WATER ELECTROLYSIS TECHNOLOGIES: COMPARISON OF MATURITY, OPERATIONAL AND COST EFFICIENCY

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Abstract. An electrolysis system uses electricity to split water molecules into hydrogen and oxygen. In this process, the electrolysis system produces hydrogen, and the remaining oxygen escapes to the atmosphere or is captured or stored for use in industrial processes, or for other purposes. This study provides a detailed assessment of four major electrolysis technologies (alkaline water electrolysis, proton exchange membrane electrolysis, solid oxide electrolysis, and anion exchange membrane electrolysis), their characteristics, key players in the global electrolyser market, and recent trends that define electrolysis technology and market development. The scope of this study extends not only to the analysis of electrolysis technologies, but also to an overview of the availability of critical materials, shortages or disruptions in supply of which can prove challenging or even harmful for those markets/regions with limited excess platinum group metals (platinum, palladium, rhodium, ruthenium, iridium, and osmium) and rare earth metals. Also, for two electrolysis technologies: alkaline water electrolysis and proton exchange membrane electrolysis, a comparison of efficiency and initial calculation of CAPEX for installations with medium and large installed capacities (5 and 100 MW) was presented.

Keywords: electrolysis, green hydrogen, AWE, PEM, critical materials, market overview.

Introduction

Electrolysis is a process of oxidation – reduction, during which direct current is passed through a substance to make chemical changes to it. As a result, the substance loses or obtains electrons. The process is carried out in an electrolytic cell, an installation consisting of positive and negative electrodes (anode and cathode) separated and soaked in solution and containing positive and negatively charged ions [1]. In the process of water electrolysis, water molecules are split into their basic components, hydrogen and oxygen, using electricity [2]. If electricity is generated from renewable energy sources (RES; e.g. wind, solar etc.), green hydrogen is produced as the result [3].

Although the laws of electrolysis were first described by Faraday in 1833, hydrogen production in this way, for various reasons, started almost a century later. In particular, the production of hydrogen by electrolysis technology requires demineralized water, the use of which is economically viable only if the water is extracted from freshwater. Therefore, it was in the regions of Northern Europe with high freshwater concentrations that large-scale green hydrogen production developed. Specifically, Norsk Hydro in Ryukan, Norway, created and commissioned the world's first water electrolyser complex in 1940. The facility ran until the 1970s. A similar plant also operated in Gloma fjord, Norway, from 1953 to 1991 [4].

In 2023, electrolyser market size was valued at USD 443.95 million, with projected to grow till USD 471.87 million in 2024 and USD 717.50 million in 2032, exhibiting a CAGR of 5.38% during the forecast period (2024-2032) [5]. The electrolysers market is dominated by a select group of leading players, equipped with vast portfolios, global distribution networks and local manufacturing facilities. These electrolyser manufacturers are actively engaged in the development of advanced electrolyser systems and technologies, highlighting improved properties to meet growing market demands.

The technological diversity of the global electrolyser market is on the upward path, and is shown in Figure 1, while Figure 2 depicts global electrolyser market revenue share in 2023, by installed capacity [6].

At the same time, Table 1 summarizes leading global megawatt-scale electrolyser producers, most of whom are based in China, the US and several European countries.

Both in Europe and globally the main source of hydrogen production is the process of steam methane reforming, where the natural gas is used as a raw material for hydrogen production. In principle, this technology is also applicable to the production of green hydrogen when natural gas is replaced by biomethane, but this technology does not appear in practice in the production process of green hydrogen at this stage. Global hydrogen demand reached more than 97 Mt in 2023 and could reach almost 100 Mt

DOI: 10.22616/ERDev.2025.24.TF061

in 2024. However, this increase should be seen because of wider economic trends rather than the result of successful policy implementation. Hydrogen demand remained concentrated in refining and industry applications, where it has been used for decades. Even if demand for green and other forms of low-emissions hydrogen grew almost 10% in 2023, it still accounts for less than 1Mt [7].

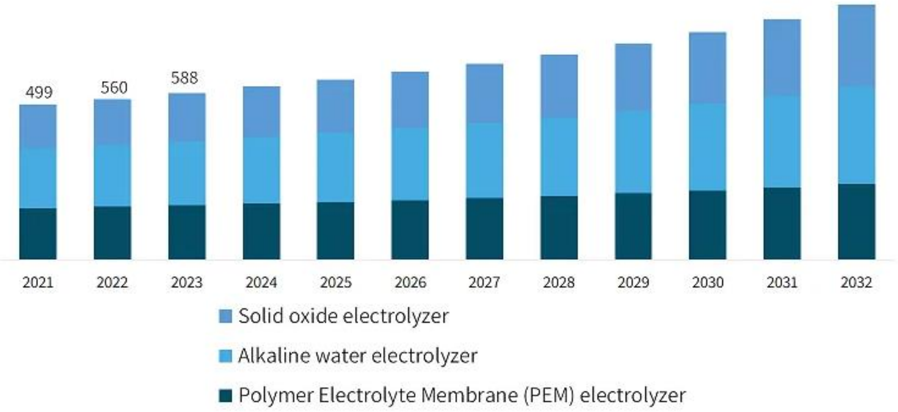

Fig. 1. **Technological diversity of the global electrolyser market (2021-2032est.) [6]**

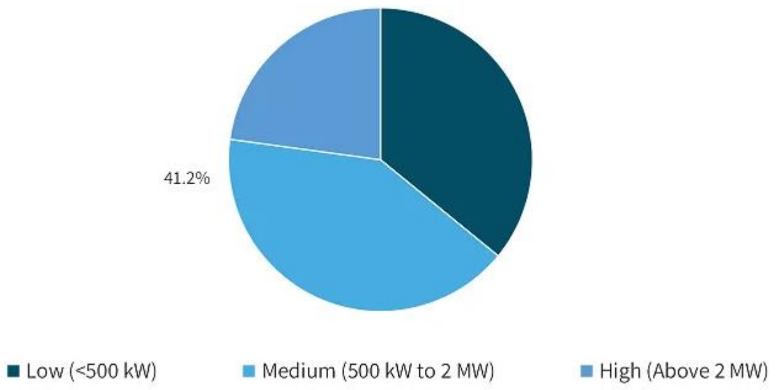

Fig. 2. **Global electrolyser market revenue share (%), by installed capacity (2023) [6]**

Table 1

Leading global electrolyser producers (2024, by total installed capacity, MW

Company	Country	Capacity (MW)
LONGi Hydrogen Technology Co., Ltd.	China	5000
Plug Power, Inc.	US	2500
Hygreen Energy	China	2000
Bloom Energy Corporation	US	2000
ITM Power Plc	Great Britain	1500
PERIC Hydrogen Technologies Co., Ltd.	China	1500
McPhy Energy S.A.	Italy	1300
Electric Hydrogen Co.	US	1200
Thyssenkrupp Nucera AG & Co. KGaA	Germany	1000
John Cockerill S.A.	China	1000
Cummins, Inc.	US	1000
Nel ASA	Norway	500
HydrogenPro ASA	Norway	500
Sunfire GmbH	Germany	500
Ohmium International, Inc.	India	500

The goal of the research is to provide comparison of maturity, basic operational parameters and cost efficiency of two most widespread and two emerging water electrolysis technologies, with an accent on comparison of the two most widespread ones: alkaline water electrolysis (AWE) and proton exchange membrane electrolysis (PEM).

The methodological basis of this research is a literary review method, both looking into scientific and professional sources dedicated to hydrogen water electrolysis evolution, critical material availability and technology development trends. Literature reviews still play a critical role in scholarships because science is a cumulative endeavor, where contents of published data pools grow in geometric progression. Rigorous knowledge syntheses are becoming indispensable in keeping up with an exponentially growing number of sources, assisting practitioners and academics in evaluation and contents of many empirical and conceptual papers. Therefore, during the research process, the authors use generally accepted, source analysis based qualitative methods – analysis, synthesis and logically constructive and comparative methods.

Water electrolysis typology and cost optimization

There are currently four main types of electrolysis systems at different stages of technological maturity and market penetration: AWE, PEM, SOEC and AEM.

For AWE, electrodes are immersed in an alkaline solution, usually potassium hydroxide, which allows ion transfer and therefore enables the electrolysis process. Electrode-containing cells are separated by a permeable ion-conducting membrane. This membrane is gas-tight and thus prevents the mixing of oxygen and hydrogen. AWE is characterised by operating at high temperatures and pressures, high long-term stability and relatively low investment costs. The highest level of effectiveness has been achieved, along with readiness for widespread industrial use. AWE is primarily used in mineral fertilizer and chlorine production. Currently, AWE facilities account for nearly two-thirds of global water electrolyser capacity. AWE electrolyzers can operate at 30 bar pressure, use thick membranes and nickel-based electrodes. While their relatively simple design also makes them the cheapest water electrolysis technology, thick membranes reduce their performance to 60-80% [8-9].

As opposed to AWE, PEM works in acidic environments. PEM electrolyzers do not contain liquid electrolytes, but solid, acidic, proton-conducting membranes. This allows protons to pass through but blocks electrons. The membrane thus actively participates in the ion proton management process. PEM is characterized by operation at low temperature and high pressure and currently entering in the active scaling phase. Although PEM electrolysis is a new technology, it already covers one-fifth of global hydrogen production in the electrolysis process. PEM electrolyzers operate at high pressure due to the use of thin perfluorosulfonic acid (PFSA) membranes, which translate into more than 80% technical performance efficiency [10]. PEM has a compact and simple design and benefits from intermittent loading (quick response to variable RES generation) [11]. However, in the acidic environment of PFSA, gold and titanium coated electrodes and other rare earth metals such as platinum, iridium and ruthenium should be used as catalysts, which significantly increases the cost of electrolysers.

SOEC again requires the use of a solid electrolyte cell, usually composed of ceramic materials such as yttrium stabilized zirconium electrolyte (YSZ). The solid electrolyte separates the anode and cathode. SOEC requires ceramic materials due to very high temperatures, it provides a rapid response, determined by a high temperature, which increases the efficiency of the process. It also demonstrates the sensitivity of technology to temperature variations, as testing of large-scale industrial prototypes is ongoing. A high temperature regime (500-850 °C) is critical for SOEC technology as it uses heat to produce hydrogen from water vapor and is best used where a permanent heat source (nuclear or industrial installations) is available. SOEC exhibits higher efficiency than other electrolysis technologies but is not suitable for use under variable load conditions [12].

In AEM, the anode and cathode are separated by an anion exchange membrane. AEM is characterized by using alkaline solutions with potentially high current density and the degree of technological maturity that has not yet reached the level of universal commercialization. AEM electrolysis operates at significantly lower temperatures (50-60 °C) and in the pressure range (1-30 bar) [13]. This technology combines the less harsh conditions of alkaline electrolysis with simplicity and high efficiency of PEM electrolysis. AEM being wristed at the level of industrial prototypes is commercialized by a few companies [14].

The principal schemes of the electrolysis process for above-mentioned technologies are shown in Figure 3.

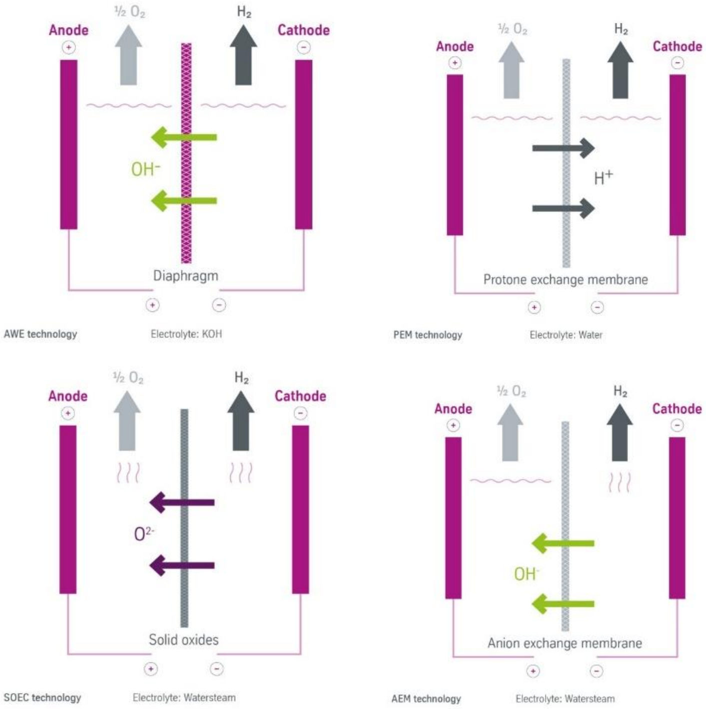

Fig. 3. **Principal schemes of electrolysis process for AWE, PEM, SOEC and AEM (source: Thyssenkrupp Nucera)**

All four water electrolysis technologies are rather similar as of their design principles. Cells in all technologies contain anode and cathode, as well as membrane and electrolyte. However, even if the four technologies have a similar structure, the electrolysis process itself takes place in them differently. These differences are mainly due to the materials needed and used to transmit the current, as well as the working temperature. The choice of materials is determined by the configuration of the electrolyser and the choice of the electrolyte. The comparison of basic characteristics of AWE, PEM, SOEC and AEM are listed in Table 2.

Table 2

Comparison of basic characteristics of AWE, PEM, SOEC, AEM (developed by the authors)

Characteristic	AWE	PEM	SOEC	AEM
Electrolyte	Solution of potassium hydroxide	PFSA membrane	Yttrium stabilized zirconium (YSZ)	Anion exchange ionomer
Cathode	Nickel, nickel-molybdenum alloy	Platinum, platinum-palladium alloy	Nickel, YSZ	Nickel and nickel alloys
Anode	Nickel, nickel-cobalt alloys	Ruthenium oxide, iridium oxide	YSZ	Nickel, iron, cobalt oxides
Operational temperature (°C)	60-80	50-80	500-850	50-60
Pressure (Bar)	30	70	1-25	1-30
Exploitation period (h)	60 000 -100 000	20 000-60 000	~ 20 000	20 000 – 60 000
Technological maturity	Mature	Commercialized	Demonstration	Large scale prototype

In addition, cost optimization remains crucial to the intensity of deployment of all water electrolysis technologies. While cost reductions for AWE technology have been moderate over the past few decades, for PEM technology it has reached a significant amount. Despite this, PEM electrolyzers are still around 30% more expensive than their AWE counterparts.

The reduction in PEM costs was mainly achieved through the implementation of effective R&D measures, as these technologies had very limited market penetration. CAPEX for the development of various water electrolysis systems currently stands at USD 500-1400·kW^{-1} for AWE, USD 1100-1800·kW^{-1} for PEM, as well as USD 2800-5600·kW^{-1} for SOEC technology [15]. CAPEX projections for AWE and PEM technologies by 2030 are shown in Figure 4.

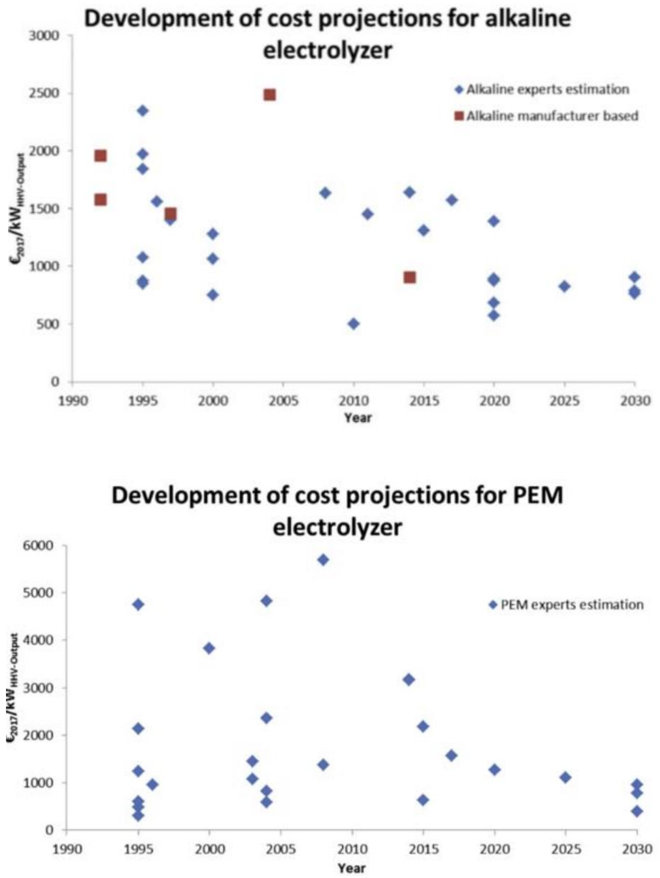

Fig. 4. **CAPEX estimate for AWE and PEM technologies (source: Université catholique de Louvain)**

Availability of critical materials

Building a successful hydrogen economy relies heavily on a deep understanding of the equipment and materials used throughout the hydrogen value chain, including the production, storage, transportation and use of resources. The production of green hydrogen requires critical materials used in fuel cells, electrolysers, hydrogen storage and hydrogen transport technologies [16].

In this context, the term “critical” does not mean either the physical or chemical characteristics of materials or minerals, or the size of their reserves; it indicates the availability and economic significance of these raw materials. For example, the critical nature of minerals is determined by the following parameters: future availability, capacity to increase production and supply at sufficient speed, inflation and cost growth, as well as the geopolitical and strategic situation.

Critical raw materials in green hydrogen production include platinum (Pt), iridium (Ir), palladium (Pd) and ruthenium (Ru), known as platinum group metals, as well as rare earth metals such as neodymium (Nd) and dyspnosia (Dy). In addition, nickel (Ni), cobalt (Co), zirconium (Zr) and manganese (Mn) are essential for certain types of hydrogen production and storage technologies. These materials are crucial for the development of hydrogen technologies but are particularly exposed to supply chain (logistics) and geopolitical risks [17].

The availability of critical materials varies for each type of electrolyser: for example, nickel needed by AWE is relatively common, with global resources estimated at 350 million tons (mainly in Australia, Indonesia, South Africa, Russia and Canada) [18]. By contrast, PEM's required platinum is much less common, and its reserves are much smaller. Worldwide platinum deposits are estimated at 70 thousand tons, 90% of which are concentrated in one country, South Africa (see Figure 5) [19].

Meanwhile, Figure 6 shows estimated demand for nickel, platinum and palladium for electrolyser production by 2040 relative to global mining rates of these resources in 2019. This suggests a significant increase in platinum and palladium demand and a relatively low increase in nickel demand is expected, meaning platinum and palladium have the greatest potential to become a risk in the supply chains of critical materials important to water electrolysis technologies.

However, there is some uncertainty in future resource demand forecasts, both in the medium and long term, related to the sensitivity of the analysis to the projected pace of development of electrolyser technologies and the annual production forecasts of equipment [20].

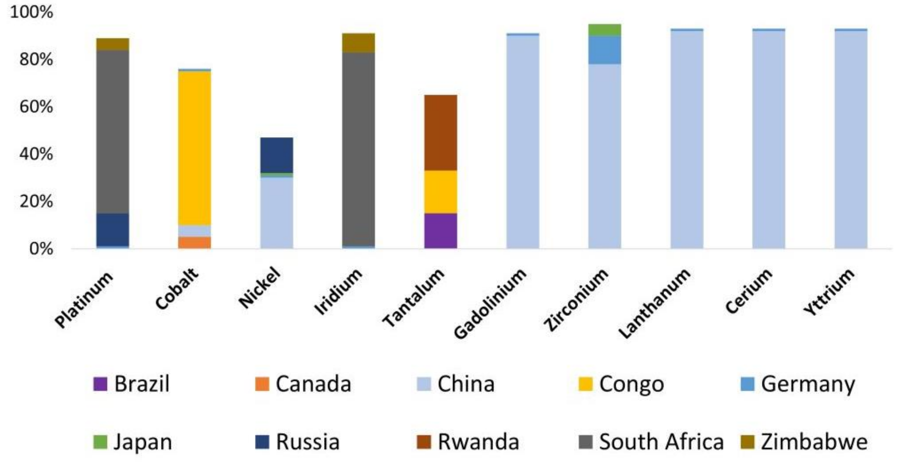

Fig. 5. **Global availability of critical materials for water electrolysis technologies (by country, %; source: IEA)**

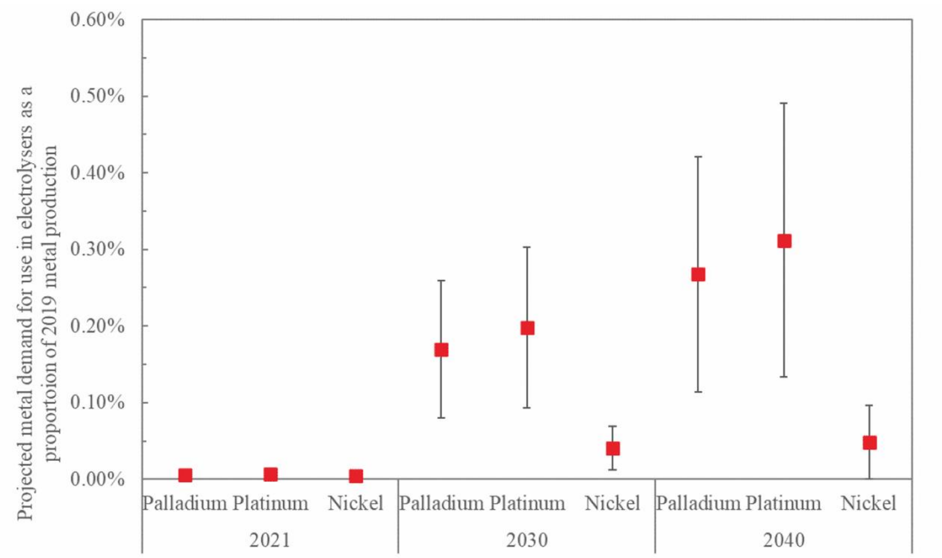

Fig. 6 **Demand for nickel, platinum and palladium to produce electrolysers (source: BloombergNEF)**

The technology comparison: AWE and PEM

The key to producing green hydrogen is to choose the most appropriate electrolysis technology and type of electrolyser. In their range, two of the most mature technologies are most often highlighted: AWE and PEM. As more industries exploit the potential of hydrogen as a clean energy carrier, it is important for stakeholders to understand the strengths and weaknesses of these two technologies to make the right choice for an electrolysis solution tailored to a particular company or industrial activity area.

When choosing one of the electrolyser technologies, one must consider several factors unique and specific to the planned project: electricity costs, load stability, working pressure, available area, project size and operating conditions.

- High-pressure AWE electrolyzers offer a range of advantages over lower pressure solutions: they consume less energy, more easily track changing RES loads and enable hydrogen to be fed directly into an industrial process. In addition, there is no need to invest in additional pressure equipment to reduce overall costs and avoid the purchase and operation of additional compressors.
- PEM technology requires expensive limited-access materials, including platinum-group rare earths metals and fluoropolymers. These materials increase overall costs and insufficient or limited supplies of them may threaten the availability of PEM electrolysers. For example, PEM electrolysers need around 300-400 kg of iridium per 1 GW hydrogen production capacity, while the total yearly production of iridium is only around 8-9 tons since commercially it is only produced as a by-product of nickel and copper production [21].
- PEM electrolyzer electrode separation requires the use of fluoropolymers belonging to a class of chemicals called PFAS. Known as “forever chemicals”, they are extremely persistent in the environment. If they end up in the human body, they can cause health problems such as liver damage, thyroid disease, obesity, fertility problems and various types of tumors.
- AWE and pressure AWE electrolyzers are best suited for most applications. They are particularly suitable for large-scale installations and can be easily adapted to changing industrial needs. They offer more flexibility, more resilient and reliable technology and products that meet the hydrogen quality requirements of practically all industries.
- For the transport sector or other more specialized sectors, PEM could be a primary choice, as it ensures a higher degree of purity of hydrogen, which meets particularly stringent quality requirements.
- Hydrogen purity requirements are also an extremely important decision-making factor. In cases where the degree of purity of the hydrogen produced is insufficient, it must be further purified. A few hydrogen purity standards are currently being used globally based on two categories of application: industrial applications (pure hydrogen) and applications in hydrogen mobility solutions (the highest purity hydrogen). The standardization of the degree of purity of hydrogen for both groups is shown in Table 3.

Table 3

Standardization of the degree of purity of hydrogen

Component	Unit	The highest purity level	High purity level
H_2	%	99.999	99.995
N_2	ppm	13.097	29.778
O_2	ppm	0.49	4.82
Moisture	ppm	1.7	5.43

- When choosing between AWE, pressure AWE and PEM electrolysers, it is imperative to be guided by a holistic assessment, considering factors such as efficiency, cost, scalability and compliance with the priorities of a given project.
- The modular design of PEM electrolysers allows for great scalability, facilitating the configuration of systems of varying sizes according to actual operational needs. The scalability of electrolyser installation can be based on various technological approaches. Increasing the module size can lead to some benefits in economies of scale, with these greater for the balance of plant. The stack has limited economies of scale since it cannot be indefinitely increased in

size but will most likely be increased in number. This is due to problems that include, for example, leakage, limitations in the manufacturing of large-scale components, mechanical instability for large-scale components, the maximum area of the cell etc. The balance of plant, however, can have strong economies of scale. For instance, a compressor that is ten times larger (1MW to 10MW) is not ten, but only about four times more expensive. This would reduce the impact that such a compressor has on the overall cost, since the stack would be 9-10 times more expensive for the same capacity increase. This leads to the stack having a larger contribution to the total cost, as module size increases.

Results and discussion

Comparison of the effectiveness of PEM and AWE technologies, in accordance with sustainability, scalability, existing technology implementation experience and reliability, hydrogen purity and a range of technological and operational characteristics, is given in Table 4.

Table 4

Basic comparison of effectiveness of PEM and AWE technologies

Characteristic	**AWE**	**PEM**
Suitability for large scale hydrogen production	**Projects with 100 + MW installed capacity have been implemented**	MW-level installed capacity projects have only recently started to be implemented
Experience	**More than 50 years of professional experience with 1 + GW total installed electrolyser capacity worldwide**	About 15 years of commercial exploitation experience with some tens of MW installed capacity in the world
Reliability	**Minimum maintenance requirements, high tolerance levels for non-exceptionally high purity air and water**	Advanced, high-automation technology is less tolerant of non-ultra-high purity air and water
Hydrogen purity	Purity meets the requirements of most hydrogen industrial consumers, high	**Highest purity level applicable also for use in fuel cell installations, the highest**
Stack size	**Up to 5 MW**	1-2.5 MW
CAPEX	**Low**	Approximately 15% higher than AWE
Materials	**Widely available and relatively cheap materials are used**	Rare earth metals and platinum group metals are used which are relatively expensive and/or limited access
Exploitation cycle	**~ 80 000h**	~ 50 000h
Cost	**Lower**	Higher
Launch time	Long	**Short**
Load change response	Slow	**Fast**
Scalability	**Ideally scalable**	Partially scalable
Operational temperature	60-80°C	**50-70°C**
Exploitation costs	**Low**	High
Material costs	**Low**	High

On the other hand, the comparison between PEM and AWE main components CAPEX for two scaling scenarios, 5 and 100 MW (as for 2020 and 2030), are summarized in Table 5. It shows comparative CAPEX positions of PEM and AWE systems, based on their cost intensity in $EUR \cdot kW^{-1}$ of installed capacity, with stack investments being one of the most significant (from 185 and 149 for AWE to 294 to 212 for PEM in 2020). It is obvious that few expense categories, like stack, power electronics, instruments and engineering costs dominate over other in terms of their weight in CAPEX both for AWE and PEM installations. Decrease in costs for both technologies is expected by 2030, but it could be deemed as significant only in case of AWE 100MW installation – here, for instance, stack expenses are predicted to drop from 149 to 64 or almost three-fold. At the same time, for PEM decrease in stack expenses is expected to go down from 212 to 143 or about 33%. Regarding power electronics, the expense drop estimate is practically equal for PEM and AWE. In case of PEM 100MW installation, the expense drop estimate is about 37%, but in case of AWE – about 36%. For instrument costs the expense drop in 2030 for 100MW AWE installation is expected to be equal to 30%, but for PEM – to 32%. Engineering cost decrease for 100MW installations is also expected to take place, with drop of about 30% for PEM and 34% for AWE. In Table 5 the significant difference between PEM and AWE technologies and their CAPEX is indicated in only one category: pressure adjustment (compression). It is taken as a reference that PEM electrolysers do not need any external compressors as they operate at high pressure (up to 35-40bar), but AWE electrolysers may need them, as their normal operational pressure range is 0 to 16 bar [22]. However, not all AWE electrolyser installations need external compression unit support, some high-pressure installations can produce hydrogen at 32 bars with no external compressors used.

Table 5

Comparison between PEM and AWE main components CAPEX (2020/2030, 5 and 100 MW, EUR·kW^{-1}; based on data from *Fraunhofer Institute for Solar Energy Systems ISE*)

	PEM				AWE			
Year	**2020**		**2030**		**2020**		**2030**	
Installed capacity, MW	**5**	**100**	5	100	**5**	**100**	5	100
Stack	**294**	**212**	205	143	**185**	**149**	99	64
Power electronics	**195**	**193**	123	122	**160**	**159**	102	101
High voltage converter	**0**	**25**	0	27	**0**	**25**	0	26
BoP cathode and H_2 purification	**76**	**18**	82	18	**80**	**22**	83	21
BoP anode	**26**	**18**	25	12	**24**	**16**	24	12
H_2O purification	**9**	**1**	10	1	**9**	**1**	9	1
Cooling	**12**	**6**	10	5	**10**	**4**	9	4
Compression	**0**	**0**	0	0	**123**	**47**	128	49
Pipelines	**98**	**90**	73	63	**95**	**88**	70	60
Instruments	**122**	**71**	91	49	**118**	**70**	88	48
Buildings	**19**	**19**	15	15	**22**	**22**	19	19
Engineering costs	**128**	**65**	95	46	**124**	**60**	95	40

Rare case studies were carried out indicating the cost reduction potential for different installed capacity scenarios of same electrolysis technology or different technologies. Regarding one technology, there is an example from a case study performed in Germany, which, based on bottom-up design and cost assessment of 2015, found cost reduction potential close to 50% for a 100MW AWE electrolyser (EUR 520·kW^{-1}) versus a 5MW AWE electrolyser (EUR 1070·kW^{-1}) by 2020 [23]. If comparing with the data reflected in Table 5, it is seen, that, indeed, significant cost reduction can be archived in AWE electrolyser capacity scaling from 5 to 100MW. However, percentwise from AWE installation cost data presented in Table 5 (2020), it is obvious that saving close to 50% was not reached. In 2020, the indication of cost savings for scaled up AWE project with 100MW installed capacity in comparison to 5MW capacity stood at about 31%.

Conclusions

Escalating interest in water electrolysis technologies occurs worldwide, as green hydrogen production is one of the most promising RES vectors for decarbonization of regional and global national economies. However, green hydrogen production is often limited due to economic issues and technology maturity reasons. Currently, two technologies – AWE and PEM, appear as the most significant and most commercialized in the global green hydrogen production. There are number of water electrolysis producers who offer AWE and PEM electrolysers in the global market with MW-scale installed capacities.

However, at the level of basic comparison of effectiveness, the two technologies have yet not achieved obvious parity. While PEM technology demonstrates advantages in terms of hydrogen purity, electrolyser launch time, operational temperature and load change response, AWE still prevails in terms of suitability for large scale hydrogen production, experience, reliability, stack size, CAPEX, material costs, and exploitation costs. As for comparison between PEM and AWE main components CAPEX for water electrolysis installations of 5 and 100 MW in 2020, AWE prevails significantly in two categories – stack and power electronics, and this cost gap, especially in stack costs, is expected to remain, if not widen, in 2030. At the same time, in terms of necessary hydrogen compression, PEM technology advantages are prevailing.

As for critical materials, AWE technology is the most sustainable of the two, as it does not require usage of platinum group metals and rare earth minerals, on which PEM technology is totally dependent at its current stage of development.

Acknowledgements

This research was funded by project **"**Development of a medium-power PEM electrolyser with a new generation of catalytic coatings**"** (No. 1.2.1.2./1/24/A/CFLA/003).

Author contributions:

Conceptualization, A.B., L.J., A.L.; methodology, A.L.; software, A.B..; validation, A.B. and L.J.; investigation, A.B., L.J., A.L..; data curation, A.L.; writing – original draft preparation, A.B., L.J.; writing – review and editing, A.L.; visualization, A.B.; project administration, A.B.; funding acquisition, A.B., L.J., A.L. All authors have read and agreed to the published version of the manuscript.

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