GREEN MEANS GO
CCM BREAKTHROUGHS LIFT THE FUTURE OF GREEN HYDROGEN

Catalyst-Coated Membrane (CCM) Technology

Honeywell UOP's unique CCM technologies drive down the cost of hydrogen production so electrolyzer manufacturers can scale to meet the world's growing need for green hydrogen.

Honeywell
UOP

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WELCOME TO THE GREEN HYDROGEN ECONOMY

"Hydrogen could play a central role in helping the world reach net-zero emissions by 2050. As a complement to other technologies, including renewable power and biofuels, hydrogen has the potential to decarbonize industries including steel, petrochemicals, fertilizers, heavy-duty mobility (on and off-road), maritime shipping and aviation, as well as to support flexible power generation (among other applications). In 2050, hydrogen could contribute more than 20 percent of annual global emissions reductions."[1]

McKinsey Sustainability

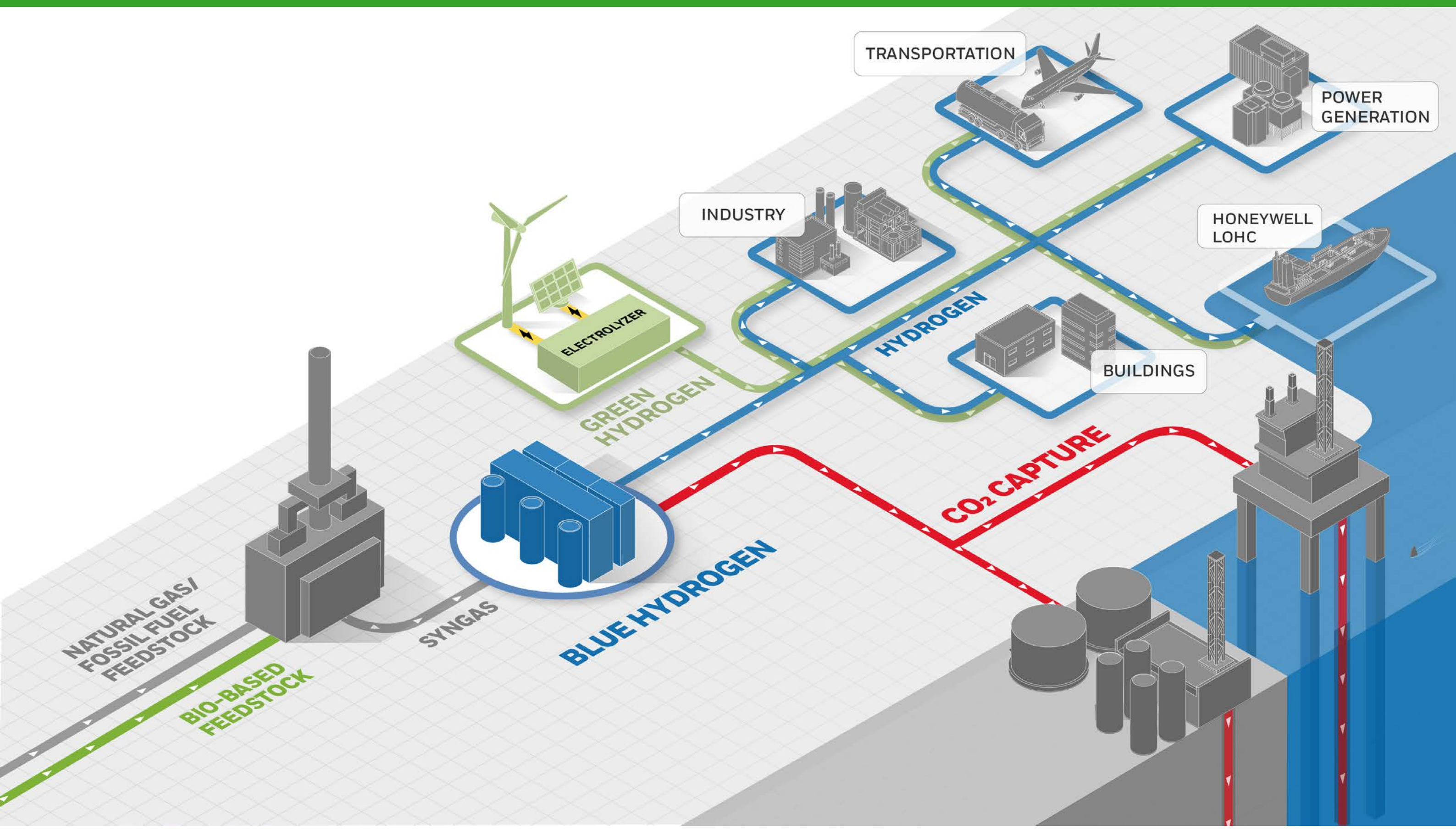
[1] McKinsey & Company. (2023). Five charts on hydrogen's role in a net-zero future. Retrieved from https://www.mckinsey.com/capabilities/sustainability/our-insights/five-charts-on-hydrogens-role-in-a-net-zero-future.

ENABLING A HYDROGEN ECONOMY

Hydrogen is the cleanest available fuel because burning it produces only heat and water. This makes hydrogen a promising solution for pursuing a zero-emissions future to avoid the most extreme effects of climate change.

The use of hydrogen as a fuel is not a new idea, but in recent years it has moved to the forefront as decision makers recognize the clear benefits inherent in the hydrogen economy:

- Hydrogen is a carbon-free molecule, so its use has no environmental impact.
- While hydrogen is widely used in various industrial processes today, it has numerous other applications that can help decarbonize hard-to-electrify industries.
- Hydrogen can help reduce global dependence on fossil fuels and transform hard-to-abate industries like steel production, chemical manufacturing, long-haul transport, shipping, and aviation.
- When used in a vehicle or powerplant, hydrogen generates 2.5-3 times more energy per unit of mass than fossil fuels.[2]
- Hydrogen can be easily transported in liquid or gas form using pipelines, trucks, ships, or rail cars.
- When produced in an electrolyzer using electricity from a renewable source, the result is “green hydrogen,” a versatile and resilient zero carbon solution.



[2] Tashie-Lewis, B. C., & Nnabuife, S. G. (2021). Hydrogen Production, Distribution, Storage and Power Conversion in a Hydrogen Economy - A Technology Review. Chemical Engineering Journal Advances, 8. Retrieved from https://www.sciencedirect.com/science/article/pii/S2666821121000880.

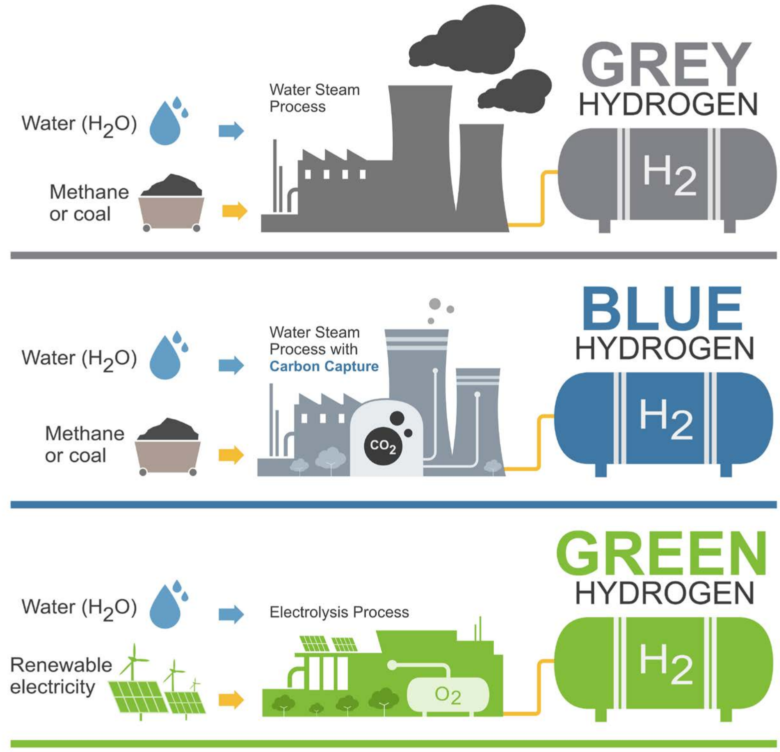
HYDROGEN PRODUCTION BY THE COLORS

Almost all hydrogen produced in the U.S. is made by natural gas reforming, but hydrogen can also be captured as a valuable byproduct of refining and other industrial processes. Gas reforming can produce either "gray hydrogen" or "blue hydrogen," depending on whether the CO_2 produced during the process is released into the atmosphere or captured and sequestered. Hydrogen produced as a byproduct of the carbon capture utilization and sequestration (CCUS) process is blue hydrogen. "Green hydrogen" is produced using an electrolyzer system, powered by renewable electricity, to split water into hydrogen and oxygen molecules.[3]

BLUE AND GREEN HYDROGEN ARE THE FUTURE OF DECARBONIZATION

While hydrogen leaves no carbon footprint as it is consumed, the same cannot be said about the steam methane reforming (SMR) process used to produce about 95%[4] of the world's hydrogen supply. SMR uses natural gas or another methane source that is reacted with high-temperature steam (700°C–1,000°C) in the presence of a catalyst to produce hydrogen gas (H_2) and carbon dioxide (CO_2).

In most cases, the CO_2 produced by the SMR process is released into the atmosphere, which causes as much pollution and environmental damage as burning the same amount of natural gas directly.[5] An estimated 830 million tons of CO_2 are emitted each year to produce about 74 million tons of "gray hydrogen" using fossil fuels[4] and the SMR process.



The process for producing "blue hydrogen" also relies on hydrocarbons but instead of releasing CO_2 into the atmosphere, producers use carbon capture, utilization, and sequestration (CCUS) technology that traps most carbon emissions from the SMR process. The captured carbon dioxide can be injected and stored underground, or it can be used to produce things like fuels, chemicals, and building materials.

Because of CCUS, blue hydrogen production leaves a much smaller carbon footprint than gray hydrogen production.[3] The transition from gray to blue hydrogen is essential as the global "hydrogen economy" expands and the demand for "green hydrogen" grows over time. Blue hydrogen will account for 85% of the world's hydrogen supply by 2030.[6]

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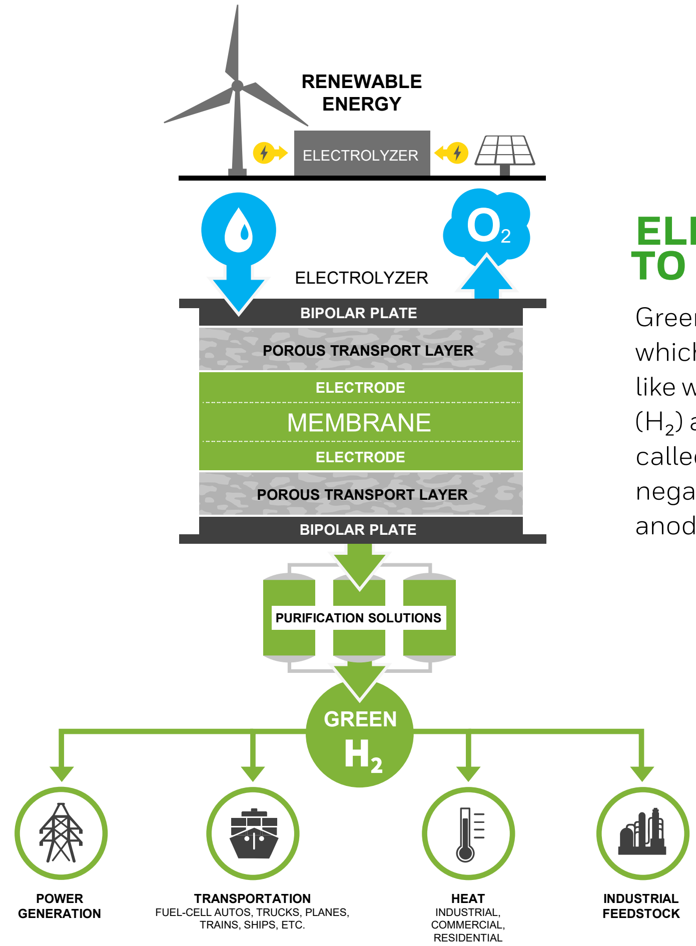
[3] World Economic Forum. (2021). Grey, blue, green – the many colours of hydrogen explained. Retrieved from https://www.weforum.org/agenda/2021/07/clean-energy-green-hydrogen/.

[4] MIT Climate Portal. (2021). Hydrogen. Retrieved from https://climate.mit.edu/explainers/hydrogen.

[5] Singh, S., Jain, S., Venkateswaran, P., Tiwari, A. K., Nouni, M. R., Pandey, J. K., & Goel, S. (2015). Hydrogen: A sustainable fuel for future of the transport sector. Renewable and Sustainable Energy Reviews, 51, 623-633. Retrieved from https://www.sciencedirect.com/topics/engineering/natural-gas-steam-methane-reforming.

[6] GlobalData. (2021, September 1). *Blue hydrogen to account for 85% of low-carbon hydrogen capacity in North America by 2030, says GlobalData*. Retrieved from https://www.globaldata.com/media/oil-gas/blue-hydrogen-account-85-low-carbon-hydrogen-capacity-north-america-2030-says-globaldata/.



ELECTROLYSIS IS THE PATHWAY TO GREEN HYDROGEN

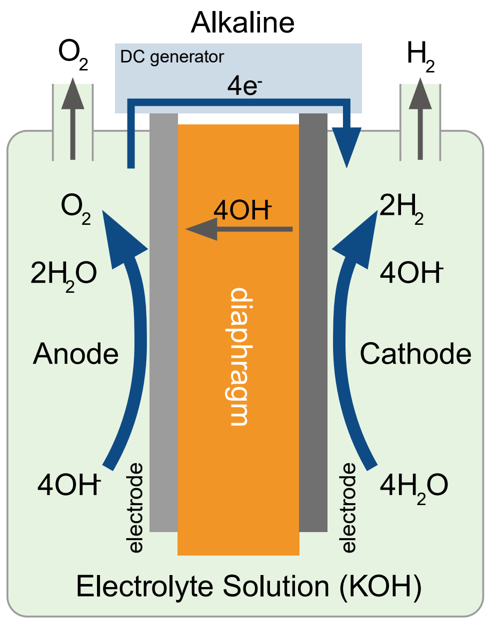
Green hydrogen is produced through water electrolysis, which uses electricity generated by renewable sources like wind, solar, and hydro to split water into hydrogen (H_2) and oxygen (O_2). This process takes place in a unit called an electrolyzer consisting of two electrodes – a negatively charged cathode and a positively charged anode – separated by a membrane called an electrolyte.

ALKALINE WATER ELECTROLYSIS

Alkaline water electrolysis (AEL) is today's most mature electrolysis process. AEL creates hydrogen gas (H_2) at the cathode by pulling negatively charged hydroxide ions (OH-) out of water molecules and transporting them across a liquid electrolyte solution, such as potassium hydroxide (KOH). Once they reach the anode, hydroxide ions are oxidized to form water (H_2O) and oxygen gas (O_2).

While AEL currently requires the lowest capital investment, it has a number of disadvantages compared to the proven proton exchange membrane (PEM) electrolysis and anion exchange membrane (AEM) electrolysis, an up-and-coming technology.

For example, the KOH electrolyte solution used in AEL is highly corrosive, which presents a variety of handling and disposal challenges for electrolyzer manufacturers. Other downsides include a lower operating pressure, low current density, and poor dynamic response to intermittent electrical sources such as renewable solar and wind. These shortcomings affect electrolyzer operational efficiency and product-gas purity.



Anode: $4OH^- \leftrightarrow 2H_2O+O_2+4e^-$

Cathode: $4H_2O+4e^- \leftrightarrow 2H_2+4OH^-$

"Source: IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi."

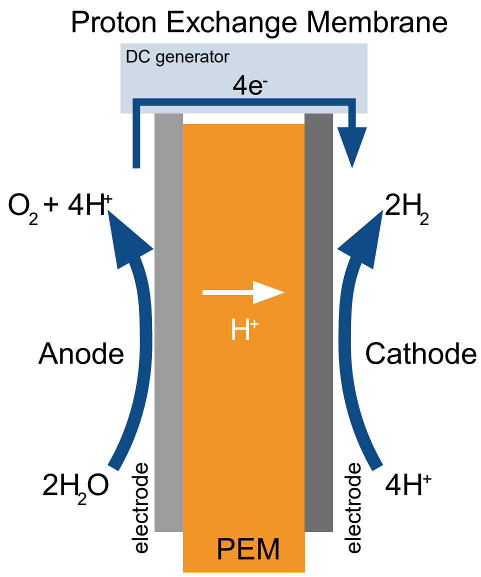
[7] U.S. Department of Energy (DOE). (n.d.). *Hydrogen Production: Electrolysis*. Retrieved from https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis.

PROTON EXCHANGE MEMBRANE ELECTROLYSIS

The proton exchange membrane (PEM) electrolysis process differs from AEL in both its process and form. The PEM process starts at the anode catalyst, where water is transformed into oxygen gas (O_2) and positively charged hydrogen ions (H+), also known as protons. The hydrogen ions then travel across an electrolyte layer to the cathode, where they are reduced by the electrolyzer current to form hydrogen gas (H_2). Importantly, PEM uses a solid polymer electrolyte layer to transport ions, in contrast to the electrolyte liquid used in AEL.[7]

PEM electrolysis is the best currently available alternative to AEL. Already proven on a commercial scale, the PEM electrolysis process is a ready-now and ready-to-scale solution to the world's rapidly expanding green hydrogen demand.

Groundbreaking PEM technology produces ultra-pure green hydrogen through a significantly improved process to split water into hydrogen and oxygen using a proton-conducting membrane. The PEM process benefits from high current density, fast response, and a smaller equipment footprint. PEM electrolysis eliminates the need for a caustic electrolyte liquid and achieves lower kilowatt hours per kilogram of hydrogen.



Anode: $2H_2O \leftrightarrow O_2 + 4H^+ + 4e^-$

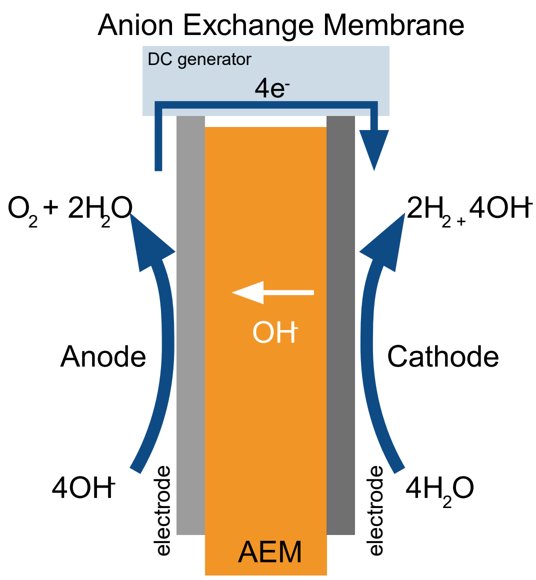
Cathode: $4H^+ + 4e^- \leftrightarrow 2H_2$

"Source: IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi."

ANION EXCHANGE MEMBRANE ELECTROLYSIS

Anion exchange membrane (AEM) electrolysis shares traits of both AEL and PEM. It uses the same chemical process as AEL, with hydrogen gas (H_2) forming at the cathode followed by oxygen gas (O_2) and water (H_2O) formation at the anode. However, like PEM, AEM involves a solid polymer electrolyte layer instead of an electrolyte liquid for ion transport.[7]

AEM electrolysis is currently in lab-scale development and has been showcased in small commercial demonstrations. AEM is expected to perform as well as the PEM technology but uses a lower-cost transition metal catalyst and stack materials, which will drive down capital costs significantly. Development continues to prove out the technology and scale to larger AEM units. These factors make AEM a potential future disruptor.



Anode: $4OH^- \leftrightarrow 2H_2O + O_2 + 4e^-$

Cathode: $4H_2O + 4e^- \leftrightarrow 2H_2 + 4OH^-$

"Source: IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi."

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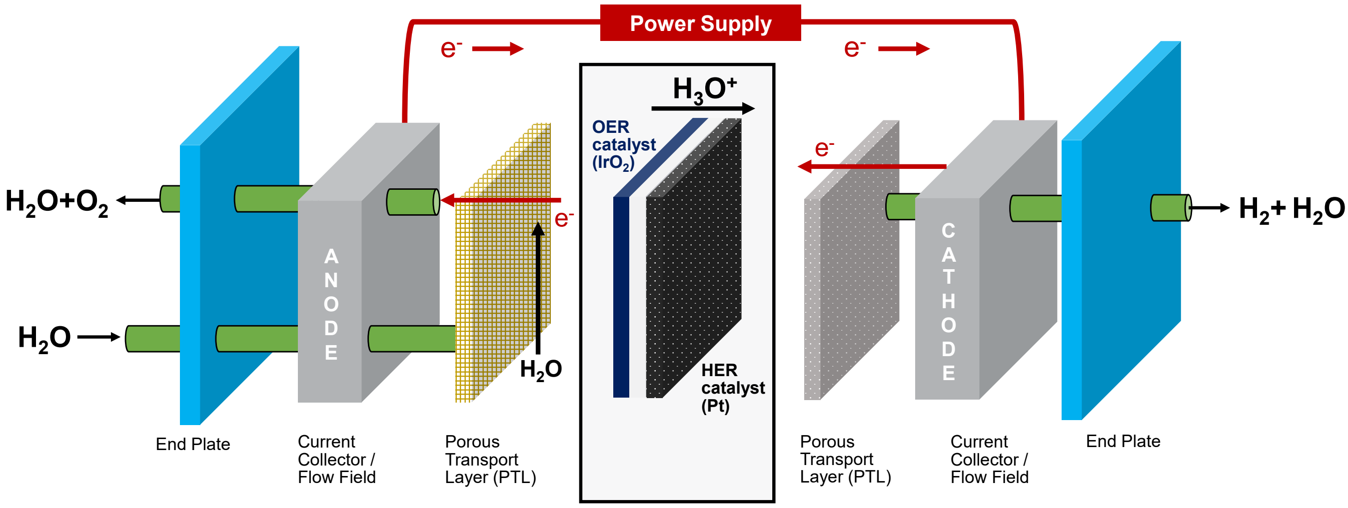
[8] International Energy Agency (IEA). (n.d.). Electrolysers. Retrieved from https://www.iea.org/energy-system/low-emission-fuels/electrolysers.



CATALYST COATED MEMBRANES

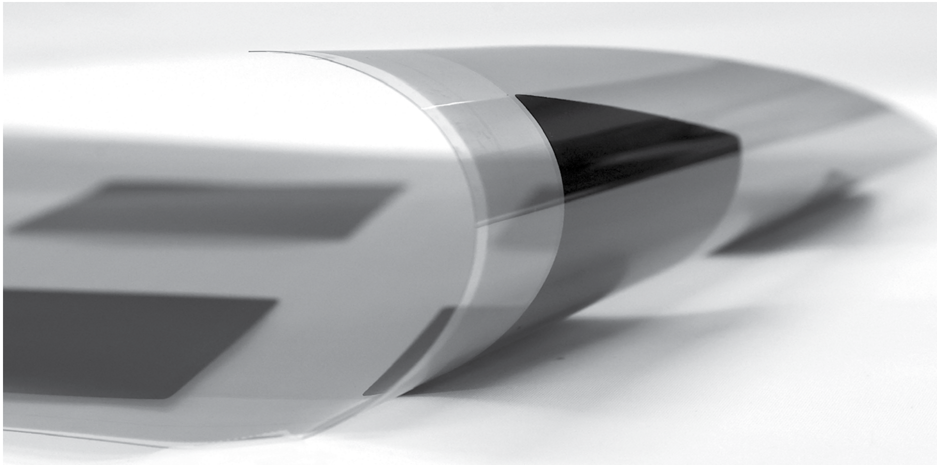
Catalyst coated membranes (CCMs) are the heart of PEM and AEM electrolyzer processes. Both electrolyzer technologies use a catalyst cathode and anode to stimulate an electro-chemical reaction that separates water molecules into oxygen, protons, and electrons. On the other side of the membrane, the protons and electrons are reassembled to form hydrogen. The innovation of this component affects all other aspects of the stack and plays a critical role in total production cost and efficiency.

HONEYWELL PIONEERS MEMBRANE INNOVATIONS

Leveraging more than 40 years of membrane and catalyst R&D and manufacturing experience, Honeywell UOP has developed breakthrough next-generation CCMs that are ready today to help electrolyzer manufacturers (OEMs) and green hydrogen producers achieve higher levels of performance for their current PEM and future AEM electrolyzers.

For electrolyzer original equipment manufacturers and green hydrogen producers, the Honeywell UOP PEM CCM solution offers many advantages, including:

- Improved electrolyzer efficiency
- 35% lower stack costs[9, 10]
- Lower operating expenses resulting from lower electricity input[9, 10]
- Lower cell and stack voltage at a given current density[9, 10]
- 55% higher current density at a given voltage[9, 10]
- Lower precious metal group catalyst loadings (Pt, Ir) [11]
- 45% lower hydrogen crossover[12]
- Better stability and mechanical strength[13]



[9] Based on internal UOP data and validated by third-party electrolyzer OEMs.

[10] Based on a PEM water electrolysis system using renewable power to produce 2,220 metric tons H2/year with 8,760 operating hours/year.

[11] Honeywell UOP's catalyst coated membrane (CCM) exceeded the 2022 DOE platinum group metal (PGM) targets by at least 55%. https://www.energy.gov/eere/fuelcells/technical-targets-proton-exchange-membrane-electrolysis.

[12] Based on UOP internal lab test results of UOP's HiFlux-114P PEM CCM, UOP's Nafion 115-based PEM CCM, and a commercially available Nafion 115-based PEM CCM.

[13] Based on UOP internal lab test results of UOP's HiFlux-114P PEM CCM and a commercially available N212 CCM, showing a 35% improvement in tensile strength (23°C, 30% RH).

"PEM hydrolysis is expected to capture 40% of the total electrolyzer market by 2030[14] as the world moves along the path from gray to blue to green hydrogen. This creates an enormous opportunity for electrolyzer OEMs. Exciting advancements like Honeywell's new CCM technologies are ready now to drive higher levels of electrolyzer performance to meet the needs of the future hydrogen economy."

Kevin Quast, Green Hydrogen Commercial Lead
Honeywell UOP

Honeywell CCM outperformed commercially available membranes both in a lab environment and in a rigorous test and validation process jointly conducted with several leading electrolyzer manufacturers. Honeywell UOP's PEM CCM achieves 55% higher hydrogen production per area than commercially available CCM, enabling a 35% electrolyzer stack CapEx cost reduction for PEM water electrolysis.[9,10]

HYDROGEN ECONOMY HINGES ON TECHNOLOGY AND GOVERNMENT SUPPORT

Despite its many advantages, green hydrogen still represents a very small portion of total hydrogen production today. Electrolysis accounted for just 4% of global hydrogen production in 2021 and about 1% is considered green hydrogen, according to the International Renewable Energy Agency (IRENA).[15]

Electrolytic hydrogen in 2021 came mostly from demonstration projects, for a total capacity of just 0.7 gigawatts.[16] Hydrogen – primarily green hydrogen – is projected to provide 12% of the world's energy needs by 2050,[17] which will require production capacity to grow exponentially.[16] While ready-now technologies like the Honeywell UOP CCM can help optimize production and drive down the cost of green hydrogen, this is only part of the answer as the world sets its sights on energy transition and decarbonization.

Government policies and incentives will play a critical role in expanding the availability and reducing the cost of green hydrogen. For example, the Inflation Reduction Act (IRA) in the U.S creates a new Hydrogen Production Tax Credit to incentivize domestic production of green hydrogen. The IRA also includes the Hydrogen Shot,[18] an effort to accelerate breakthroughs and cut the cost of green hydrogen by 80% from about $5 currently to $1 per kilogram by 2030.

The European Union has embraced a hydrogen strategy designed to stimulate green hydrogen demand, scale up production capacity, and drive down costs. This includes incentives to spur innovation and support broader adoption of green hydrogen.[19] In addition, the United Nations launched a Green Hydrogen Catapult[20] to bring down the cost of green hydrogen by 50% by 2026.

More than 680 large-scale hydrogen projects have been announced globally, amounting to $240 billion in direct investments. The projects include giga-scale production, large-scale industrial usage, transport, and infrastructure.[1]

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[14] Rethink Research. (2023). Global Hydrogen Market Forecast 2050: H2 Still Accelerating. Retrieved from https://rethinkresearch.biz/report/global-hydrogen-market-forecast-2050-h2-still-accelerating/.

[15] International Renewable Energy Agency (IRENA). (n.d.). Hydrogen. Retrieved from https://www.irena.org/Energy-Transition/Technology/Hydrogen.

[16] IEA. (2021). Global Hydrogen Review 2021. Retrieved from https://www.iea.org/reports/global-hydrogen-review-2021/executive-summary.

[17] International Renewable Energy Agency (IRENA). (2021). World Energy Transitions Outlook. Retrieved from https://www.irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook.

[18] DOE. (2021, June 7). Hydrogen Shot. Retrieved from https://www.energy.gov/eere/fuelcells/hydrogen-shot.

[19] European Commission. (2020). *Key actions of the EU Hydrogen Strategy*. Retrieved from https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen/key-actions-eu-hydrogen-strategy_en.

[20] Green Hydrogen Catapult. (n.d.). *Home*. Retrieved from https://greenh2catapult.com/.

DRIVING DOWN COSTS IS FUNDAMENTAL

Not surprisingly, it costs 59% less to produce blue hydrogen than green in 2023, but green hydrogen is on a path to undercut blue in the next decade.[21] That is good news because driving down the levelized cost of green hydrogen (LCOH) is essential to achieving the world's energy transition and decarbonization goals. Green hydrogen must be competitively priced to enable its broad adoption as a primary energy source.

The cost of renewable electricity to power the electrolyzer unit is the largest single expense for green hydrogen producers. Growing world demand for electricity generated with solar, wind, and hydro power will also make more renewable energy available to hydrogen producers. This also creates an incentive to produce green hydrogen in locations with ready access to renewable resources.

Green hydrogen's global cost structure will benefit from the electrolysis industry's ambitious expansion plans, which will allow companies to benefit from economies of scale. For example, increasing stack production using gigawatt-scale manufacturing facilities will reduce costs significantly. Materials purchased in volume can also reduce total costs.

Driving down the cost of green hydrogen will also require reductions in capital and operating costs at locations where electrolysis is installed. Using Honeywell UOP CCM technology in electrolyzers reduces stack costs by 35% by using a high ionic conductivity membrane with high activity anode and cathode catalysts that enables 55% higher hydrogen production per area. Alternatively, the Honeywell UOP CCM technology can be leveraged by lowering cell voltage at a given current density to improve efficiencies and lower electricity demand.[9, 10]

THE HONEYWELL UOP DIFFERENCE

"Growing demand for green hydrogen is changing the game for PEM electrolyzer OEMs, who have already committed to building factories that can produce more than 42 gigawatts per year as PEM grows its market share to 40% by 2030.[14] Having a strong and reliable membrane supplier – like Honeywell – that specializes in CCM production is one of the best ways electrolyzer companies can drive better stack performance and better profit margins."

Maya Gomez, Director, Green Hydrogen CCM
Honeywell UOP

By leveraging ready-now manufacturing assets and a strong, responsive supply chain, Honeywell UOP is scaling up to meet the needs of the world's PEM and AEM OEMs. Only Honeywell has the right combination of proprietary polymers, membranes, and catalysts to enable breakthrough performance, along with the manufacturing expertise to bring everything together for customers.

Tested and proven in an operating pilot-scale CCM manufacturing site, Honeywell is now leveraging existing manufacturing assets to scale its CCM manufacturing capabilities to meet customer demand. Our Honeywell UOP manufacturing sites are dedicated to following a disciplined operating system that prioritizes safety, quality, and on-time delivery to meet the needs of our customers.

Honeywell UOP has been on innovation's leading edge for more than a century, pioneering breakthroughs to make energy, petrochemical, and gas processing companies more efficient, profitable, and sustainable. Today, we are a leading provider of process technology, catalysts, adsorbents, equipment, and consulting services.

Honeywell UOP innovations range from a pioneering hydrocarbon cracking process demonstrated in 1914 to processes to produce unleaded gasoline in the 1960s and development of the first automotive catalytic converter in 1970. Over the last 15 years the company has led the way in the development of sustainable diesel and aviation fuels, key elements of our extensive sustainability portfolio.

No one has more experience developing catalysts, which has been a Honeywell UOP strong suit for more than 80 years, and we introduced the first membranes for gas applications in the 1980s. Our Separex™ spiral wound membrane elements have been the oil and gas industry's choice for acid gas and vapor-phase water removal for decades, and our experience in membrane development and manufacturing translates directly to the needs of hydrogen producers in the 2020s and beyond.

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[21] BNEF. (2023). Hydrogen Levelized Cost Update: Green Beats Gray. Retrieved from https://about.bnef.com/blog/2023-hydrogen-levelized-cost-update-green-beats-gray/.

More than 700 scientists and engineers from nearly 40 counties are the backbone of Honeywell UOP and the source of the innovative solutions we have provided to customers for more than a century. Working together in high-performing international teams, we constantly search for new ways to meet customers' needs and make the world a better place.

For more information on Honeywell UOP CCM technology contact our team at Green Hydrogen (honeywell.com).

For more information

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