DRIVING DECARBONISATION

GREEN HYDROGEN PRODUCTION WHITE PAPER

Fyfe's Commitment to Sustainable Solutions and Green Hydrogen Innovation

FYFE

FOREWARD

At Fyfe, we are actively contributing to the energy industry's decarbonisation efforts through our skilled multidisciplinary engineering design, surveying, and environmental team. By leveraging our expertise, we aim to support the development and implementation of innovative solutions for green hydrogen production and other sustainable technologies. Our team's comprehensive approach allows us to assess and optimise project viability, ensuring that environmental considerations are integrated into the design process from the outset. We are committed to collaborating with stakeholders across various sectors to facilitate a smoother transition toward a hydrogen-based economy, helping to achieve the ambitious decarbonisation goals set for the coming decades. Through our sustainable approach and technical excellence, we aspire to make a valuable contribution in the energy transition sector.

Green hydrogen production methods and technical targets

As countries increasingly focus on deep decarbonisation strategies, hydrogen is set to play a pivotal role in achieving these goals. This is especially true in sectors where direct electrification poses challenges, such as steel production, chemicals, long-haul transport, shipping, and aviation. To maximise its potential, it is essential that hydrogen is low carbon from the outset, ideally being produced through green methods, such as the electrolysis of water powered by renewable electricity.

While regulations and market design play crucial roles in fostering this transition, the cost of producing green hydrogen remains a significant hurdle to its widespread adoption. Encouragingly, production costs are on the decline, primarily driven by the decreasing costs of renewable energy. However, green hydrogen is currently more expensive than blue hydrogen, which is generated from fossil fuels with carbon capture and storage. Continued efforts to drive further cost reductions will be vital for scaling up green hydrogen use and enhancing its competitiveness in the market.

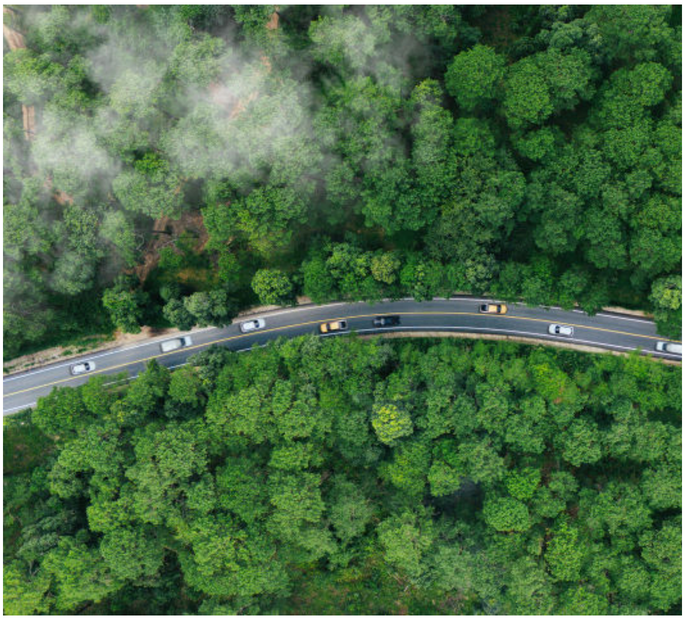
Green hydrogen, produced from renewable electricity, offers a promising link between renewable energy sources and a variety of end-use applications. It serves as a valuable complement to electrification, bioenergy, and direct renewable energy use. The potential of green hydrogen greatly surpasses that of fossil fuels, as it harnesses the abundant resources of solar and wind energy, which can meet and exceed current and future global energy demands.

Green hydrogen represents just one of the many pathways for hydrogen production. Other methods include utilising bioenergy, methane, and coal, as well as producing hydrogen directly from solar energy. Currently, the majority of hydrogen production relies on methane and coal, but incorporating Carbon Capture and Storage (CCS) can significantly reduce its carbon footprint. CCS technology may be particularly advantageous in regions where low-cost natural gas is available and where there are suitable underground reservoirs. In the short term, CCS also shows promise for large-scale industrial applications.

When green hydrogen is produced at scale and at a competitive cost, it opens up exciting possibilities for further conversion into various energy carriers, including ammonia, methanol, and liquid hydrocarbons. As a versatile fuel, hydrogen can be utilised in fuel cells, which are electrochemical devices that generate electricity by combining hydrogen with oxygen from the air. Additionally, it can be combusted in engines and turbines, showcasing its potential in diverse energy applications.

In this white paper, we will explore various methods of green hydrogen production in depth, detailing the technical parameters and key performance indicators essential for their success. We will assess the current state of technologies. Additionally, we will outline the technical targets necessary for 2050 to ensure these methods can be scaled effectively to meet global demand. This includes clearly defined benchmarks for efficiency, cost, and sustainability. By providing comprehensive insights into both the opportunities and challenges of green hydrogen production, this white paper aims to contribute to a strategic roadmap that aligns technological advancements with the decarbonisation goals of various sectors and fosters a smooth transition toward a hydrogen-based economy.

Electrolysers are essential devices in the production of hydrogen through the process of electrolysis, where water is split into hydrogen and oxygen using electrical energy. There are four primary types of electrolysers, each with its own unique characteristics and advantages.



FOUR MAIN GREEN HYDROGEN PRODUCTION METHODS:

1. Alkaline Electrolyser

2. Proton Electrolyte Membrane

3. Solid Oxide Electrolysers

4. Anion Exchange Membrane

1

ALKALINE ELECTROLYSIS

ALKALINE ELECTROLYSIS

The first generation of alkaline electrolysers, which flourished between 1800 and 1950, marked a pivotal era in the development of electrolysis technology, primarily for the production of ammonia. These systems were predominantly powered by hydropower, taking advantage of low-cost electricity generated from water sources.

Alkaline electrolysis involves using an alkaline solution, typically potassium hydroxide (KOH), as the electrolyte, which facilitates the electrochemical reactions necessary to split water into hydrogen and oxygen. During this period, the focus was largely on ammonia synthesis due to its significance in agriculture as a key component of fertilisers.

The process was relatively simple and utilised abundant and inexpensive hydropower resources, which made it an attractive option for large-scale industrial applications. The technology was essential for supporting the growing agricultural demands of the time, particularly as populations surged and food production needed to keep pace.

The early designs of these electrolysers were quite rudimentary by modern standards, often resulting in lower efficiency and higher operational costs. However, the groundwork laid during this generation set the stage for future advancements in electrolyser technology. Moreover, the success of alkaline electrolysis highlighted the importance of renewable energy sources in industrial processes, a concept that continues to gain relevance in the context of today's emphasis on sustainability and carbon reduction.

One key drawback of alkaline electrolysers is their prolonged cold start-up time, which often spans 50-60 minutes. This significant delay posed challenges for industries that relied on rapid production adjustments, as it meant that after being powered down, the systems would take a while to reach optimal operational efficiency. Consequently, this limitation affected overall productivity, particularly in sectors needing flexibility.

Pressurised alkaline electrolysers have emerged as a notable enhancement compared to their atmospheric counterparts, largely due to their improved efficiency and reduced cold start-up times. By operating at elevated pressures, these systems can generate hydrogen more rapidly, which is particularly advantageous for applications that require quick adjustments and consistent production rates.

ADVANTAGES OF ALKALINE ELECTROLYSIS

1. Mature Technology: Alkaline electrolysis is a well-established and proven technology with decades of development. This maturity translates into relatively lower operational risks and a wealth of experience in design, deployment, and maintenance.

2. Cost-Effectiveness: Compared to other electrolyser types, such as Proton Exchange Membrane (PEM) electrolysers, alkaline electrolysers typically have lower upfront capital costs. This is primarily due to less expensive materials and simpler construction processes, making them an attractive option for large-scale hydrogen production.

3. Scalability: Alkaline electrolysers can be easily scaled up to meet varying hydrogen production needs. This flexibility allows them to be integrated into both small and large installations, accommodating a range of applications from renewable energy integration to industrial hydrogen supply.

4. Durability and Longevity: Alkaline electrolysers generally have a longer operational lifespan compared to other technologies. With proper maintenance, they can operate effectively for many years, reducing the need for frequent replacements and thereby lowering lifetime costs.

5. Less Sensitivity to Impurities: The alkaline electrolyte is less sensitive to impurities in the water used for electrolysis, making alkaline systems less demanding in terms of water quality compared to PEM electrolysers. This can lower operational costs and simplify the water treatment requirements.

ALKALINE ELECTROLYSIS

Alkaline Electrolysers Cell:

The design of these systems features a straightforward stack configuration that lends itself to ease of manufacturing. They utilise high-concentration KOH as the electrolyte, paired with durable ZrO2-based diaphragms and nickel-coated stainless steel for the electrodes. The primary ionic charge carrier, the hydroxyl ion (OH-), facilitates the electrochemical reaction through the permeation of KOH and water within the porous diaphragm structure.

This design enables the production of hydrogen and oxygen gases (H_2 and O_2), which are dissolved in the electrolyte. However, this can lead to intermixing of the produced gases, which limits operational efficiency in lower power ranges and poses challenges for higher pressure applications. To address this issue, thicker diaphragms are employed, though they can introduce higher resistance and decrease overall efficiency.

Some manufacturers mitigate gas intermixing further by incorporating spacers between the electrodes and diaphragms. While these additions help maintain gas separation, they also increase ohmic resistance across the electrodes, which can significantly reduce current density at a given voltage.

Nonetheless, advancements in design—such as zero-gap electrodes, thinner diaphragms, and innovative electrocatalyst concepts—are making strides to close the performance gap with PEM technology. Moreover, traditional alkaline designs are recognised for their reliability, often achieving lifetimes exceeding 30 years, showcasing their durability and effectiveness in different applications.

Alkaline Electrolyser Balance of Plant

The recirculation process in alkaline electrolysers creates a pressure drop that requires specific pumping characteristics. Traditionally, the energy consumed by this pumping has been a very small fraction of the stack's total power consumption and recent advancements from various manufacturers are improving this performance.

Once the alkaline solution exits the stack, it is essential to separate it from the gases produced. This separation is efficiently achieved using gas-water separators strategically positioned above the stack (Figure 1). The KOH/water solution is then recirculated back to the stack. In this arrangement, the gas phase is captured at the top of the separator, while the water phase can be removed from the bottom. The water column within the separator also acts as a buffer, accommodating fluctuations in load specifications.

To maintain optimal performance, the water management system plays a crucial role in regulating the filling level of each gas separator. Additionally, considerations for water permeation through the diaphragm are important for ensuring system efficiency and reliability.

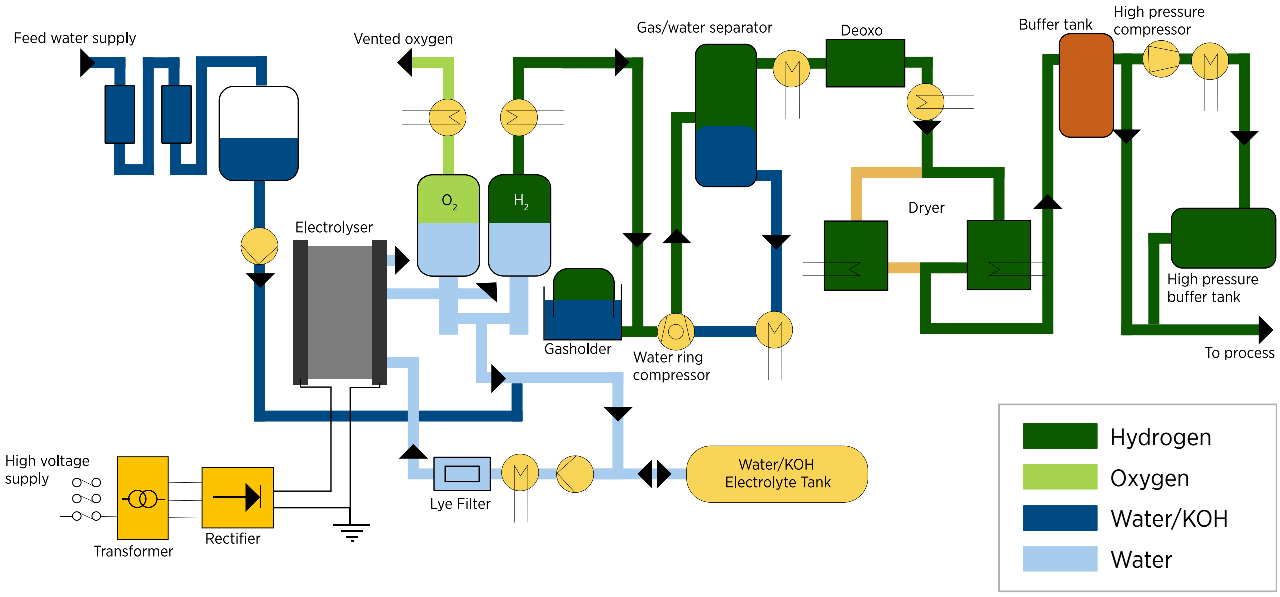


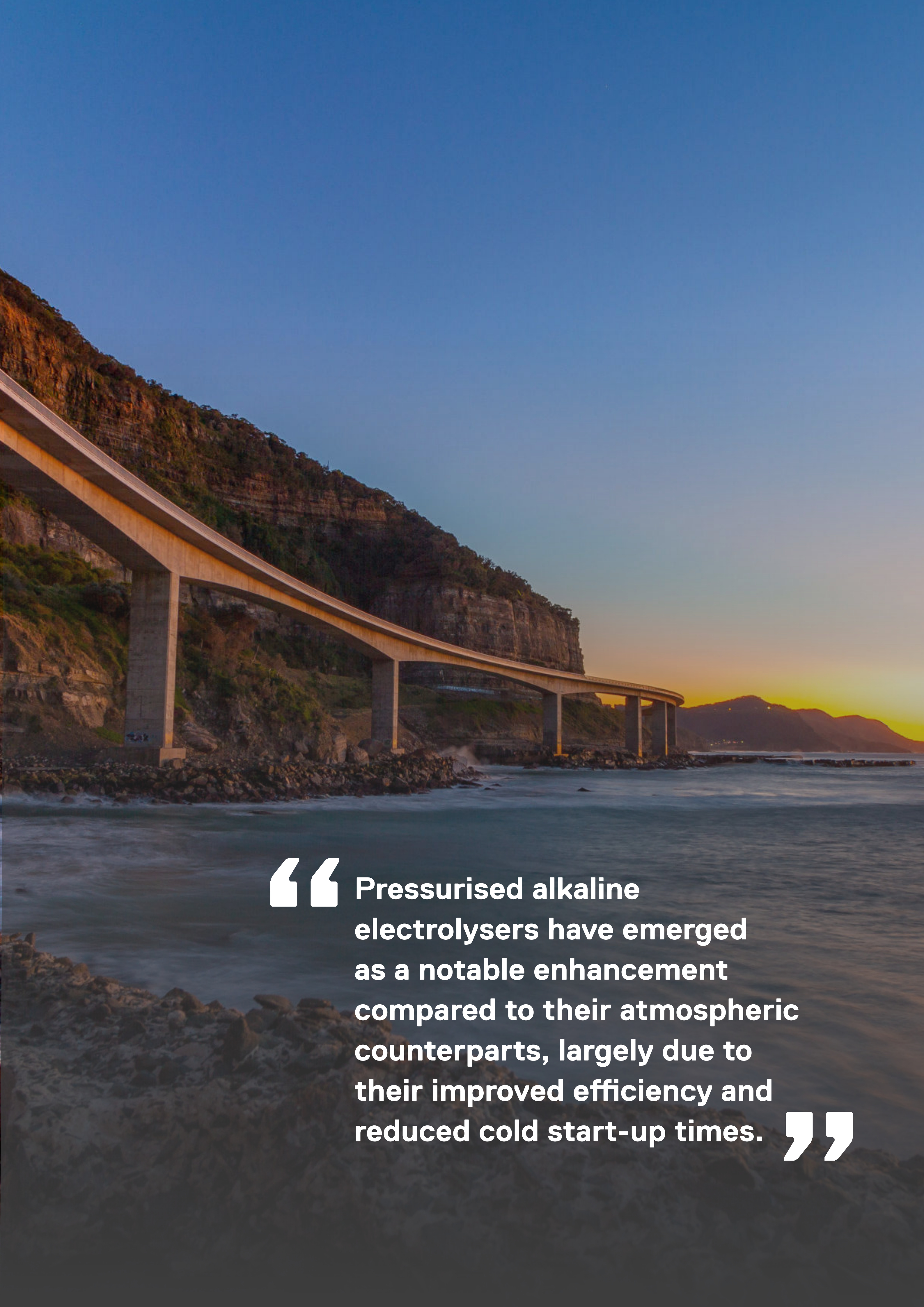
Figure 1 - Typical system design and balance of plant for an alkaline electrolyser. [1]

Alkaline Electrolysers Technical Targets:

Table 1 summarises the U.S. Department of Energy (DOE) technical targets for liquid alkaline electrolysis. Many combinations of performance, efficiency, lifetime, and cost targets can achieve the central goal of low-cost hydrogen production of USD $2/kg H_2 by 2026 and USD $1/kg H_2 by 2031. The targets listed here were developed with input from experts from industry and national laboratories; they can be considered a starting guidepost for technology developers.

Table 1 - Technical Targets for Liquid Alkaline Electrolyser Stacks and Systems [2]

Characteristics	Units	2022 Status	2026 Targets	Ultimate Targets
Stack				
Performance		0.5 A/cm2 @ 1.9 V/cell	1.0 A/cm2 @ 1.8 V/cell	2.0 A/cm2 @ 1.7 V/cell
Electrical Efficiency	kWh/kg H_2 (% LHV)	51 (65%)	48 (69%)	45 (74%)
Average Degradation Rate	mV/kh (%/1,000 h)	3.2 (0.17)	2.3 (0.13)	2.1 (0.13)
Lifetime	Operation h	60,000	80,000	80,000
Capital Cost	$/kW	250	100	50
System				
Energy Efficiency	kWh/kg H_2 (% LHV)	55 (61%)	52 (64%)	48 (70%)
Uninstalled Capital Costs	$/kW	500	250	150
H_2 Production Cost	$/kg H_2	>2	2.00	1.0



> Pressurised alkaline electrolysers have emerged as a notable enhancement compared to their atmospheric counterparts, largely due to their improved efficiency and reduced cold start-up times.

2

PROTON ELECTROLYTE MEMBRANE (PEM)

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PEM technology represents a significant advancement in electrochemical systems, primarily due to its ability to utilise pure water as a feedstock. This is in stark contrast to alkaline systems that require caustic solutions, which can complicate both operation and maintenance.

The reliance on pure water offers several advantages. Firstly, it simplifies the overall system design, leading to fewer components and lower installation complexity. This can translate to reduced costs and easier scalability for various applications. Additionally, with fewer corrosive chemicals involved, the safety risks associated with handling hazardous materials are minimised, which is a vital consideration in many industrial settings.

Moreover, PEM technology is known for its superior efficiencies and power densities. It allows for a more effective conversion of chemical energy into electrical energy. The result is a system that not only occupies a smaller physical footprint but also delivers higher performance levels compared to traditional alkaline systems. This efficiency can lead to lower operational costs over time and enhance the viability of PEM technology in various energy applications, including renewable energy systems, fuel cells for transportation, and stationary power generation.

PEM electrolysers' disadvantages include reliance on precious metals like platinum for catalysts, which increases costs. Furthermore, their durability is limited, leading to degradation over time and ultimately impacting long-term efficiency and performance.

ADVANTAGES OF PEM ELECTROLYSERS

1. High Purity Hydrogen Production: PEM electrolysers generate hydrogen at an exceptional purity level (around 99.999%), making them ideal for fuel cells and specific industrial processes requiring such quality.

2. Efficient Energy Use: They boast higher energy efficiency than their alkaline counterparts, optimising energy consumption during hydrogen production.

3. Compactness with High Power Density: Their ability to operate at greater current densities allows for a more compact system, facilitating more efficient space usage for hydrogen output.

4. Fast Response to Power Fluctuations: PEM electrolysers can quickly adjust to changes in power inputs, which makes them excellent for integration with renewable energy sources like solar and wind that can be intermittent.

5. High Hydrogen Output Pressure: The capability to produce hydrogen at elevated pressures can minimise the need for further compression, leading to cost savings in the overall system.

6. Lightweight and Space-Efficient Design: Their compact and lightweight nature is advantageous for mobile applications or situations where space is limited.

7. Decentralised and On-site Production: The flexibility of PEM electrolysers supports decentralised hydrogen production, catering to the specific demands of various industries or applications.

PROTON ELECTROLYTE MEMBRANE (PEM)

PEM Electrolyser Balance of Plant

A PEM electrolyser operates through several key stages. It begins with the feed water supply, requiring pure water to prevent damage. The water undergoes further purification in an ion exchanger (Figure 2) before a circulation pump directs it into the electrolyser.

Inside the electrolyser, which consists of low-pressure and high-pressure sides, the process begins with purified water input. An electric current, supplied by a transformer and rectifier, initiates electrolysis, splitting water molecules into hydrogen and oxygen (O_2).

The resulting gases pass through gas separators, where water is condensed and removed, and oxygen is vented. The separated hydrogen then goes through further processing, including storage in a gas reservoir, compression to increase pressure, removal of residual oxygen in a deoxo unit, and drying to achieve high-purity hydrogen.

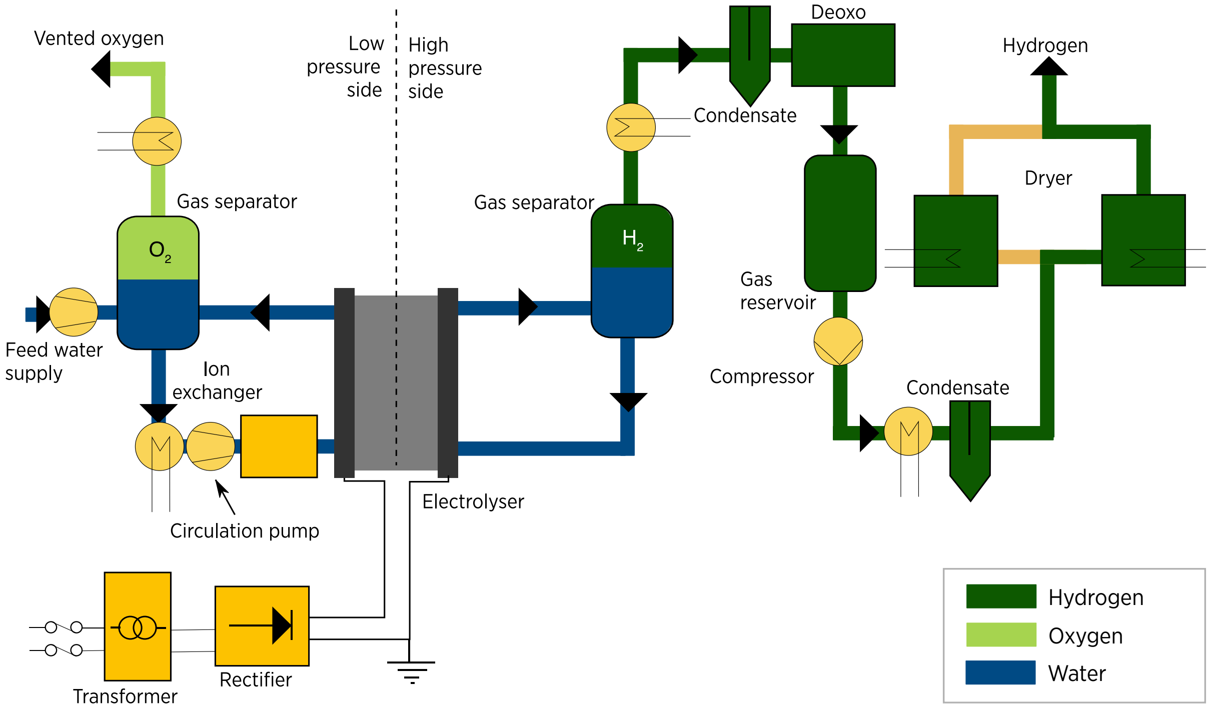


Figure 2 - Typical system design and balance of plant for a PEM electrolyser. [1]

PEM Electrolysers Technical Targets:

Table 2 summarises the U.S. Department of Energy (DOE) technical targets for PEM electrolysis. Many combinations of performance, efficiency, lifetime, and cost targets can achieve the central goal of low-cost hydrogen production of USD \$2/kg H_2 by 2026 and USD \$1/kg H_2 by 2031. The targets listed here were developed with input from experts from industry and national laboratories; they can be considered a starting guidepost for technology developers.

Table 2 - Technical Targets for PEM Electrolyser Stacks and Systems [3]

Characteristics	Units	2022 Status	2026 Targets	Ultimate Targets
Stack				
Total Platinum Group Metal Content (both electrodes combined	mg/cm^2	3.0	0.5	0.125
	g/kW	0.8	0.1	0.03
Performance		2.0 A/cm^2 @1.9 V/cell	3.0 A/cm^2 @1.8 V/cell	3.0 A/cm^2 @1.6 V/cell
Electrical Efficiency	mV/kh H_2 (% LHV)	51 (65%)	48 (69%)	43 (77%)
Average Degradation Rate	mV/kh (%/1,000 h)	4.8 (0.25)	2.3 (0.13)	2.0 (0.13)
Lifetime	Operation h	40,000	80,000	80,000
Capital Cost	\$/kW	450	100	50
System				
Energy Efficiency	kWh/kg H_2 (% LHV)	55 (61%)	51 (65%)	46 (72%)
Uninstalled Capital Costs	\$/kW	1,000	250	150
H_2 Production Cost	\$/kg H_2	>3	2.00	1.0

> PEM technology is known for its superior efficiencies and power densities. It allows for a more effective conversion of chemical energy into electrical energy. The result is a system that not only occupies a smaller physical footprint but also delivers higher performance levels compared to traditional alkaline systems.

3

SOLID OXIDE ELECTROLYSERS (SOE)

SOLID OXIDE ELECTROLYSERS (SOE)

SOEs operate at elevated temperatures of 700-850°C, which offers several advantages. This temperature range facilitates favourable kinetics, allowing for the use of relatively inexpensive nickel electrodes. Additionally, the demand for electricity is reduced since part of the energy needed for separation can be supplied through heat, enabling the utilisation of waste heat and achieving apparent efficiencies that can exceed 100%. Furthermore, this technology presents the potential for reversibility, functioning both as a fuel cell and an electrolyser. It also enables co-electrolysis of CO2 and water to create syngas, a vital building block for the chemical industry.

However, there are challenges to address. Thermo-chemical cycling, particularly during shutdown and ramping periods, can lead to accelerated degradation and reduce the operational lifespan of the cells. Other degradation concerns include sealing issues at higher differential pressures, contamination of electrodes by silica used in sealants, and additional contaminants that may arise from piping, interconnects, and sealing materials. Currently, SOEs are primarily deployed at the kilowatt scale, although some demonstration projects are successfully reaching the 1 MW mark, showcasing their potential for larger-scale applications in the future.

ADVANTAGES OF SOE ELECTROLYSERS

1 High Efficiency: Solid Oxide Electrolysers (SOEs) operate at temperatures between 700-1000 °C, which accelerates reaction kinetics. This higher operational temperature allows for reduced electrical energy input while producing the same amount of hydrogen, leading to enhanced energy conversion efficiency when compared to traditional lower-temperature electrolysis methods.

2 Potential for Waste Heat Utilisation: The elevated temperatures at which SOEs function create opportunities for harnessing waste heat from various industrial processes or nuclear reactors. This integration can significantly lower the overall energy consumption and costs associated with hydrogen production. For instance, the incorporation of a pre-heater can enhance energy efficiency by maximising the use of available thermal energy.

3 Fuel Flexibility (Co-electrolysis): SOEs possess the unique capability to perform co-electrolysis, wherein steam is combined with gases like carbon dioxide (CO_2). This versatility allows for the simultaneous production of syngas—comprising hydrogen and carbon monoxide—as well as other valuable chemicals, thus broadening the application possibilities beyond just hydrogen generation.

4 Solid-State Design: Employing a solid ceramic electrolyte is a key feature of SOEs. This design choice eliminates the dependence on liquid electrolytes, which often face complications such as corrosion and leakage. Consequently, this solid-state approach can lead to simpler, more robust system designs and improve the overall reliability of the technology.

5 High-purity hydrogen Output: One of the standout benefits of SOEs is their ability to produce high-purity hydrogen. This quality is particularly critical for applications like fuel cells, which typically require hydrogen free of impurities.

SOLID OXIDE ELECTROLYSERS (SOE)

SOE Electrolyser Balance of Plant

SOE operates by first supplying liquid water, which is heated in an evaporator to produce high-temperature steam. This steam is further pre-heated (Figure 3) before entering the electrolyser stack, the core component where electrolysis occurs at temperatures of 700-1000 °C. An electric current, supplied via a transformer and rectifier, splits the water molecules into hydrogen and oxygen.

The output includes high-purity hydrogen gas, while any unreacted steam and water are separated and recycled back to the evaporator.

Figure 10. Typical system design and balance of plant for a solid oxide electrolyser.

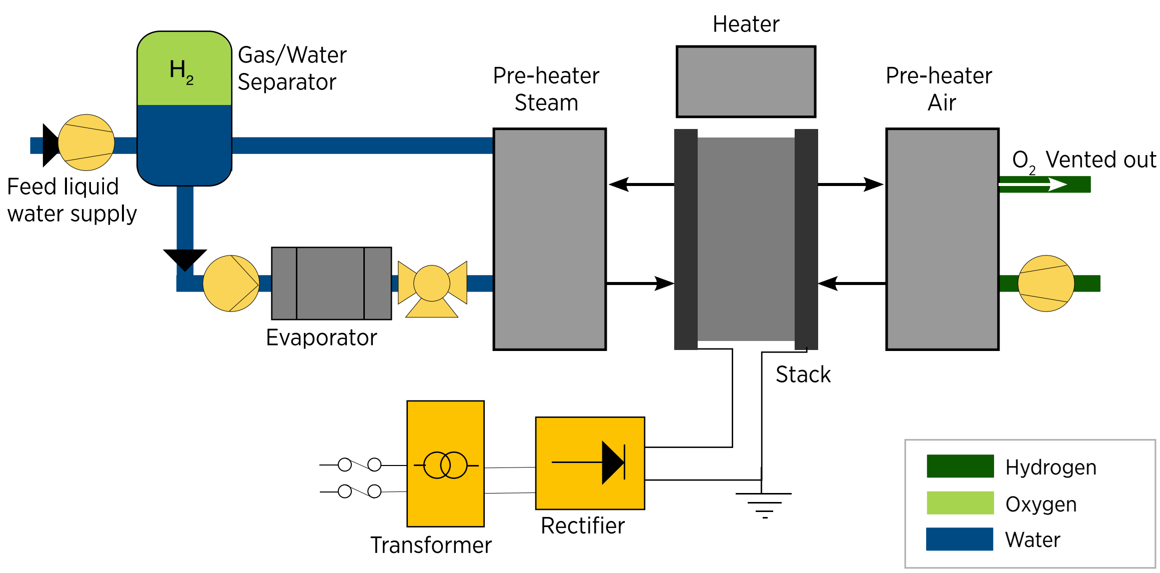


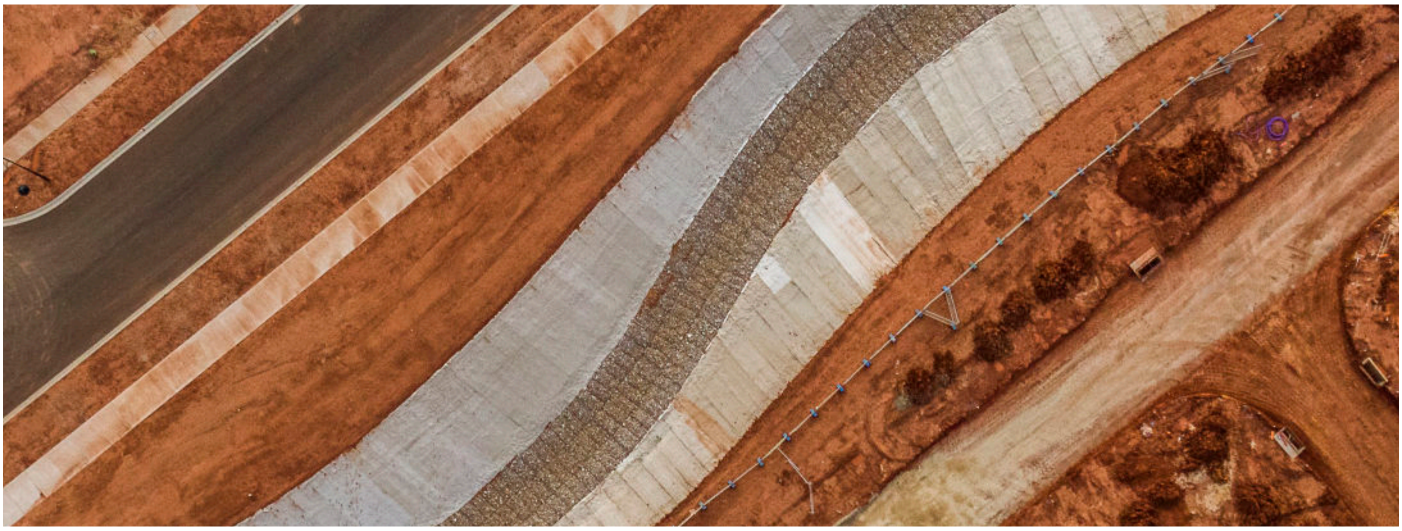
Figure 3 - Typical system design and balance of plant for a solid oxide electrolyser. [1]

SOE electrolysers Technical Targets:

Table 3 summarises the U.S. Department of Energy (DOE) technical targets for high-temperature electrolysis. Many combinations of performance, efficiency, lifetime, and cost targets can achieve the central goal of low-cost hydrogen production of USD $2/kg H_2 by 2026 and USD $1/kg H_2 by 2031. The combination of targets listed here was developed with input from experts from industry and national laboratories; it can be considered a starting guidepost for technology developers.

Table 3 - Technical Targets for High Temperature Electrolyser Stacks and Systems [4]

Characteristics	Units	2022 Status	2026 Targets	Ultimate Targets
Stack				
Performance	A/cm^2 @1.28 V/cell	0.6	1.2	2.0
Electrical Efficiency	kWh/kg H_2 (% LHV)	34 (98%)	34 (98%)	34 (98%)
Average Degradation Rate	mV/kh (%/1,000 h)	6.4 (0.50)	3.2 (0.25)	1.6 (0.12)
Lifetime	Operation h	20,000	40,000	80,000
Capital Cost	$/kW	300	125	50
System				
Energy Efficiency	kWh/kg H_2 (% LHV)	38 (88%)	36 (93%)	35 (95%)
Energy Efficiency	kWh/kg H_2 (% LHV)	47 (71%)	44 (76%)	42 (79%)
Uninstalled Capital Costs	$/kW	2,500	500	200
H_2 Production Cost	$/kg H_2	>4	2.00	1.0



> **“Solid Oxide Electrolysers (SOE) presents the potential for reversibility, functioning both as a fuel cell and an electrolyser. It also enables co-electrolysis of CO2 and water to create syngas, a vital building block for the chemical industry.”**

4

ANION EXCHANGE MEMBRANE (AEM)

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The advancement of AEM technology presents exciting opportunities, with only a handful of companies currently commercialising it and a limited scope for deployment. AEM holds great promise due to its combination of a more benign operational environment compared to alkaline electrolysers and the simplicity and efficiency characteristic of PEM electrolysers. One of its key advantages is the potential use of non-noble catalysts and titanium-free components, along with the capability to operate under differential pressure like PEM systems.

However, some challenges remain to be addressed, particularly regarding the chemical and mechanical stability of AEM membranes, which can impact their longevity.

Enhancing performance can involve optimising the conductivity properties of the membrane or incorporating supporting electrolytes like KOH or sodium bicarbonate (NaHCO3).

ADVANTAGES OF AEM ELECTROLYSERS

1. Cost Efficiency: AEM electrolysers may offer a more affordable alternative to PEM electrolysers because they can employ non-noble metal catalysts, such as nickel or iron, instead of the costly platinum group metals required in PEM systems.

2. Energy Efficiency: AEM electrolysers have the potential to deliver high energy efficiency when converting electricity and water into hydrogen and oxygen.

3. High-Quality Hydrogen Production: They are capable of generating high-purity hydrogen gas that is often suitable for various applications without needing additional purification processes.

4. Lower Operating Temperatures: Typically operating below 100°C, AEM electrolysers usually require less complex and costly systems compared to Solid Oxide Electrolysers (SOEs), which operate at higher temperatures.

5. Quick Start-Up and Response: AEM electrolysers are known for their rapid start-up times and quick response rates compared to traditional alkaline electrolysers. This makes them particularly advantageous for use with intermittent renewable energy sources.

6. Higher Current Densities: AEM electrolysers can handle higher current densities than conventional alkaline systems, resulting in a more compact design for achieving specific hydrogen production rates.

ANION EXCHANGE MEMBRANCE (AEM)

AEM Electrolyser Balance of Plant

An AEM electrolyser operates by first supplying low conductivity water for purification (Figure 4). This water is then passed through an ion exchanger to remove additional ions, which helps ensure both the efficiency and longevity of the system. The purified water is introduced into an electrolyte tank containing a dilute alkaline solution. A circulation pump is used to circulate the electrolyte solution between the tank and the electrolyser.

The electrolyser features a high-pressure hydrogen side and a low-pressure oxygen side. During the process of electrolysis, an electric current is applied to split water into hydrogen and oxygen. The membrane effectively separates the hydrogen and oxygen gases.

In terms of gas processing, the oxygen gas is vented from the electrolyte tank, ensuring it is kept separate from the electrolyte solution. Meanwhile, the hydrogen gas is stored in a reservoir where it undergoes drying and compression before being stored in a high-pressure tank for later use.

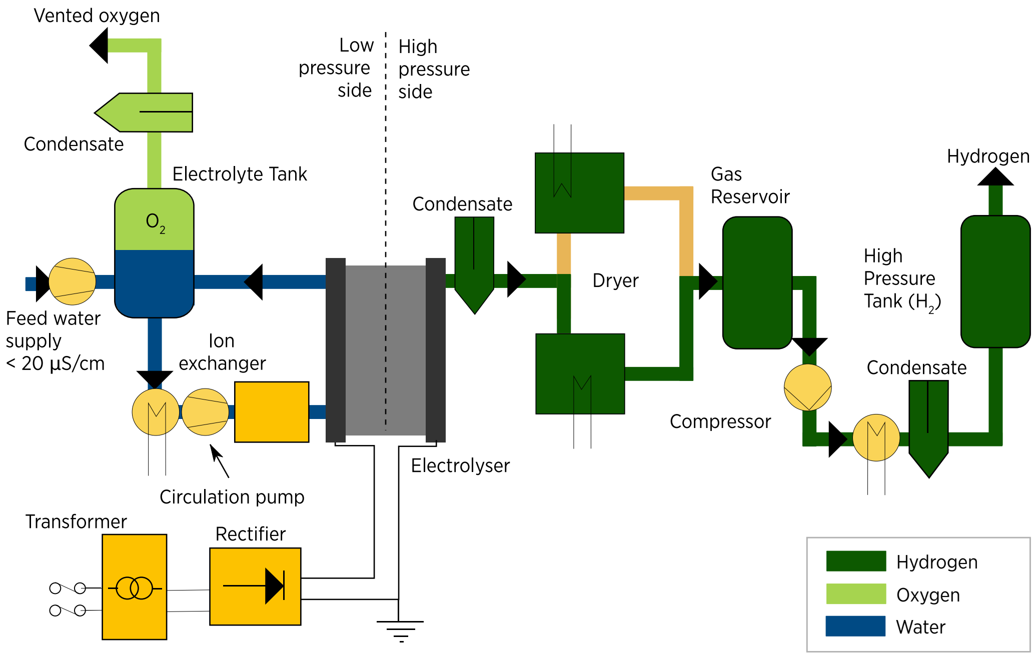

Figure 4 - Typical system design and balance of plant for an AEM electrolyser. [1]

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[3] U.S. Department of Energy (DOE) technical targets for proton exchange membrane (PEM) electrolysis.
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[4] U.S. Department of Energy (DOE) technical targets for high temperature electrolysis.
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