

# ***Fuel Cells***

Electric Energy Storage and  
New Energy Sources for  
Electric Vehicles (EE546)

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- **Teaching and learning are mutually motivating**
- Please feel free to give your suggestions on our teaching and learning

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## **Lectures:**

- **Location:** ST111
- **Time & Date:** 18:30 – 21:20, Tuesday, 2 Sept 2025 – 25 Nov 2025
- Total number of lectures: 13 (incl. summary and review)

## **Office hours:**

- **Time & Date:** 14:00 – 17:00, Friday
- You may email me in advance to double check my availability.

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Fuel Cell Fundamentals

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PEMFC and SOFC Materials

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Fuel Cell Characterization

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Fuel Cell Electric Vehicles (FCEVs)

Proton-exchange membrane / Polymer electrolyte membrane fuel cell (PEMFC)  
Solid-oxide fuel cell (SOFC)

# Fuel Cell Fundamentals

Historical development, perspectives, working principles, performance, advantages, etc.

# Historical Development of Fuel Cells



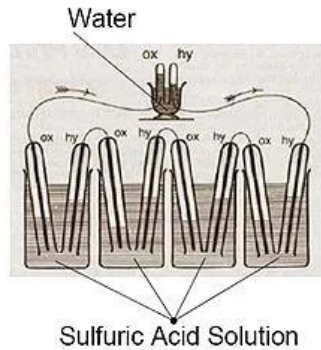
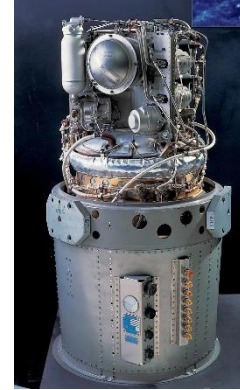
**UK, 1838**

The fuel cell was firstly referenced by William Grove.



**US, 1958**

General Motors developed Grubb-Niedrach fuel cell, the first commercial use of a fuel cell.



Francis Thomas Bacon developed a 5-kW stationary fuel cell.

**UK, 1932**



Hydrogen began to be used in NASA's space program, primarily for rocket propulsion and as a fuel for fuel cells.

**US, 1958**

Ref: [https://ethw.org/Bacon%27s\\_Fuel\\_Cell](https://ethw.org/Bacon%27s_Fuel_Cell)

Ref: <https://americanhistory.si.edu/fuelcells/pem/pem2.htm>

Ref: <https://ids.si.edu/ids/deliveryService?id=NASM-99-15155.01&max=900>



# Historical Development of Fuel Cells



**US, 1966**

General Motors developed the first fuel cell road vehicle.



**US, 1991**

Roger Billings developed the first hydrogen fuel cell automobile.



UTC Power commercialized a large stationary fuel cell for cogeneration power plants.

**US, 1990s**



FCX Clarity, first commercially available fuel cell vehicle, was developed by Honda.

**Japan, 2008**

Ref: <https://www.motorbiscuit.com/chevy-electrovan-first-fuel-cell-car/>

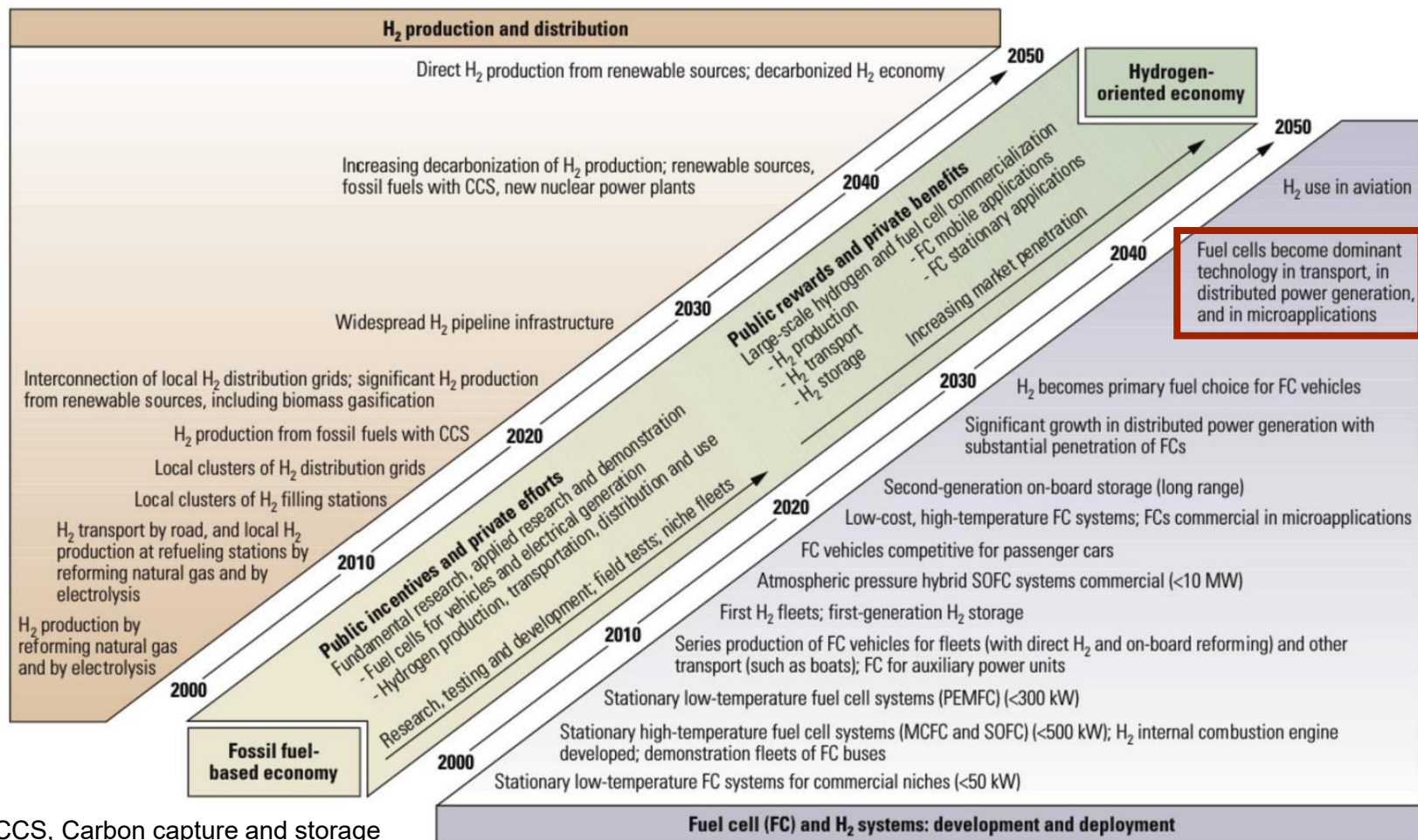
Ref: [https://en.wikipedia.org/wiki/UTC\\_Power](https://en.wikipedia.org/wiki/UTC_Power)

Ref: <https://www.rogerebillings.com/hydrogen/>

Ref: [https://en.wikipedia.org/wiki/Honda\\_Clarity](https://en.wikipedia.org/wiki/Honda_Clarity)

## EU's hydrogen and fuel cell program

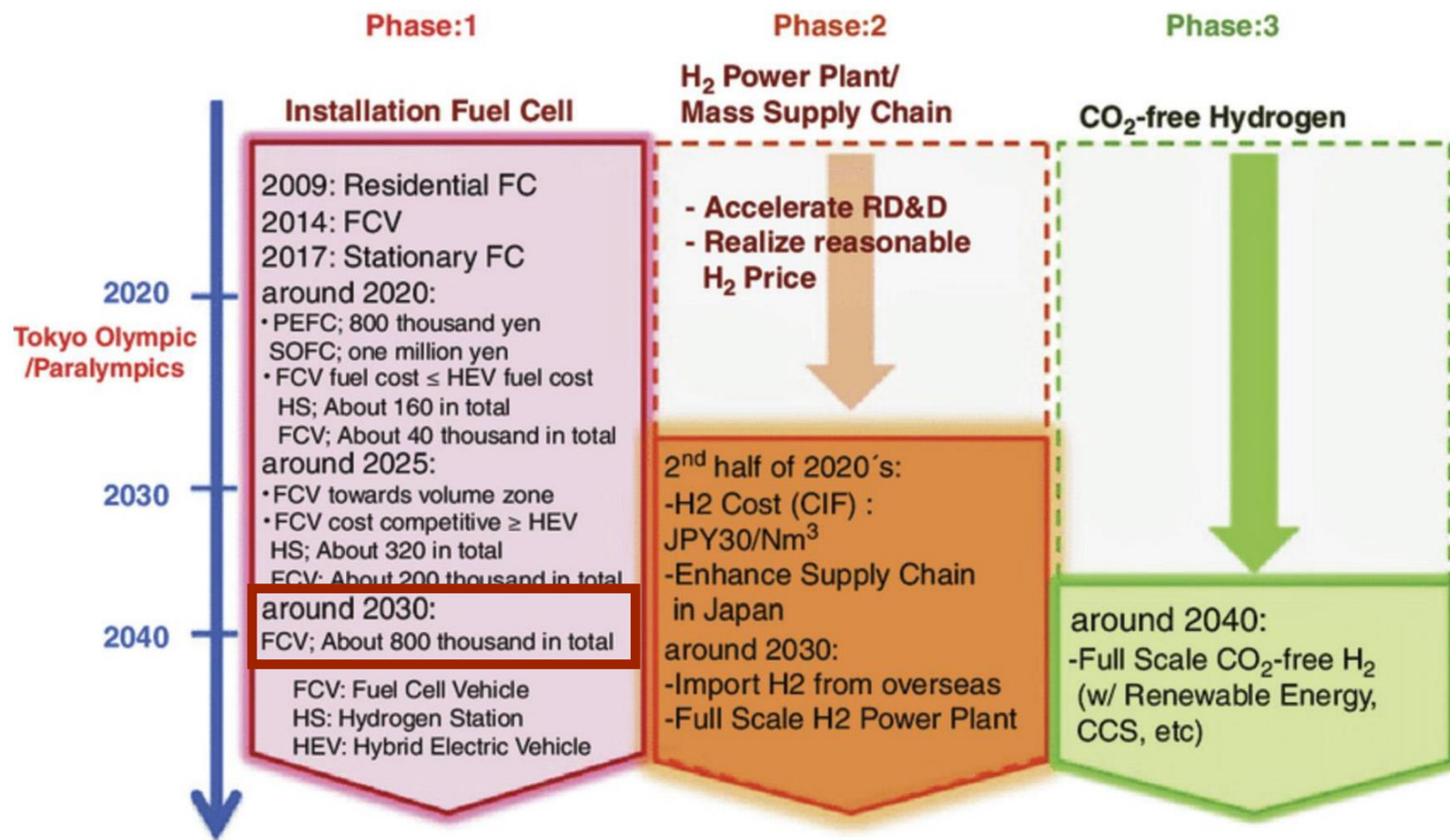
The program has two parallel rails, one on **hydrogen production** and the other on **fuel cell development**, aiming to **make fuel cells become dominant technology in transportation**.





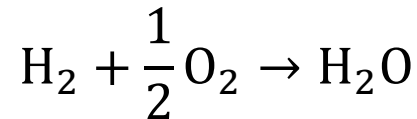
## Japan's hydrogen and fuel cell program

The program focuses on **Installation of Fuel Cell**, **H<sub>2</sub> Power Plant/Mass Supply Chain**, and **CO<sub>2</sub>-free Hydrogen** to achieve a more sustainable future, targeting **about 800 thousand fuel cell vehicles (FCVs) in around 2030**.

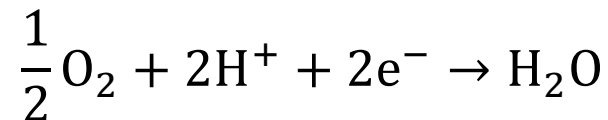


## Combustion of hydrogen

The chemical equation for the **combustion of hydrogen**, which is the **primary energy source for fuel cells**, is:



The above reaction can be split into two electrochemical half reactions. One of the possible separations is:



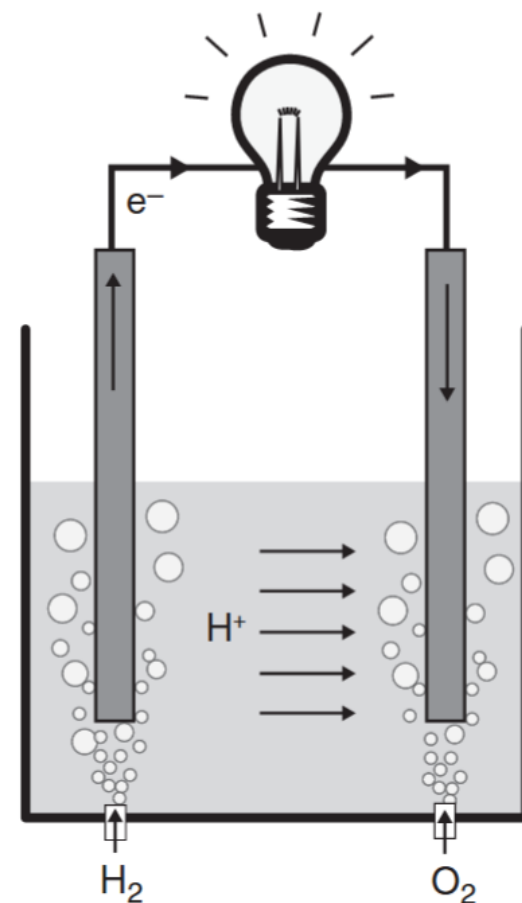
By **spatially separating these reactions**, the electrons are forced to flow through an external circuit (thus constituting an electric current) and **do useful work** before they can complete the reaction. In addition, **catalysts** are generally used to increase the speed and efficiency of the electrochemical reactions. By applying the above principle, the fuel cell can be developed.

## Fuel cell example & structure

The figure shows **an example of a fuel cell**. The fuel cell consists of two **electrodes** dipped into **electrolyte**.

Hydrogen gas, bubbled across the left electrode, is split into protons ( $\text{H}^+$ ) and electrons ( $\text{e}^-$ ). The **protons can flow through the electrolyte** which is sulfuric acid in this example, but the **electrons cannot**.

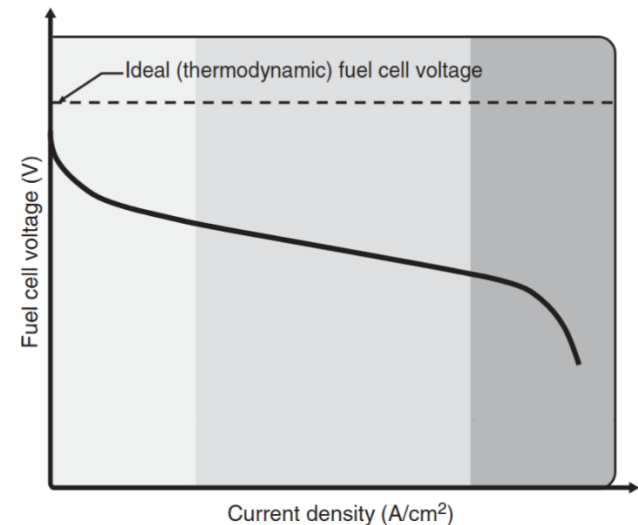
Instead, the **electrons flow through a piece of wire** that connects the two electrodes. When the electrons reach the right electrode, they recombine with protons and bubbling oxygen gas to produce water. If a load (a light bulb in this example) is introduced along the path of the electrons, the flowing **electrons will provide power to the load**, causing the light bulb to glow.



## i-V curve and j-V curve

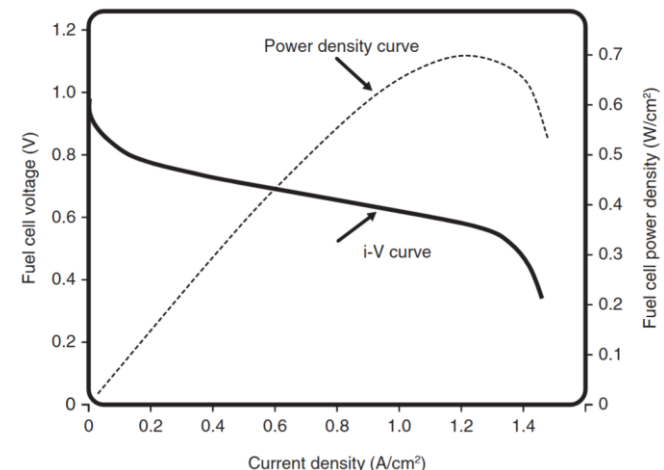
The current-voltage (i-V) curve and current density-voltage (j-V) curve show the voltage output of the fuel cell for a given current and current density output, respectively.

In practice, the actual voltage output of a real fuel cell is less than the ideal thermodynamically predicted voltage.



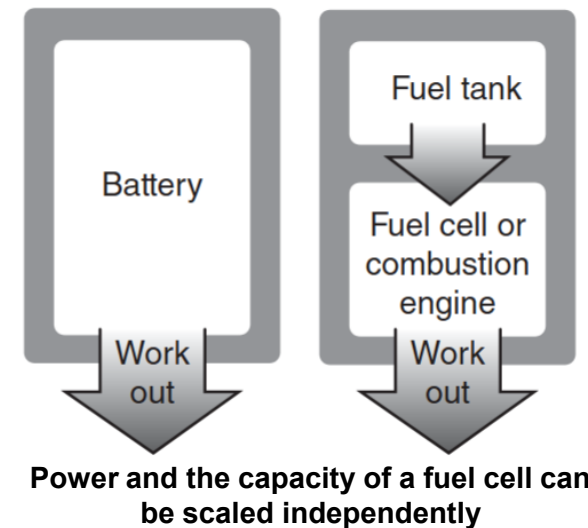
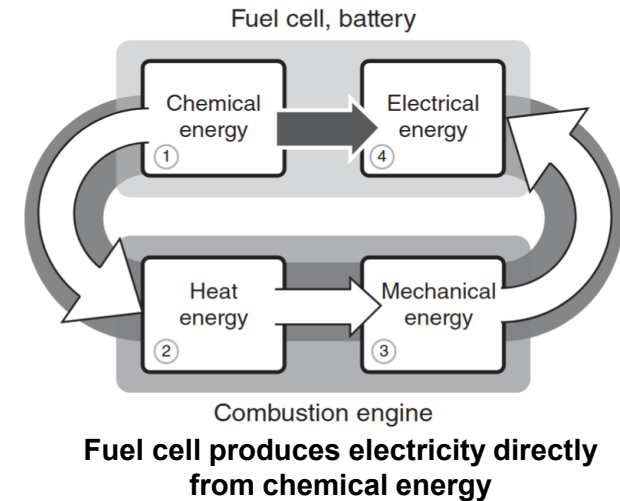
## Power density curve

The power density curve is produced by multiplying the voltage by the corresponding current density at each point on the i-V / j-V curve. The power density increases with increasing current density, reaches a maximum, and then falls at still higher current densities. Fuel cells are designed to **operate at or below the power density maximum**.



Fuel cells offer several advantages, including:

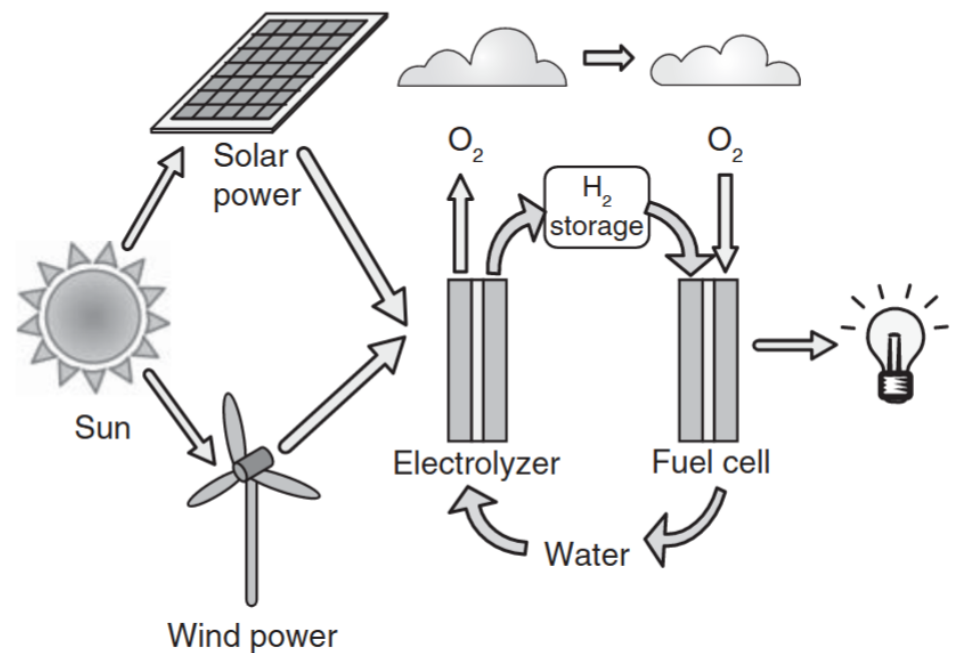
- **Efficient:** Produce electricity directly from chemical energy, often far more efficient than combustion engines.
- **Reliable and long-lasting:** Fuel cells can be solid-state, meaning no moving parts.
- **Silent:** The absence of moving parts also results in quiet operation.
- **Low-emission:** Emissions of pollutants such as  $\text{NO}_x$ ,  $\text{SO}_x$ , and particulates are virtually eliminated.
- **Scalable:** Fuel cells allow easy independent scaling between power (determined by the fuel cell size) and capacity (determined by the fuel reservoir size).
- **Quick-recharged:** Unlike batteries that require lengthy recharging, fuel cells can be quickly refueled.





Fuel cells are environmentally friendly if employed correctly. The Hydrogen economy, where the fuel cell plays a prominent role, depicts a clean and sustainable energy future, where  $\text{H}_2$  **fuel cells** are coupled with **electrolyzers** and **renewable energy generation** technologies to provide a completely closed-loop and pollution-free energy economy.

For example, **when the sun is shining or the wind is blowing**, the electricity produced from solar and wind energy can be used to power cities directly, while producing extra hydrogen on the side via electrolysis. **Anytime the wind stops or night falls**, however, the fuel cells can be dispatched to provide on-demand power by converting the stored hydrogen into electricity. In such a system, fossil fuels are completely eliminated.



# Fuel Cell Types

Alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), polymer electrolyte membrane fuel cell (PEMFC), molten carbonate fuel cell (MCFC), solid-oxide fuel cell (SOFC), etc.

## Fuel cell types

There are five major types of fuel cells, differentiated from one another by their **electrolyte**. These variations in electrolyte not only influence the operational characteristics of the fuel cells but also their efficiency, temperature range, and potential applications. Each of the following types can use **hydrogen**, the primary energy source for these cells, as its energy source:

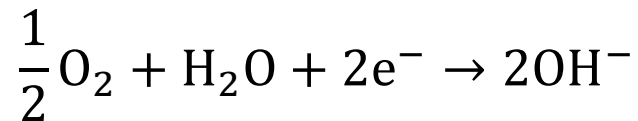
- Alkaline fuel cell (AFC)
- Phosphoric acid fuel cell (PAFC)
- Polymer electrolyte membrane fuel cell (PEMFC)
- Molten carbonate fuel cell (MCFC)
- Solid oxide fuel cell (SOFC)

## Introduction

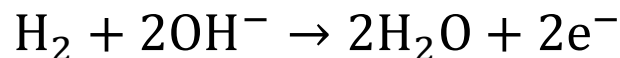
The alkaline fuel cell (AFC) has been widely recognized as the first practical fuel cell that consumes the hydrogen fuel to produce the electric energy.

The AFC consists of two porous **electrodes**, separated by the porous matrix saturated alkaline solution as the **electrolyte**, while the potassium hydroxide (KOH) is a common choice.

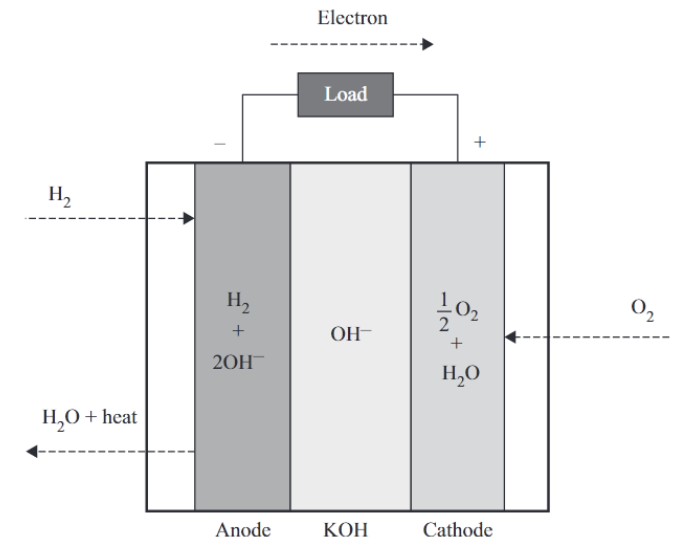
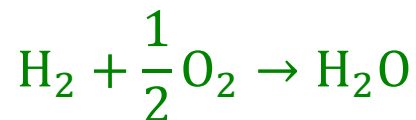
The AFC generates electricity via a redox (i.e., **oxidation** and **reduction**) reaction. The reaction at the **positive electrode (cathode)** is:

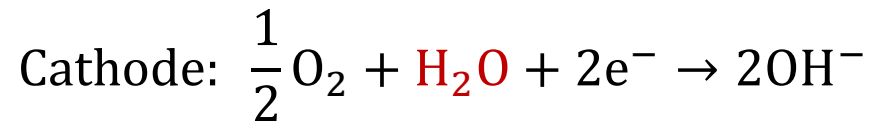


and at the **negative electrode (anode)**:



Hence, the **overall reaction** is:





## Advantages

- **Low material costs:** many metal-based catalysts are stable in an alkaline environment. Thus, under some conditions, nickel (rather than platinum) catalysts can be used as the cathode catalyst.

## Disadvantages

- **Must use pure H<sub>2</sub> and O<sub>2</sub>:** The AFC cannot tolerate even atmospheric levels of carbon dioxide (CO<sub>2</sub>), because the presence of CO<sub>2</sub> degrades the KOH electrolyte as follows:  $2\text{OH}^- + \text{CO}_2 \rightarrow \text{CO}_3^{2-} + \text{H}_2\text{O}$ .
- **Must remove water from the system:** In AFCs, water is consumed at the cathode while it is produced (twice as fast) at the anode. The water must be removed to avoid diluting the KOH electrolyte, which can lead to performance degradation

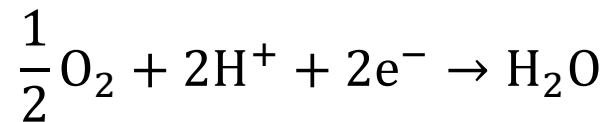


## Introduction

The phosphoric acid fuel cell (PAFC) is one of the most mature fuel cell technologies, it has been generally accepted as the first commercialized fuel cell across the electric power industry.

The PAFC employs the liquid phosphoric acid ( $\text{H}_3\text{PO}_4$ ) as the **electrolyte**, and the carbon paper that coated with platinum **catalyst** as the **electrodes**.

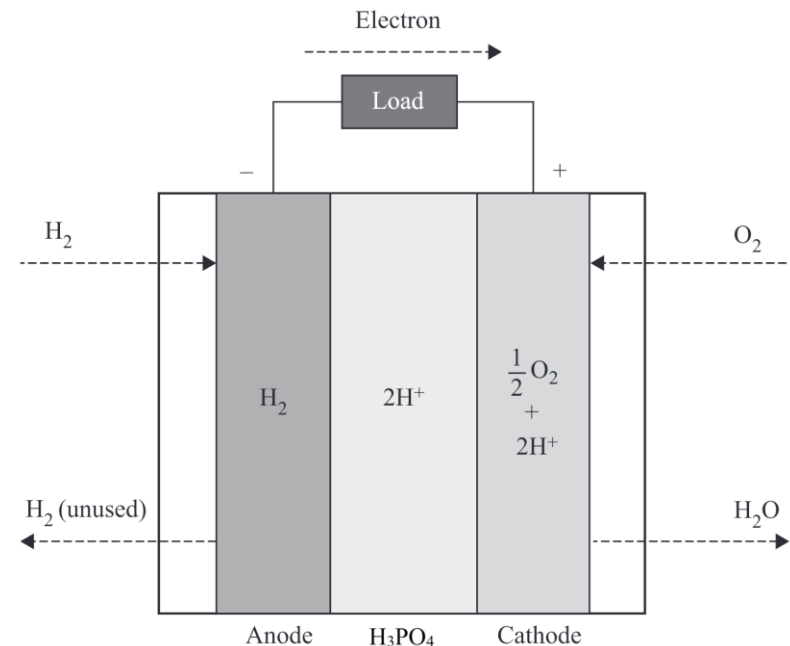
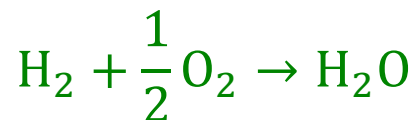
The reaction at the **positive electrode (cathode)** is:



and at the **negative electrode (anode)**:



Hence, the **overall reaction** is:



## Advantages

- **Mature technology:** The PAFC has been used for stationary power generators and is also finding application in large vehicles such as buses.
- **Electrolyte is relatively low cost:** The raw materials for the electrolyte (phosphoric acid) are relatively easy to obtain, and the production process is well-established.

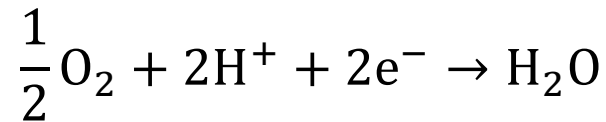
## Disadvantages

- **Expensive catalyst:** The reaction needs to be triggered with platinum-based catalysis, making the PAFC suffer from higher material costs.
- **Susceptible to poisoning:** Because PAFCs employ platinum catalysts, they are susceptible to carbon monoxide (CO) and sulfur (S) poisoning, which may result in the catalyst being deactivated.
- **Electrolyte must be replenished during operation:** Because the electrolyte gradually evaporates to the environment (especially during higher-temperature operation), it must be replenished during operation.

## Introduction

Because the polymer electrolyte membrane fuel cell (PEMFC) uses the proton conducting membrane as the electrolyte, PEMFC is sometimes known as the *ion exchange membrane fuel cell* or the *solid polymer electrolyte fuel cell*.

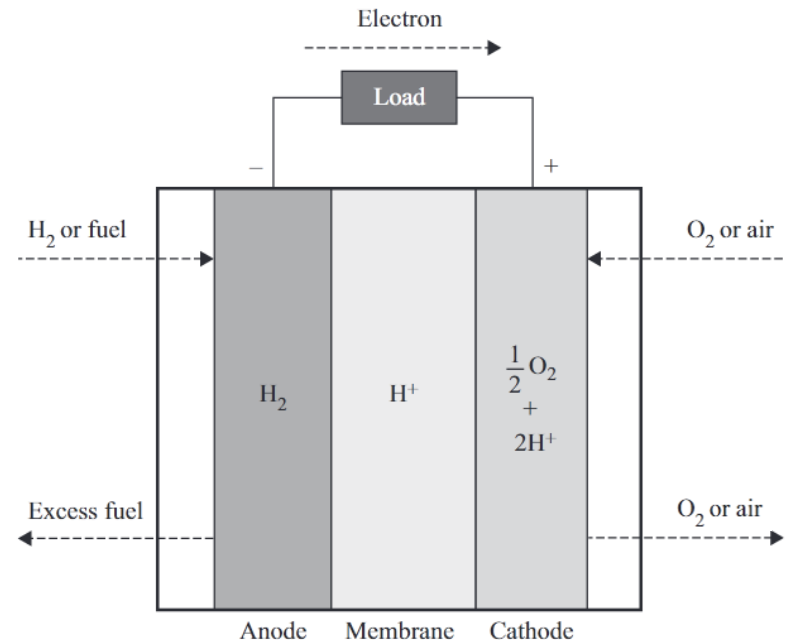
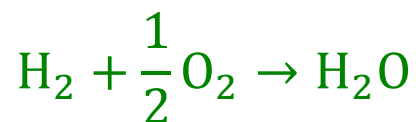
The PEMFC commonly employs carbon as the **electrodes**, with the metallic platinum as the **catalyst**, and the solid polymer membrane as the **electrolyte**. The reaction at the **positive electrode (cathode)** is:



and at the **negative electrode (anode)**:



Hence, the **overall reaction** is:



## Advantages

- **High power density:** The entire sandwich structure (electrode–catalyst–membrane–catalyst–electrode) is less than 1 mm thick, resulting in the merit of high power density.
- **High efficiency:** Because the electrolyte can be constructed as very thin sheets, the internal cell resistance can be effectively minimized, the high efficiency can be achieved.
- **Suitable for portable applications:** The operating temperature of the PEMFC is lower than 100°C, making it applicable for portable applications. **In vehicle systems, the PEMFC is a prime candidate.**

## Disadvantages

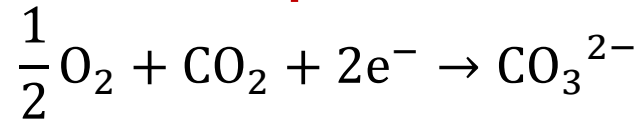
- **Expensive catalyst:** Because of the low operating temperature, platinum-based materials are the only practical catalysts current available, contributing to the high costs of the PEMFC.

## Introduction

Molten-carbonate fuel cells (MCFCs) are high-temperature fuel cells that operate at **temperatures of 600°C and above**.

The **electrodes** are typically based on nickel, which provides **catalytic activity and conductivity**. The **electrolyte** is usually a molten mixture of alkali carbonates,  $\text{Li}_2\text{CO}_3$  and  $\text{K}_2\text{CO}_3$ , immobilized in a  $\text{LiO}-\text{AlO}_2$  matrix.

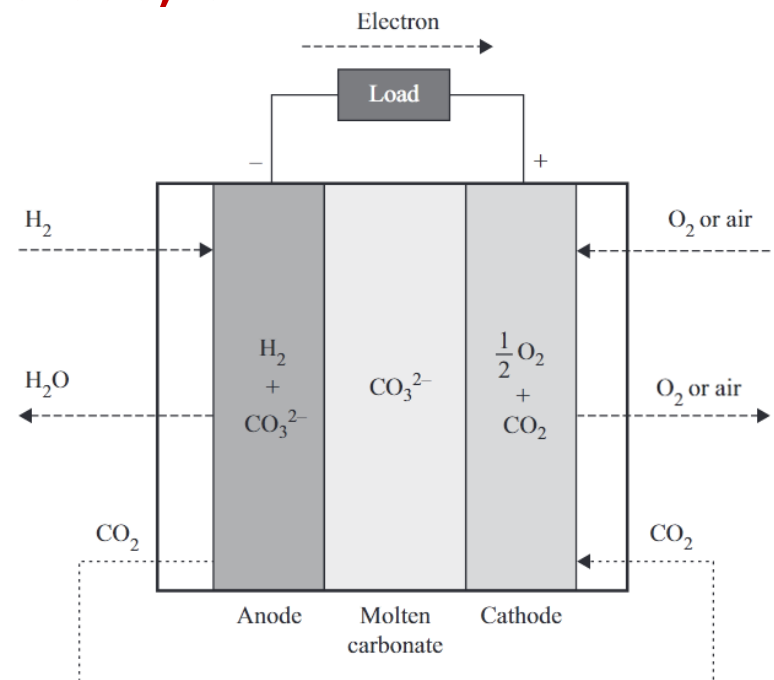
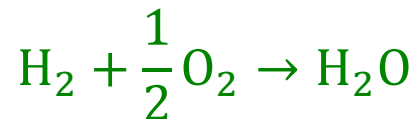
The reaction at the **positive electrode (cathode)** is:



and at the **negative electrode (anode)**:



Hence, the **overall reaction** is:





## Advantages

- **Fuel flexibility:** Due to the high temperature, the MCFC can run on hydrogen, simple hydrocarbons (e.g., methane), and simple alcohols.
- **High quality waste heat:** High-temperature waste heat can be utilized in heat and power applications, largely improving system efficiency.

## Disadvantages

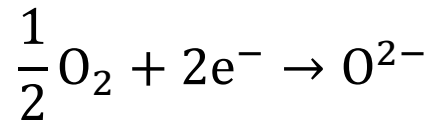
- **Must implement CO<sub>2</sub> recycling:** In the MCFC, CO<sub>2</sub> is produced at the anode and consumed at the cathode. Therefore, MCFC systems must extract the CO<sub>2</sub> from the anode and recirculate it to the cathode.
- **Lifetime issue:** The use of corrosive electrolytes, combined with high-temperature operation, threatens the lifespan of the MCFC.
- **Not suitable for frequent startup/shutdown:** Due to stresses created by the freeze–thaw cycle of the electrolyte during startup/shutdown cycles, the MCFC faces potential mechanical stress issues.

## Introduction

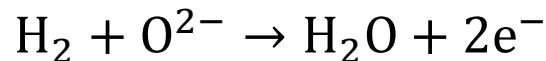
As compared with other representative fuel cells, the solid oxide fuel cell (SOFC) exhibits the highest operating temperature, up to around 1,000°C.

The SOFC employs a solid ceramic **electrolyte**, with yttria-stabilized zirconia (YSZ) being the most popular electrolyte material. The most common material for the **anode electrode** in the SOFC is the nickel–YSZ cermet. The **cathode electrode** is usually a mixed ion-conducting and electronically conducting (MIEC) ceramic material.

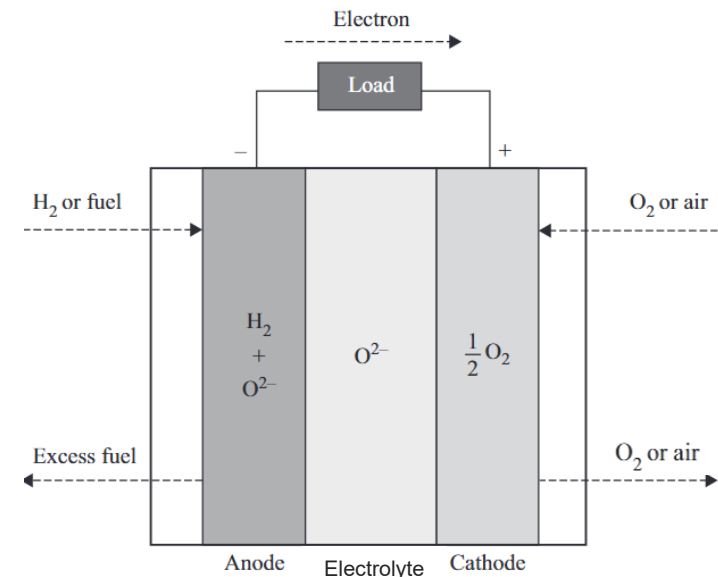
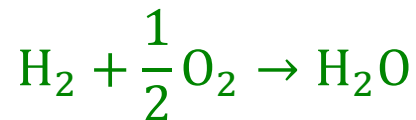
The reaction at the **positive electrode (cathode)** is:



and at the **negative electrode (anode)**:



Hence, the **overall reaction** is:



## Advantages

- **Nonprecious catalyst:** The reaction rate at the electrodes is fast enough without the presence of the noble metals as catalysts because of the high temperature.
- **Simple structure and construction:** The SOFC consists of all solid components, resulting in reduced complexity.
- **Enhanced tolerance to gaseous impurities:** The high operating temperature of the SOFC provides increased resilience against the presence of gaseous contaminants.

## Disadvantages

- **High-temperature materials issues:** The high operating temperatures can lead to thermal stresses and chemical changes at the interfaces between cell components.
- **Expensive components and fabrication:** The high requirements for each component result in high raw material (e.g., rare-earth or scarce elements) and processing costs.

# Comparison of Fuel Cell Types



Types	AFC	PAFC	PEMFC	MCFC	SOFC
<b>Electrolyte</b>	Liquid KOH (immobilized)	Liquid H <sub>3</sub> PO <sub>4</sub> (immobilized)	Polymer membrane	Molten carbonate	Ceramic
<b>Charge carrier</b>	OH <sup>-</sup>	H <sup>+</sup>	H <sup>+</sup>	CO <sub>3</sub> <sup>2-</sup>	O <sup>2-</sup>
<b>Operating temperature (°C)</b>	90–100	150–200	<100	600–700	500–1000
<b>Catalyst</b>	Platinum	Platinum	Platinum	Nickel	Perovskites
<b>Fuel compatibility</b>	H <sub>2</sub>	H <sub>2</sub>	H <sub>2</sub> , methanol	H <sub>2</sub> , CH <sub>4</sub>	H <sub>2</sub> , CH <sub>4</sub> , CO
<b>Electrical efficiency (%)</b>	60	40	40–60	50	60
<b>Cell voltage (V)</b>	1.0	1.1	1.1	0.7–1.0	0.2–0.4
<b>Stack power (kW)</b>	1–100	50–100	<1–250	300–3000	<1–3000

While **PAFCs** and **AFCs** benefited from early historical development, the other fuel cell types have caught up. Due to the high energy/power density and low operating temperature, the **PEMFC** and the **direct methanol fuel cell (DMFC)** appear suited for portable power applications. Both the **PEMFC** and the **SOFC** can be applied to residential power and other small-scale stationary power applications. High-power applications (above 250 kW or so) are best served by **SOFC**.

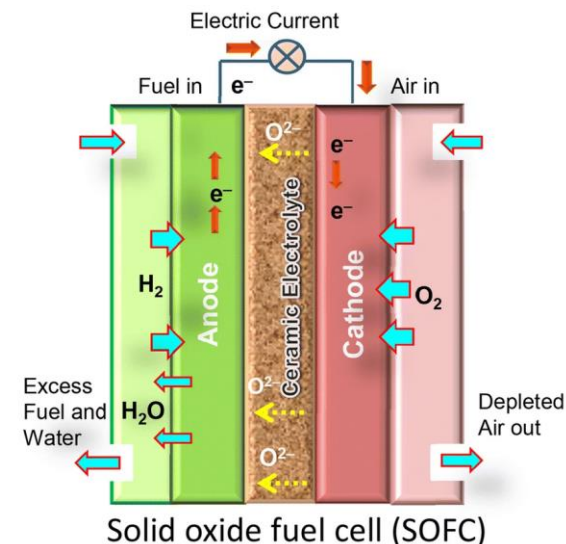
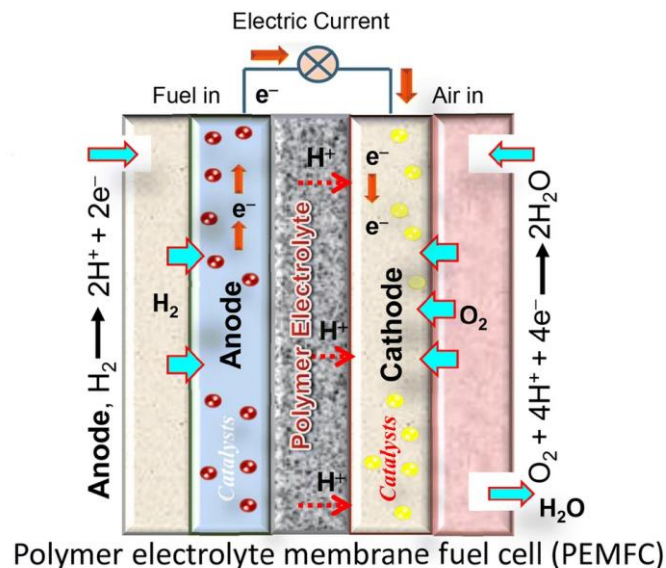
# PEMFC and SOFC Materials

Electrolyte and electrodes/catalysts materials for PEMFCs and SOFCs



Of the five primary fuel cell types we have discussed, **PEMFCs** and **SOFCs** offer the best prospects for continued improvement and eventual application.

For **PEMFCs**, there are actually dozens of polymer electrolyte and catalyst material combinations, each offering potential advantages (but also often disadvantages). Similarly, there are many interesting and sometimes highly compelling alternative **SOFC** electrolyte, anode, and cathode materials.



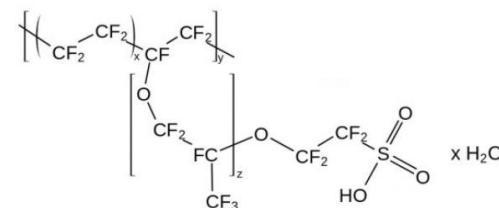
## Introduction

The electrolyte materials **must conduct ions**, but **not electrons**. Most PEMFC electrolytes are based on polymeric membranes that conduct  $H^+$  ions. Because many of these polymer materials rely on water-based vehicle mechanisms for ionic transport, water management is crucially required for most PEMFC-based systems.

## Perfluorinated polymers

Perfluorinated polymers like **Nafion** are the most popular and important electrolytes for PEMFC applications. Nafion has a backbone to provide **mechanical strength**. It also includes sulfonic acid ( $SO_3^-H^+$ ) to provide charge sites for proton transport. Nafion exhibits **extremely high ionic conductivity**. However, Nafion must be fully hydrated with liquid water to maintain the conductivity, thus the **water management schemes** are typically necessary for the fuel cell system.

# Nafion

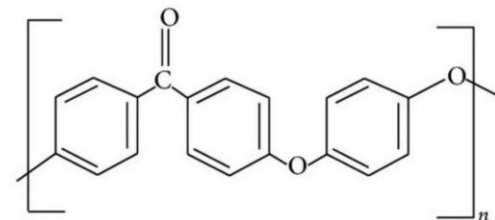


## Sulfonated hydrocarbon polymers

Aromatic hydrocarbon polymers can serve as the backbone for electrolytes, with polyether ether ketone (**PEEK**) being one of the most common materials used. These aromatic membranes are typically sulfonated to enhance proton conductivity. While they are **significantly cheaper**, their **ionic conductivity is lower** compared with Nafion.

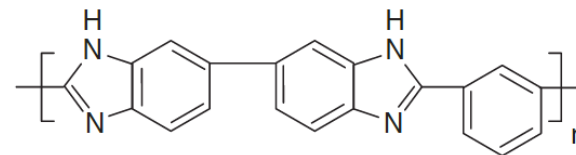
### PEEK (Polyether ether ketone) Plastic

Chemical Structure



## Phosphoric acid doped polybenzimidazole

Phosphoric acid doped polybenzimidazole (PBI) exhibits a proton conduction mechanism that **does not require the presence of liquid water**. It possesses remarkable **thermal stability**, higher **mechanical strength**, and improved **impurity tolerance**. However, it suffers **durability issues**.

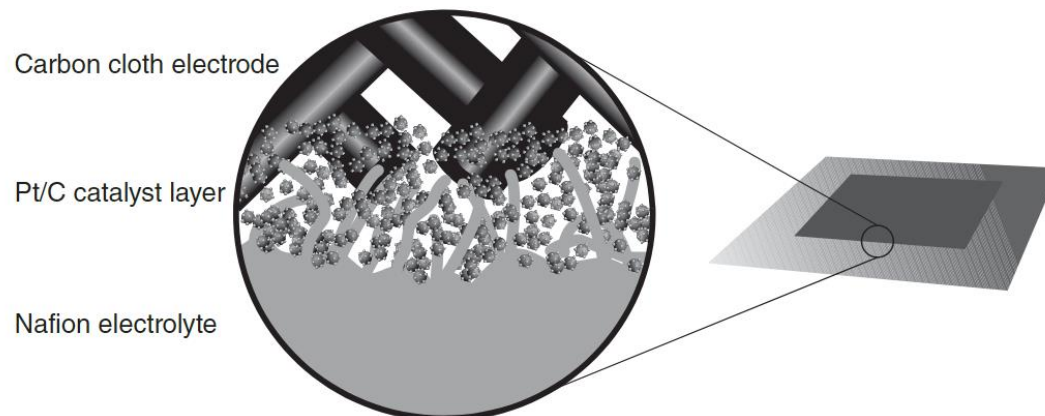


## Dual-layer approach

To reduce the use of **noble material catalysts** while proving high electrical conductivity and high porosity, PEMFC electrodes are typically fabricated using a dual-layer approach:

1. **Catalyst layer:** A thin but highly active catalyst layer is deposited on the electrolyte.
2. **Electrode layer (gas diffusion layer, GDL):** A thicker inexpensive, porous, and electrically conductive layer is then bonded on top of the catalyst layer to provide protection and facilitate current collection.

This results in a dual-layer catalyst/electrode structure, maximizing catalytic activity, gas access, and electrical conductivity, while minimizing costs.



## Gas diffusion layer (GDL) materials

Most PEMFCs employ carbon-fiber-based GDL materials. The two most common GDL materials are **carbon fiber cloths** and **carbon fiber papers**. Carbon fiber materials are chosen due to their good electrical conductivity and high porosity (typically >70% porous). Furthermore, carbon fiber materials exhibit excellent stability and corrosion resistance along with good mechanical properties.

**Carbon fiber cloth:** Made by weaving carbon fiber filaments into a thin, flexible fabric. Carbon cloths are known for their mechanical resilience, low density, and high permeability.



**Carbon fiber paper:** Produced by bonding carbon fibers into a thin, stiff, and lightweight sheet. Carbon paper materials tend to be denser and less permeable than the carbon fiber cloth counterparts.

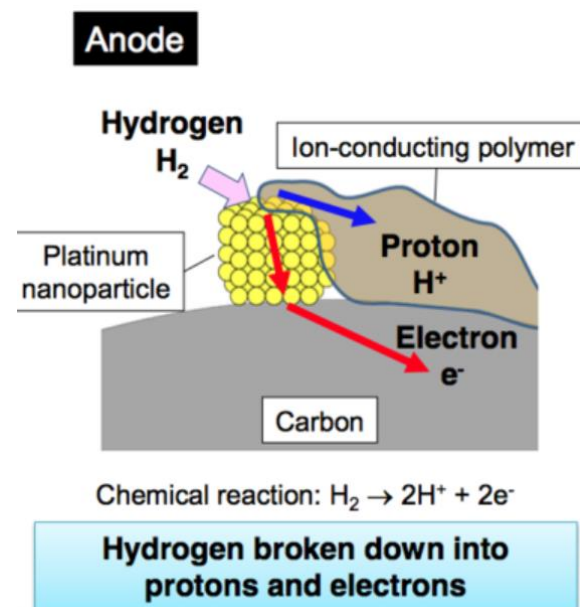


## Anode catalyst

In a standard H<sub>2</sub> fuel cell, PEMFC anode catalysts must facilitate the hydrogen oxidation reaction (HOR):



Currently, the **best electrocatalyst for the HOR is platinum (Pt)**. The extremely high activity of Pt is believed to be due to a nearly optimal bonding affinity between Pt and hydrogen. The bonding is **strong enough** to promote facile absorption of H<sub>2</sub> from the gas phase onto a Pt surface and subsequent electron transfer, but the bonding is **weak enough** to allow desorption of the resultant H<sup>+</sup> ion into the electrolyte.

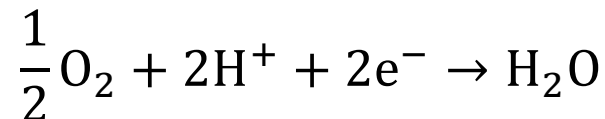


Although Pt is expensive, only extremely small amounts of Pt catalyst are required for HOR using the well-developed Pt/C catalyst approach. **The expense of the anode Pt catalyst for HOR is relatively modest** compared with the expense associated with other components in a fuel cell.

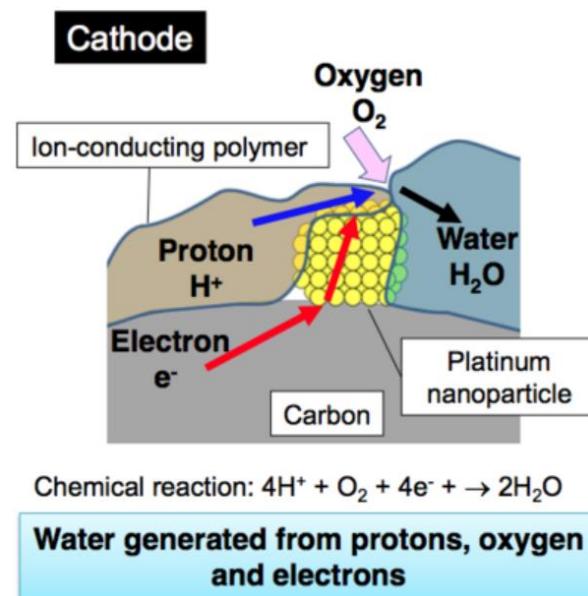


## Cathode catalyst

The reaction proceeding at the cathode of a PEMFC will be the oxygen reduction reaction (ORR):



The dominant catalyst of choice for the cathode ORR is also **Pt**. Unfortunately, Pt is considerably less active for the ORR than for the HOR. This means that **significantly higher Pt loading levels are required** in PEMFC cathodes. Pt loading levels at the cathode are currently 8–10 times higher than those at the anode.



Significant effort is therefore underway to reduce catalyst costs in PEMFC cathodes: 1) optimize current Pt/C catalysts; 2) develop new Pt alloy catalysts that are even more active; and 3) develop inexpensive and Pt-free catalysts.

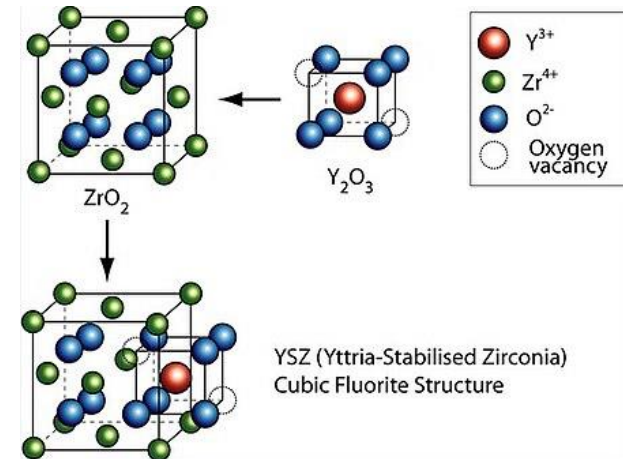


## Introduction

SOFCs are based on crystalline oxide ceramic electrolyte materials that conduct ions via defect hopping mechanisms. SOFC electrolytes are **not sensitive to membrane hydration and do not necessarily require sophisticated water management systems**. However, to obtain sufficiently high ion conduction through oxide membranes, it is typically necessary to operate SOFC devices at **temperatures in excess of 700°C or 800°C**.

## Yttria-stabilized zirconia

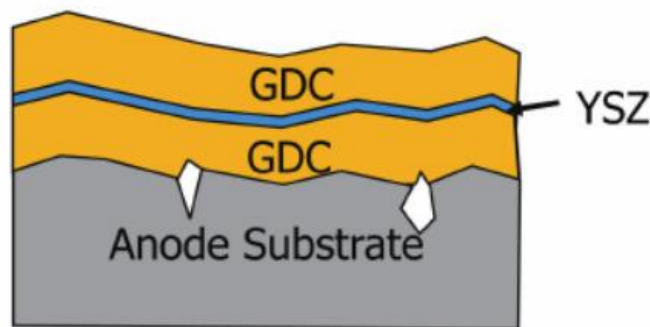
Yttria-stabilized zirconia (YSZ) is arguably the **most important electrolyte material for SOFCs** and it possesses a number of advantages, including **good ionic conductivity, little or no electronic conductivity, excellent chemical stability and chemical inertness, and high fracture toughness**. YSZ is created by doping  $\text{ZrO}_2$  with a certain percentage (around 8 mol %) of  $\text{Y}_2\text{O}_3$ , and this appropriate amount of doping leads to an increase in ionic conductivity.



## Doped ceria

Doped ceria is another common material for the SOFC electrolyte obtained by doping ceria ( $\text{CeO}_2$ ). Samaria- and gadolinia-doped ceria materials are often abbreviated SDC and GDC, respectively. They generally show **higher ionic conductivity** than YSZ. However, it also shows significant **electronic conductivity** under reducing conditions. Thus, its suitability for fuel cell environments is still being debated.

In response to this challenge, **GDC/YSZ “multilayer” electrolytes** have been explored that utilize GDC on the cathode side and YSZ on the anode side. Thin-film GDC/YSZ electrolyte assemblies have been shown to deliver power densities as high as  $400 \text{ mW/cm}^2$  at relatively low temperatures.



## Introduction

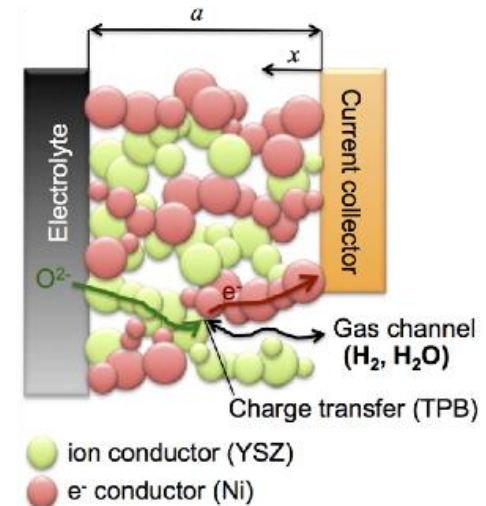
SOFC electrode materials need to simultaneously provide **high porosity, high electrical conductivity, and high catalytic activity**. However, the **high-temperature environment** experienced in SOFCs provides additional challenges. In order to ensure thermal and chemical compatibility under harsh operating conditions, most SOFC electrode materials either are **electrically conductive ceramic materials** or are **mixed ceramic–metal composites** (known as **cermets**).

## Dual-layer approach

Similar to PEMFC electrodes, most SOFC electrode structures use a **dual-layer approach**. The first layer, immediately adjacent to the electrolyte, is an extremely thin catalytically active functional layer. A second, much thicker and porous electrode layer is also often employed to provide mechanical support and protection for the catalyst layer, while also offering excellent electrical conductivity and high porosity for gas access.

## Ni-YSZ cermet anode materials

Currently, **most SOFCs employ Ni-YSZ cermet anodes**. In Ni-YSZ cermet anodes, the Ni provides electronic conductivity and catalytic activity, while the YSZ provides a structural framework as well as ionic conductivity to the electrode, thus effectively broadening the triple-phase boundaries (TPB).



## Ceria-based anode materials

Recently, there has been growing interest in using doped ceria materials for SOFC anodes. The dopant, like Ni, acts as the electrocatalyst on the anode. The primary advantage of doped ceria-based materials is their ability to suppress carbon deposition, which **facilitates the direct use of hydrocarbon fuels** in SOFCs. For example, the methane oxidation reaction can proceed directly on doped ceria as:



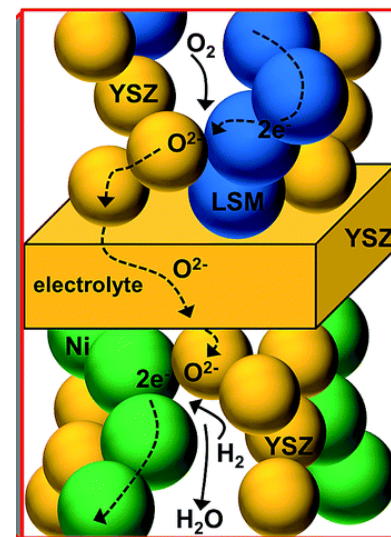
## Cathode materials

Due to the instability of metal conductors in high-temperature oxidizing environments, **SOFC cathodes are typically ceramic**. As a result, their electronic conductivity is much lower than that of SOFC anodes, impacting optimal cathode design, especially regarding thickness.

A thick cathode results in significant ionic resistance, whereas a thinner cathode raises electronic resistance. An optimal cathode thickness can therefore be derived that minimizes the total ionic and electronic resistance.

## Lanthanum strontium manganite (LSM)

In YSZ-based SOFCs, the dominant cathode material is strontium-doped  $\text{LaMnO}_3$  perovskite, or LSM. **LSM is the cathode of choice due to its good physical and chemical stability, electrical conductivity, and catalytic activity**. However, oxygen ion conductivity is very low in LSM, and therefore LSM-based cathodes are typically mixed with YSZ to form LSM–YSZ composite cathodes, where YSZ provides high ionic conductivity.

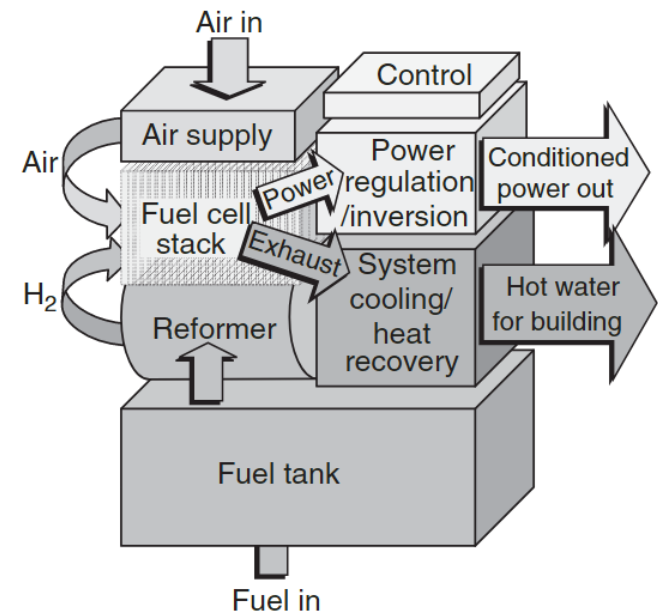


# Fuel Cell Systems

Fuel cell stack, thermal management subsystem, and fuel delivery subsystem.

The ultimate goal of any fuel cell system is **to deliver the right amount of power to the right place at the right time**. To meet that goal, a fuel cell system generally includes **a set of fuel cells in combination with a suite of additional components**. Multiple cells are required since a single fuel cell provides only about 0.6–0.7 V at operational current levels (at or below the maximum power density point). Other components besides the fuel cells themselves include subsystems that provide the fuel supply, cooling, etc. The major subsystems, included in a typical fuel cell system, including the following:

- Fuel cell subsystem (Fuel cell stack)
- Thermal management subsystem
- Fuel delivery/processing subsystem



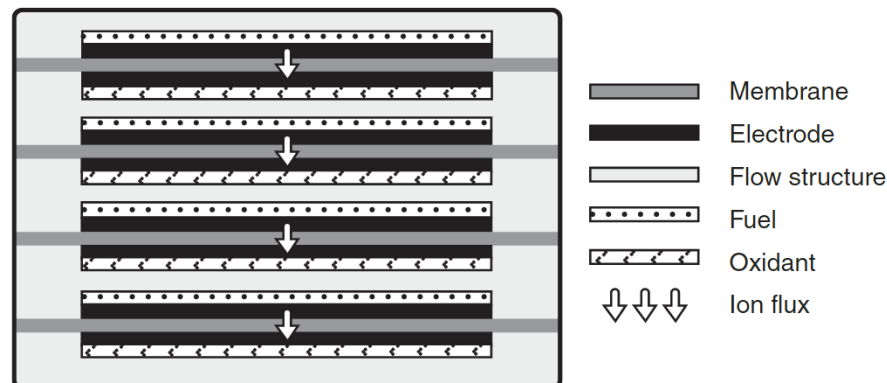


## Introduction

The output voltage of a single hydrogen fuel cell typically ranges from 0.6 to 0.7 V at its operational current levels. However, most real-world applications require electricity at several, tens, or even hundreds of volts. Thus, **fuel cell stacking**, connecting fuel cells in series, allows full cell systems to meet any voltage requirements.

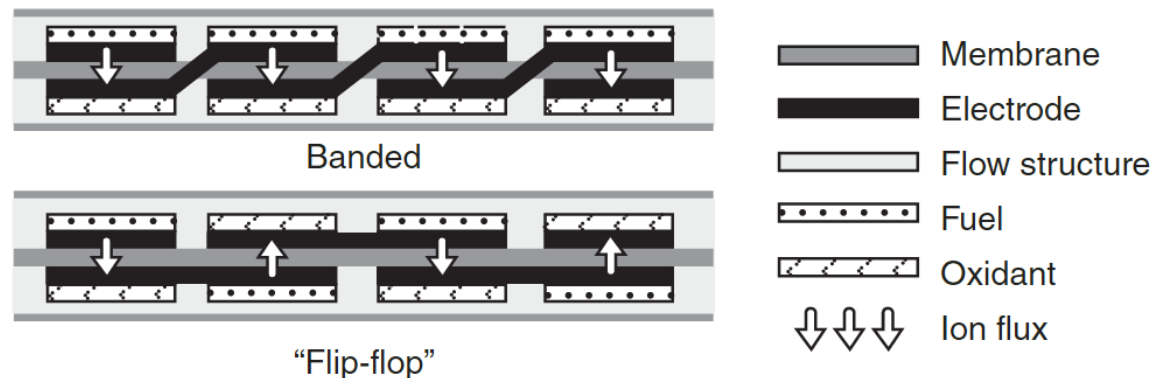
## Vertical stacking

The most common form of fuel cell interconnection is vertical stacking (**bipolar plate stacking**). In this configuration, a single conductive flow plate is in contact with both the anode electrode of one cell and the cathode electrode of the next, connecting the two fuel cells in series. The plate serves as the anode in one cell and the cathode in the next cell, hence the name *bipolar plate*.



## Planar stacking

Planar interconnection designs, in which cells are connected laterally, have also been explored. While planar designs are less suitable to large-scale power systems because of their **increased electrical resistance losses**, they provide form factor advantages for certain portable applications. This approach is sometimes referred to as a “window pane” design, whereby, a few smaller cells are linked laterally, emulating the appearance of a window with a few panes.



The upper diagram shows the **banded electrolyte design**, which has a critical disadvantage: interconnections must cross the electrolyte, limiting design flexibility and potentially increasing resistive losses. To address these challenges, the planar **flip-flop configuration** is proposed, as illustrated in the lower diagram, where electrodes from two different cells are interconnected on the same side of the electrolyte.

## Introduction

Fuel cells are typically only 40–60% electrically efficient, with unconverted energy released as electrochemical waste heat. Excessive heat generation can lead to overheating and thermal gradients, negatively impacting performance.

Thermal management subsystem can involve either “passive” or “active” cooling of the fuel cell stack. The choice between these two approaches strongly depends on fuel cell type, size, and operating strategy.

## Passive cooling

Small, low-temperature fuel cells (such as PEMFCs) frequently can rely on passive cooling, which typically includes

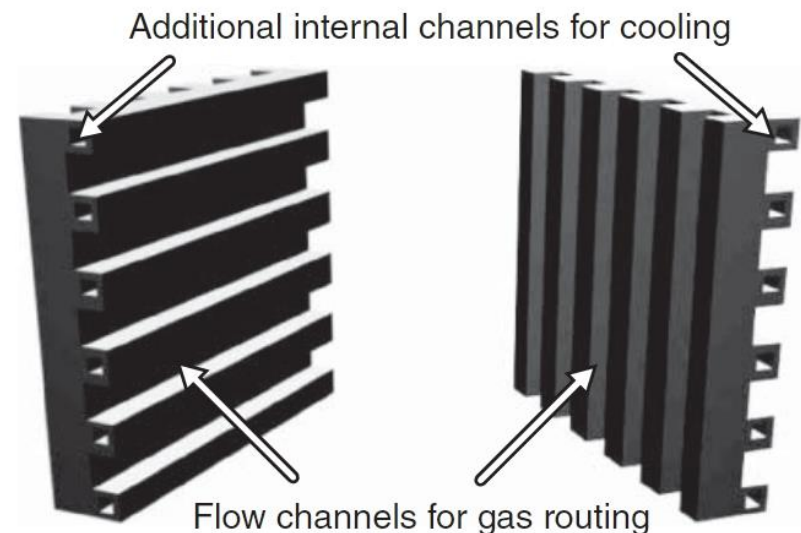
1. Cooling via **natural convection of air** against the external surface area of the fuel cell stack.
2. Cooling via **the free or forced convection of reactant and/or product gases** through the fuel cell stack.

## Active cooling

Many types of fuel cell systems are more likely to require active cooling, which typically involves:

1. The addition of at least **one other cooling stream** (on top of the reactant and product streams) that absorbs heat via forced convection of a fluid against or through the fuel cell stack.
2. Running existing reactant and/or product streams at **higher flow rates** than that needed for electrochemical reaction alone so as to enhance forced convection.

Automotive PEMFC stacks may be designed with electrochemical cells interspersed in a rough ratio of one-to-one with “cooling cells” that use bipolar plate channels to flow liquid coolant.



## Introduction

**Providing fuel for a fuel cell** is often the most difficult task that a system designer faces. Almost all practical fuel cells today use hydrogen or compounds containing hydrogen as fuel. As a result, there are effectively two main options for fueling a fuel cell: **1) Use hydrogen directly. 2) Use a hydrogen carrier.**

## H<sub>2</sub> storage

In a hydrogen storage system, the fuel cell is **supplied directly with H<sub>2</sub> gas**. It has the advantages of optimal performance due to pure hydrogen use, reduced contamination risks, simplified system design, and environmental benefits, as the only byproduct is water.

The common ways to store hydrogen are:

- 1) Compressed H<sub>2</sub>:** The most straightforward way to store hydrogen
- 2) Liquid H<sub>2</sub>:** Hydrogen gas can be cooled to 22 K to condense into a liquid, allowing for low-pressure storage.
- 3) Metal hydride:** Metal hydride materials (iron, titanium, nickel, etc) can absorb H<sub>2</sub> gas by dissociating H<sub>2</sub> molecules into H atoms and release the stored H<sub>2</sub> gas upon heating.

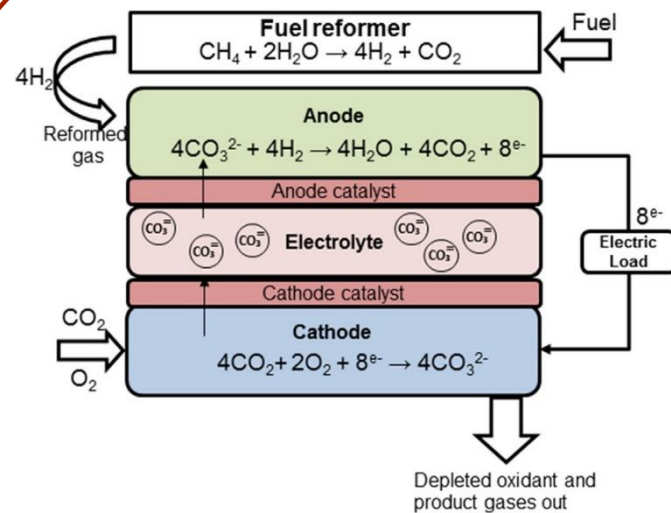
## H<sub>2</sub> carrier

A hydrogen carrier is a convenient chemical substance that is used to convey hydrogen to a fuel cell. H<sub>2</sub> carriers include methane (CH<sub>4</sub>), methanol (CH<sub>3</sub>OH), gasoline (C<sub>n</sub>H<sub>1.87n</sub>), and so on. Using an H<sub>2</sub> carrier instead of hydrogen gas can permit greatly higher energy storage densities.

There are three ways to use hydrogen carriers:

1. **Direct electro-oxidation:** The H<sub>2</sub> carriers can be electro-oxidized directly in the fuel cell.
2. **External reforming:** The H<sub>2</sub> carriers are reformed (chemically processed) into hydrogen gas outside the fuel cell, then the hydrogen gas is used by the fuel cell to produce electricity.
3. **Internal reforming:** Similar to external reforming, but the reforming process takes place on the catalyst's surface within the fuel cell.

PolyU developed the 1<sup>st</sup> Ammonia Fuel Cell EV.



# Fuel Cell Characterization

In-situ characterization techniques & ex-situ characterization techniques



## Overview

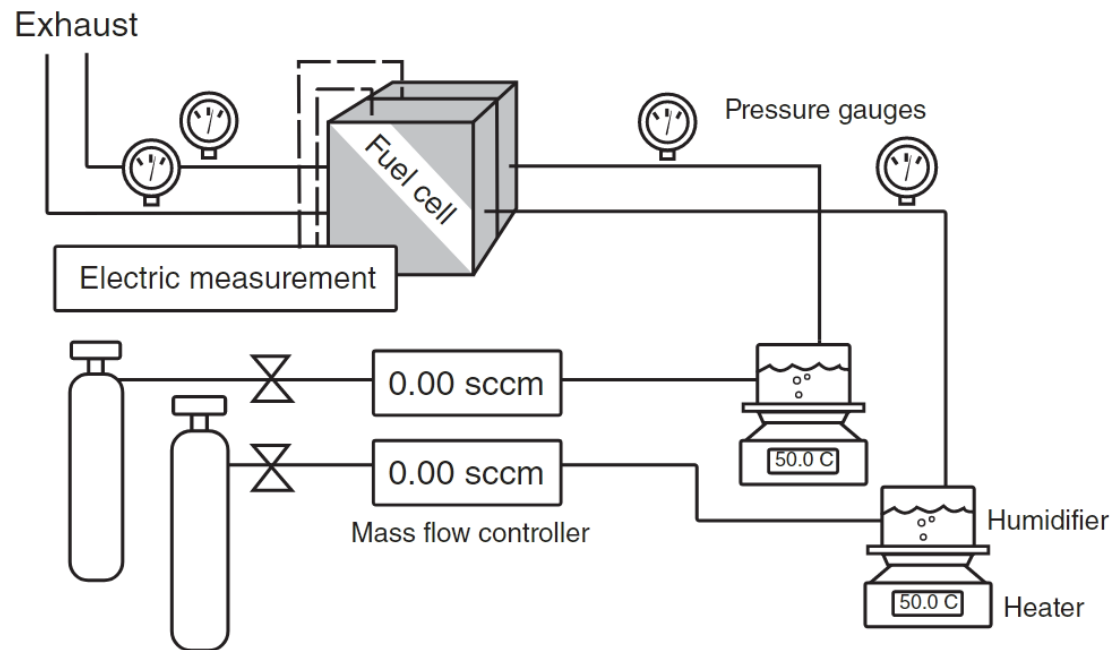
Characterization techniques permit the quantitative comparison of fuel cell systems, distinguishing good fuel cell designs from poor ones.

We divide fuel cell characterization techniques into two types:

- **In situ characterization techniques:** These techniques use the electrochemical variables of voltage, current, and time to characterize the performance of fuel cell devices **under operating conditions**.
- **Ex situ characterization techniques:** These techniques characterize the detailed structure or properties of the individual components composing the fuel cell, but generally only **components removed from the fuel cell environment** in an unassembled and nonfunctional form.

## Test setup

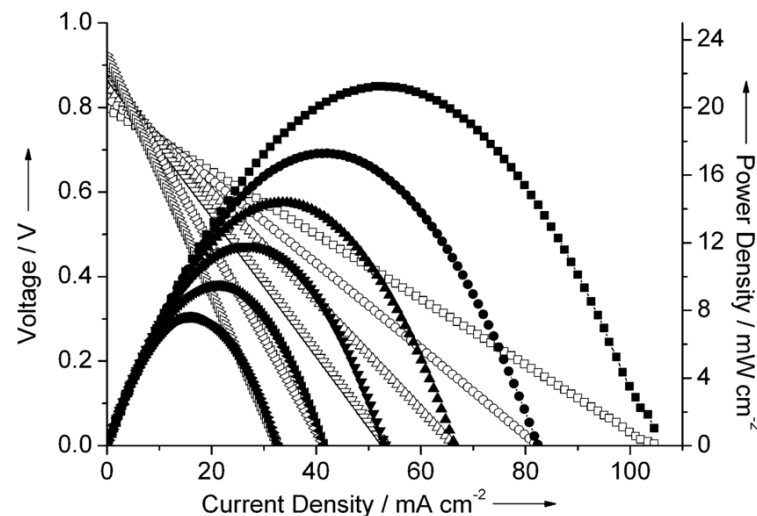
Because fuel cell performance strongly depends on the operating conditions, the setup must allow flexible control over the operating pressures, temperatures, humidity levels, and flow rates of the reactant gases. The setup for PEMFCs is:



where the pressures, temperatures, humidity levels, and flow rates of gases are controlled.

## Current-voltage measurement

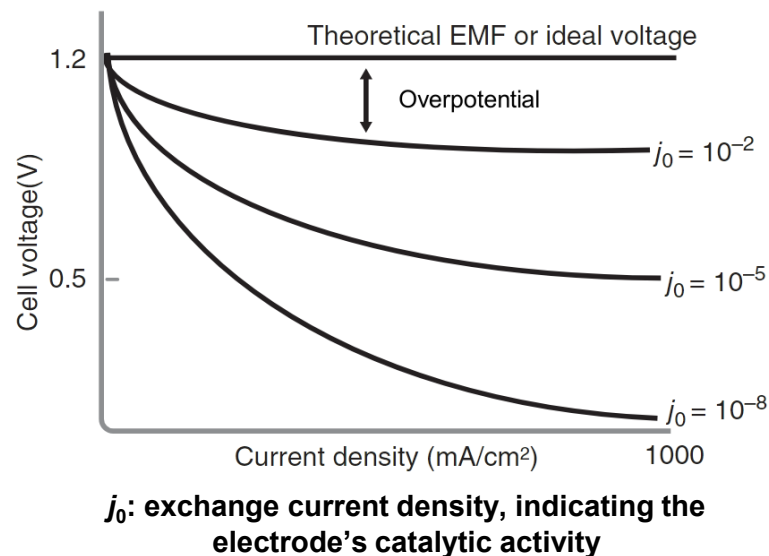
The performance of a fuel cell is best summarized by its current-voltage response (i-V or j-V curve). The curve is usually measured by drawing a fixed current and measuring the corresponding output voltage. By stepping the current demand, the entire curve can be determined.



## Overpotential

Overpotential is the **difference between the ideal voltage and actual voltage under operating conditions**. It consists of:

- Activation overpotential  $\eta_{\text{act}}$
- Resistance overpotential  $\eta_{\text{ohmic}}$
- Concentration overpotential  $\eta_{\text{conc}}$

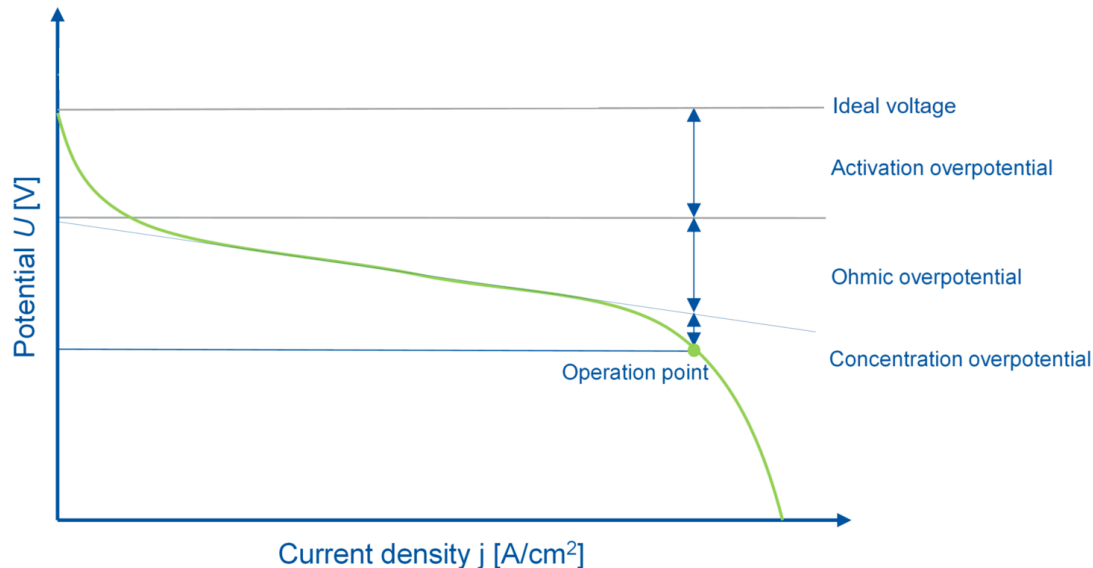


## Overpotential (cont'd)

- **Activation overpotential**  $\eta_{\text{act}}$  depends on the activation energy of the redox event.
- **Resistance overpotential**  $\eta_{\text{ohmic}}$  is caused by ionic and electronic resistances in the fuel cell. It can be calculated by:  $\eta_{\text{ohmic}} = iR_{\text{ohmic}}$ , where  $R_{\text{ohmic}}$  is the fuel cell's ohmic resistance.
- **Concentration overpotential**  $\eta_{\text{conc}}$  spans a variety of phenomena that involve the depletion of charge-carriers at the electrode surface.

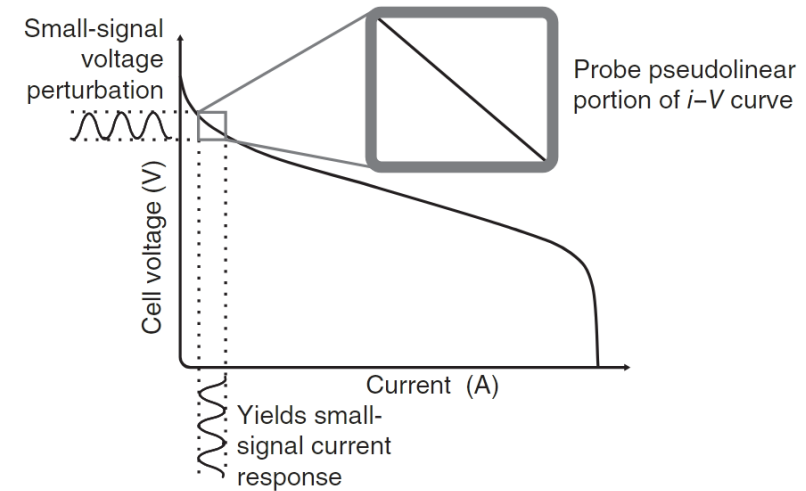
**Total overpotential**  $\eta_{\text{tot}}$  can be calculated by:

$$\eta_{\text{tot}} = \eta_{\text{act}} + \eta_{\text{ohmic}} + \eta_{\text{conc}}$$

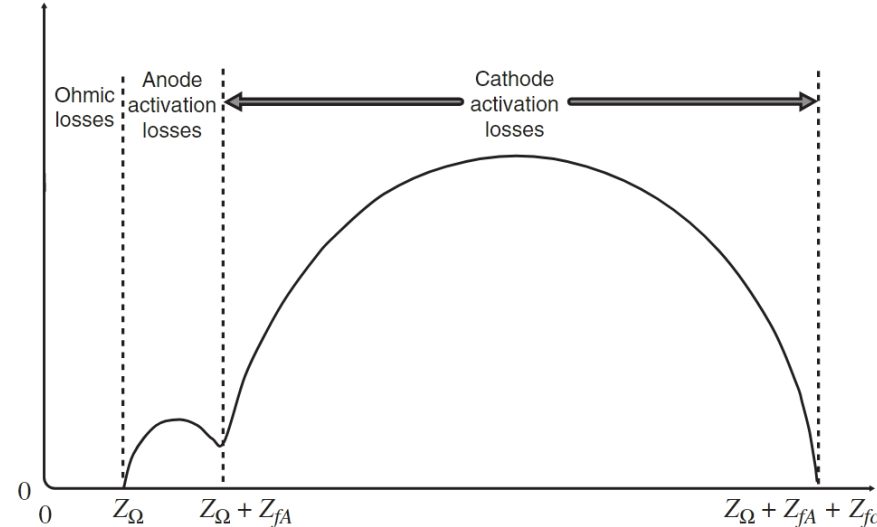


## Electrochemical Impedance Spectroscopy (EIS)

EIS is a more sophisticated test to differentiate between all the major sources of loss in a fuel cell. Impedance measurements are usually made by applying a small sinusoidal voltage and monitoring the current response.



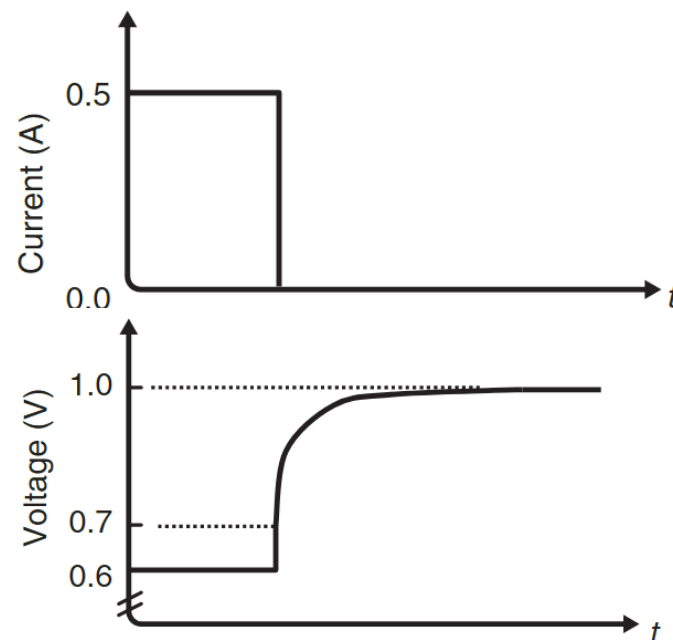
**Nyquist plots** can be used to summarize the measured impedance:



$Z_{\Omega}$ ,  $Z_{fA}$ , and  $Z_{fC}$  are the ohmic, anode activation, and cathode activation impedance, respectively.  $Z_{\Omega} = R_{ohmic}$

## Current interrupt measurement

The current interrupt method can **provide some of the same information provided by EIS**. While **not as accurate or as detailed** as an impedance experiment, current interrupt has several major advantages compared to impedance: **extremely fast, simpler measurement hardware, able to be conducted in parallel with j-V curve measurement**.



The basic idea is, when a constant-current load is abruptly interrupted, the resulting time-dependent voltage response will be representative of the various components in the fuel cell.

**Resistance overpotential refers to the change in voltage when the current is suddenly interrupted.**



While the in situ electrical characterization techniques are the most popular methods used to study fuel cell behavior, ex situ characterization techniques can provide enormous **additional insight** into fuel cell performance.

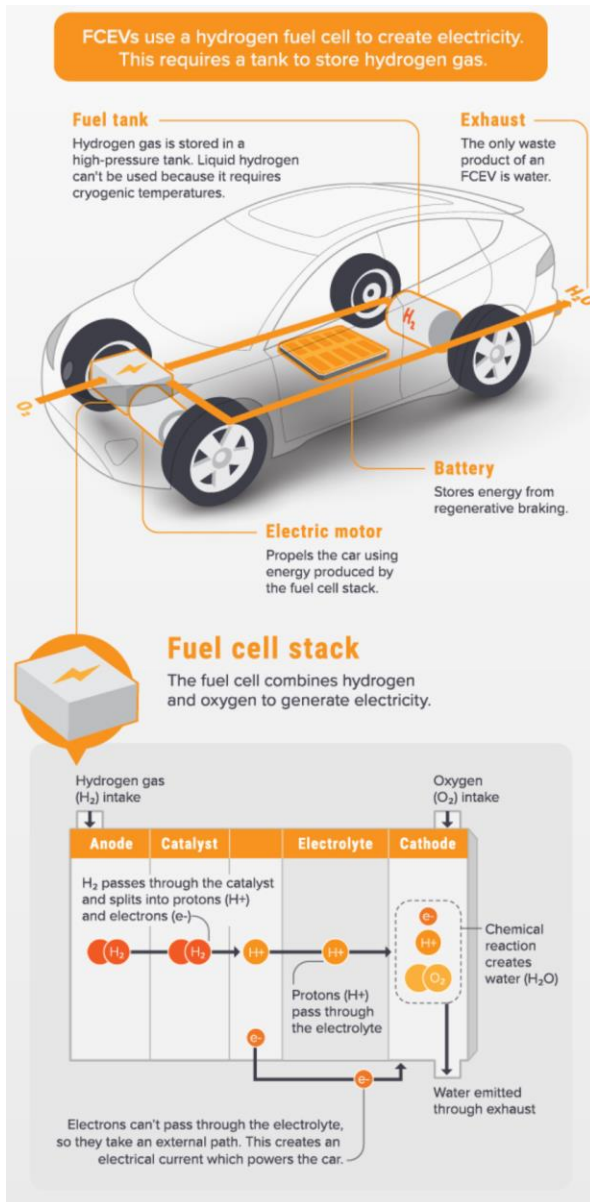
Most ex situ techniques focus on evaluating the **physical or chemical structure** of fuel cell components in an effort to identify which elements most significantly impact fuel cell performance. Ex situ characterization techniques include:

- **Porosity determination:** examining the ratio of void space to the total volume of the material.
- **Surface area determination:** for the most accurate surface area determination, an ex situ technique known as the Brunauer–Emmett–Teller (BET) method can be employed.
- **Gas permeability:** determining permeability, which measures the ease with which gases move through a material.
- **Structure determinations:** significant information about microstructure, porosity, pore size distribution, and interconnectedness is gleaned from microscopy, and specific quantitative structural information can be provided from x-ray diffraction measurements



# Fuel Cell Electric Vehicles (FCEVs)

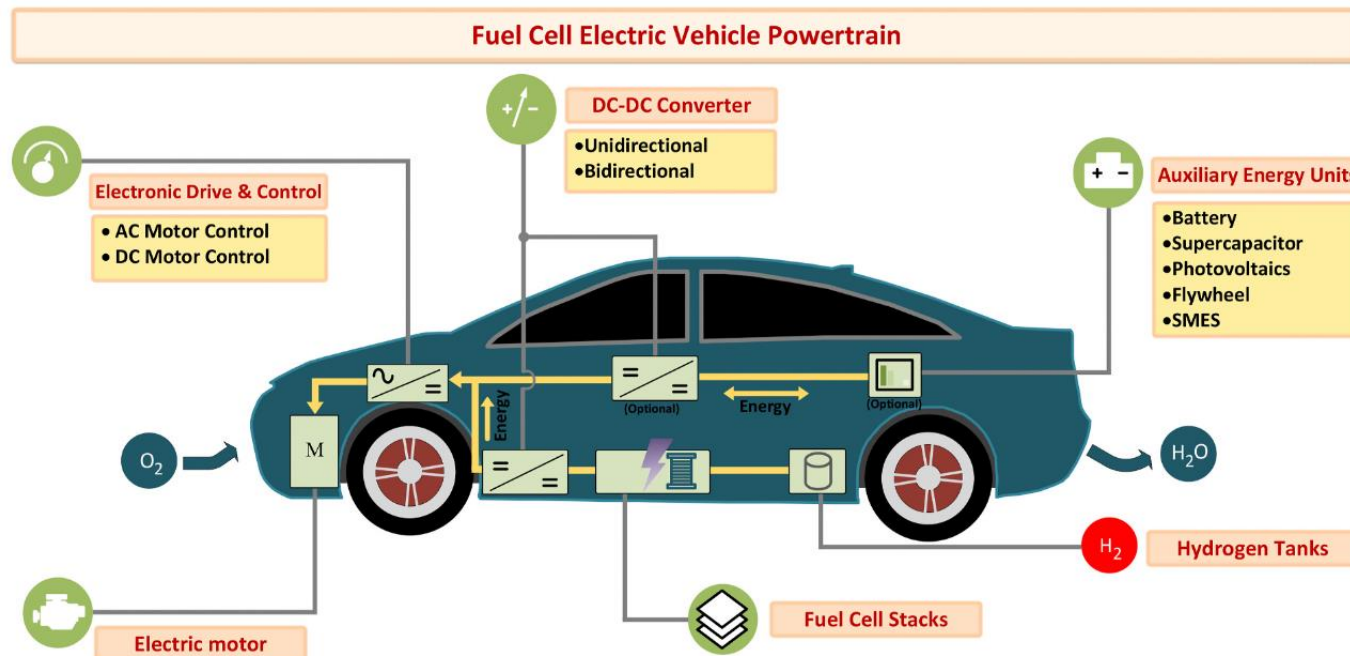
FCEV powertrain, classification, and examples.



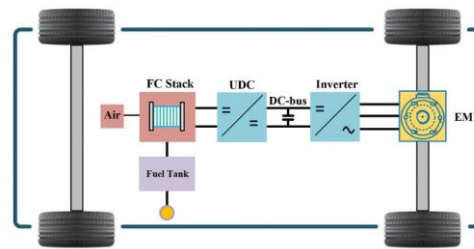
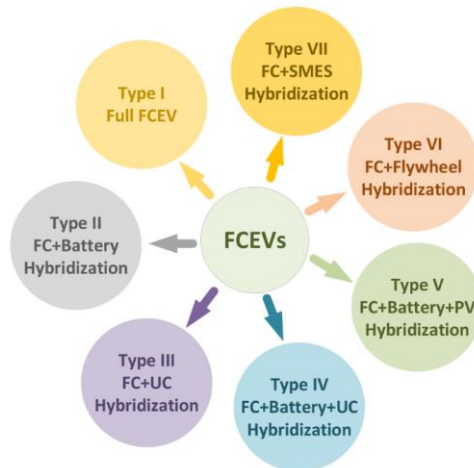
The environmentally friendly characteristics of fuel cells make them desirable for various transportation applications, including passenger cars, light commercial vehicles, buses, and trucks. These transportation applications, which consist of a **fuel cell** instead of a battery, or combination with **auxiliary energy generation units** are called **fuel cell electric vehicles (FCEVs)**.

Most FCEVs are known as low-pollutant vehicles that give off heat energy and water in addition to electrical power for kinetic energy. In addition, FCEVs not only aid in supporting a clean ambient but also diminish the financial damage of fuels compared with traditional vehicles.

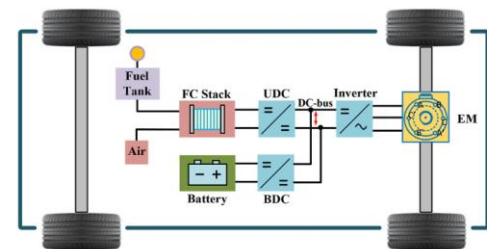
The FCEV powertrain includes a **fuel cell stack**, a **hydrogen tank**, **DC-DC converters**, a **motor drive converter**, an **electric motor**, and an optional **auxiliary energy unit**. In the operation of an FCEV, the fuel cell stack supplies energy to the DC bus and keeps the required DC bus voltage. Then, the DC-DC converter directly connected to the fuel cell is a system element to keep the DC bus voltage constant and transfer the energy generated for the propulsion of the vehicle to the motor drive converter. Finally, the electric motors supervised by the drive controller convert electrical energy into kinetic energy.



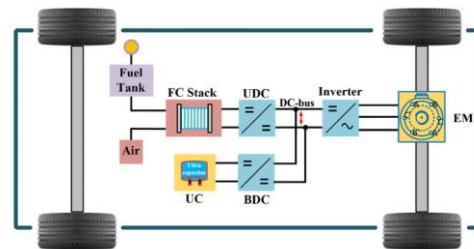
Because different power supplies, including **fuel cells (FCs)**, **batteries**, **ultracapacitors (UCs)**, **photovoltaics (PV)**, **flywheels**, and **superconducting magnetic energy storage (SMES)**, have different characteristics, they are often combined to supply energy for FCEVs. Thus there are several **types of FCEVs according to their power supplies**.



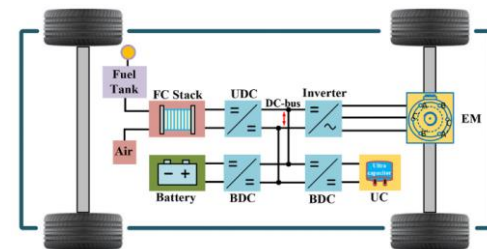
The powertrain of full FCEV structure (Type I).



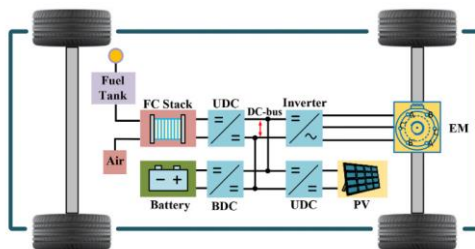
The powertrain of FC + Battery hybridization (Type II).



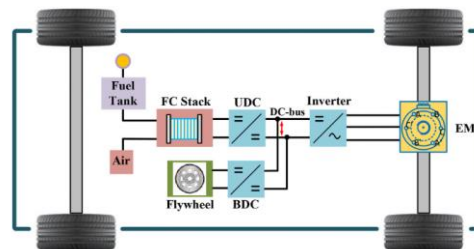
The powertrain of FC + UC hybridization (Type III).



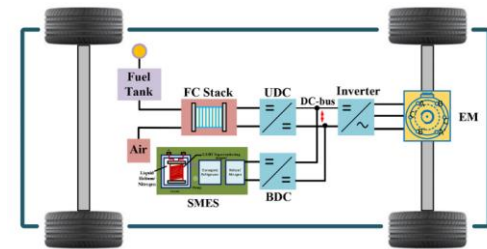
The powertrain of FC + Battery + UC hybridization (Type IV).



The powertrain of FC + Battery + PV hybridization (Type V).



The powertrain of FC + flywheel hybridization (Type VI).



The powertrain of FC + SMES hybridization (Type VII).

**Hyundai Tucson FCEV**, released in 2014, utilizes the **PEMFC and battery** as its power supplies, achieving a top speed of 160 km/h and a range of up to 594 km.



**Honda Mirai FCEV**, initially launched in 2015, employs a **PEMFC and battery** for its power sources, reaching a maximum speed of 160 km/h and a range of up to 480 km.



**Mercedes-Benz GLC FCELL**, introduced in 2020, employs a **PEMFC and battery** as its power sources, reaching a maximum speed of 150 km/h and a range of up to 478 km.



**Hyundai Nexo**, launched in 2020, utilizes a **PEMFC, battery, and ultracapacitor** for its power sources, achieving a top speed of 179 km/h and a range of up to 570 km.



Ref: <http://www.cleanfleetreport.com/road-test-2017-hyundai-tucson-hydrogen-fuel-cell/>

Ref: <https://greencarjournal.com/dont-miss/next-gen-toyota-mirai-fcev/>

Ref: <https://www.autoevolution.com/news/mercedes-benz-glc-f-cell-is-the-world-s-first-plug-in-hybrid-fuel-cell-car-108473.html>

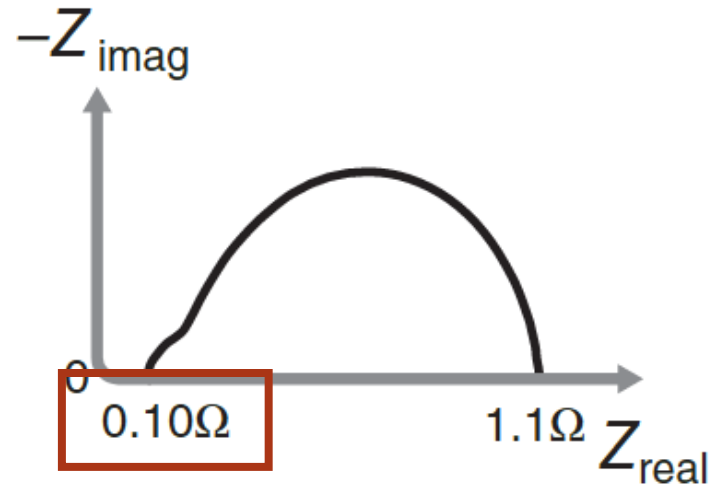
Ref: <https://www.hyundaicanada.com/en/evhub/electrification>

# Example Questions & References

# Example Question 1



Given the Nyquist plot obtained from EIS measurements of the fuel cell, what is its  $R_{\text{ohmic}}$ ?



## Solution:

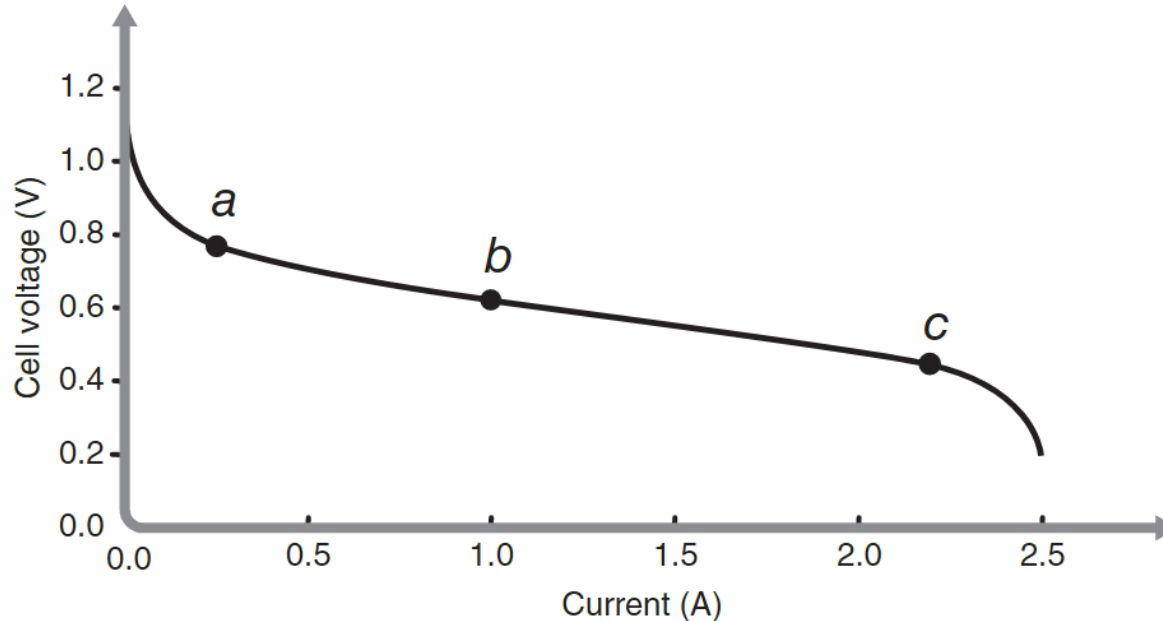
Based on the intersection point on the  $Z_{\text{real}}$  axis,  $R_{\text{ohmic}}$  can be determined to be  $0.1\Omega$ .



## Example Question 2



The  $i$ - $V$  curve is obtained from a fuel cell with  $R_{\text{ohmic}} = 0.1 \, \Omega$ . At point **a**, the current is  $0.25 \, \text{A}$ ; calculate the resistance overpotential at this point.



**Solution:** The resistance overpotential is the product of current and ohmic resistance:

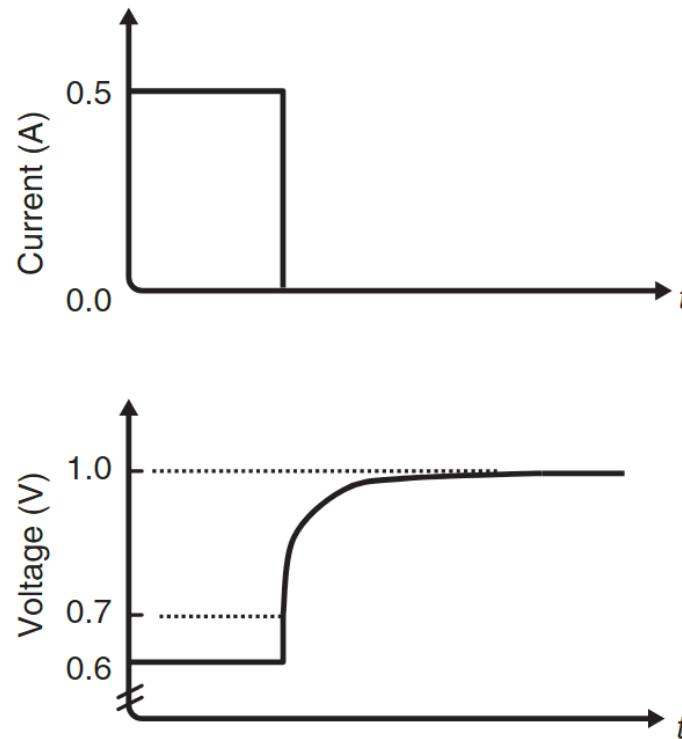
$$\eta_{\text{ohmic}} = iR_{\text{ohmic}} = 0.25 \times 0.1 \, \text{V} = 0.025 \, \text{V}$$



# Example Question 3



Calculate  $\eta_{\text{ohmic}}$  and  $R_{\text{ohmic}}$  from the current interrupt data:



**Solution:** When the fuel cell is held under 0.5-A current load, the steady-state voltage is 0.6 V. When the current is abruptly zeroed, the cell voltage instantaneously rises to 0.7 V. Thus,  $\eta_{\text{ohmic}} = 0.7 - 0.6 \text{ V} = 0.1 \text{ V}$ .  $R_{\text{ohmic}}$  is calculated by:

$$R_{\text{ohmic}} = \frac{\eta_{\text{ohmic}}}{i} = \frac{0.1 \text{ V}}{0.5 \text{ A}} = 0.2 \Omega$$

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