Ultrapure water for electrolysis

Discover the mission-critical feedstock for MW- and GW-scale green hydrogen and ammonia projects of the future

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For each kilogram of green hydrogen produced, 9-10 litres of ultrapure water are consumed by electrolysis. This equates to circa 200 litres of water per MW of electrolyser capacity. To generate that amount of ultrapure water, circa 1.5 times as much fresh water is required.

Most large-scale green hydrogen projects are proposing to use renewable power generation from wind and solar resources. The optimum location for wind power generation is often offshore, and the best places to generate low-cost solar power are generally in arid desert locations. Neither location has unlimited access to fresh water, so seawater extraction and desalination will be required.

To generate desalinated fresh water, approximately twice as much seawater is required. So, for each litre of ultrapure water, three litres of seawater must be extracted and processed. Seawater processing to ultrapure water will be an essential aspect of the MW- and GW-scale green hydrogen and green ammonia projects of the future.

Desalination is key for electrolysis in arid locations with ideal wind and solar conditions

Electrolysers are an expensive capital asset and represent a high portion of the capital investment for green hydrogen projects. Project economics can be improved if the electrolysers have a high utilisation rate, meaning they operate for many months per year and many hours per day.

Integration of wind and solar can improve the firmness of renewable power generation. Hybrid schemes of this kind will be optimal in countries such as Egypt, Australia, Namibia, Oman, and Chile. However, these locations are not blessed with abundant fresh water supply. Seawater extraction in many of these places is possible, but desalination adds to the cost and complexity of ultrapure water production.

The technologies that will bring fresh water to electrolysis schemes are exactly those that are relied on today to make potable water available in arid locations. Desalination is used extensively in the Middle East to make water available for the emerging vertical farming sector and coastal cities.

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Water tankers deliver fresh water to many villages in South Asia, and drilling for groundwater is common in inland locations without natural rivers. While the technologies are known, they must be adapted to make fresh water available for green hydrogen projects.

Globally competitive green hydrogen and green ammonia production

International competitiveness is essential for GW-scale projects that are being developed to produce green ammonia from green hydrogen as a clean energy vector for international trade. The market is global, and the customers are free to choose the lowest cost supplier. Shipping costs are small in comparison to renewable power generation and electrolysis costs, so optimal electrolyser utilisation and low-cost renewable power generation are essential.

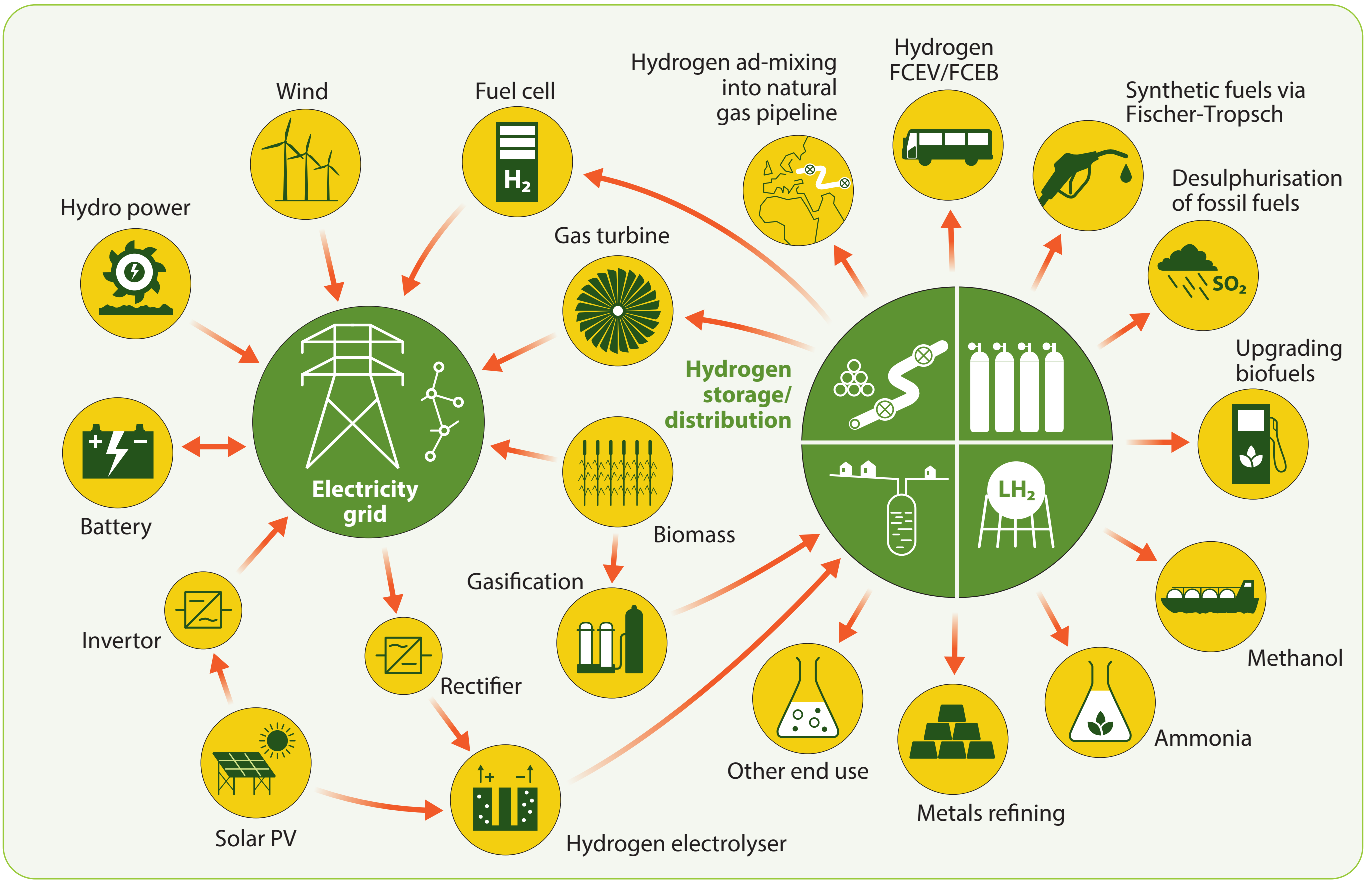

Figure 1 Renewable hydrogen production, distribution, storage, and utilisation value chains

Some of the renewable power modes are more than variable, they are intermittent, meaning that power generation falls to zero for periods of time. Alkaline electrolysers are the cheapest technology to purchase, but they do not cope well with unplanned shutdowns. They prefer that a minimum protective current is permanently flowing. This avoids corrosion of the electrodes and degradation of electrolysis efficiency.

High-capacity batteries can be integrated into the power supply system to ensure a trickle of power flows during periods of no wind or sunlight. Alternatively, power can be drawn from the grid to complement the renewable power generation. However, using grid power may undermine the ‘green’ credentials of the hydrogen and reduce its marketability.

There are only a few locations, such as the Magallanes in southern Chile, where the wind blows steadily throughout the year. These advantaged locations can offer high electrolyser utilisation based on wind-only renewable power supply schemes. Most other locations would seek to integrate wind and solar power to balance the variability of these two sources.

Green hydrogen superpowers of the future will be nations or regions that have ideal conditions for integrated wind and solar. The perfect conditions for green hydrogen electrolysis are locations where the wind picks up during the late afternoon and blows steadily through the night until the sun rises at dawn.

Southern Chile, western Namibia, and the east coast of Oman stand out as excellent green hydrogen production locations. West Australia, north-western Saudi Arabia, north-eastern Egypt, and parts of northern and western China are also blessed with ideal conditions for integrated wind and solar power generation. However, in each of these locations, the rainfall is neither sufficient nor steady enough to provide water for large-scale electrolysis.

Desalination for green hydrogen projects on the Red Sea coast

Helios is the world’s first GW-scale green hydrogen project to be announced and taken through to Final Investment Decision (FID). It is sponsored by Air Products, ACWA Power, and ENOWA, a subsidiary of NEOM. The scheme will use atmospheric pressure alkaline electrolysers from thyssenkrupp nucera to generate green hydrogen from integrated wind and solar power. Air separation units will produce nitrogen to react with the hydrogen in a Haber-Bosch synthesis loop to make green ammonia for export.

The Helios project will be implemented in Tabuk in north-western Saudi Arabia. This is an arid region with less than 2mm of rainfall per month in winter and no precipitation in summer. To support the green hydrogen project, a purpose-built desalination plant will extract seawater from the Red Sea to produce 500,000 m^3 a day of fresh water.

The Suez Canal Economic Zone in Egypt lies on the opposite shore of the Red Sea. It stretches from Port Said at the northern end of the Suez Canal to Al Sokhna at the Canal's southern tip. The zone has attracted many green hydrogen project developers, such as France's EDF Renewables (through the Green Fuel Alliance), Norway's Scatec, Australia's Fortescue Future Industries, and UAE-based AMEA Power.

Filtration and purification processes involved in production of ultrapure water

Process	Function	Impurity removal
Mechanical grate	Remove large debris	Solid debris is physically removed from the grate to be disposed of
Raw water intake	Draw seawater or river waste	N/A
Pre-chlorination and flocculation	Chlorine and $Al_2(SO_4)_3$ precipitate heavy metal ions	Flocs are removed in the multimedia filter bed
Multimedia sand and gravel bed	Remove mud, sludge, sand, algae, and flocs	Backwash with air and water
Activated carbon filter	Chlorine and dissolved organic compound removal	Spent activated carbon filter cartridge is replaced and disposed of
Water softening	Replace Ca^2 and Mg^2 hard water ions with Na ions	Backwash with brine
Low-pressure reverse osmosis (LPRO)*	Remove mono-and multi-valent ions and microbes	Backwash with water frequently, backwash with chemicals occasionally
Pure water buffer tank	Intermediate storage of water	Microbes multiply during storage and ions can dissolve into the water
Electro de-ionisation (EDI)	Polishing to removed traces of ions	Ions build up in the concentrate discharge
Ultraviolet (UV) sterilising lamp	Kill bacteria and other microbes	Dead organisms are removed during ultrafiltration
Ultrafilter	Remove dead organisms	Backwash with water frequently, backwash with chemicals occasionally
Degassing	Remove dissolved nitrogen and CO_2	Gases are vented to atmosphere
Introduce water to electrolyser water/lye recirculation circuit	Top up water in electrolyser to enable hydrogen and oxygen generation	Degassing, EDI, and filtration may be used in the electrolyte recirculation circuit to remove impurities generated in the electrolyser
EDI and degassing	Pure water purification in the PEM water recycle loop to remove dissolved ions from corrosion and CO_2 from dissolved hydrocarbon decomposition on the electrolyser	As above
Filtration and degassing	Lye filtration to remove precipitated carbonates formed by reaction of CO_2 with lye, CO_2 degassing	Lye filter backwash to water treatment plant

* Thermal desalination may take place here, if required or the reverse osmosis may be operated as high-pressure sea water reverse osmosis (SWRO or HPRO) if desalination is required

Table 1

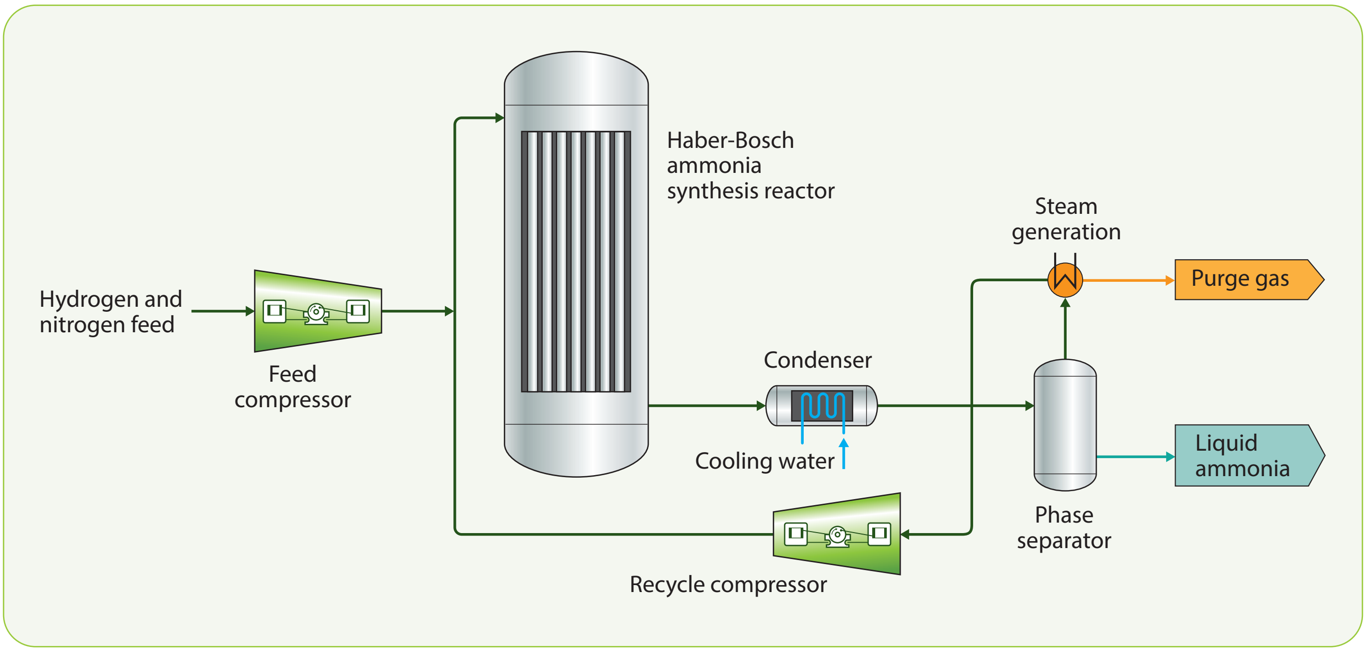

Figure 2 The Haber-Bosch Ammonia synthesis process

The AMEA Power project involves USD $2 billion of investment and will be located close to the port of Ain Sokhna in the Suez Canal Economic Zone. It will produce 390,000 tonnes of green ammonia per annum to predominantly serve export markets. The hydrogen electrolysis scheme will require more than a million cubic metres of water per year.

Fresh water from the Nile is required for other purposes, such as crop irrigation and to serve population centres, which are built up along the banks of the river. Therefore, major desalination facilities will be required to support the AMEA Power project and other green hydrogen projects in the Suez Canal Economic Zone.

Ultrapure water comes at a cost, but reliable supply is mission-critical

With freshwater feed, the capital cost of the equipment for ultrapure water supply for a typical green hydrogen project will be around 4-8% of the electrolyser scheme. Where desalination is also required, the capital cost of the whole water processing facility may represent 10-15% of the total equipment Capex for a green hydrogen electrolyser scheme.

To put this level of capital expenditure into context, the power management system involving the transformer and rectifier to provide direct current (DC) electricity for the electrolyser would be around 20% of the total project Capex. So, water treatment is an essential element of the scheme but is unlikely to be the dominant fraction of the green hydrogen project budget.

With a freshwater feed, the operating cost of the ultrapure water plant will generally be less than 1% of the total green hydrogen plant Opex. This is a combination of dosing chemical costs and electrical power for high-pressure water pumps.

The cost of the freshwater procurement may be 1-2% of the total operating cost if it is withdrawn from a local pipeline supply or brought in by road tanker. With seawater supply, that operating cost may rise to be around 3% of a green hydrogen scheme due to additional complexity.

The capital and operating costs of ultrapure water are a small proportion of the project total, but the consequences of failure can be very high; reliability is therefore key. An interruption to the water supply would mean the electrolyser must shut down. For a PEM system, that is unlikely to result in equipment damage. However, for alkaline or solid oxide electrolysers, an unplanned shutdown may result in degradation of the electrolyser's performance and a reduction in its efficiency.

Impure water can be extremely damaging to the valuable electrolysers. Calcium or magnesium cations in the water will rapidly damage a proton exchange membrane (PEM) electrolyser membrane due to interaction with the water-splitting catalyst that coats the membrane. Alkaline and solid oxide electrolysers also have sensitivities to poisons in the water.

Ultrapure water for solid oxide electrolysis and ammonia production

Ammonia production (see **Figure 2**) also requires a vast amount of boiler water to generate superheated steam. The reaction between hydrogen and nitrogen to make ammonia is highly exothermic, and the reaction heat is recovered as steam to ensure energy efficiency. For each tonne of ammonia produced, there are approximately four tonnes of ultrapure boiler water required.

The equipment used to generate this boiler feed water is similar to that required to generate the water for electrolysis, and economies of scale and synergies can be achieved by combining the equipment.

Most of the steam is used to drive the compressor that feeds the nitrogen and hydrogen gas mixture to the Haber-Bosch ammonia synthesis loop. Additional steam is used to drive the refrigeration compressor that is required to recycle incondensable gases from the ammonia liquefier.

It is common to use steam turbines on the drives of these machines to avoid the losses of converting the steam to power. After expansion in these turbines, some lower-grade steam is available for export.

The solid oxide electrolysis (SOEC) technology (see **Figure 3**) is well aligned to green ammonia projects. The reason is related to process integration potential and energy efficiency. Waste heat from the Haber-Bosch ammonia synthesis loop can be used to reduce the electrical power input requirement to the SOEC electrolyser, which operates at high temperatures and is fed with steam, not water. When fed with steam, the SOEC requires about 20% less power than a PEM or alkaline electrolyser to generate the same amount of hydrogen.

The catalysts that are used in the cells within an SOEC are highly sensitive to sulphate ions as well as silicates, siloxanes, and aluminium oxides. These impurities must be reduced to less than five or 10 parts per billion to avoid degradation of the SOEC performance.

The typical feed for an electrolyser is referred to as ‘Grade 2’ in the ISO 3696:1987 standard, with a maximum conductivity of 0.1 mS/m – identical to ASTM D1193-06(2018) ‘Type 2’ water. Both the ASTM and ISO standards have Silica specifications, but the permitted amount differs by almost a factor of 10 between the two standards. Also, neither standard explicitly specifies total sulphur. These points highlight the importance of researching the precise ultrapure feed water specification that the electrolyser manufacturer requires and designing a suitable ultrapure water treatment facility.

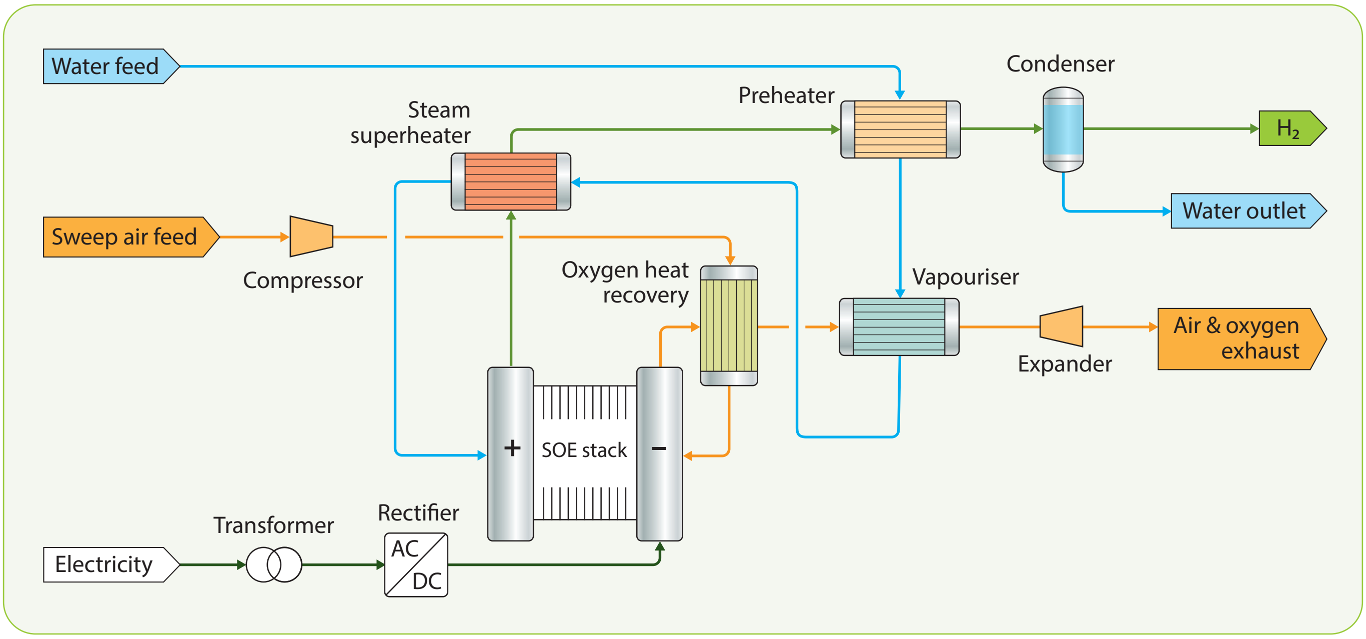

Figure 3 The solid oxide electrolysis process for hydrogen generation

Technologies for ultrapure water generation

Electrolyser feed water must be prepared in a similar way to boiler feed water. Many thermal power plants withdraw river water or seawater and purify that raw water prior to it being vaporised and introduced as the working fluid for the steam turbines. The higher the pressure of operation, the lower the permitted levels of impurities. However, ultrapure water for electrolysis must be even more pure than boiler water prepared for 30 bar steam generation operation.

> “Reverse osmosis is a core technology for the final stages of freshwater purification and seawater desalination”

In the early stages of water purification, various filtration processes are used (see **Table 2**). Initially, a rough metal grate can be used to trap fish, leaves, logs, or other debris, such as floating plastic waste. After this, additives may be used to flocculate dissolved metals. For example, aluminium sulphate addition is commonly used. Pre-chlorination can support the flocculation of heavy metals.

A multimedia or sand bed filter can then be used to trap the flocculated particles. It will also remove sludge, algae mud, and entrained sand from the raw water. This filter must be backwashed periodically, and the resultant water should be purified prior to discharge to the drain, sea or river.

An activated carbon filter can then be used to trap the chlorine, which would corrode membranes that are used in subsequent water purification processes and also damage the PEM electrolyser membrane. Chlorine might have been used in the pre-chlorination stage. It could also have been dosed to mains water to avoid microbial contamination.

The activated carbon filter will also remove dissolved organic material. Spent activated carbon filter cartridges are not regenerated in situ, they must be replaced. Often, the cartridges are exchanged by a service provider. The saturated activated carbon is generally incinerated.

Following the activated carbon filter, water softening can be used to remove calcium and magnesium ions in hard water areas. These are especially damaging to PEM electrolyser membrane electrode assembly catalysts.

Reverse osmosis (RO) is a core technology for the final stages of freshwater purification and seawater desalination. To purify fresh water, low-pressure reverse osmosis (LPRO) can be used. It operates at around 15 bar. The power consumption of an LPRO plant is in the order of 10 kWh per cubic metre of water purified. Between 70 and 85% of the water is recovered.

Separation process for water purification						
Feed component	**Mechanical screen**	**Multimedia granular filter**	**Microfiltration (MF)**	**Ultrafiltration (UF)**	**Nanofiltration (NF)**	**Reverse osmosis (RO)**
Water	↘	↘	↘	↘	↘	↘
Monovalent ions	↘	↘	↘	↘	↘	↗
Divalent/ multivalent ions	↘	↘	↘	↘	↗ ↘	↗
Dissolved organic substances	↘	↘	↘	↘	↘	↗
Viruses	↘	↘	↘	↗	↗	↗
Bacteria, protozoa, suspended solids	↘	↘	↗	↗	↗	↗
Sand, mud, algae and slime	↘	↗	↗	↗	↗	↗
Large debris	↗	↗	↗	↗	↗	↗

Table 2

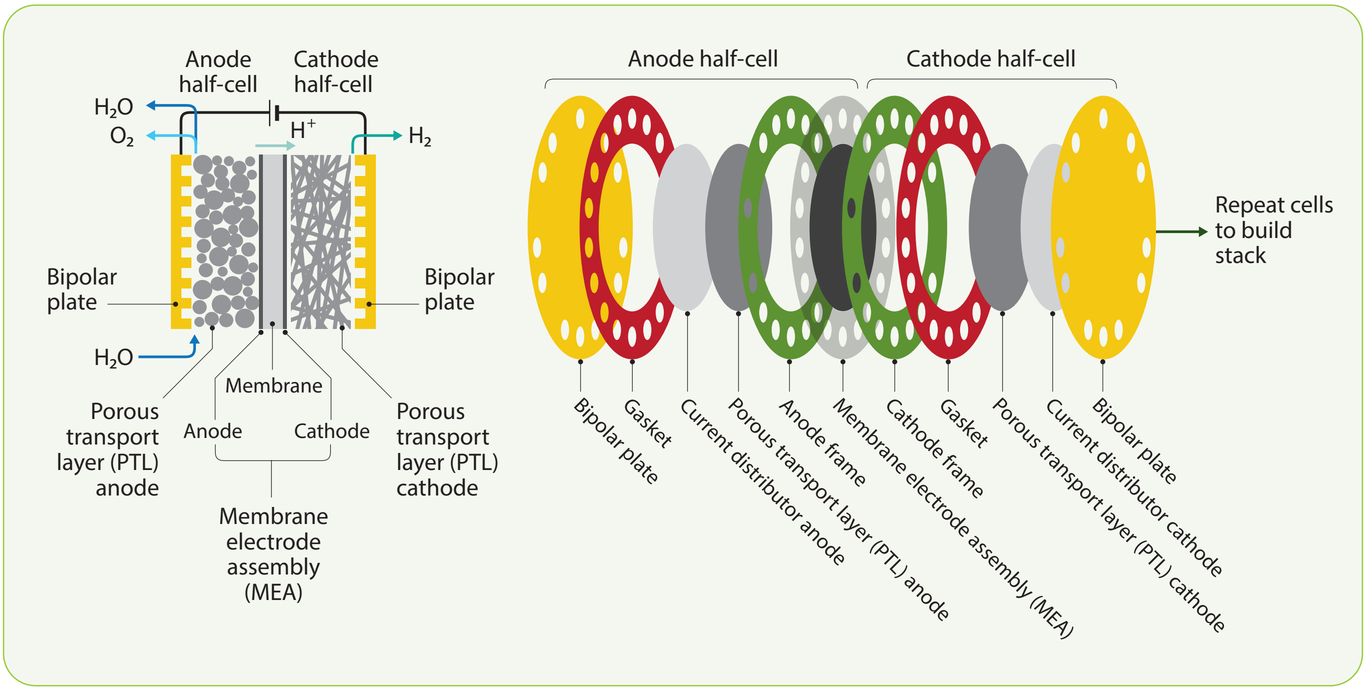

Figure 4 PEM electrolyser stack architecture and critical components

For seawater reverse osmosis (SWRO), a higher operating pressure of around 80 bar is used to achieve desalination. Due to the higher-pressure operation, the power draw is around four times that of the LPRO system.

SWRO is a common desalination process and has largely replaced less efficient thermal desalination. However, where waste heat from power generation can be used for desalination, thermal desalination techniques using mechanical vapour recovery to upgrade steam can be the most economic option.

Polishing, degassing, and sterilisation

After LPRO to purify the fresh water, intermediate buffer storage is generally implemented. As water is withdrawn from the storage, it may flow through an electro deionisation (EDI) plant for polishing. Here, the power requirement is similar to LPRO at 10 kWh/m^3 of water. The concentrate discharge from the EDI plant can be fed to the LPRO inlet to recover water.

EDI is a mature technology that has been applied to create demineralised water for supercritical steam generation, for example in concentrated solar plants. It is also used to purify water for direct injection to gas turbines for NOx reduction. Many petrochemical, pharmaceutical, and semiconductor facilities also rely on EDI for ultrapure water supply.

After the EDI process, microbial contamination can be removed. Post-chlorination is not a suitable technology due to the incompatibility of chlorine with the sensitive electrolyser components, such as the polymer electrolyte membrane that is at the heart of the membrane electrode assembly (MEA) in a PEM electrolyser. Therefore, a UV steriliser lamp is generally used to kill any bacteria that may be present.

Following the UV lamp, an ultrafilter traps the dead bacteria. The power requirement for the ultrafilter may be around 3 kWh/m^3 of water. The ultrafilter is periodically backwashed to clear the filter media cake. As with other backwash waters, this waste must be treated prior to discharge.

Degassing of the pure water may also be required. Dissolved oxygen, nitrogen, and carbon dioxide (CO_2) gases will always be present in the feed water. CO_2 is unwelcome in the electrolyser since it is broken down through electrolysis to form carbon monoxide (CO). This will be an impurity in the hydrogen, making the product unsuitable for fuel cell applications.

At this stage, the ultrapure water is finally ready to be introduced to the electrolyser water or lye recirculation circuit.

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