

DELIVERABLE D4.4

PUBLIC

Electrolysers towards EU MAWP 2023 targets and beyond



**Co-funded by
the European Union**

Sara Andrenacci, Yejung Choi, Yash Raka,
Belma Talic, and Luis Colmenares-Rausseo
(SINTEF)

Quality Assurance: Elodie Pahon (UBFC)

Project acronym: HAEOLUS

Project title: Hydrogen-Aeolic Energy with Optimised eElectrolysers Upstream of Substation

Project number: 779469

Call: H2020-JTI-FCH-2017-1

Topic: FCH-02-4-2017

Document date: October 03, 2022

Due date: June 30, 2022

Keywords: Hydrogen, Variable Renewable Energy, Electrolysers, Water Electrolysis, AWE, PEMWE, AEMWE, SOEL, PCCE, Key Performance Indicators

Abstract: The Fuel Cell and Hydrogen 2 Joint Undertaking and its successor Clean Hydrogen Joint Undertaking set a series of key performance indicators (KPIs) that allows tracing the progress toward hydrogen production from renewable electricity coupled with water electrolysis. They are related to Energy consumption (KPI 1); Capital Expenditure (KPI 2); Efficiency Degradation (KPI 3); Flexibility (KPI 4); and Hot/Cold start (KPI 5). These 2023 KPIs are general technical goals settled to be fulfilled by all water electrolysis technologies. In that sense, the Clean Hydrogen JU settled for 2024, 2030, and beyond KPIs accordingly to each water electrolysis technology. Even though the KPIs are now adapted to each technology, the conditions assumed for each KPI are far to be a standard procedure on how it should be measured making it very difficult to do a direct comparison among technologies and between manufacturers. Despite that, these settings might be difficult to be reached with some of the available technologies due to their current inherent characteristics and especially for those less mature technologies. Nowadays, there is no specific electrolyser technology outperforming the rest across all the features essential for the effective production of renewable hydrogen. Nevertheless, currently, due to their maturity and despite their limitations, both AWE and PEMWE technologies will draw the main attention, although further R&D of AEMWE, SOEL, and PCCEL would bring those less mature technologies as alternative solutions in the future. In the end, innovation, and competition among these key technologies and their manufacturers, will lead to technological improvements and a better fit for different technologies and system designs on a case-by-case basis.

Revision History

Date	Description	Author
2022/July/13	First compiled version	Luis Colmenares-Rausseo (SINTEF)
2022/Sep/22	Revision by QA	Elodie Pahon (UBFC)
2022/Oct/02	Revised version completed	Luis Colmenares-Rausseo (SINTEF)

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 779469.

Any contents herein reflect solely the authors' view. The FCH 2 JU and the European Commission are not responsible for any use that may be made of the information herein contained.

Table of Contents

1.	Introduction	3
1.1.	OBJECTIVE.....	3
1.2.	MAIN RENEWABLE ENERGY TECHNOLOGIES	3
1.2.1.	INTERMITTENT NATURE OF RENEWABLES.....	5
1.3.	ENERGY STORAGE TECHNOLOGIES	5
1.4.	HYDROGEN AND RENEWABLE ENERGY SOURCES.....	6
2.	Renewable Hydrogen Production	7
2.1.	MAIN WATER ELECTROLYSIS TECHNOLOGIES.....	9
2.1.1.	OPERATING PRINCIPLE OF THE WATER ELECTROLYSIS TECHNOLOGIES.....	9
2.1.2.	WATER ELECTROLYSERS AT SYSTEM LEVEL.....	13
2.1.3.	COMMERCIALY AVAILABLE ELECTROLYSER UNITS.....	17
2.1.4.	LARGEST ELECTROLYSER DEMONSTRATION PROJECTS OF FCH 2 JU	20
2.1.5.	ADVANTAGES AND DISADVANTAGE OF WATER ELECTROLYSIS TECHNOLOGIES	20
3.	State-of-the-art and KPIs for Renewable Hydrogen Production.....	21
3.1.	FUEL CELL AND HYDROGEN JOINT UNDERTAKING – MULTI-ANNUAL WORK PLAN 2014 – 2020	21
3.2.	CLEAN HYDROGEN JOINT UNDERTAKING – STRATEGIC RESEARCH AND INNOVATION AGENDA 2021 – 2027	22
3.2.1.	KPIs FOR ALKALINE WATER ELECTROLYSIS (AWE)	22
3.2.2.	KPIs FOR ANION EXCHANGE MEMBRANE WATER ELECTROLYSIS (AEMWE).....	23
3.2.3.	KPIs FOR PROTON EXCHANGE MEMBRANE WATER ELECTROLYSIS (PEMWE).....	23
3.2.4.	KPIs FOR SOLID OXIDE ELECTROLYSIS (SOEL)	23
3.2.5.	KPIs FOR FLEXIBLE ELECTROLYSER OPERATION.....	24
4.	KPI 1: Energy consumption	24
4.1.	THEORETICAL EFFICIENCY	24
4.2.	PATHWAY TOWARDS REACHING KPI 1 TARGETS	29
5.	KPI 2: Capital Expenditure (CAPEX).....	32
5.1.	CHALLENGES	32
5.2.	METHODOLOGY	32
5.3.	ASSESSMENT.....	32
5.4.	KEY PERFORMANCE INDICATOR	34
5.5.	POTENTIAL PATHWAYS TO COST REDUCTION FOR REACHING KPI (2023).....	34
5.5.1.	STACK LEVEL	34
5.5.2.	SYSTEMS LEVEL	35
5.5.3.	LEARNING BY DOING	36
6.	KPI 3: Efficiency Degradation	38
6.1.	PATHWAY TOWARDS REACHING KPI 3 TARGETS	42
7.	KPI 4: Flexibility and KPI 5: Hot and Cold Start-up	44
7.1.	LOAD RANGE	44
7.2.	KPI 5: HOT AND COLD START UP.....	45
7.3.	PATHWAY TOWARDS REACHING KPI 4 AND 5 TARGETS	46
8.	Achievements of water electrolysis technologies towards MAWP	47
8.1.	KPI 1: ENERGY CONSUMPTION	48
8.2.	KPI 2: CAPITAL EXPENDITURE	48
8.3.	KPI 3: EFFICIENCY DEGRADATION	49
8.4.	KPI 4 AND 5: FLEXIBILITY AND HOT/COLD START UP	50
9.	Summary	51

1. Introduction

1.1. Objective

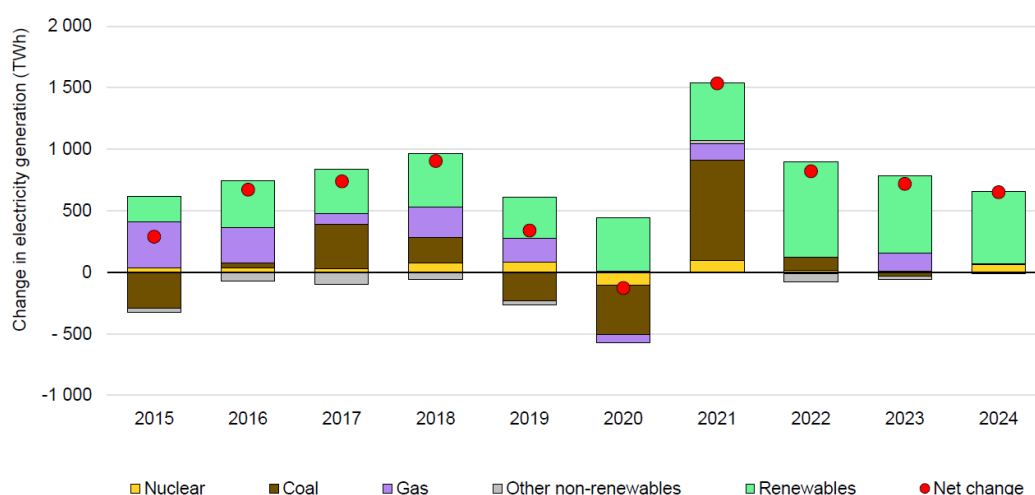
The Fuel Cell and Hydrogen 2 Joint Undertaking and its successor Clean Hydrogen Joint Undertaking set a series of key performance indicators (KPIs) that allows tracing the progress toward hydrogen production from renewable electricity coupled with water electrolysis.

In that regard, this deliverable intends to identify the main challenges by water electrolysis technology for reaching those future targets (KPIs) besides evaluating and ranking solutions to these challenges.

The deliverable will initially present an overview of renewable energy sources (RES) and their nexus with hydrogen production. Subsequently, the basis of the different water electrolysis technologies will be presented highlighting their maturity, advantages, and disadvantages. KPIs set by technology will be presented assessing those KPIs with the aim of identifying the most suitable technology and pathways to reach the MAWP 2023 targets and beyond. Finally, an overview will be presented.

1.2. Main renewable energy technologies

The energy from renewable sources can be used and reused without requirement of an exhaustible element. Beyond the source is the product (waste) after electricity is produced which in case of coal and natural gas requires environmental mitigation and an excess of energy for that while for RES would not be the case. In that sense, renewable energy is often referred to as clean energy. Thus, as the International Energy Agency (IEA) reported in 2021, the electricity sector needs to move from being the highest emitting sector in 2020 to being the first sector to hit net zero globally by 2040 meanwhile supporting decarbonise other sectors.¹ In that sense, it expects RES to be responsible for a significant contribution to the global electricity generation in the coming years with a growing average of 6% per year.²



IEA. All rights reserved.

Figure 1.1. Global change in electricity generation, 2015-2024.²

¹ IEA (2021): Net Zero by 2050. A Roadmap for the Global Energy Sector

² IEA (January 2022): Electricity Market Report.

There are five major renewable energy sources (RES):

1. Solar energy from sun
2. Geothermal energy from heat inside the earth
3. Wind energy
4. Biomass from plants
5. Hydropower from flowing water

Among the RES, solar and wind are the two most used. Both energy sources have been rapidly growing in the last decade while the other clean sources have been roughly static (Figure 1.2). While solar power can be an efficient way to drive down the cost of electricity and power homes and businesses, wind shows a solid efficiency rating. Furthermore, wind and solar are the lowest cost source of electricity on a levelized basis, with ever-increasing global experience of integrating them into grids at high levels.

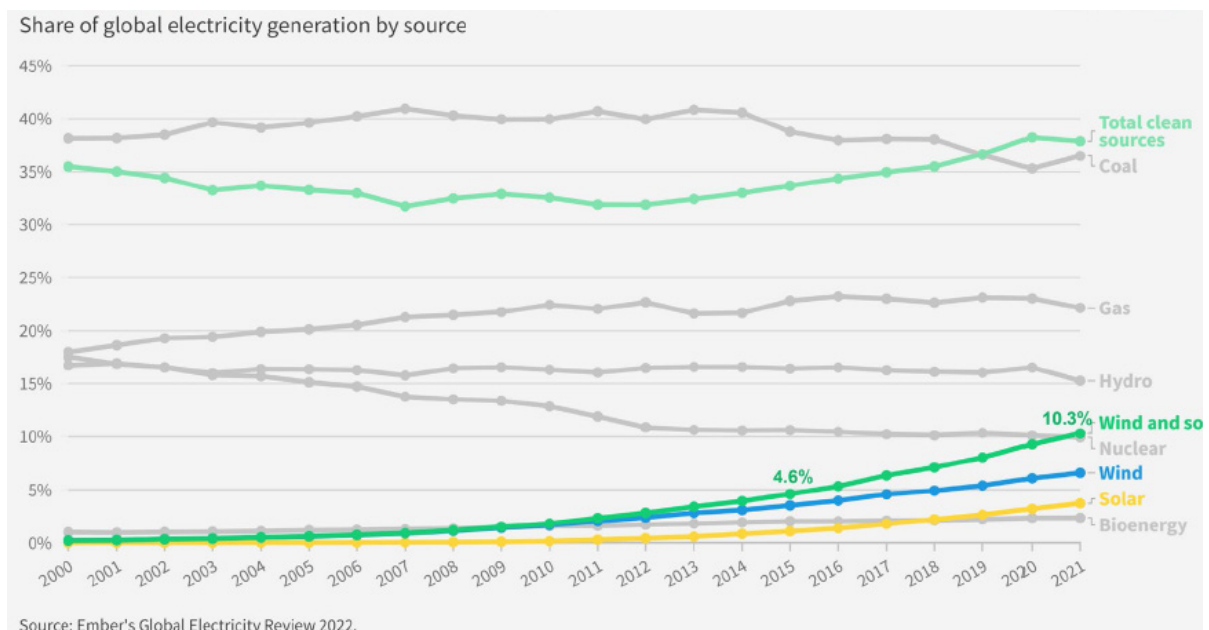


Figure 1.2. Share of global electricity generation by source.¹

In 2021, solar generation rose 23%, and wind by 14%. Combined, this takes them to more than 10% of global electricity generation in 2021. All clean electricity sources generated 38% of the world's electricity in 2021, more than coal (36%).¹ Taken together both sources, they represent now the fourth largest source of electricity in the world. Nevertheless, to be on a pathway that keeps global heating to 1.5 Celsius degrees, wind and solar need to sustain high compound growth rates of 20% every year to 2030.

¹ Global Electricity Review 2022. EMBER, March 2022

1.2.1. Intermittent nature of renewables

RES are affected by environmental, seasonal, and daily cycles that can limit their use or efficiency. As such, renewable energy cannot always consistently produce energy at all hours of the day. They produce energy intermittently instead of on demand and hence are known as Variable Renewable Energy (VRE). VRE includes wind, solar, and hydro-electric power. Solar and wind energy production in Europe have been known to fluctuate between 0 to 23 and 24 GW of energy respectively during peak times. This intermittent nature has always been an issue limiting the growth of renewable energy.¹

The challenge associated with integrating variable sources of electricity stems from the fact that the power grid was designed around the concept of large, controllable electric generators. Today, power plants produce the right amount of electricity at the right time to meet electric demand consistently and reliably, because the grid has very little storage capacity and hence, the balance between electricity supply and demand must be always maintained.² Consequently, without energy storage to balance energy supply and demand, further expanding the share of renewables would not be possible. Therefore, demand response and storage are emerging as key tools for increasing flexibility promoting the growth and integration of VRE.

1.3. Energy storage technologies

Energy storage can allow energy to be stored during high renewable generation or low demand periods, and to be used during low renewable production or high demand periods. Energy storage is also important for energy management, frequency regulation, peak shaving, load levelling, seasonal storage, and standby generation during a fault. One can categorize the storage technologies by storage duration (long-term, short-term storage), by the kind of storage (electrical, mechanical, chemical, thermal, etc.) or by other criteria like capital cost, capacity, efficiency, and environmental impact. The various storage technologies are in different stages of maturity and are applicable in different scales of capacity.^{3,4}

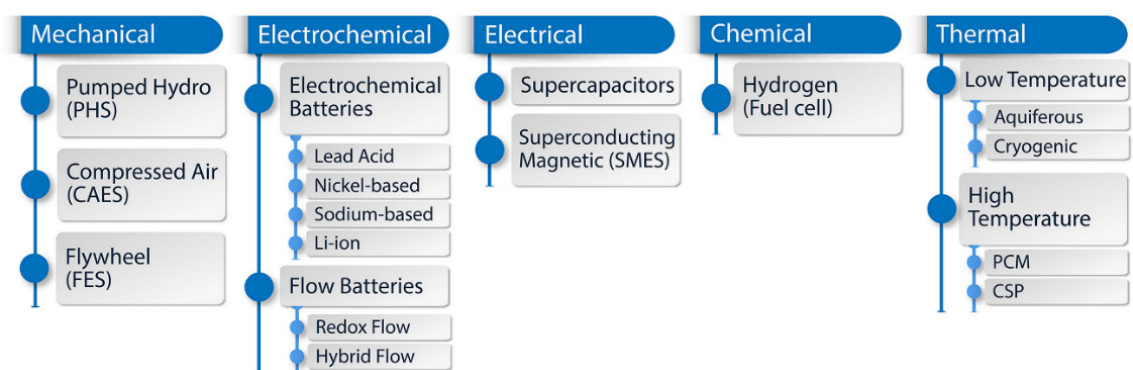


Figure 1.3. Classification of energy storage technologies by the form of stored energy.⁴

One promising option to fulfil this dispatchable energy role is hydrogen energy storage. Hydrogen energy storage is a process wherein the surplus of energy created by renewables during low energy

¹ What is Intermittency? Energyx ([LINK](#)).

² Renewable Energy Intermittency Explained: Challenges, Solutions, and Opportunities by Robert Fares. 2015.

³ Electronics, 8 (2019) 729. <https://doi.org/10.3390/electronics8070729>

⁴ Renewable and Sustainable Energy Reviews, 94 (2018) 804. <https://doi.org/10.1016/j.rser.2018.06.044>

demand periods is used to power electrolysis. The large-scale production and use of hydrogen as an energy carrier can be an important contributor to the transformation of the global energy system by helping with the use, integration, and deployment of VREs.

1.4. Hydrogen and Renewable Energy Sources

With its Green Deal, Europe strives to be the world's first climate-neutral continent and reach net-zero emissions of greenhouse gases by 2050.¹ This ambitious target can only be realised with substantial efforts to develop new and innovative energy systems that are efficient, sustainable, and flexible. In this respect, the EU H₂ strategy identifies the massive potential of hydrogen as an energy carrier that can unlock the full potential of renewable energy sources (RES), store excess power, provide grid balancing, and facilitate the decarbonisation of industry (e.g., chemicals, iron, steel, etc.) and transport where it is proving difficult to meaningfully reduce emissions. Transport is responsible for a quarter of the EU's greenhouse gas (GHG) emissions, being road transport the highest contributor with a share of 72% in 2019. According to the European Commission, considering all existing policy measures, transport carbon dioxide (CO₂) emissions are projected to be 3.5% higher in 2030 than in 1990 and to fall by only 22% by 2050 compared to 1990 levels. Road transport specifically is projected to decrease emissions by 4% by 2030 and 35% by 2050, compared with 1990.² The decrease will be largely driven by increased efficiency of vehicles, including a shift to electric vehicles. Thus, transport is identified as one of the most difficult sectors to decarbonize due to current cultural mobility patterns, the fact that transport is the least diversified energy end-use sector, the continuous growth of global demand for mobility, and the technical limitations to replacing oil-based fuels. In this sector, the dynamics derived from the interaction between the energy, the technology and the economy are crucial aspects of the decarbonization process.³

The fast deployment of RES can be driven by the large-scale green hydrogen production demand. By 2050, IRENA estimates around 4-16 TW of solar and wind global generation capacity to be deployed to produce green hydrogen and its derived products.⁴ It is a significant expansion of today's solar and wind power capacity which represents 1 TW from a global power generation capacity of 7 TW.

Despite hydrogen can facilitate the penetration of a higher share of RES, decarbonization of the industrial sector, and the cross-sectorial coupling, only 1% of the European hydrogen supply comes from renewable electricity as the global hydrogen production (95%) is based on fossil fuels such as natural gas (grey H₂) and coal (black H₂) with associated 830Mt CO₂ per year.⁵ Decarbonizing the hydrogen sector and driving down the production costs of the so-called renewable (green) hydrogen remain key challenges for the European energy sector. Nevertheless, hydrogen production through water electrolysis can provide significant flexibility to match the seasonality of renewable energy generation. Thus, the large deployment of electrolyzers into high renewable power systems will be a fundamental pillar of the transformation of the power sector.⁶

¹ https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

² European Environment Agency Report: Transport and environment report 2021. Decarbonising road transport — the role of vehicles, fuels, and transport demand (No.2/2022). IRENA: Global Energy Transformation A Roadmap to 2050 (2019).

³ Ignacio de Blas et al. Energy Strategy Reviews 32 (2020) 100543. <https://doi.org/10.1016/j.esr.2020.100543>

⁴ IRENA: Hydrogen: A renewable energy perspective (2019). IRENA: Global energy transformation: A roadmap to 2050 (2019a).

⁵ Hulst, N. The clean hydrogen future has already begun (2019). IRENA Green hydrogen: A guide to policy making (2020).

⁶ IRENA: Green Hydrogen Cost Reduction (2020).

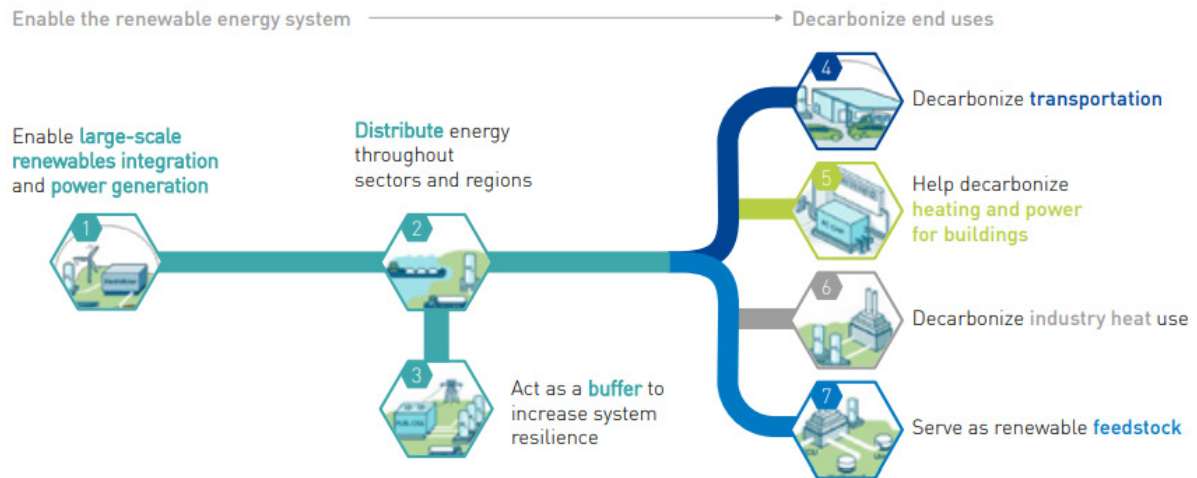


Figure 1.4. Hydrogen as an enabler of the energy transition in Europe and decarbonization end uses.¹

2. Renewable Hydrogen Production

Hydrogen will need a primary energy source to be produced. Therefore, it must be generated from any feedstock that possesses in its composition hydrogen atoms. Depending on the raw material the hydrogen production technology can be categorized as conventional or renewable.

In conventional technologies, hydrogen is generated from fossil sources like natural gas, coal, oil, etc. generating carbon dioxide (CO₂) as a by-product. When Carbon Capture and Storage (CCS) is in place the generated hydrogen is known as blue hydrogen. In case, that CCS is not implemented the hydrogen is labelled as grey. This leads to non-renewable hydrogen production. Nuclear power is also considered for the generation of hydrogen. It may include low and high temperature steam electrolysis using heat and electricity from the nuclear reactor.²

On the other hand, renewable technologies generate hydrogen from primary energy derived from renewable sources like either biomass or water. While biomass-based processes emit CO₂ as well as a by-product like conventional technologies, water-splitting processes such as electrolysis require electricity to split the water into hydrogen and oxygen. In this case, the hydrogen is named green hydrogen if the electricity is provided by RES such as solar or wind power. Green hydrogen will be the cleanest energy carrier which will be not the case when the electricity used is generated from fossil fuels. In this manner, the energy source and the production process will determine whether the generated hydrogen will be labelled as grey, blue, or green considering the last two as carbon-neutral hydrogen.

¹ Hydrogen Roadmap Europe: A Sustainable Pathway for the European Energy Transition (2019).

² IEA: Global Hydrogen REVIEW (2021). World Nuclear Association: Energy and the Environment. [Hydrogen Production and Uses](#) (2021).

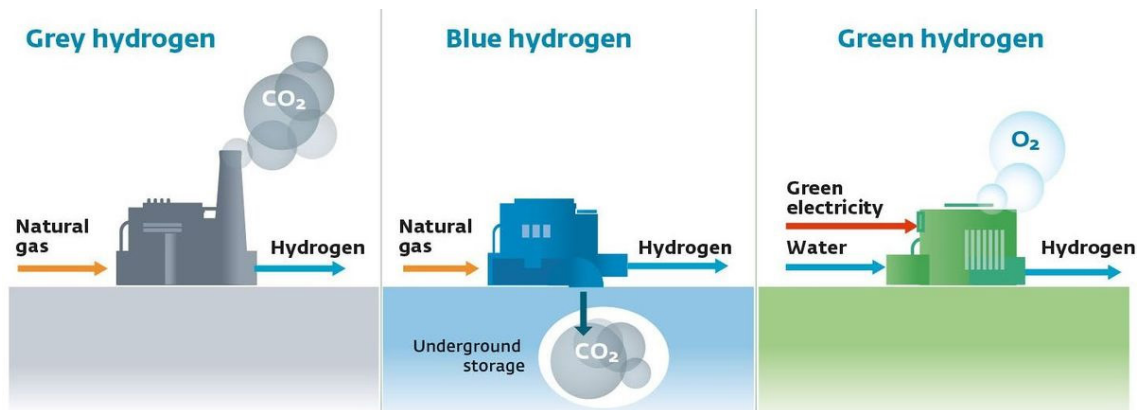


Figure 2.1. Representation of grey, blue, and green hydrogen.¹

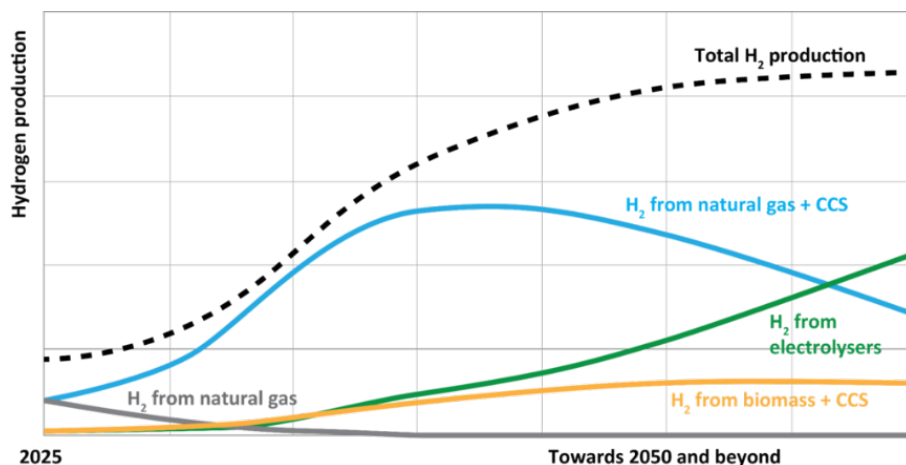


Figure 2.2. Indicative production of hydrogen from natural gas, biomass, and electrolysis using RES.²

In the global energy transition, both the blue and the green hydrogen will play an important role to meet the targets. The industry needs to keep looking at any potential technology enabling environmentally friendly and cost-efficient energy systems where the transition may go from grey through blue to green hydrogen to achieve the decarbonization of the system and contribute to climate targets.

On 8 July 2020, the EU Commission adopted the Energy System Integration³ and Hydrogen Strategies.⁴ Together they aim to address a vision on how to accelerate the transition towards a more integrated and clean energy system, in support of a climate neutral economy. The Hydrogen Strategy identifies as the priority for the EU to develop renewable hydrogen, produced using mainly wind, hydro, and solar energy. This should be the main form of hydrogen in the long-term, towards 2050, supported by the very high shares of renewable electricity. In the mid-term, other forms of low-carbon hydrogen

¹ What is hydrogen and how is it made? The World of Hydrogen: <https://www.theworldofhydrogen.com/gasunie/what-is-hydrogen/>

² Hydrogen: The Future Is Green, But The Path There Is Multicoloured (2020). Stefania Gardarsdottir. [SINTEF Blog](https://www.sintef.no/en/news/2020/07/hydrogen-the-future-is-green-but-the-path-there-is-multicoloured). Hydrogen for Europe (2019). IFPEN and SINTEF [report](https://www.sintef.no/en/news/2019/07/hydrogen-for-europe).

³ Strategy for Energy System Integration. COM (2020) 299 final.

⁴ A Hydrogen Strategy for a climate neutral Europe. COM (2020) 301 final.

will also be needed, both to support the uptake of hydrogen as energy carrier and feedstock, and to replace most polluting forms of producing hydrogen. Water electrolysis will be the main technology supported, covering both high TRL types: Alkaline Water Electrolysis (AWE), Proton Exchange Membrane Water Electrolysis (PEMWE), Solid Oxide Electrolysis (SOEL) and less mature types: Anion Exchange Membrane Water Electrolysis (AEMWE) and Proton Conducting Ceramic Electrolysis (PCCEL).

2.1. Main Water Electrolysis Technologies

Water electrolysis is a promising method for green hydrogen production from renewable sources like solar and wind. Electrolysis is the process of using electricity to split water into hydrogen and oxygen molecules. This reaction takes place in a unit called an electrolyser. Electrolysers consist of several cells composed of an anode and a cathode separated by an electrolyte. Electrolysers technologies are differentiated based on the electrolyte material and temperature of operation.

There are four main different water electrolysis technologies: Alkaline Water Electrolysis (AWE), Anion Exchange Membrane Water Electrolysis (AEMWE), Proton Exchange Membrane Water Electrolysis (PEMWE) and Solid Oxide Electrolysis (SOEL). In the follow, a brief explanation of each technology is provided.

2.1.1. Operating Principle of the Water Electrolysis Technologies

a) Alkaline Water Electrolysis (AWE)

Alkaline electrolysis is the most mature of the electrolyser technologies and has been traditionally viewed as a standard for large industrial scale production of hydrogen.¹ Figure 2.3 shows the working principle of alkaline electrolyzers. The cell is composed of two gas evolving electrodes immersed in a liquid electrolyte separated by a porous separator(diaphragm) that selectively permeates ions and blocks gas bubbles. Typical electrode materials are electrically conductive porous metal framework often covered with a catalyst coating layer. Unlike the corrosive environment of PEM electrolyzers, the alkaline environment enables free utilization of non-platinum group metal (PGM) electrodes as catalyst and electrode materials. Numerous combinations of different transition metals have been extensively reviewed in the literature and shown excelling performance over PGM catalyst. Moreover, the use of relatively robust porous separators endows alkaline electrolyzers with high durability and tolerance to impurities, leading to longer estimated lifetime among the currently available electrolyser technologies.²

¹ C. Mittelsteadt, T. Norman, M. Rich, J. Willey, Ch. 11 - PEM Electrolyzers and PEM Regenerative Fuel Cells Industrial View, in: P.T. Moseley, J. Garche (Eds.), *Electrochem. Energy Storage Renew. Sources Grid Balanc.*, Elsevier, Amsterdam, 2015: pp. 159–181. <https://doi.org/10.1016/B978-0-444-62616-5.00011-5>

² J. Koponen, Review of water electrolysis technologies and design of renewable hydrogen production systems, (n.d.) 94

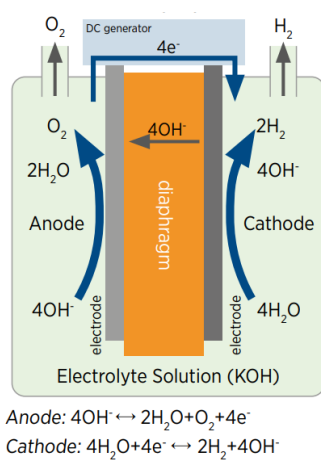


Figure 2.3. AWE and half reactions.¹

The porous separators placed between the electrodes are often composed of asbestos, porous ceramics, polymers, and their composites. An example of the composite separator is Zirfon Perl™ made of a composite of zirconia and polysulfone network retaining excellent wettability and shape retaining property of zirconia and flexibility of polymer. Zirfon materials are currently being widely used and may be considered as state-of-the-art separators in alkaline electrolyzers.

Wetting the porous separator and the electrodes is the electrolyte composed of 25-30 % potassium hydroxide aqueous solution. The electrolyte solution circulates throughout the cell and helps cool the cell as well. As water is consumed on the cathode side and produced on the anode side, streams of both sides need mixing prior to re-entering the cell to prevent

concentration or dilution of the electrolyte within the cell. However, the streams may carry small amounts of dissolved gases and may result in contamination of the product gases through the mixing process. Such problem limits its operation at higher pressure levels. Thicker separators (0.252 mm) or spacers between electrodes and the separators are proposed as a solution to this issue but the high thickness result in high ohmic resistance across the electrodes and may drastically reduce the current density. Current advanced designs use zero-gap electrodes with thinner separators and advanced electrocatalysts to increase the current density. As for relieving the gas mixing issue, catalytic gas purification processes may be an auxiliary method.

In a typical cell, all the above-described key components are flat packed between flat metal plates denoted as bipolar plates. The bipolar plates enable serial connection of multiple cells which then becomes an alkaline electrolyser stack. The bipolar plates are produced in manifold surface structure to facilitate movement of electrolyte throughout the cell as well as efficient removal of gas produced from the cell.

Currently, alkaline electrolyzers enable the highest scale of green hydrogen production-to-investment costs ratio, with system sizes ranging between 1.8 and 5,300 kW, and the investment costs between 800 and 1,500 USD/kW. This is 2–2.5 times lower in the typical investment costs than that of the PEM electrolyzers.

Nevertheless, alkaline electrolyzers possess several disadvantages. Its most significant drawbacks are the high lower limit of minimum load and the intrinsic design to operate at fixed process conditions, which hinders coupling with certain types of renewables.² Although this limitation can be partially alleviated with the use of batteries and control systems, alkaline electrolyzers may not be the ideal option for variable renewable energy sources such as solar PV or wind.^{3,4}

¹ IRENA: Green Hydrogen Cost Reduction (2020).

² Ionmtr Innovations (2020) Hydrogen production cost by AEM water electrolysis. Vancouver, BC: Ionmtr Innovations Inc.

³ Becker, M., Brauns, J., and Turek, T. (2021) Battery-buffered alkaline water electrolysis powered by photovoltaics, *Chemie Ingenieur Technik*, 93, pp. 655–63

⁴ Mittelsteadt, C., Norman, T., Rich, M., and Willey, J. (2015) PEM electrolyzers and PEM regenerative fuel cells industrial view, in Moseley, P.T. and Garcke, J. (ed.) *Electrochemical energy storage for renewable sources and grid balancing*, Amsterdam: Elsevier, pp. 159–81.

Finally, the general commercially available alkaline electrolyzers tend to produce hydrogen of lower purity than other electrolyzers, for instance PEM, while consuming more energy.¹ Furthermore, the use of corrosive alkaline electrolytes holds a safety threat in case of leakage or gas mixing (hydrogen and oxygen mixture are highly flammable), therefore the system must be carefully designed and maintained.²

b) Anion Exchange Membrane Water Electrolysis (AEMWE)

To overcome the challenges in alkaline electrolyzers, anion exchange membrane (AEM) polymer technologies are being developed. Though AEM is still at a relatively early development stage, it holds a promising potential to become a more successful tool in green hydrogen production coupled with variable renewable energy sources.

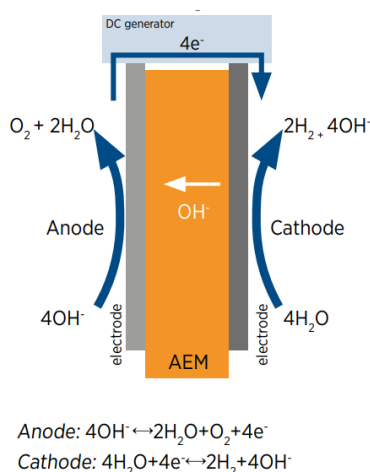


Figure 2.4. AEMWE and half reactions.³

While maintaining the advantage of the alkaline system that enables use of inexpensive catalysts and electrode materials, AEM installations also use less corrosive alkaline electrolyte solution of lower concentration,⁴ and efficiently inhibit electrolyte and gas leakages by replacing the diaphragms with anion exchange membranes. As a result, AEM not only provides reduced energy consumption and increased efficiency, but also generates higher purity hydrogen.⁵

Whilst representing a step forward from the classic alkaline electrolyzers AEM electrolyzers still have unresolved issues. Just like the classic alkaline electrolyzers, their minimum load is still quite high, remaining at around 10–20 % of design capacity.⁶ In addition, while proving more efficient than alkaline electrolyzers, AEM still has relatively lower

performance to PEM systems,⁷ not to mention the substantially limited scale of currently available AEM compared to the massive availability of alkaline and PEM electrolyzers. Finally, the extreme sensitivity of the membrane towards carbon dioxide (CO₂) intrusion and the decreasing ionic conductivity over time leads to significant decline in AEM performance, which is reflected by the short lifetime of AEMs (around 30,000 hours).⁸

¹ Sheffield, J.W., Martin, K.B., and Folkson, R. (2014) Electricity and hydrogen as energy vectors for transportation vehicles, in Folkson, R. (ed) Alternative fuels and advanced vehicle technologies for improved environmental performance, Cambridge, UK: Woodhead Publishing.

² Santos, D.M.F., Sequeira, C.A.C., and Figueiredo, J.L. (2013) Hydrogen production by alkaline water electrolysis, Quimica Nova, 36, 1176.

³ IRENA: Green Hydrogen Cost Reduction (2020).

⁴ Vincent, I. and Bessarabov, D. (2018) Low-cost hydrogen production by anion exchange membrane electrolysis: A review, Renewable and Sustainable Energy Reviews, 81 (1), pp. 1690–704.

⁵ Mandal, M. (2021) Recent advancement on anion exchange membranes for fuel cell and water electrolysis, ChemElectroChem, 8, 36–45.

⁶ Stanislaw, L.N., Gerhardt, M.R., and Weber, A.Z. (2019) Modeling electrolyte composition effects on anion-exchange membrane water electrolyzer performance, ECS Transactions, 91 (8), pp. 767–79.

⁷ Faid, A.Y., Barnett, A.O., Seland, F., and Sunde, S. (2018) Highly active nickel-based catalyst for hydrogen evolution in anion exchange membrane electrolysis, Catalysts, 8 (12), pp. 1–13.

⁸ Vega, J.A., Chartier, C., and Mustain, W.E. (2010) Effect of hydroxide and carbonate alkaline media on anion exchange membranes, Journal of Power Sources, 195 (21), pp. 7176–80.

c) Proton Exchange Membrane Water Electrolysis (PEMWE)

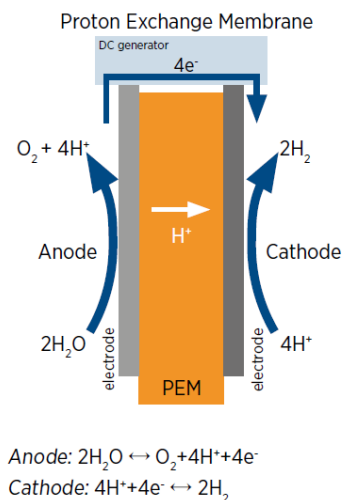


Figure 2.5. PEMWE and half reactions.³

Proton exchange membrane (PEM) electrolysis was the first electrolyser based on the concept of solid polymer electrolyte.¹ In PEM electrolysis, electricity drives the reaction of water towards production of hydrogen and oxygen, as shown in Figure 2.5. At the anode, the water molecules are split into oxygen (O_2) and protons (H^+), releasing electrons (e^-). The protons migrate through the PEM, while the electrons are conducted through an external circuit, finally recombining at the cathode to form hydrogen(H_2).²

At the single cell level, the membrane electrode assembly (MEA) is typically composed of a thin perfluorosulfonic acid (PFSA) membrane (i.e., Nafion®) and the gas diffusion electrodes. The catalyst layers are typically PGM based: iridium oxide (IrO_2) at the anode and platinum nanoparticles on a carbon substrate (Pt/C) at the cathode side.³ The MEA is encased between two porous transport layers (PTLs) and bipolar plates (BPPs). Due to the acidic operating environment, PTLs and BPPs must be resistant to corrosion, so usually based on titanium and coated with noble metals such gold or platinum, to minimize interfacial contact resistance (ICR) across the components. Several cell units can be then connected in series to form a PEM electrolyser stack, with gasket grooves to provide sealing and manifolds as inlet and outlets for water and gases streams.

d) Solid Oxide Cell (SOC) Technology – Solid Oxide Water Electrolysis (SOWE)

The basic operating principle of the solid oxide cell (SOC) is shown in Figure 2.6. The cell is based on an oxide ion conducting ceramic material, typically yttria stabilized zirconia (YSZ) or gadolinium doped ceria (GDC). The cathode material is typically a composite of Ni and the electrolyte material while the anode is a perovskite oxide such as $\text{La}_{1-x}\text{Sr}_x\text{MnO}_3$ (LSM) or $\text{La}_{1-x}\text{Sr}_x\text{Co}_{1-y}\text{Fe}_y\text{O}_3$ (LSCF), sometimes also mixed with the electrolyte. There are several other material combinations available and under research, but these are the ones mostly used in commercial systems.

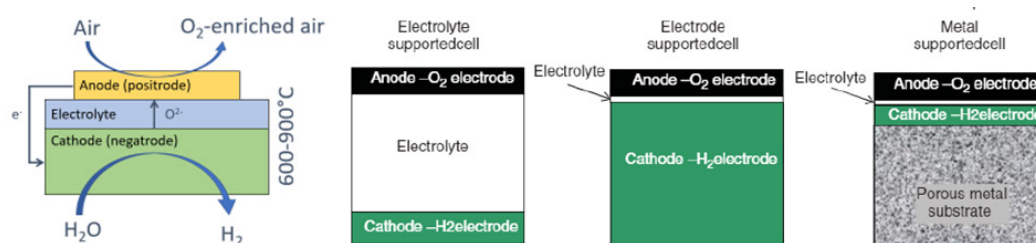


Figure 2.6. Operating principle of solid oxide electrolysis cell and cell configurations.⁴

¹ J.H. Russell, L.J. Nuttall and A.P. Fickett American Chemical Society Division of Fuel Chemistry Preprints, 18 (3) (1973), pp. 24-40

² Kumar, S.S. and Himabindu, V. (2019) 'Hydrogen production by PEM water electrolysis – A review', Materials Science for Energy Technologies, 2 (3), 442–54

³ IRENA: Green Hydrogen Cost Reduction (2020).

⁴ Adapted from R. Maric, J. Roller, and R. Neagu, J. Therm. Spray Tech. 20, 696–718 (2011). <https://doi.org/10.1007/s11666-011-9645-x>

The cell is mechanically supported by either the electrolyte, the cathode, or a porous metal layer, as shown in Figure 2.6. YSZ electrolyte-supported cells are mechanically very robust but need to be operated at high temperature (850-900 °C) to ensure sufficient conductivity through the thick electrolyte. Cathode- and metal-supported cells can be operated at lower temperatures, down to 650°C with an YSZ electrolyte. Even lower temperatures are possible with a GDC electrolyte material, but this is currently only used by a single commercial manufacturer (Ceres Power).

To increase production capacity, multiple cells are stacked and electrically connected in series using interconnectors. Two main types of stacks are available, tubular, and planar, see Figure 2.7. Planar stacks generally offer higher power densities, while tubular stacks are considered more robust and can better tolerate pressure differences between the anode and cathode compartments. Planar commercial stacks typically contain 30-250 cells/stack. The active area per cell is typically between 100-200 cm² in commercial cells.¹ There are efforts put into increasing the cell footprint and recently Dynelectro reported successful production of cells up to 1000 cm².²

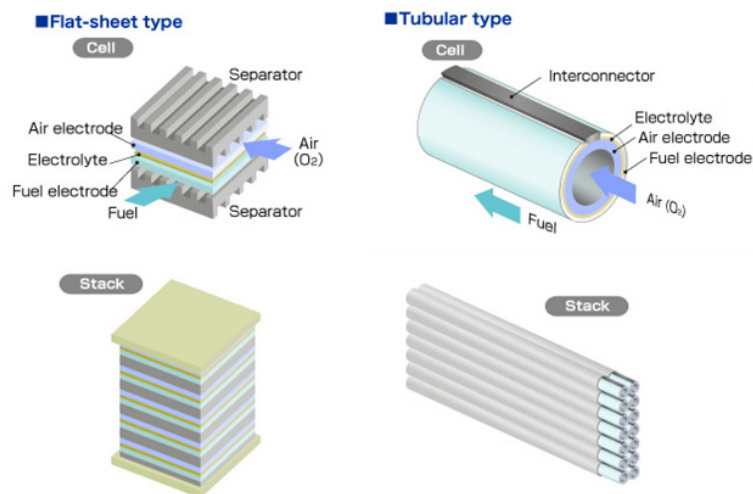


Figure 2.7. Different SOFC geometries. Upper row shows single repeating unit, bottom row shows stack of multiple cells connected in series.³

2.1.2. Water Electrolysers at System level

a) Alkaline and AEM Electrolysers

Alkaline electrolysers require circulation of the electrolyte (KOH) in and out of the stack components, which then leads to a drop in pressure that requires specific pumping characteristics. This affects the efficiency, in most cases less than 0.1 % of the total stack power consumption but may largely vary depending on the manufacturers. Nevertheless, some alkaline systems operate without pumping peripherals. The circulating electrolyte solution needs a gas separation process after leaving the stack. The circulating electrolyte is flown through the gas/water separator placed above the stack at a certain height, where the liquid phase is removed at the bottom and flows back to the stack and the gas

¹ J. Mouginn, G. Cubizolles, A. Hauch, J. Pennanen, J. Alvarez, S. Pylypko, M. Potron, B. Marquillier, S. Hody, G. Cesareo, S. Fiorot, G. Perez, Development of an Efficient rSOC Based Renewable Energy Storage System, ECS Trans. 103 (2021) 337–350. <https://doi.org/10.1149/10301.0337ecst>

² A. Energy Supply DK, 28-årig dansk forsker bag stort gennembrud inden for produktion af grøn brint, Energy Supply DK. (n.d.). [Link](#).

³ <https://www.osakagas.co.jp/en/rd/fuelcell/sofc/sofc/system.html>

removed at the top. The water column filled in the gas/water separator also functions as a buffer storage for when load specifications change. The water level of each gas/water separator is regulated by the water management system, and water permeation through the diaphragm also needs to be considered.

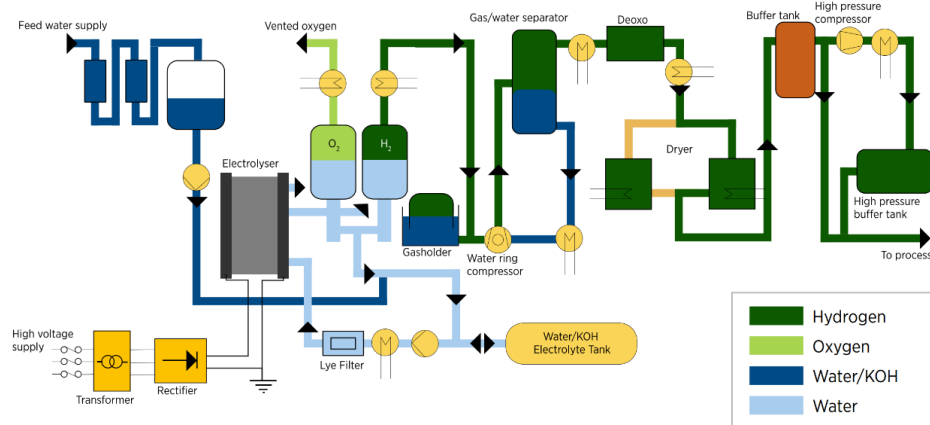


Figure 2.8. Typical system design and balance of plant for an alkaline electrolyser.¹

The water phase can be removed at the bottom and the gas phase at the top (see Figure 2.8). The water column within the separator also serves as a buffer storage for changing load specifications. The water management system regulates the filling level of each gas separator, and water permeation via the diaphragm needs to be considered. A mixing pipe is present between the gas/water separators of the anode and the cathode to balance the OH⁻ charges throughout the consumption and production during the electrochemical reaction. The unavoidable need to balance the charges within the cell makes it more challenging to operate at differential pressures in a stack level.

Nevertheless, pressurised operations are available in some designs with pressures ranging up to 200 bar, but such operations are only enabled by keeping both sides (hydrogen and oxygen) of the stack at high pressure and utilizing high-pressure vessel. More resistance cell frames, and balance of plant (BoP) materials are required to achieve high-pressure configurations.

There is scarce information at system level for **AEMWE** due to the low maturity of this technology. Nevertheless, its configuration is expected to be like PEM system design (see Figure 2.9). There is still a lot of R&D to be done in this technology, mainly on the membrane development. In that regard, in the follow alkaline assessment will be done mainly on the classical alkaline electrolysis technology.

b) Proton Exchange Membrane Water Electrolysis (PEMWE)

In a PEM electrolyser system, the cells are connected in series to form stacks and larger electrode areas are manufactured (approaching 2,000 cm²), aiming at large MW units that still must be validated.¹ The balance of plant (BoP) design, that supplies water and electricity, comprehends circulation pumps, heat exchangers for temperature control and pressure control units. Moreover, on the cathode side are found a gas-separator, a de-oxygenation component, a gas dryer and a compressor for processing and handling of the produced hydrogen.

¹ IRENA: Green Hydrogen Cost Reduction (2020).

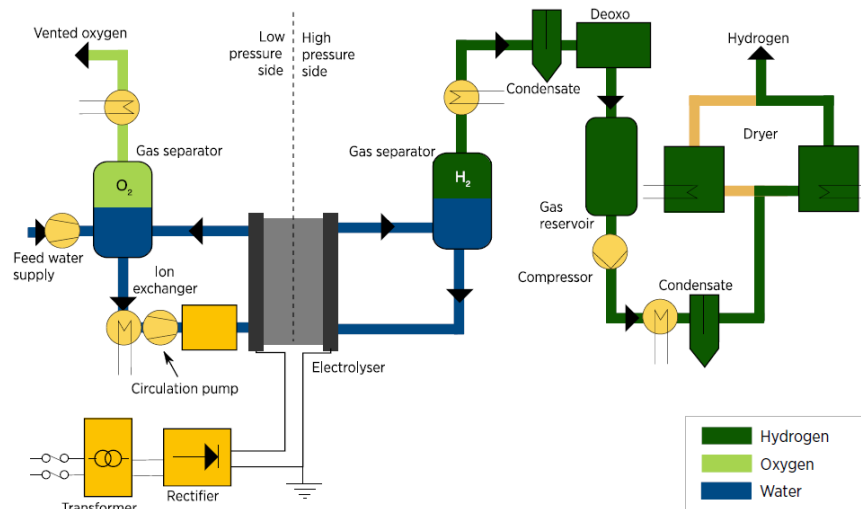


Figure 2.9. Typical system design and balance of plant for a PEM electrolyser.¹

Three plant design are possible based on the operational pressure: atmospheric, differential, and balanced pressure. At atmospheric pressure, the plant is operated at constant pressure (<1 atm); under differential pressure, the electrolyser is typically operated between 30 to 70 bar (here the efficiency is reduced by the need of thicker membranes for improved mechanical stability and reduce gas crossover). Lastly, with balanced pressure operation, anode and cathode should be operated under the same pressure level.¹

c) Solid Oxide Cell (SOC) Technology

Individual SOC stacks are integrated into modules, which are subsequently integrated into systems. A possible configuration with typical power at each level is illustrated in Figure 2.10. for the system produced by Sunfire. In addition to several stacks, the module contains a gas processing unit for steam and air supplying and safe extraction of hydrogen and oxygen. The gas processing unit includes several heat exchangers and compressors or blowers. The module also contains a supply and discharge unit for supplying power to the stacks. Several modules are combined in a system with power electronics and fluid interface unit up to the desired production capacity. A basic process flow diagram for a typical system is shown in Figure 2.11.

The optimal size and number of modules to build up a MW-sized system has not been established as there are few systems built of this size. A discussion about expected challenges in scaling up SOEC systems to MW size can be found in Saarinen et al.². According to this, the biggest technical challenge is implementation of piping with uniform gas flows to several hundred stacks. The study recommended to build smaller modules (i.e., fewer stacks in each) to decrease probability of system failure due to failure of a single stack and estimated 10 stacks per module as an upper limit considering piping and heat balance. Ideal size considering maximum efficiency of a DC/DC converter is 400-600 V, corresponding to 308-462 cells in series.

¹ IRENA: Green Hydrogen Cost Reduction (2020).

² V. Saarinen, J. Pennanen, M. Kotisaari, O. Thomann, O. Himanen, S.D. Iorio, P. Hanoux, J. Aicart, K. Couturier, X. Sun, M. Chen, B.R. Sudireddy, Design, manufacturing, and operation of movable 2 × 10 kW size rSOC system, Fuel Cells. 21 (2021) 477–487. <https://doi.org/10.1002/face.202100021>

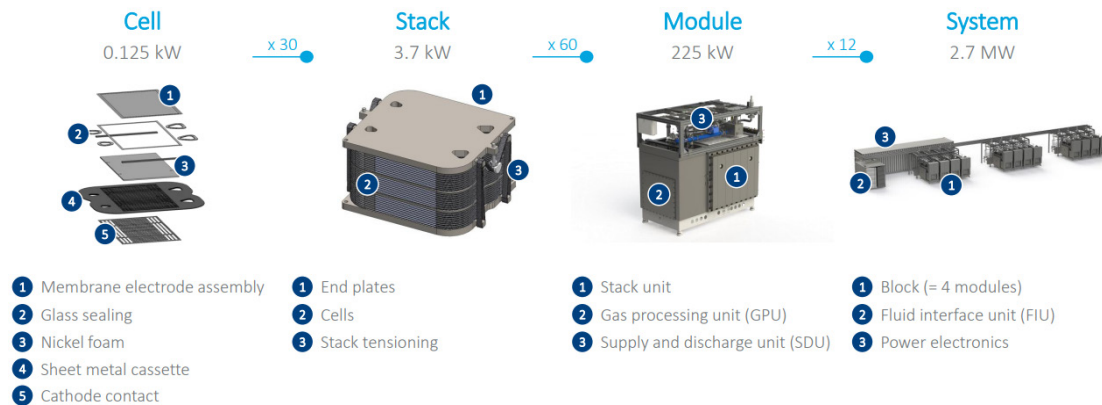


Figure 2.10. Built-up of SOEC cell, stack, module, and system, exemplified by Sunfire.¹

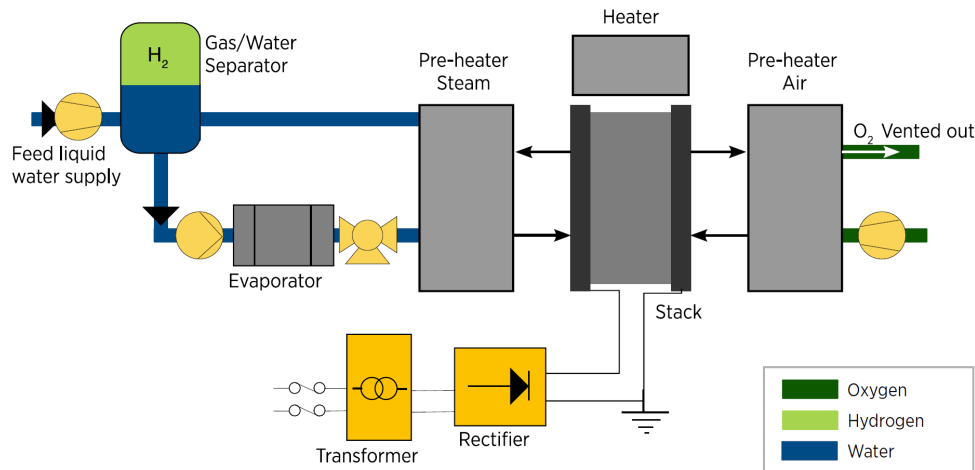


Figure 2.11. Generic configuration of a basic SOEL system.²

SOECs are typically operated at 80-90% steam utilization, leaving 10-20 % steam left in the produced hydrogen that needs to be separated out. Furthermore, 10-20 % of hydrogen is recirculated in the system and supplied at the stack inlet to avoid oxidation of the Ni-based fuel electrode. Air is used as a sweep gas on the anode side of the cell to aid with temperature control of the stack and avoid challenges with handling of pure oxygen at high temperature. In addition, an air sweep decreases performance degradation caused by leakage of H₂ from the cathode to the anode and slightly improves performance by lowering the OCV. However, the oxygen produced during electrolysis is a potentially valuable by-product in certain applications and the challenges with handling pure oxygen are manageable. NASA has developed a SOEC for Mars missions with primary purpose to produce pure oxygen from electrolysis of CO₂.³

¹ O. Posdziech, Production of Renewable Hydrogen and Syngas Via High-Temperature Electrolysis, Multiplhy project workshop, 08/09-03-2021.

² IRENA: Green Hydrogen Cost Reduction (2020).

³ J. Hartvigsen, S. Elangovan, L. Frost, MOXIE Development Driven Prospects for ISRU and Atmosphere Revitalization, 48th International Conference on Environmental Systems, Albuquerque, New Mexico (July 2018).

2.1.3. Commercially Available Electrolyser Units

a) Alkaline Electrolysis Systems

The size of commercial AWE systems ranges from 50 kW to 6 MW, although larger units, up to 20 MW plants are being offered as commercially available products. The energy consumption for these MW systems ranges from 3.8 to 5.4 kWh/Nm³. However, alkaline stacks are normally operated at much lower current densities (mostly in the range of 0.2-0.6 A/cm²) and thus slightly higher overall system efficiencies compared to other electrolyser technologies. Table 2.1 shows an overview (non-exhaustive) of alkaline electrolysis companies and the size, power, temperature, pressure, and efficiency of their electrolyser products.

Table 2.1. Overview of major AWE manufacturers and technical specifications.¹

Manufacturer (location)	Series	H ₂ rate, Nm ³ /h	Nominal Power, MW	Max Pressure, bar	Stack: Energy consumption kWh/Nm ³	Load flexibility, %
ELB (DE)	LURGI SE	1400	6	30	4.3-4.65	25-100
Suzhou Jingli (CN)	DQ 1000	1000	4.7	16	4.7	10-110
Verde (US)	Verde - 1000	1000	4.5	30	4.2	n.a.
IHT (CH)	S-556	760	3.5	32	4.3-4.65	25-100
PERIC (CN)	zdQ-600	600	2.8	15	4.6	n.a.
NEL Hydrogen (NO)	NEL A485	485	2.1	atm.	3.8-4.4	20-100
ELB (DE)	ELB ND4	480	2	atm.	4.3-4.6	25-100
Teledyne (US)	NH - 450	450	2.7	10	(5.9)	17-100
McPhy (US)	McLyzer	400	2	atm.	n.a.	n.a.
Tianjin Mainland (CN)	FDQ - 400/3.0	400	1.76	30	< 4.4	n.a.
Ener Blue (CH)	L-size	375	1.6	60	4.3	n.a.
ELB (DE)	BAMAG S300E	330	1.5	atm.	4.7	25-100
Uralhimmich (RU)	BEU - 250	250	n.a.	10	n.a.	n.a.
HT-Hydratechnik (DE)	EV 150	220	1.1	atm.	5.3	20-100
Uralhimmich (RU)	FV - 200	200	n.a.	atm.	n.a.	n.a.
McPhy (US)	McLyzer	100	0.5	45	n.a.	n.a.
Idroenergy (JT)	Model 120	80	0.4	6	5.6	n.a.
Green Hydrogen (DK)	HyProvide a60	60	0.25	30	4.2	15-100
Etogas (DE)		62.5	0.3	15	4.8	10-110
ErreDue (IT)	G256	21	0.11	30	5.4	20-100
Hydrogenics (CA)	HySTAT-100-10	15	0.08	10(25)	5.2	40-100
Sagim (FR)	M 5000	5	0.03	7	5	n.a.
Linde AG (DE)	HYDROSS	n.a.	n.a.	25	n.a.	25-100

¹ Adapted from A. Buttler and H. Spliethoff. Renewable and Sustainable Energy Reviews 82 (2018) 2440-2454. <https://doi.org/10.1016/j.rser.2017.09.003>

b) PEM Electrolysis Systems

MW-scale stacks are offered by Giner, Hydrogenics, Siemens, and ITM. Today's PEM electrolyzers are most commonly below 10 MW, although PEM systems ≥ 10 -20 MW even 100 MW (ITM in REFHYNE¹ EU project) and 200 MW (SHELL²) are being planned. The energy consumption for these MW systems ranges from 4.8 to 5.5 kWh/Nm³. However, PEM stacks are normally operated at much higher current densities (mostly in the range of 1.5-2 A/cm²) and thus slightly lower overall system efficiencies compared to other electrolyser technologies. Table 2.2 contains a list (non-exhaustive) of commercial manufacturers of PEM water electrolyzers and the technical details of their stacks.

Table 2.2. Overview of major PEMWE commercial manufacturers and technical specifications.³

Manufacturer (location)	Series	H ₂ rate, Nm ³ /h	Nominal Power, MW	Max Pressure, bar	Stack: Energy consumption, kWh/Nm ³	Load flexibility, %
Giner Inc. (US)	Allagash	400	2	40	5	n.a.
Hydrogenics (CA)	HyLYZER-3000	300	1.5	30	5-5.4	1-100
Siemens (DE)	SILYZER 200	225	1.25	35	5.1-5.4	0-160
Proton OnSite (US)	M400	50	0.25	30	5	0-100
ITM Power (GB)	HGA / MEP / GEP	127-1000*	0.7-5*	20-80	5.5	n.a.
AREVA H2Gen (FR)	E120	30	0.13	35	4.4	10-150
H-TEC (DE)	ELS450	14.1	0.06	30/50	4.5	n.a.
Angstrom Advanced (US)	HGH170000	10	0.06	4	5.8	n.a.
Kobelco Eco-Solutions (JP)	SH/SL60D	10	0.06	4-8	5.5-6.5	0-100
Sylatech (DE)	HE 32	2	0.01	30	4.9	n.a.
GreenHydrogen (DK)	HyProvide P1	1	0.01	50	5.5	n.a.
Hystar	Vega, Mira	226-1255*	0.9-5.5*	4	4.1-4.4	15-110

* System level

c) Solid Oxide Cell Technology

The major commercial manufacturers of solid oxide cell components and systems are listed in Table 2.3. Some of the manufacturers listed primarily work with solid oxide fuel cells but are included in the overview as their cells/stacks in principle also can be operated in solid oxide electrolysis mode.

¹ <https://refhyne.eu/refhyne-2/>

² Shell to start building Europe's largest renewable hydrogen plant ([LINK](#))

³ Adapted from A. Buttler and H. Spliethoff. Renewable and Sustainable Energy Reviews 82 (2018) 2440-2454. <https://doi.org/10.1016/j.rser.2017.09.003>

Table 2.3. Overview of major commercial manufacturers of solid oxide cell components and systems.

Company	Commercial product(s)	Operating mode*	Cell and stack type	Operating T / °C
Ceres Power	Stacks	SOFC	Metal-supported, planar	500-600
Sunfire	RSOC, μ -CHP, SOEC	SOFC, SOEC, Reversible	Electrolyte-supported, planar	~850
SOLIDpower	μ -CHP,	SOFC	Fuel electrode supported, planar	~750
Haldor Topsoe	CO ₂ electrolysis system ("eCOs")		Fuel electrode supported, planar	~750
Bloom Energy	SOFC, SOEC systems	SOFC, SOEC		
Elcogen	Cells and stacks		Fuel electrode supported, planar	600-750
Kyocera	μ -CHP	SOFC	Flat tubular	700-750
Sylfen	rSOC	rSOC	*Stacks from Elcogen	
OxEon energy	CO ₂ electrolysis	SOEC, SOFC, rSOC	Electrolyte supported, planar	
Saint Gobain		SOFC (developing for SOEC)	All-ceramic monolith	
Toshiba			Current: Tubular, Future: planar	

An overview of technical specifications for the commercial electrolyser systems/stacks is given in Table 2.4. Note that these are data as reported by the manufacturer and that some of them specify larger systems than have been demonstrated to date.

Table 2.4. Data from commercial SOEC manufacturers taken from technical datasheets.

Technical parameter	HTAS	Sunfire Hylink	Bloom Electrolyser	OxEon
Net production rate (Nm ³ /h)	32 000	750	87	~0.5 kg/h
Power rating (kW)	100 000	2 680	360 (module)	18 kWe
Dynamic range capacity (%)	10..100	5..100	20..100	
Hot idle ramp time		< 10 min	6	
Specific power consumption – stack, DC (kWh/Nm ³ H ₂)	3.1	3.3	n.a.	n.a.
Specific power consumption – system, AC (kWh/Nm ³ H ₂)	Depends on heat integration and pressure needed	3.6*	4.1 / 3.5 with external steam supply @120°C	n.a.
Steam input (kg/h)	27 000	860	103	~4.5 kg/h
Footprint (m ²) (kW/m ²)	8 400 (12)	300 (8.9)	5.02 (71)	10x10 cm cells

* At ambient pressure, LHV of H₂ referred to AC input.

2.1.4. Largest electrolyser demonstration projects of FCH 2 JU¹

1. HYBALANCE (2014): 1.25 MW PEM (operating) providing hydrogen to a light metal industry, including electricity grid balancing, Hobro, Denmark.
2. DEMO4GRID (2016): 3 MW alkaline for hydrogen provision to a food industry where hydrogen will be combusted displacing natural gas in an oil boiler, Völs, Austria.
3. H2FUTURE (2016): 6 MW PEM installed and operating since late 2019 in a steel plant in Linz, Austria.
4. REFHYNE (2018): 10 MW pressurised PEM to be installed at Shell's Cologne refinery, Germany.
5. HAEOLUS (2018): 2.5 MW PEM to be installed at a remote wind farm in Varanger, Norway.
6. DJEWELS (2019): 20 MW pressurised AWE to be installed at Nobian's Delfzijl site in the Netherlands.
7. MULTIPLHY (2019): 2.6 MW SOEL to be installed at NESTE's Rotterdam biorefinery, Netherlands.
8. REFHYNE2 (2021): 100 MW pressurised PEM to be installed at Shell's Cologne refinery, Germany.

2.1.5. Advantages and Disadvantage of water electrolysis technologies

Some typical pros and cons by water electrolysis technology are summarized in Table 2.5.

Table 2.5. General overview of advantages and disadvantages by water electrolysis technology.²

Technology	AWE	AEMWE	PEMWE	SOEC
Advantages	Inexpensive catalysts & materials Mature technology (TRL 9) Low-cost production High lifetime Impurities' tolerance Low CAPEX	Inexpensive catalysts (PGM-free) Inexpensive materials (CRM-free) No electrolyte leakage High H ₂ purity High current densities Compact design Low CAPEX Low OPEX	Low minimal load Relative mature (TRL 7-9) High flexibility Rapid power-up /power-down rate High H ₂ purity Compact design High current densities operation Low OPEX High compatibility with renewable energy sources	Low minimal load Inexpensive catalysts High efficiency Low OPEX
Disadvantages	Low flexibility Low H ₂ purity Slow start-up Electrolyte leakage Corrosion Low current densities Bulky stack design High OPEX	Low maturity (TRL 2-5) Medium lifetime High minimal load Sensitivity to CO ₂ Membrane lifetime Small size system available	High-cost catalysts (PGMs group) High-cost materials/coatings (Ti & Pt-based) PFSA membranes Difficulty to replace PGMs (Pt/Ir) High CAPEX	Relative low maturity (TRL 5-7) Low production available High operating temperatures Bulky design High CAPEX

¹ http://cordis.europa.eu/project/rcn/199464_en.html (2) http://cordis.europa.eu/project/rcn/207243_en.html (3) <https://cordis.europa.eu/project/rcn/207465/en.html> (4) <https://cordis.europa.eu/project/id/779579> (5) <https://cordis.europa.eu/project/id/779469> (6) <https://cordis.europa.eu/project/id/826089> (7) <https://cordis.europa.eu/project/id/875123> (8) <https://cordis.europa.eu/project/id/101036970>

² Adapted from A. Patonia and R. Poudineh. Cost competitive green hydrogen: how to lower the cost of electrolyzers? OIES (2022)

As shown in Table 2.5 there is no specific electrolyser technology outperforming the rest across all the features essential for effective production of green hydrogen. Nevertheless, currently, due to their maturity, both AWE and PEMWE technologies will draw the main attention, although further R&D of AEMWE and SOEL will bring those currently less mature technologies as alternative solutions in the future. The future technology mix will depend on innovation and competition among key technologies and manufacturers, leading to technological improvements and a better fit for different technologies and system designs in each specific application.¹

3. State-of-the-art and KPIs for Renewable Hydrogen Production

According to the International Energy Agency's Net Zero by 2050 report, achieving global net-zero emissions by 2050 would require producing around 306 million tonnes of green hydrogen from renewable energy sources each year. This would also require a global electrolyser capacity of ca. 3,600 GW. To achieve these ambitious production targets, stringent technology targets and key performance indicators (KPIs) have been implemented.

3.1. Fuel Cell and Hydrogen Joint Undertaking – Multi-Annual Work Plan 2014 – 2020

The state-of-the-art (2012) and future targets for hydrogen production from renewable electricity for energy storage and grid balancing set by the FCH JU in the MAWP² are summarized in the following table:

		State-of-the-art	2017	2020	2023
KPI 1	H2 production electrolysis, energy consumption (kWh/kg) @ rated power	57-60 @100kg/d	55 @500kg/d	52 @1000+kg/d	50 @1000+kg/d
KPI 2	H2 production electrolysis, CAPEX @ rated power including ancillary equipments and comissioning	8.0 M€/t/d	3,7 M€/t/d	2.0 M€/t/d	1.5 M€/t/d
KPI 3	H2 production electrolysis, efficiency degradation @ rated power and considering 8000 H operations / year	2% - 4% / year	2% / year	1,5% / year	<1% / year
KPI 4	H2 production electrolysis, flexibility with a degradation < 2% year (refer to KPI 3)	5% - 100% of nominal power	5% - 150% of nominal power	0% - 200% of nominal power	0% - 300% of nominal power
KPI 5	H2 production electrolysis, hot start from min to max power (refer to KPI 4)	1 minute	10 sec	2 sec	< 1 sec
	H2 production electrolysis, cold start	5 minutes	2 minutes	30 sec	10 sec

Haeolus project based its targets on the FCH 2 JU MAWP. Those 2023 KPIs are general technical goals to be fulfilled by all water electrolysis technologies. These setting might be difficult to reach by some

¹ IRENA: Green Hydrogen Cost Reduction (2020).

² Fuel Cells and Hydrogen Joint Undertaking Multi Annual Work Plan 2014-2020
https://ec.europa.eu/research/participants/data/ref/h2020/other/legal/itis/fch-multi-workplan_en.pdf

of the technologies especially those less mature. In that sense, the Clean Hydrogen JU defined KPIs accordingly to the water electrolysis technology. Common KPIs are only those related to flexible electrolyser operation as can be seen further below.

For renewable hydrogen production via water electrolysis, the key objectives¹ for realising the 2030 vision are:

1. Reducing electrolyser CAPEX and OPEX.
2. Improving dynamic operation and efficiency, with high durability and reliability, especially when operating dynamically.
3. Increasing current density and decreasing footprint.
4. Demonstrate the value of electrolysers for the power system through their ability to provide flexibility and allow higher integration of renewables.
5. Ensure circularity by design for materials and for production processes, minimising the life-cycle environmental footprint of electrolysers.
6. Increasing the scale of deployment.
7. Improved manufacturing for both water and steam electrolysis.

In the follow, the KPIs for renewable hydrogen production set by the Clen Hydrogen JU are presented.

3.2. Clean Hydrogen Joint Undertaking – Strategic Research and Innovation Agenda 2021 – 2027

3.2.1. KPIs for Alkaline Water Electrolysis (AWE)

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Electricity consumption @ nominal capacity	kWh/kg	50	49	48
2	Capital cost	€/ (kg/d)	1,250	1,000	800
		€/kW	600	480	400
3	O&M cost	€/ (kg/d)/y	50	43	35
4	Hot idle ramp time	sec	60	30	10
5	Cold start ramp time	sec	3,600	900	300
6	Degradation	%/1,000h	0.12	0.11	0.1
7	Current density	A/cm ²	0.6	0.7	1.0
8	Use of critical raw materials as catalysts	mg/W	0.6	0.3	0.0

¹ Clean Hydrogen Joint Undertaking. Strategic Research and Innovation Agenda (SRIA) 2021 – 2027.

3.2.2. KPIs for Anion Exchange Membrane Water Electrolysis (AEMWE)

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Electricity consumption @ nominal capacity	kWh/kg	55	53	48
2	Capital cost	€/(kg/d)	2,250	1,200	600
		€/kW	1,000	550	300
3	O&M cost	€/(kg/d)/y	34	27	21
4	Hot idle ramp time	sec	30	15	5
5	Cold start ramp time	sec	1,800	450	150
6	Degradation	%/1,000h	> 1.0	0.9	0.5
7	Current density	A/cm ²	0.5	0.6	1.5
8	Use of critical raw materials as catalyst	mg/W	1.7	0.4	0

3.2.3. KPIs for Proton Exchange Membrane Water Electrolysis (PEMWE)

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Electricity consumption @ nominal capacity	kWh/kg	55	52	48
2	Capital cost	€/(kg/d)	2,100	1,550	1,000
		€/kW	900	700	500
3	O&M cost	€/(kg/d)/y	41	30	21
4	Hot idle ramp time	sec	2	1	1
5	Cold start ramp time	sec	30	10	10
6	Degradation	%/1,000h	0.19	0.15	0.12
7	Current density	A/cm ²	2.2	2.4	3
8	Use of critical raw materials as catalysts	mg/W	2.5	1.25	0.25

3.2.4. KPIs for Solid Oxide Electrolysis (SOEL)

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Electricity consumption @ nominal capacity	kWh/kg	40	39	37
	Heat demand @ nominal capacity		9.9	9	8
2	Capital cost	€/(kg/d)	3,550	2,000	800
		€/kW	2,130	1,250	520
3	O&M cost	€/(kg/d)/y	410	130	45
4	Hot idle ramp time	sec	600	300	180
5	Cold start ramp time	h	12	8	4
6	Degradation @ U _{TN}	%/1,000h	1.9	1	0.5
7	Current density	A/cm ²	0.6	0.85	1.5
8	Roundtrip electrical efficiency	%	46	50	57
9	Reversible capacity	%	25	30	40

3.2.5. KPIs for Flexible electrolyser operation

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Ramp duration	sec	18	18	10
2	Stability	%	2.9	2.5	2.5
3	Ramp precision	%	1.9	0	0
4	Reliability	%	90	99	99

The production of renewable hydrogen by coupling VRES to electrolyzers put demanding requirements on the capability of the electrolyzers. In the follow it will overview the different KPIs (FCH2JU MAWP), to assess the technical progress of the AWE, PEMWE and SOEL as main technologies towards green hydrogen generation.

4. KPI 1: Energy consumption

4.1. Theoretical efficiency

Splitting a mole of liquid water to produce a mole of hydrogen at 25°C requires 285.8 kJ (High Heating Value, HHV) of energy (237.2 kJ as electricity and 48.6 kJ as heat). The energy demand for electrolysis is given by the enthalpy (ΔH) of the water splitting reaction:

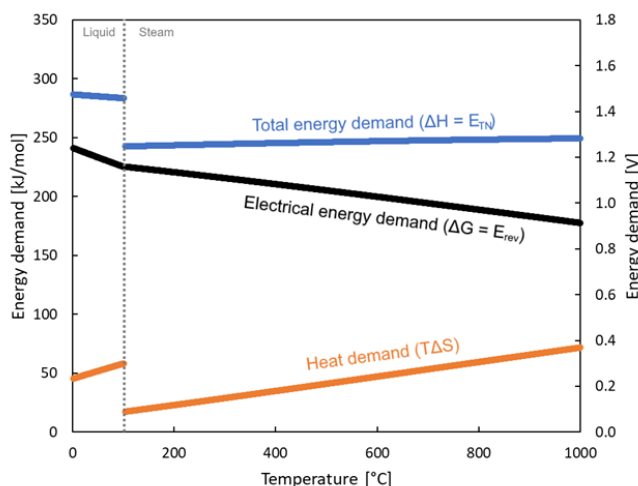
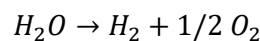


Figure 4.1. Energy demand for electrolysis of water and steam as function of temperature.¹

Figure 4.1 shows the total energy demand as a function of temperature. The total energy demand is nearly independent of temperature while the electrical energy demand (Gibbs' energy, ΔG) decreases, and the heat demand (enthalpy, $T\Delta S$) increases as the temperature increases. This means that at high operating temperatures, a greater amount of the required energy can be supplied as heat. Thus, high temperature electrolysis has an inherent thermodynamic benefit over low temperature electrolysis, especially for applications where steam is available.

¹ Buttler, A. and Spliethoff, H. (2018). Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews*, 82, 2440-2454.

Some of the required heat will be generated by the cell due to the resistance of the passing current (Joule heating). The cell voltage at which the heat generated by the cell is equal to the heat demand by the reaction is the so-called thermoneutral voltage and is given by:

$$E_{TN} = \frac{\Delta H}{nF}$$

Where ΔH is the equal to the entropy of the reaction, n is the number of electrons transferred ($=2$) and F is Faraday's constant.

In PEM and alkaline electrolysis cells the heat requirement is supplied from the extra heat generated, due to internal resistance as the electric and ionic currents flow through the cell. This heat requirement is directly traceable back to the electricity supplied. In other words, 285.8 kJ (not 237.2 kJ) of electricity is the minimum required to split water in these cells. This translates into a cell voltage of 1.481 V. The thermoneutral voltage is nearly invariant with temperature and equal to ca. 1.291 V for electrolysis of steam and 1.481V for electrolysis of liquid water.

A cell operated below this so-called thermoneutral voltage will cool down during operation, while a cell operated above the thermoneutral voltage will generate excess heat. The thermoneutral voltage of 1.291 V corresponds to an energy demand of ca. 34.5 kWh/kg H_2 , which can be taken as the theoretically maximum efficiency for electrolysis of steam. For electrolysis of water the minimum energy demand is ca. 39 kWh/kg H_2 .

As seen in Figure 4.1, the total energy demand is significantly reduced (5.6 kWh/kg) when the reactant is steam instead of liquid water. Therefore, SOEL systems have huge efficiency benefit in applications where steam is readily available. On the other hand, low temperature electrolyzers require to be operated above the thermoneutral voltage because of overvoltage (activation overvoltage, ohmic resistance and concentration overvoltage). As a result, excess heat is produced, needing external cooling.

The thermoneutral voltage is also the voltage that corresponds to the High Heating Value (HHV) of hydrogen. It is used when calculating cell and stack voltage efficiency. A similar calculation can be performed for water vapor using the Low Heating Value (LHV). The thermoneutral voltage for splitting water vapor at 25 °C is 1.253 V. In the case of global system efficiency, however, both the electrical input and the heat input from the external source must be included.

Electrolyser manufacturers appear to have standardized on kWh/Nm³ or kWh/kg as a measure of system efficiency, which sidesteps the LHV versus HHV controversy. It is worth stating that the highest attainable efficiency is 83% (ratio of reversible free energy potential (1.229 V) over the thermoneutral voltage (1.481 V)) when referencing electrolyser system and stack efficiencies to the LHV.

Alkaline Water Electrolysis (AWE)

According to a market survey published by Buttler and Spliethoff in 2018¹, commercial alkaline electrolysis stacks have rated efficiency in the range of 63-71 % LHV and specific energy consumption

¹ Buttler, A. and Spliethoff, H. (2018). Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews*, 82, 2440-2454.

of 4.2-4.8 kWh/Nm³ of H₂. When considering the system comprehensive of rectification and utilities (compression excluded), η_{LHV} decreases to 51-60 % and the energy consumption increases to 5.0 to 5.9 kWh/Nm³ of H₂ produced. See Figure 4.2 for a summary of the AWE IU curves from literature.

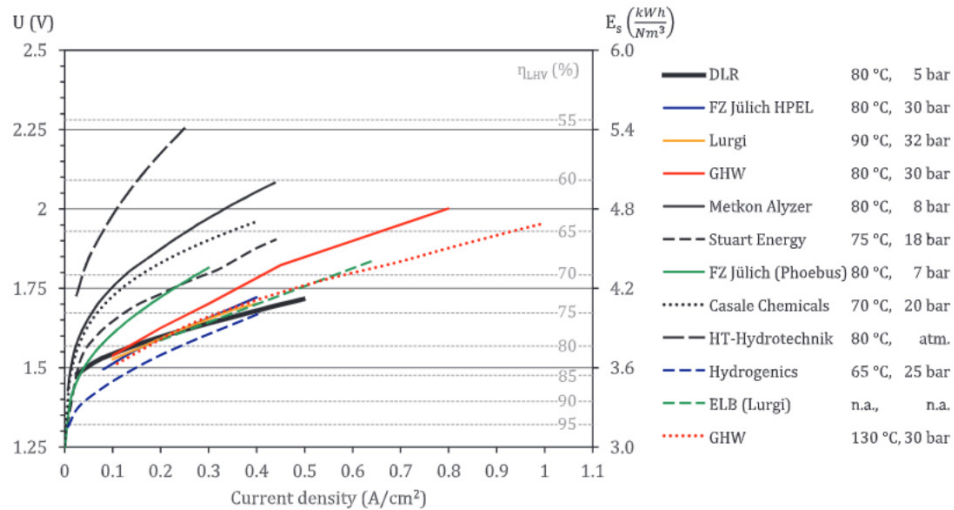


Figure 4.2 AWE IU curves and specifics (manufacturer and operating temperature and pressure).¹

Performance gains for system efficiencies appear to be limited beyond a system size of approximately 100-300 kW (Figure 4.3). This is most likely due to the modularity of systems above a certain size. Based on the data currently publicly available from the manufacturers, the state-of-the-art performance by alkaline electrolyzers is ~50 kWh/kg. These values correspond almost exactly to the FCH 2 JU target for 2020.²

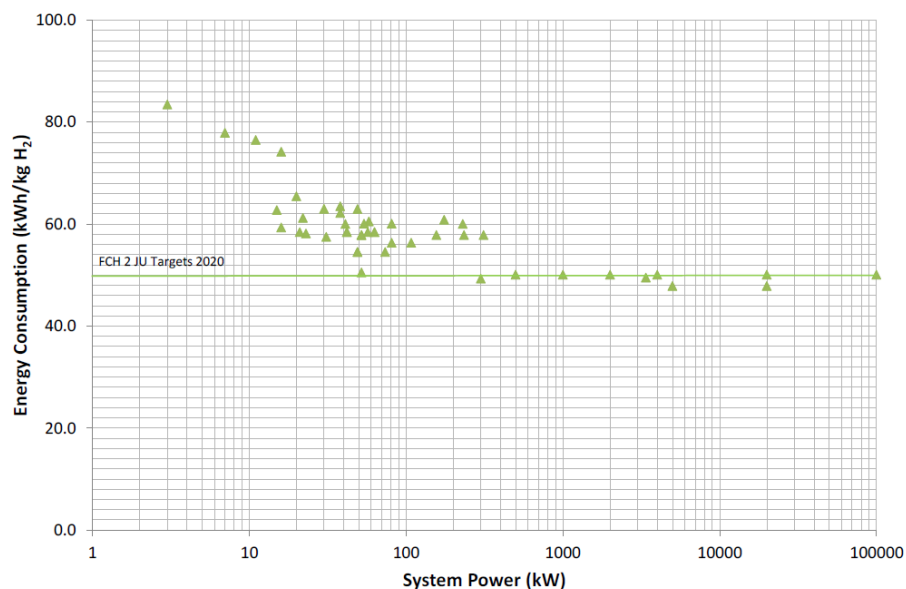


Figure 4.3 Energy Consumption vs. System Power for commercially available alkaline electrolyzers.²

¹ Buttler, A. and Spliethoff, H. (2018). Renewable and Sustainable Energy Reviews, 82, 2440-2454.

² Davies J, Dolci, F., and Weidner, E. (2021) Historical Analysis of FCH 2 JU Electrolyser Projects. JRC Technical Report.

According to relevant projects (HARI: 36 kW electrolyser, maximum compression at 137 bar; Res2H2: 25 kW electrolyser, maximum compression at 220 bar), the overall efficiency of AWE including compression is approximately 50% at HHV ($\eta_{LHV} = 42\%$).^{1,2} Note that the HARI project had poor rectifier efficiency of 72–89%. Power-to-Gas project reported a total efficiency of 53 % in LHV at full load operation and a slightly increased 55 % at minimum load, with 10 bar hydrogen pressure and all auxiliaries.³ The efficiency of the rectifier in Power-to-Gas project was 94.6% at full load and 98% at minimum load.

The stack efficiency is very dependent by the operating temperature. In an alkaline electrolyser, an increase of 10 °C results in decrease of 0.01-0.1 V (0.02–0.24 kW h/Nm³) in cell voltage (specific energy consumption). However, at higher temperatures the heat-derived increase in efficiency is reduced.

PEM Water Electrolysis (PEMWE)

PEMWE stacks have efficiencies between 60 and 68% LHV and specific energy consumption of 4.4-5.0 kWh/Nm³.⁴ At the system level, similar as for alkaline electrolysis stacks, η_{LHV} decreases to 46-60% and the energy consumption increases to 5.0 to 6.5 kWh/Nm³ of H₂ produced. It is also to be noted that smaller systems in general (alkaline as well), typically below 0.5 MW, reported lower efficiencies. Figure 4.4 shows a series of I-U curves realized with stacks of different manufacturers. Most of them are capable to operate between 1 and 2 A/cm², and at 2 A/cm² the presented voltages recorded vary between 1.65V and 2.5V, where alkaline electrolyzers can only achieve up to 1 A/cm² (Figure 4.2).

As for alkaline electrolyzers, performance gains appear to be limited beyond a system size of approximately 100-300 kW (Figure 4.5). This is again most likely due to the modularity of systems above a certain size. The current state-of-the-art for PEM electrolyzers is ~55 kWh/kg at larger system sizes, which corresponds almost exactly to the FCH 2 JU target for 2020.⁵

In the DonQuichote project⁶, the employed PEM stack (Hydrogenics) had specific consumption (DC) of 4.47 kWh/Nm³ (50 kWh/Kg) operated with an output of 30 Nm³/h. The consumption of the system (when considering utilities, rectification, and compression to 450 bar) was 5.25 kWh/Nm³ (59 kWh/Kg).

The Siemens PEM electrolysis system used at Energiepark Mainz⁷ showed optimal efficiency (4.7 kWh/Nm³) when operated at 27% of the rated power and decreased efficiency at peak total power (6.2 MW) up to 6.1 kWh/Nm³ (68 kWh/kg).

Increased efficiency can be achieved in low-temperature electrolysis systems with utilization of waste heat and integration of the produced oxygen. They have been showcased in the Stromlückenfüller project⁸ (stack by H-TEC) and in the BioCat project⁹ (AWE by Hydrogenics), respectively.

¹ Gammon R, Roy A, Barton J, Little M. Case Study - Hydrogen and Renewables Integration (HARI): IEA-Hydrogen Implementing Agreement; 2006.

² Mentado D, Ramirez P, Suarez S, Piernavieja G RES2H2–2007 Final technical report; 2008

³ Zuberbühler U, Specht M, Stürmer B, Brinner A, Brellochs J, Feigl B. et al. Verbundprojekt Power-to-Gas - Errichtung und Betrieb einer Forschungsanlage zur Speicherung von erneuerbarem Strom als erneuerbares Methan im 250 kW_{el} Maßstab. Schlussbericht zum Teilvorhaben; 2014.

⁴ Buttler, A. and Spliethoff, H. (2018). Renewable and Sustainable Energy Reviews, 82, 2440-2454.

⁵ Davies J, Dolci, F., and Weidner, E. (2021) Historical Analysis of FCH 2 JU Electrolyser Projects. JRC Technical Report.

⁶ Vaes J. Field Experience with Hydrogenics' Prototype Stack and System for MW PEM electrolysis. Freiburg, Germany

⁷ Schönberger D. P2G durch Elektrolyse – eine flexible Speicherlösung. Zürich; 2016

⁸ Joule GP. Stromlückenfüller. 2017. https://www.gpioule.de/fileadmin/Content/Downloads/DE/Produktblaetter/Stromlueckenfueller_DE.pdf

⁹ Thomas D. Electrolyzer technology of the BioCat project. Copenhagen; 2016

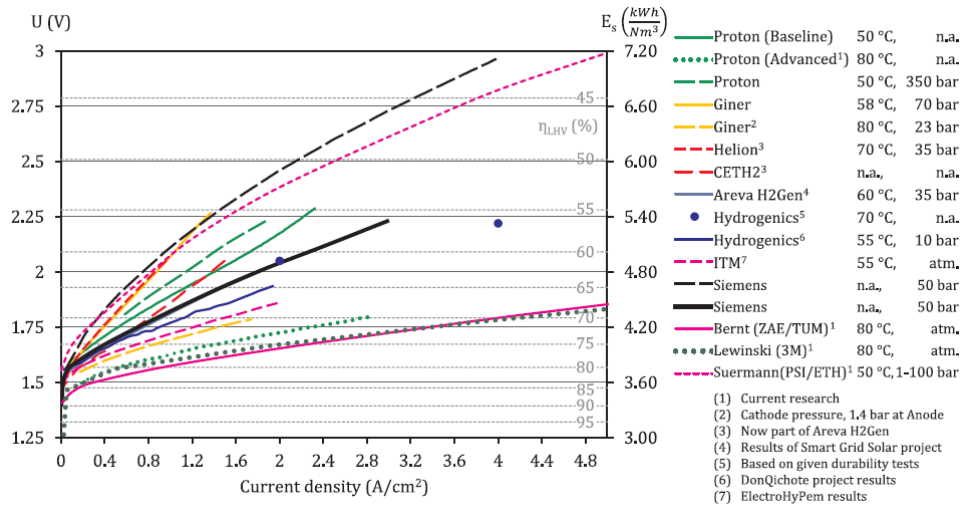


Figure 4.4. PEMWE I-U curves and specifics (manufacturer and operating temperature and pressure).¹

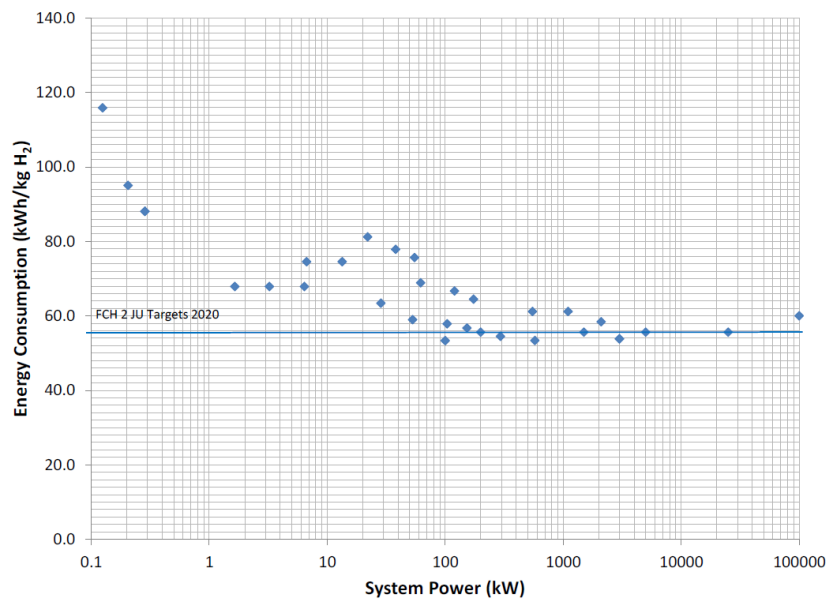


Figure 4.5 Energy Consumption vs. System Power for a range of commercially available PEM electrolyzers.²

Solid Oxide Electrolysis (SOEL)

At the stack level, the maximum efficiency of SOEL is limited by the steam utilization (SU), which is defined as the percentage of steam supplied to the stack inlet that is converted to hydrogen at the stack outlet. The SU is limited to 80-90% to avoid localized steam starvation caused by variations in local current density (due to temperature variations). Furthermore, the efficiency depends on the operating current density or cell voltage. Increasing the current density increases the resistance and therefore the specific energy consumption per kg of produced hydrogen, as illustrated in Figure 4.6. The efficiency is higher at higher operating temperature because of improved conductivity in the

¹ Buttler, A. and Spliethoff, H. (2018). Renewable and Sustainable Energy Reviews, 82, 2440-2454.

² Davies J, Dolci, F., and Weidner, E. (2021) Historical Analysis of FCH 2 JU Electrolyser Projects. JRC Technical Report.

electrolyte. Despite the higher power consumption, it is desirable to operate the stacks at a higher current density to reduce necessary cell area and thus CAPEX costs.

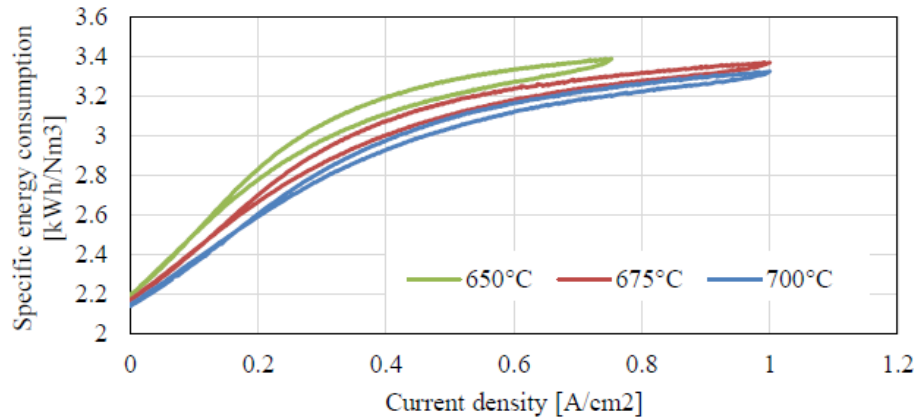


Figure 4.6. Specific energy consumption for Elcogen stack.¹

On the system level, the efficiency is further reduced due to heat losses to the surroundings (1-3 %), power consumption by the compressors/blowers and gas separation units, and power losses in the inverter (3-5 %). The overall efficiency will depend on whether the system is fed with steam at high temperature, or water that needs to be evaporated and heated. The output pressure of the produced H₂ also influences efficiency (lower efficiency for higher output pressure).

Sunfire reports 84 % overall system efficiency (LHV to AC) with an input of steam at 150 °C, corresponding to a power consumption of 38 kWh/kg H₂.² The efficiency is projected to increase to 88 % by 2030, through improvements in the system efficiency. Bloom Energy reports system specific power consumption of 39 kWh/kg H₂ with an input of steam at 120 °C.³

Note that the efficiency values are typically reported for operation close to thermoneutral, which requires operation under steady-state conditions. For dynamic operation of the system (varying load/production rate), the electricity consumption will be higher as a higher air flow will be needed to maintain a constant temperature in the stack, requiring higher power consumption by blowers/compressors. Efficiency improvements may be possible by designing better operational control strategies.

4.2. Pathway towards reaching KPI 1 targets

Alkaline Water Electrolysis (AWE)

Below are brief explanations on some of the strategies for efficiency improvement in AWE system.

¹ T. Lehtinen, M. Noponen, Solid Oxide Electrolyser Demonstrator Development at Elcogen, ECS Trans. 103 (2021) 1939–1944.
<https://doi.org/10.1149/10301.1939ecst>

² O. Posdziech, K. Schwarze, J. Brabandt, Efficient hydrogen production for industry and electricity storage via high-temperature electrolysis, Int. J. Hydrog. Energy. 44 (2019) 19089–19101. <https://doi.org/10.1016/j.ijhydene.2018.05.169>

³ https://www.bloomenergy.com/wp-content/uploads/Data-Sheet_Bloom-Electrolyzer-10-MW_UPDATED-6.24.22.pdf

Increase current densities: The current densities of the stacks can be increased from 0.5 A/cm² up to 2-3 A/cm² at a cost of lower efficiency.¹ Some manufacturers have accomplished higher current densities as high as 1.2 A/cm² at 2 V. Power densities of 2-3 W/cm² were achieved by using thinner diaphragms/membranes. Still, to catch up with PEMWE, AWEs need improvement in voltage efficiency by optimizing ohmic losses and electrode kinetics.

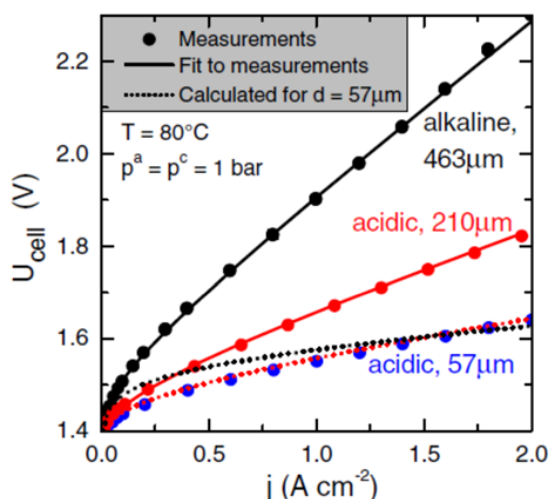


Figure 4.7. Relationship between voltage (inversely proportional to efficiency) and current density (proportional to the production volume) for various diaphragm thickness in AWE.²

Thinner diaphragm or membrane: This strategy would improve efficiency and therefore reduce electricity consumption. Thinner diaphragms experience lower resistance to transporting the OH⁻ species. However, this often comes at the penalty of increased gas permeation that leads to higher safety concerns. Moreover, mechanical robustness can be an issue for a thin diaphragm, with a risk of pinhole formation. Nevertheless, the diaphragm thickness needs approach those of PEM and AEM for better performance. The current diaphragm thickness of AWE is about 460 μm. Thickness reduction down to 50 μm would improve the efficiency from 53 % to 75 % at 1 A/cm² (Figure 4.7).

Novel catalyst compositions and electrode architecture: AWE have traditionally encountered multiple challenges in moving away from the archaic electrode designs and therefore been limited from reaching sufficiently higher efficiencies for both cathode and anode reactions.

Simply increasing the surface area of the catalyst has been achieved with the traditional Raney-Ni catalysts (nickel-aluminium [Ni-Al], nickel-zinc [Ni-Zn]) and is considered an easy challenge. The rest of the challenge points however are considered relatively moderate or difficult as any novel concept needs to meet the long-term durability and low-cost level of the current nickel-coated stainless steel perforated sheets. For this very reason, Raney-Ni electrodes have been limited for large scale electrodes in commercial use due to its low mechanical robustness and costly manufacturing techniques.

Novel PTL concepts: AWEs need to efficient PTLs with resolved mass transport limitations (such as gas bubble resistance, trapping inside the PTLs) and alternative protective coating for reduced interfacial resistances on the anode. PTL integrated with the electrode and the membrane could be the long-term goal to fulfil the aforementioned tasks.

¹ IRENA: Green Hydrogen Cost Reduction (2020).

² Schalenbach, M. et al. (2016), Acidic or alkaline? Towards a new perspective on the efficiency of water electrolysis, Journal of the Electrochemical Society, 163/11, pp. F3197.

PEM Water Electrolysis (PEMWE)

The strategic areas identified for improvement of PEM electrolysis efficiency are:

- 1) Reducing membrane thickness will increase efficiency. Nafion N117 (180 μm thick) causes loss of 25% (at 2 A/cm^2) of efficiency. Commercially available thinner membranes (e.g., 20 μm) would reduce the efficiency losses to 6 % (at 2 A/cm^2). Membrane thickness below 5 μm does no longer produce desirable effects. However, thinner membranes imply lower durability since they have decreased mechanical strength and will more easily for pinholes. Especially during differential pressure operation, the mechanical stress could lead to delamination of the CCMs.
- 2) Improving PTLs for good support of thin membranes and avoid creep failure.
- 3) Pt coated PTLs on the anode side prevent oxidation of the underlaying titanium and decrease the interface resistance, hence improving electrical efficiency. PTL's interface resistance takes up 4 % of hydrogen LHV.^{1,2}
- 4) Mitigate poisoning of the membrane by contaminants.
- 5) Integration of recombination catalysts to react gases permeated through crossover.³

Solid Oxide Electrolysis (SOEL)

The KPI for electricity and heat demand for SOEL is defined *at rated capacity* considering AC power and tap water as input and atmospheric hydrogen as output. Most of the commercial manufacturers and literature sources only provide the electricity demand at system level, assuming steam at 100-200°C as input. As seen above, the electricity consumption under these conditions is already below the Clean Hydrogen JU targets for 2024 (< 39 $\text{kWh}_{\text{el}}/\text{kg}$). The heat demand is not specified but must be at least 5.6 kWh/kg to evaporate water to steam.

Further increase of efficiency to reach 2030 targets (37 $\text{kWh}_{\text{el}}/\text{kg}$ and 8 $\text{kWh}_{\text{heat}}/\text{kg}$) require improvements on both stack and system level.

On **stack level**, the following strategies may lead to improved efficiencies:

- 1) Improving catalytic activity of oxygen electrode to reduce overpotential
- 2) Improving electrical contacting between oxygen electrode and interconnect to reduce ohmic resistance.
- 3) Optimising flow-field design of interconnect to enable more efficient heat distribution across the stack.

On the **system level**, the following strategies may lead to improved efficiencies:

- 1) Improving efficiency of blowers and compressors
- 2) Improving AC/DC converter efficiency.
- 3) Operating the stack at elevated pressures. Sunfire⁴ claims 5-7 % points efficiency gain are possible by operating at 15 bar due to reduced compressor power.

¹ Liu, C., et al. *Electrochemistry communications*, 97 (2018) 96-99. <https://doi.org/10.1016/j.elecom.2018.10.021>

² Kang, Z., et al., *Electrochimica Acta*, 354 (2020) 136641. <https://dx.doi.org/10.1016/j.electacta.2020.136641>.

³ Klose, C., et al., *Journal of The Electrochemical Society*, 165 (2018) F1271. DOI: 10.1149/2.1241814jes

⁴ Posdziech, O., Schwarze, K., & Brabandt, J. *International Journal of Hydrogen Energy*, 44 (2019) 19089-19101. <https://doi.org/10.1016/j.ijhydene.2018.05.169>

Most of the improvements on system level involve designing components specifically for SOEL application instead of using components originally designed for other applications.

5. KPI 2: Capital Expenditure (CAPEX)

In this section we introduce the current cost drivers for different electrolyser technologies, challenges associated with the assessment, methodology used to compare different technologies, identifying key cost drivers, CAPEX and OPEX predicted target values and potential pathways to achieve them.

5.1. Challenges

At present with the market availability and maturity of PEM and AWE, they remain highly expensive in both CAPEX and OPEX compared to fossil fuel based H₂ production. PEM systems are 50-60% more expensive than AWE.¹ The cost considerations are challenging for electrolyser systems such as AEM and SOEC stacks as they have limited manufactures involved in commercialisation and many components are still at lab scale. Moreover, there are very few systems deployed as pilot projects with total system size in few kW.

Comparing different technologies on cost considerations of electrolyser systems is challenging due to scarcity of data, confidentiality, commercial competitive advantage, and studies that share the cost estimates have inconsistent boundaries (for e.g., distinction between cost contribution from stack, balance of plant and system) and in some cases unspecified.

5.2. Methodology

Here the approach used is same as IRENA and divide the costs at three levels, cell unit, stack, and system. The study focuses on AWE and PEMWE. A cell unit that includes catalyst coated membrane (PEM), diaphragms (AWE), electrodes and manufacturing of these components. In addition to cells, the stacks include porous transport layer (PTLs), bipolar plates (BP), end plates and other parts such as spacer, frames, seals, bolts etc. A balance of plant (BoP) includes power electronics (i.e., rectifiers, choppers, and transformers), water purification, hydrogen gas processing (compressor and dryer), cooling components (heat recovery, heat rejection, pumps), control system, safety system and other components such as valves and piping are included. The systems scale includes BoP addition to the stack cost.

5.3. Assessment

As shown in Table 5.1. PEMWE and AWE, the manufacturing cost of the different components at cell level dominates with 42 and 72% of the total cell cost, respectively.¹ In a PEME precious platinum group metals (PGM) are used in fabrication of electrodes and membranes which accounts for almost of the cell cost. In general, PGMs are expensive because of their least abundance, availability from unstable market and energy intensive production process. The cell contributes to 24 and 57% of the total stack cost for PEMWE and AWE respectively.¹ At stack level, bipolar plate (53%) in case of PEMWE due to use of titanium (expensive due to high manufacturing cost) and layer of Pt or Au.¹ In case of AWE the cell accounts for 57% due to the high manufacturing cost of the electrodes. According to Patonia et.

¹ IRENA: Green Hydrogen Cost Reduction (2020).

al.¹ SOEL and AEMWE cells are made of cheaper metals and thus the stack cost is about 30 and 19% of the total cost of the system.

For PEMWE and AWE electrolyser technologies stack contributes to 45% of the total cost of the system. At systems scale, power supply/ power electronics account to half of the total cost of balance of plant and is 27 % of the total cost of system. But in case of SOEL and AEMWE the power electronics costs 7-8 times higher than PEME and AWE in absolute terms as shown in Table 5.2.

Due to intermittent nature of renewable energy sources the resulting power or the voltage will be variable, and this can trigger degradation as SOEL and/or AEMWE will have extremely high operating temperatures, mechanically unstable electrodes, brittle ceramics, and sealing issues. Hydrogen processing/ Gas conditioning is equally expensive across all the technologies in absolute terms. In case of PEMWE and AWE its 20% of the total cost of balance of plant and 11% of the total cost of system. The BoP for SOEL and AEMWE is 2 to 8 times as expensive as BoP of PEMWE and AWE.

Table 5.1 Cost breakdown (in %) for a 1 MW electrolyser from cell to systems scale.²

Key Components	Components/Processes	AWE	PEMWE
Cell	Manufacturing	72	42
	Diaphragm/Membrane	14	21
	Electrodes	15	28
	Contribution to Stack	57	24
Stack	Porous transport layer	8	17
	Structural layer	14	-
	Sealing, frames	4	3
	Bipolar plate	7	53
	Stack assembly and end plates	10	3
	Diaphragm/ Electrode package	57	24
	Contribution to System	45	45
Balance Of Plant	Power supply/ Power electronics	50	50
	Deionised water circulation	22	22
	Hydrogen processing/ Gas conditioning	20	20
	Cooling	8	8
	Contribution to System	55	55

Table 5.2 Indicative cost range of electrolyser component (\$/kW) at 1 MW scale estimated in 2020.²

Key Components	AWE	PEMWE	SOEL	AEMWE
Stack	270-450	400-870	690-2,000	>177
Power Electronics	81-135	100-217.5	690-2,000	~167.5
Gas Conditioning	81-135	67-145	140-400	~139.5
Balance Of Plant	108-180	100-217.5	780-2,267	~447
Total	540-900	667-1450	2300-6667	>931

¹ A. Patonia and R. Poudineh. Cost competitive green hydrogen: how to lower the cost of electrolyzers? The Oxford Institute for Energy Studies (2022)

² Adapted from IRENA: Green Hydrogen Cost Reduction (2020).

5.4. Key performance indicator

The target capital and operational costs for various electrolyser technology are stated in Table 5.3.

Table 5.3. Electrolyser expense's goal for 2030.¹

	Unit	PEMWE	AWE	SOEL	AEMWE
Capital Cost	€/kg/d	600	800	800	600
	€/kW	300	400	520	300
O & M Cost	€/kg/d/y	21	35	45	21
Potential Components	Stack	CCM, PTL, BP	Electrodes	Electrodes, Electrolytes	CCM
	System	Rectifier, water purification	BoP	BoP	Rectifier

5.5. Potential pathways to cost reduction for reaching KPI (2023)

5.5.1. Stack level

Materials in PEMWE (such PGMs group) and SOEL (zirconium, lanthanum, cerium, and yttrium) are critical due to its limited availability from countries such as South Africa, Congo, and China, respectively. PGMs in PEMWE can be reduced while maintaining the performance. Currently in PEMWE platinum and iridium use about 1 and 1-2.5 g per kW.

Table 5.4. Scenarios with iridium and platinum loading for PEM electrolyzers.²

	Unit	Present	Future
Current Density	A/cm ²	2	5
Electrode area	cm ²	1200	5000
Iridium loading	mg/cm ²	5	0.2
	g/kW	1.3	0.4
Platinum loading	mg/cm ²	2	0.05
	g/kW	0.5	0.1

Strategies to reduce dependency on critical materials:

- 1. Minimisation of use:** Substituting the materials, reducing their amount per unit of installed capacity, or use of different technology mix (AWE, AEME) to achieve a lower overall use. Using high surface area supported catalyst (titanium or tin oxide support), improved catalyst manufacturing techniques (nanostructured thin film catalysts), thinner layer of coating material (atomic layer deposition). Reengineering the electrode by use of support nanoparticles of iridium on high conductive semi-conductor oxides, by alloying iridium to other transition metals, by changing the morphology of the electrode or by shaping the iridium nanoparticle.
- 2. Increase durability or increase efficiency:** Higher productivity of the stack (smaller area, less material per kg hydrogen). Increased durability same amount of material allocated over greater hydrogen production

¹ Adapted from Clean Hydrogen Joint Undertaking. Strategic Research and Innovation Agenda (SRIA) 2021 – 2027

² Adapted from IRENA: Green Hydrogen Cost Reduction (2020).

3. **Recycling:** Recovering noble metals using methods such as hydrometallurgical treatment, transient dissolution, acid process and selective electrochemical dissolution. These treatments can be used to extract platinum from PEMWE.

These treatments can reduce iridium content by 96% and platinum by 97.5%.

5.5.2. Systems level

As stack has limited economies of scale (limitations on manufacturing of large-scale components, due to mechanical instability issues for large-scale components) increasing the module size can reap benefits in economies of scale for balance of plant. A study identified that 3-4 MW module size as a max. size single stack size and multi stack can achieve significant change in the cost increase for every additional MW capacity, but this is highly dependent on stack design, however, and will vary from one manufacturer to another. It was found that the largest economies of scale are reaped around the 1,020 MW module size.¹

Increasing manufacturing capacity of a plant allows significant reduction in component cost by performing a high throughput, automated manufacturing operation (roll to roll manufacturing of the catalyst coated membrane (for AEMWE/PEMWE) and advanced coating processes for metal plates). Increased manufacturing scale can decrease cost contributions to buildings cost, improve the utilisation of equipment (i.e., increasing the volume produced from each unit and reducing the cost contribution) and improve the process yield (reducing losses). A 50% cost reduction for a 100 MW AWE compared to 5 MW.

In case of AEMWE, cost reduction by mass-manufacturing, standardisation, and supply efforts on a single stack offering can be achieved. Standardisation meaning learning-by-doing this is applying lessons learned from deployment and optimising the installation of equipment through the execution of multiple projects. On the contrary, the balance of plant can have strong economies of scale. For example, upscaling a compressor ten times from 1 MW to 10 MW costs four times. Increasing in production rate, from 10 MW/year to 1 GW/year, can reduce cost by 40% in the balance of plant and the largest cost reductions of 50%-60% can be achieved in the deionized water circulation and the cooling systems.²

SOEC are currently produced on a small scale. Significant reductions in CAPEX may therefore be expected by adoption of mass-manufacturing processes. In addition, cost reductions are achievable by the following improvements in the technology:

- 1) Improvements on cell level to enable operation at higher current density under thermoneutral condition. Operating at higher current density will decrease CAPEX as it will allow for production of greater amounts of hydrogen per cell area. Currently, cells are operated at 0.4-1 A/cm², but Fuel Cell Energy has demonstrated operation up to 6 A/cm².³ For operation at thermoneutral voltage, the current is limited by the resistance of the cell, which can be reduced e.g., by developing thinner electrolyte, anode with lower overpotential, and by improving contact between anode and interconnect.

¹ IRENA: Green Hydrogen Cost Reduction (2020).

² Mayyas, A. et al., Manufacturing cost analysis for proton exchange membrane water electrolyzers, NREL (2019).

³ Tang, Eric, et al. FuelCell Energy, Inc., Danbury, CT (United States), 31 March 2018. <https://doi.org/10.2172/1513461>.

- 2) Increasing stack size (footprint of each cell and number of cells per stack) will reduce amount of steel needed for stack casing and manifold of individual stacks and thus the raw material costs.
- 3) On system level, developing and mass-manufacturing components (compressors, heat exchangers etc.) specifically for SOEC application.

CAPEX is also linked to the maximum cell and stack size. Active cell area of SOEC is currently limited to $< 0.06 \text{ m}^2$. Larger cells are desirable but difficult to obtain for two reasons:

- A. difficulty of producing larger cells that are flat and defect free. However, this challenge may be solved by improved and more automated manufacturing.
- B. increasing the cell size increases the temperature gradient across the cell, leading to thermomechanical stresses and increasing the degradation rate due to larger overpotential variation across the cell.

5.5.3. Learning by doing

The fact that renewable energy technologies follow learning curves (their historically observed cost reductions relate to the cumulative installed capacity) is often considered to be the most important and fundamental prerequisite for their significant decrease in costs.¹

Like solar PV, electrolyzers are expected to initially benefit from module efficiency driven by government-funded and private R&D, and at a later stage from scale economies and, to some extent, from learning-by-doing. Although the learning rates of such intermittent renewables as onshore wind and solar PV appear to be within a range that is close to the estimated learning rates of the three currently most promising electrolyser technologies (AWE, PEMWE, and SOEL as shown in Table 5.5), it would be misleading to expect that the cost decrease of water electrolysis will exactly follow the cost reduction pattern of these renewables.

The experience curve or learning rate refers to the decline in production cost on doubling the cumulative capacity of a specific technology. The cost reduction can be achieved by a lower contribution from fixed costs, a reduction in the production time, standardisation, specialised companies for certain parts of the value chain, and alternative processing steps, including simplification.

With the increase in production capacity the components with a high learning rate will represent a smaller share of the overall cost as capacity increases, as their cost decrease is larger than components with a low rate. The overall learning rate goes towards the lower values with larger capacities as is shown in Figure 5.1. As noticed in Fig. 5.1, using a fixed value learning rate can result in an overestimation of the potential cost decrease.

¹ Grafström, J. and Poudineh, R. A critical assessment of learning curves for solar and wind power technologies. Oxford, UK: OIES (2021).

Table 5.5. Learning rate by stack component for three types of electrolyzers.¹

Technology	Component	Learning rate (%)
AWE	Structural rings	5
	Polytetrafluoroethylene seal	8
	Bipolar plates	18
	(Pre)electrodes	18
	Membrane	18
	Flanges	5
	Tie rods	5
PEMWE	Stack assembling	8
	Small parts	5
	MEA manufacturing	8
	Catalysts	8
	Membranes 8%	18
	Current collectors	18
	Bipolar plates	18
	End plates	8
SOEL	Stack assembling	8
	Electrolyte	18
	Catalysts	18
	Porous transport layer	18
	Interconnector	18
	Sealings	5
	End and pressure plates	8
BoP	Power supply	12
	Gas conditioning	7
	Small, purchased parts	12-15
	Machining	10
	Welding	10

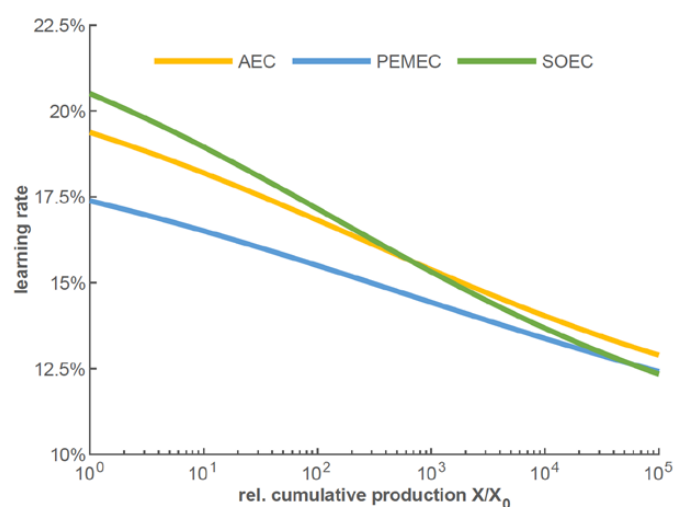


Figure 5.1. Variable learning rate based on components for AWE, PEMWE, and SOEL.²

¹ Adapted from Böhm, H., et al., Estimating future costs of power-to-gas: A component-based approach for technological learning", IJHE (2019).

² IRENA: Green Hydrogen Cost Reduction (2020).

6. KPI 3: Efficiency Degradation

Alkaline and AEM Water Electrolysis

The reported stack lifetime of commercial AWE systems range between 55,000 to 96,000 hours at 0.25 to 1.5 % efficiency degradation.¹ Annual voltage degradation has been reported to be around 10 to 15 mV, which is equivalent to 1-2 μ V per hour and 0.5-1 % in efficiency degradation.² As the numbers indicate, AWE boasts longest lifetime and lowest degradation rate among other water electrolyser technologies.^{1,3} Nevertheless, AWEs still experience some degradation issues. Below is a list of factors that affect AWE's lifetime.

1. **Gas permeation:** diaphragms/membranes in AWEs/AEMs are constantly exposed to a flow of KOH, permeating gases, and local hot spots of deposited impurities on the electrode coatings. These form small pin-hole failures in the beginning, but the size of these pinholes gradually increases over time and lead to gas contamination. Considering that stacks usually come in hundreds of cells of large areas reaching up to 3 m in diameter, inspecting is practically impossible. Instead, an indirect method is used where the hydrogen concentration within the oxygen stream on the oxygen side is monitored until it reaches a certain limit (2 %) followed by repairing or disposing the stacks.
2. **Electrode deactivation:** catalyst poisoning/deactivation of the electrodes by foreign elements present in the electrolyte and the system.
3. **Nickel alloys:** the corrosive nature of the highly concentrated KOH electrolyte requires the use of inorganic ZrO_2 diaphragms and Ni and Zn-based materials. Some alloy materials can easily leach out and contaminate the electrodes, threatening the efficiency and durability of the cell.
4. **Water impurities:** The quality of water in circulation has been proven to greatly impact the lifetime of the plant. Most of the core elements including the diaphragm and the catalysts can be adversely affected by impurities within the water, such as Fe, Cr, Cu, Si, Al, and B.

AEM electrolyzers are known to have much shorter lifetime and lack information on long-term operation. The poor stability of the polymer used in the anion exchange membrane (AEM) and the catalyst layers are the major obstacles to its lifetime, especially in the operational conditions employing KOH as the electrolyte. In KOH, the hydroxide (OH^-) moiety attacks polymer backbone and collapses the membrane, followed by catalyst dissolution in a short period of time.⁴

Parrondo et al. conducted a study on AEM membrane degradation using polysulfone (PSF) backbone membrane grafted with cationic groups. After operating for 6 hours at 200 mA/cm², the PSF AEM cell voltage increased from 1.6 to 2.4 V.⁵ The results suggested that the short-term instability in the electrolyser was owing to CO_2 intrusion while the irreversible efficiency drop is mainly attributed to the polymer backbone degradation. The cationic groups grafted along the polymer backbone are suspected to have caused backbone degradation through ether and quaternary carbon hydrolysis.⁶

¹ Felgenhauer M, Hamacher T. Int J HydrogEnergy 2015;40(5):2084–90.

² Barisic M. Alkalische elektrolyseure—industrielle anwendungen und dynamischer Betrieb. München; 2014.

³ D. Lim et al. Energy Conversion and Management 245 (2021) 114516 <https://doi.org/10.1016/j.enconman.2021.114516>

⁴ IRENA: Green Hydrogen Cost Reduction (2020).

⁵ J. Parrondo, C.G. Arges, M. Niedzwiecki, E.B. Anderson, K.E. Ayers, V. Ramani. RSC Adv., 4 (2014), pp. 9875-9879

⁶ J. Müller, A. Zhegür, U. Krewer, J.R. Varcoe, D.R. Dekel. ACS Mater. Lett., 2 (2020), pp. 168-173

PEM Water Electrolysis (PEMWE)

PEM electrolyzers have a reported lifetime (updated 2020) of 50,000 to 90,000 hours. This is lower than alkaline systems (up to 100,000 hours). Factors that induce degradation of a PEM electrolyser's components, hence affecting its lifetime are:

- 1) **Operating conditions:** Harsher operation conditions than 50-60°C, 10 bar and 2 A/cm² require to design the stack with thicker membranes, higher catalyst loadings and protective coatings on PTLs and BPPs.
- 2) **Variable load:** When the operation of an electrolyser is coupled with RES, there will be fluctuations of the voltage load that causes additional degradation and corrosion of the stack components.
- 3) **Gas permeation:** Especially under differential pressure, the membrane's mechanical stability is compromised. The permeation of gases (crossover) is increased, causing degradation.
- 4) **Anode dissolution:** IrO₂ can be subjected to dissolution depending on the operating conditions.
- 5) **Water impurities:** Membrane, ionomer, catalyst and PTLs can undergo degradation due to impurities in the circulated water, that increase along operation.

Frensch et al.^{1,2} investigated the degradation response of PEMWE to different operation modes. These were comprehensive of static operation at different temperatures, cycling at different speed and a solar PV profile. They found that dynamic operation led to more abundant release of fluoride from the ionomer (that is enhanced by fast potential switches, which improved the performance but could also lead to membrane thinning, hence long-term degradation). However, they did not find decrease of membrane thickness after test, so they claimed the emission could originate from the cathode catalyst layer. The other operation modes lead to increased ohmic resistance, attributed to passivation of Ti components, since they did not find major degradation on the anode catalyst layer. They also found that higher operating temperature increased the cell performance but accelerated membrane degradation and Ti passivation.

Weiß et al.³ used an AST dynamic protocol to mimic the fluctuation of RES by operating between high, low current density (3 vs. 0.1 A/cm²) and idle periods. They found that the OCV periods caused an increase in ohmic resistance that decreased electrochemical performance. This was not observed by replacing the idle phases (where the anode potential tended to decrease to 0 V) with holds at 1.3 V. Therefore, they suggest application of a small current density (<<1% maximum power required) during idle periods to avoid degradation due to dynamic operating the PEM electrolyser.

Solid Oxide Electrolysis (SOEL)

Degradation rate of SOEC stacks varies depending on operating conditions such as temperature, current density, gas composition etc. In general, the degradation increases with increasing operating

¹ Siracusano, S. et al. Journal of Power Sources, 366 (2017) 105-114. <https://doi.org/10.1016/j.jpowsour.2017.09.020>

² Frensch, S. H. et al. International Journal of Hydrogen Energy, 44 (2019) 29889-29898. <https://doi.org/10.1016/j.ijhydene.2019.09.169>

³ Weiß, A. et al. Journal of the electrochemical society, 166(8), (2019) F487. DOI: 10.1149/2.0421908jes

temperature (for diffusion driven processes), increasing steam concentration at the stack inlet and increasing current density/steam conversion/electrode overpotential (these three are interrelated).

The KPI for degradation of SOEL in the Clean Hydrogen JU SRIA is defined as percentage loss of production rate (hydrogen output power) at thermoneutral voltage measured over minimum 2,000 h of testing. Since the production rate is directly proportional to the applied current density, the degradation rate may also be expressed as percentage decrease in current density giving thermoneutral voltage. On the other hand, degradation rates in literature are commonly reported as percentage increase in voltage or area specific resistance measured at constant current density. The conversion between these two definitions of degradation requires knowledge on the performance of the specific cell/stack in terms of voltage-current relation (iV-curve).

Major sources of degradation are:

- **Cell level:**

- 1) Ni migration away from the active area of the electrode. This is typically the dominant degradation mechanism of SOEC, especially for electrode supported cells operated at high current density (large overpotentials).¹
- 2) Destabilization of the LSCF-based oxygen electrode by strontium segregation and accumulation of insulating SrZrO₃ at the barrier layer.²
- 3) for cells with an LSM-YSZ type electrode, operation at high current density causes a higher pO₂ gradient in the YSZ electrolyte, which promotes O₂ "bubble" formation at the interface with the electrode.³
- 4) for electrolyte-supported cells, degradation is dominated by increase in ohmic resistance, in part due to decreasing conductivity of the electrolyte.

- **Stack level:**

- 5) Typically, higher degradation rates are observed, caused by pollutants from the interconnect (Cr poisoning), the glass-based sealing material (Si deposition) or from the gasses (sulfur-based impurities for CO₂ electrolysis).
- 6) Thermomechanical degradation due to stresses induces by large temperature gradients.

- **Module/system level:**

- 7) degradation is typically caused by failure or unwanted behaviour by the balance of plant components, for example, instabilities in steam supply.⁴

Elcogen reports voltage decay of 0.2%/1,000 h or resistance increase of 5 mΩcm²/1,000 h during first 1,000 h of operation of electrolysis stack⁵. Measurement was made at 700 °C, 62.2 A, with SU of 62.5 %, 10 mol.% H₂ flush.

Sunfire cell tested at EIFER for 16,000 h demonstrated degradation below 0.6 %/1,000 h (< 7.3 μV/h) at current density of 0.9 A/cm² (T = 847 °C, SC = 51%).⁶

¹ M.B. Mogensen et al. Fuel Cells. 21 (2021) 415–429. <https://doi.org/10.1002/face.202100072>.

² F. Monaco et al. J. Hydrog. Energy. 46 (2021) 31533–31549. <https://doi.org/10.1016/j.jhydene.2021.07.054>.

³ R. Knibbe et al. J. Electrochem. Soc. 157 (2010) B1209. <https://doi.org/10.1149/1.3447752>.

⁴ C.M. Stoots et al. Int. J. Hydrog. Energy. 35 (2010) 4861–4870. <https://doi.org/10.1016/j.jhydene.2009.10.045>.

⁵ A. Hauch et al. Science. 370 (2020). <https://doi.org/10.1126/science.aba6118>.

⁶ J. Schefold et al. Electrochimica Acta. 179 (2015) 161–168. <https://doi.org/10.1016/j.electacta.2015.04.141>.

Skaftø et al.¹ reported single cell degradation rate of 108 mΩcm²/kh during operation at 700 °C in 50/50 H₂/H₂O and 1.27 V/-0.73 A/cm² and claimed this is only slightly above SoA cells reported in literature. AC/DC operation of the cell under an average current of 0.55 A/cm² and otherwise similar conditions decreased the degradation rate to 15 mΩcm²/kh.

Testing of YSZ electrolyte supported cell at 775°C, -1 A/cm² and 10/90 H₂/H₂O reported a degradation rate of 19-40 mV/1,000 h (1.7-3.8%) during 9300 h of testing². The degradation decreased with time and the highest values were measured due to unplanned events. Degradation was mainly attributed to the steam electrode.

Testing of electrolyte supported cell at 0.9 A/cm², 847 °C and 75 % H₂O for more than 20,000 h resulted in average voltage degradation rate of 0.57 %/kh³. Mainly increase in ohmic resistance. For testing Ni-YSZ supported cell at 800 °C, -1 A/cm² and 10/90 H₂/H₂O it was reported degradation rate of 25 mV/1,000 h after long-term (4400 h) operation⁴. The cell had initially (250 h) a higher degradation rate.

Lang et al.⁵ reports on testing of 30-cell Sunfire stack in electrolysis (3370 h) and reversible mode (2,500 h). Degradation in SOEC mode was 193 mV/kh (0.5%/kh) at 0.52 A/cm² and 820 °C with 70% SU. Reversible operation was at 750 °C, 8 h at SOEC (-0.38-0.52 A/cm²) and 8 h at SOFC (0.18 A/cm²) with 4 h switching between modes, during which degradation in SOEC mode was 506 mV/kh (1.24%/kh). Main degradation was due to increase in ohmic resistance.

Yang et al.⁶ studied the effect of temperature for degradation of SOEC operated at the thermoneutral voltage. Cells were operated potentiostatically, with the temperature determining the current density. Higher initial temperature results in higher initial current density (800 °C – 1.5 A/cm², 750 °C – 1.3 A/cm², 700 °C – 0.9 A/cm²), but also higher initial degradation, with the current density stabilizing at 0.69; 0.68 and 0.39 A/cm², respectively. Analysis of overpotential on different parts of the cell based on cell voltage and impedance data.

Two-cell stack developed by Julich tested at 800 °C, -0.5 A/cm² and 50 % H₂O resulted in average degradation of 0.4%/kh on the voltage and 2.7%/kh on the ASR after long term (8,000-21,000 h) operation. Initial degradation of the stack was higher (0.7-1.9%/kh voltage).⁷

Comparison of degradation on cell, 30-cell stack and 90-cell module level for electrolyte supported cells is reported in⁸. The stack-level degradation rate was 10.5 mV/kh (0.8%/kh relative to thermoneutral), which was 5.5 mV/kh higher than degradation on single cell level. On module level, failure was caused by issues with the balance of plant.

Cell degradation is dependent on the operating conditions. As degradation typically increases with hydrogen production rate (current density), a cell operated at a lower current density will be able to operate for a longer time before reaching an unacceptably high voltage. Some have therefore argued

¹ T.L. Skaftø et al. J. Power Sources. 523 (2022) 231040.

² J. Schefold et al. J. Electrochem. Soc. 159 (2011) A137–A144. <https://doi.org/10.1149/2.076202jes>.

³ J. Schefold et al. Int. J. Hydrog. Energy. 42 (2017) 13415–13426. <https://doi.org/10.1016/j.ijhydene.2017.01.072>.

⁴ X. Sun et al. Fuel Cells. 19 (2019) 740–747. <https://doi.org/10.1002/fuce.201900081>.

⁵ M. Lang et al. Fuel Cells. 20 (2020) 690–700. <https://doi.org/10.1002/fuce.201900245>.

⁶ Y. Yang et al. Chem. Eng. J. 417 (2021) 129260. <https://doi.org/10.1016/j.cej.2021.129260>.

⁷ Q. Fang et al. ECS Trans. 78 (2017) 2885–2893. <https://doi.org/10.1149/07801.2885ecst>.

⁸ A. Léon, et al. J. Power Sources. 510 (2021) 230346. <https://doi.org/10.1016/j.jpowsour.2021.230346>.

to evaluate lifetime performance as a KPI, as this provides info on how much hydrogen the cell will be able to produce during its entire time of operation.¹ The end-of-life voltage for the cell depends on the application and the amount of heat available at the site as a voltage above thermoneutral can be exploited to evaporate water. Larger degradation rates have been reported for electrolyte supported cells than for electrode supported cells.²

6.1. Pathway towards reaching KPI 3 targets

Alkaline and AEM Water Electrolysis

Pathways to reduce the degradation of AWE electrolyser stack components:

- 1) Gas permeation bound together with low pressure operation has been a constant issue for generations of AWE diaphragms. Various efforts have been made in mitigating this issue, and some manufacturers have claimed to have solved it. One of the approaches to resolve the gas permeation issues of AWE is the adoption of polyphenylene sulphide fabric diaphragms, which negatively impacts hydrogen production and limit gas permeation.
- 2) Electrode deactivation issues in AWE have been prevented in some systems electrochemically by applying small idle protective currents (within a few microamperes of current) to avoid potential reversal in the cathode. This could lead to less active electrodes over a longer period of time.

As for AEM, the mitigation strategies for its chemical stability concern of the membrane are still under investigation. Some of the pathways to mitigate degradation from chemical deterioration of the polymer membranes are:

- 1) **Computational quantum chemistry and density functional theory:** These methods can be employed to simulate the correlations between the AEM membrane's chemical stability, ionic conductivity, and the degradation mechanism.^{3,4,5}
- 2) **Chemical modification of the membrane:** Some attempts to chemically improve the cation stability of the polymer membrane have been made, including incorporation of beta hydrogen spacers or by attaching the cation groups to the long alkyl pendant groups on the polymer backbone. Such strategies proved promising for AEM degradation mitigation in multiple studies.^{6,7,8,9}
- 3) **Novel polymer chemistry for high reaction resistance:** Another rising type of degradation-resistant AEM polymer is the "spiro-ionenes" (spiro: twisted structure of two or more rings linked together by one common atom; ionene: polymer having ionic groups as part of the main chain). Such type of AEMs exhibited high thermal and alkaline stability in a cell, showing no degradation for over 1,800 hours in 1 M KOH at 80 °C.¹⁰ This is potentially owing to the fact

¹ J. Schefold et al. J. Electrochem. Soc. 159 (2011) A137–A144.

² A. Léon, et al. J. Power Sources. 510 (2021) 230346. <https://doi.org/10.1016/j.jpowsour.2021.230346>.

³ G. Yang et al. Int. J. Hydrog. Energy, 41 (2016), pp. 6877-6884

⁴ C. Chen et al. J. Am. Chem. Soc., 138 (2016), pp. 991-1000

⁵ D. Henkensmeier et al. J. Electrochem. Energy Convers. Stor., 18 (2021), Article 024001

⁶ C.G. Arges, V. Ramani. Proc. Natl. Acad. Sci. USA, 110 (2013), pp. 2490-2495

⁷ M. Tomoi, K. Yamaguchi, R. Ando, Y. Kantake, Y. Aozaki, H. Kubota J. Appl. Polym. Sci., 64 (1997), pp. 1161-1167

⁸ M.R. Hibbs J. Polym. Sci. Part B Polym. Phys., 51 (2012), pp. 1736-1742

⁹ H. Long, K. Kim, B.S. Pivovar. J. Phys. Chem. C, 116 (2012), pp. 9419-9426

¹⁰ T.H. Pham, J.S. Olsson, P. Jannasch J. Am. Chem. Soc., 139 (2017), pp. 2888-2891

that the constrained ring conformation can create high transition state energy barrier for substitution and elimination reactions as opposed to the more reaction prone methyl groups.^{1,2}

PEM Water Electrolysis (PEMWE)

Pathways to reduce the degradation of PEM electrolyser stack components:

- 1) A solution to decrease degradation associated with gas crossover is to use an additional catalyst on the anode side to reconvert the permeated H₂.³
- 2) The degradation of the anode electrode due dissolution of IrO₂ catalyst could be counteracted by higher catalyst loadings (i.e., > 5mg.cm⁻² or 2.5 g/kW).
- 3) To decrease the degradation and oxidation of the Titanium-based components, it is possible to exploit protective coatings on the Ti surface, i.e., > 1 mg/cm² Pt coating on Ti PTLs.
- 4) The degradation caused by impurities present in the deionized water can be slowed down by upgrading the water purification system.

It is to be noted that all the mitigation strategies proposed for the factors limiting PEM electrolyser's lifetime contribute to increasing stack's and system's costs.

The stack degradation due to variable load operation is still extensive subject of study. As showed previously, Weiß et al.⁴ proposed as a mitigation strategy the application of small bias current (<<1% nominal power) during idle periods.

Solid Oxide Electrolysis (SOEL)

Based on review of dominant degradation mechanisms in state-of-the-art SOEL, the following possible pathways are identified as promising for reducing degradation and reaching the KPI targets:

- 1) Improved understanding of causes for Ni migration in the anode to develop strategies for mitigation. Possible approaches could be engineering of the electrode microstructure or doping of the Ni.
- 2) Developing denser diffusion barriers between YSZ electrolyte and LSCF/LSC electrodes to prevent Sr segregation at the electrolyte/electrolyte interface causing increase in resistance.
- 3) For cells utilizing LSM (or similar materials without significant ionic conductivity), challenges with O₂ bubble formation could be avoided by switching to electrodes made of mixed ion and electronic conductive materials, such as LSCF.
- 4) Improved protective coatings on interconnect to mitigate Cr volatilization and associated poisoning of the anode.
- 5) Develop sealants with lower volatility of elements such as Si to prevent cell poisoning.
- 6) Design interconnect flow-fields/stack geometries with improved heat transfer capability to reduce thermal gradients across the stack.

¹ M.G. Marino, K.D. Kreuer. *ChemSusChem*, 8 (2015), pp. 513-523

² C. Li, J.-B. Baek *Nano Energy* 87 (2021) 106162 <https://doi.org/10.1016/j.nanoen.2021.106162>

³ Klose, C. et al. *Journal of The Electrochemical Society*, 165(16), (2018) F1271. [DOI: 10.1149/2.1241814jes]

⁴ Weiß, A. et al. *Journal of the electrochemical society*, 166(8), (2019) F487. DOI: 10.1149/2.0421908jes

- 7) Design balance-of-plant equipment specifically for SOEL application with improved reliability, e.g., of steam supply.

7. KPI 4: Flexibility and KPI 5: Hot and Cold Start-up

Flexibility is defined by a feasible load range (minimum load and overload possibility), the load gradients, start-up time (warm, cold) and stand-by losses. Warm start is defined as start-up from heated stand-by or idle mode, which means that the system is held at operating temperature and pressure if necessary. A cold start is defined as start-up from ambient temperature after a long shut-down.

7.1. Load Range

Because of the variability renewable sources, a large operational range to adapt to the variability of the supplied power. As a matter of fact, the operating load as an impact on temperature and pressure conditions, generating underproduction of heat at lower loads for example. Since the balance of plant has a constant energy demand, low loads (lower than 30% of nominal power) will lead to higher energy consumption per kg of H₂ produced¹. When the sourced power is higher than the nominal power of the electrolyser, the stress of the overload might degrade the stack components and require additional cooling in the system, enhancing operational costs².

For large electrolyser systems comprising several stacks the load can be varied by shutting off/on some of the stacks completely. This gives a wider load range. For smaller systems, the load variation is limited by load system components as operation away from thermoneutral requires heating/cooling of the stack, typically achieved by air blowing on the oxygen electrode and use of heat exchangers. The dimensioning of the air blower and heat exchangers will pose a limit on the load variation. Thermal management will also put a limit on the maximum rate of load changes. Note that most experimental results reported on load cycling have been performed in a furnace, which ensures constant temperature during the load variation.

Alkaline Water Electrolysis (AWE)

The minimal load for AWE is limited around mainly 20-25% (as shown in Table 2.1) of nominal hydrogen production. This is due to an increasing gas impurity with decreasing the current density. This fact is caused by the lowered gas production rate while the contamination fluxes remain almost constant. In that sense, operation at 100% nominal power is recommended.

PEM Water Electrolysis (PEMWE)

This technology demonstrates good flexibility ranges, between 0 % and 100 % (Table 2.2) due to the low gas permeability of the membrane. However, at high pressure (or due to thinner membranes for improved performance) PEMWE also faces critical gas contamination at low current densities. Some vendors advertise the possibility of overload operation (*ca.* 160 %); however, this is dependent on the

¹ Bourasseau, C., & Guinot, B. (2015). Hydrogen: a storage means for renewable energies. Hydrogen production. Wiley-VCH, Weinheim, 311.

² Wulf, C., Linssen, J., & Zapp, P. (2018). In Hydrogen supply chains (pp. 309-345). Academic Press. <https://doi.org/10.1016/B978-0-12-811197-0.00009-9>

definition of nominal load (nominal current density) and requires power supply and thermal management to be dimensioned for maximum load.

Solid Oxide Electrolysis (SOEL)

Reversible operation (rSOC) is possible for SOEL, allowing for an operating load range of -100 to 100% (Table 2.3). However, if the cell is operated below thermoneutral voltage, external heat must be supplied to prevent the stack from cooling. Larger load flexibility on stack level is because of stable, constant steam supply during the load change. In a system, the steam supply would vary proportional to the current load.

Part load operation of rSOC system is reported by Peters et al.¹. Constant steam utilization of 70%, and constant flow of H₂ and air to the stack was kept while reducing the power supplied to the stack. The stack was operated below thermoneutral, so the system efficiency decreased to ca 35 % when the load was decreased to 10 % of nominal power due to the increased need to supply heat. Not much change to the power consumed by steam and air blower.

Posdziech et al.² reports on a 200 kW SOEC system showing part load ability down to 50 %. On a stack level (30 cells), tests showed that the load could be increased from 0 to 80 % in 1 ms 18 times without measurable damage to the stack. The stack was operated as a rSOC and 100 cycles switching from SOFC to SOEC in 3.2 min and back to SOFC in 1.7 min were demonstrated. Sunfire claims load flexibility from 1 to 100 % in 15 minutes is possible.

Skaftø et al.³ has proposed a novel control strategy to mitigate temperature gradients in the stack with changes in current density. The operating mode is rapidly switched between endothermic electrolysis (below thermoneutral voltage) and exothermic fuel cell. The thermal inertia of the stack results in a small temperature gradient and on average thermoneutral operation. This mode of operation is claimed to reduce degradation rate of the stack on account of a lower overpotential and an "impurity expelling effect".

7.2. KPI 5: Hot and Cold Start up

PEMWE and AWE are held on temperature in stand-by mode due to the lower electrochemical performance in cold operation and the required time for heat-up. Warm start-up time from heated and pressurised stand-by mode to full load is possible within 1–5 min for AWE and with seconds for PEMWE. On a MW-scale, less than 10 s from idle or stand-by mode to full load are reported by Siemens and Proton Onsite (acquired by NEL).

The heat-up time of the electrolyser determines the time for cold start-up. The heating of the electrolyser by internal losses is limited by the maximum current or the maximum voltage of the rectifier, as well as by corrosion at high voltages or current densities respectively. The maximum voltage becomes limiting at low operating or start-up temperature as this results in high overpotentials during start-up. Therefore, a cold start results in high cell voltages at low current densities limiting the maximum power of the electrolyser at the beginning.

¹ R. Peters et al. J. Electrochem. Soc. 168 (2021) 014508. <https://doi.org/10.1149/1945-7111/abdc79>.

² O. Posdziech et al. Int. J. Hydrog. Energy. 44 (2019) 19089–19101. <https://doi.org/10.1016/j.ijhydene.2018.05.169>.

³ T.L. Skaftø et al. J. Power Sources. 523 (2022) 231040. <https://doi.org/10.1016/j.jpowsour.2022.231040>.

For large-scale industrial AWE plants designed for continuous operation, necessary heat-up times of 2h have been reported. For some commercial alkaline models, the power increase is limited at low temperature to ensure the stack and system leak-tightness and to minimise mechanical stress to the system due to rises in operating temperature.

PEMWE have shorter heat-up times compared to AWE following from the more compact design and lower thermal capacity and in some cases lower operating temperature. Stated cold start-up time (from standby to nominal production rate) for PEMWE systems are in the range of 5–10 min.

A SOEL module has to be held at the high operating temperature of 700–900 °C in idle mode. Otherwise, a long start-up time (10-15 h) is necessary to heat the system up and to avoid the risk of thermal stress. Sunfire claims that flexible operation from 1 % to 100 % in 15 min is possible when the system is at operating temperature.

7.3. Pathway towards reaching KPI 4 and 5 targets

A. Patonia and R. Poudineh¹ have assessed the operation flexibility of the different water electrolysis technologies. A summary of their main assessment is presented below.

At the system level, the BOL has a constant demand for energy (e.g., pumps and cooling) that does not depend on the production of hydrogen. Hence, operating with a load lower than the electrolyser nominal power (<30 %) turns eventually into a greater energy consumption per kg of H₂. In addition, an electrolyser operating on lower loads lead to less heat production making it harder for the device to reach the optimal temperature. In that sense, electrolysers with greater tolerance to lower minimum load appear to be more suitable for power-to-hydrogen production, as their ultimate efficiency losses are less affected.

At the same time, intermittent renewables can also generate surplus power, which will also have to be dealt with. For electrolysers, operating in overloads (>100% nominal power) usually means efficiency losses and additional stress for the materials, which may potentially result in a reduced lifetime for the system. In general, fluctuations of electricity input cause degradation of materials in both the electrical and mechanical parts of electrolyser systems, when compared to constant load operation.

Among the water electrolysis technology, AWE is the one with the highest need for improving its minimal operating load (currently about 10-20% of nominal power). In fact, due to their relatively high minimum load, most alkaline systems need to be completely shut down and depressurized when not enough electricity is provided. After this, the electrolyser also needs to be flushed so that no unwanted reactions of the remaining hydrogen take place. On the other side, the upper nominal tolerance level for AWE electrolysers is about 100% (MAWP 2023 set at 300%). It is known that AWE has been designed to give respond to the form of power supply at the time of their initial development. Hence, they have been traditionally purposed for stationary applications with grid connections, rather than intermittent power supplies from variable renewables that are not integrated into the grid. Besides redesigning the alkaline electrolyser to be adapted to the current needs, it has been suggested further R&D focus on the diaphragm to improve the range of operating load for AWE systems.

¹ A. Patonia and R. Poudineh. Cost competitive green hydrogen: how to lower the cost of electrolysers? The Oxford Institute for Energy Studies (2022) and references therein.

PEMWE and SOEL systems have already made their first steps on the path towards achieving greater variability tolerance with a load range of between 5 and 120 % and 3 and 125 %, respectively. Although the minimal load is very close to the set KPI in the MAWP 2023, the upper load is still far to be reached for both systems. It has been proposed for PEMWE to concentrate R&D effort on the membrane while SOEL electrodes and electrolytes must be improved for achieving the MAWP 2023 target. On the other hand, although SOEL are potentially capable of very fast electric load changes due to their broad load range, their start-ups and shut-downs need to be conducted slowly and the temperature should be kept above 600 °C. If these electrolyzers need to be shut down, their cold start-up will normally take more than 60 minutes. All this makes PEM electrolyzers that need only several minutes (up to 30 min) to gain their optimal operating temperature particularly remarkable.

In general, PEM electrolyzers are more suitable in terms of operating with intermittent power supplies than the rest of the systems. Hence, because of their efficiency, PEM electrolyzers may ultimately be cheaper to operate if coupled with solar and wind power.

8. Achievements of water electrolysis technologies towards MAWP

To make renewable hydrogen cost-competitive against the hydrocarbon-based H₂, the cost of renewable energy and electrolyser themselves must decrease. Currently, any of the available water electrolysis technologies are suitable for the large production of green hydrogen.

Despite having a higher minimum load and thus not being particularly tolerant to power produced by variable renewable energy source (VRES), AWE systems offer the largest systems size at the lowest cost. In contrast, PEMWE is the most suitable for coupling with VRES but is significantly more expensive due to the high content of PGM. The reduction of PGMs and critical raw materials without losing the demonstrated advantages of PEMWE technology is the main R&D challenge for this technology. This challenge should be the driving force for improving it as the most suitable solution for coupling with intermittent renewable energy sources. SOEL is also quite expensive due to the material used, but this technology needs additionally to reduce its cold start-up time. If this is achieved, fully commercialized SOEL systems could significantly reduce the consumption of electricity for the hydrogen production process due to their greater efficiency (around 90 %). This would ultimately lead to the cost reduction of renewable hydrogen.

ALKALINE ELECTROLYSER: It is a well-established technology for hydrogen production with relatively cost-effective stacks available in the MW range. However, alkaline electrolyzers experience high ohmic losses across the electrolyte and separator and hence operate at relatively low current densities compared to PEM electrolyzers. Historically the systems have shown poor dynamic behaviour, with limited load flexibility. This occurs because the separators are not very effective at preventing cross-diffusion of gases.

PEM ELECTROLYSER: The main advantages of PEMWE include the high current density, high voltage efficiencies, and the fact that these electrolyzers operate well under dynamic operation and partial load and are highly responsive. This makes PEMWE the best-suited technology for coupling with VRES. The main drawbacks are durability (related to catalyst loss and membrane lifetime) and cost, partly due to the catalysts consisting of expensive PGMs. As for alkaline electrolyzers, performance gains

appear to be limited beyond a system size of approximately 100-300 kW. This is again most likely due to the modularity of systems above a certain size.

SOLID OXIDE ELECTROLYSER: This technology is considered to be still at the research stage but with a significant margin of improvement especially at material level. Due to their high operating temperature, SOEL has the advantage of operating at high efficiency. Therefore, they would be particularly useful in industrial applications where waste heat can be recycled to the electrolyser stacks. Furthermore, its ability to be operated under reverse mode (i.e., as fuel cell) opens its potential in energy storage and grid balancing in connection with VRES, however, the major drawback is that the high temperature operation leads to long start-up times and slow response.

Based on the data currently publicly available^{1,2,3,4} and what has been reported in the sections above, in the follow it will be sum up the status concerning the technical targets set by the FCH 2 JU MAWP 2023 and Clean Hydrogen JU SRIA for each water electrolysis technology.

8.1. KP 1: Energy consumption

The state-of-the-art performance of *alkaline electrolysers* is in the range of **47 to 62 kWh/kg**. These values are in concordance with FCH 2 JU target for 2023 (see Section 3.1) and those set for AWE in the Clean Hydrogen JU SRIA (Section 3.2.1).

For *PEM electrolyser* (Table 2.2) the average energy consumption reported for commercial stack devices is about **55 kWh/Kg** being as good as **46 kWh/Kg**. At larger system sizes (10MW) is reported a range from **50 to 80 kW/Kg**. Thus, it considers PEMWE technology meeting the technical target set by both the MAWP 2023 and Clean Hydrogen JU for the years 2020, 2024, and even 2030 (stack level).

In the case of *SOEL*, it is already considered a very highly efficient technology compared to AWE and PEMWE not requiring significant improvement in that respect from now until 2030 (see Section 3.2.4). Their high temperatures minimise power loss during electrolysis by mean of decreasing the reactions overpotentials and thus increasing the electrolyser efficiency. Despite of their low TRL, SOEL systems seems to be among the most advanced in terms of reducing electricity consumption. At stack level is reported an energy consumption as low as **35-50 kWh/Kg** (system level: 40-50 kWh/Kg). These values agree favourably with both the state of the art and the stated target values of FCH 2 JU and Clean Hydrogen JU.

8.2. KPI 2: Capital expenditure

Regarding CAPEX (KPI 2), it is difficult to access such information. Nevertheless, the capital cost of a 10 MW *AWE system* is currently in the range of **420 and 850 EUR/kW**. This range corresponds to the target in FCH 2 JU 2023 and Clean Hydrogen JU 2024. However, it has to be pointed out that targets set by MAWP, and Clean Hydrogen are set with a capital cost estimation based on 100 MW production

¹ Buttler, A. and Spliethoff, H. (2018). Renewable and Sustainable Energy Reviews, 82, 2440-2454.

² IRENA: Green Hydrogen Cost Reduction (2020).

³ A. Patonia and R. Poudineh. Cost competitive green hydrogen: how to lower the cost of electrolysers? OIES (2022) and references therein.

⁴ Davies J, Dolci, F., and Weidner, E. (2021) Historical Analysis of FCH 2 JU Electrolyser Projects. JRC Technical Report.

volume. In that regard, it could be hard to assume that such KPI 2 is achieved to date by the AWE system.

Like AWE, it is difficult to obtain CAPEX information on **PEM electrolyzers**. Nevertheless, the capital cost for a system size of 10 MW is reported to be in the range of **600 to 1,200 EUR/kW**. That range falls into the target set for 2023 and 2024 (see section 3.1). But, as mentioned, MAWP 2023 target is set based on 100 MW production volume including a 10-year system lifetime operation under steady-state operation. Therefore, it is fair enough to assume that PEM electrolyser has not achieved up to date this KPI either. However, compared to alkaline electrolyzers, there is a greater opportunity for cost reduction as PEMWE technology is at a much earlier stage of development and may depend on the level to which PGM loadings can be reduced or replaced.

SOEL technology is considered in the early stage of development requiring a considerable cost reduction to become commercially available. Like the already commercialized PEM systems, solid oxide electrolyzers also use scarce materials which increases their cost significantly. As reflected in the Clean Hydrogen JU SRIA, this technology needs to reduce their state-of-the-art cost by four times to meet 2030 targets. Current estimated SoA (2020) cost are about **2,130 EUR/kW**.¹

8.3. KPI 3: Efficiency degradation

The degradation (%/1,000 h) is defined as the percentage efficiency loss when run at nominal capacity. The MAWP 2023 KPI 3 corresponding to efficiency degradation is aiming to a degradation rate in the order of <2.3 $\mu\text{V/h}$ (< 1%/year). Clean Hydrogen JU SRIA, set degradation targets as function of the water electrolysis technologies (see section 3.1) which is more adapted to the degree of development of the existing technologies. However, in both documents the target value is most likely assigned to a presumable steady state operation. Therefore, the target does not address the issue of load flexibility or use under dynamic operation as coupled with VRES, which are the key challenges that need to be addressed by the water electrolysis technologies since the degradation rate under flexible operating conditions would be a relevant parameter as it is expected to be higher due to the stressed conditions that materials, components, and system are exposed. In general, fluctuations of electricity input cause degradation of materials in both the electrical and mechanical parts of electrolyser systems, when compared to constant load operation. In addition, lack of long-term stack testing makes difficult to assess this KPI. Short tests are used to extrapolate the data and estimated degradation rates and/or stack lifetime. However, degradation mechanisms might be different at different time scale of the testing. Furthermore, how the testing has been performed (operating conditions) is crucial on the calculated degradation rate. All in all, there is still challenges for understanding the durability of water electrolysis technologies when operating in combination with VRES (flexible operation).

It has been reported^{2,3,4} for **AWE** a stack lifetime of 55,000 to 96,000 h at an efficiency degradation of 0.25-1.5%/year and degradation rates in the order of 1-2 $\mu\text{V/h}$. On the other hand, for **PEMWE** is reported stack lifetime about 60,000 to 100,000 h being the degradation rate in the range of 4-8 $\mu\text{V/h}$ (efficiency degradation of 0.5-2.5 %/year). As literature reported, AWE and PEMWE achieve

¹ Clean Hydrogen Joint Undertaking. Strategic Research and Innovation Agenda (SRIA) 2021 – 2027.

² Buttler, A. and Spliethoff, H. (2018). Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews*, 82, 2440-2454.

³ A. Patonia and R. Poudineh. Cost competitive green hydrogen: how to lower the cost of electrolyzers? The Oxford Institute for Energy Studies (2022).

⁴ IRENA: Green Hydrogen Cost Reduction (2020).

comparable stack lifetime although PEMWE trends to have higher degradation rate. In both technologies although it has been progress there is still a lot to do and understand for reaching the MAWP KPI 3 and corresponding Clean Hydrogen JU targets under VRES conditions.

For **SOEL** the same conclusions that for AWE and PEMWE can be drawn. As mentioned, operating conditions have a significant impact on degradation due to it increases at higher current densities and elevated temperature. In the case of SOEL, degradation also tends to increase at higher steam concentration and higher steam conversion.¹ It has been reported for short lifetime test a degradation rate in the range of 0.4-6%/1,000 h at temperatures of 650-850 °C and current density below 1 A/cm². The expected lifetime for SOEL is at the current 20,000 to 90,000 h.^{2,3}

8.4. KPI 4 and 5: Flexibility and Hot/Cold start up

Due to the challenges mentioned in the previous section, **alkaline electrolyzers** have mostly been deployed in a continuous mode, e.g., for stationary hydrogen production in an industrial environment and not for coupling with VRES. Although commercial manufacturers (Table 2.1) reported load flexibility in the range of 20-100%, AWE systems are not now ready to reach KPI 4 (operational flexibility, section 3.1). In contrast, AWE start-up time from cold standby to nominal production rate was reported as less than 3600 seconds,¹ while warm start-up was reported as less than 60 seconds. Although those values represent the SoA for 2020, they are still far of reaching 2023 and 2024 KPIs set by the MAWP and Clean Hydrogen, respectively.

On the other hand, **PEM electrolyzers** considered as the most suitable for coupling with intermittent renewable energy sources shows a load range about 0-150% (Table 2.1) meeting the MAWP 2023 target for the lower load but far of the requested overload value (i.e., 300% of nominal power). In addition, PEM electrolyser can react very fast within the range of less of 10 seconds (MW scale) for warm start-up time from already heated and pressurized stand-by mode to full load, whilst cold start-up time (from standby to nominal production rate) are generally stated as 5-20 minutes for this technology. Like AWE technology, PEM electrolyzers are still under their process to meet 2023 and 2024 KPIs (see section 3.1).

Coupling **solid oxide electrolyzers** to VRES may result in faster degradation and shorter lifetime for this technology due to thermochemical cycling, especially under shutdown/ramping periods. Nevertheless, it estimated that SOEL could conduct overload operations in the range of 3 to 125 % (under reversible mode it can be considered as -100 to 100%) which means a first step towards greater variability tolerance. In contrast, their start-ups and shutdowns need to be conducted keeping the operating temperature (hot start) to reach a hot start around 15 minutes. If the SOEL must be shut down, the cold start will take more than 600 minutes. In both cases, SOEL technology is under their way to meet the technical KPIs settled by the Clean Hydrogen JU for 2024, although system level testing needs to be demonstrated. MAWP 2023 targets are out of the range for this technology.

All in all, there is no specific electrolyser technology outperforming the rest across all the features essential for effective production of green hydrogen. Currently, both AWE and PEMWE technologies will drive the force paving the way for coupling electrolyser to VRES. AWE technology is under its own to meet the future targets (e.g., efficiency, cost, lifetime) but with the handicap of not being suitable

¹ IRENA: Green Hydrogen Cost Reduction (2020).

for flexible operation. On the other hand, PEM technology is growing relative fast matching beside energy consumption some of the harsher technical targets as flexibility. It makes this technology very attractive to be operated with VRES. However, the lack of knowledge concerning its long-term lifetime (degradation) and the requested decrease of PGM/CRM as catalysts but keeping its efficiency and flexibility keep this technology away to be the dominant among the water electrolysis technologies.

In the end, innovation, and competition among these key technologies (including less mature AEMWE, SOEL, and PCCEL) and their manufacturers, will lead to technological improvements and a better fit for different technologies and system designs on a case-by-case basis.

9. Summary

The Fuel Cell and Hydrogen 2 Joint Undertaking and its successor Clean Hydrogen Joint Undertaking set a series of key performance indicators (KPIs) that allows tracing the progress toward hydrogen production from renewable electricity coupled with water electrolysis. In that regard, this deliverable intends to identify the main challenges by water electrolysis technology for reaching those future targets (KPIs).

Energy storage can allow energy to be stored during high renewable generation or low demand periods, and to be used during low renewable production or high demand periods. One promising option to fulfil this dispatchable energy role is hydrogen energy storage. Hydrogen energy storage is a process wherein the surplus of energy created by renewables during low energy demand periods is used to power electrolysis. The large-scale production and use of hydrogen as an energy carrier can be an important contributor to the transformation of the global energy system by helping with the use, integration, and deployment of Variable Renewable Energy Sources (VRES).

The Hydrogen Strategy identifies as the priority for the EU to develop renewable hydrogen, produced using mainly wind, hydro, and solar energy. This should be the main form of hydrogen in the long-term, towards 2050, supported by the very high shares of renewable electricity. Water electrolysis will be the main technology supported, covering both high TRL types: Alkaline Water Electrolysis (AWE), Proton Exchange Membrane Electrolysis (PEMWE), Solid Oxide Electrolysis (SOEL) and less mature types: Anion Exchange Membrane Water Electrolysis (AEMWE) and Proton Conducting Ceramic Electrolysis (PCCEL). Currently, due to their maturity, both AWE and PEMWE technologies will draw the main attention, although further R&D of AEMWE, SOEL, and PCCEL would bring those currently less mature technologies as alternative solutions in the future.

Haeolus project based its targets on the FCH 2 JU MAWP Key Performance Indicators for 2023. They are related to Energy consumption (KPI 1); Capital Expenditure (KPI 2); Efficiency Degradation (KPI 3); Flexibility (KPI 4); and Hot/Cold start (KPI 5). These 2023 KPIs are general technical goals settled to be fulfilled by all water electrolysis technologies. However, these settings might be difficult to be reached with some of the technologies due to their inherent characteristics but especially those less mature. In that sense, the Clean Hydrogen JU defined KPIs for 2024, 2030, and beyond accordingly to each water electrolysis technology.

Even though the KPIs are now adapted to each technology, the conditions assumed for each KPI are far to be a standard procedure on how it should be measured. Consequently, nowadays, the available

technical information reported somewhere is most likely based on conditions and assumptions sometimes very different from those used by the FCH2 JU or Clean Hydrogen JU to set the KPIs. This mismatch in how the KPIs are measured or determined makes it very difficult to do a direct comparison among technologies and between manufacturers. Furthermore, in both documents the technical target values are assigned to a presumable steady state operation. Therefore, they may not address properly the issue of load flexibility or use under dynamic operation as coupled with VRES, which are the key challenges that need to be addressed by the water electrolysis technologies since for example the degradation rate under flexible operating conditions would be a relevant parameter as it is expected to be higher due to the stressed conditions that materials, components, and system are exposed. In addition, lack of long-term stack testing makes difficult to assess the KPIs.

Despite having a higher minimum load and thus not being particularly tolerant to power produced by VRES, AWE systems offer the largest systems size at the lowest cost. In contrast, PEMWE is the most suitable for coupling with VRES but is significantly more expensive due to the high content of PGM. The reduction of PGMs and critical raw materials without losing the demonstrated advantages of PEMWE technology is the main R&D challenge for this technology. SOEL is also quite expensive due to the material used, but this technology needs additionally to reduce its cold start-up time. If this is achieved, fully commercialized SOEL systems could significantly reduce the consumption of electricity for the hydrogen production process due to their greater efficiency (around 90 %). This would ultimately lead to the cost reduction of renewable hydrogen.

Nowadays, there is no specific electrolyser technology outperforming the rest across all the features essential for the effective production of green hydrogen. As pointed out, both AWE and PEMWE technologies will be the driving force paving the way for coupling electrolyser to renewable energy sources like the sun and/or the wind. AWE technology is under its own to meet the future targets (e.g., efficiency, cost, lifetime) but with the handicap of not being suitable for flexible operation. On the other hand, PEM technology is growing relative fast matching beside energy consumption some of the harsher technical targets as flexibility. It makes this technology very attractive to be operated with VRES. However, the lack of knowledge concerning its long-term lifetime (degradation) and the requested decrease of PGM/CRM as catalysts but retaining its efficiency and flexibility keep this technology away to be dominant among the water electrolysis technologies.