Clean Power Hydrogen: Membrane-Free Electrolysis for Low-Cost Hydrogen Production

Scalable, Reliable and Efficient Solutions for Mission Critical and Co-located Applications

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July 2025

Executive Summary

Hydrogen is widely recognised as important in the transition to sustainable, decarbonised energy systems, as the Clean Flexibility Roadmap, published jointly by the UK Department for Energy Security and Net Zero, The National Energy System Operator and OFGEM, July 2025, made clear.

While traditional hydrogen production is carbon-intensive, green hydrogen—produced via electrolysis powered by renewable energy offers a zero-emissions alternative. However, conventional water electrolysis technologies rely on expensive membranes made from hard to source or controversial materials and PFA ‘forever chemicals’, raising costs and limiting scalability. Membrane-free electrolysis provides a lower cost, innovative approach to clean hydrogen production for co-located and mission critical applications.

The UK Governments 2025 Clean Power Action Plan noted that *“although electrification provides the most potential for reaching net zero, it is not the solution for every use of energy across the economy, and will need to be supplemented by targeted deployment of CCUS and hydrogen”*

This White Paper explores how lower cost Membrane-Free hydrogen technology provides that solution; it’s advantages, market potential and future opportunities. It explores its capacity to accelerate the adoption of clean hydrogen for a net-zero future in hard to abate sectors where electrification is compromised.

Background: Conventional Electrolysis Approaches

Conventional commercial electrolysers fall mostly into two categories:

- Proton Exchange Membrane (PEM) Electrolysers: Utilise a polymer membrane to separate hydrogen and oxygen, supporting high current densities and faster response times than Alkaline. However, they struggle to maintain efficiency when powered by variable wind and solar sources. They require precious metal catalysts (such as platinum and iridium) and use PFA 'forever chemicals' already banned in several countries.
- Legacy Alkaline Electrolysers (AEL): Use a liquid alkaline electrolyte and a porous separator. They are less expensive than PEM but have lower efficiency and slower response times making them incompatible with intermittent or variable renewable energy sources, like wind and solar.

Both technologies rely on membranes or separators to prevent the mixing of gases and ensure product purity. Membranes add significant capital and operational costs, especially in large-scale or remote applications, and over time all membranes degrade, foul and eventually fail.

What is CPH2 Membrane-Free Electrolysis?

CPH2 Membrane-Free technology uniquely employs cryogenic separation of hydrogen and oxygen rather than physical membranes in the electrolyser stack. It delivers high-purity hydrogen and oxygen without the risk of degradation, fouling and failure.

Cryogenic separation plays a pivotal role in maintaining the purity of the generated gas. After the electrolytic generation of hydrogen and oxygen, the gases are initially combined then dried. To efficiently and thoroughly separate these gases, the system deploys cryogenic technology—cooling the gas mixture. At very low temperatures, the differing physical properties of hydrogen and oxygen become pronounced: oxygen condenses into a liquid sooner than hydrogen due to its higher boiling point, allowing the hydrogen to be isolated in a highly pure, gaseous form. The oxygen is re-vapourised and is also produced to a high purity. A patented heat exchange system ensures the cryogenic separation is performed using the lowest amount of input energy.

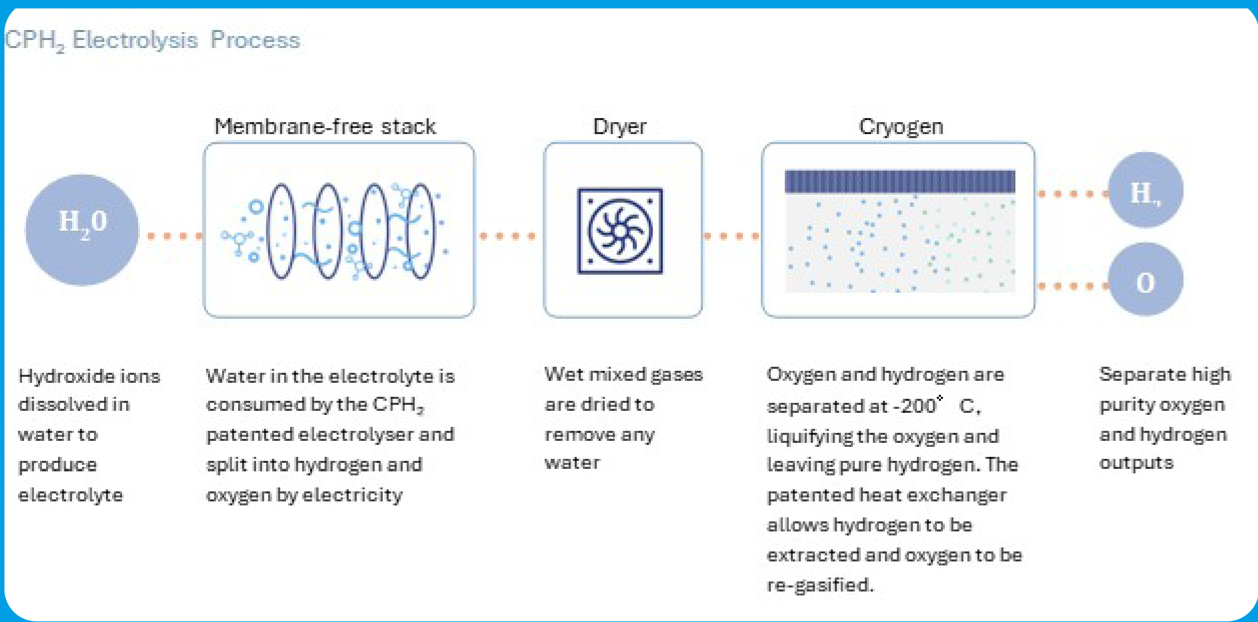

Figure 1: CPH2 Electrolysis Process

Electrolyser Polarisation Curve: Alkaline, PEM, and CPH2 Technology

Comparative Data Illustration

To visualise the performance differences between key electrolyser types, the polarisation curve plots cell voltage (V) against current density (A/cm^2).

The overvoltage in an electrolysis cell is an indication of the power efficiency. The reversible cell voltage at low temperature electrolyser conditions is 1.48v and represents 100% efficiency. This is the equilibrium voltage at which the cell can be electrolysed without losses. The overvoltage (the difference between the actual cell voltage and the reversible or equilibrium cell voltage) represents the electrolyser inefficiency. In simple terms, lower voltage means lower power consumption and a more efficient electrolyser stack.

Traditional PEM electrolysers demonstrate higher current densities at lower voltages compared to alkaline electrolysers. Electrodes loaded with expensive Platinum and Iridium make the hydrogen and oxygen evolution reactions go faster, lowering the resistance and overvoltage. Because of the high cost of these electrodes, and constraints imposed by the need to limit the rate of hydrogen permeation through the membrane into the oxygen system, commercial PEM electrolysers operate at current densities of 2A/cm^2.

Alkaline electrolyser chemistry and the use of nickel electrodes that are less reactive for hydrogen and oxygen dictate that Alkaline stacks have a higher voltage for a given current density than PEM stacks. To get competitive efficiencies, Alkaline stacks operate at lower current densities than PEM which means greater installed electrode area. A typical commercial Alkaline electrolyser operates at 0.5-1.0 A/cm^2 and comparable overvoltage and stack efficiencies to PEM systems. The management of hydrogen leakage across the membrane into the oxygen system remains a critical challenge for Alkaline systems and imposes constraints on the degree to which they can modulate with variable input electricity. This makes them incompatible with intermittent and renewable power sources like wind and solar.

Figure 2 shows a typical cell of PEM and Alkaline Stacks. Each cell consists of a catalyst coated membrane, a porous gas diffusion layer either side of the membrane made of sintered titanium mesh and current collector with engraved flow channels. All these components have a unique element and require a dedicated supply chain. This introduces a constraint on scalability.

Quoted values from the industry body Hydrogen Europe put the cost of a PEM stack at €450,000 per installed stack MW. Pressurised Alkaline is lower but within a comparable range.

The CPH2 membrane-free stack has a simple cell structure consisting of two water jet cut stainless steel bipolar plates separated by a gasket. See figure 3. The reaction rates against stainless steel for hydrogen and oxygen evolution reactions are lower than both PEM and Alkaline. The polarisation curve has the highest voltage for a given current density. However, this is counterbalanced with increased cell area for the CPH2 stack which is inexpensive. At 0.2A/cm², the costs of the CPH2 stack is one third the cost of a PEM stack and yet has ten times the installed area.

The CPH2 system does not use a membrane as a way of separating gases. Instead, that's carried out in a downstream cryogenic system. This separation method is not subject to impaired function at turndown which makes the CPH2 stacks compatible with intermittent renewable energy resources.

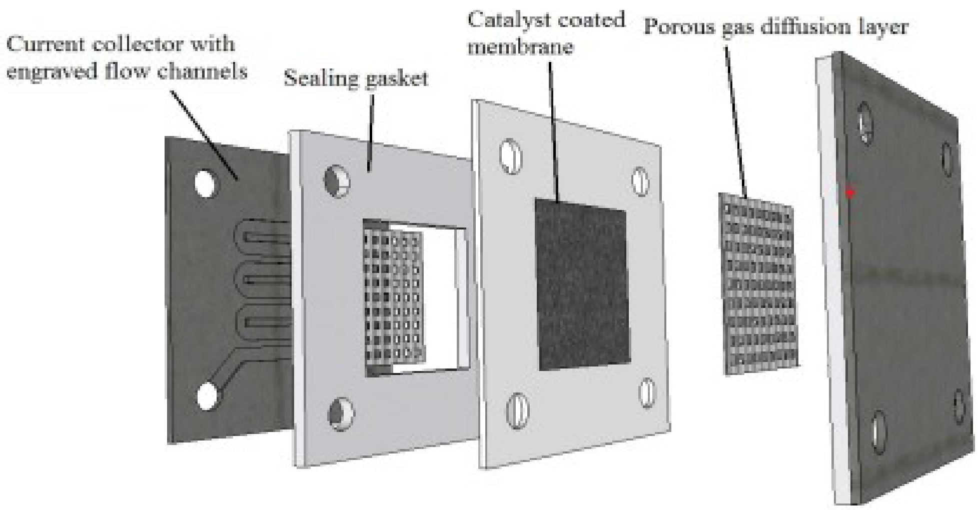

Figure 2: Schematic showing the CCM setup, with the catalyst layer deposited directly onto the membrane. Reference Zero Gap Cell Design for Alkaline Electrolysis PhD Thesis Robert Phillips Swansea University 2019

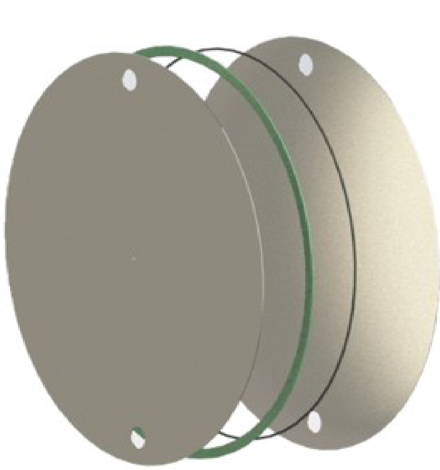

Figure 3: CPH2 MFE Electrolyser Cell

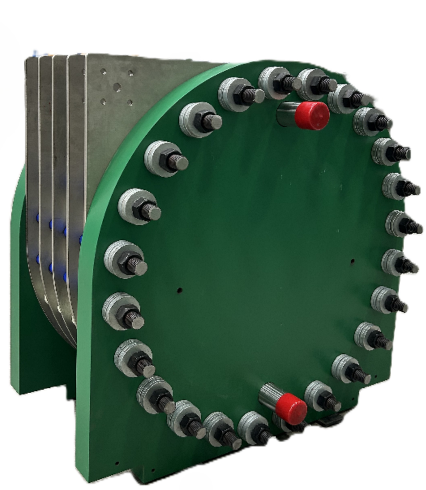

Figure 4: CPH2 MFE Electrolyser Stack

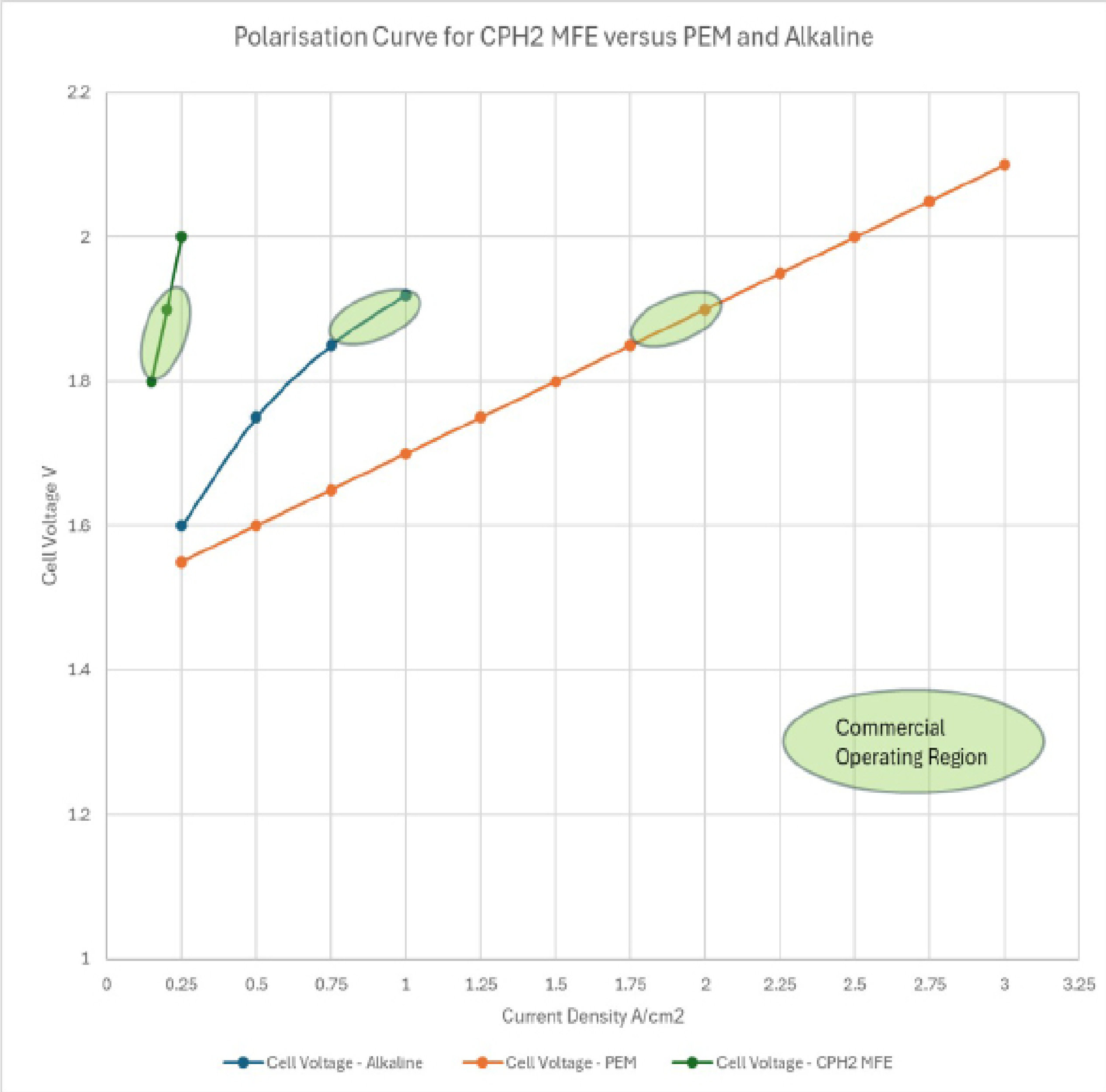

Figure 5: Typical polarisation curve for CPH2 MFE versus PEM and Alkaline Electrolysers

In summary we can illustrate three technologies with different polarisation curves but operating within a matching cell voltage range of 1.8-1.9v in figure 5. This translates to a stack efficiency of 78-82% (50.6-48.8 kWh/kg H2 (based on 100% faradaic efficiency and) reversible or equilibrium cell voltage of 1.48v)

The CPH2 stack has significantly lower cost and complexity than the PEM stack (approximately 1/3 of the cost). Alkaline stacks are cheaper than PEM but have significant complexity compared to Membrane-Free technology. Alkaline stacks cannot modulate or operate during input electricity turndowns and are therefore incompatible with intermittent power sources.

The CPH2 polarisation curve has been validated at commercial and operational stacks at CPH2 customer site tests in Belfast. Northern Ireland Water chose to employ the Membrane-Free technology to split hydrogen and oxygen efficiently and reliably.

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Rectifiers available	16
Cable current total	191A
PSU current	197A
Voltage	44.6V
Cell	1.7V
KOH Temp	23.5degC
KOH Flow	218L/min

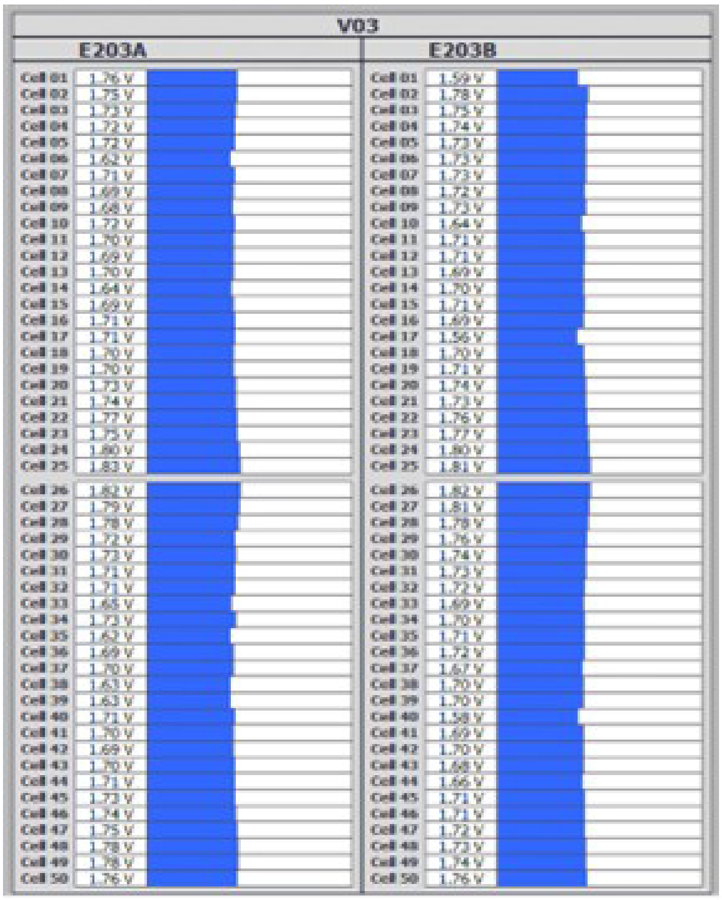


Figure 6: Continous Voltage Monitoring Data for Operating Stack in CPH2 MFE FAT test

Turndown challenges with PEM

The crossover charts from Agate and Trinke et Al (Figure 7) are also reproduced in the new ISO standard for PEM electrolysers (ISO 22734). In keeping with the polarisation curve, PEM systems initially get more efficient as you turn them down following the curve. However, they cannot follow the full polarisation curve due to membrane crossover. It is typical of a PEM stack to operate at high cathode pressures on the hydrogen side (up to 35 bara) and ambient anode pressure on the oxygen side.

According to Martin and Trink, at moderate pressures and current densities of less than 1A/cm², hydrogen concentrations greater than the 4% Lower Explosion Limit for hydrogen in oxygen are observed on the anode side. This places a limit on the turndown load of a PEM stack. It cannot operate below 1A/cm² which is only 50% of the normal load. A typical PEM stack size is 1MW, in such scenarios this would cause significant loss of efficiency where the 1MW system contains a single stack. For Alkaline Electrolysers the turndown performance is even more restricted.

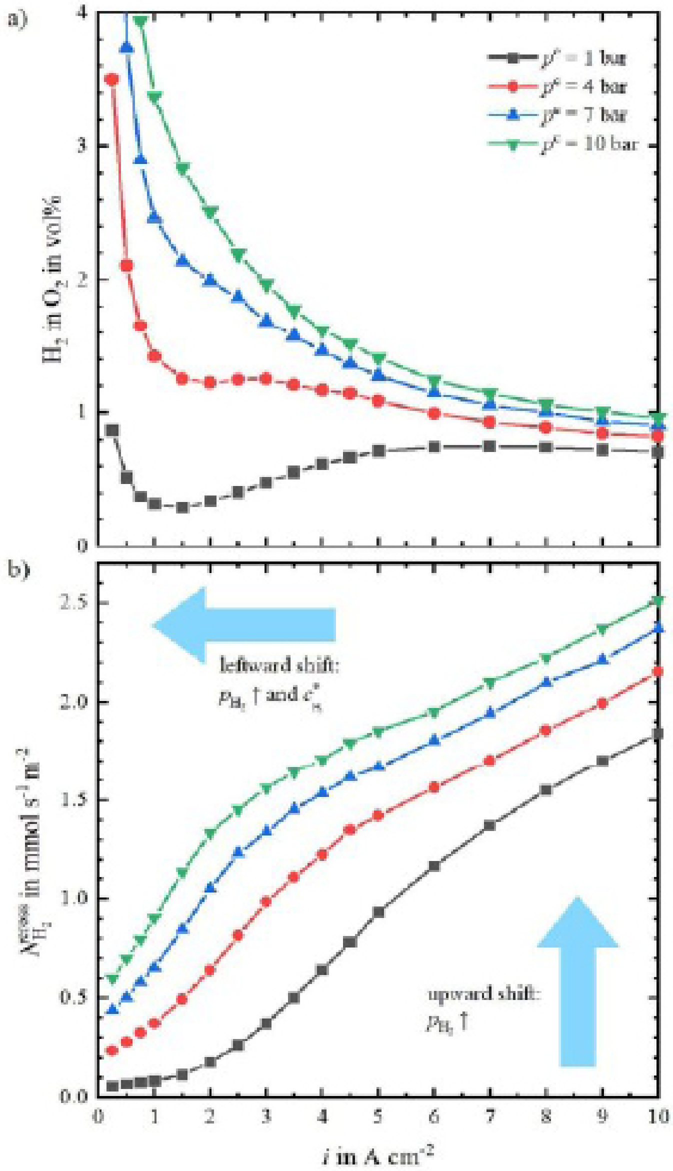


Figure 7: Hydrogen Crossover at all Cathode Pressures and 80 °C for PEM Electrolysers from Agate and Trinke et Al (Journal of the Electrochemical Society 2022). In a) the hydrogen in oxygen content and b) the hydrogen crossover flux is shown as a function of the current density.

The CPH2 1MW system is divided into 8 modular stacks which turn off in sequence according to the plant load. Thereby the CPH2 MFE-220 stacks operate at the point of maximum efficiency across a wide load range of 10-100%. Projected AC power versus nominal load can be seen in figure 8.

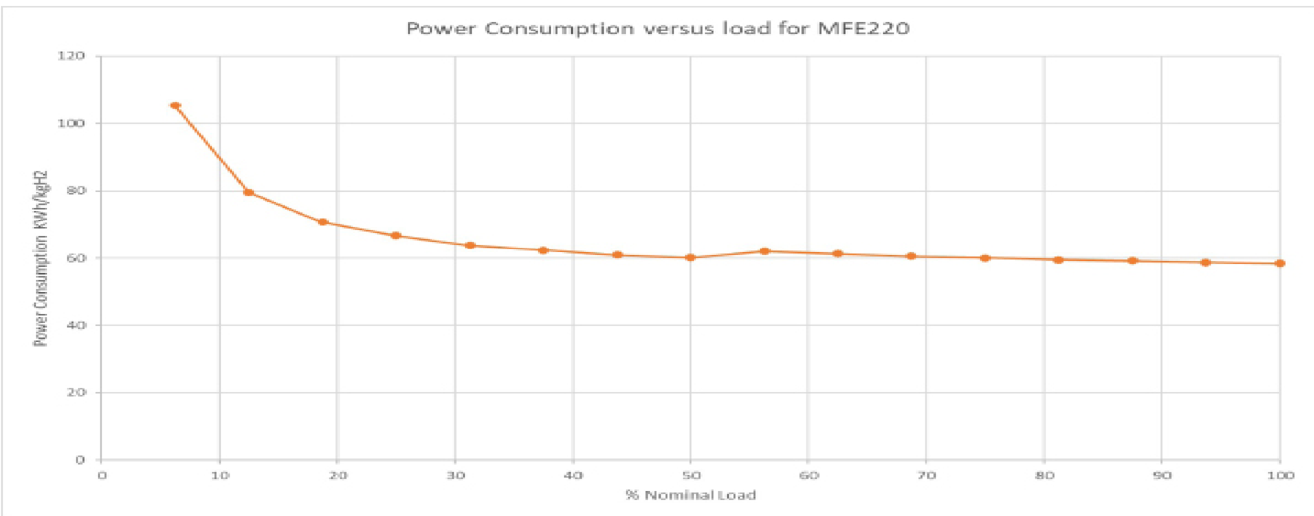


Figure 8: Projected AC Power Consumption versus % nominal load for MFE220. Performance based on bringing stacks online sequentially. Stack operation at 70 °C and 10wt% KOH

Cryogenic Separation

Cryogenic separation is based on the principle that at 77K (the temperature of liquid nitrogen at atmospheric pressure), oxygen condenses to a liquid and hydrogen remains in the vapour phase. Cryogenic cooling is energy intensive and to cool from an ambient temperature of 293K (20°C) to 77K (-196°C) using only a cryogenic refrigerator would require more energy than is technically practical and commercially feasible.

Breakthrough CPH2 technology enables the interchange of heat between the produced hydrogen and oxygen, with the incoming hydrogen oxygen mixture, which recovers most of the thermal energy otherwise lost. This leaves just 10K (10°C) of cooling to be performed by the cryogenic refrigerator.

The cooling energy requirement is 3.0 kWh/kg H2 of electrical energy using the current Fabrum PTC-1000 Cryocooler. For future larger systems, higher coefficients of performance are possible with potential to decrease the cooling electrical energy requirement down to 1.0kWh/kg H2.

Figure 9: Cryogenic Separator from CPH2 MFE110 on site in Belfast.

Mixed Gas Safety

The electrolyser contains up to 1.0 kg of hydrogen as a hydrogen/oxygen mixture, mainly within electrolyte separators and dryers.

Mixtures of hydrogen and oxygen present a known safety hazard with a risk of ignition leading to explosion. The electrolyser design has been subjected to and incorporated extensive Hazard and Operability Studies (HAZOP) and Layer of Protection Analysis (LOPA). It has been operated in specialist test facilities, and following independent approval, tested on-site at operational customer premises.

Detailed analysis and siting recommendations were developed by the independent consultants WSP. They produced a Quantitative Risk Analysis report which fully informs safe customer installations, including the first at Northern Ireland Water in Belfast, agreed within their stringent safety protocols.

The electrolyser control system is fully autonomous and can be initiated, operated, shutdown and purged to a safe condition in all operational scenarios, from a remote location. To ensure the control system meets the highest level of integrity, there are independent logic controllers for process control and safety functions.

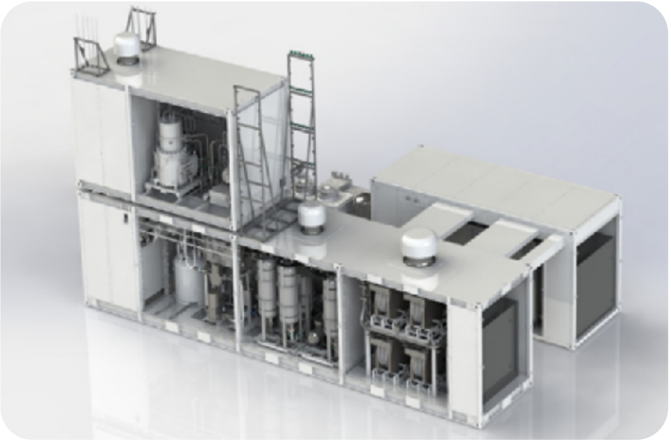
Successful completion of test phase

The CPH2 / Northern Ireland Water electrolyser successfully passed its site acceptance test on 1 May 2025. All site acceptance tests were independently witnessed by Lagan MEICA Limited, the principal contractor, and ARUP, representing Northern Ireland Water, demonstrating efficient and safe cryogenic separation of hydrogen and oxygen products utilising unique and patent-protected technology. The input power was 125kW at the electrolysis stacks.

Figure 10: Operational CPH2 electrolyser at Northern Ireland Water, Belfast

The hydrogen purity was 99.999 vol% verified by an online mass spectrometer. Oxygen purity was greater than 99.5vol% exceeding medical grade requirements.

Building upon this success, a larger MFE220 model (see figure 11 below) is currently in final stages of assembly and scheduled for testing in late 2025, targeting up to 450kg/day of hydrogen production and 3600 kg/day of oxygen production.



MFE220	
Hydrogen Production (kg/day)	450
Hydrogen Purity (vol%)	Up to 99.999 (to ISO 14687 for fuel cells)
Oxygen Production (kg/day)	3600
Oxygen Purity (vol%)	20
Hydrogen Pressure (barg)	20

Figure 11 & 12: MFE220 3D Render and MFE220 Specification

Lower Levelised Cost of Hydrogen

The Levelised Cost of Hydrogen (LCOH) is used to estimate the average cost of producing hydrogen over the lifetime of a production facility. It helps compare different hydrogen production technologies on a consistent basis.

There are four areas where the patented CPH2 technology has been shown to improve levelised costs versus current and legacy technologies.

- The compatibility with intermittent power allows Membrane-Free technology to access lower electricity cost from curtailed electricity grid operations and off grid supplies, maintaining efficient production as the power input varies.
- The reliability, durability and low initial capital cost of the Membrane-Free stack reduces the lifetime cost of ownership and reduces OPEX requirements long-term.
- The fully automated system lowers operating costs and makes effective remote operations feasible.
- Pure oxygen, tested above medical grades, is a valuable co-product which is not easily produced with traditional types of electrolysers.

Advantages of Membrane-Free Electrolysis

Technical Benefits:

- Robustness and Durability: Membrane-Free systems are less susceptible to degradation, fouling, or failure associated with a high-cost membrane.
- Ease of Maintenance: Simpler designs and supply chains translate into fewer replacement parts, reducing downtime and service costs.
- Use of simple, lower-cost materials (e.g. stainless steel, non-precious metals)
- Low ionic stack resistance due to the elimination of the membrane, which generates high power efficiency
- Scalability: The modular design supports co-location alongside customer premises, plants and assets, achieving operational resilience by bringing supply adjacent to demand, at the right size to meet a defined and ongoing need.

Environmental Impact:

- Sustainable Materials: Use of recyclable components and avoiding PFA 'forever chemicals' already banned in several countries.
- Dual Gas Utilisation: Oxygen byproduct used in wastewater treatment, reducing energy consumption by up to 30% along with biomass plant efficiency enhancement, life science and medical uses.
- Reduced Carbon Footprint: No reliance on rare, hard to source, or high emission generating materials.
- Facilitates greater use of otherwise curtailed (wasted) renewable energy. This can restore some wind and solar projects to profitability and support electricity grid balancing and resilience.

Economic Efficiency:

- Cost Reduction: Eliminates the need for expensive membranes and precious metal catalysts, lowering both capital expenditure (CAPEX) and operational expenditure (OPEX).
- Flexible Integration: Compatible with intermittent renewable energy sources like wind and solar, benefitting from the growing periods of low-cost or even free electricity produced when compromised by system non-synchronous penetration on electricity grids.
- Material Availability: Avoids reliance on scarce or geopolitically sensitive materials, such as platinum, iridium, or fluorinated polymers. Unlike PEM manufacturing, Membrane-Free technology does not use PFA 'forever chemicals' banned in several countries and under review across the EU and UK.

Challenges and Considerations

Like all groundbreaking technologies, Membrane-Free electrolysis has significant future opportunities for development. Significant investment is now being deployed to achieve the next breakthroughs. Hydrogen was one of the five sectors which will benefit from the additional £5.8 billion allocated to the National Wealth Fund according to a July 2025 report from the UK Government. Advancements may include:

- System Footprint: Engineering solutions for proven and safe gas separation increase the physical size of the electrolyser. Investment in the next generation will see this reduce over time.
- Future product certification: National product standards for hydrogen purity, pressure, and safety must be demonstrated in every country. The successful testing in one, does not confer the same accreditation in another. Next generation products will be accredited globally.

Applications optimised for mission critical operations

Membrane-Free electrolysis is well-positioned to serve diverse markets, with a particular emphasis on mission critical applications within water and power systems infrastructure. The Future Energy Pathways report, jointly issued by UK Government, the National Electricity System Operator and lead regulator OFGEM in July 2025 noted that “Hydrogen to Power can play a key role in our electricity system at a range of scales”.

Where operational resilience is paramount, electrification discounted, and the right sizing of supply, co-located with demand is preferred, then MFE technology is optimum. When used with renewable energy sources, the whole solution is very low carbon.

Reliable Water Supply - global industry value estimated at >$350 billion

Waste water-treatment requires significant energy input and volume will only grow. Electrolysis provides high purity oxygen that makes the treatment process much more efficient, and green hydrogen for multiple downstream uses.

Biomass Plant Efficiency - global industry value estimated at >$55 billion

Oxygen enriched biomass accelerates combustion reaction, burning out more of the fuel. This delivers increased efficiency and lower regulated NOx emissions for biomass and energy-from-waste plants around the world. There are applications at larger scale too. The UK Environmental Permitting Regulations 2024, provisionally expected to come into force from 28 February 2026 states that *“legislation will require new build and substantially refurbishing unabated gas and other combustion power plants in England to be built in such a way that they can readily convert to hydrogen-firing or by retrofitting carbon-capture technology within the plant’s lifetime”*.

Electricity Grid Support - global industry value estimated at >$380 billion

The need to curtail renewable energy production is growing across global electricity grids; a multi-billion-dollar problem. Wind and solar optimised hydrogen production is part of the 'non-synchronous penetration' solution for network operators and renewable asset developers. The Future Energy Pathways report, jointly issued by UK Government, the National Electricity System Operator and lead regulator OFGEM in July 2025 added that their *"analysis indicates that Hydrogen to Power is also cost effective at relatively low load factors, providing a key role in a post-2030 power system as greater renewable deployment reduces the running hours for flexible capacity."*

Data Centre Uptime - global industry value estimated at > $30 billion

Data-centre demand is growing fast; uptime is their critical success factor. Hydrogen can replace diesel generator back-up. Produced on site the hydrogen is always available unlike high carbon diesel which must be delivered to a growing number of remote locations.

Life Sciences & Medical - global industry value estimated at > $1 trillion

Life sciences and medical uses of high purity hydrogen and oxygen include therapeutic treatments, medical devices, drug development, gas chromatography-mass spectrometry and process analytical technologies.

Environmental and Societal Impact

The adoption of Membrane-Free electrolysis technology can help accelerate the shift from fossil-fuel derived hydrogen (grey hydrogen) to clean, renewable hydrogen (green hydrogen), reducing global greenhouse gas emissions. By lowering the cost and complexity of hydrogen production, this technology can enable broader participation in the hydrogen economy for otherwise hard to abate sectors and developing regions. This lower cost, high efficiency, modular solution facilitates co-located deployment at the right size for new, previously uneconomic applications.

Outlook and Research Directions

Membrane-Free electrolysis is a rapidly advancing field, with ongoing research targeting several areas for further technological development.

- Optimising stack cell designs for even higher efficiencies and lower costs
- Engineering development to further lower CAPEX of components such as cryogenics, containerisation and power electronics
- Additional capital cost reduction and efficiencies as manufacturing scales up globally.
- Integrating artificial intelligence for process control and predictive maintenance

Industry collaborations, government incentives, and academic research will be important contributions to the next breakthroughs of technical and market barriers.

Conclusion

Membrane-Free electrolysis is the next generation in clean hydrogen production technology. By eliminating the need for expensive, fragile membranes, precious metals and forever chemicals, and by enabling integration with renewable power, and flexible, scalable designs, this approach makes green hydrogen economic for a wider range of applications.

As the number of installations grow, Membrane-Free electrolysis will play a vital role in global efforts to decarbonise and enhance energy resilience and security at state and company level. It can improve biomass plant efficiency, maintain reliable water supplies, support life sciences, keep data centres running, support electricity grids and the wind and solar assets connected to them. All this can be achieved while helping to meet our vital climate targets.