

Green Ammonia & Fuel Cell

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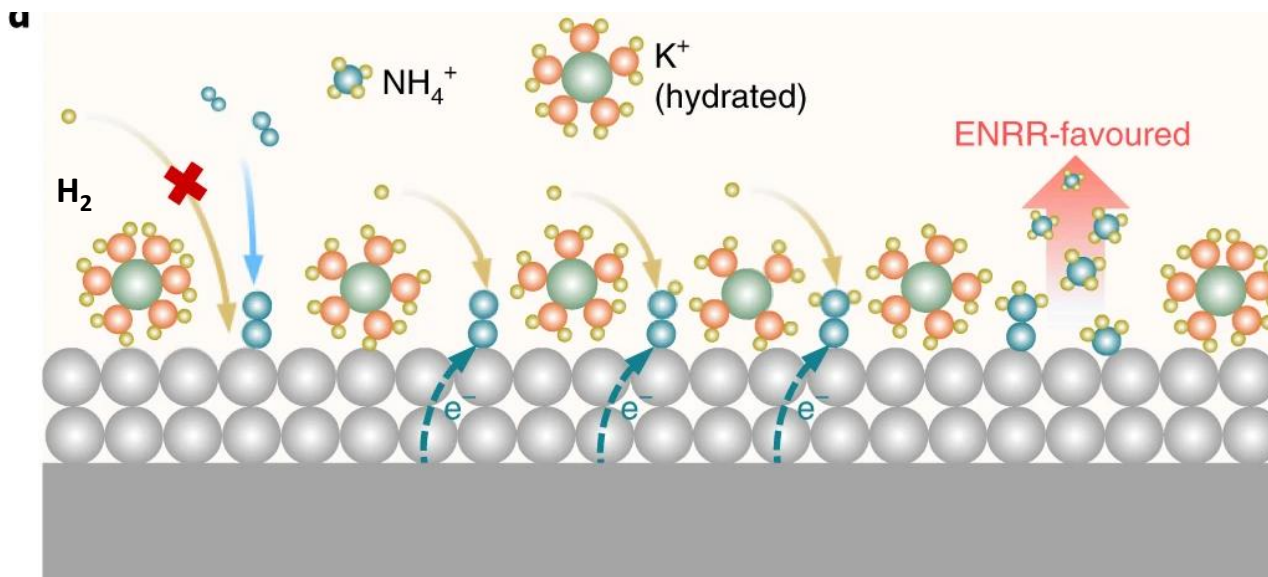
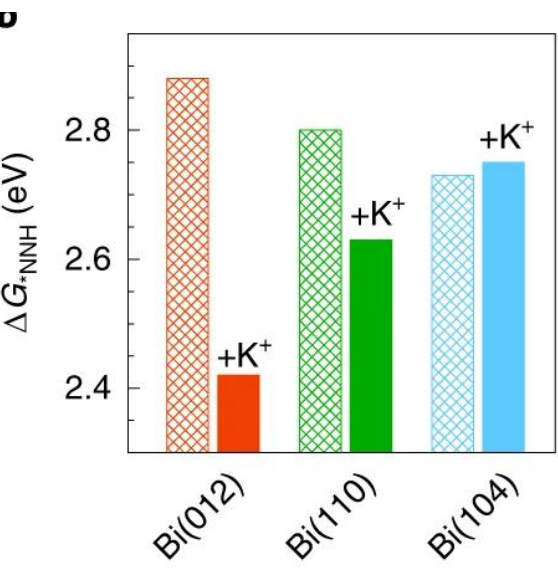
Prof. Sayam Sengupta

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Promoting nitrogen electroreduction to ammonia with bismuth nanocrystals and potassium cations in water [Nature Catalysis | VOL 2 | MAY 2019 | 448–456]

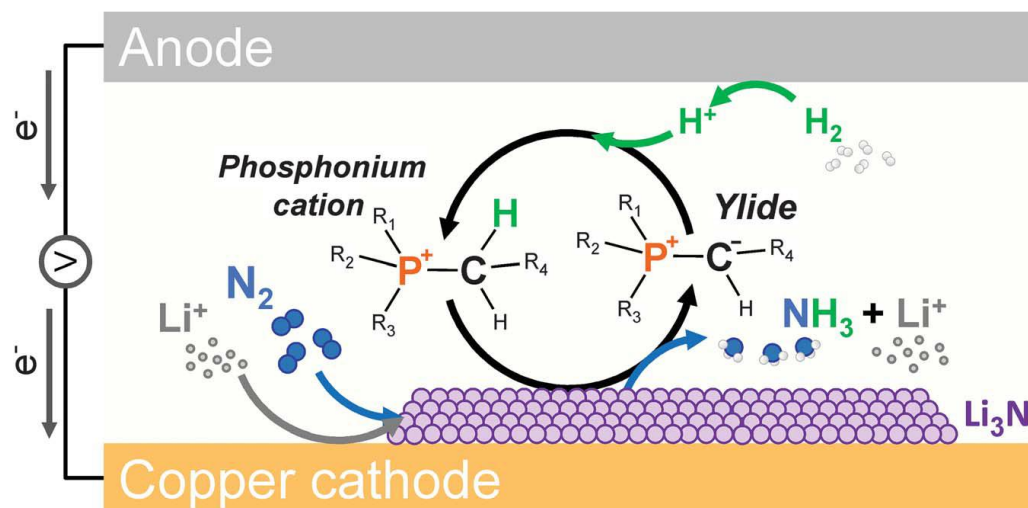
This study presents a strategy to enhance both selectivity and activity of the electrochemical nitrogen reduction reaction (ENRR) using bismuth nanocrystals and potassium cations. Bi demonstrates intrinsically high ENRR activity owing to the **strong interaction between its 6p band and nitrogen 2p orbitals, which lowers the free-energy change (ΔG) for nitrogen activation**. Concurrently, potassium cations stabilise key N-reduction intermediates and regulate proton transfer, thereby further decreasing ΔG and enhancing selectivity. As a result, a high Faradaic efficiency of 66% and an impressive ammonia yield of 200 mmol g⁻¹ h⁻¹ (0.052 mmol cm⁻²h⁻¹) are achieved in aqueous electrolyte under ambient conditions.



In acidic solutions without K⁺ cations, protons can be transferred to the surface readily, and HER will dominate. K⁺ hinders proton transfer to the catalyst surfaces. Nitrogen will be adsorbed preferentially, and the ENRR is promoted.

Green ammonia!

Nitrogen reduction to ammonia at high efficiency and rates based on a phosphonium proton shuttle: *Science* 372, 1187–1191 (2021)



The cathode process involves the reduction of Li^+ to Li^0 which reacts with N_2 to produce Li_3N . This on protonation release NH_3 . The proton carrier is the phosphonium cation, which forms an ylide structure in its deprotonated state; this cycles to the anode where it is regenerated back to the phosphonium form through the reaction with H^+ derived from the oxidation of H_2 .

The salt also provides additional ionic conductivity, enabling high NH_3 production rates of 53 ± 1 nanomoles per second per square centimeter at $69 \pm 1\%$ faradaic efficiency in 20-hour experiments under 0.5-bar hydrogen and 19.5-bar nitrogen. Continuous operation for more than 3 days is demonstrated.

Electroreduction of nitrogen with almost 100% current-to-ammonia efficiency

Nature volume 609, pages722–727 (2022)

This study demonstrates that using a high-concentration imide-based lithium-salt electrolyte forms compact ionic layering at the electrode–electrolyte interface, suppressing electrolyte decomposition and stabilizing N₂ reduction. The approach achieves ammonia yield rates of $150 \pm 20 \text{ nmol s}^{-1} \text{ cm}^{-2}$ with nearly 100% current-to-ammonia efficiency, highlighting the crucial role of interfacial chemistry in advancing green ammonia synthesis.

LiNTf₂ as the Li-NRR electrolyte at a nickel wire electrode under 15 bar dinitrogen pressure, using tetrahydrofuran as solvent and ethanol as proton carrier.

bis(trifluoromethylsulfonyl)imide (NTf₂⁻) and bis(fluorosulfonyl)imide (FSI⁻) were used as electrolyte

Faradaic efficiency (FE) is a measure of how effectively the electrical charge supplied to an electrochemical system is used to drive the desired chemical reaction. It represents the fraction of total electrons that contribute to forming the target product (e.g., ammonia in ENRR), rather than side reactions like hydrogen evolution.

Mathematically:

$$FE = \frac{nFz}{Q} \times 100\%$$

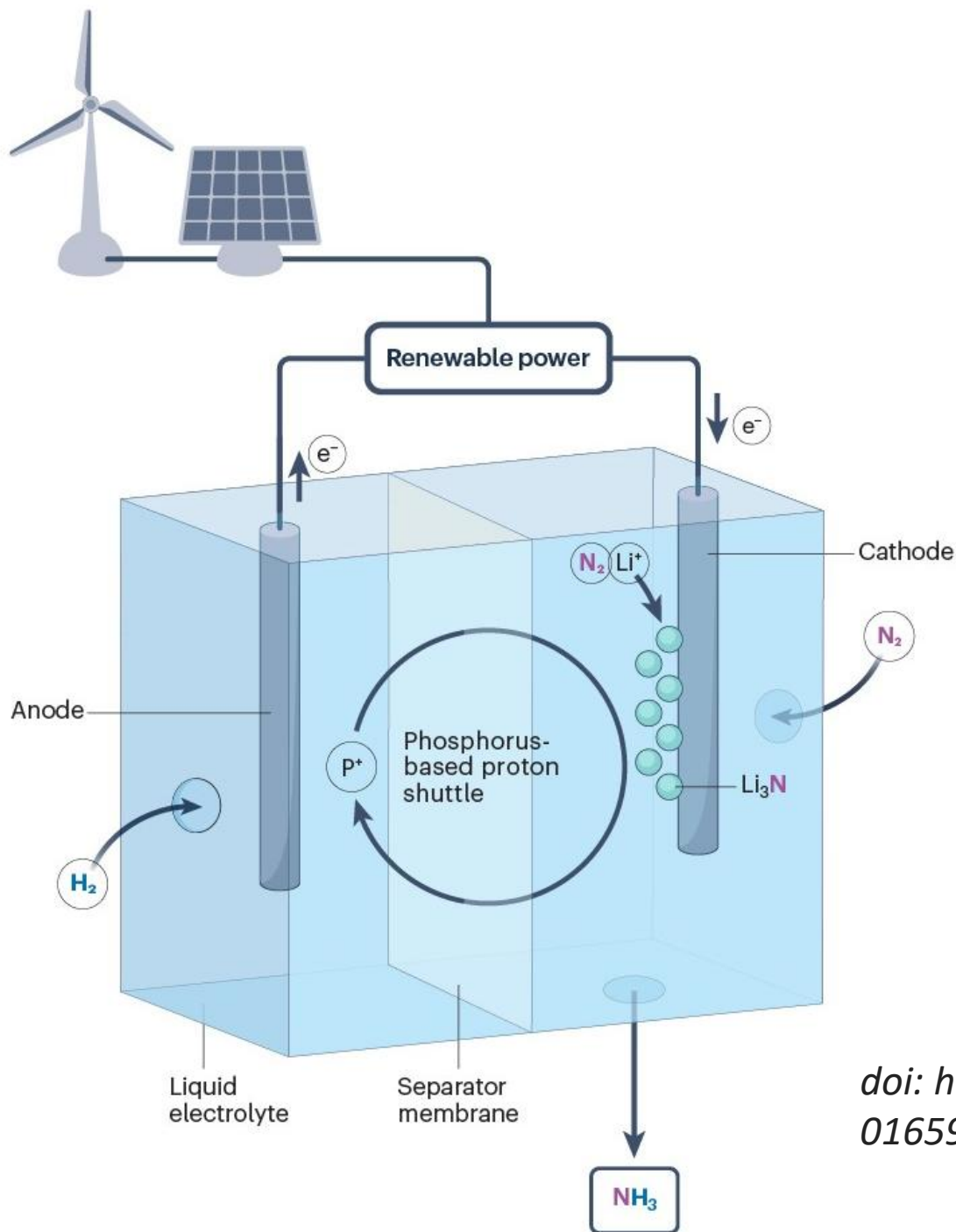
n : moles of product formed,

F : Faraday constant (96,485 C mol⁻¹),

z : number of electrons transferred per molecule of product, and

Q : total charge passed.

High FE indicates high reaction selectivity and energy efficiency.

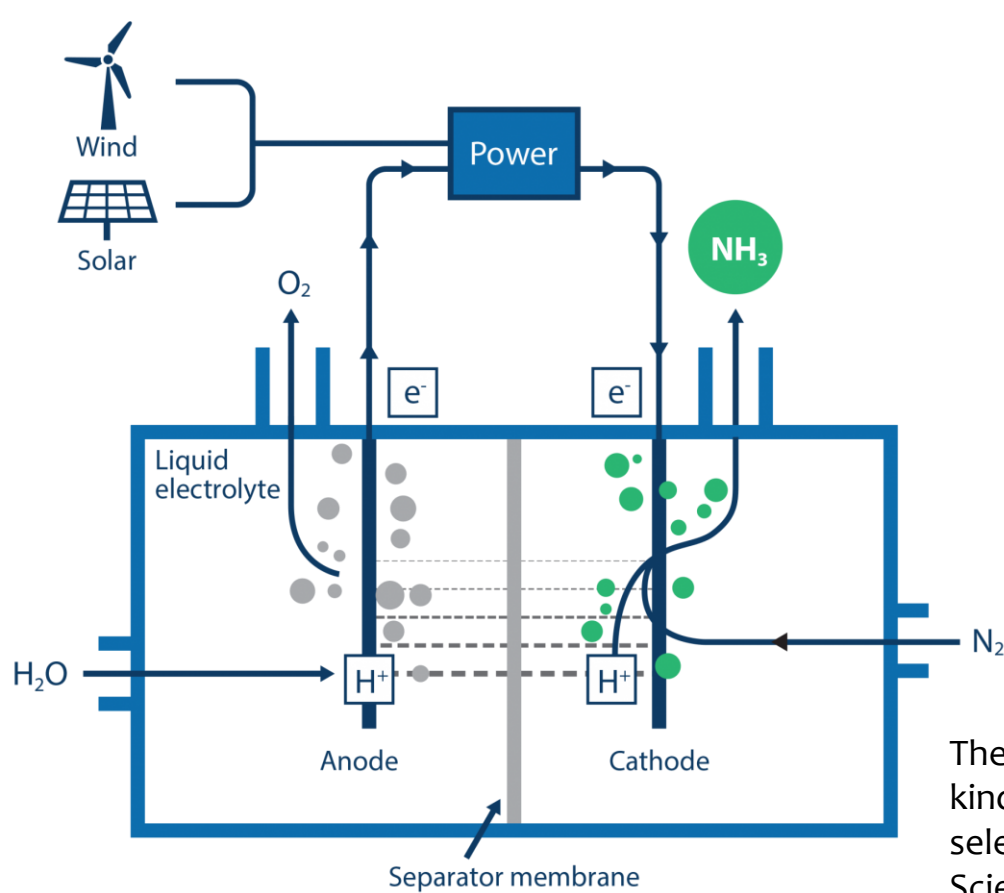


Jupiter Ionics in Melbourne, Australia, spun off from Monash University, Melbourne, in 2021.

It is a curious quirk of chemistry that when lithium atoms work together, they can break one of the strongest known chemical bonds. Lithium can take the triple-bonded nitrogen molecule (N_2) and, under ambient conditions, break it in two.

**A report in Nature OUTLOOK
24 May 2023**

doi: <https://doi.org/10.1038/d41586-023-01659-w>



The MacFarlane Simonov Ammonia Cell

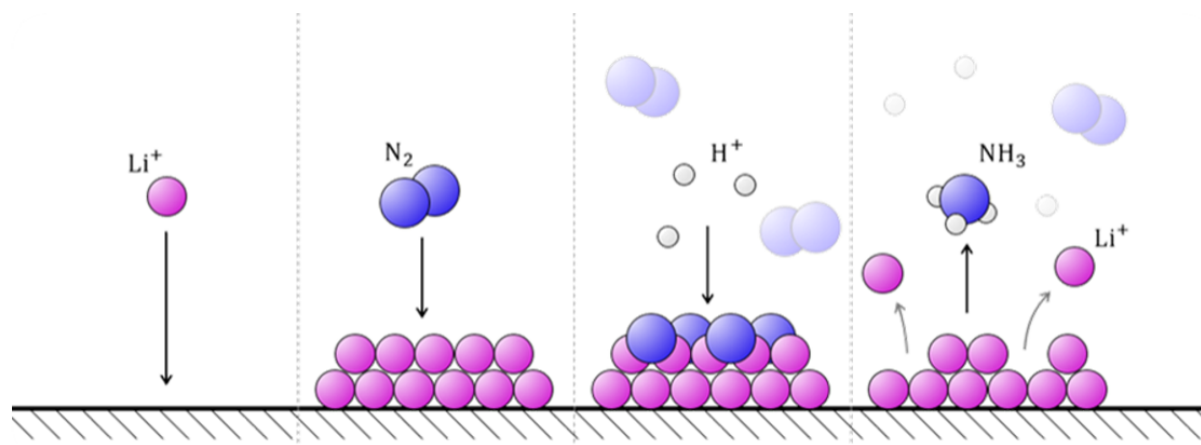
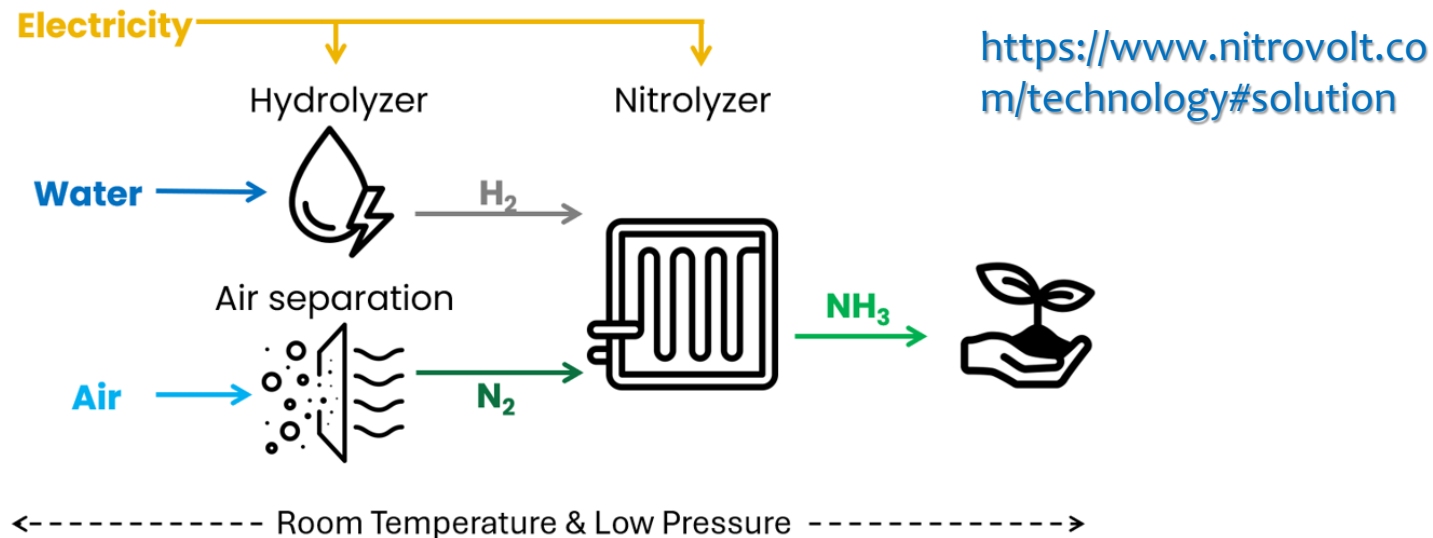
*A cell comprises two separated electrodes in a conductive liquid or gel electrolyte. Battery cells use chemical reactions to generate electrical energy. Conversely, electrolytic cells like ours use electrical energy to drive chemical reactions.

The MacFarlane Simonov Ammonia Cell is the first of its kind to demonstrate ammonia generation with 100% selectivity, and has shown good stability in lab tests. *Science*, 2021, 372, 1187-1191, 10.1126/science.abg2371



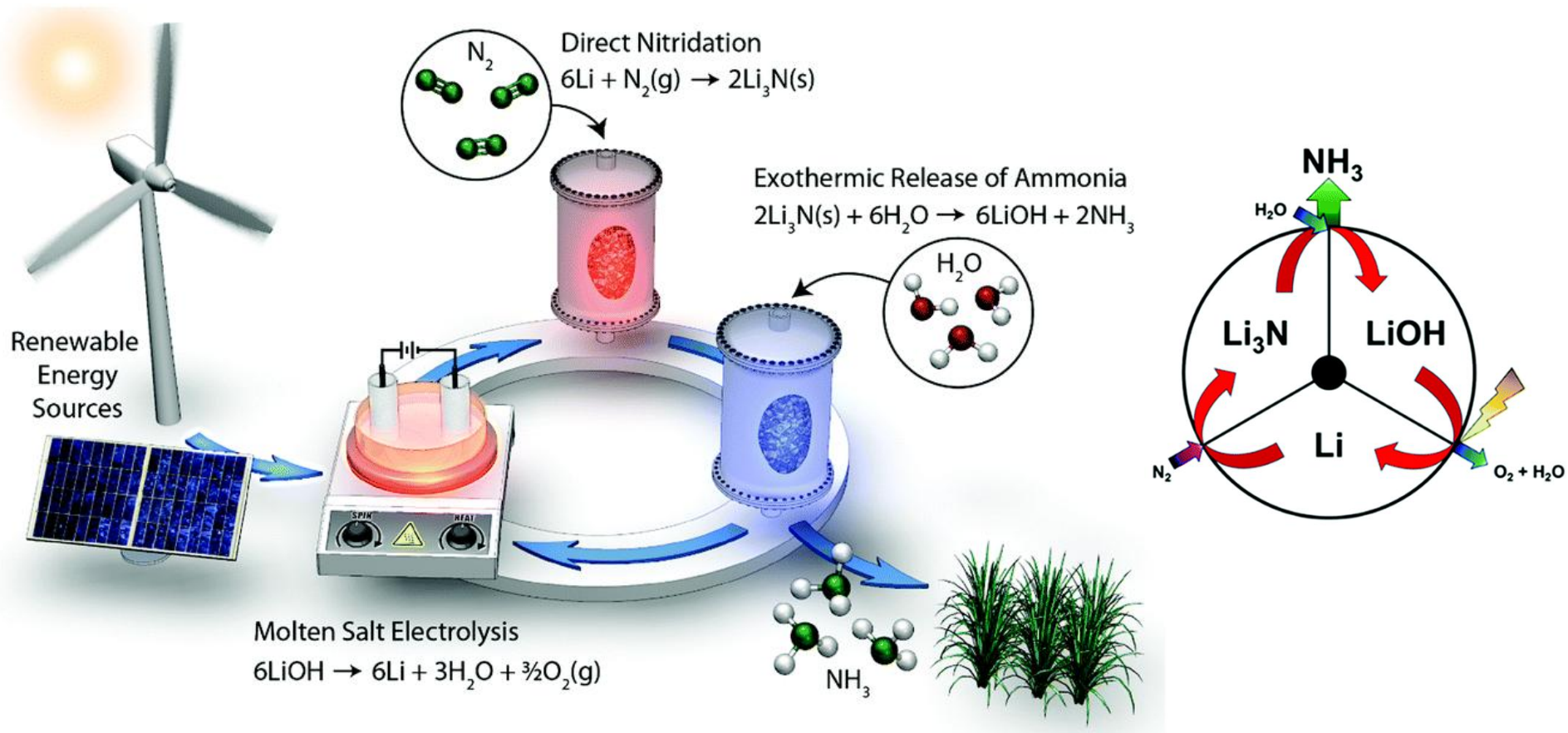
Our Technology

We use air, water, and renewable energy in a patented electrochemical process to produce green ammonia.



The process happening inside the Nitrolyzer unit is based on the reduction of lithium salt to metallic lithium. This metallic lithium will then react with nitrogen to form a nitride. The nitride is easily protonated by hydrogen sourced via water splitting. This leads to the formation of ammonia, and the lithium is released back into solution, to be recycled and start the reaction again. This process happens continuously in our patent-pending flow-cell reactor, making ammonia on demand.

Ammonia synthesis from N_2 and H_2O using a lithium cycling electrification strategy at atmospheric pressure



Step 1: LiOH electrolysis: Total cell: $6\text{LiOH} \rightarrow 6\text{Li} + 3\text{H}_2\text{O} + \frac{3}{2}\text{O}_{2(\text{g})}$

Cathode: $6\text{Li}^+ + 6\text{e}^- \rightarrow 6\text{Li}$

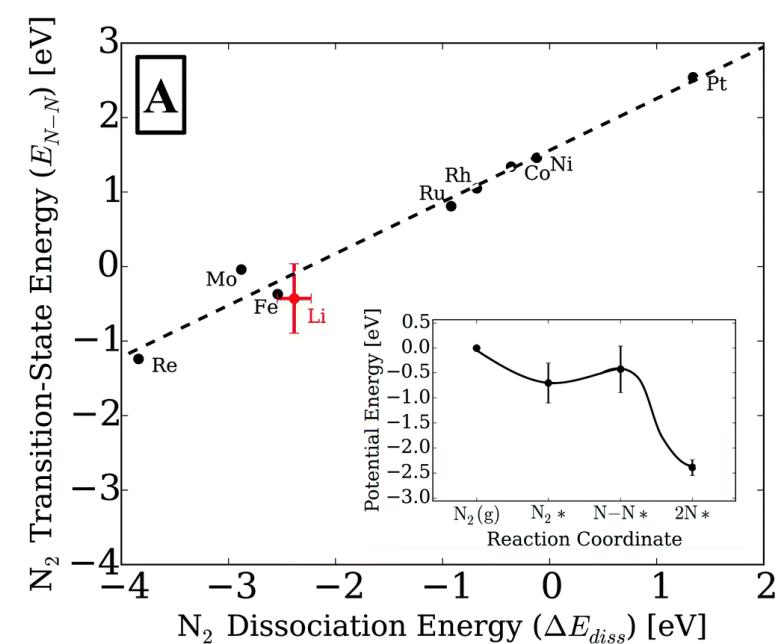
Anode: $6\text{OH}^- \rightarrow 3\text{H}_2\text{O} + \frac{3}{2}\text{O}_{2(\text{g})} + 6\text{e}^-$

Step 2: Direct reaction of metallic Li with N_2 to form Li_3N

$6\text{Li} + \text{N}_{2(\text{g})} \rightarrow 2\text{Li}_3\text{N}_{(\text{s})}$

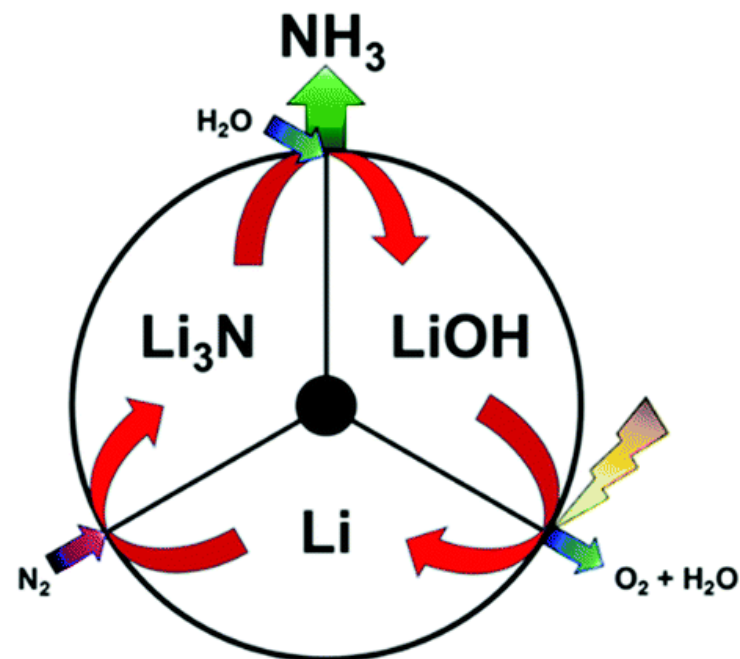
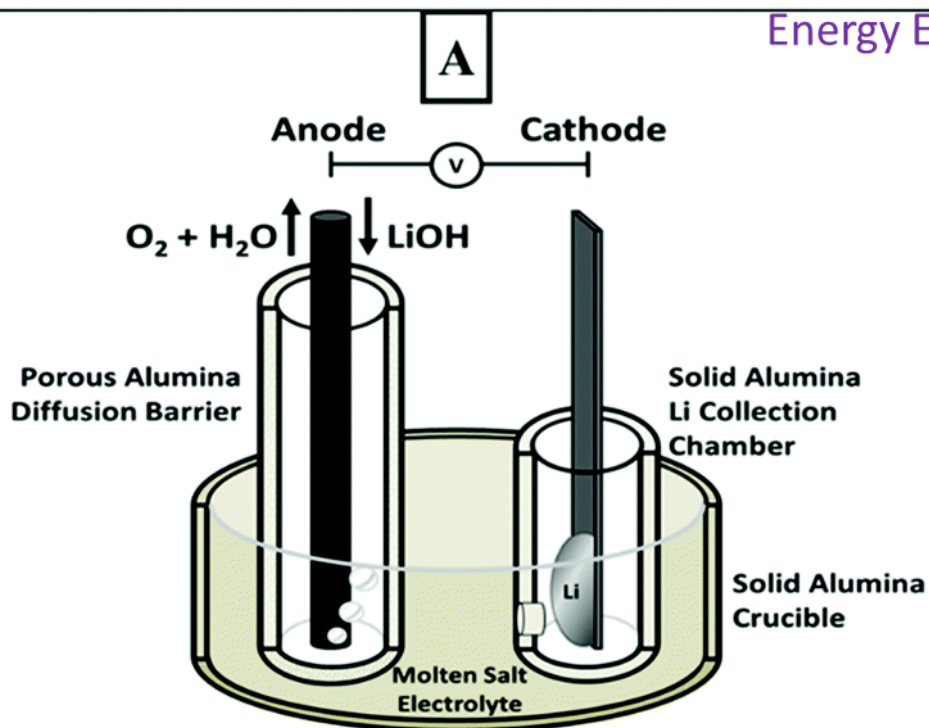
Step 3: Release of NH_3 by reaction with H_2O :

$2\text{Li}_3\text{N}_{(\text{s})} + 6\text{H}_2\text{O} \rightarrow 6\text{LiOH} + 2\text{NH}_3$



The three steps of the demonstrated process are LiOH electrolysis, direct nitridation of Li, and the exothermic release of ammonia from Li_3N , which reproduces the LiOH, completing the cycle. The process uses N_2 and H_2O at atmospheric pressure and reasonable temperatures, and, while approaching industrial-level electrolytic current densities, we report an initial current efficiency of 88.5% toward ammonia production

Energy Environ. Sci., 2017,10, 1621-1630



Membrane electrode assembly: The sequential parts of membrane electrode assembly (MEA) are anode diffusion layer (ADL), anode catalyst layer (ACL), electrolyte membrane, cathode catalyst layer (CCL) and cathode diffusion layer (CDL). Both the electrodes are supported on macroporous carbon paper or carbon cloth called as diffusion layer backing.

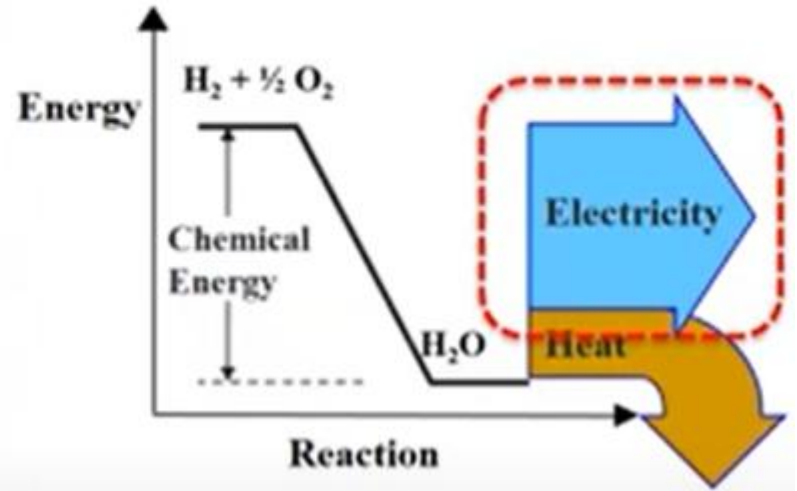
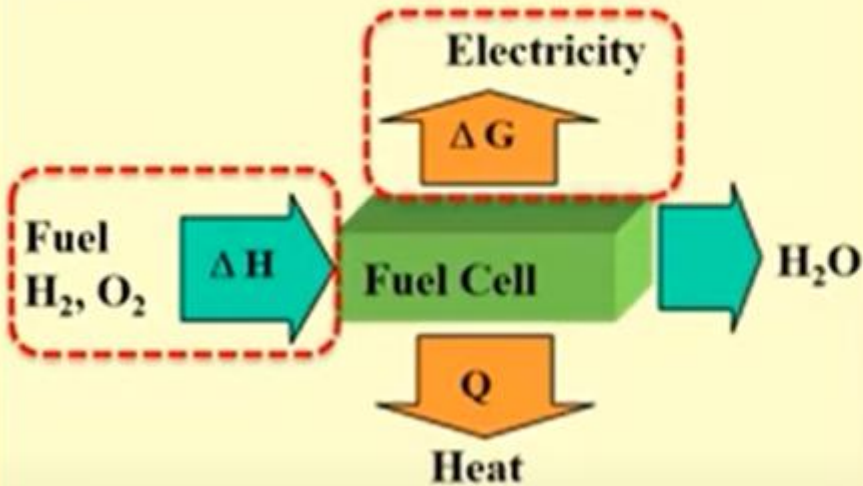
Electrolyte membrane: The most common and important part in the MEA is the electrolyte membrane which separates the anode and the cathode compartment and also acts as a proton carrier. **Perfluorinated polymer membrane, known as Nafion[®]**, is the most commonly used membrane in the passive Direct Methanol Fuel Cell (DMFC) due to its high chemical stability, mechanical strength, thermal stability and excellent proton conductivity (0.1 S cm^{-1} in the fully hydrate state).

Requirements of electrolyte membrane The common requirements of passive DMFCs membranes to expand the passive DMFC commercialization are & **Low methanol crossover (MCO) & High ionic conductivity & High mechanical and chemical durability & High stability and strength of membrane & High operation temperature & Low cost & Low Ru crossover** (if anode catalyst contains Ru)

Requirements of anode catalyst Anode electrode serves two purposes; it effectively collects electrons and also delivers/ collects reactants (MeOH) and product (CO_2) species. Thus, the anode electrode must also provide: **High catalytic activity & High porosity & High electrical conductivity & High surface area & Highly stable and durable & Low cost & Significantly lower affinity to CO.**

Fuel Cell

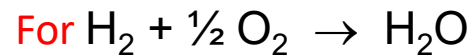
Fuel cell converts the chemical energy of fuel into thermal and electrical energy.



$$\text{Intrinsic efficiency } (\varepsilon_i) = \frac{\text{Electricity}}{\text{Chemical Energy}}$$

$$\varepsilon_i = \frac{\Delta G}{\Delta H}$$

In fuel cell, the change in Gibbs Free Energy (ΔG), is the part of the reaction enthalpy change (ΔH) that is converted into electrical energy: $\Delta G = \Delta H - T\Delta S$



$$\Delta S = (s_f)\text{H}_2\text{O} - (s_f)\text{H}_2 - \frac{1}{2} (s_f)\text{O}_2$$

$$\Delta H = (h_f)\text{H}_2\text{O} - (h_f)\text{H}_2 - \frac{1}{2} (h_f)\text{O}_2$$

$$\Delta G = (g_f)\text{H}_2\text{O} - (g_f)\text{H}_2 - \frac{1}{2} (g_f)\text{O}_2$$

Temperature (T)

Gibbs Free Energy (G)

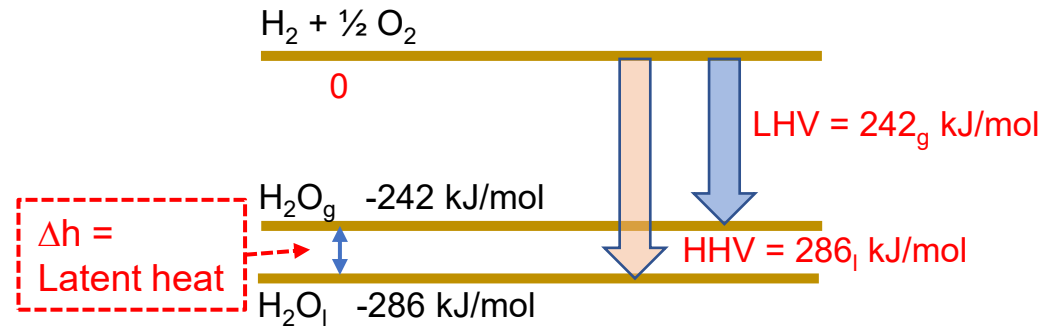
Enthalpy (H)

Entropy (S)

Efficiency loss in the Fuel Cell

High Heating value (HHV) of H_2 combustion ($\text{H}_2 + \text{excess O}_2$) is measured in calorimetric bomb: Product: **Water** [H_2O_l] @ 25°C

Low Heating value (LHV) of H_2 combustion ($\text{H}_2 + \text{excess O}_2$) is measured in calorimetric bomb: Product: **Vapour** [H_2O_g] @ 25°C



Intrinsic Energy (ΔH)

- This is the **total energy content** of the fuel, released when it reacts completely with an oxidant to form products (e.g., $\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$).
- It includes both the **useful electrical work** (ΔG , Gibbs free energy) and the **heat generated** ($T\Delta S$).
- Mathematically:

$$\Delta H = \Delta G + T\Delta S$$

- For hydrogen oxidation at 25°C :

- $\Delta H = -286 \text{ kJ mol}^{-1}$ (HHV)
- $\Delta G = -237.3 \text{ kJ mol}^{-1}$
- $T\Delta S = -48.7 \text{ kJ mol}^{-1}$

$$\text{HHV} - \text{LHV} = \text{latent heat } (\Delta h) = 48.7 \text{ kJ/mol}$$

Thus, the **intrinsic (enthalpic) energy** of hydrogen is 286 kJ mol^{-1} , but only 237 kJ mol^{-1} can be converted into electrical energy under reversible conditions; the remainder appears as heat.

- **Anode:** Electrode where the fuel is oxidized (e^- s are released).
- **Cathode:** Electrode where the oxidant (often O_2) is reduced (e^- are accepted).
- **Electrolyte: membrane)** A medium that allows certain ions (e.g., H^+ or O^{2-}) to pass between the (or electrodes, forcing the e^- to travel via an external circuit (thereby delivering electric power).
- **External circuit:** the path the electrons take from the anode to the cathode to generate usable electrical current.

At the **anode** (oxidation): $H_2 \rightarrow 2H^+ + 2e^-$

At the **cathode** (reduction): $1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$

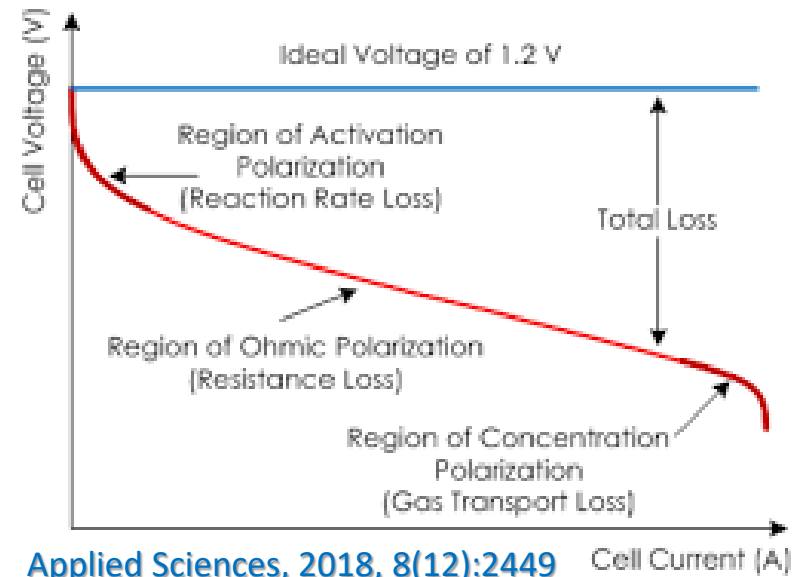
Overall cell reaction: $H_2 + 1/2O_2 \rightarrow H_2O$

In a practical fuel cell, the half-cell reactions are more complex than the simplified equations shown.

The reactant gases (H_2 and O_2) are chemisorbed on the catalyst surfaces at their respective electrodes. The reactions should therefore be represented as surface-mediated processes.



Overall cell reaction: $H_2 + 1/2O_2 \rightarrow H_2O$

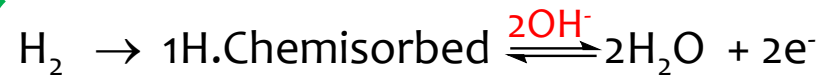


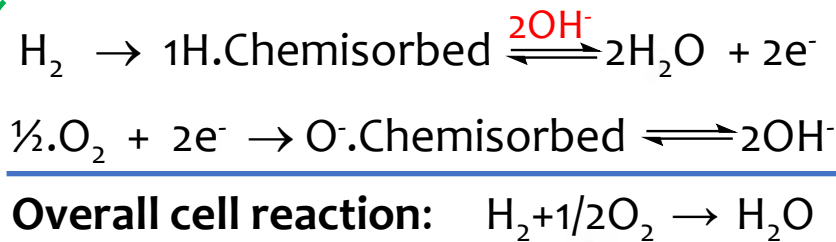
The **intrinsic energy** of a fuel in a fuel cell corresponds to its **enthalpy of reaction (ΔH)**, representing the total chemical energy available when the fuel is completely oxidized. For hydrogen, this value (286 kJ mol^{-1} at 25°C , based on the higher heating value) includes both the useful electrical energy and the heat released. Only the **Gibbs free energy change (ΔG)**—about $237.3 \text{ kJ mol}^{-1}$ —is theoretically convertible into electrical work, while the remaining **$T\Delta S$ ($\approx 48.7 \text{ kJ mol}^{-1}$)** appears as thermal energy. Thus, the intrinsic energy defines the upper thermodynamic limit of the fuel's energy content, and the ratio $\Delta G/\Delta H$ (≈ 0.83 for hydrogen) represents the maximum theoretical efficiency of an ideal fuel cell operating reversibly.

The fuel cell's efficiency (η) under ideal, reversible conditions is: 83%

$$\eta = \frac{\Delta G}{\Delta H}$$

These observations indicate that the equilibrium potential of a fuel cell is determined by the equilibrium between the chemisorbed gases and the electrolyte, rather than between the free gases and the electrolyte. Since chemisorption is not reversible for this purpose—the heat of chemisorption is dissipated before reaction occurs—a higher heat of chemisorption causes a greater deviation of the cell potential from its theoretical value. Experimental results show that the open-circuit potential varies with the heat of chemisorption of hydrogen on the catalyst, demonstrating that the equilibrium involves chemisorbed hydrogen. Consequently, the electrode catalyst plays a dual role: it not only governs the open-circuit potential but also enhances the kinetics of the electrochemical reactions.





J. Chem. Edu.
1959, 36, 68-73

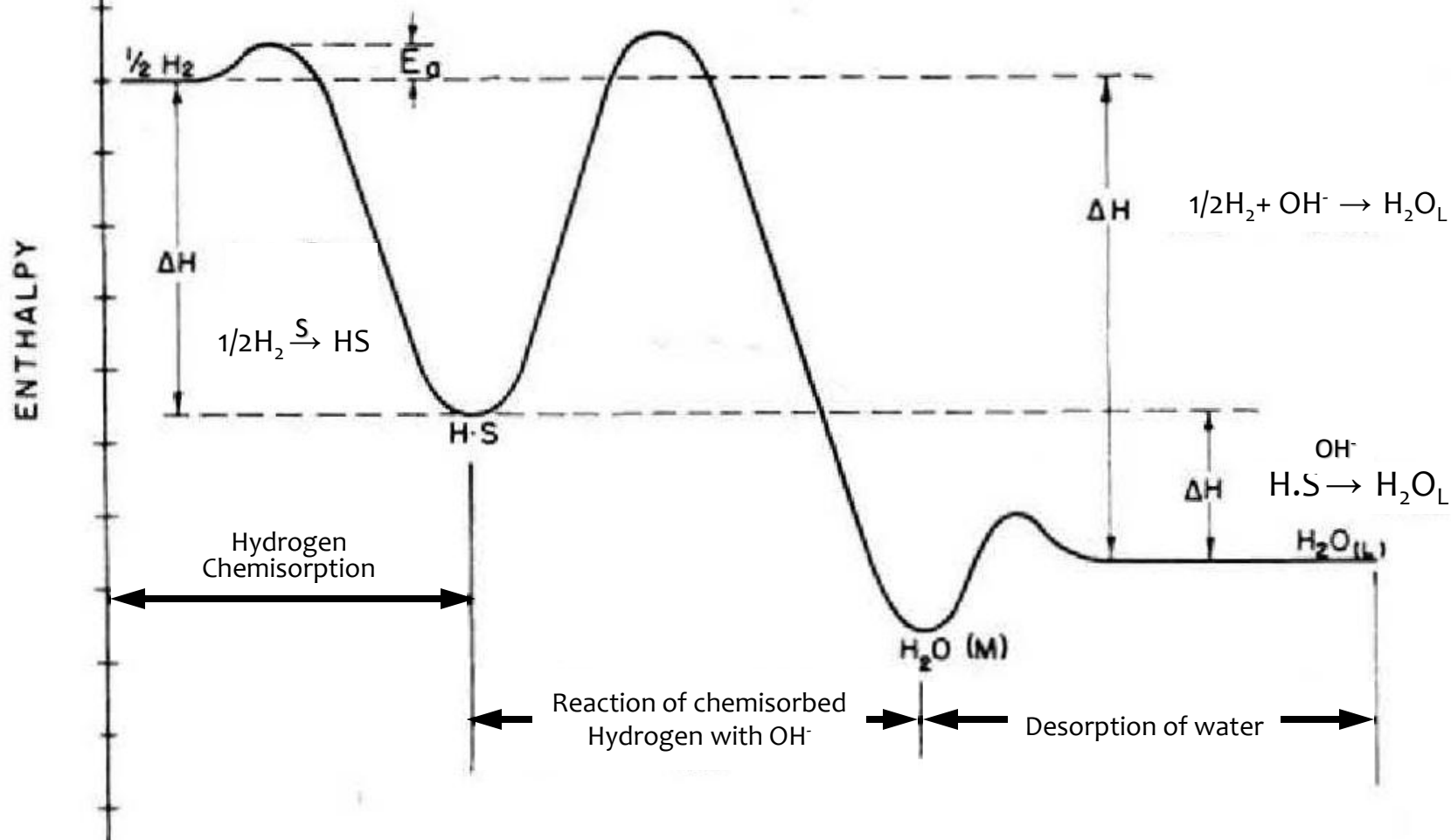
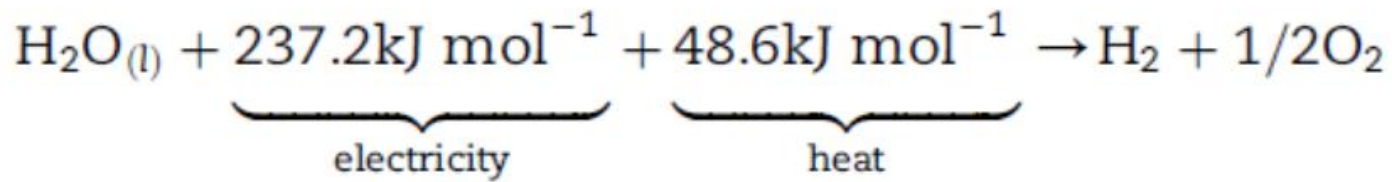
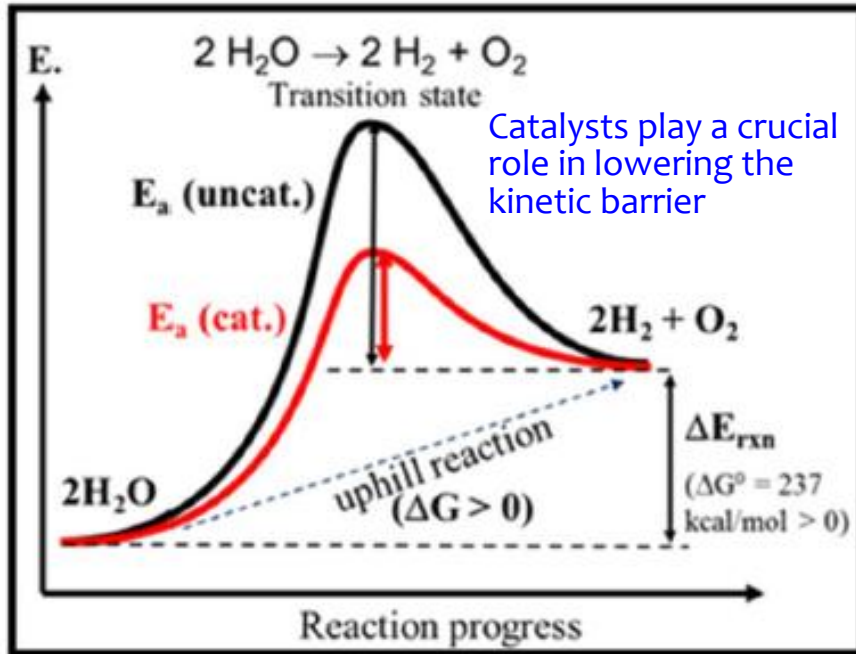


Figure 6. Course of the reaction at the hydrogen electrode.



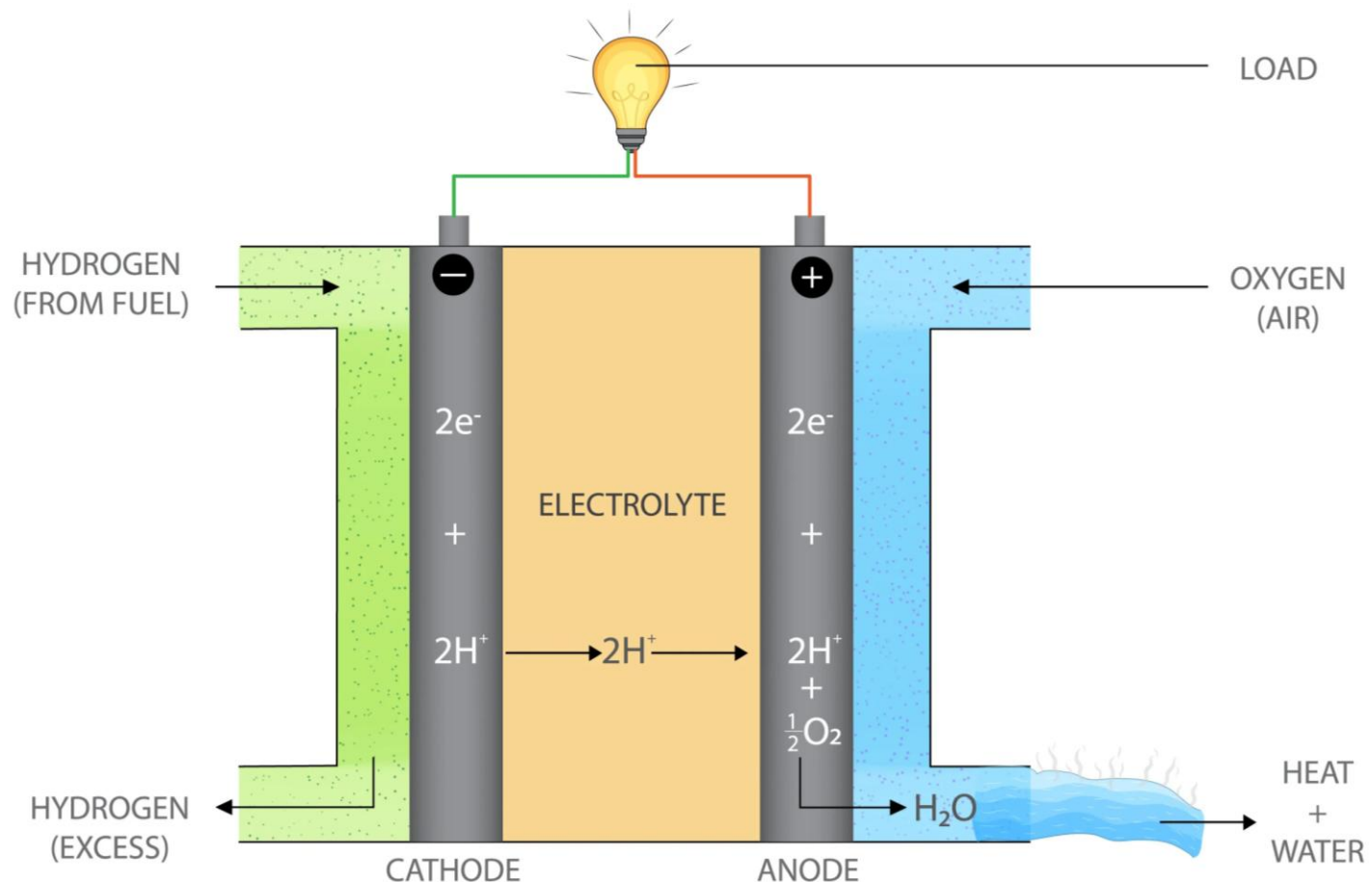
a



Yttria (Y_2O_3) is added to zirconia to create yttria-stabilized zirconia (YSZ) — a stable, oxygen-ion-conducting ceramic that is crucial for the electrolyte and anode support in SOFCs.

- Platinum (Pt).
- Alloy catalysts such as Pt–Ru, Pt–Ni, and Pt–Co improve CO tolerance
- Non-precious catalysts, including transition-metal oxides (e.g., MnO_2 , Co_3O_4 , Fe–N–C complexes), nitrogen-doped carbon materials, and conductive polymers
- In solid oxide fuel cells (SOFCs), high-temperature operation allows the use of non-noble catalysts such as Ni-based cermets at the anode and perovskite-type oxides (e.g., $\text{La}_{1-x}\text{Sr}_x\text{MnO}_3$) at the cathode

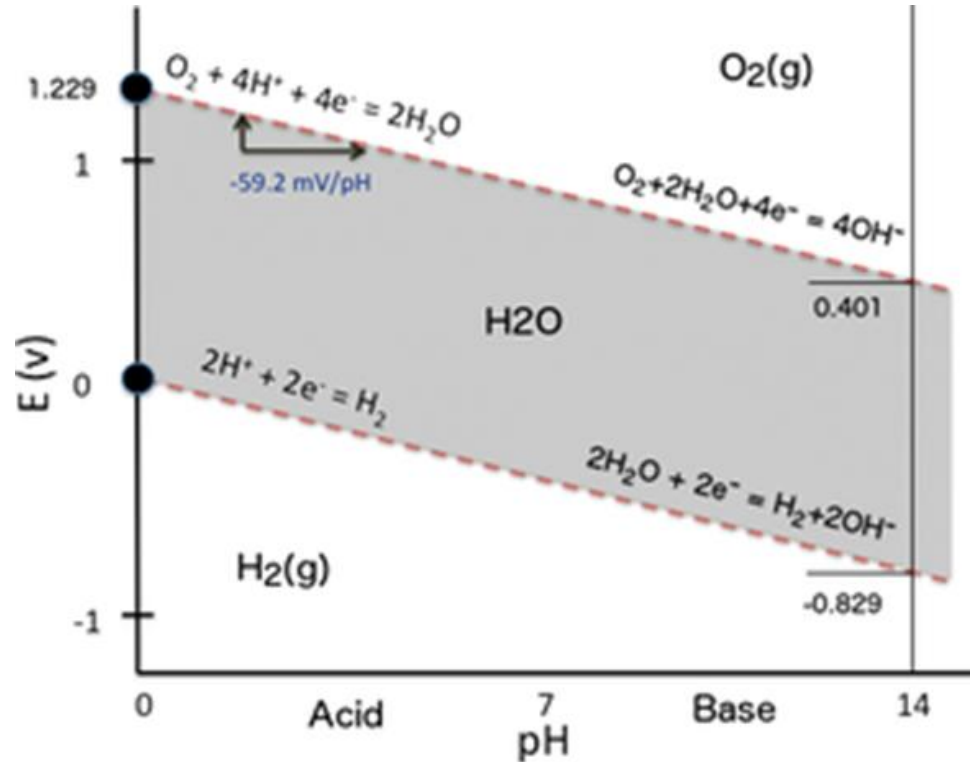
A fuel cell is an electrochemical device that continuously converts the chemical energy of a fuel (typically hydrogen) and an oxidant (usually oxygen or air) into electrical energy, accompanied by heat and reaction products such as water. Unlike a battery, which operates using stored reactants in a closed system, a fuel cell requires a continuous external supply of fuel and oxidant to sustain its operation.



Fuel cells are electrochemical devices to convert chemical energy into electrical energy. They offer higher electrical efficiency ($\geq 40\%$) compared to conventional power generation systems such as reciprocating engine ($\approx 35\%$), turbine generator ($30\text{--}40\%$), photovoltaics ($6\text{--}24\%$) and wind turbines ($\approx 25\%$). Other advantages include fuel flexibility, base load and off-grid applications. Noise-free operation and modular construction are added features that allow its further application in small residential, automotive, portable electronic devices, as well as off-grid electricity generation in remote areas, marine and space applications.

H_2 has the highest gravimetric energy density. When it is used as the fuel in a fuel cell, it features not only high efficiency in energy conversion, but also produces zero pollution as it emits only water as a byproduct. Efforts on water splitting cells for H_2 production from renewable sources and fuel cells for effective conversion of H_2 to electricity has become a global drive towards a sustainable power package of the future.

The thermodynamic potential is 1.23 V at 25 °C and 1 atm. However, due to the kinetic barrier for the reaction, water electrolysis requires a higher potential than thermodynamic potential (1.23 V) to overcome the kinetic barrier. The excess potential is also known as overpotential (η) which mainly comes from the intrinsic activation barriers present on both anode and cathode.

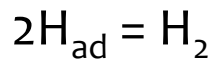
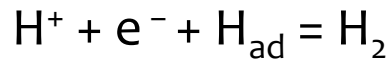
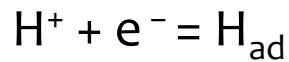


Overpotential serves as a quantitative descriptor of catalytic performance:

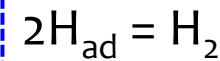
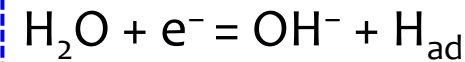
Low overpotential → high catalytic activity and efficiency

High overpotential → sluggish kinetics and poor catalytic performance

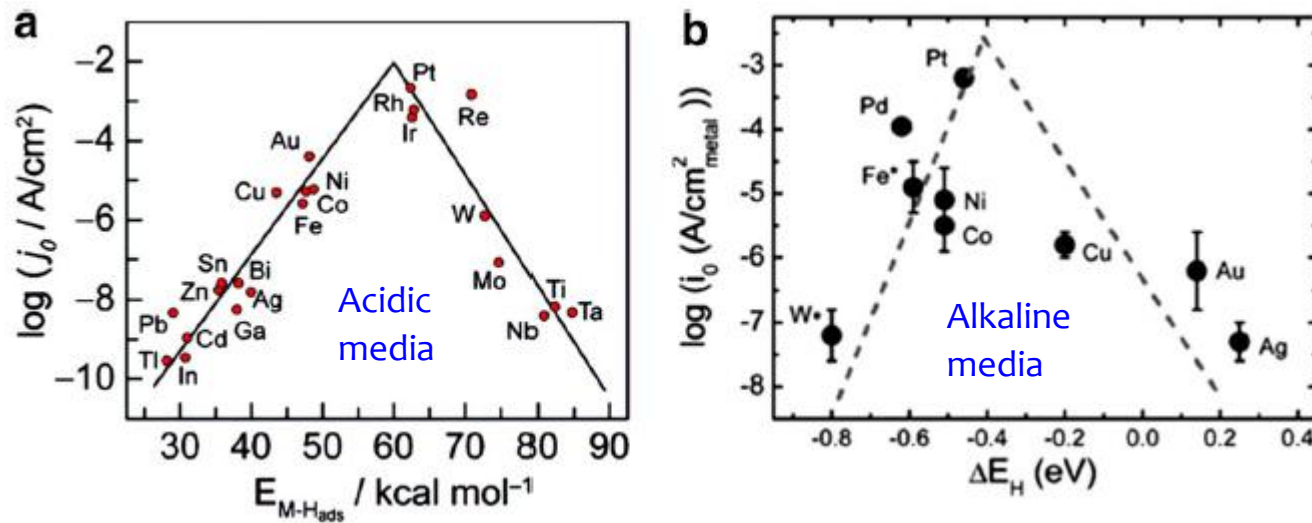
H_2 evolution Reaction in $pH < 7$



H_2 evolution Reaction in $pH > 7$



It is vital to trade off H_{ad} , hydroxy adsorption (OH_{ad}), and water dissociation from the catalytic surface for HER activity in alkaline media. The free energy of hydrogen adsorption (ΔG_H) is widely accepted to be a descriptor for a hydrogen evolution material. A moderate value of hydrogen binding energy will benefit HER process.

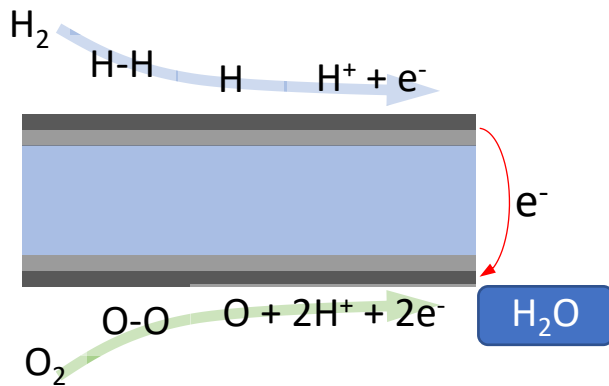


Volcano plots: a exchange current density vs. the M–H bond energy for each metal surface; b exchange current density on monometallic surfaces vs. the calculated HBE (for alkaline media)

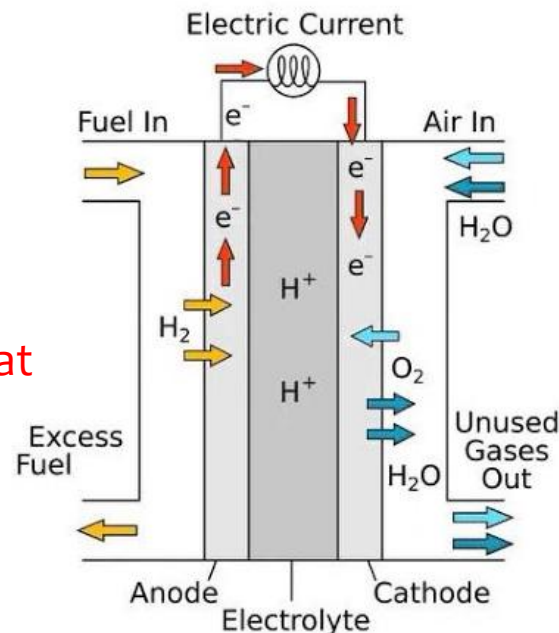
A fuel cell is an electrochemical cell that converts the chemical energy of a fuel (often hydrogen) and an oxidizing agent (often oxygen) into electricity through a pair of redox reactions.

Fuel cells are different from most batteries in requiring **a continuous source of fuel and oxygen (usually from air) to sustain the chemical reaction**, whereas in a battery the chemical energy usually comes from metals and their ions or oxides that are commonly already present in the battery, except in flow batteries. Fuel cells can produce electricity continuously for as long as fuel and oxygen are supplied.

Fuel Cell



Overall Reaction

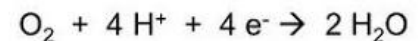


AT THE ANODE (- electrode)
OXIDATION TAKES PLACE

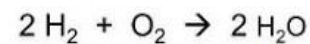


These H⁺ ions move through the electrolyte (often a polymer or membrane)

AT THE CATHODE (+ electrode)
REDUCTION TAKES PLACE



OVERALL REACTION



Selective Proton Transport in Fuel Cell Electrolytes:

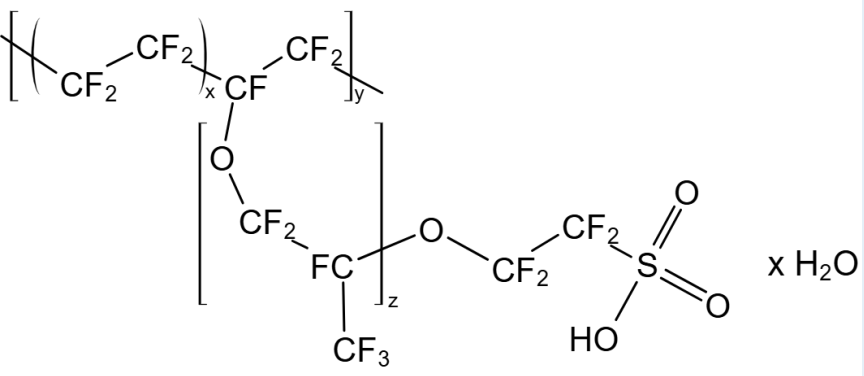
In a proton-exchange membrane fuel cell (PEMFC), the electrolyte (membrane) is specifically designed to conduct protons (H^+) while blocking electrons and gases such as H_2 and O_2 . This selective ion transport is essential to maintain charge balance and electrical isolation between the electrodes.

1. Structure of the Electrolyte

The most common electrolyte is Nafion, a **perfluorosulfonic acid (PFSA)** polymer consisting of:

- A hydrophobic fluorocarbon backbone (like Teflon) for mechanical and chemical stability.
- Hydrophilic sulfonic acid ($-SO_3H$) side groups that attract and hold water.

When hydrated, the sulfonic acid groups dissociate, forming mobile protons (H^+) and negatively charged $-SO_3^-$ sites that are fixed to the polymer framework.

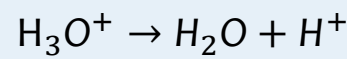


Nafion is currently a brand of the Chemours company

Mechanism of Proton Conduction

H^+ move through the membrane via two primary mechanisms:

- **Vehicle mechanism:** Protons associate with H_2O molecules to form hydronium ions (H_3O^+), which diffuse through interconnected water channels.



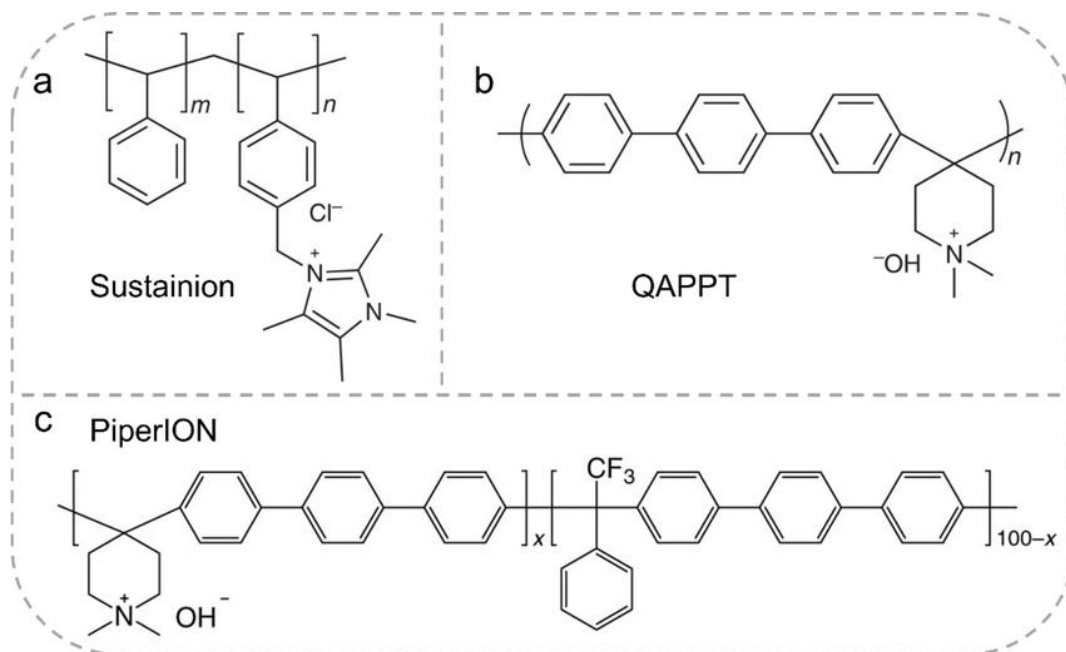
- **Grotthuss (hopping) mechanism:** Protons "hop" along a network of H-bonds between H_2O molecules and SO_3H^- groups, rapidly transferring charge without significant mass transport.

Alkaline polymer electrolytes (anion exchange membranes, AEMs) are being developed to replace liquid KOH.

Examples: quaternary ammonium–functionalized polymers (e.g., FAA-3, Sustainion®, PiperION™).

Advantages: reduced CO₂ sensitivity, no electrolyte leakage, improved durability.

In short, **aqueous KOH** is the traditional electrolyte for AFCs, while **solid AEMs** represent the next generation for safer and more efficient alkaline fuel cells.



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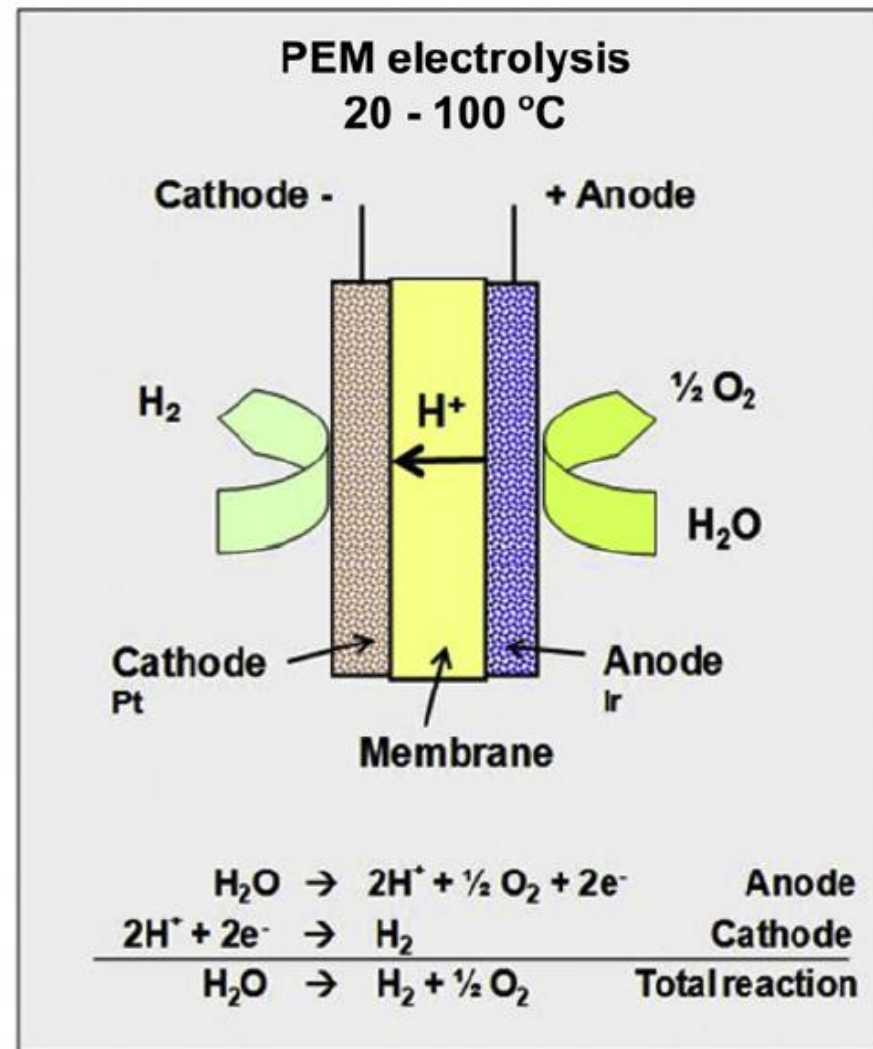
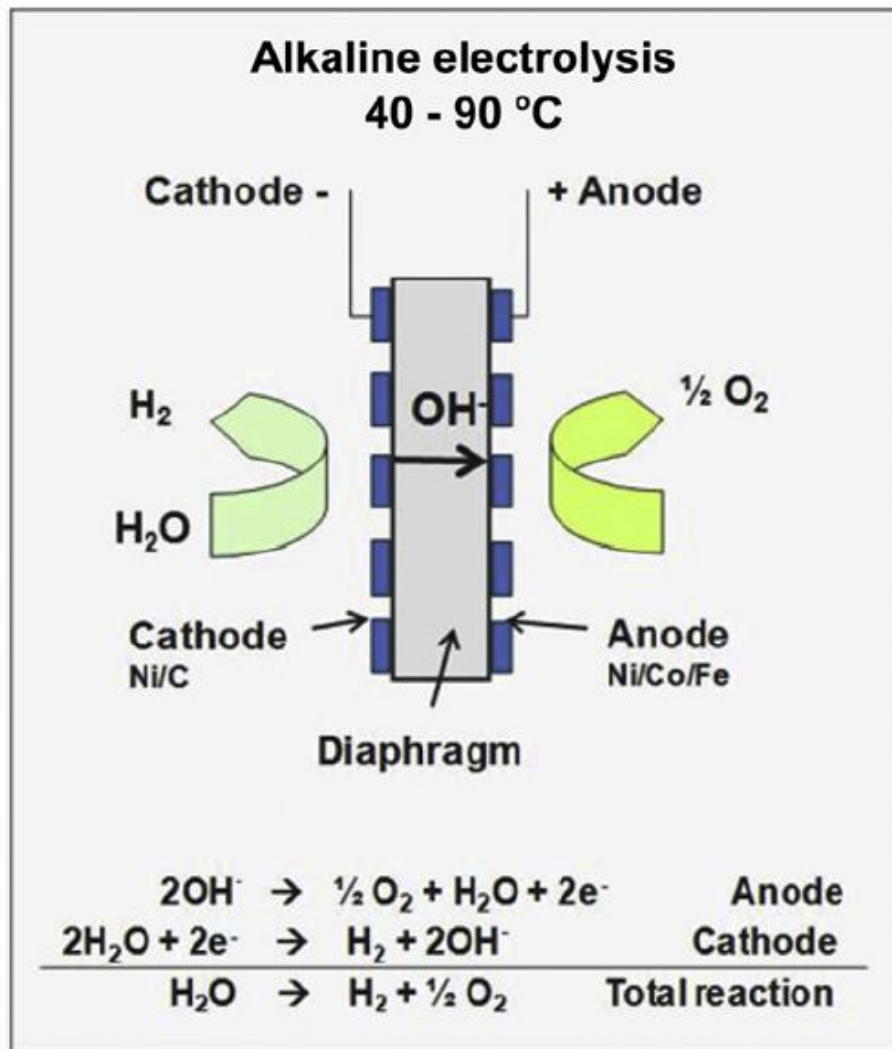
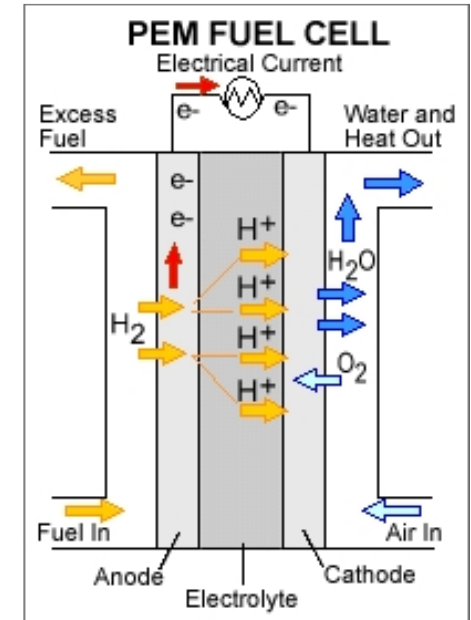
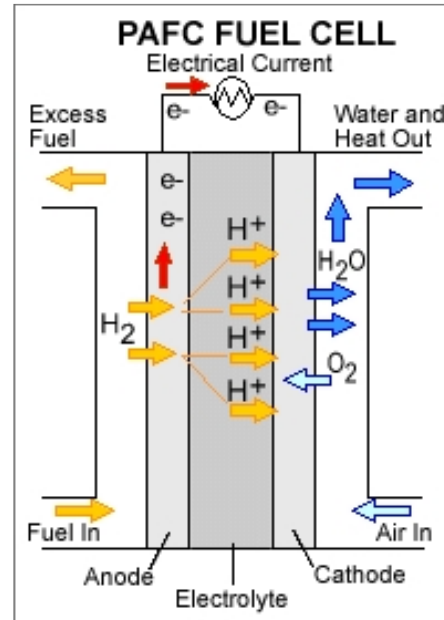
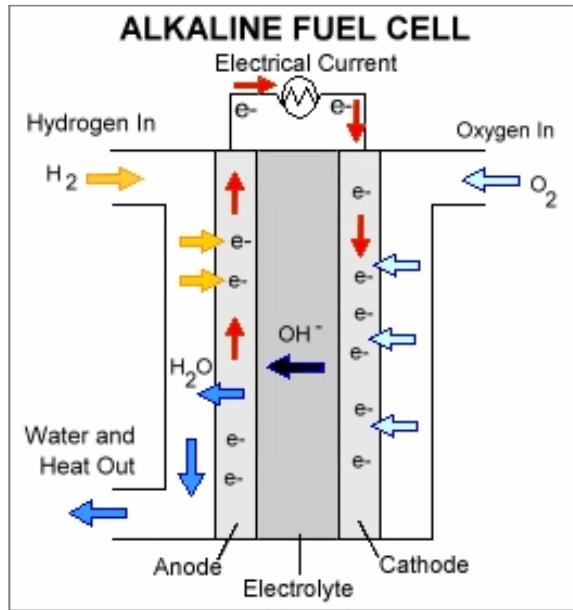


Fig. 2 – Schematic of the operating principle of an alkaline and PEM water electrolysis cell.



Phosphoric acid fuel cells (PAFC): Introduced for the first in early 1960s. Acid electrolyte cells are more tolerant to CO_2 and allow the use of normal air and nonpure hydrogen.

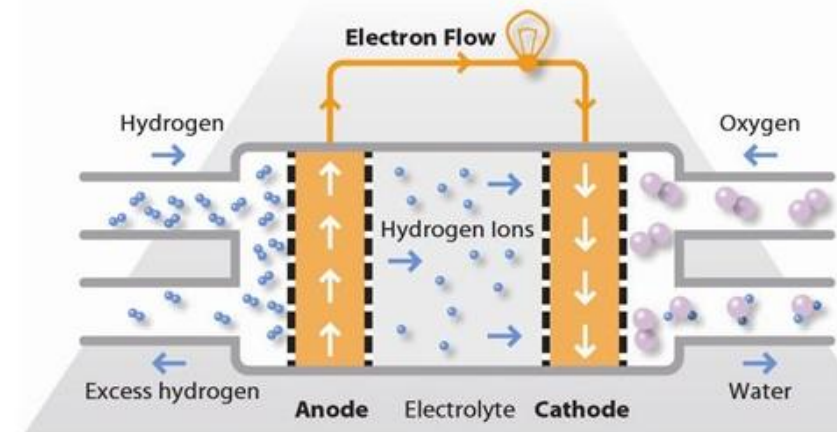
Proton exchange membrane (PEM) fuel cells also called polymer electrolyte membrane fuel cells (**PEMFC**) use a water-based, acidic polymer membrane as the electrolyte with Pt-based electrodes. Limited by its stability, it works at a relatively lower temperature ($< 100^\circ C$). Polymer which selectively allows protons to be diffused from one face to the other (fluoropolymer (PFSA) Nafion, a DuPont product).

PEMFC

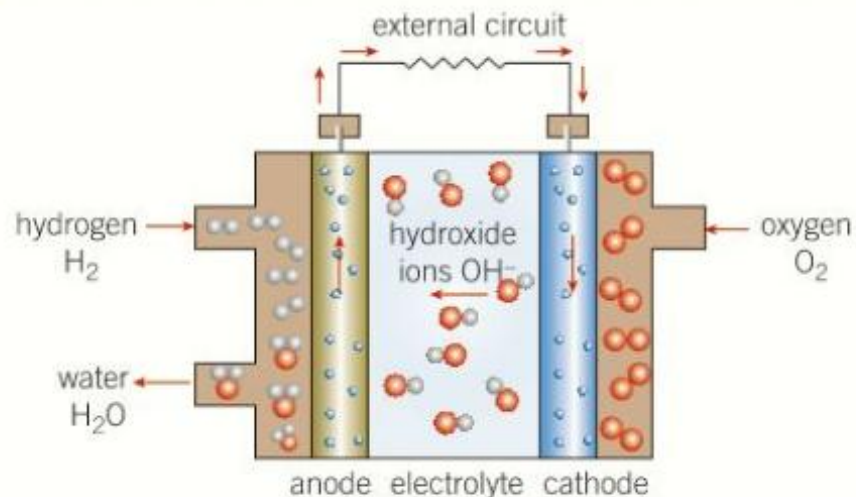
Anode : $H_2 \rightarrow 2H^+ + 2e^-$

Cathode : $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$

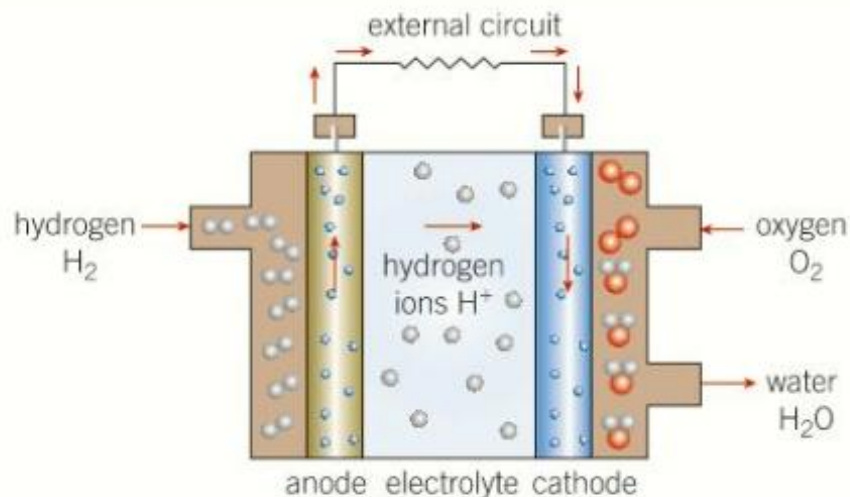
Overall : $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$



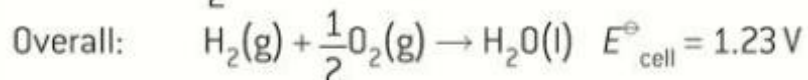
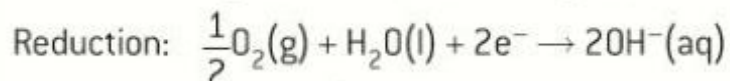
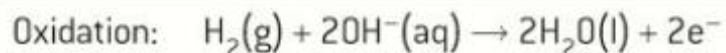
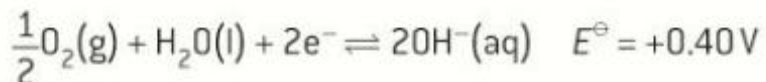
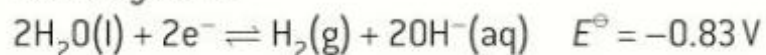
Alkali hydrogen fuel cell



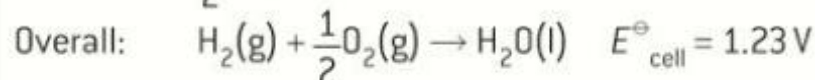
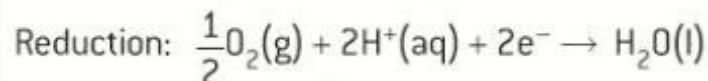
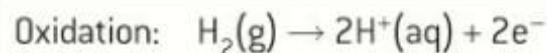
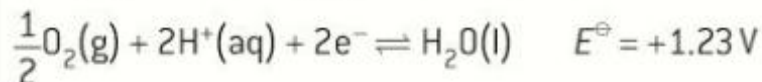
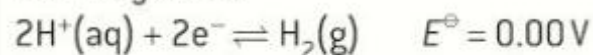
Acid hydrogen fuel cell



Redox systems



Redox systems



1. Chemical Nature and Stability

- Nafion has a fully fluorinated backbone similar to Teflon (PTFE), which gives it exceptional chemical and thermal stability.
- Under typical PEM fuel cell conditions ($\leq 100\text{ }^{\circ}\text{C}$, humidified environment), the membrane remains stable and does not release toxic species.
- However, at high temperatures ($> 250\text{ }^{\circ}\text{C}$) or in strong oxidative environments, partial decomposition can occur, generating fluorinated by-products such as HF, COF_2 , or perfluorinated fragments — all of which are toxic and corrosive.

[Environ Sci Technol. 2024 Apr 9;58(14):6415-6424. doi: 10.1021/acs.est.3c06289]

2. Environmental Persistence Nafion is not biodegradable and is extremely persistent in the environment due to its strong C–F bonds.

- During manufacture (e.g., polymerization of perfluorinated monomers) or incineration, small PFAS-related compounds can be released — including perfluorooctanoic acid (PFOA), historically used as a processing aid.
- These compounds are now recognized as persistent organic pollutants (POPs) with potential health effects (endocrine disruption, bioaccumulation, carcinogenicity).

[Environ Sci Process Impacts. 2020 Dec 16;22(12):2307-2312. doi: 10.1039/doiem00355g]

3. Current Safety and Regulations

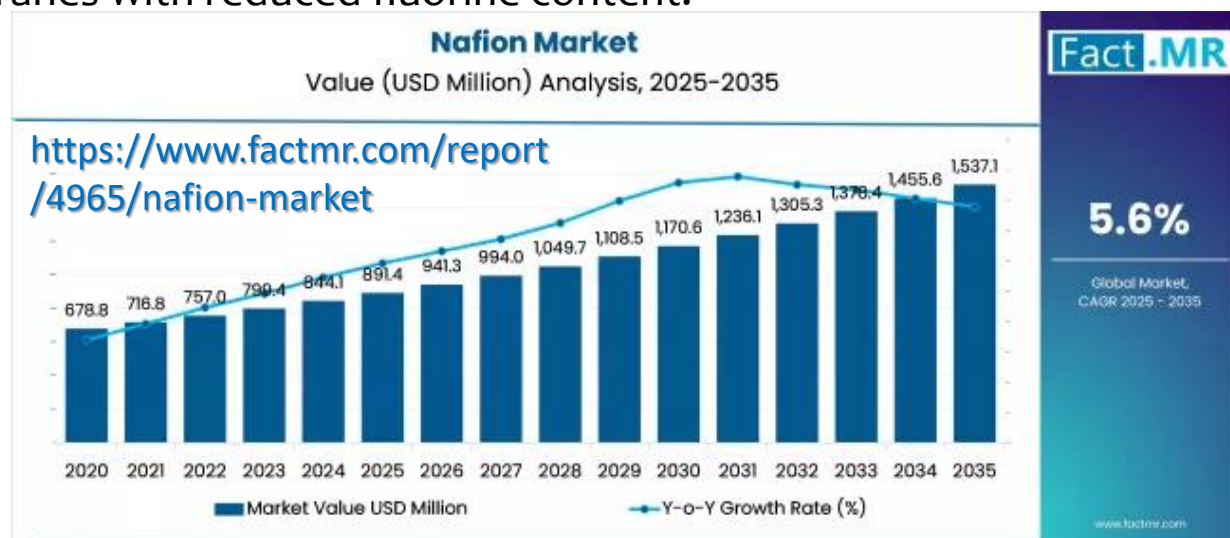
- Modern production of Nafion has largely eliminated PFOA and other long-chain PFAS processing agents, following EPA and EU REACH regulations.
- The membrane form of Nafion used in fuel cells is considered safe for industrial and laboratory use as long as it is handled below decomposition temperatures and not combusted.
- Disposal should be done via controlled high-temperature incineration with scrubbing systems to capture HF and other fluorinated emissions.

4. Emerging Alternatives

Research is increasingly focusing on PFAS-free proton-conducting membranes, such as:

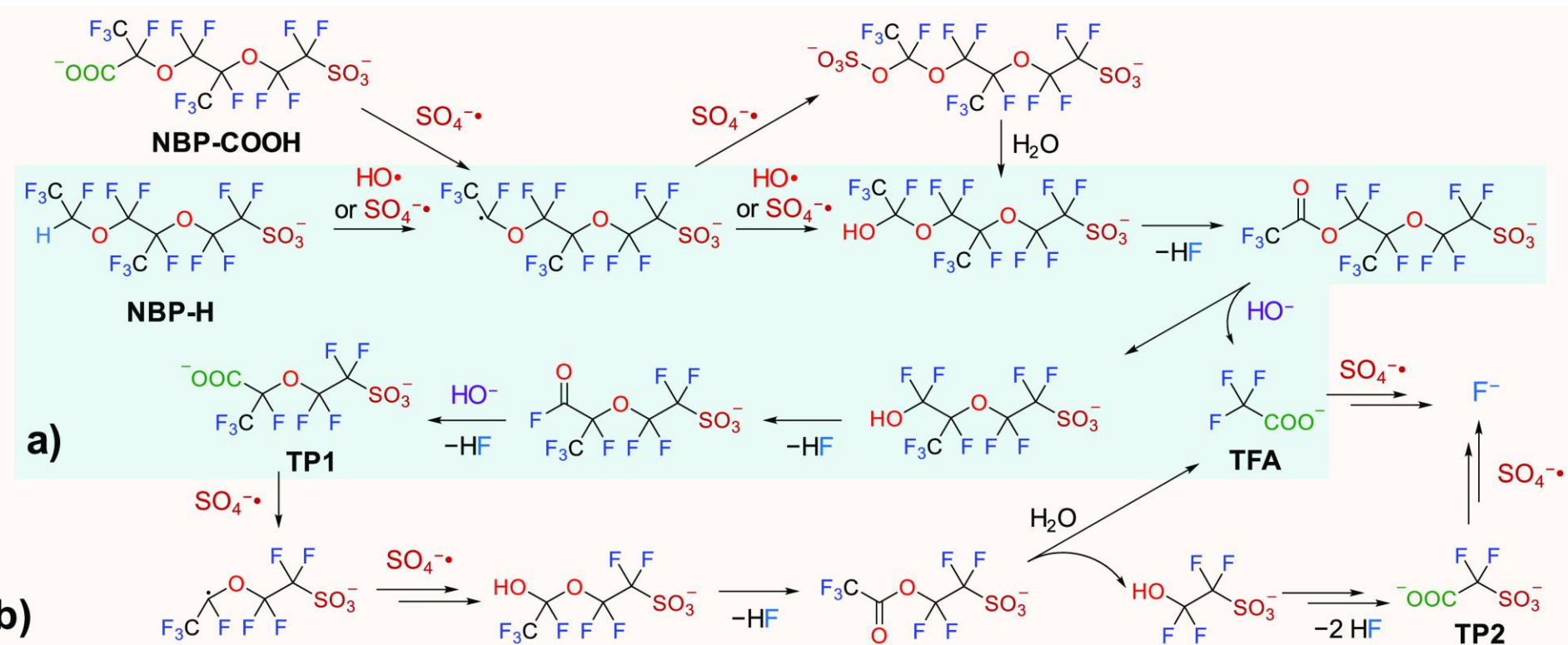
- Hydrocarbon-based ionomers (e.g., sulfonated poly(ether ether ketone), sPEEK)
- Polybenzimidazole (PBI) membranes for high-temperature PEMFCs
- Composite or bio-based membranes with reduced fluorine content.

The global Nafion Market is projected to increase from USD 891.4 million in 2025 to USD 1,537.1 million by 2035, with a **CAGR of 5.6%**, driven by rising demand for proton exchange membranes in fuel cells, hydrogen electrolyzers, and redox flow batteries.



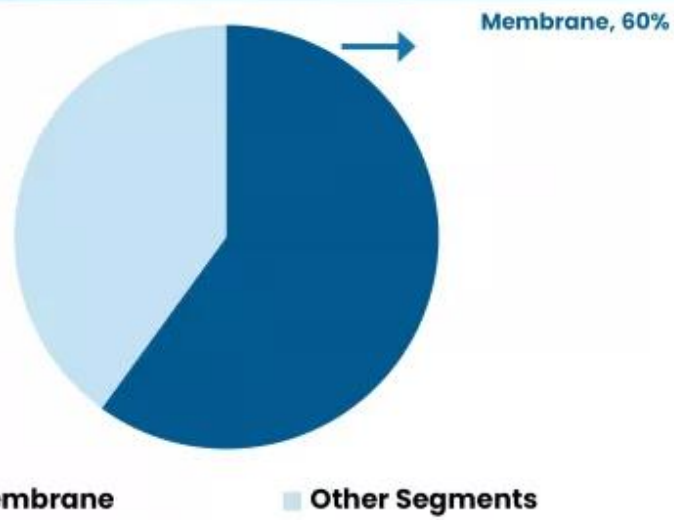
Oxidative Transformation of Nafion-Related Fluorinated Ether Sulfonates: Comparison with Legacy PFAS Structures and Opportunities of Acidic Persulfate Digestion for PFAS Precursor Analysis

[Environ Sci Technol. 2024 Apr 9;58(14):6415-6424. doi: 10.1021/acs.est.3c06289]



Nafion Market
Analysis by Form

<https://www.factmr.com/report/4965/nafion-market>



Fact.MR

100% = 891.4 USD Million

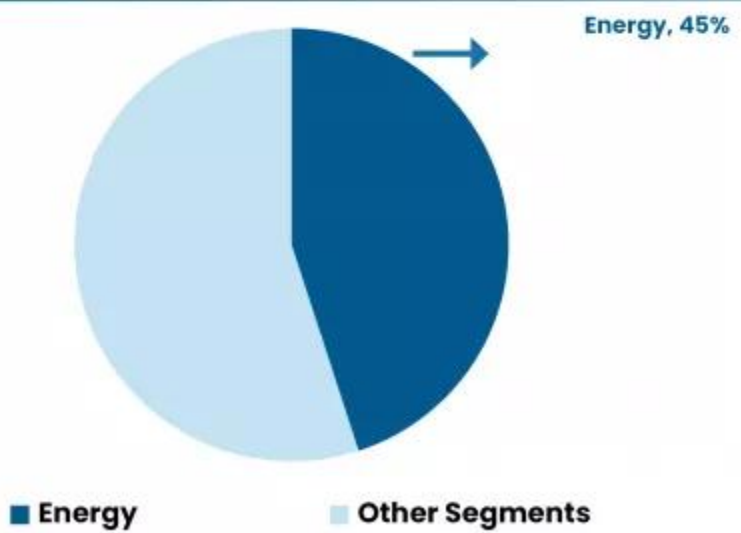
- Dispersion
- Resin
- Other Segments

www.factmr.com

Prominent players in the Nafion market include The Chemours Company, Solvay SA, AGC Inc., Dongyue Group Ltd., and others.

<https://www.factmr.com/report/4965/nafion-market>

Nafion Market
Analysis by Application



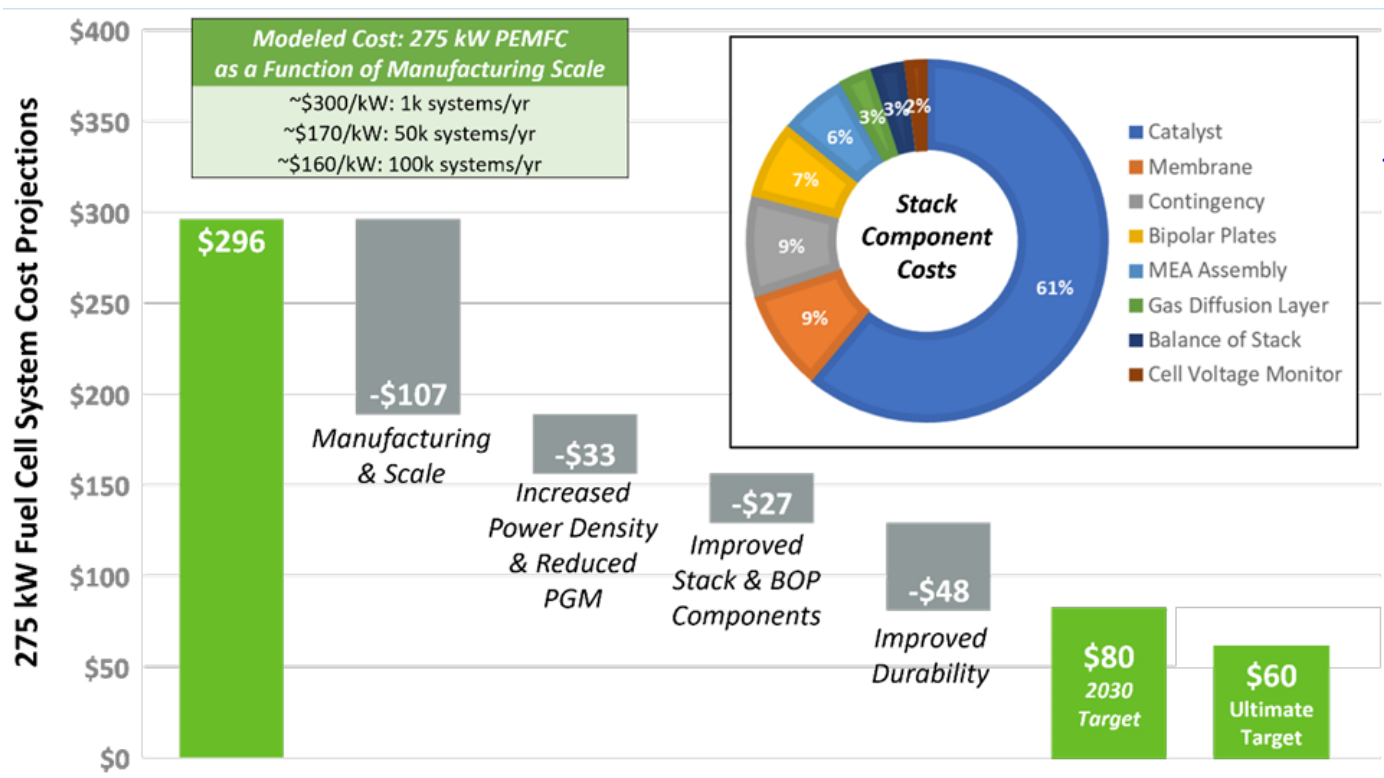
Fact.MR

100% = 891.4 USD Million

- Chemical Processing
- Drying & Humidification
- Other Segments

www.factmr.com

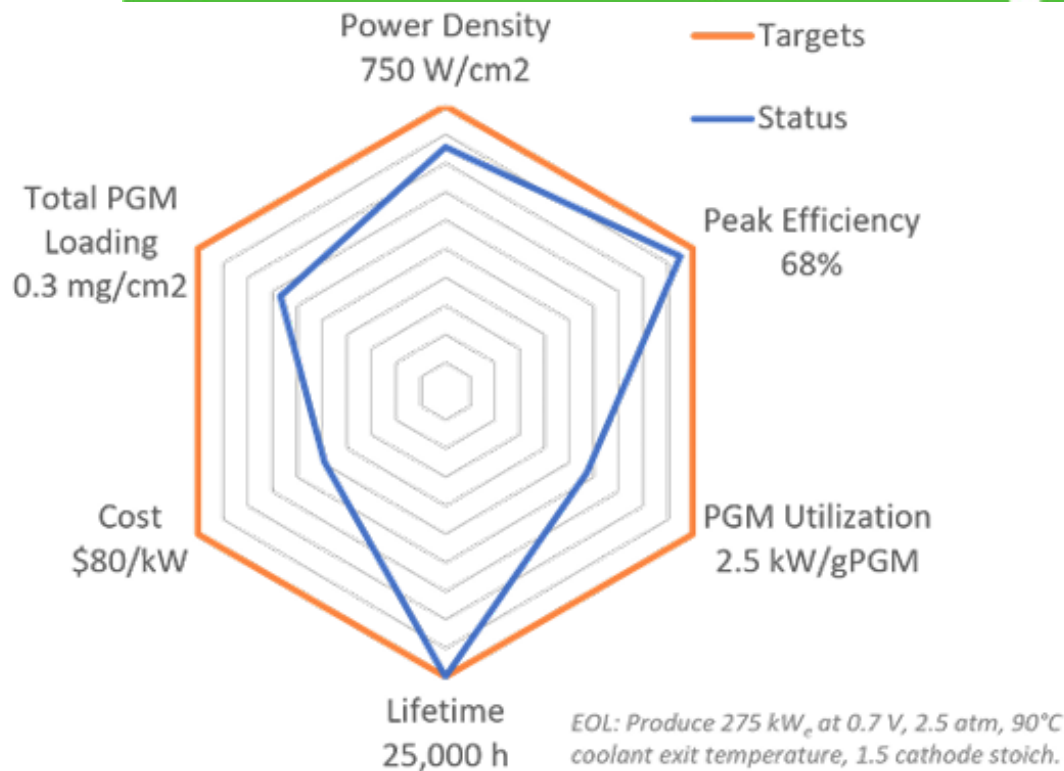
The MYPP (Multi-Year Program Plan) outlines HFTO’s pathways to meet its targets, analyzing key factors in each area and showing how funded efforts address them. For example, this figure highlights major **fuel cell cost drivers and potential reductions across manufacturing**, power density, components, and durability, with similar charts for electrolyzers and hydrogen storage systems.



Hydrogen and Fuel Cell Technologies Office (HFTO)

Figure ES.2. Example of “waterfall” chart showing pathways to meeting HFTO cost-reduction targets

25,000 h Lifetime is a Primary Requirement



Analysis Notes

- Stack oversized by 67% and overloaded with PGM for 25,000-hour electrode lifetime
- Analysis addresses heat rejection requirements
- Active and stable catalysts are needed to meet 750 mW/cm² power density at EOL with 0.3 mg/cm² total PGM loading

Spider chart for fuel cell system status versus targets from recent analysis, assuming a stack oversized and overloaded with platinum group metal as catalyst, meeting the 25,000-hour lifetime.

Spider charts highlight that several sub-targets must be addressed simultaneously to achieve cost-competitive fuel cell options for the specific example of heavy-duty applications. The spider chart, along with the waterfall chart, shows the types of related improvements that need to be made. The subprogram updates these charts annually for presentation at the DOE Hydrogen Program's Annual Merit Review and Peer Evaluation Meeting.

Advantages of a Fuel Cell

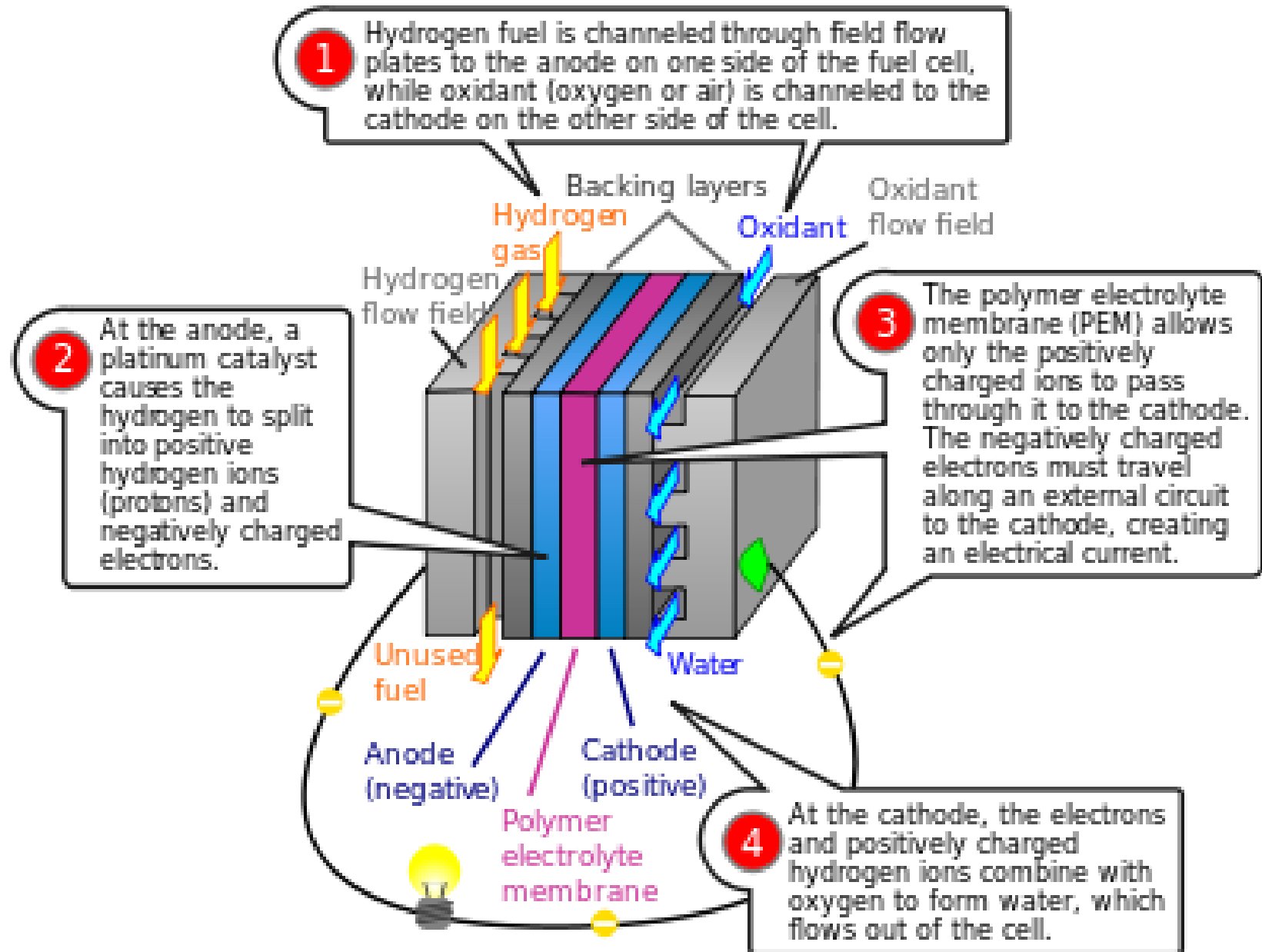
1. Fuel cells deliver the least toxic gaseous emissions; hence, they are considered to be eco-friendly in nature.
2. They are small-sized and hence portable in nature; therefore, they can be carried to far-flung places where a conventional power supply is hard to reach.
3. The by-product of a fuel cell is pure water, which can be used for several other purposes.
4. Fuel cells operate very silently; hence, they do not produce any noise pollution.
5. Fuel cells have very high efficiency; hence, they are much better than several other energy resources.

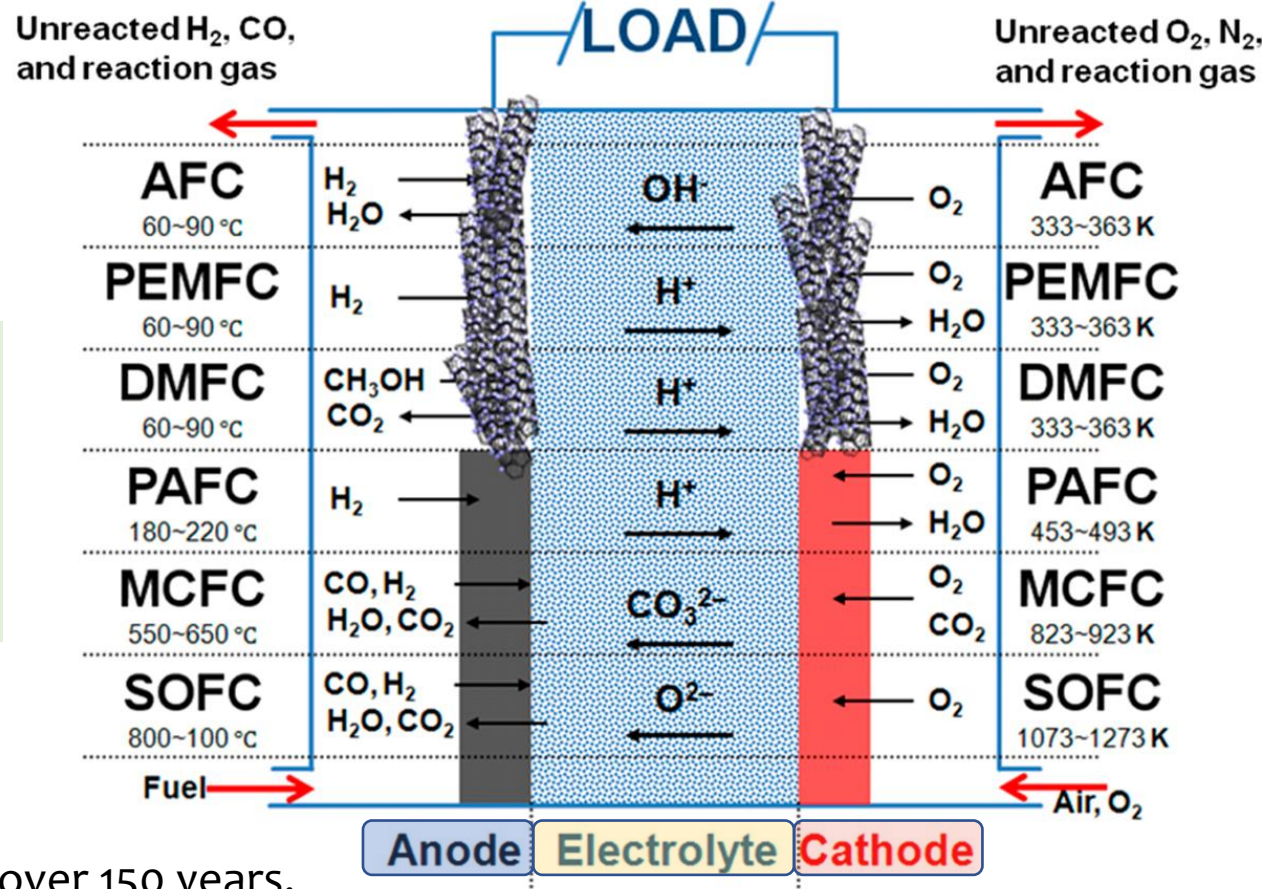
https://link.springer.com/chapter/10.1007/978-3-031-05984-1_18

Disadvantages of a Fuel Cell

1. Ensuring the continuous availability of hydrogen (fuel) and oxygen (oxidant) to run the fuel cell is a major concern.
2. Production and storage of hydrogen to run the fuel cell are also tough.
3. Several fuel cell types are still under research; hence, many of them are not yet completely commercialised for common/industrial use.
4. Fuel cells are still not cost-effective; hence, they could hardly compete with other energy resources.
5. There is still a huge lack of awareness regarding this energy resource; hence, it is not so popular among the masses.
6. Lack of proper government policies is also responsible for the slow absorption of this technology in our society.

Proton exchange membrane fuel cell





AFC: Alkaline Fuel cell
 PEMFC: H^+ exchange membrane fuel cell
 DMFC: Direct methanol fuel cell
 PAFC: phosphoric acid fuel cell
 MCFC: Molten carbonate fuel cell
 SOFC: Solid oxide fuel cell

Fuel cells have been known for over 150 years. Only recently this has been considered as candidates for the dominant energy conversion devices in a variety of future applications. Certain fuels have been examined for use in fuel cells; many fuels have been ignored because of their lower energy densities compared to that of hydrogen. After hydrogen, the next best fuel in terms of energy density is CH_3OH . In addition, **methanol offers certain specific advantages over hydrogen; it is cheap, plentiful, and renewable, and since it is a liquid, it is easily stored, transported, and distributed** (the existing infrastructure can be exploited). Direct use of methanol as an electrochemically active fuel enormously decreases the difficulty in constructing an energy conversion system, thereby reducing the complexity and cost.

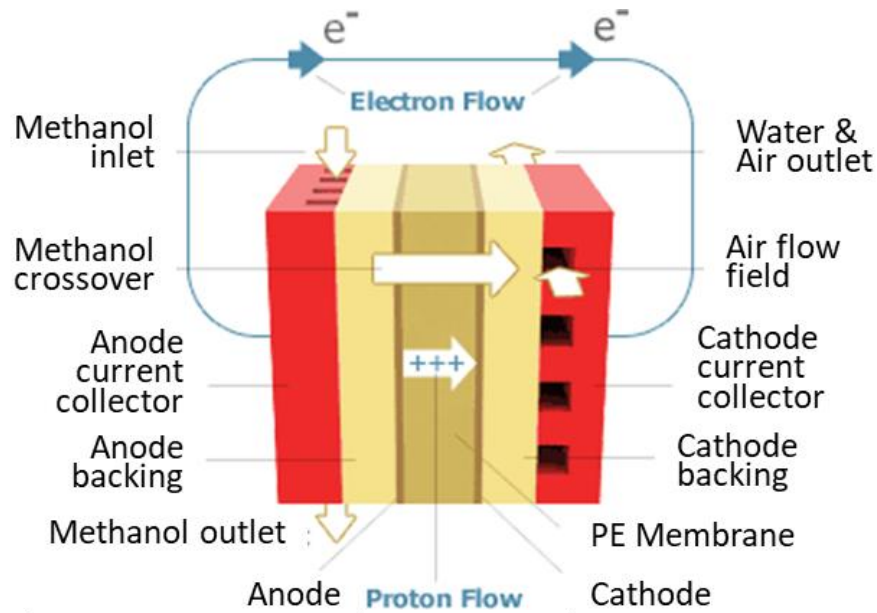
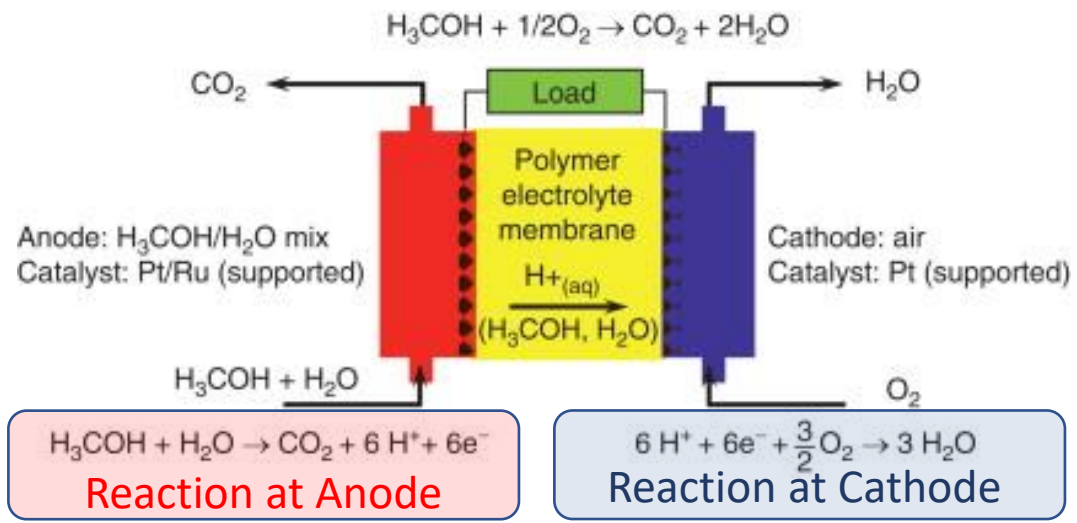
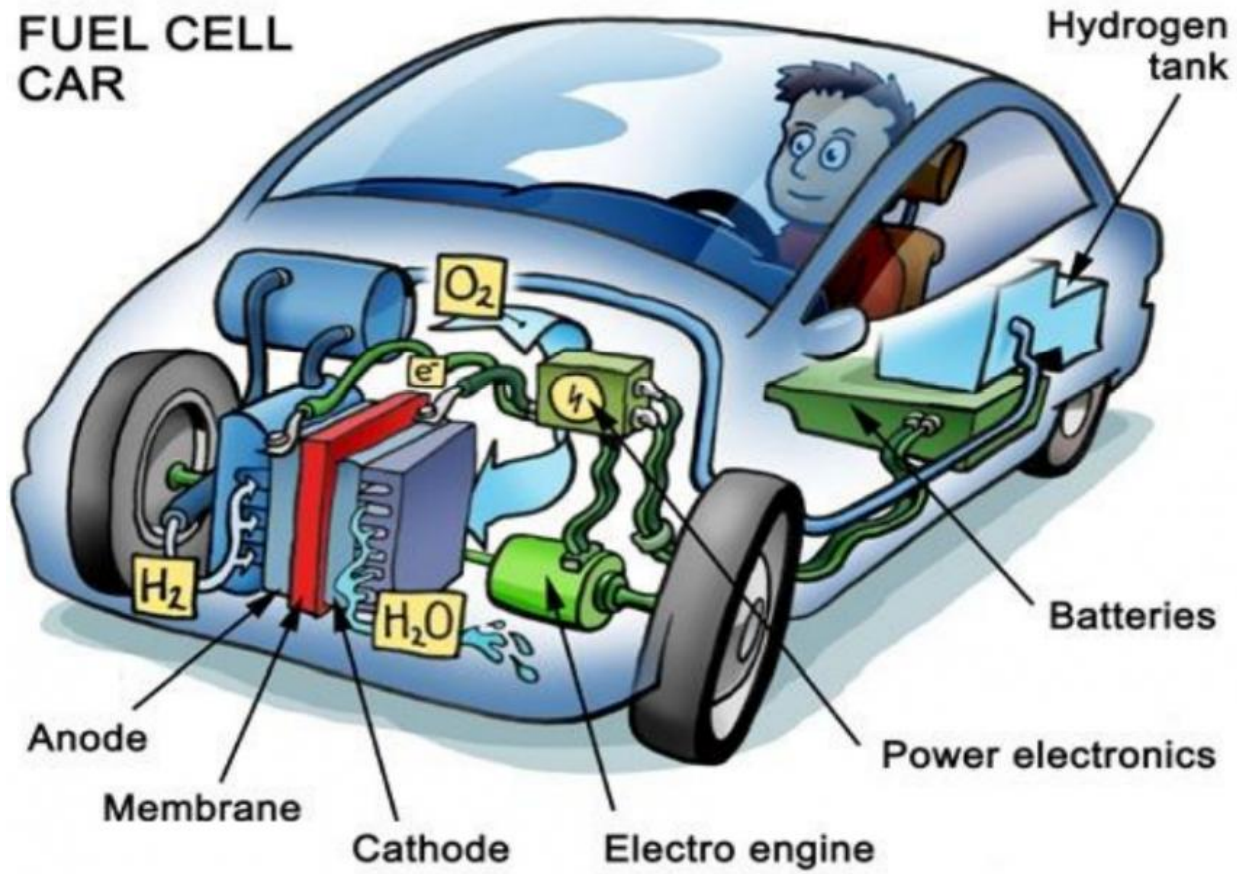
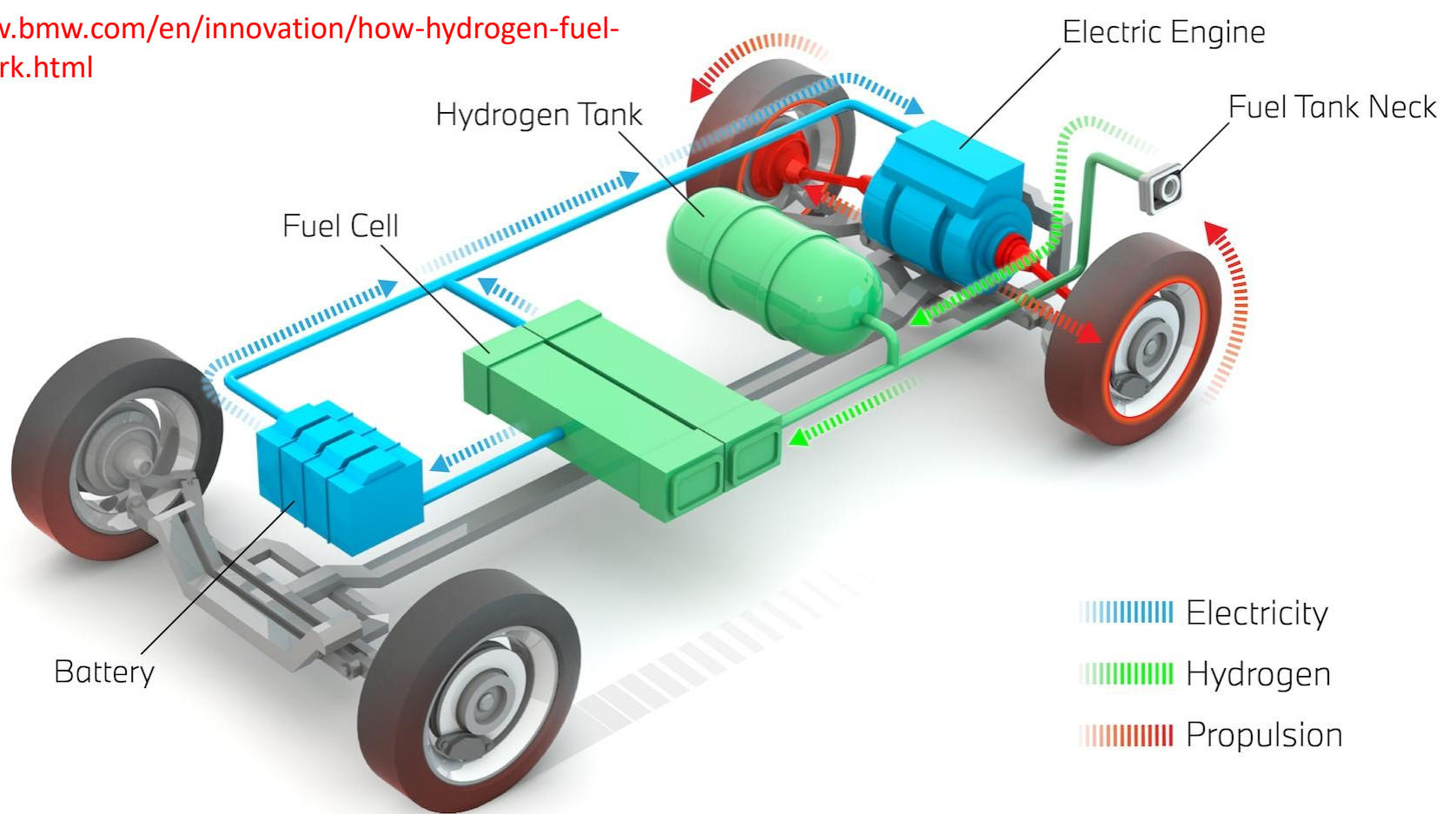


Table 1. Chemical and Electrochemical Data of Various Fuels^a

fuel	ΔG° (kcal/mol)	E°_{theor} (V)	E°_{max} (V)	energy density [(kW h)/kg]
hydrogen	-56.69	1.23	1.15	32.67
methanol	-166.80	1.21	0.98	6.13
ammonia	-80.80	1.17	0.62	5.52
hydrazine	-143.90	1.56	0.28	5.22
formaldehyde	-124.70	1.35	1.15	4.82
carbon monoxide	-61.60	1.33	1.22	2.04
formic acid	-68.20	1.48	1.14	1.72



cell.com/iscience/home



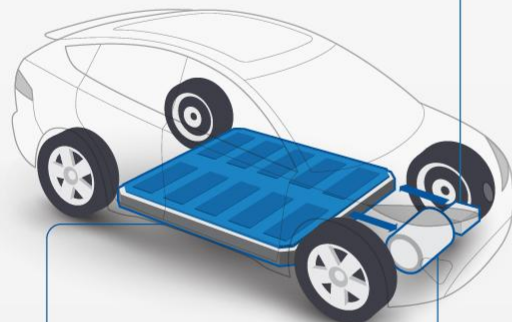
Lithium Ion BATTERY vs Hydrogen FUEL CELL

Electric Vehicles

BEVs contain a large battery to store electricity.

Onboard charger

Converts AC electricity from power outlets into DC power.

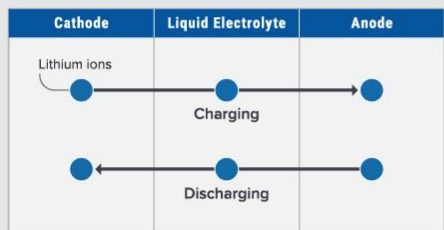


Electric motor

Propels the car using energy from the battery.

Lithium-ion battery

Lithium ions create an electrical current by moving between the negative (anode) and positive (cathode) electrodes.



The longest-range BEV is the 2022 Lucid Air Dream Edition, which has an EPA rating of **505 miles**.



The longest-range FCEV is the 2022 Toyota Mirai XLE, which has an EPA rating of **402 miles**.

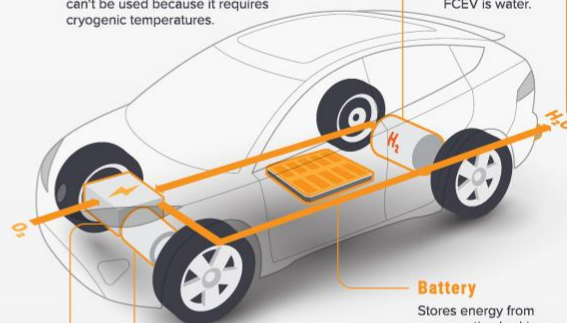
FCEVs use a hydrogen fuel cell to create electricity. This requires a tank to store hydrogen gas.

Fuel tank

Hydrogen gas is stored in a high-pressure tank. Liquid hydrogen can't be used because it requires cryogenic temperatures.

Exhaust

The only waste product of an FCEV is water.



Battery

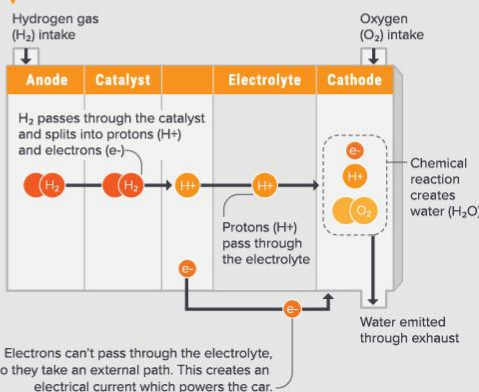
Stores energy from regenerative braking.

Electric motor

Propels the car using energy produced by the fuel cell stack.

Fuel cell stack

The fuel cell combines hydrogen and oxygen to generate electricity.



<https://www.mining.com/web/visualized-battery-vs-hydrogen-fuel-cell/>

The Hydrogen Economy

