



## Lesson 13

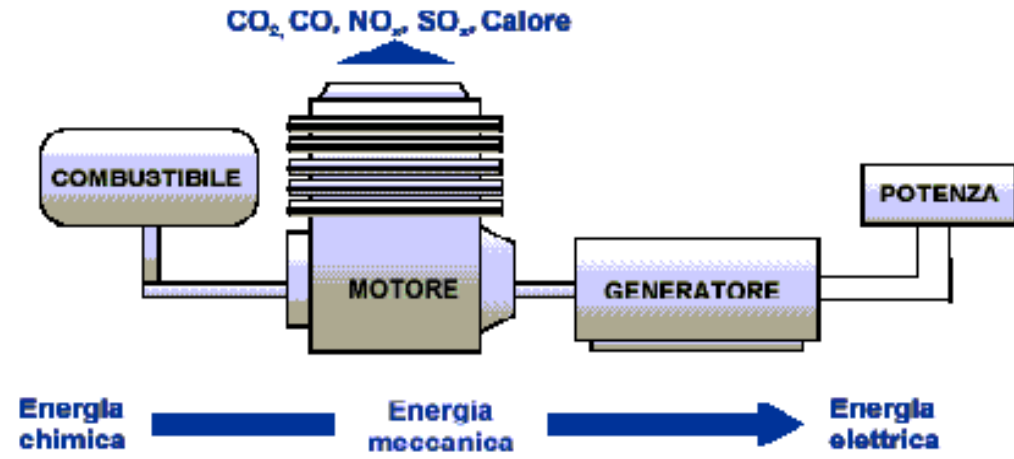


# Thermomechanical Measurements for Energy Systems (MENR)

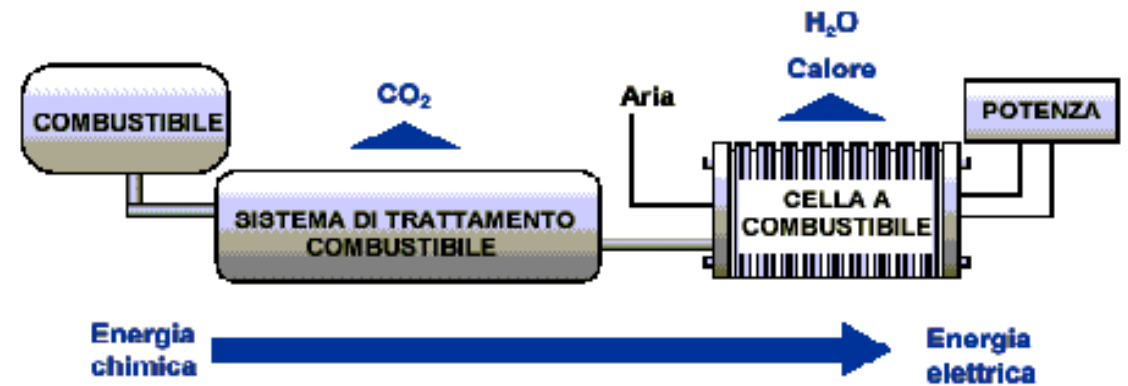
# Measurements for Mechanical Systems and Production (MMER)

# Hydrogen Fuel Cells

Fuel cells are *electrochemical devices* capable of converting the chemical energy of a fuel (usually hydrogen) directly into electricity without the intervention of a thermal cycle, obtaining therefore higher conversion efficiency compared to conventional heat engines ...



SISTEMA TRADIZIONALE



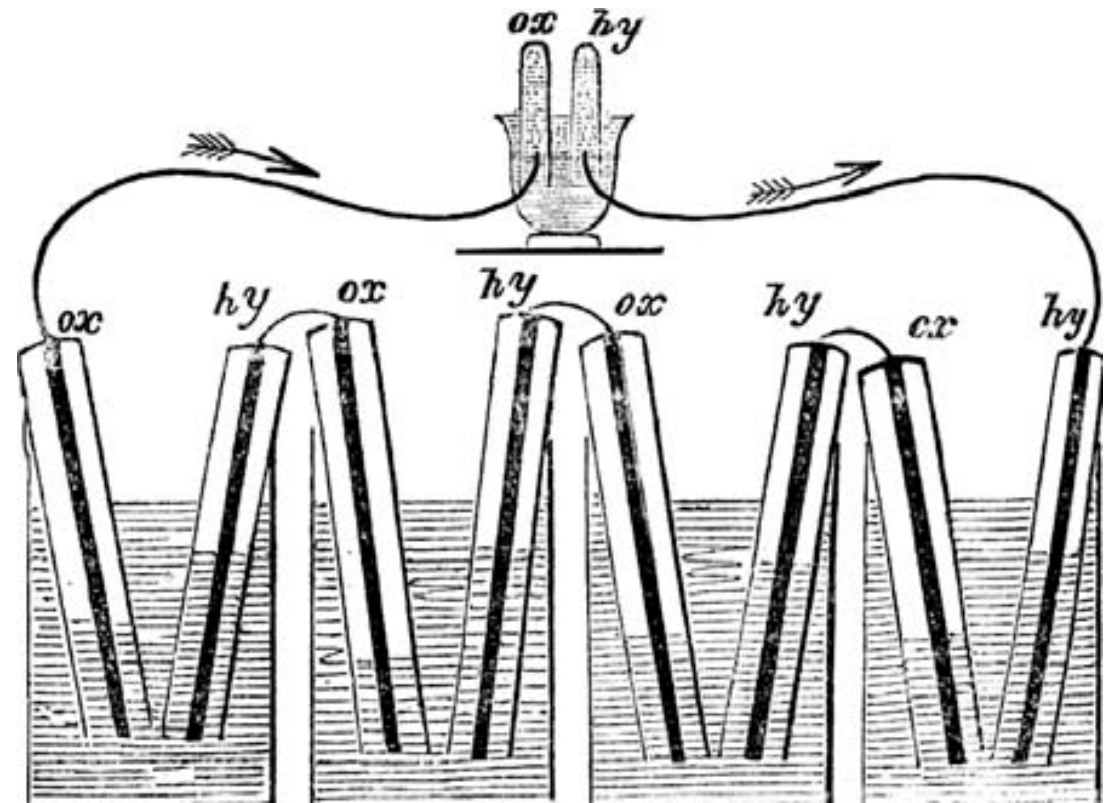
SISTEMA CON CELLA A COMBUSTIBILE

## A brief history of Fuel Cells

The first fuel cell was built by Sir William Grove in 1839, who used *platinum electrodes* and *sulphuric acid* as *electrolyte*. Later, starting in 1890, William White Jacques used phosphoric acid instead of sulfuric acid. These early devices were however characterized by a low current density (low efficiency).

Bacon, after 1930, replaced the first acid electrolyte of the cells with an *alkaline electrolyte* and continued to develop the system (cell of Bacon) today known by the acronym AFC (***Alkaline Fuel Cells***). The AFC were so popular that in the years' 60 they were chosen by NASA for the APOLLO lunar mission.

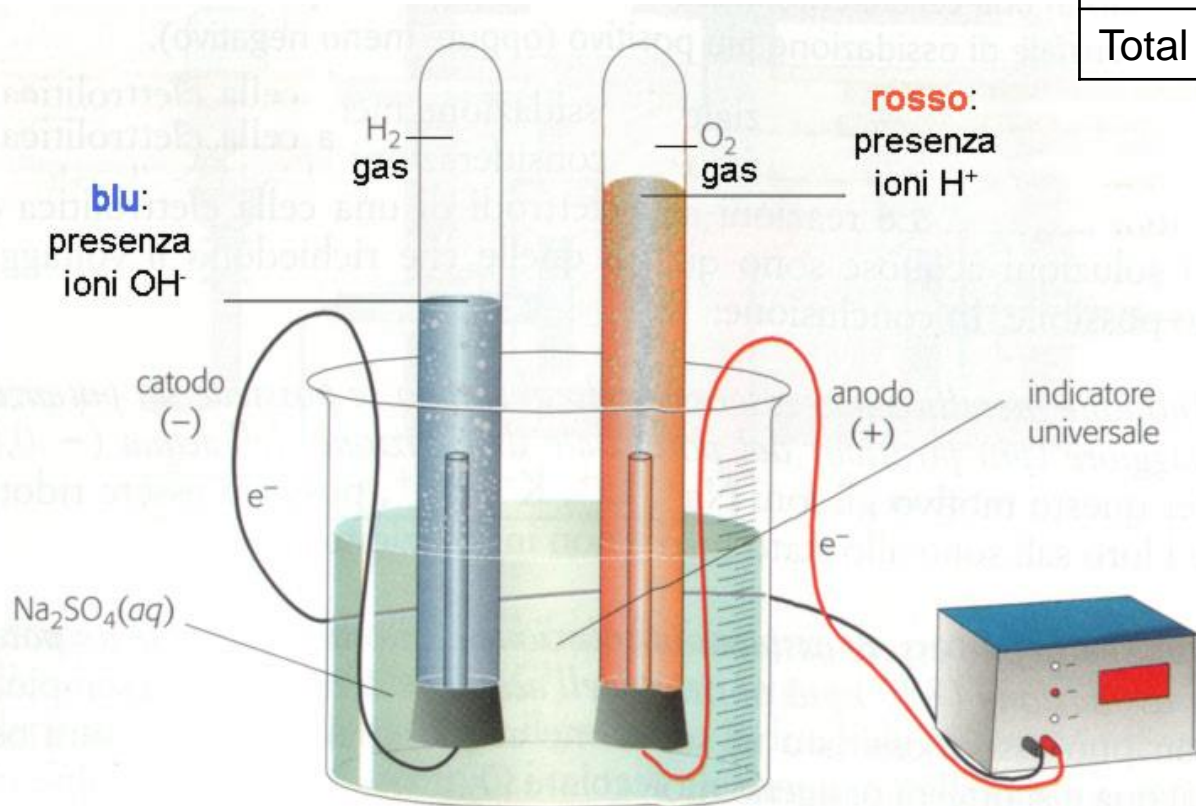
At the end of the years' 50 the use and the development of the PEMFC (***Proton Exchange Membrane Fuel Cells***) began; these cells use a special polymer membrane as electrolyte for exchanging protons. The production grew in the USA and was used by NASA for the space project GEMINI.



# ELECTROLYSIS of WATER

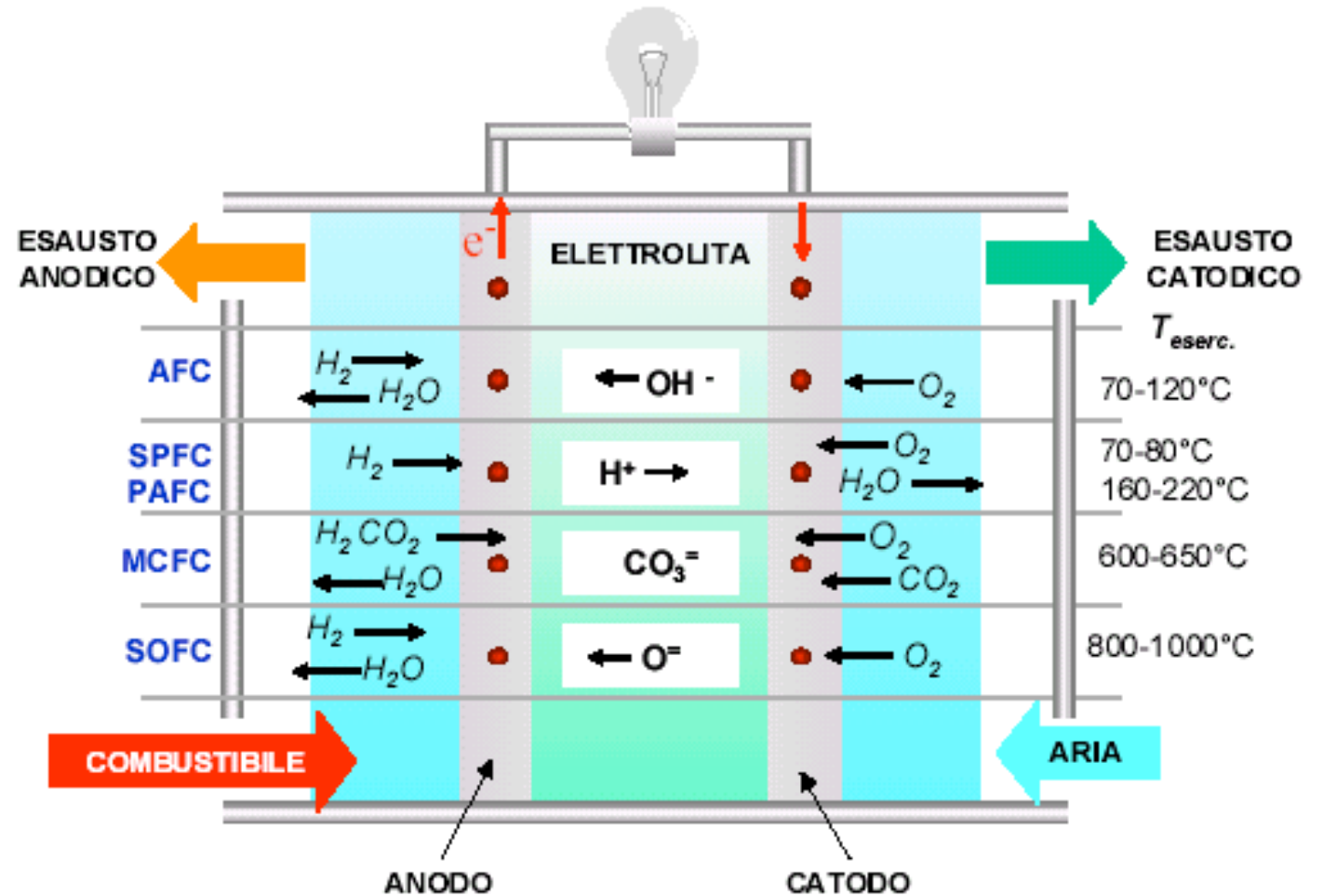
The water is decomposed into its constituent elements, hydrogen and oxygen (the presence of salt  $\text{Na}_2\text{SO}_4$  dissolved in the water serves to increase the conductivity of aqueous solution). At the **negative electrode** we have the **reduction (cathode)** of the water with formation of gaseous  $\text{H}_2$ , while the **positive pole** we have the **oxidation (anode)** with production of  $\text{O}_2$  gas.

<b>Anode (+) : oxidation</b>	$2 \text{H}_2\text{O} \rightarrow \text{O}_2 + 4\text{H}^+ + 4 \text{e}^-$
<b>Cathode (-) : reduction</b>	$4 \text{H}_2\text{O} + 4\text{e}^- \rightarrow 4 \text{OH}^- + 2 \text{H}_2$
Total reaction of the process :	$2 \text{H}_2\text{O} \rightarrow \text{O}_2 (\text{g}) + 2 \text{H}_2 (\text{g})$ g = gas

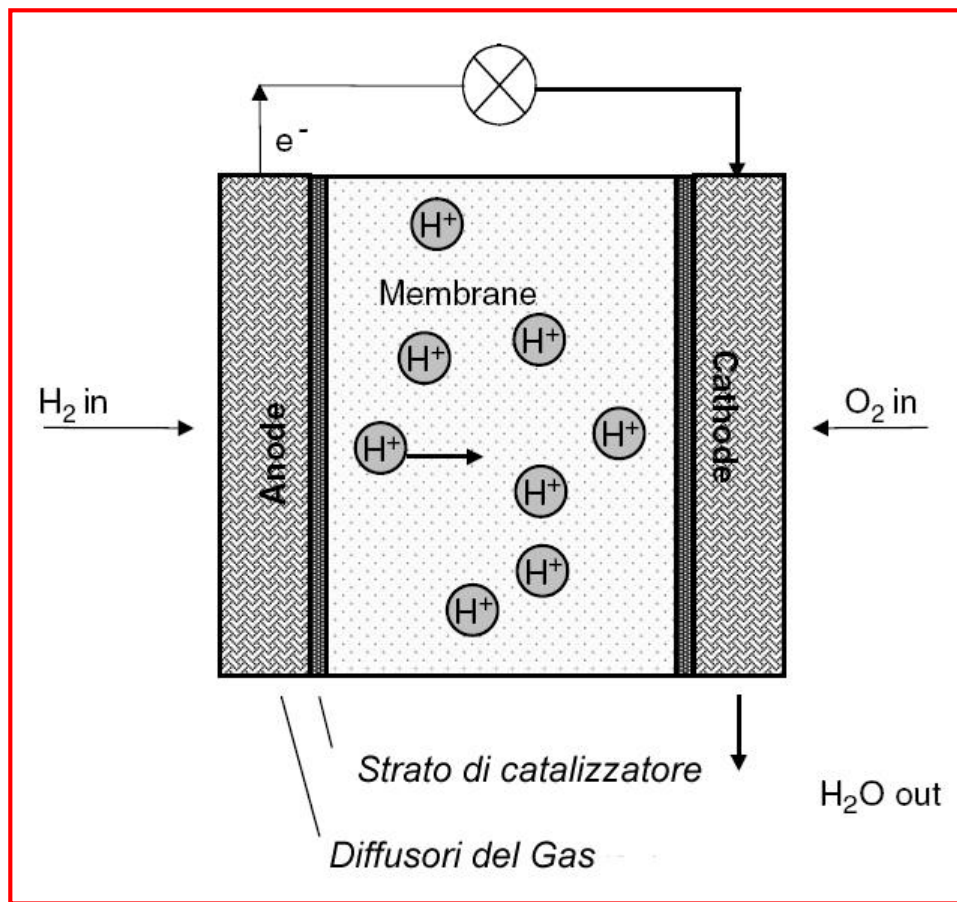


# CLASSIFICATION and WORKING SCHEME of the FUEL CELLS

- ✓ AFC  
Alkaline Fuel Cell
- ✓ PEMFC (SPFC)  
Proton Exchange Membrane Fuel Cell
- ✓ PAFC  
Phosphoric Acid Fuel Cell
- ✓ MCFC  
Molten Carbonate Fuel Cell
- ✓ SOFC  
Solid Oxide Fuel Cell



## PEM: polimeric electrolyte cell



*anodo :*



*catodo :*



### PROS

- low operating temperature
- easy starting (order of minutes)
- high yield (power density)
- no corrosion problems (typical of other types of cells with liquid electrolyte)
- Quite simple construction

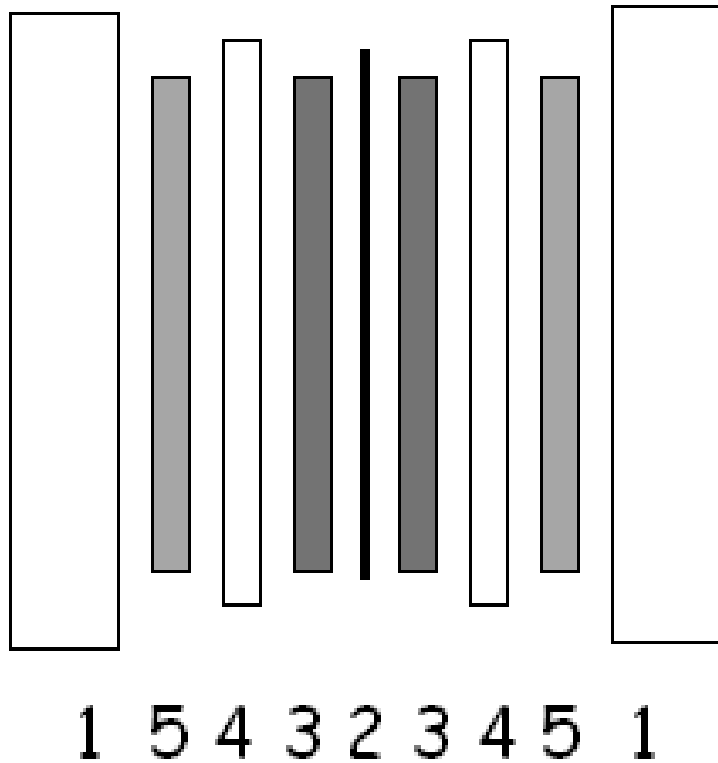
### CONS

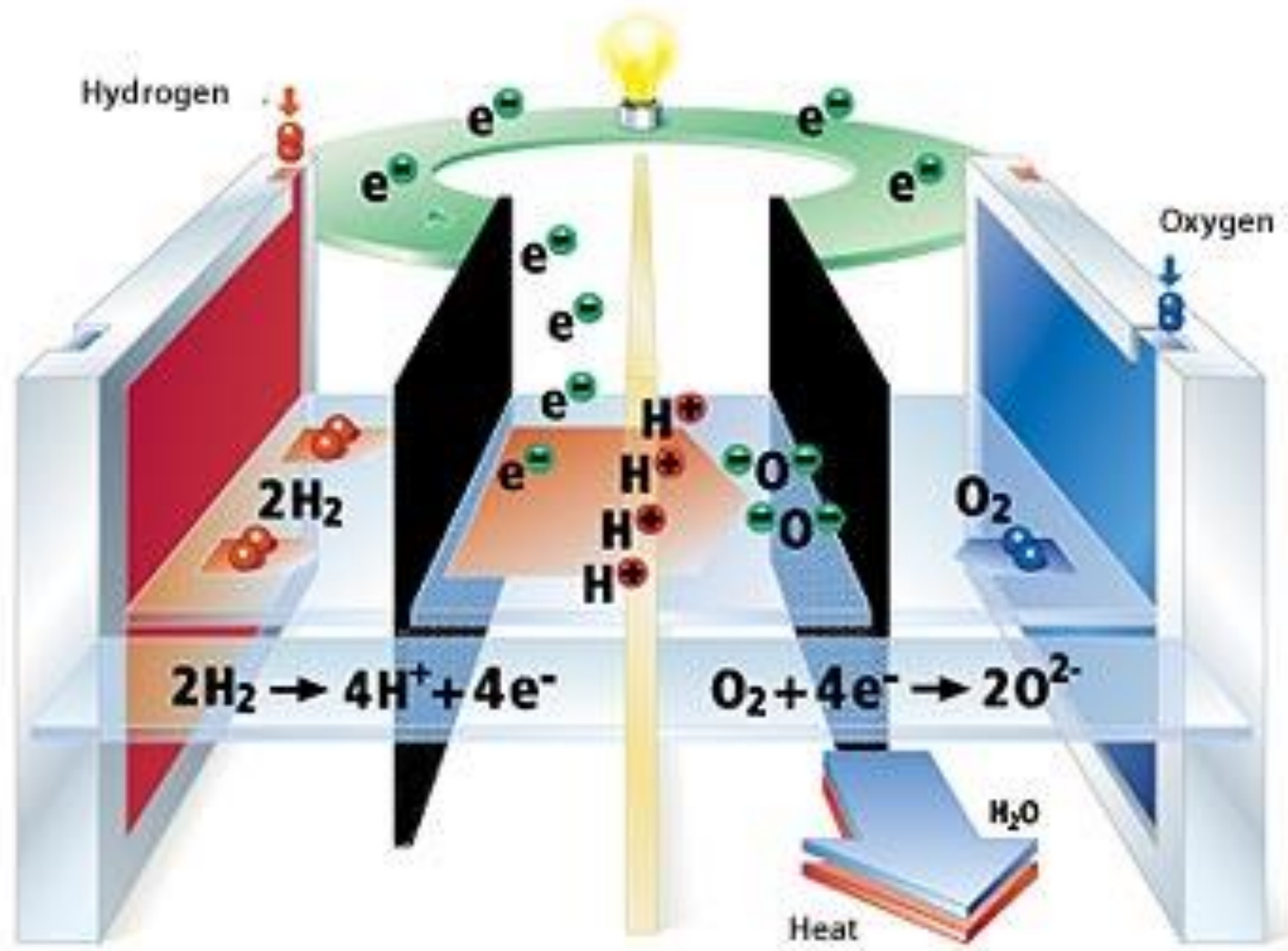
- poor tolerance to the presence of CO in the fuel
- difficult thermal integration between the fuel treatment system and the stack

As mentioned, there are various types of fuel cells. However, for automotive traction the best candidate appears to be the ***Polymer Electrolyte Cell***.

In the figure are represented in order:

1. The **bipolar plates** which make up the cell's terminals, to them is connected the external electrical circuit that will use the current produced by the cell.
2. The **proton exchange membrane** which forms the electrolyte that allows ions to migrate.
3. The **electrodes** which represent the active sites where hydrogen oxidation and oxygen reduction happens; the membrane and electrode together is typically referred to as MEA (*Membrane Electrode Assembly*).
4. The **sealing system** which ensures the device sealing of the reagents and the cooling fluid.
5. The **gas diffusion layers** which convey the reagents to the active sites and are made up of tiny channels distributed close to the electrode.





Bipolar-Plate  
(Anode)

Gas Diffusion Layer  
with Catalyst

Membran

Gas Diffusion Layer  
with Catalyst

Bipolar-Plate  
(Kathode)

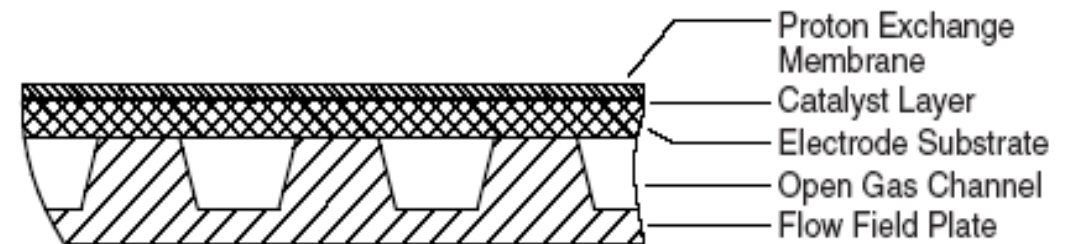
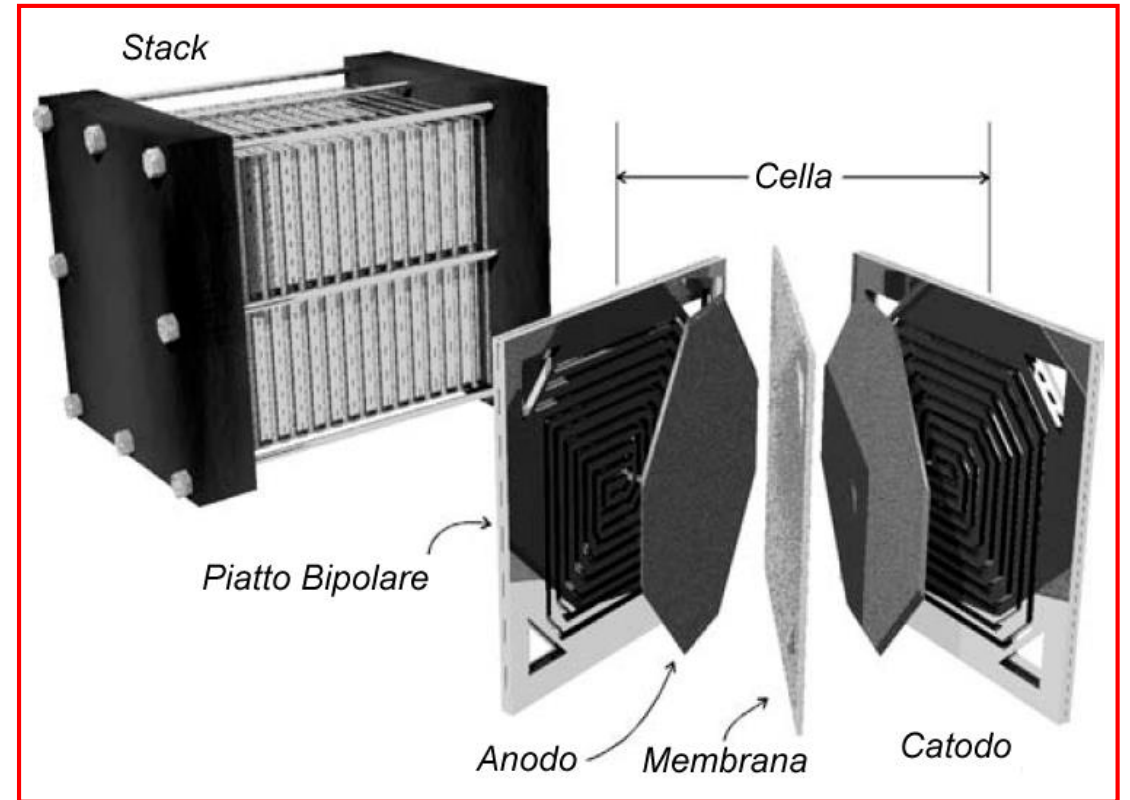


**Why don't we allow the reagents to pass directly through the catalytic layer ?**

**Why is the electrode substrate necessary ?**

The substrate, being of porous material, allows access of the reagent gases under the structure of the bipolar plates. At the same time, it provides a conductive path to the patterned area of bipolar plates.

Bipolar plates must operate a balance between *gas supply* and *electrons conduction*. The best conductor, a solid sheet full, would not allow access to any gas while a completely open structure would not allow any current to flow.



## A FEW ELEMENTS OF THE CELL THERMODYNAMICS

The energy available at the equilibrium conditions (*constant pressure and temperature*) in a cell is given by the change of **free energy**:

$$\Delta G = -nFE_{rev} \quad \left\{ \begin{array}{l} H_2 \rightarrow 2H^+ + 2e^- \\ \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \end{array} \right.$$

where:

$n$  number of electrons participating in the reaction = 2

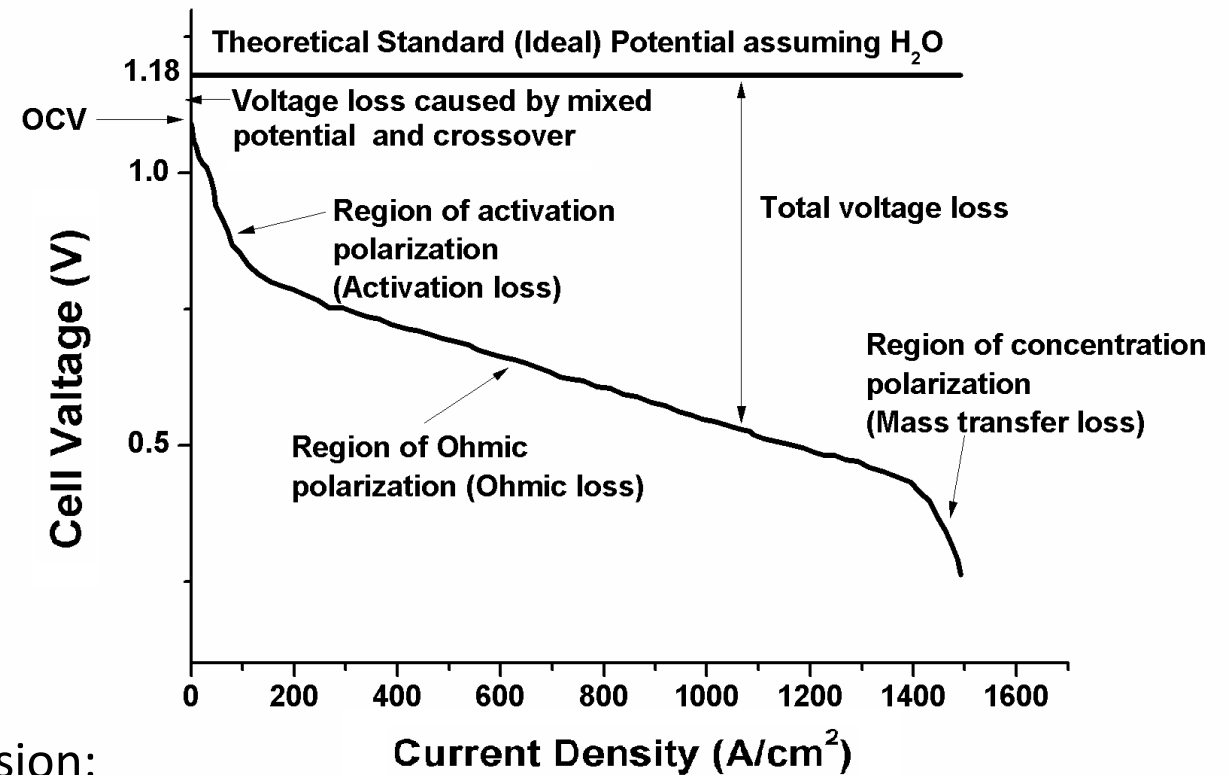
$F$  Faraday constant = 96484 C/mol

$E_{rev}$  reversible cell potential

**Nerst's equation** determines the thermodynamic potential of the complete redox reaction; this potential represents the e.m.f. (electromotive force) of the cell in open circuit conditions :

$$E = \frac{-\Delta G_E^0}{2 \cdot F} + \frac{R \cdot T}{2 \cdot F} \cdot \ln \frac{p_{H_2} \cdot (p_{O_2})^{1/2}}{p_{H_2O}}$$

A fuel cell operating in standard conditions, that uses hydrogen and oxygen electrodes in open circuit, is capable of supplying a voltage  $E_{rev}$  of 1,229 V. When the cell delivers a current to an utilizer, polarization phenomena arise that cause localized voltage surges resulting in lowering of the measurable voltage at the electrodes.



The measurable voltage then has the following expression:

$$V_{FC} = E_{rev} - (V_{ohm} + V_{att} + V_{con})$$

where  $V_{FC}$  is the overall voltage measurable at the cell terminals and the three terms  $V_{ohm}$ ,  $V_{att}$ ,  $V_{con}$  summarize the effects of the cell polarization.

# Cell polarization effects

## Activation Polarization (activation loss)

it is correlated with the speed of the reactions at the electrodes. In the case of electrochemical reactions where  $V_{att}$  is in the order of 50-100 mV, it can be expressed by the **equation of Tafel** :

$$V_{att} = \frac{RT}{\alpha nF} \ln \frac{i}{i_0} = a + b \log i$$

$$a = -2.3 \frac{RT}{\alpha nF} \log i_0$$

$$b = 2.3 \frac{RT}{\alpha nF}$$

where  $\alpha$  = charge transfer coefficient

$i_0$  = exchange current density

Activation polarization is correlated to the slow reaction parts, to this kind of polarization contribute processes involving adsorption of reagents, electron transfer towards the double layer, desorption of electronic products and the nature of the surface.

## Ohmic Polarization (ohmic loss)

is caused by the resistance encountered by the ions to cross the membrane and by the resistance of the electrons moving along the electrode. It can be placed under the form:

$$V_{ohm} = i \cdot R$$

where R is the total resistance of the cell. The most significant loss occurs in the electrolyte and can be reduced by decreasing the distance between the electrodes and by using electrolytes with high ionic conductivity.

## Concentration polarization (concentration loss)

is caused by mass transport phenomena of reactant gases and products that hinder the reactions at the electrodes: near these, given their limited porosity and the speed with which the reactants are consumed, concentration gradients are generated that, added to the difficulties of gases diffusion into the electrolyte and of the products movements to and from the areas of reaction, determines the occurrence of the phenomenon.

Mass transit speed can be described by the first Fick's law :

$$i = \frac{nFD}{\delta} (c_b - c_s)$$

$D$  diffusion coefficient of reagent species  
 $c_s$  reagent species concentration in the bulk  
 $c_b$  concentration on the electrode surface  
 $\delta$  diffusion layer thickness

When the electrode is governed only by diffusion phenomena, we reach a current limit  $i_L$  which is defined as :

$$i_L = \frac{nFDc_b}{\delta}$$

In the case where we can assume negligible the  $\eta_{att}$ , the concentration polarization  $V_{con}$  is expressed by:

$$V_{con} = \frac{RT}{nF} \ln \frac{c_s}{c_b} = \frac{RT}{nF} \ln \left( 1 - \frac{i}{i_L} \right)$$

Polarizations always act in the sense of *raising the potential of the electrode* where the oxidation reaction runs (anode) and *lowering the electrode potential* where the reduction reaction runs (cathode).

We have therefore:

$$V_{FC} = E_{rev} - V_{ohm} - V_{att} - V_{con}$$

# FUEL CELL Efficiency

## Thermodynamic efficiency :

the energy efficiency of a cell is defined as:

$$\eta_t = \frac{\textit{Lavoro utile}}{n_{H_2} \Delta H}$$

In terms of power we can write :

$$\eta_t = \frac{P_e}{F_{H_2} \Delta H}$$

{	$L_u$	usable work [J]
	$P_e$	power output [W]
	$n_{H_2}$	number of hydrogen moles [mol]
	$F_{H_2}$	hydrogen moles consumed per second [mol/s]
	$\Delta H$	reaction enthalpy equal to 284.000 [J/mol]

## Voltage efficiency :

when the cell produces electricity, the cell voltage ( $V$ ) is less than the voltage that we would have with open circuit ( $E_{rev}$ ). The *voltage efficiency* is defined by the ratio between the voltage output under load and the theoretical voltage :

$$\eta_v = \frac{V}{E_{rev}}$$

## Fuel utilization factor and theoretical efficiency :

$$u = \frac{F_t}{F_r} = \frac{N_{\text{cell}} \cdot I}{2 \cdot F_a}$$

$F_t$  **theoretical hydrogen flow rate** [mol/s] which is responsible of the chemical reaction associated with the power supply of the cell

$F_a$  **Faraday constant** = 96484 C/mol , which is the electric charge (in Coulomb) associated with *one mole of electrons*

$N_{\text{cell}}$  number of cells that make up the stack

$$F_t = \frac{N_{\text{cell}} \cdot I}{2 \cdot F} = \frac{N_{\text{cell}} \cdot I}{2 \cdot 96484 \frac{\text{C}}{\text{mol}}}$$



The constant “2” in the denominator is because for every mole of hydrogen, two protons and two electrons are formed !

$$\eta_{\text{teorico}} = \frac{V \cdot I}{F_t \cdot \Delta H} = \frac{V \cdot I}{\frac{N_{\text{cell}} \cdot I}{2 \cdot F_a} \cdot \Delta H} = k V$$



The *theoretical efficiency* of a FC is proportional to the voltage that settles at its terminals !



## Our lab experience :

- Determine the current-voltage characteristic curve and the power curve of the PEM fuel cell ...
- Determine the Energy efficiency of the PEM fuel cell ...

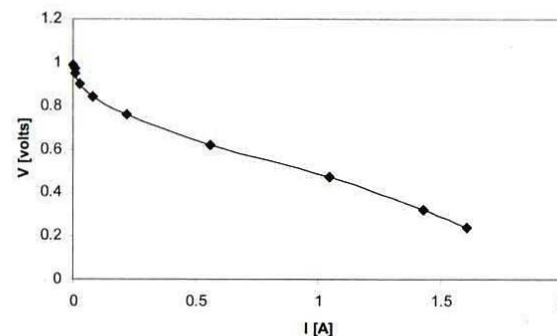
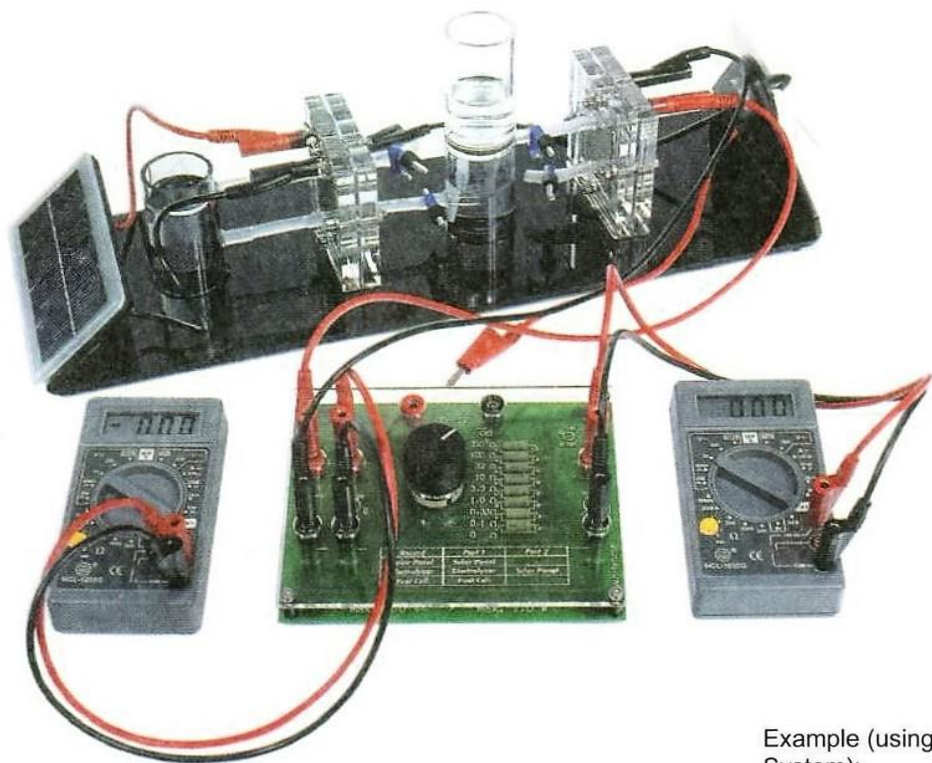


Figure 1.3.1.c: Voltage-current characteristic of fuel cell

$$\eta_{energy} = \frac{E_{useful}}{E_{input}} = \frac{E_{electric}}{E_{hydrogen}}$$

Example (using the h-tec JuniorBasic Hydrogen Experimentation System):

R [Ω]	U [V]	I [A]	P [W] calculated: P=V·I
∞	0.99	0.00	0.000
330	0.97	0.01	0.001
100	0.94	0.01	0.001
33	0.90	0.03	0.027
10	0.84	0.08	0.075
3.3	0.76	0.22	0.167
1	0.62	0.56	0.347
0.33	0.47	1.05	0.494
0.1	0.32	1.43	0.458
0	0.24	1.61	0.386

Figure 1.3.1.b: Table of measurements  
Measurement of the voltage and current values of the fuel cell with different load resistances.

Example (using the h-tec JuniorBasic Hydrogen Experimentation System):

V <sub>H2</sub> [cm <sup>3</sup> ]	t [s]	V [volts]	I [A]	P [W] calculated: P=V·I
20	0	0.813	0.128	0.104
15	281	0.770	0.120	0.092
10	605	0.678	0.106	0.072
Mean		$\bar{V} = 0.754$	$\bar{I} = 0.118$	$\bar{P} = 0.089$

Figure 1.3.2.b: Table of measurements  
A fuel cell continuously converts hydrogen gas introduced as fuel into electrical energy. The values of time, voltage and current for certain hydrogen consumptions (5 cm<sup>3</sup> increments) have been recorded in this table.

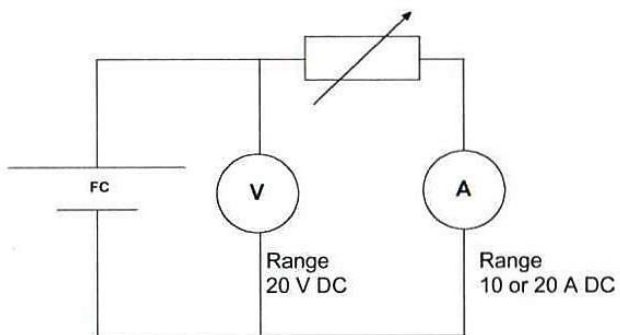
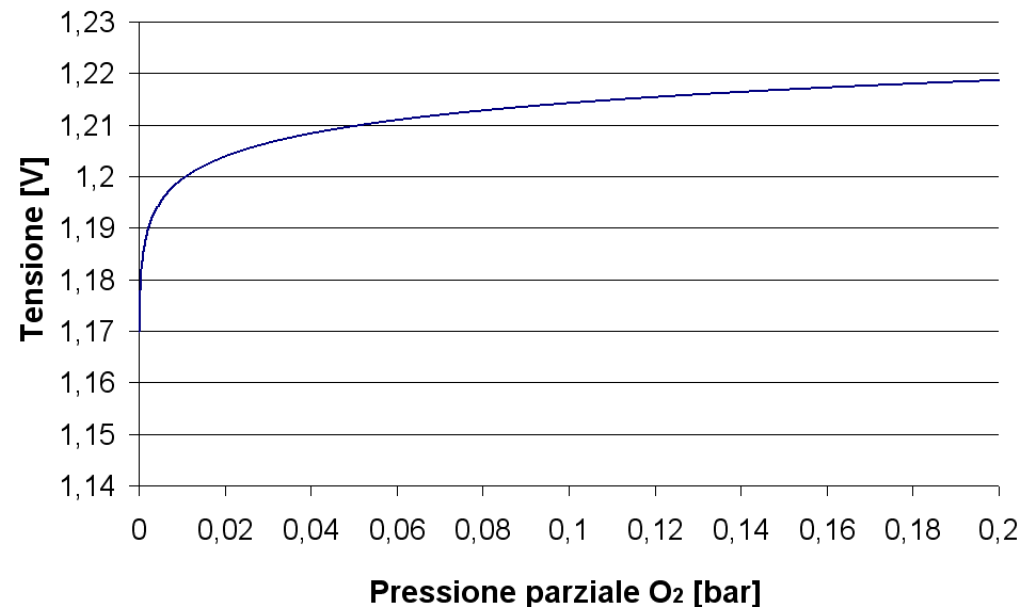


Figure 1.3.1.a: Setup for determining current-voltage characteristic of fuel cell (FC = Fuel Cell)

## SELF-BREATHING and SELF-HUMIDIFYING Fuel Cells

The power generation of a fuel cell is *limited by the air flow*, by the pressure values of the incoming gas and by the amount of water supplied to the cell itself. To eliminate complicated controls on the system and simplify the functional schemes, sometimes we choose a ***self-humidifying*** and ***self-breathing*** cell. In fact, generally the cell oxidizing gas is supplied with a compressor by adjusting the oxygen incoming pressure, but this implies a substantial expenditure of energy to the power supply. On the other hand, the self-breathing cells suffer of a particular problem (***oxygen starvation***) that occurs when the partial pressure of oxygen falls below a critical level, in any place, within the cathode air ducts. This phenomenon results in a rapid decrease of the cell voltage, which in extreme cases, can also lead to the damage of the membrane of the cell itself.

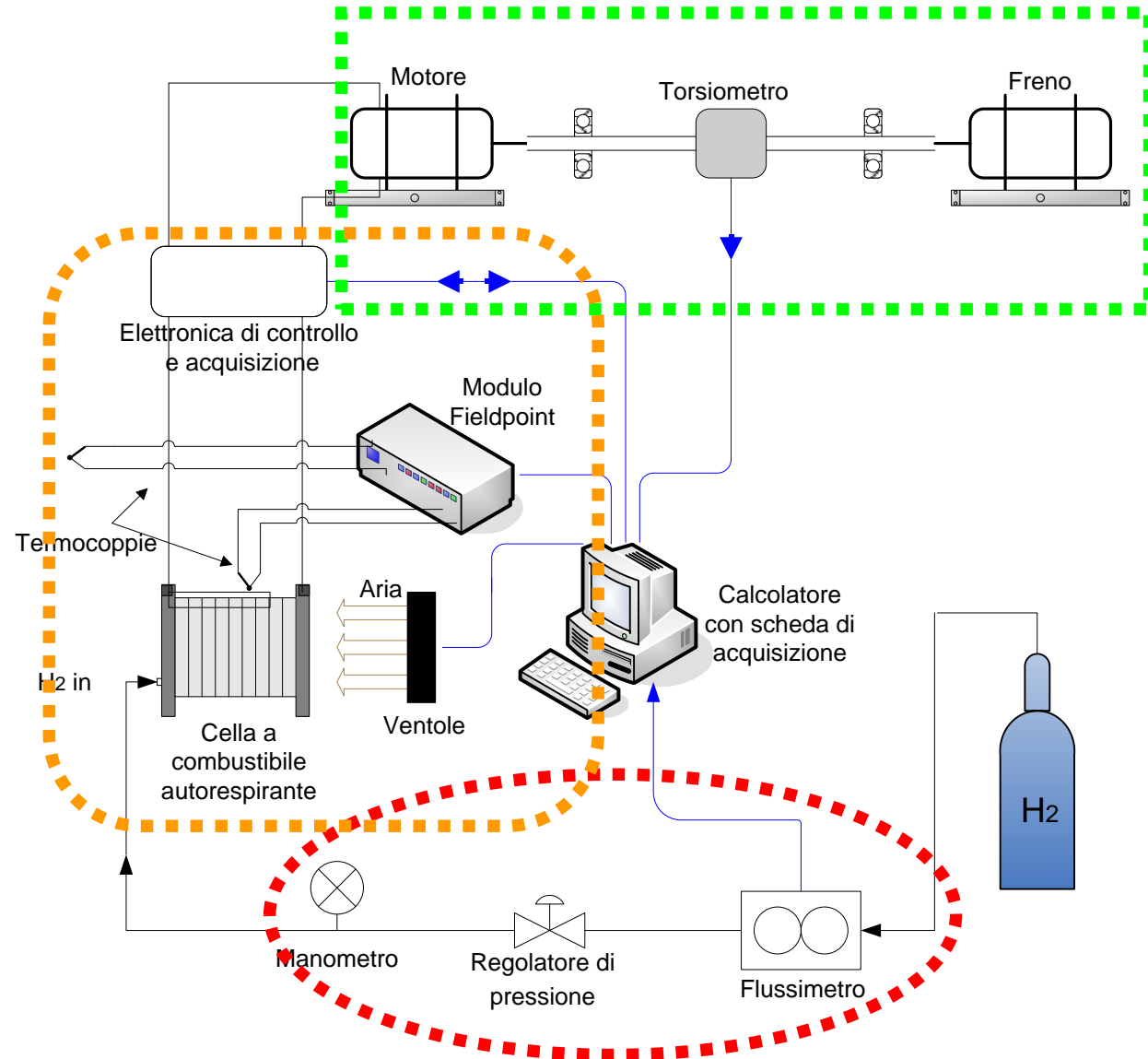


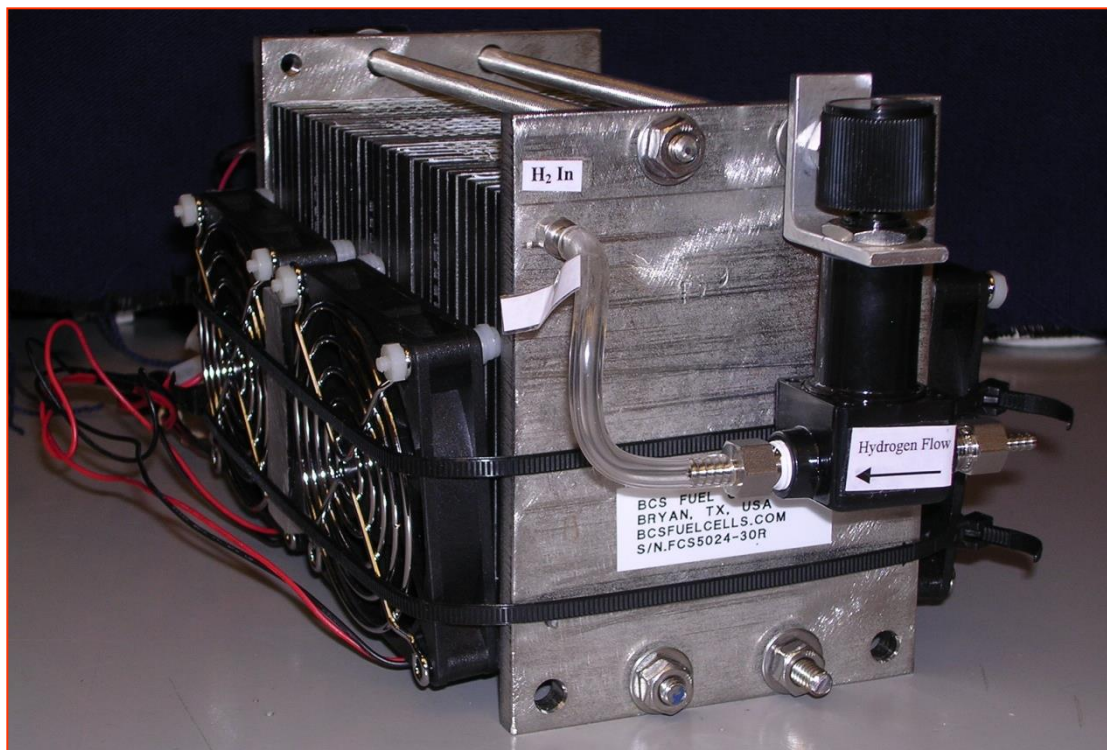
# CATENA DI MISURA DI UN BANCO PROVA PER UN SISTEMA DI TRAZIONE A CELLE A COMBUSTIBILE

- Linea Idrogeno
- Parte Elettrica
- Parte Meccanica

Parametri monitorati:

- Tensione e corrente erogate
- Flusso  $H_2$
- Temperatura stack
- Velocità angolare albero motore
- Coppia torcente
- Potenza assorbita ausiliari
- Rendimenti

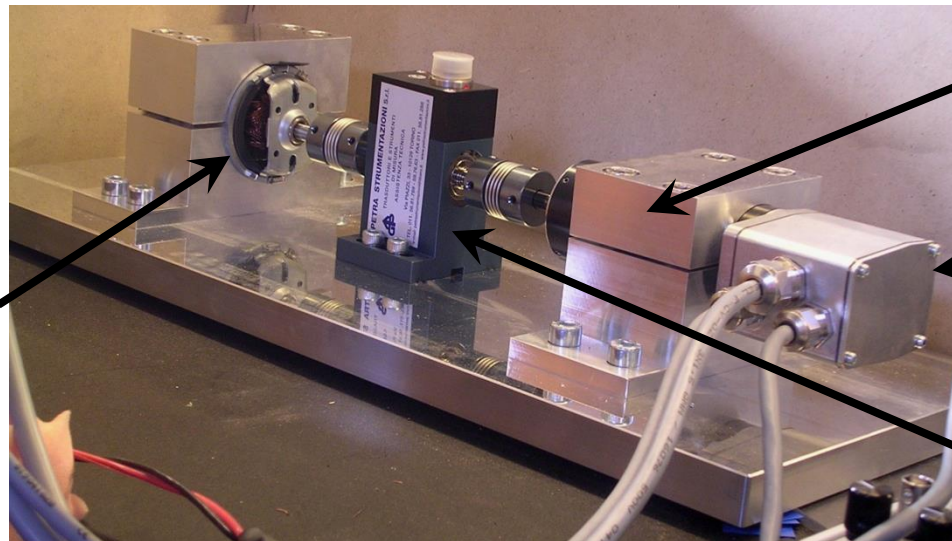




## Cella a Combustibile

### Caratteristiche:

- ✓ Potenza: 150W @ 15V
- ✓ Reagenti: idrogeno/aria
- ✓ P idrogeno: 2 psig
- ✓ T: 58°C
- ✓ Tipo di cella: PEM

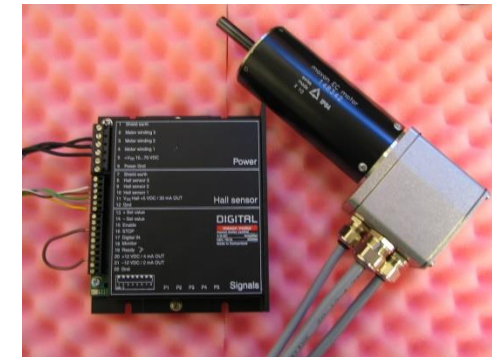


Motore Elettrico brushless

Encoder

Torsiometro

Freno



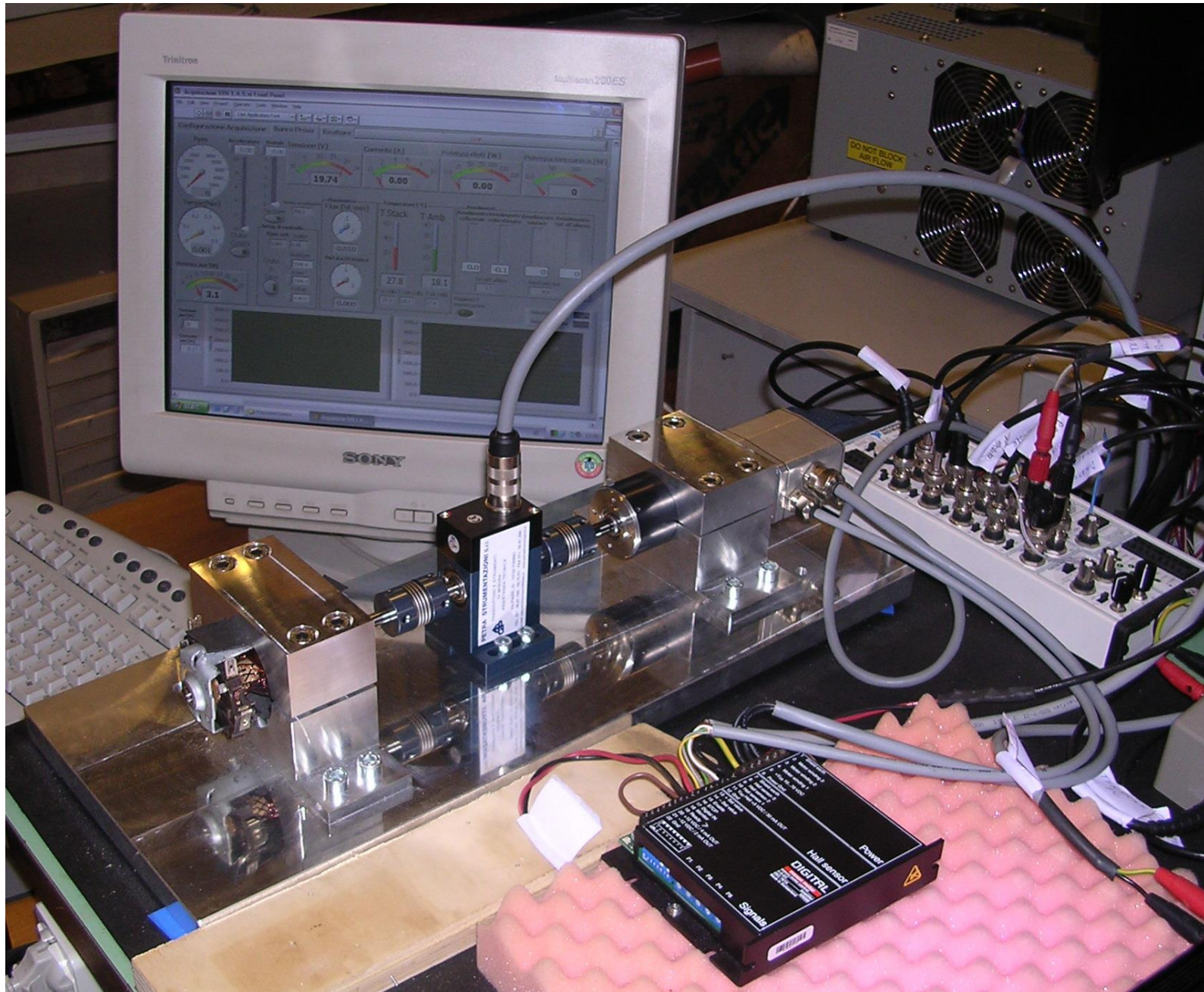
# Programma di acquisizione in LabView

The screenshot shows a LabView interface titled "Acquisizione SYN 1.4.5.vi". The interface includes several control panels and data displays:

- Control Panels:**
  - Configurazione Acquisizione:** Includes a "STOP" button and a "Rpm" gauge.
  - Banco Prova:** Includes a "Ventole" gauge and a "Flussimetro Flux [l/min]" gauge.
  - Reattore:** Includes a "Tensione [V]" gauge, a "Corrente [A]" gauge, a "Potenza elett [W]" gauge, and a "Potenza meccanica [W]" gauge.
  - Setup di controllo:** Includes "Rpm set" (1280), "Epsilon" (2.00), "Guadagno" (550E-6), "V max" (2000.0), "V offset" (0.0010), and "Save" buttons.
  - Temporali:** Includes a "Potenza aux [W]" gauge.
- Data Displays:**
  - Rendimenti:** A bar chart showing efficiency values: 45.5 (cella reale), 52.2 (cella stimato), 56 (motore), and 25 (rendimento tot all'albero). Below it are "%Coeff utilizzo" (87.1) and "Rend solo mot" (65.9).
  - Graphs:** Two graphs at the bottom showing "Tensione aux [V]" and "Corrente aux [A]" over time.

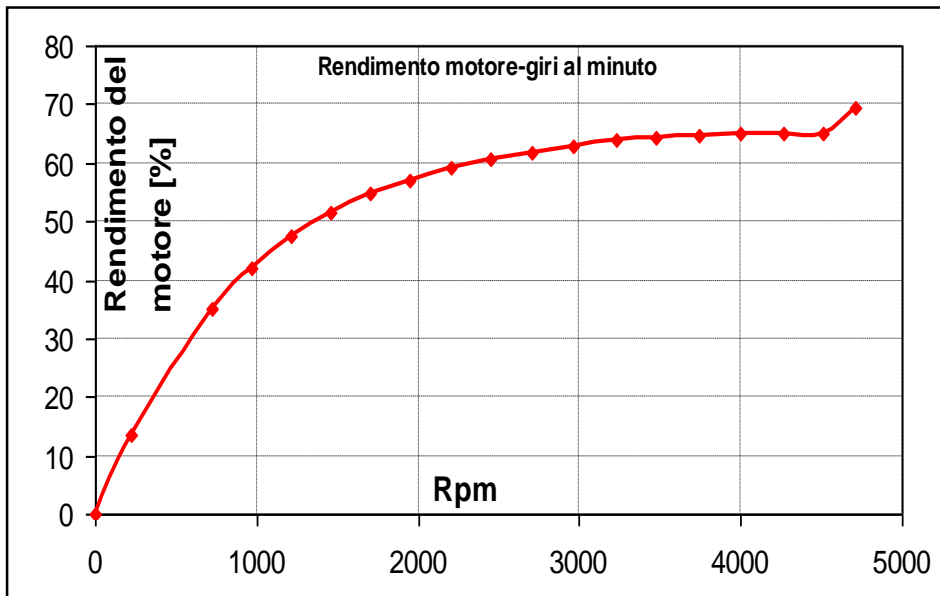
Annotations and labels on the image include:

- Red boxes:** "Set Up Acquisizione" and "Monitoraggio Banco Prova".
- Text labels:** "Parametri Tensione erogata dalla cella", "Corrente erogata dalla cella", "Potenza elettrica erogata", "Potenza Meccanica", "Set Up PID Forzanti", "Set Up di controllo", "Set Up Parametri Temporal", "Grafici della richiesta erogate", "Set Up Rendimenti motore e Velocità di set point", "Rendimenti", "Rendimento cella reale", "Rendimento cella stimato", "Rendimento motore", "Rendimento tot all'albero", "%Coeff utilizzo", "Rend solo mot".
- Red arrows:** Point from labels to specific UI elements like gauges, buttons, and graphs.



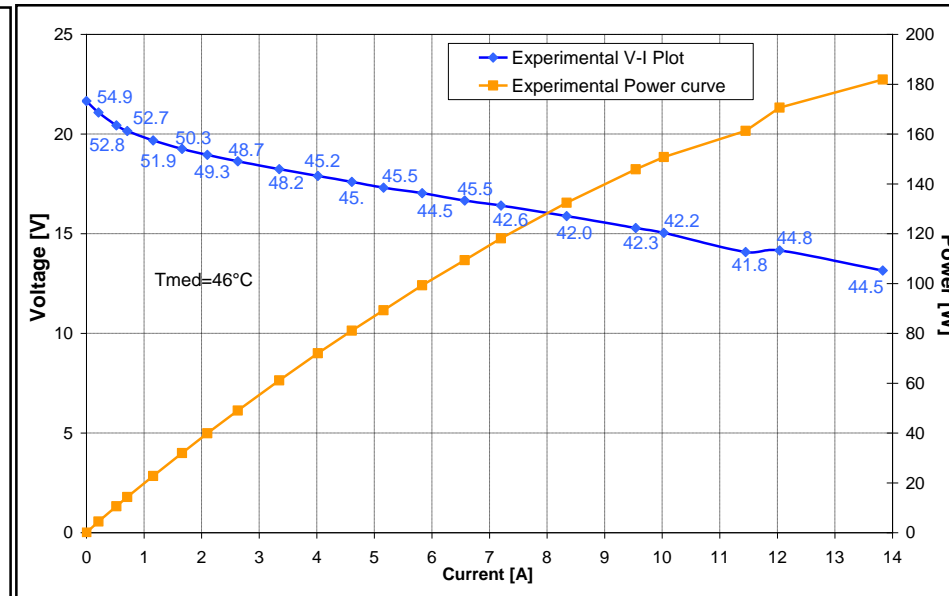
# Caratterizzazione statica

## Motore



- Rendimento elevato ad alti giri
- Penalizzazione nel ciclo urbano

## Cella a combustibile



- Rendimento abbastanza costante in ampio range di potenze
- Lieve diminuzione del rendimento ad elevate potenze
- Tempo di avvio rapido (circa 5 min)

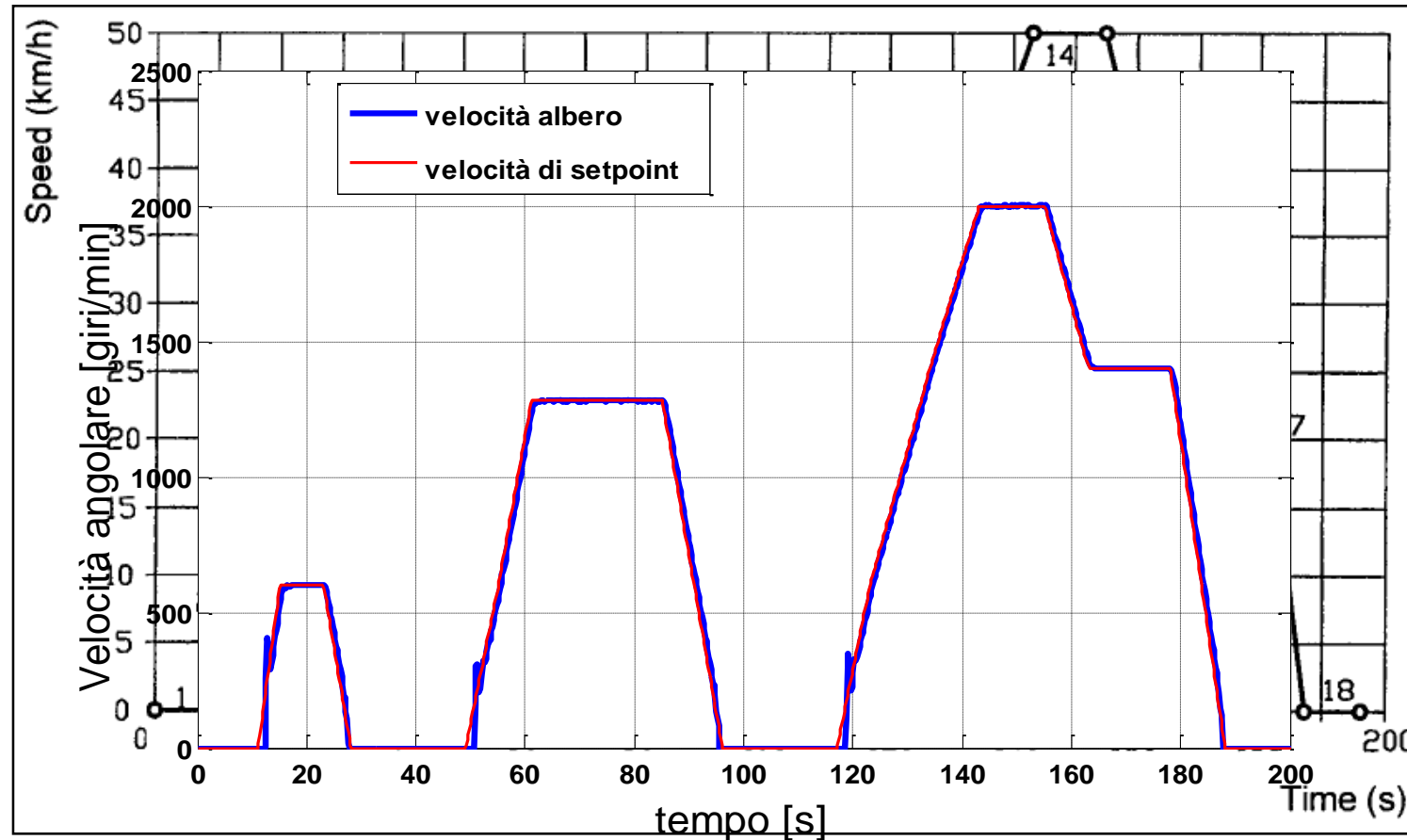
# Ciclo urbano standard

Ciclo Urbano Standard

Norma UNI-EN 1986-1



Calcolo del rendimento del  
sistema  
cella + motore elettrico





# Risultati sperimentali

Rendimento istantaneo

$$\eta = \frac{W_e}{F \cdot \Delta H}$$

Rendimento medio

$$\bar{\eta} = \frac{E}{n_{H_2} \Delta H} = \frac{\sum_i W_i \cdot \Delta t}{\sum_i F_i \cdot \Delta t \cdot \Delta H} = \frac{\sum_i W_i}{\sum_i F_i \cdot \Delta H} = \frac{W_{tot}}{F_{tot} \cdot \Delta H}$$

Incertezze associate:

$$\varepsilon_\eta = \sqrt{\left( \frac{\partial \eta}{\partial W} \varepsilon_W \right)^2 + \left( \frac{\partial \eta}{\partial F} \varepsilon_F \right)^2} = \sqrt{\left( \frac{1}{F \cdot \Delta H} \varepsilon_W \right)^2 + \left( -\frac{W}{F^2 \cdot \Delta H} \varepsilon_F \right)^2}$$

$$\varepsilon_{\bar{\eta}} = \sqrt{\left( \frac{\partial \bar{\eta}}{\partial W_{tot}} \varepsilon_{W_{tot}} \right)^2 + \left( \frac{\partial \bar{\eta}}{\partial F_{tot}} \varepsilon_{F_{tot}} \right)^2} = \sqrt{\left( \frac{1}{F_{tot} \cdot \Delta H} \varepsilon_{W_{tot}} \right)^2 + \left( -\frac{W_{tot}}{F_{tot}^2 \cdot \Delta H} \varepsilon_{F_{tot}} \right)^2}$$

dove :

$$\varepsilon_{W_{tot}} = \sqrt{\sum_i \varepsilon_{W_i}^2}$$

$$\varepsilon_{F_{tot}} = \sqrt{\sum_i \varepsilon_{F_i}^2}$$

Potenza meccanica all'albero:

$$W_{mecc} = C \cdot \omega \quad [W]$$

Rendimento meccanico istantaneo:

$$\eta_{mecc} = \frac{W_{mecc}}{F \cdot \Delta H}$$

Rendimento meccanico medio:

$$\bar{\eta}_{mecc} = \frac{E}{n_{H_2} \cdot \Delta H} = \frac{\sum_i W_{i\ mecc} \cdot \Delta t}{\sum_i F_i \cdot \Delta t \cdot \Delta H} = \frac{W_{mecc\ tot}}{F_{tot} \cdot \Delta H}$$