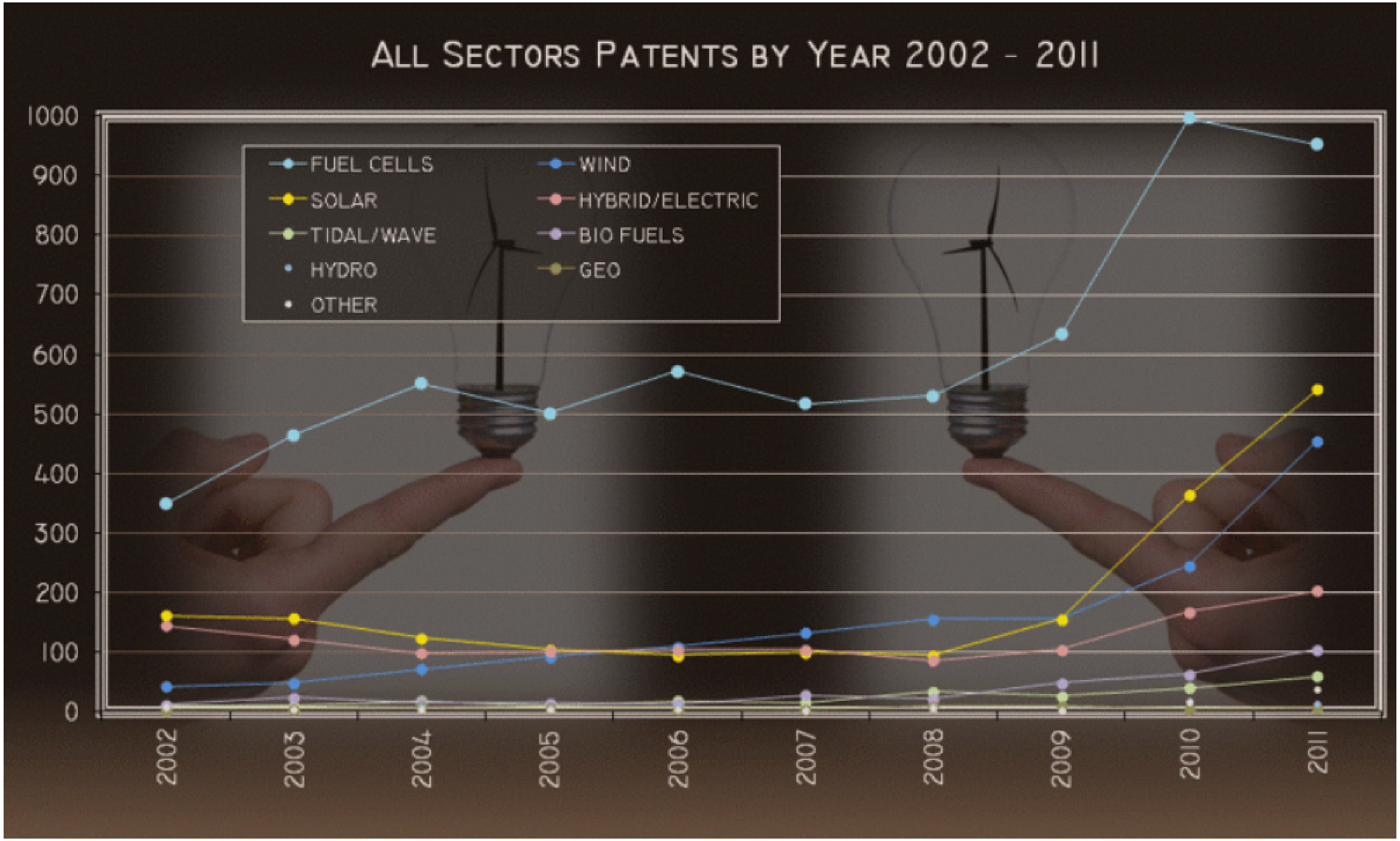


Figure 19: US Patent and Trademark Office Clean Energy Patent Awards By Sector, 2002-2011.
Source: Heslin Rothenberg Farley & Mesiti P.C.

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# 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 |

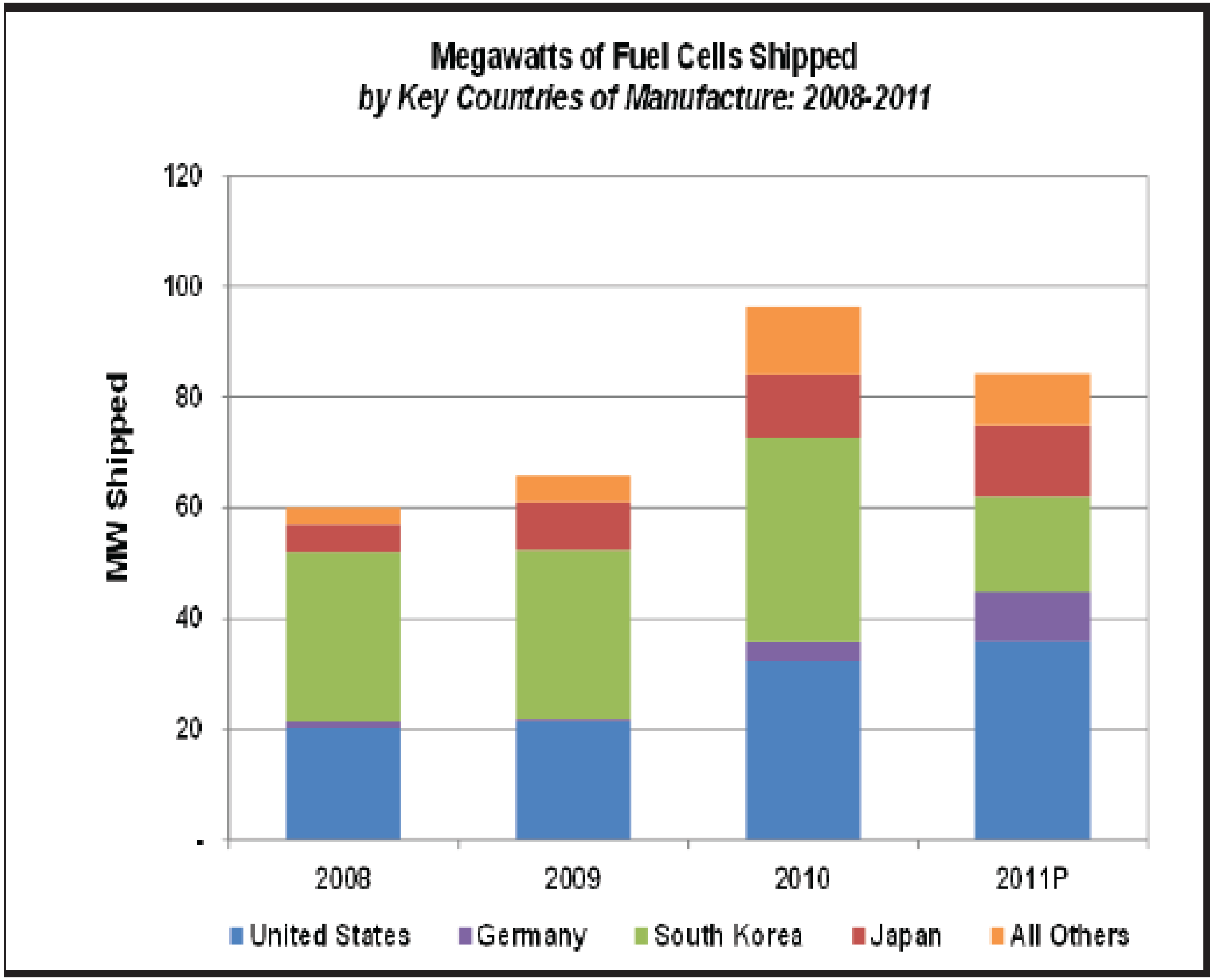
DOE

# 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




Pike Research

# Fuel cell costs

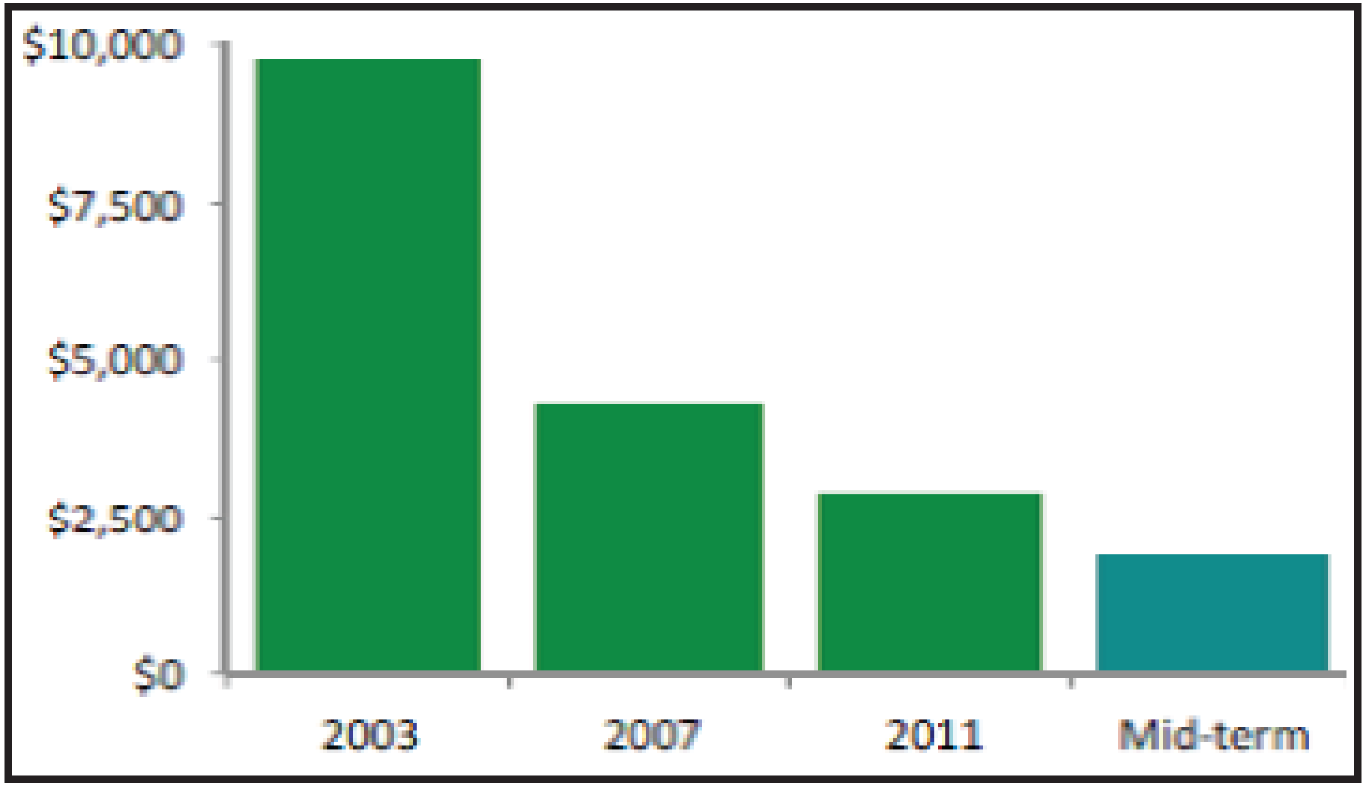



Figure 3: FuelCell Energy Cost Reduction.
Source: FuelCell Energy.

# Fuel Cell Powered Fork Lifts – Ideal Niche Market


# Fuel Cell Powered Fork Lifts
# Ideal Niche Market

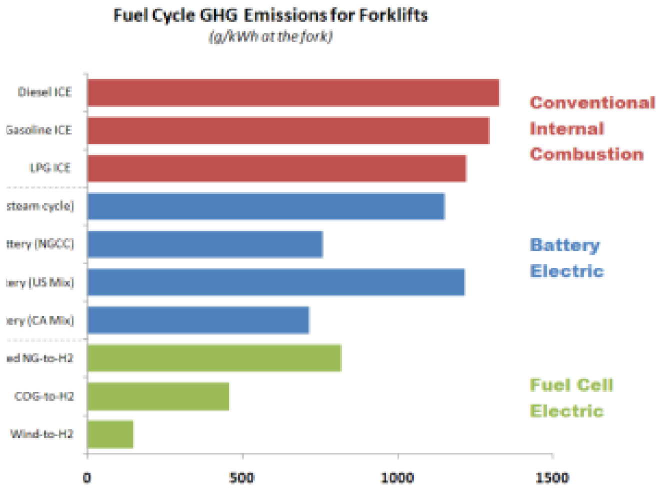
**The Case for Forklifts***

Compared to conventional orklifts, fuel cell forklifts have:

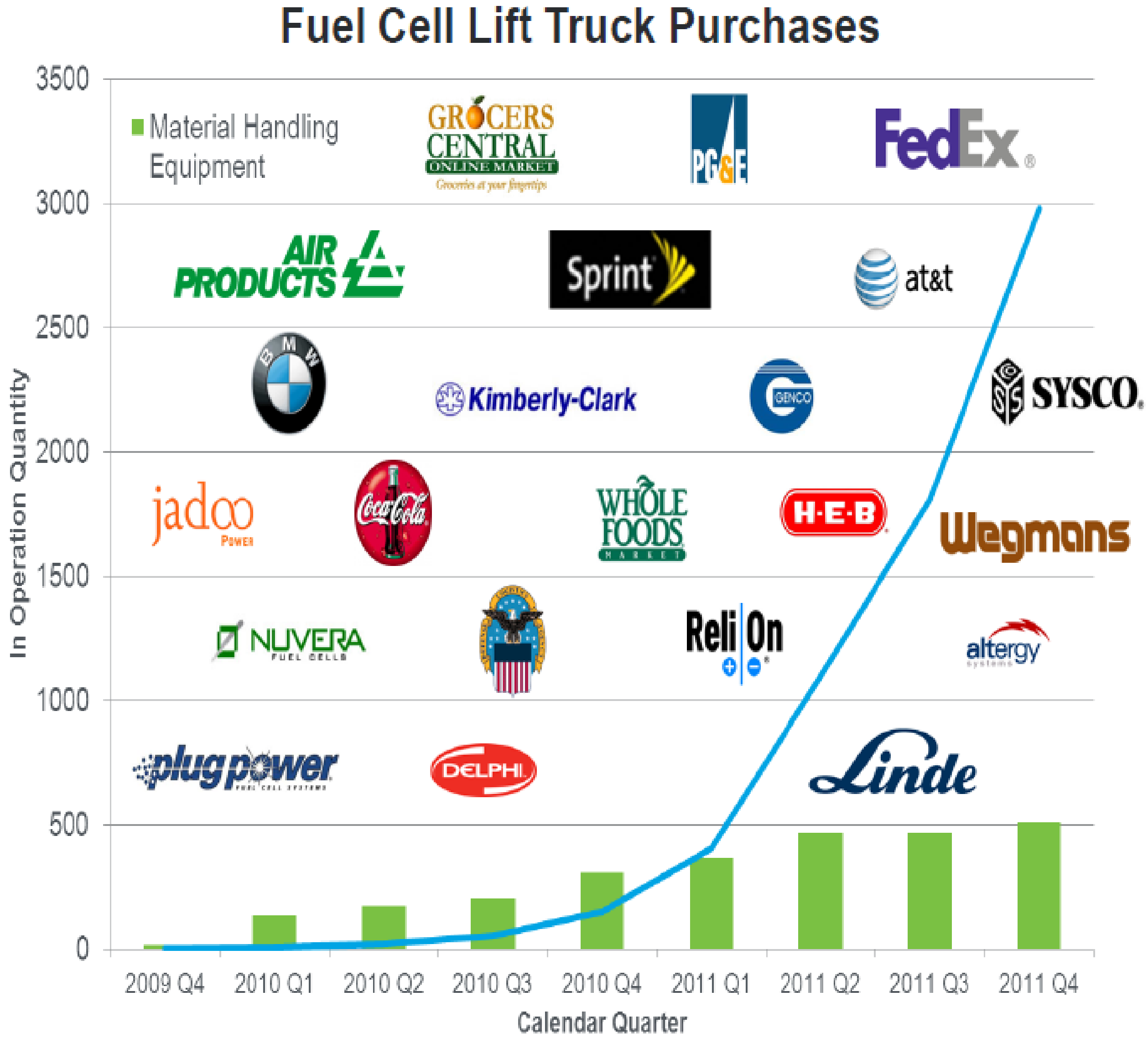
1.5 X lower maintenance cost

8 X lower refueling labor cost

2 X lower net present value of total system cost




*Preliminary Analysis*



# 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

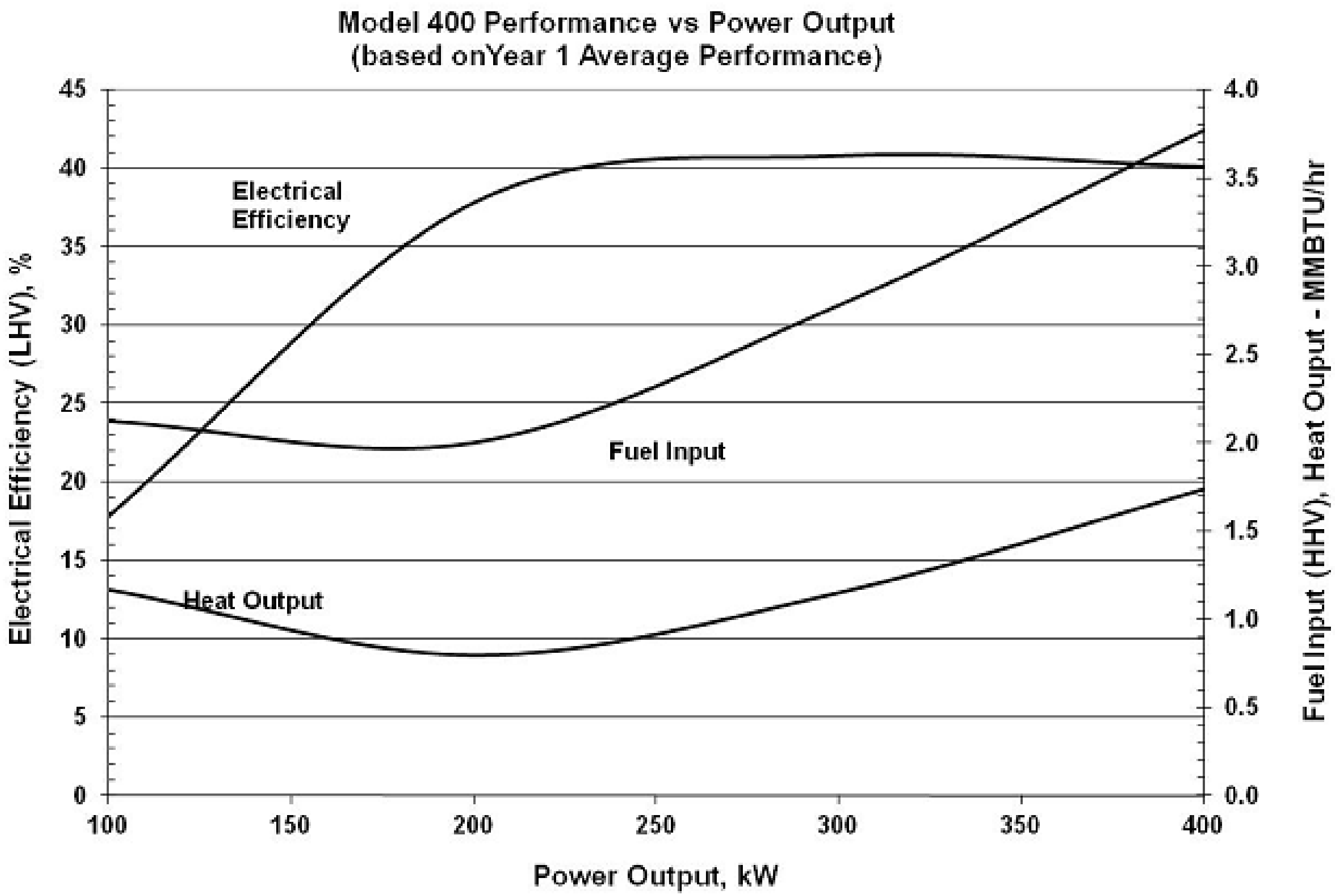
| | | New model | |
|---|---|---|---|
| Launch date | | April 1, 2011 (scheduled) | |
| Performance | Electricity generation output | 250W-750W | |
| | Rated generation efficiency | 40% (LHV)<br>36% (HHV) | |
| | Rated heat recovery efficiency | 50% (LHV)<br>45% (HHV) | |
| | Water tank capacity | 200 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

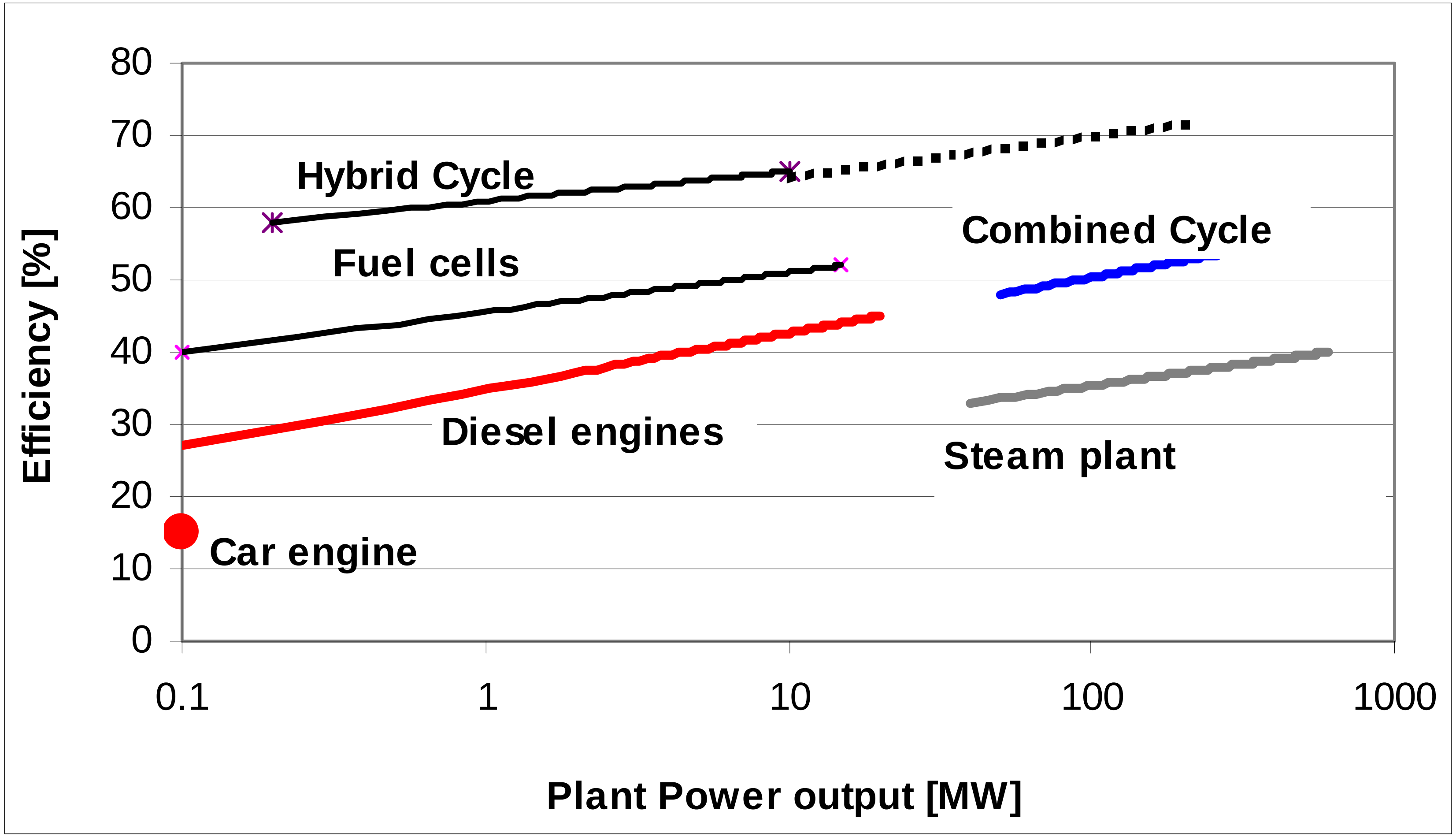


Model 400 Performance vs Power Output
(based onYear 1 Average Performance)
Electrical Efficiency
Fuel Input
Heat Output
Electrical Efficiency (LHV), %
Fuel Input (HHV), Heat Ouput - MMBTU/hr
Power Output, kW
0
5
10
15
20
25
30
35
40
45
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
100
150
200
250
300
350
400

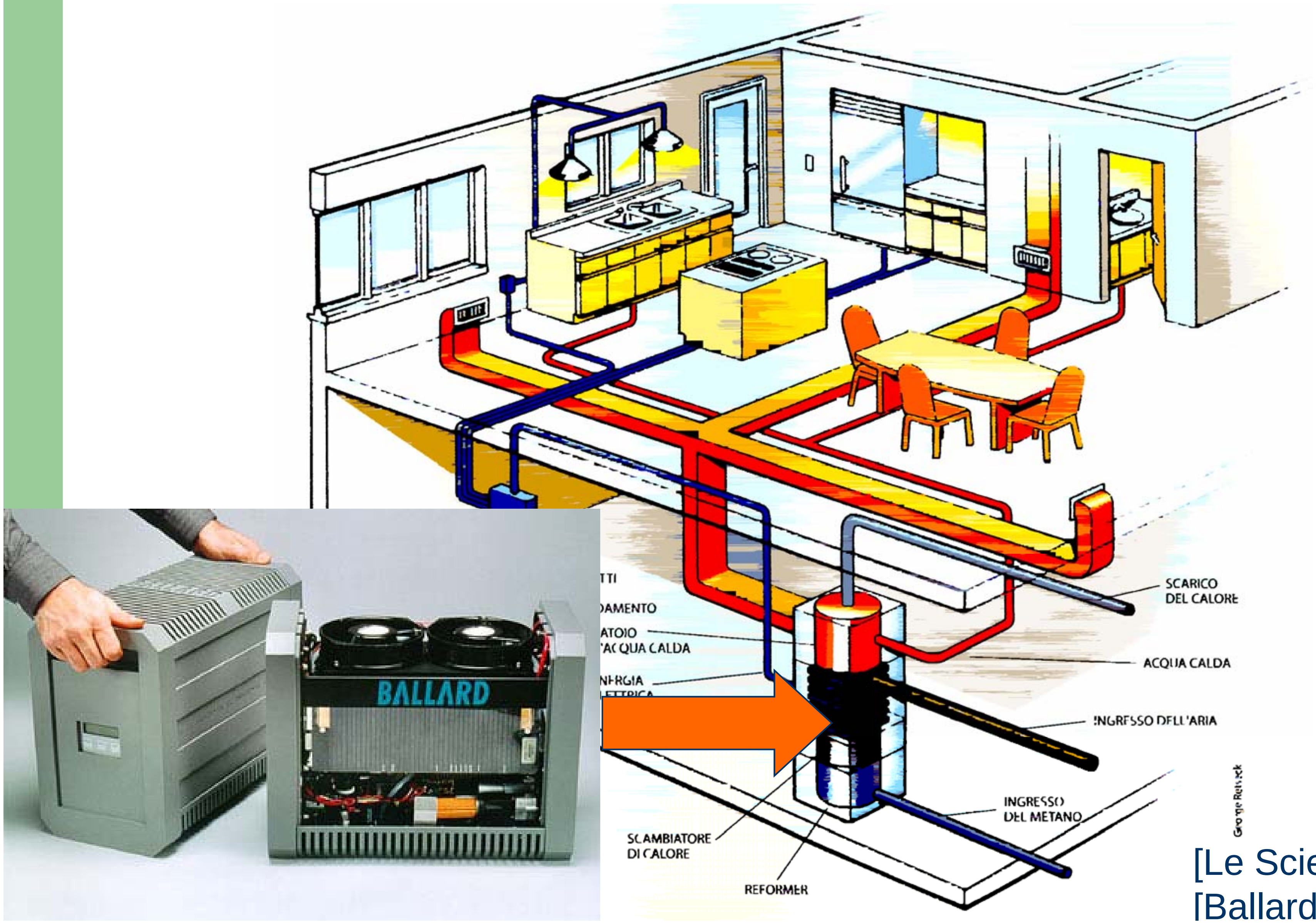
# Topics

- 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

THANK YOU!