The Australian Hydrogen
Research Network

Hydrogen Production by Water Electrolysis

An introduction to the technologies and their status

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Contents

1. Introduction – what is electrolysis?

Electrolysis is the process of using DC electricity to drive a chemical reaction that otherwise would not occur spontaneously. The process can be used to split water into its chemical elements of hydrogen and oxygen:

$$H_2O = H_2 + \tfrac{1}{2} O_2$$

This reaction takes place in equipment called an **electrolyser**. Electrolysers can range in size from small, appliance-size equipment that is well-suited for small-scale distributed hydrogen production to large-scale, central production facilities that could be tied directly to renewable or other non-greenhouse-gas-emitting forms of electricity production. If the electricity used to promote this reaction is from renewable sources such as solar and wind, there is essentially no carbon used in the production of hydrogen and it is commonly termed green hydrogen.

2. How does an electrolyser work?

The simplest form of water electrolyser is a cell containing water and two electrically conducting electrodes that are used to supply the electricity. A membrane or diaphragm separates the two electrodes, although as we shall describe later there are membrane less electrolysers under development. When a DC voltage is applied between the electrodes, the water decomposes and hydrogen gas is liberated at the negative electrode (cathode) and oxygen at the positive electrode (anode). Gases are produced so long as the electricity is supplied.

In a single water electrolysis cell the voltage required to kick-off the reaction depends on a number of factors such as temperature and the conductivity of the water, but it is usually below 1 volt DC. Commercial electrolysers consist of several cells electrically connected in series or parallel. A group of cells is known as a stack. Depending on the number of cells within a stack, the applied voltage can be 100 volts DC or more.

In commercial electrolysers intended for large scale hydrogen production, several other items of equipment are required to complete the package. These may include a water purifier (usually a reverse osmosis system) to purify the available water to a level required by the electrolyser stack, and a purifier to remove water and other contaminants from the hydrogen produced, to achieve the required quality for the particular application.

All electrolysers are inefficient. That is, the energy embodied in the hydrogen generated is less than the energy supplied as electricity. Any energy that is not converted to hydrogen is manifest as heat, so to prevent the equipment from overheating, the stacks must be cooled. The necessary cooling system can be a significant item of equipment and add to the cost of the electrolyser installation, especially for very large systems.

Commercial electrolyser stacks require DC electricity which is usually obtained by rectification (AC to DC conversion) of the local distributed electricity grid supply. Again, the exact nature of the required power electronics to achieve the AC to DC conversion will depend on the operating characteristics of the electrolysis cells and the voltage and frequency of the supply. Historically industrial electrolysers have always been grid-connected and it is only very recently that attention has started to be given to powering stacks with DC electricity from solar PV cells for example. Clearly direct coupling of an electrolyser to a DC power source such as solar PV panels would eliminate losses inherent in inverters converting DC from solar to AC grid and then rectification from AC back to DC for the electrolysis stack.

The exact nature of the various 'balance of plant' items such as the pater and gas purifiers, power electronics and colling system depends on the type of electrolyser. There are currently two principal types of electrolysers being produced in quantity commercially for hydrogen production with several others at an advanced stage of development. The Alkaline Electrolyser has been well established industrially over many decades. By contrast the Proton Exchange Membrane (PEM) Electrolyser is a relatively new technology. In this paper the following sections describe these two technologies. Further sections introduce the rapidly emerging Anion Exchange Membrane and Solid Oxide Electrolysers and other novel types that are not yet available commercially.

3. Alkaline Electrolysers

3.1. Principle of operation

The basic principle of operation of the alkaline electrolyser is given in Figure 1. Application of DC electricity to metal electrodes immersed in an electrolyte (typically 20-40 wt. % aqueous potassium hydroxide solution) causes hydrogen to be liberated at the cathode (negative electrode) and oxygen to be liberated at the anode (positive electrode).

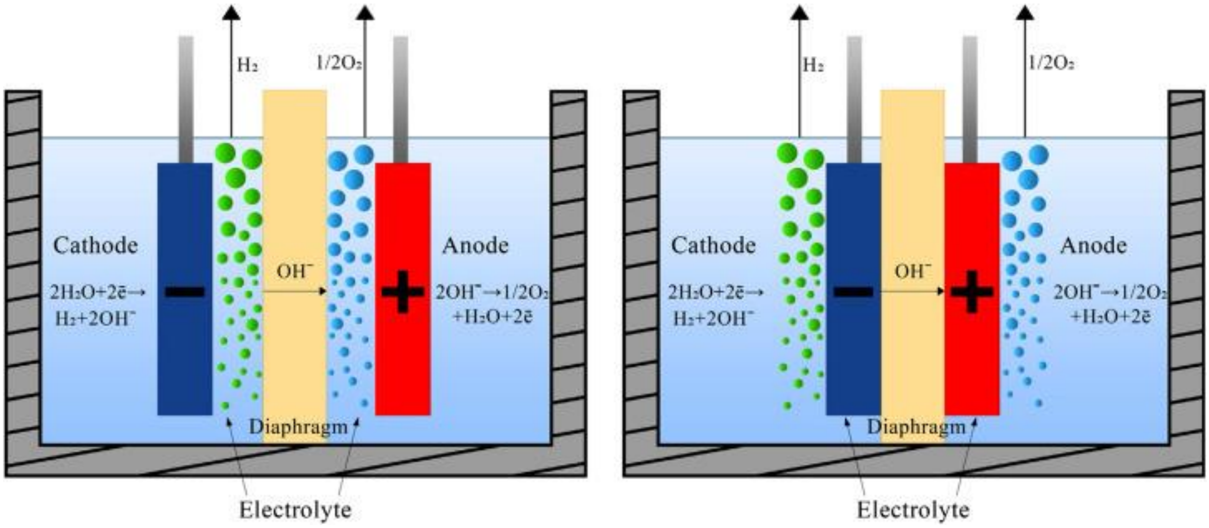

Fig. 1. Schematic diagram of the alkaline electrolysis cell. (Left) Gap design; (Right) zero-gap design.

At the cathode of an alkaline electrolyser water decomposes to liberate hydroxide OH^- ions as well as hydrogen gas. These ions migrate to the anode where they react to produce oxygen, water and electrons. The applied DC voltage serves to draw electrons from the anode and supply them to the cathode.

3.2 Commercial systems technology status

The more traditional industrial electrolysers have a gap between each electrode in which there is a diaphragm or membrane that separates the two halves of the cell. In the 1960s a zero-gap concept emerged where the electrodes are touching the diaphragm resulting in a more compact design and higher current density. Most modern electrolysers are built using planar cells that are sandwiched together in a filter press arrangement (Figures. 2 and 3) in which each cell is separated from the next by bipolar plates (as with fuel cells). The bipolar plate serves to electrically connect the cells in series. There are some technical disadvantages with the filter press arrangement and the way that cell stacks are constructed varies with manufacturer. For the alkaline electrolyser the diaphragm is porous with conductive alkaline electrolyte solution filling the open pores. Until the 1970s the diaphragm was made from asbestos when it was abandoned on health grounds. Since then, a wide variety of oxide-ceramic and polymer materials have been employed, particularly various polysulfone composites. One of the most common is ZIRFON manufactured by Agfa. A recent study by the German Fraunhofer Institute[1] has confirmed that an alkaline electrolyser using this membrane can be as efficient as a PEM electrolyser. The anode and cathode have generally been made of porous metals, typically Raney nickel. These do suffer some degradation over time caused mainly by impurities in the water supply, but in comparison with the precious metals used in PEM electrolysers they are cheap and render the alkaline electrolyser the lowest cost option for most commercial applications.

The zero-gap approach is used in currently available commercial systems, otherwise for most alkaline electrolysers, the technology remains the same as it has for many decades. There are continual improvements being made to produce thinner and more robust diaphragms and the electrode materials are being improved to allow relaxation of the water supply requirements. Cells operate typically below 100°C as higher temperatures reduce the life of the separator and hydrogen purity becomes compromised. There is also a compromise on current density to a range of below 400-500 mA/cm2. Higher current densities could help to reduce capital costs, but lower current densities lead to better conversion efficiency (hydrogen production per kWh of electricity supplied) due to the lower voltage. The optimal current density is therefore a compromise between performance and cost. Such a compromise is also a feature of most fuel cells.

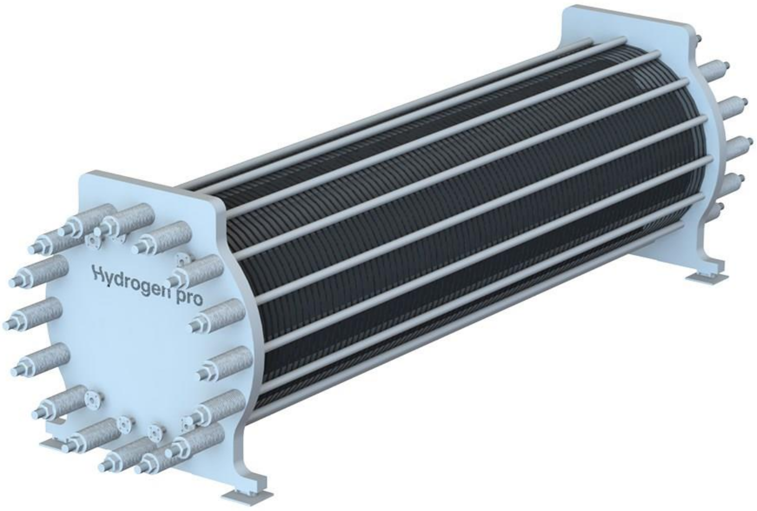

Fig. 2 Alkaline electrolyser filter-press stack design (Hydrogen Pro, Denmark)

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[1] Press release 5th Feb 2021. Retrieved from https://www.agfa.com/corporate/news-item/agfas-zirfon-membranes-make-alkaline-electrolysis-the-most-efficient-technology-for-the-production-of-hydrogen/

Fig. 3 Small packaged alkaline electrolyser by Cummins/Hydrogenics showing filter-press cell stacks at the bottom of the enclosure package (covers removed for clarity).

The following is a selection of leading suppliers of commercial alkaline electrolysers:

- NEL (Norway) https://nelhydrogen.com
- Hydrogenics (Cummins) https://www.cummins.com/new-power/applications/about-hydrogen/electrolysis
- Thyssenkrupp Nucera AG (Germany)https://www.thyssenkrupp.com/en/company/innovation/technologies-for-the-energy-transition/water-electrolysis.html
- Teledyne Energy Systems Inc. (USA) https://teledynees.com
- McPhy (France) https://mcphy.com/en
- Green Hydrogen Systems (Denmark) https://greenhydrogensystems.com
- Next Hydrogen (Canada) https://nexthydrogen.com
- Sunfire (Germany) https://www.sunfire.de/en/
- Hydrogen Pro (Norway – made in China) https://hydrogen-pro.com
- Erreduegas (Italy) https://erreduegas.it/en/
- Suzhou Green Hydrogen (China) https://sghec.com/
- Beijing Peric Hydrogen Technologies Co. Ltd. (China) https://h2peric.com/
- SinoHy Energy (China) https://sinohyenergy.com
- Yangzhou Zhongdian hydrogen production equipment Co., Ltd. (China) http://www.cn-hydrogen.com
- Tianjin Mainland Hydrogen Equipment Co., Ltd. (China) https://cnthe.com/en/
- John Cockrill Jingli Hydrogen https://h2.johncockerill.com/en/products/electrolysers/ https://www.jinglihydrogen.com/

Most of these developers will supply equipment in various scales. Some such as NEL and Thyssenkrupp are focusing on systems at the MW scale and larger, aiming to improve efficiency and reduce capital cost by volume production.

Next Hydrogen (Canada) https://nexthydrogen.com is one of the few developers in recent years that claim a step change in alkaline cell performance through innovative cell and stack design. Essentially, the company has eliminated some of the flow restrictions of electrolyte inherent in traditional bipolar stack designs. This yields higher current density (therefore more compact stacks) and improved dynamic response. The dynamic response has been seen as a possible disadvantage for alkaline cells when coupled with intermittent renewable energy. The team developing the Next Hydrogen products have a long history with the Stuart Energy company (one of the founders of the technology in the early 1900s and acquired by Hydrogenics in 2022) but in terms of the new technology Next Hydrogen may be viewed as a start-up company.

Another company to emerge from the Stuart Energy company, led by family member Andrew T. B. Stewart is **Hydrogen Optimised** which is a subsidiary of US-based Key DH Technologies Inc. Hydrogen Optimnized is focused on building 50 MW RuggedCell^{TM} systems. These electrolysers have demonstrated the ability to ramp from zero to 50,000 amperes in under 10 seconds and then very quickly reduce the current to any level, even down to zero amperes. This capability supports the system’s integration with intermittent renewable energy sources such as wind or solar, and with use on grids or micro-grids with widely varying power availability.

Another innovative electrolyser company that has taken the alkaline systems to a new level is **Aquahydrex** Https://aquahydrex.com. The technology was first proposed in around 2012 by researchers at the University of Wollongong (see section 5.3) who, by the application of new materials at the anode and cathode, improved the release of hydrogen and oxygen gases as bubbles in the liquid electrolyte and reduced the need for circulation of the electrolyte external to the stack.

3.3 Alkaline electrolysers in Australia

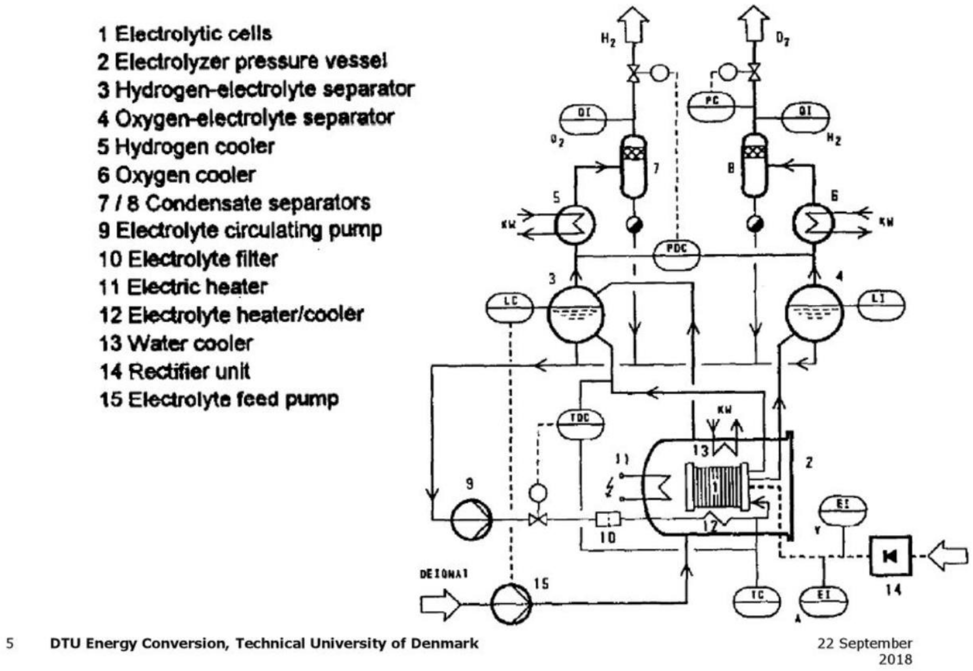
The following significant alkaline electrolysis systems are currently in operation in Australia:

- 200kW Hydrogenics, Sir Samuel Griffith Centre, Nathan Campus, Griffith University
- 432kW (40-90kg per day) Green Hydrogen Systems (Denmark), Hydrogen Fuels Australia, hydrogen production and refuelling station at Truganina, near the Melbourne suburb of Laverton, in Victoria. Commissioning expected early 2023.

There are likely other smaller systems installed in power stations providing hydrogen for generator cooling, and smaller systems such as a 4 kW McPhy system installed in Queensland at the Electrygen facility at Beerwah. Alkaline systems are under consideration for medium scale production for hydrogen refuelling stations and for large scale hydrogen export projects.

3.4 Balance of plant

It would be misleading to think that any electrolyser is simply a stack of electrolysis cells. Figure. 4 gives some idea of the components that are required in a modern alkaline electrolyser that make up the immediate balance of plant (BoP). The components include pumps for feeding and circulating the liquid electrolyte and water, heaters and filters and vessels external to the stack for separating the hydrogen and oxygen from the circulating electrolyte (water).



1 Electrolytic cells
2 Electrolyzer pressure vessel
3 Hydrogen-electrolyte separator
4 Oxygen-electrolyte separator
5 Hydrogen cooler
6 Oxygen cooler
7 / 8 Condensate separators
9 Electrolyte circulating pump
10 Electrolyte filter
11 Electric heater
12 Electrolyte heater/cooler
13 Water cooler
14 Rectifier unit
15 Electrolyte feed pump

5 DTU Energy Conversion, Technical University of Denmark 22 September 2018

Fig. 4 Process flow diagram of modern alkaline electrolyser

In addition to the components shown in Figure. 4, most electrolysers require water purification, usually in the form of a reverse osmosis system to remove minerals and other matter that would poison or degrade the electrodes within the cells. Each manufacturer of cells has a minimum level of purity required for the cells which will depend on the particular design of cells and electrodes. The hydrogen that is produced by an alkaline electrolyser also requires some purification in terms of water removal and oxygen clean-up. In the system at Griffith University, for example, the system is in three separate packages – an RO system, the electrolyser itself, and a gas purifier.

4. Proton Exchange Membrane (PEM) Electrolysers

4.1 Principle of operation

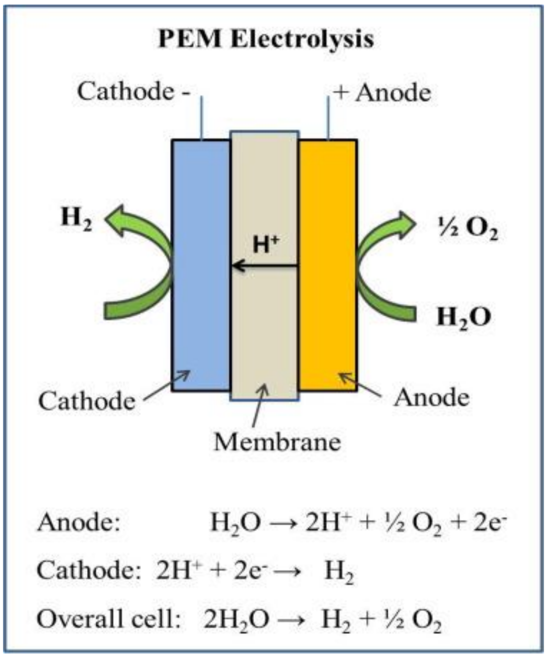


Fig. 5. Operating principle of the PEM electrolyser

In the PEM Electrolyser a solid polymer membrane separates the two electrodes. Unlike the Alkaline Electrolyser in which OH- ions pass between the two electrodes via a liquid electrolyte phase within the pore structure of the diaphragm, in a PEM electrolyser it is protons that move from the anode to the cathode through the solid polymer membrane. The polymer membrane is able to conduct positively charged hydrated protons (H^+) so long as it is hydrated. In practical terms this means the cell must operate below 100°C at atmospheric pressure to prevent the membrane from dying out. The chemistry of the PEM electrolyser is therefore slightly different to the alkaline type, as shown in Figure 5.

One of the biggest advantages of the PEM electrolyser is its ability to operate at high current densities. This can result in more compact stacks operational with high volumetric power density and potentially lower capital cost (CAPEX). The high current density can also lead to lower operating costs (OPEX). The membrane can also be made very thin (100-200 microns) which makes it very responsive to changes in load – ideal for applications where intermittent renewable energy (solar or wind) is the source of electricity. At the start of operation, the membrane is non-permeable to gases which means the hydrogen generated by the PEM electrolyser is very pure. Given these advantages there are several issues that contribute to the high cost of the PEM electrolyser:

1. The polymer electrolyte is acidic which rules out base metal catalysts for the electrodes. In practice platinum group metals are the only catalysts that can provide adequate lifetime for the stacks.
2. Catalysts of platinum particles supported on carbon can lose activity over time, limiting the guaranteed lifetime of stacks.
3. The cell/stack housing cannot be made of stainless steel as with the alkaline electrolyser for the same reasons. Titanium or titanium alloys are commonly used for the bipolar plates and cell housing.

(4) The membrane fabrication is expensive and the material itself degrades during use with the possibility of holes forming which allow oxygen to migrate into the hydrogen product and vice versa, also limiting the operating life of the stacks.

4.2 Commercial systems technology status

The PEM electrolyser technology first made an appearance some 20 years ago through the development of PEM fuel cells, which can be traced to the 1950s and developments by GE in the USA followed by Ballard Power Systems in Canada. A few companies such as Proton Onsite (now part of the NEL company) and ITM-Power focused in the 1990s on systems for small scale production for stationary applications whereas the goal of electrical giant Siemens was to produce electrolysers for submarines, a market also addressed by Vickers Shipbuilding and Engineering in the UK. Plug Power was established in the USA in response to the lead taken by Ballard Power Systems in Canada. Much of the current interest in PEM electrolyser technology in Asian countries is in response to the technical leadership shown by ITM-Power. The industrial gas giant Linde took a major shareholding in ITM-Power and established ITM Linde Electrolysis (ILE) GmbH in January 2020. Their website proclaims that ILE will focus on providing global green gas solutions at the industrial scale using ITM Power's modular PEM electrolyser technology and Linde's world class EPC expertise to deliver turnkey solutions to customers.

Current commercial suppliers of PEM electrolysers are:

- NEL (Norway) https://nelhydrogen.com
- ITM Power (UK) https://itm-power.com
- Plug Power (USA) https://plugpower.com
- H-TEC Systems (part of the MAN group) (Germany) https://h-tec.com
- Green Hydrogen (China) https://sghec.com/
- Siemens (Germany) https://new.siemens.com/global/en/markets/chemical-industry/applications/hydrogen.html
- SinoHy Energy (China) https://www.sinohyenergy.com/pem-electrolysis-and-refueling-equipment/
- IMI Critical https://imi-critical.com
- Cummins – acquired Hydrogenics in 2019 - https://www.cummins.com/news/releases/2019/09/09/cummins-closes-its-acquisition-hydrogenics

Table 1 provides a summary of the main technical differences between the alkaline and PEM electrolyser technologies. Note that the differences are dependent on the supplier of the electrolyser and the target application.

Table 1. Characteristics of Alkaline and PEM electrolysers

	Alkaline electrolyser	**PEM electrolyser**
Electrolyte	30 wt.% KOH solution	solid polymer, e.g., Dupont Nafion
Working pressure	< 3.2 MPa	<5 MPa
Operating temperature °C	80-90	50-80
History	Long history of industrial use (Norsk- Hydro built a 10000Nm^{3}h^{-1} plant in 1939)	Relatively new technology (ITM Power founded in 2001)
Operational Characteristics	Prefer to run at steady state, low response to load changes; isobaric operation	Wide operating range – can meet substantial changes in demand. Black start capability, 10 s response time. Potential for high differential pressure
	Highly corrosive electrolyte (KOH) Product >99.8% H2 requires purification	Safe, solid electrolyte, no harmful materials Product >99.99% H2 requires minimal purification (water removal)
	Moderate current density	High current densities – more compact design
	Ability to operate at elevated pressures (10-34 MPa)	Pressure limited by need to constrain liquids
	Significant O&M costs including replacement of electrolyte	Very low O&M costs
Manufacturing cost	Low	High
Lifetime	10 years before re-build	3-5 years before stack replacement

Figure 6 shows a PEM electrolyser comprising 3 integrated cell stacks, manufactured by ITM Power. Note the vertical arrangement of cells in contrast to alkaline cells that are usually stacked horizontally. The vertical arrangement makes better use of gravity to help ensure gas tight seals between each cell.

Fig. 6 Packaged PEM electrolyser system by ITM-Power

4.3 PEM electrolysers in Australia

The following commercial PEM electrolysis systems are currently in operation or proposed:

- 500kW Cummins-Hydrogenics, Western Sydney Green Gas Project (Jemena), NSW
- 260kW NEL model C30 PEM electrolyser, Clean Energy Innovation hub at ATCO Jandakot, Perth, WA
- 75 kW NEL ActewAGL Hydrogen Refuelling Station, Fyshwick, ACT
- 2.5 MW NEL (Proposed) Geelong New Energies Service Station Project, Viva Energy Australia. Under construction.
- 250kW ITM-Power, 60 kg per day ALTONA (Toyota Ecopark Hydrogen Demonstration)
- 220kW ITM-Power, BOC production facility at Bulwer Island and HRS installed and currently being commissioned at Port of Brisbane.
- 1.25 MW Siemens, Australian Gas Networks/AGIG operational since May 2021.
- 40 kW Nel model H6 PEM electrolyser, QUT, Brisbane.

5. Anion exchange membrane (AEM) electrolysers

5.1 Principle of Operation

Given some of the disadvantages of alkaline compared with PEM electrolysers outlined in Table 1, researchers have been investigating solid polymer anion exchange membranes, i.e., membrane materials that are able to conduct OH^- ions rather than H^+ ions. This feature enables the use of lower cost (non-platinum) electrode materials like those used in Alkaline Electrolysers with a zero-gap architecture of a modern PEM electrolysers. Electrolysis cells with anionic exchange membranes

(AEM) have a lower concentration of alkaline electrolyte than conventional alkaline electrolysers. In AEM cells the anionic ion conducting membrane replaces caustic liquid electrolyte of the alkaline electrolyser. This avoids corrosion issues associated with the alkaline liquid and offers a potentially more compact design than the traditional alkaline approach. Anion exchange membranes are more complex to manufacture compared with the common per fluorinated sulfonic acids[2] used in PEM fuel cells and electrolysers and are therefore not so commercially advanced.

5.2 Status of AEM electrolysers

Anion exchange membranes have been used in fuel cells by the UK company AFC Energy, and in electrolysers by the Italian company Enapter (https://www.enapter.com/aem-electrolyser). Currently Enapter is only making small (2kW) electrolysers that Enapter and integrators can modularise to MW scale. An Enapter electrolyser with four 2kW modules (8kW) is being tested in Australia by QUT and elsewhere in Australia such as those under test by CIT and Evoenergy, Lavo and Southern Green Gas (see https://www.enapter.com/applications). The first MW scale system is on order for delivery to North America. Enapter has scaled its production to 3MW in Q4 2022.

An Israel-based technology company Hydrolite (https://www.hydrolite-h2.com/aem-electrolyzer-technology) is working on both AEM fuel cells and electrolysers.

6 Solid Oxide Electrolysers (SOEC)

6.2 Principle of operation

The solid oxide fuel cell (SOFC) has been under development since the 1970s backed by large companies such as Westinghouse Electric, Siemens, ABB/Sulzer and Rolls Royce. In Australia, Ceramic Fuel Cells Ltd (CFCL) was a start-up company based in Melbourne that was spun out of CSIRO research in the early 1990s. The company produced domestic 2kW commercial SOFC systems that achieved CE approval and were deployed from 2010. The CFCL technology was further developed in Europe and has been continued by SolydEra. In parallel with CFCL, US-based Bloom Energy also developed a commercial product but at a larger scale. A solid ceramic material such as zirconia as the electrolyte in the SOFC operates at high temperatures (typically above 800°C, at atmospheric pressure). The concept of using the solid oxide cell in reverse, i.e., as an electrolyser has been championed by Haldor Topsoe who have been supplying ceramic oxide-ion conducting materials to researchers for many years. Carrying out electrolysis at elevated temperatures has the advantage of higher conversion efficiency than the low temperature electrolysers described above brought about partly by eliminating the need for cooling the cells.

At such high temperatures water that is supplied to the SOEC becomes steam and the chemistry of the water splitting reaction is slightly different to that in both the alkaline and PEM electrolysers. In the SOEC, water is split into hydrogen and oxygen O^{2-} ions at the cathode (Fig. 7). It is the oxygen ions that migrate through the solid electrolyte and at the anode they lose their electrons and oxygen gas is liberated. High efficiencies, towards 90%, are being achieved when SOEC are integrated with available industrial sources of steam.

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[2] Perfluorinated sulfonic acid is the general chemical term for the proto-conducting membrane used in PEM fuel cells and electrolysers. The most common such material has the trade mark Nafion being a polymer synthesised with acidic proton-conducting side chains.

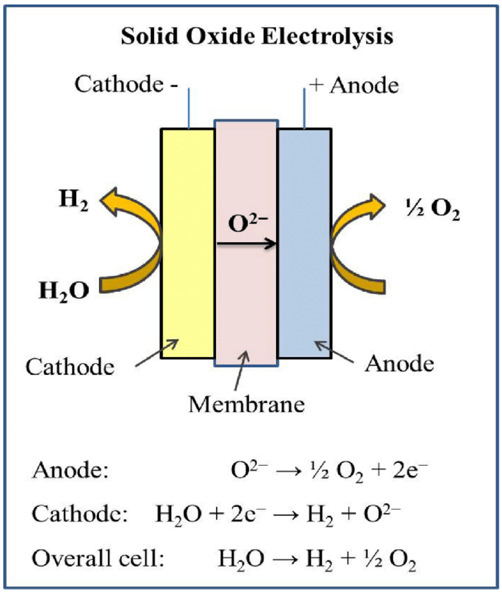

Fig. 6 Principle of operation of the solid oxide electrolyser

As well asl being able to electrolyse water to produce hydrogen and oxygen, the SOEC can electrolyse carbon dioxide to carbon monoxide and oxygen (see Fig. 8). The carbon monoxide can be mixed with hydrogen to form syngas (a mix of hydrogen and carbon monoxide). Alternatively, the SOEC can co-electrolyse both steam and carbon dioxide to form syngas directly from the same solid oxide stack. Syngas is the precursor to green fuels such as methanol, kerosene and diesel. The co-electrolysis capability in SOEC is absent in the low temperature electrolysers and is attracting interest in Europe for e-Kerosene production as a form of synthetic jet fuel or aviation fuel produced from power-to-liquids (PtL) from renewable energy sources.

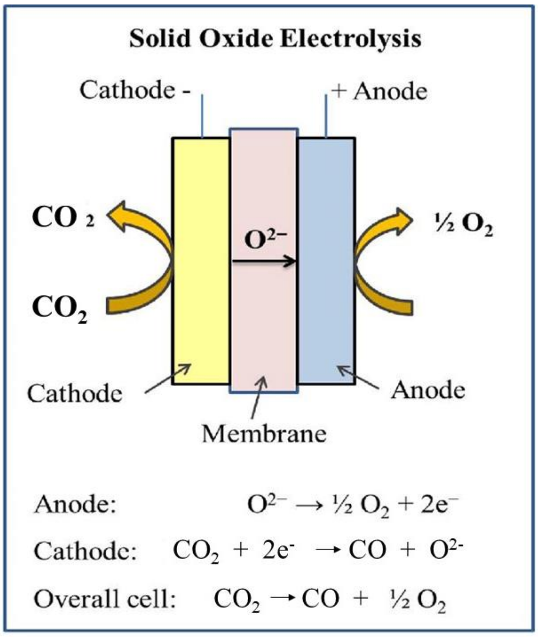

Fig. 8 Operating principle of the electrolysis of CO2 using a solid oxide cell

6.2 Current status of Solid Oxide Electrolysis

There is much ongoing R&D expertise in solid oxide technology, within SOFC developers such as Ceres Power, SolydEra, Kyoxer, Acumentrics, and Adelan, potential electrolyser suppliers such as Hoeller Electrolyser GmbH, Cummins Inc, Mitsubishi Hitachi Power and organisations such the CSIRO, Fraunhofer IKTS, PNNL, AIST, Karlsruhe University, Imperial College, Birmingham University, and KFA Julich. The US company Bloom Energy has been one of the first to offer commercial products. And whilst there are currently no commercial SOECs in operation, there is certainly growing interest in the technology. In the IEA Hydrogen projects database (https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database) there are numerous projects in the multi-MW scale in concept or feasibility stages for production of hydrogen, methanol, ammonia and e-Kerosene. Of interest notable are:

- Bloom Energy (https://www.bloomenergy.com/bloomelectrolyzer) The technology was first demonstrated with the US Idaho National Laboratory and in May 2021 a collaboration was announced between Bloom Energy and Baker Hughes (compression systems). Orders for units have been accepted since 2021 and shipments of the first systems were expected in Q4 of 2022 according to the website.

- Haldor Topsoe (https://info.topsoe.com/green-hydrogen). So far no operating systems are reported. In September 2022 the company announced a deal with First Ammonia (FA) a New York City start-up backed by a $5.5 bn hedge fund firm. The deals is to supply 5 GW of SOECs with the first 500 MW allocated to facilities in Wilhelmshaven Germany and the US Southwest. See https://www.rechargenews.com/energy-transition/topsoe-wins-world-s-largest-ever-hydrogen-electrolyser-order-in-5gw-green-ammonia-deal/2-1-1299119. In August of this year, Topsoe also confirmed a final investment decision to build a manufacturing plant in Denmark for the SOECs with an initial capacity of 500MW/year (expandable to 5GW).

- Ceres Power has announced a MW scale demonstrator with Shell in Bangalore, India for 2023 (https://www.ceres.tech/news/agreement-with-shell-to-locate-a-mw-scale-electrolyser-in-bangalore-india/)

- In July 2022 it was announced that, as part of the European *MultiPLHY* project, Sunfire (Germany) is installing the world's first 2.6 MW solid oxide electrolyser to produce green hydrogen at Neste's renewable products refinery in Rotterdam. The company has delivered the first two electrolysis modules – setting new technology standards in the market.

- Sunfire is also a partner in the GrInHy2.0 Project and has demonstrated high efficiency hydrogen production (84% LHV) in what it has described as the worlds largest high temperature electrolyser producing 200 Nm3 hydrogen per hour. (https://www.sunfire.de/en/news/detail/worlds-largest-high-temperature-electrolyzer-achieves-record-efficiency).

- Norske eFuel project is making use of SOEC due to its capability of co-electrolysing CO_2 and H_2O. (https://www.norsk-e-fuel.com/technology)

7 Other types of water electrolyser

The operating principle of the fuel cell is the reverse of electrolysis, i.e., in a fuel cell oxygen and hydrogen are combined to produce electricity. Therefore the alkaline, PEM and solid oxide electrolysers described in the previous section are essentially the reverse of the alkaline, PEM and sold oxide fuel cell. Indeed the PEM fuel cell can be operated as an electrolyser and such technology is generally referred to as a reversible or unitisedregenerative fuel cell[3]. The molten carbonate fuel cell is also currently being investigated by several researchers as another type of steam electrolyser, similar to the SOEC and may be beneficial for large scale production in that the materials costs are relatively low[4]. A similar approach could be taken with a phosphoric acid electrolyser and was first considered by NASA in the 1960s.[5]

Given that the precious metal catalyst, membrane and titanium cell housing of a PEM electrolyser all contribute significantly to its high capital cost (CAPEX), researchers have sought ways to lower the cost and improve performance by eliminating the membranes in electrolysers. There are three broad approaches that are being investigated:

7.1 Separation of oxygen and hydrogen external to the cell

This is the approach taken by the UK company CHP2 (Clean Power Hydrogen) (https://cph2.com). The electrolysis cell is a conventional alkaline cell but with no membrane. The main aim of the CPH2 technology is to eliminate CAPEX and degradation contributions from the membrane. In the CHP2 cell, both gaseous hydrogen and oxygen are produced, allowed to mix and the mixed gases exit from the top of the cell directly into a dryer and then a cryogenic separation unit or cryo-cooler. The cryo-cooler then lowers the temperature of the mixed gas to below -183°C causing the oxygen to condense as liquid. The liquid is then decanted and the remaining cold gaseous hydrogen brought back up to room temperature. Good separation of the gases is claimed and even though in the system there is a small inventory of potentially explosive H2/O2 mixture, the safety risk appears to be manageable, at least with the first systems. It remains to be seen if this is the case with commercial scale equipment. The cryo-cooler for the CPH2 system is supplied by AFCryo, a New Zealand based manufacturer of composite cryostats and cryogenic cooling systems. CPH2 and AFCryo have agreements to build 2 x 1MW system, to be delivered late 2022/early 2023.

The CPH2 concept promises substantially lower CAPEX (estimated 30% less than current PEM electrolyser costs). It's worth noting that CPH2 is one of the few private companies that has successfully moved to public ownership by IPO early in 2022 raising capital of some 30milion GBP ($36 million USD) and has ambitious target of 4GW MFE annual production by 2030; of this 1GW will be in-house manufacturing and assembly and 3GW will be via license agreements.

7.2 Separation of oxygen and hydrogen by decoupling the evolution reactions

In conventional water electrolysis, the water oxidation and reduction reactions are coupled in both time and space, as they occur simultaneously at the anode and a cathode in the same cell. This introduces challenges, such as product separation, and sets strict constraints on material selection and process conditions. In the two-step electrochemical-chemical cycle developed by Israel-based H2-Pro (https://www.h2pro.co/), the reactions are decoupled by dividing the process into two steps:

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[3] Bahman Shabani, Reza Omrani, Saeed Seif Mohammadi, Biddyut Paul and John Andrews, Electrochemical Methods for Hydrogen Production (9) pp 306-349, Royal Society of Chemistry, 2019.

[4] Hu, Lan, Lindberg G and Lagergren C, *.J.Phys. Chem. C* 2016, 120, 25, 13427–13433

[5] Clifford, J., "Water-Vapor Electrolysis Cell with Phosphoric Acid Electrolyte," SAE Technical Paper 670851, 1967, https://doi.org/10.4271/670851.

an electrochemical step that reduces water at the cathode and oxidizes the anode, followed by a spontaneous chemical step that is driven faster at higher temperature, which reduces the anode back to its initial state by oxidizing water. The operation is summarised in the Figures 8 and 9. [6]

As can be seen from Figures 9 and 10, the E-TAC process is more complex than conventional alkaline electrolysis but offers advantages of potentially high pressure H2 generation as well as improved overall process efficiency (>95% is predicted by the company).

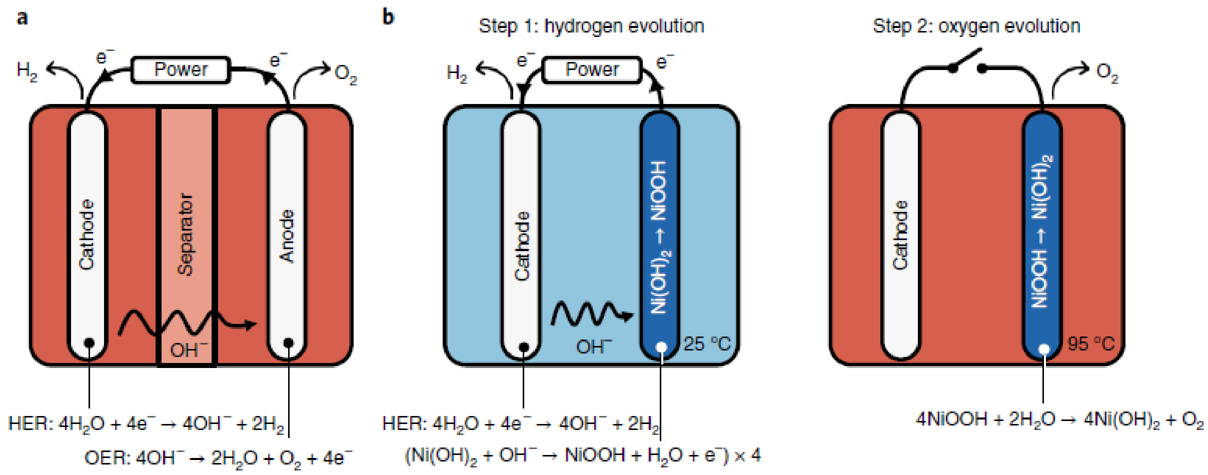

Fig. 8 Comparison of conventional alkaline electrolysis (a) and the two-stage E-TAC water splitting mode championed by H2-Pro (b).

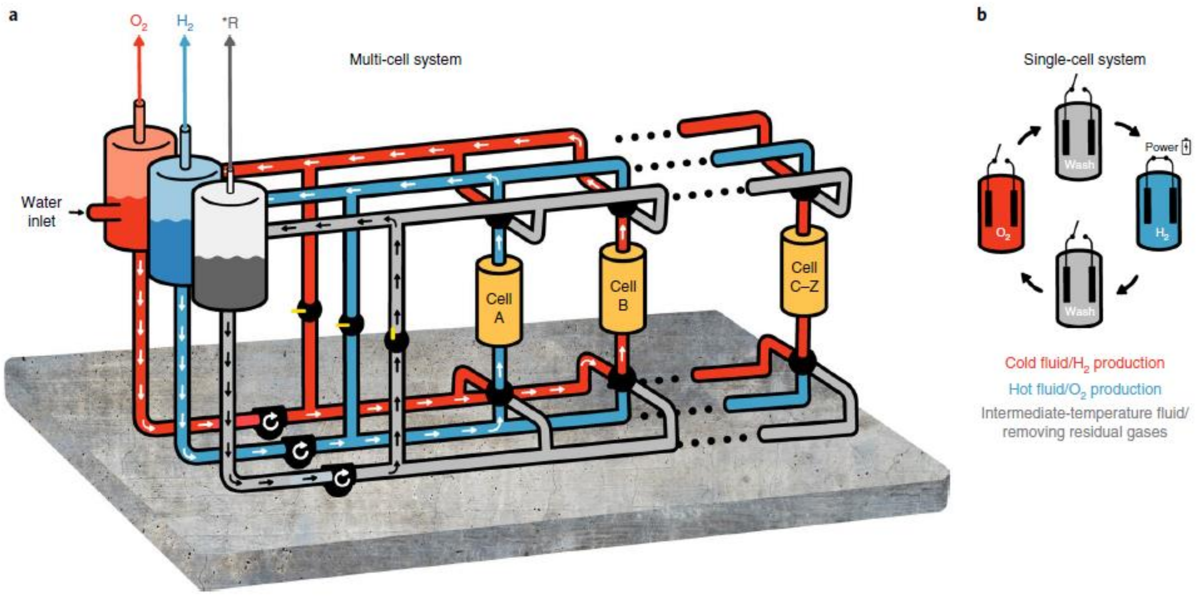

Fig. 9. Schematic of multi-cell E-TAC process. **a.** General electrolyte flow in the process, showing the cold electrolyte circulating in cell A, generating H2 gas, that is separated in the middle blue tank on the left, whilst in cell B hot electrolyte circulates to generate O2 that is separated in the red tank on the left. Intermediate temperature wash fluid in the grey tank is circulated through a bypass most of the time. The fluid is used to 'push' the cold and hot electrolyte solutions to their respective tanks at the end of the H2 or O2 generation

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[6] Dotan, H., Landman, A., Sheehan, S.W. *et al.* Decoupled hydrogen and oxygen evolution by a two-step electrochemical–chemical cycle for efficient overall water splitting. *Nat Energy* **4**, 786–795 (2019). https://doi.org/10.1038/s41560-019-0462-7

steps. **b.** Single-cell cycle, showing the regenerative operation in each cell, where H2 is generated under an electric bias at ambient temperature, and O2 is generated at a hotter temperature without applying electric bias (open circuit). *R, residual gases.

7.3 Separation of oxygen and hydrogen within the cell by separating the gas bubbles

A paper by Prof Gerry Swiegers et al[7] has reviewed three different approaches to membrane-free electrolysis cells:

(a) Laminar flow within a micro-fluidic reaction chamber is used to entrain the hydrogen and oxygen bubbles in separate parallel streams that do not mix.
(b) Closely-packed porous electrodes have liquid electrolyte divergently pumped through them to sweep the produced hydrogen and oxygen bubbles to different locations.
(c) Using gas-diffusion electrodes using capillary forces and other effects to directly extract the gases through the electrodes as they are produced, thereby avoiding discernible bubble formation, and eliminating the need for a separator membrane to keep the gases separate. An example of the use of such gas diffusion electrodes employing Gore-Tex polymer is the Aquahydrex alkaline electrolyser referred to earlier. A further development is that of the HySata electrolysis cell (https://hysata.com). In this cell, the water is fed between two gas diffusion electrodes upwards by capillary action as shown in Figure. 10.

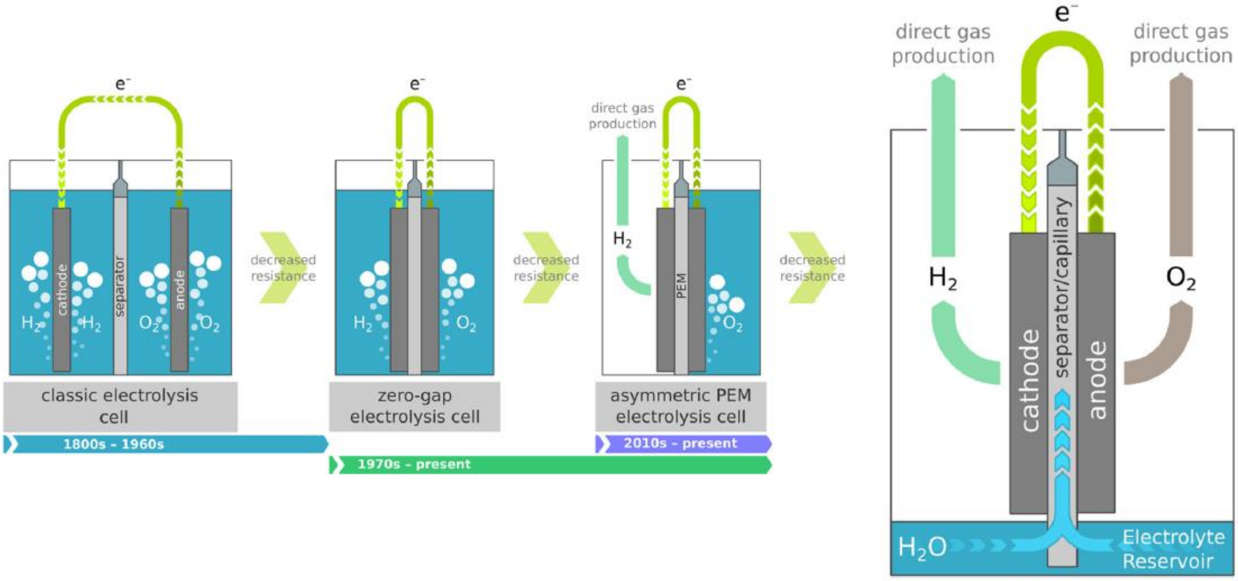

Fig. 10 Conceptualization of the Capillary-Fed Electrolysis (CFE) cell. Inspired by the historic evolution of water electrolysis cell architecture culminating in the direct production of one of the gases, the CFE directly produces both gases. Liquid electrolyte is continuously drawn up the separator by a capillary effect, from a reservoir at the bottom of the cell. The porous, hydrophilic separator sustains the flow rate required for water electrolysis.

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[7] Swiegers, GF et al., Current status of membraneless water electrolysis cells. Electrochemical Materials and Engineering, November 2021. https://doi.org/10.1016/j.coelec.2021.100881

8 Costs of electrolysis

8.1 CAPEX

Commercial electrolyser packages (including rectifier, water treatment and gas purifiers) are costly items of equipment. Values of between \$1000 and \$3000 per kW are the norm for small systems (i.e. below about 1 MW) and slightly lower costs are expected for larger systems. Such costs are a response to a steady demand of electrolysers for established applications. It is generally recognised that if demand escalates due to increased demand for hydrogen, then CAPEX may fall as manufacturers gear up production to meet demand. It is also likely that there will be cost reduction on account of improvements in the technology but given the mature markets for traditional electrolysers, it is likely these will be small, and step changes in costs are more likely to be due to innovations in alternatives as listed in sections 5, 6 and 7 above. There is a general observation that electrolyser capital costs are decreasing in real terms over the years.

There have been many academic articles written about cost projections for electrolysers and studies commissioned by organisations such as the European Commission and the National Renewable Energy Laboratory in the USA. A good up to date review was published by the International Energy Agency (https://www.iea.org/reports/electrolysers) in September 2022. The report concludes that the past year has been a record year of electrolysis deployment, with more than 200 MW of capacity entering operation, a threefold increase on 2020. Total installed capacity has reached 0.5 GW and is expected to grow to over 1 GW by the end of 2022. The realisation of all the projects in the pipeline could lead to an installed electrolyser capacity of 134-240 GW by 2030, twice the expectations from last year. Also, electrolyser manufacturing capacity has doubled since last year, reaching nearly 8 GW per year. However, electrolysis capacity is growing from a very low base and requires a significant acceleration to get on track with the Net Zero Emissions by 2050 Scenario, which requires expanding electrolysis capacity to above 700 GW by 2030.

The IEA concludes, when adjusted for inflation, the cost reductions for the alkaline technology have generally been moderate over recent decades, while PEM technology has shown significant cost reductions, now approaching the cost of alkaline systems. These cost reductions have been realised mainly through R&D in the absence of significant market penetration. CAPEX requirements are currently in the range of USD 500-1 400/kW$_e$ for alkaline electrolysers and USD 1 100-1 800/kW$_e$ for PEM electrolysers, while estimates for solid oxide electrolyser cell (SOEC) electrolysers range across USD 2 800-5 600/kW.

In 2019 the IEA[8] gave some projections of cost reductions for electrolysis as follows: For alkaline electrolysers present costs (2019) are between A\$714-2000/kW (today) and A\$571-1214/kW (2030). For polymer electrolyte membrane (PEM) electrolysers they are between A\$1571-2571/kW (today) and A\$928-2143/kW (2030). However, lower capital costs have been reported. In 2017, Nel reported an alkaline electrolyser cost of A\$1000/kW for 2015 and a projection of a little over A\$700/kW for 2020. The Norwegian company reported that large electrolyser facilities were already at capital expenditure parity with medium sized steam methane reforming (SMR) plants (Løkke, 2017[9]) and in January 2021 predicted a levelized cost of \$1.50/kg hydrogen by 2050. In 2019 NREL gave a more detailed cost breakdown for electrolysers and forecasts to decrease with annual production rate as shown in Figure 11.

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[8] IEA (2019) The Future of Hydrogen. International Energy Agency, Paris.

[9] Løkke (2017) Nel Group – presentation by Jon André Løkke, Chief Executive Officer. https://www.fch.europa.eu/sites/default/files/S2.3-J.A.L%C3%B6kke%2CNel.pdf

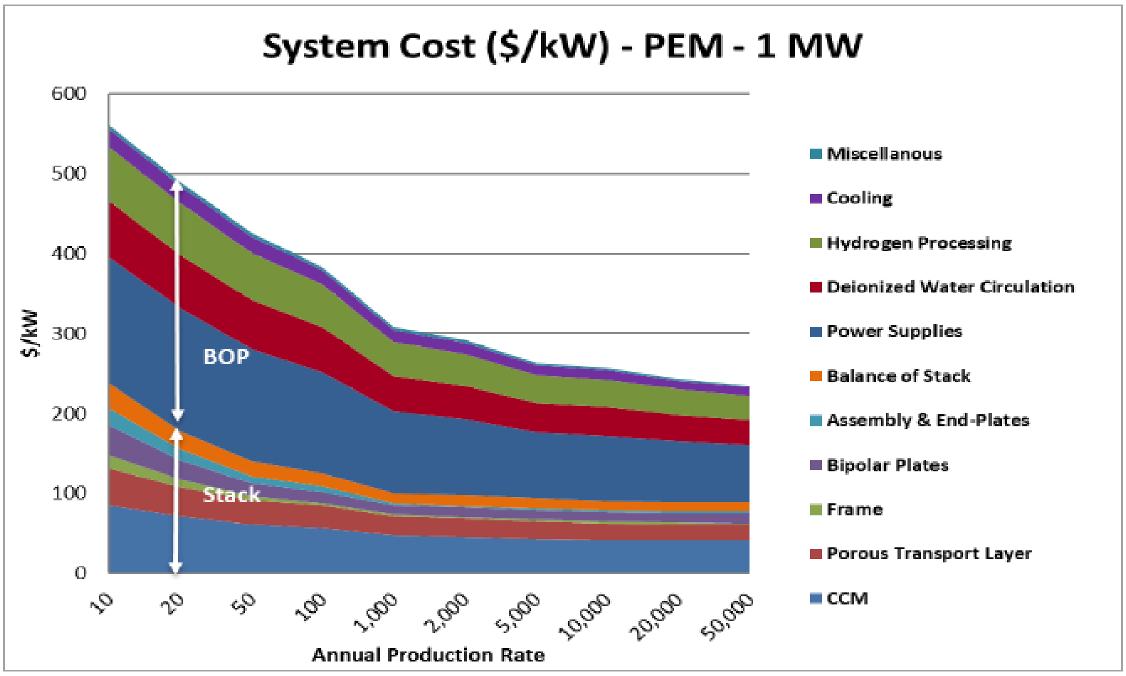

Fig. 11. 1-MW PEM electrolyser system cost at different annual production rates (the annual production rate is the number of systems produced in one year). [10]

An analysis published in November 2022 projects CAPEX for both alkaline and PEM technologies reflecting both plant size and technology development to 2030. [11] The analysis predicts that the CAPEX gap between AEL and PEMEL technologies will decrease significantly towards 2030 with plant size in the 1-10 MW range. Beyond this, only marginal cost reductions can be expected with CAPEX values approaching 320-400 $/kW for large scale (greater than 100 MW) plants by 2030 with subsequent cost reductions possible. Learning rates for electrolysers were estimated at 25-30% for both AEL and PEMEL, which are significantly higher than the learning rates reported in previous literature. What is also clear from the analysis is that in the early years, costs vary enormously but as development progresses for both alkaline and PEM systems, the CAPEX reach asymptotic values, as shown in Figure 12.

As the number of projects and their sizes ramp up, so too is the amount of capital committed to them, only slightly offset by declining costs so far. The IEA estimates that more than USD 1.5 billion was spent on projects at advanced stages in 2021, i.e., those with a final investment decision and under construction, mostly projects aiming for commissioning in 2022 or 2023. This is a threefold increase from the equivalent spending in 2020. Much of this relies on government funding, support that continues to underpin project viability, which would otherwise have been harder hit by market uncertainties since 2020. To complicate matters further is the global economic climate which is not only affecting the cost of capital for large projects, but also post-COVID, the global supply chains for advanced technologies such as electrolysers. Therefore, any published cost reductions need to be treated cautiously.

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[10] Mayyas, Ahmad et al, Manufacturing cost analysis for Proton Exchange Membrane Water Electrolysers. National Renewable Energy Laboratory, NREL/TP-6A20-72740.

[11] Abuta Reksten et al, Projecting the future cost of PEM and alkaline water electrolysers; a CPEX model including electrolyser plant size and technology development. Int. Journal of Hydrogen Energy, 47(2022), 38106-38113.

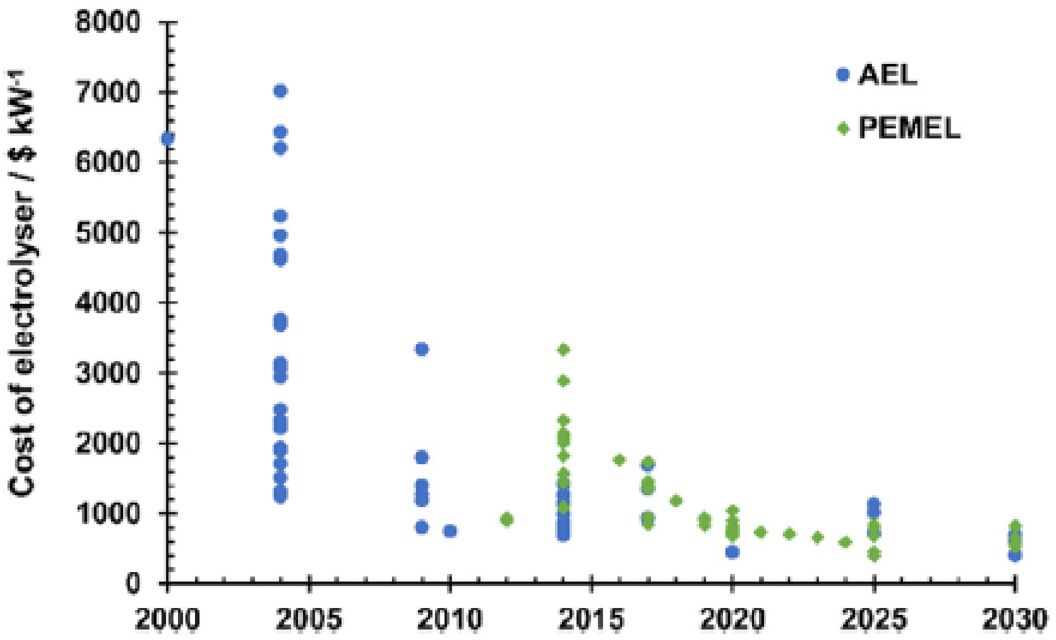

Fig. 12 Literature data for electrolyser costs from 2000 until 2030 based on 14 references in Reksten et al. (2022)[8].

8.2 Other costs

In addition to the initial CAPEX of electrolysers the operation and maintenance costs also need to be considered over the lifetime of the plant. In the case of the PEM electrolyser this may include stack replacement costs after 5 years or more of continuous operation. Apart from that, the routine maintenance costs of alkaline systems are generally higher than those of PEM electrolysers.

Water is another cost element. In general, the purity of water for alkaline systems is less stringent than for PEM systems as the catalysts employed are less prone to degradation by impurities. Most commercial electrolysers at the scale of around 1 MW employ reverse osmosis systems to purify the feed water. Supply water that is high in impurities will therefore result in a higher water consumption than supplies that require less purification. Fundamentally to produce 1 kg of hydrogen requires a minimum of 9 litres of water (9 kg) at ambient conditions. In practice this can be 10 litres or more depending on the specification and purity of the water. For systems in the mufti-MW or GW scale, the issue of water availability becomes significant and it is expected that for export-scale projects desalination plants will be required to purify seawater to supply the electrolysers. In evaluating potential electrolyser all these issues need to be considered on a case-by-case basis.

Many predict that electrolyser capital cost will get to a point where the target production cost of H2 below $2 per kg may be reached in the near future, if the current trend of development continues. However, large GW scale hydrogen production technologies will likely be constrained by the availability of special materials such as membrane polymers and critical strategic metals for electrodes and catalysts unless equipment and technologies are designed in keeping with a circular manufacturing or economy approach. The ability to recycle end-of-life electrolysers and upcycling the component materials as much as possible is likely to be an important area of concern in the future. Other low-cost alternative metals require further investigation provided they can achieve similar performance and durability of the current electrolyser materials. Further research and development is clearly needed to reduce capital and operating costs to ensure the widespread production of green hydrogen by electrolysis of water.

9. Further reading

Electrochemical Water Electrolysis, Fundamentals and Technologies, Ed By Lei Zhang, David P. Wilkinson, Xuelliang Sun and Jiujun Zhang, CRC Press, ISBN 9781138329324, 2020.

PEM Water Electrolysis, Volumes 1 and 2, Dmitri Bessarabov and Pierre Millet, Academic Press, USBN 978-0128111451, 2018.

Electrochemical Power Sources: Fundamentals, Systems and Applications: Hydrogen Production by Water Electrolysis, Tom Simolinka and Jurgen Garche (eds), Elsevier, ISBN 978-0128194249, 2021.

Hydrogen Production by Electrolysis, Agata Godula-Jopek, ISBN: 978-3-527-67652-1, Wiley. 2015.

For more information on electrolysis in Australia please check out

https://research.csiro.au/hyresource and

Https://research.csiro.au/hyresarch

10. Acknowledgements

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