sciendo

LATVIAN JOURNAL OF PHYSICS
AND TECHNICAL SCIENCES
2025, N 5

DOI: 10.2478/lpts-2025-0039

PURSUING OPPORTUNITY: A MULTI-DIMENSIONAL ANALYSIS OF GREEN HYDROGEN PRODUCTION TECHNOLOGIES

D. Kronkalns[1], L. Zemite[1,2*], L. Jansons[3], A. Backurs[4]

[1]Faculty of Computer Science, Information Technology and Energy,
Institute of Power Engineering,
Riga Technical University,
12-1 Azenes Str., LV-1048, Riga, LATVIA
[2]Riga Nordic University,
1 Valerijas Seiles Str., building 5, Riga, LV-1019, LATVIA
[3]Faculty of Engineering, Economics and Management,
Riga Technical University,
6 Kalnciema Str., Riga, LV-1048, LATVIA
[4]Faculty of Engineering and Information Technologies,
Latvia University of Life Sciences and Technologies,
2 Liela Str., LV-3001, Jelgava, LATVIA
*e-mail: prof.zemite@gmail.com

The European Union's (EU) decarbonisation strategy identifies green hydrogen as a critical energy vector for achieving climate neutrality by 2050. Electrolysis powered by renewable electricity is the most mature zero-carbon pathway for hydrogen production, yet four main electrolyzer technologies: Alkaline Electrolysis (AE), Proton Exchange Membrane Electrolysis (PEM), Solid Oxide Electrolysis (SOE), and Anion Exchange Membrane Electrolysis (AEM), differ significantly in their technical, economic, and environmental characteristics.

This study presents a comprehensive comparative assessment of these technologies, integrating peer-reviewed literature, manufacturer data, and case study evidence from industrial and pilot-scale deployments. Technical parameters analysed include efficiency, operating pressure, temperature, hydrogen purity, current density, lifetime, and operational flexibility. Economic indicators cover capital expenditure (CAPEX), operating expenditure (OPEX), cost-reduction trajectories, and material availability constraints. Environmental performance is assessed using life cycle considerations, including raw material sourcing, operational emissions, and recyclability.

The findings indicate that AE offers cost-effective large-scale production but is less suited to variable renewable integration, PEM provides high efficiency and load flexibility at higher cost, SOE delivers maximum electrical efficiency when coupled with high-temperature heat sources, and AEM shows promise for cost reduction but requires durability improvements. Results support the hypothesis that no single technology meets all requirements, and a diversified electrolyzer portfolio will optimise the EU hydrogen deployment. Policy, investment, and infrastructure planning should therefore prioritize technology complementarity, supply chain resilience, and integration strategies tailored to regional renewable energy profiles.

Keywords: *Alkaline electrolysis, anion exchange membrane electrolysis, electrolyzer technologies, proton exchange membrane electrolysis, solid oxide electrolysis.*

1. INTRODUCTION

Electricity production in the EU is increasingly based on environmentally friendly resources – the integration and growing share of renewable energy sources (RES). The share of electricity generated from RES continues to increase every year, and this trend is expected to keep growing. Over nearly two decades, from 2004 to 2023, the share of electricity generated by RES has risen by 15 %, from 9.6 % to 24.5 % of the total electricity consumed in the EU [1].

As early as 2018, a target was set for the share of electricity generated from RES in the EU to reach 32 % by 2030, in accordance with the Renewable Energy Directive 2018/2001/EU. In 2021, this target was raised to 40 %, and in 2023, in line with the Renewable Energy Directive EU/2023/2413, the target was further increased to 42.5 % [2]. According to the European Green Deal, climate neutrality must be achieved by 2050 [3].

All the above-mentioned factors highlight the EU's strong commitment to transitioning the electricity generation and consumption sector toward RES. Although these commitments represent a significant global achievement, an electricity system based on RES is characterised as variable and unpredictable, and therefore less secure. Integrating energy storage solutions is the most effective way to reduce the imbalance between production and consumption and enhance the security of the electricity system. For example, just like battery storage, hydrogen can also be used as an energy storage medium to compensate for electricity consumption and an energy carrier for transport and other purposes.

In addition to the transition toward climate neutrality, the REPowerEU strategic plan, adopted in 2022, set the goal for the EU to produce 10 million tons of green hydrogen domestically and import an additional 10 million tons by 2030. By 2050, green hydrogen is expected to cover 10 % of the EU's energy demand, with particular focus on the industrial and transport sectors [4].

There are various methods of hydrogen production, which are colour-coded.

Below is a brief overview of the main hydrogen colour coding types:

- blue hydrogen is produced through steam methane reforming, where natural gas is combined with steam. This process yields hydrogen and carbon dioxide (CO_2). The CO_2 emissions are captured and stored underground;

- grey hydrogen is also produced from natural gas using steam methane reforming. However, unlike blue hydrogen, the CO_2 emissions are not captured but released into the atmosphere. Currently, grey hydrogen is the most widely produced type globally;
- black and brown hydrogen are derived from black and brown coal (lignite). Under high temperatures, the coal is converted into a gas mixture that contains hydrogen. This method has the highest environmental impact and is against the EU's climate neutrality goals;
- pink hydrogen is produced via electrolysis powered by nuclear energy, using the fission of uranium or thorium. This method is considered relatively environmentally friendly, as it generates zero or very low CO_2 emissions. However, a major concern is the management of radioactive waste;
- turquoise hydrogen is one of the newer methods. It is based on methane pyrolysis, where methane (CH_4) is heated in the absence of oxygen at high temperatures, resulting in solid carbon and hydrogen. The solid carbon can be used to produce by-products such as car tires, rubber, batteries, electrodes, and more. This method shows strong potential, especially when combined with biomethane;
- yellow hydrogen is produced through electrolysis, where water is split into hydrogen and oxygen. The electricity used comes from the existing power grid, meaning the source of the electricity is mixed and uncertain, typically a combination of fossil fuels and RES;
- green hydrogen is produced using excess renewable energy, such as wind or solar power. The production is based on the electrolysis process, which splits water into hydrogen and oxygen. This method results in no CO_2 emissions into the atmosphere [5]–[8].

Despite its environmental benefits, green hydrogen production remains relatively expensive, currently costing 2 to 3 times more than blue hydrogen production [9]. Despite the current high costs of green hydrogen production, these costs are expected to decrease over the next decade. This projection is linked to various factors and assumptions, such as the reduction in renewable energy production costs, the belief that electrolysis technologies will become more efficient, the development of hydrogen transmission infrastructure, subsidies, rising greenhouse gas (GHG) emission prices, and increasing demand for green hydrogen [10]–[12].

By the end of 2023, an additional 44 new green hydrogen production and consumption projects were registered in the EU, bringing the total number of such projects to 144, of which 88 have a minimum capacity of 0.5 megawatt (MW). These additional 44 projects, with a combined capacity of 88.11 MW, brought the total installed capacity to nearly 259 MW. By 2026, the total installed capacity of such green hydrogen plants is projected to exceed 2100 MW [13].

The goal of this research is to conduct a comprehensive comparative evaluation of four principal water electrolysis technologies, with the objective of determining their technical, economic, and environmental suitability for large-scale green hydrogen production in the EU. The study aims to identify the operational contexts, integration strategies, and infrastructure requirements that optimise the performance and cost-effectiveness of each technology.

It is hypothesised that no single electrolyzer technology can fully satisfy all technical, economic, and environmental

requirements for EU-wide green hydrogen production, and that an optimal deployment strategy will involve a diversified portfolio of electrolyzer types. This portfolio approach will maximise integration with variable renewable energy sources, minimise lifecycle emissions, and reduce dependency on constrained raw materials, thereby increasing resilience and cost competitiveness across different regional and industrial contexts.

Research questions formulated for this study are as follows:

- What are the comparative technical performance characteristics (efficiency, operating conditions, flexibility, and lifetime) of AE, PEM, SOE, and AEM electrolyzers under current commercial operation?
- How does each technology perform when integrated with variable RES such as wind and solar in different EU regional contexts?
- Which deployment configurations (centralised, distributed, and industrial cluster integration) are most suitable for each electrolyzer technology?
- How can a mixed-technology portfolio be structured to optimise EU-wide hydrogen production capacity, cost-effectiveness, and supply chain resilience by 2030 and beyond?

However, the study is subject to several limitations that should be considered when interpreting the findings. First, the technical and economic data used in comparative analysis are derived from published literature, manufacturer specifications, and pilot project reports, which may not fully capture performance variations in diverse operational contexts. Second, cost projections rely on learning curve assumptions and market trend forecasts that are inherently uncertain and may be affected by unforeseen supply chain disruptions, policy changes, or technological breakthroughs. Third, environmental impact assessments are limited by the availability and consistency of life cycle data for emerging technologies, particularly AEM, for which operational datasets remain scarce. Fourth, the analysis does not include exhaustive modelling of future electricity price volatility, which could significantly influence operational economics. Fifth, the regional integration scenarios focus on the EU contexts and may not be directly applicable to markets with different infrastructure, regulatory frameworks, or renewable energy profiles. While the study considers operational integration with variable RES, it does not simulate the full range of grid stability, balancing, and storage requirements at a system level.

2. MATERIALS AND METHODS

The study applied a structured, comparative analysis methodology to evaluate four principal water electrolysis technologies to assess their technical, economic, and operational suitability for large-scale deployment in green hydrogen production across the EU. The methodological framework was designed to ensure consistency in parameter measurement, comparability across technologies, and relevance to both current and projected EU energy transition goals.

The primary data sources included peer-reviewed scientific publications, European Commission's technical reports, industry white papers, and manufacturer datasheets. Data validation was performed by cross-referencing independent reports from at least two separate organisations for each

key parameter. Where discrepancies were found, averaged values or consensus ranges were applied, ensuring a balanced representation of technology performance.

The analytical process was divided into four stages. First, each electrolyzer type was described in terms of its operating principle, core materials (electrolytes, membranes, catalysts), and fundamental electrochemical reactions. Second, technical performance indicators were compiled, including operating temperature, pressure, system efficiency, hydrogen purity, energy consumption per unit of hydrogen, current density, lifetime, and scalability potential. Third, economic indicators were quantified, with CAPEX and OPEX values benchmarked for 2023 and projected for 2030, incorporating cost-learning curve projections based on cumulative installed capacity. Fourth, operational characteristics were assessed, including flexibility, load-following capability, tolerance to feedstock impurities, start-up time, and environmental impact over the device's life cycle.

Tabular comparisons were developed to present advantages, disadvantages, and key operational parameters in a format that supports multi-criteria decision-making. Each table was constructed to provide clear contrasts between the four technologies, while ensuring that the data remained directly traceable to its source. This tabulation was complemented by narrative synthesis, highlighting both converging and diverging performance trends.

In addition to static performance metrics, the study considered dynamic operational profiles. For AE and PEM technologies, which dominate the current EU electrolyzer market, special attention was given to their integration with variable RES such as wind and solar.

Case studies were selected based on their relevance to the EU policy objectives, technological maturity, and representativeness of industrial-scale implementation. Examples included the Fukushima Hydrogen Energy Research Field (FH2R) for AE, the Yara Herøya plant for PEM, the GrInHy2.0 SOEC project in Germany, and the Enapter NEXUS 1000 AEM installation in Braunschweig. Each case study was analysed to extract real-world operational data, including annual hydrogen output, capacity factor, load management strategies, and grid integration approaches. For each project, the role of electrolyzer technology in local energy systems was evaluated, with emphasis on whether hydrogen was used for industrial feedstock, energy storage, transport fuels, or grid balancing.

All electrochemical reaction equations were reviewed and presented to ensure chemical accuracy and clarify the mechanisms underlying hydrogen generation. Schematic diagrams were used to illustrate process flow from renewable electricity generation to hydrogen output, with voltage drop points (V_1, $V_{2}2$, etc.) indicated for system modelling purposes.

The comparative assessment also incorporated environmental impact analysis, referencing life-cycle assessment data where available. This included material sourcing, manufacturing footprint, operational emissions when powered by 100 % renewable electricity, and end-of-life recycling potential for electrolyzer components.

Overall, the methodological approach integrated both current and forward-looking perspectives. The current performance and cost data were presented alongside 2030 projections, enabling scenario analysis for technology selection under different policies, market, and resource availability conditions.

By combining quantitative metrics, qualitative evaluation, and case study insights, the materials and methods framework provided a comprehensive foundation for the subsequent results and discussion.

3. GREEN HYDROGEN PRODUCTION TECHNOLOGIES

There are several electrolysis technologies for green hydrogen production, each with specific advantages, limitations, and deployment contexts. AE is the most mature and widely deployed, offering low capital costs and large-scale production capability, though with moderate efficiency and slower response to variable electricity supply. PEM provides high efficiency and rapid load-following capability, making it suitable for direct coupling with intermittent renewable sources, though it requires costly precious metal catalysts. SOE operates at high temperatures and achieves high electrical efficiency, particularly when integrated with waste heat from industrial processes, but is less flexible in dynamic conditions. AEM is an emerging approach that combines aspects of alkaline and PEM technologies, aiming for lower costs while maintaining reasonable efficiency, but it remains at an early stage of commercialization [14].

Green hydrogen has broad applications across sectors. In industry, it can replace fossil-based hydrogen in ammonia production, steelmaking, and refining. In the transport sector, it can fuel fuel-cell electric vehicles, especially in heavy-duty, maritime, and aviation contexts where batteries are less practical. In the power sector, hydrogen can serve as a long-duration energy storage medium, enabling seasonal balancing of renewable energy generation. It can also be blended into existing natural gas networks or used as a feedstock for synthetic fuels.

From an environmental perspective, the main advantage of green hydrogen is the near elimination of lifecycle CO_2 emissions when renewable electricity and sustainable water sources are used. However, large-scale production requires substantial renewable electricity capacity, water availability, and supportive infrastructure for storage, transport, and distribution. Water use is a consideration: producing one kilogram of hydrogen by electrolysis requires approximately nine litres of deionized water, necessitating careful resource planning in arid regions.

Green hydrogen production uses RES, which are located at the starting point of the production process (see Fig. 1). The RES generation source is connected to a power transformer, followed by a rectifier. The rectifier and power transformer together form the power electronics section, which is then followed by an electrolyzer of the selected technology. At the end of the system is the consumer, who receives the final product – hydrogen.

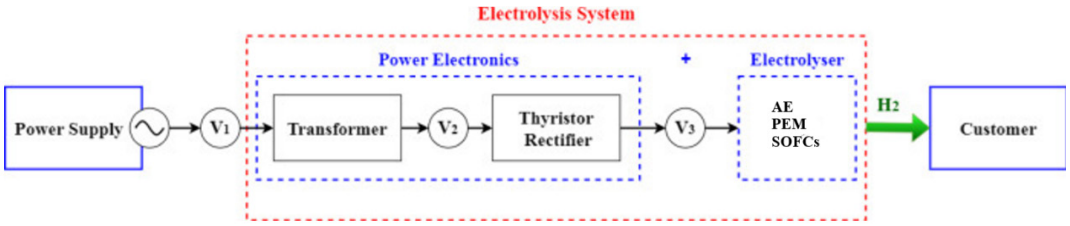


Fig. 1. Principal schematic of hydrogen production [15].

The values indicated at intermediate points of the system, V_1, V_2, etc., represent the corresponding voltage values at each node point. Today, various green hydrogen production technologies are used, each characterised by its own advantages and disadvantages.

3.1. Alkaline Electrolysis (AE)

This technology uses a liquid alkaline solution instead of a solid electrolyte – typically potassium hydroxide (KOH) or sodium hydroxide (NaOH) diluted in water. Electrodes are made of nickel or stainless steel. When voltage is applied to the electrodes, a chemical reaction occurs – at the cathode: $2H_2O+2e^- \rightarrow H_2+2OH^-$, at the anode: $4OH^- \rightarrow O_2+2H_2O+4e^-$. The overall reaction: $2H_2O \rightarrow 2H_2+O_2$.

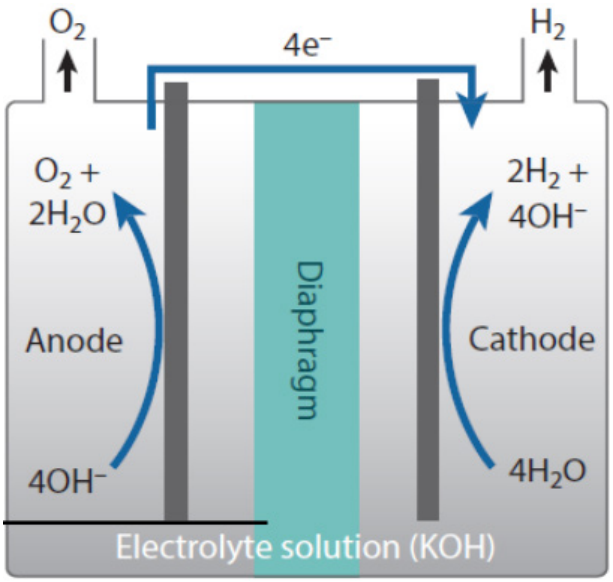


Fig. 2. The chemical process of Alkaline Electrolysis [16].

According to Fig. 2, in the chemical production process of AE, hydrogen and oxygen are produced. The advantages and disadvantages of AE technology are summarised in Table 1.

Alkaline electrolyzers are a reliable and cost-effective technology for hydrogen production, particularly well-suited for industrial applications where large volumes of hydrogen and cost optimisation are required. Their main advantages include low material costs, high tolerance to feedstock impurities, and simple, well-understood maintenance.

In addition to these benefits, there are also drawbacks, such as relatively lower efficiency, high corrosion risk, and a narrow optimal operating temperature range. Furthermore, their slow start-up and the need for specific system configurations make them less suitable for applications requiring rapid response or frequent on-off cycling, like integration with RES like wind and solar.

Table 1. AE Advantages and Disadvantages [17], [18], [14]

Advantages	Disadvantages
Low material costs: Alkaline electrolyzers use readily available and inexpensive materials, thereby reducing overall costs.	Low efficiency: Alkaline electrolyzers have lower efficiency compared to PEM-type devices.
Good tolerance to impurities: Alkaline electrolyzers can operate efficiently even when the feedstock contains impurities such as carbon dioxide or sulfur. They have a high tolerance to contaminants.	High corrosion risk: The alkaline environment can cause component corrosion, reduce the device's lifespan and increasing maintenance costs.
High hydrogen production capacity: These electrolyzers can produce significant amounts of hydrogen, making them suitable for industrial applications.	Narrow operating temperature range: Alkaline electrolyzers have a limited temperature range within which they operate optimally, which can affect performance under extreme conditions.
Basic maintenance, such as cleaning and electrolyte replacement, is required for alkaline electrolysers.	In cases where rapid response is required, such as in solar and wind parks, an additional specific setup is needed.

3.2. Protone Exchange Membrane (PEM) Electrolysis

PEM electrolysis is another method used to split water into hydrogen (H_2) and oxygen (O_2) gases. The main components of a PEM electrolyzer are two electrodes – the anode and the cathode, separated by a solid polymer electrolyte membrane, typically made from a proton-conductive material such as Nafion. The anode and cathode are usually made from precious metals, such as platinum. Currently, research is being conducted to develop more cost-effective alternatives to these expensive materials.

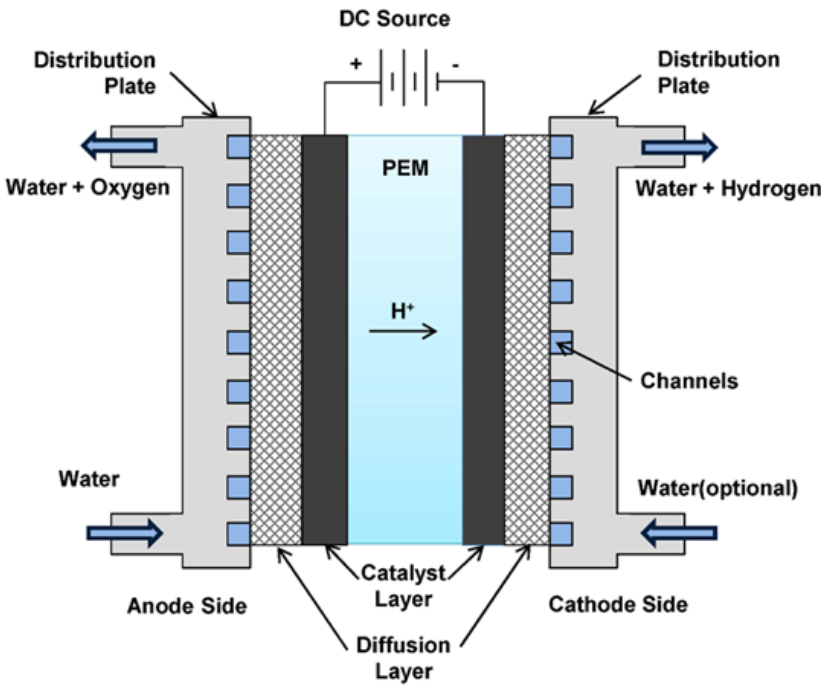


Fig. 3. Structure and operating principle of a PEM electrolyzer [19], [20].

When voltage is applied, an electric current flows through the PEM electrolyzer, which can be described by the following reactions: at the anode, water is oxidized: $2H_2O(l) \rightarrow O^2(g) + 4H+(aq) + 4e^-$. At the cathode, protons are reduced, resulting in the formation of hydrogen gas: $4H+(aq) + 4e^- \rightarrow 2H_2(g)$. The overall reaction for the PEM water electrolysis process is summarised as: $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$.

Table 2. PEM Electrolysis Technology Advantages and Disadvantages [17]

Advantages	**Disadvantages**
High efficiency: PEM electrolyzers provide a high energy conversion efficiency, typically ranging from 70 to 80 %.	High initial costs: Procurement and installation can be expensive, as PEM electrolyzers require significant capital investment.
Fast response to demand: These electrolyzers can respond very quickly to changes in hydrogen demand.	Limited production capacity: This type of equipment is not well-suited for large-scale hydrogen production due to its relatively low output capacity.
Compact design: PEM electrolyzers are relatively small and compact, making them suitable for use in limited or confined spaces.	Dependence on platinum: To ensure efficient operation, a platinum-based catalyst is required, which is costly and may reduce the efficiency of the device over time.
Low operating temperature: Compared to other electrolysis technologies, PEM electrolyzers operate at lower temperatures (typically 5–80 °C), which reduces operating costs.	

AE and PEM hydrogen production technologies are the most widely used in the EU. In 2024, alkaline technology electrolyzers accounted for 46 % of total hydrogen electrolyzer production, with an annual production capacity of 4.09 gigawatt (GW). At the same time, PEM electrolyzers made up 53 % of the total, with a capacity of 4.7 GW per year [13]. AE and PEM electrolyzer production technologies account for nearly 100 % of the technologies used in the EU; therefore, it is important to understand their advantages and disadvantages.

Table 3. Main Properties of AE and PEM Electrolizer [16], [17]

Parameter	**AE Electrolyzer**	**PEM Electrolyzer**
Electrolyte	20–30 % KOH	Perfluorosulfonic Membrane
Anode Catalyst	Nickel-plated perforated stainless steel	Iridium Oxide
Catode Catalyst	Nickel-plated perforated stainless steel	Platinum Nanoparticles
Op. temperature, C	70–90	50–80
Working pressure, MPa	0.1–3	4–7
System Efficiency, %	60–75	70–90
Hydrogen purity, %	≥99.8	≥99.99
Energy consumption, $kWhm^{-3}$	4.2–5.9	<4.3
Hydrogen pressure, MPa	0.1-1	>2
Lifespan, h	6000–80000	8000–60000
Stack cost, EUR/ kW (year 2023)	242–388	384–1071
Stack cost, EUR/ kW (year 2030)	52–79	63–234
CAPEX, EUR/kW (year 2023)	1.66	1.97
OPEX, EUR/kW/year (year 2023)	43	64

When comparing PEM and alkaline electrolyzers, several important differences emerge in both technical characteristics and applications. While alkaline electrolyzers operate using a KOH solution as the electrolyte and reach operating temperatures of around 70–90 °C, PEM-type units use a perfluorosulfonic acid membrane and operate at slightly lower temperatures, ranging from 50 to 80 °C. A significant difference also lies in operating pressure: PEM electrolyzers are capable of producing hydrogen at higher pressures, typically between 4 and 7 MPa, whereas alkaline systems are limited to approximately 0.1 to 3 MPa.

In terms of efficiency, PEM technology is superior – it provides system efficiency of up to 90 % and delivers high hydrogen purity (≥99.99 %), while alkaline systems have slightly lower efficiency – around 60–75 %, with hydrogen purity reaching ≥99.8 %. In addition, PEM devices offer rapid response to changes in electricity supply, making them particularly suitable for integration with variable energy sources such as solar or wind power.

However, these advantages come with higher costs. PEM electrolyzers rely on expensive catalysts such as platinum and iridium, and both their CAPEX and OPEX are currently higher than those of alkaline units. At the same time, alkaline electrolyzers have simpler construction, use cheaper materials such as stainless steel, and can offer a longer operational lifetime, up to 80,000 hours. Furthermore, a significant cost reduction for both technologies is expected by 2030, although PEM systems are still projected to remain more expensive.

For large-scale and continuous hydrogen production, alkaline electrolyzers are more suitable due to their simplicity and lower cost. On the other hand, in scenarios that require high efficiency, hydrogen purity, and operational flexibility, such as decentralised or mobile systems, PEM electrolyzers provide distinct advantages.

3.3. Examples of Alkaline and PEM Electrolyzers

The world's largest green hydrogen production facility – the Fukushima Hydrogen Energy Research Field (FH2R) – is in Namie, Fukushima Prefecture, Japan, and operates entirely on renewable energy. Construction began in 2018 and was completed in 2020. This project is a key part of Japanese government initiatives aimed at promoting renewable energy use and building a low-carbon society. Within the park, green hydrogen is produced, stored, and supplied on demand, and it is also used to help balance the supply–demand dynamics of the power grid. The primary scheme of FH2R's layout is seen in Fig. 4.

The park primarily uses solar energy for hydrogen production – solar panels with a total capacity of 20 MW, covering an area of 180,000 m². A 10 MW maximum-capacity alkaline water electrolysis system is used – the largest single-cell system in the world. The nominal power of this cell is 6 MW. It can produce up to 1,200 normal cubic meters (Nm^3) of hydrogen per hour, which is enough to supply approximately 560 fuel cell vehicles (FCVs) daily. Additionally, with continuous 24-hour operation at a production rate of 1,200 Nm^3, it can supply electricity equivalent to the daily consumption of about 150 households. On an annual basis, the electrolyzer's nominal capacity is 900 tonnes. Hydrogen production and storage in this park are based on demand forecasts provided by a hydrogen supply and demand prediction system. The production volume can be adjusted according to the needs of the grid management system to balance supply and demand. A

key challenge in the current testing phase is ensuring an optimal balance between hydrogen production and storage while adapting to grid needs – all without the use of energy storage batteries [21], [22].

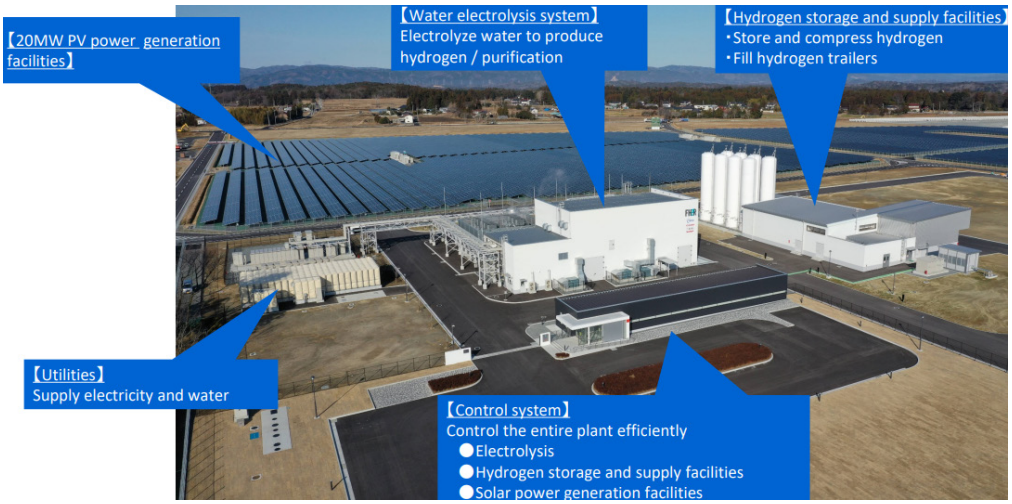


Fig. 4. Fukushima Hydrogen Energy Research Field (FH2R) [21].

The largest alkaline electrolyzer in the EU dedicated to green hydrogen production will be in Huelva, Spain. The operation of the electrolyzers will be powered by nearby solar panel parks and wind farms. The project is based on the installation of *thyssenkrupp nucera's scalum alkaline electrolyzers*, each with a nominal capacity of 20 MW (see Fig. 5). A total of 15 electrolyzers are planned, giving the hydrogen park a total production capacity of 300 MW. The expected annual output is approximately 47,000 tonnes of green hydrogen.

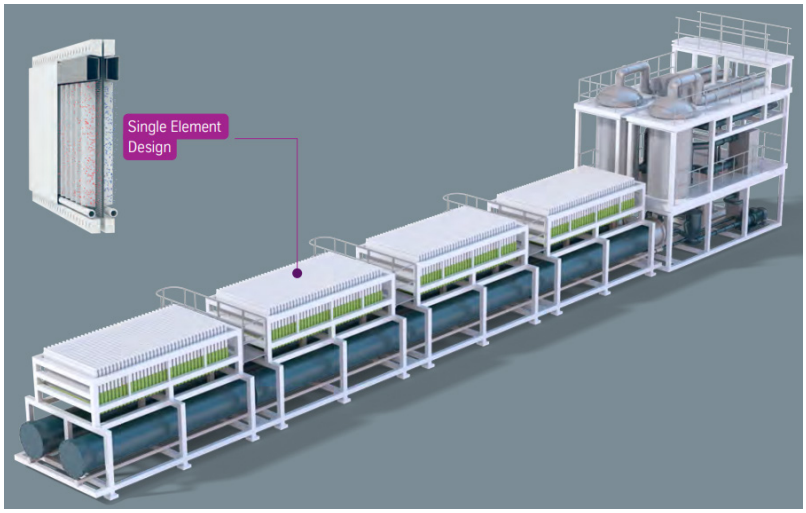


Fig. 5. Scalum 20MW AE unit [23].

According to Fig. 5, the parameters of this unit include an hourly production rate of 4,000 Nm^3, a power consumption of 4.5 kWh/Nm^3, an operating range from 10–100 %, output purity of at least 99.9 %, and a hydrogen outlet pressure of approximately 300 mbar.

The construction of this park is part of a planned strategy to develop 2 GW of green hydrogen production capacity by 2030, and it is expected to become the largest green hydrogen production hub in the EU. The hydrogen produced will be used to supply energy for local industry and heavy transport. The proximity of local ports may serve as a future enabler for exporting green hydrogen within the EU [24].

One of the most ambitious green hydrogen production projects in Europe is planned in Emden, Germany, with the goal of supporting the transition to climate-neutral industry. The project has received support from the EU as a strategic IPCEI (Important Project of Common European Interest) initiative.

Within the scope of the project, a 280 MW PEM electrolysis system will be installed, capable of producing up to 26,000 tons of green hydrogen per year. The electrolysis units will be manufactured at Siemens' new factory in Berlin. The total project cost exceeds €800 million, of which more than €500 million is funded through national and federal programs.

The hydrogen will be produced using RES, which are abundant in northern Germany. The green hydrogen will primarily be used in the steel industry and other energy-intensive sectors, helping reduce CO_2 emissions by up to 800,000 tonnes annually. The project will be implemented in phases, with operations expected to begin in 2027 [25].

Yara Herøya green hydrogen plant is in the Herøya Industrial Park in Porsgrunn, Norway. It is the largest facility of its kind in Europe and was inaugurated in 2024. The plant is based on a PEM electrolyzer through which green hydrogen and green ammonia are produced. The plant has a daily production capacity of approximately 10 tonnes of green hydrogen. This hydrogen is used to produce green ammonia, which is then converted into low-carbon emission fertilizer. Annually, around 20,000 tonnes of green ammonia are produced. By switching from natural gas to renewable energy as a feedstock, the plant reduces CO_2 emissions by 41,000 tonnes per year – equivalent to the emissions of approximately 16,000 passenger cars. The green ammonia produced at this facility is used to help decarbonise the agriculture and shipping sectors [26].

3.4. OXIDE ELECTROLYZER CELL (SOEC) TECHNOLOGY

SOECs operate by splitting steam at high temperatures using both electricity and heat to produce hydrogen and oxygen. The process is based on the conduction of oxygen ions (O^{2-}) through a solid ceramic membrane rather than the conduction of protons or hydroxide ions as in other types of electrolyzers.

In general, SOECs are supplied with hot steam on the cathode side. Reduction occurs at the cathode, where the steam receives electrons according to the following reaction: $H_2O+2e^- \rightarrow H_2+O^{2-}$. As a result, hydrogen is produced as the final product. Additionally, oxygen ions are generated and conducted through the electrolyte. The electrolyte typically consists of yttria-stabilized zirconia (YSZ) – a combination of yttrium oxide (Y_2O_3) and zirconium dioxide (ZrO_2). This electrolyte conducts only O^{2-} ions.

Next, oxidation occurs on the anode side, where the oxygen ions release electrons and form oxygen gas: $O^{2-} \rightarrow 1/2O_2 + 2e^-$. The electrons then flow back to the cathode side through the external electrical circuit (Fig. 6).

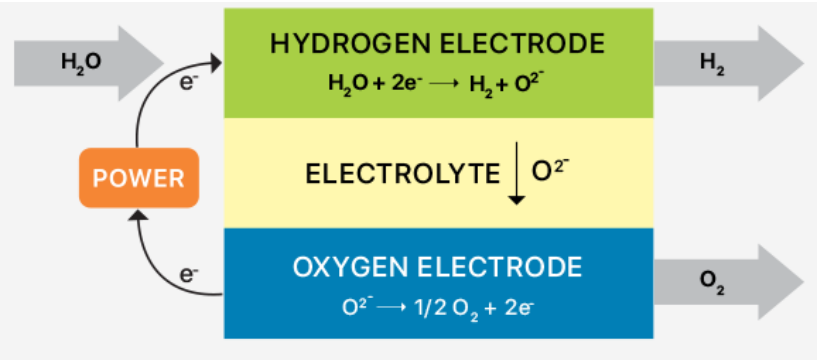


Fig. 6. SOEC method for hydrogen production [27].

In the case of green hydrogen, the operation of the electrical circuit is powered by electricity generated from RES. The SOEC system technology is capable of operating in both normal and reverse modes. In normal mode, during water splitting, steam and electricity are converted into hydrogen and oxygen; in reverse mode, hydrogen and oxygen are converted back into electricity, heat, and water. This bidirectional flow allows the same device to produce hydrogen during the day when there is excess electricity, and to generate electricity at night from the hydrogen produced earlier.

The efficiency of SOEC systems exceeds that of PEM and alkaline electrolysis systems, reaching 85 % or more. [17]. However, despite their high efficiency, the cost of SOEC systems per kilowatt-hour is estimated at around 2000 EUR [28], which is higher than in PEM and AE systems.

SOEC technology operates at temperatures ranging from 600 to 900 °C, which is a significant difference compared to PEM or AE electrolysis technologies. SOEC technology can be characterised by its advantages and disadvantages. The advantages are the following: the ability to achieve high process efficiency, the ability to perform new chemical reactions at elevated temperatures, and the potential to use non-precious metal catalysts in high-pressure processes.

On the other hand, the disadvantages include the need to operate at very high temperatures (up to 1000 °C), high thermal energy consumption, high operational costs, and expensive components, a relatively early stage of development, limited service life due to high temperatures, large and bulky equipment design [29].

SOEC technology is one of the most promising hydrogen production methods, offering excellent efficiency and being particularly suitable for use in high-temperature processes. However, to implement it on an industrial scale, significant challenges related to material durability and high production costs must be addressed. Its widespread commercial use will only be possible through further scientific research, automation of manufacturing processes, and cost optimisation.

3.5. An Example of SOEC Technology

GrInHy2.0 is an SOEC technology project located at the Salzgitter steel production complex in Germany. The electrolyzer is supplied with steam from production surplus and electricity from renewable energy sources. This SOEC technology operates at a high temperature of 850 °C. At this temperature, the ceramic electrolyte becomes capable of conducting oxygen ions. The requirement for high operating temperatures was a key factor in selecting the location. The steel production process generates a large amount of waste heat, which can be redirected to the electrolysis process, thereby increasing the overall system efficiency [30].

The installed SOEC unit has a nominal capacity of 720 kilowatts (kW) and can produce approximately 200 Nm^3 of hydrogen per hour at full load. The unit achieved an electrical efficiency of up to 84 % (HHV) – one of the highest values ever reached in practice. The produced hydrogen was not stored or exported but immediately used within the production cycle, for example, in metal surface treatment (pickling), replacing conventionally used fossil-based hydrogen [31].

The unit has already operated for over 13,000 hours with system degradation below 5 %. The expected system lifetime is 20,000 hours. To date, the unit has produced more than 100 tonnes of hydrogen at a cost of less than 7 EUR/kg [30].

The GrInHy2.0 project has undoubtedly become a model for integrating green technologies into traditional industries, reducing their environmental impact and making them more sustainable. This project proves that SOEC systems are not just a subject of research but a technology capable of operating under demanding and intensive industrial conditions. It has also demonstrated that efficient hydrogen production is not merely a goal for the future – it is already technologically feasible today. However, for such solutions to become widely accessible, continued development of materials, cost optimisation, and a supportive industrial and policy environment are essential.

3.6. Anion Exchange Membrane (AEM) Technology

In recent years, increasing attention has been given to new and promising directions – AEM electrolyzers, or anion exchange membrane electrolysis. This technology aims to combine the advantages of two well-established electrolysis types (PEM and AE) while addressing their major drawbacks.

Traditional AE uses a liquid potassium hydroxide solution as the electrolyte, whereas PEM electrolyzers operate with a solid membrane but require expensive catalysts (such as platinum) and are sensitive to impurities. In contrast, AEM electrolyzers use a solid, polymer-based membrane that conducts OH^- (hydroxide) ions, allowing the system to operate in an alkaline but solid-state environment, without liquid KOH.

This means AEM systems can use cheaper, earth-abundant catalysts – such as nickel, cobalt, and others – reducing overall costs. Additionally, AEM can operate at lower temperatures, up to 70 °C, and with a lower voltage drop, thanks to the small distance between the electrodes [32].

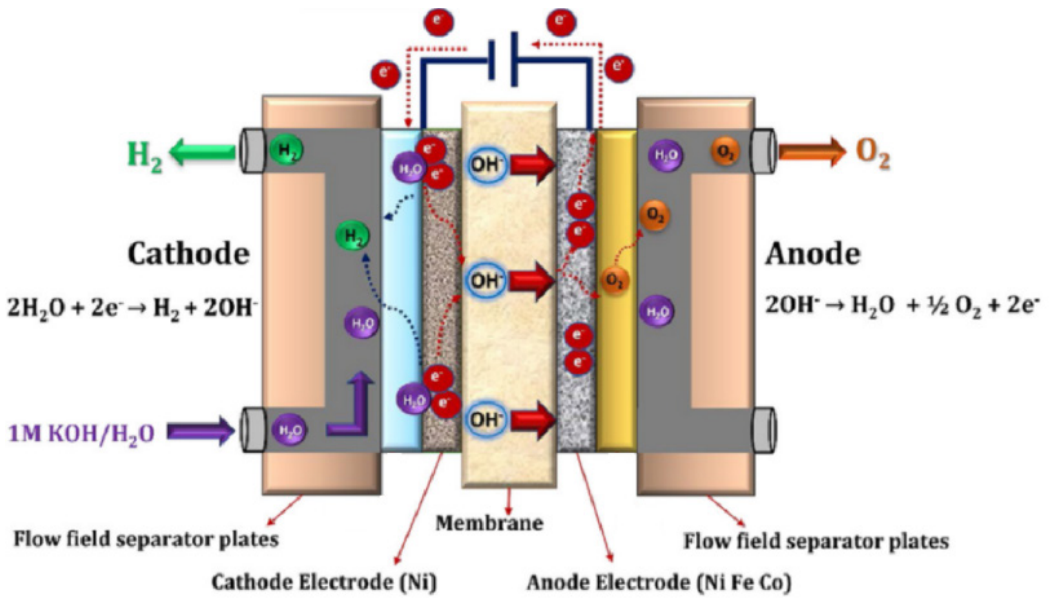


Fig. 7. The structure and operating principle of AEM electrolyzer technology.

The cathode of an AEM electrolyzer is made of nickel (Ni), while the anode is composed of nickel (Ni), iron (Fe), and cobalt (Co). The operation of an AEM electrolyzer is like that of a PEM electrolyzer, but it is characterised by an opposite ion flow direction. In an AEM electrolyzer, anions migrate from the cathode to the anode, whereas in a PEM electrolyzer, cations (protons) move from the anode to the cathode. In the AEM electrolyzer, hydroxide ions and electrons react at the anode, forming water and oxygen gas according to the anode-side (oxidation) reaction: $2OH^- \rightarrow H_2O + 1/2O_2 + 2e^-$. On the cathode side, water molecules are reduced to form hydrogen gas (H_2) and hydroxide ions (OH^-), according to the cathode-side (reduction) reaction: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$. Electrons are supplied to the cathode through an external electrical circuit, thereby completing the electric current flow. Combining both reactions results in the overall electrolysis process – the splitting of water into hydrogen and oxygen gases: $2H_2O \rightarrow 2H_2 + O_2$ [33], [34].

AEM, like other electrolyzer technologies, is still under development to improve its overall efficiency metrics. As of 2020, AEM electrolyzer cell performance indicators included a current density of 0.2–2 A/cm² at a voltage range of 1.4–2.0 V. The operating pressure of the cells was below 35 bar, with load adaptability in the range of 5–100 %. The purity of the produced hydrogen ranged from 99.9 % to 99.999 %, while voltage efficiency (based on LHV) was between 52–67 %. Electrical efficiency at the system level was estimated at 57–69 kWh/kg H_2. The cell lifetime exceeded 5,000 hours, and the typical unit power output was 2.5 kW [33].

For AEM to become a competitive green hydrogen production technology, improvements in key performance metrics are needed (for example, the long-term stability of the membrane and electrolyte in alkaline environments), as the current chemical and mechanical durability is insufficient. The conductivity of hydroxide ions (OH^-) is lower compared to protons (as in PEM), and therefore thinner membranes or higher ion concentrations are needed, which may

reduce long-term durability.

Despite these challenges, the design of AEM electrolyzers closely resembles that of PEM electrolyzers. However, AEM technology is still relatively new, and there is currently a lack of sufficient data regarding its technical parameters, for example, issues related to high differential pressure operation are not yet well-documented.

Soon, improvements are expected in the following areas: durability of AEM membranes, which determines the longevity of the technology; the purity of the produced hydrogen and oxygen; and the ability of the system to operate under high differential pressure [33].

If the shortcomings are overcome and system performance is improved, there is a possibility that this technology can become one of the most widely used electrolysis technologies in the coming decades and play a valuable role in achieving climate neutrality.

3.7. Example of AEM

An AEM electrolyzer has been installed in Germany, at the Braunschweig Research Airport. The goal is to develop the full operational cycle of green hydrogen – production, storage, and delivery to the end user.



Fig. 8. Braunschweig Research Airport AEM electrolyzer production station [35].

The installed electrolyzer (Enapter, NEXUS 1000) is a 1 MW module consisting of 420 AEM units, with a total production capacity of 450 kg of hydrogen per day. The system operates at a pressure of 350 bar, designed for refuelling heavy-duty hydrogen vehicles. The system is powered by a 150-kW solar park and includes battery storage with a capacity of 1.1 MWh. The installed battery system ensures the stability of the power supply system [36], [37].

3.8. Comparative Summary of Electrolyzer Technologies AE, PEM, SOE, and AEM

Table 4. General Comparison of Electrolyzer Technologies AE, PEM, SOE, and AEM [38]–[44]

Criterion	AE	PEM	SOE	AEM
Operating principle	Alkaline electrolyte (KOH)	Solid polymer membrane, selective proton conduction	Operates at high temperatures (700–900 °C), uses a solid oxide electrolyte that conducts oxygen ions	Operating principle similar to PEM, but uses an anion exchange membrane that conducts OH^- ions
Material (electrolyte)	Liquid alkaline solution	Solid polymer	Solid ceramic material (usually YSZ)	Solid polymer membrane
Material (electrode)	Typically made of Ni or its alloys	Materials coated with Pt or Ir	Ni-catalyst ceramic or LSC	Typically made of Ni or its alloys
Efficiency	Moderate efficiency	Very high	Highest	Moderate to high
CAPEX	Low	Very high	Moderate to high	Low to moderate
OPEX	Moderate	Moderate to high	Moderate to high	Low to moderate
Flexibility	Very low	High	Very low	Moderate
Temperature range	Room temperature	Room temperature	Very high	Room temperature
Scalability	High	High	Moderate	High
Environmental impact	Low	Low	Low	Low

Table 5. AE, PEM, SOE, AEM Advantages [38]–[44]

Criterion	AE	PEM	SOE	AEM
Advantages	Proven and widely used technology in industry with a stable operational history; A relatively cost-effective choice; Provides high efficiency in large-scale production.	Efficient operation due to low electrical resistance; Fast response, allowing adaptation to variable loads; Capable of operating at high current density.	Excellent efficiency enabled by high operating temperatures; Capable of functioning both as a fuel cell and as an electrolyzer; Possible integration with high-temperature energy systems.	Production and operational costs are lower than those of PEM technology; There is potential to achieve even higher efficiency; Compatible with alkaline electrolytes, which simplifies material selection and reduces costs.

Table 6. AE, PEM, SOE, AEM Disadvantages [38]–[44]

Criterion	AE	PEM	SOE	AEM
Disadvantages	Lower efficiency compared to other methods; Corrosive electrolyte requires durable materials; Slow response, less suitable for dynamic loads; Limited operational dynamics; Sensitive to impurities, demanding maintenance; Limited pressure, usually up to 30 bar.	High costs; Limited membrane and electrode lifespan; Requires very pure water; Fast response and good adaptability to variable loads;	High temperature requires special materials; Long startup and adaptation time; Moderate reaction speed; Sensitivity to thermal stress; Operates at low to medium pressure.	Limited membrane and electrode stability; Lower current density compared to PEM; Fast response, but further optimization needed; Requires very pure water; Typically operates at lower pressure.

4. CONCLUSION

The study results confirm that each technology offers distinct advantages and faces specific limitations, reinforcing the central hypothesis that no single electrolyzer type can optimally address all operational, cost, and sustainability requirements across diverse EU contexts.

AE technology stands out for its technological maturity, proven large-scale deployment, and relatively low capital costs. Its robustness and scalability make it a strong candidate for centralised, steady-load hydrogen production, particularly in locations with stable renewable supply or access to low-cost grid electricity. However, its slower dynamic response and lower efficiency compared to alternative technologies limit its suitability for direct integration with highly variable RES without buffering or intermediate storage.

PEM technology demonstrates high efficiency, compact system design, and exceptional load-following capabilities, making it well-suited for direct coupling with intermittent renewable generation. Its ability to operate at higher pressures reduces downstream compression requirements, further enhancing system efficiency. Nevertheless, PEM systems face challenges related to high capital costs, reliance on scarce precious metals, and the need for high-purity feed water, factors that could constrain scalability unless significant material innovations and recycling strategies are implemented.

SOE technology offers the highest electrical efficiency when operated at elevated temperatures and integrated with industrial waste heat or concentrated solar thermal systems. Its reversible operation potential, functioning as both electrolyzer and fuel cell, adds further system flexibility in specific applications. However, SOE's high operating temperatures lead to material stress, slow start-up times, and sensitivity to thermal cycling, limiting its use in fluctuating renewable supply environments. Its deployment is most advantageous in industrial clusters with steady heat availability and consistent operational demand.

AEM technology remains at an earlier stage of commercial development but holds promises to combine the lower-cost catalyst and material benefits of AE with some of the efficiency and dynamic advantages of PEM. Its ability to use non-precious metals offers potential for significant CAPEX reduction, and its compatibility with alkaline environments broadens material selection. However, limitations in current density, membrane durability, and long-term performance must be addressed before large-scale deployment becomes viable.

Environmental analysis underscores that all four electrolyzer technologies can achieve very low operational emissions when powered by renewable electricity, but differences in raw material sourcing, component manufacturing impacts, and end-of-life recyclability influence overall life cycle performance. Precious metal use in PEM and certain membrane materials in AEM represent critical areas for improvement in sustainability.

From an economic perspective, cost trajectories indicate that all technologies will benefit from economies of scale and learning curve effects, with the largest reductions expected in PEM and AEM due to current higher CAPEX baselines. However, market volatility in raw material prices, particularly for precious metals and high-grade ceramics, introduces uncertainty into long-term cost competitiveness.

The integration analysis shows that a diversified technology portfolio is the most resilient and cost-effective pathway for the EU-wide green hydrogen deployment. AE is optimal for large-scale, baseload operation; PEM is ideal for flexible, renewable-integrated applications; SOE is suited to high-temperature industrial contexts; and AEM may serve as a mid-range, modular option once technical maturity is achieved.

Policy implications point toward supporting multiple electrolyzer technologies through targeted incentives, coordinated funding, and harmonized standards for performance, safety, and environmental metrics. Investments in recycling infrastructure, material substitution, and manufacturing scale-up will be critical to overcoming resource constraints and reducing costs. Infrastructure planning should align technology deployment with renewable resource profiles, grid capacity, water availability, and hydrogen demand centres, ensuring efficient integration into the broader energy system.

Achieving the EU's 2030 and 2050 hydrogen targets will require a strategic mix of electrolyzer technologies, tailored to regional conditions and evolving market dynamics. This diversified approach will enhance system resilience, optimise renewable energy utilisation, minimise lifecycle environmental impacts, and strengthen supply chain security. The findings of this study provide a foundation for policymakers, investors, utilities, and industry stakeholders to make informed decisions on technology selection, deployment strategies, and supporting infrastructure, ensuring that green hydrogen becomes a central pillar of Europe's decarbonised energy future.

ACKNOWLEDGEMENTS

The research has been funded by the Latvian Council of Science, project "Mitigating Energy Poverty through Innovative Solutions" (project No. lzp-2023/1-02142) and "Implementation of Consolidation and Management Changes at Riga Technical University, Liepaja University, Rezekne Academy of Technology, Latvian Maritime Academy and Liepaja Maritime College for the Progress towards Excellence in Higher Education, Science and Innovation" academic career doctoral grant (ID 1014).

REFERENCES

1. Eurostat. (n.d.). *Renewable Energy Statistics.* Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics
2. EC. (n.d.). *Renewable Energy Targets*. Available at: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-targets_en
3. EC. (n.d.). *2050 Long-Term Strategy*. Available at: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en
4. EC. (n.d.). *Hydrogen*. Available at: https://energy.ec.europa.eu/topics/eus-energy-system/hydrogen_en
5. National Grid. (n.d.). *The Hydrogen Colour Spectrum.* Available at: https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum

6. Jansons, L., Zemīte, L., Zeltiņš, N., Geipele, I., & Backurs, A. (2023). Green and Sustainable Hydrogen in Emerging European Smart Energy Framework. *Latvian Journal of Physics and Technical Sciences*, *60* (1), 24–38. http://doi.org/10.2478/lpts-2023-0003
7. Zemite, L., Jansons, L., Zeltins, N., Lapuke, S., & Bode, I. (2023). Blending Hydrogen with Natural Gas/Biomethane and Transportation in Existing Gas Networks. *Latvian Journal of Physics and Technical Sciences*, 60 (5), 43–55. http://doi.org/10.2478/lpts-2023-0030
8. Savickis, J., Zemīte, L., Zeltins, N., Bode, I., Jansons, L., Dzelzitis, E., … & Ansone, A. (2020). The Biomethane Injection into the Natural Gas Networks: The EU's Gas Synergy Path. *Latvian Journal of Physics and Technical Sciences*, *57* (4), 34–50. http://doi.org/10.2478/lpts-2020-0020
9. IRENA. (n.d.). *Making Green Hydrogen a Cost-Competitive Climate Solution.* Available at: https://www.irena.org/news/pressreleases/2020/Dec/Making-Green-Hydrogen-a-Cost-Competitive-Climate-Solution?utm
10. IRENA. (n.d.). *Renewable Power Generation Costs in 2023.* Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf
11. Yusaf, T., Laimon, M., Alrefae, W., Kadirgama, K., Dhahad, H. A., Ramasamy, D., … & Yousif, B. (2022). Hydrogen Energy Demand Growth Prediction and Assessment (2021–2050) Using a System Thinking and System Dynamics Approach. *Applied Sciences*, *12* (2), 781. https://doi.org/10.3390/app12020781
12. PWC. (n.d.). *The Green Hydrogen Economy. Predicting the Decarbonisation Agenda of Tomorrow.* Available at: https://www.pwc.com/gx/en/industries/energy-utilities-resources/green-hydrogen-cost.html
13. EHO. (n.d.) The European Hydrogen Market Landscape. November 2024. Available at: https://observatory.clean-hydrogen.europa.eu/sites/default/files/2024-11/The%20European%20hydrogen%20market%20landscape_November%202024.pdf
14. Backurs, A., Jansons, L., & Laizans, A. (2025). Water electrolysis technologies: Comparison of maturity, operational and cost efficiency. In: *24th International Scientific Conference "Engineering for Rural Development": Proceedings. Vol. 24*, (pp. 275–285). 21–23 May 2025. Jelgava: Latvia University of Life Sciences and Technologies. http://doi.org/10.22616/ERDev.2025.24.TF061
15. Chaudhary, K., Bhardvaj, K., & Chaudhary, A. (2024). A Qualitative Assessment of Hydrogen Generation Techniques for Fuel Cell Applications. *Fuel*, *358*, Part A. https://doi.org/10.1016/j.fuel.2023.130090
16. NEL. (n.d.) *Introduction to Liquid Alkaline Electrolysis*. Available at: https://www.energy.gov/sites/default/files/2022-02/2-Intro-Liquid%20Alkaline%20Workshop.pdf
17. SENZA. (n.d.). *PEM Hydrogen Generator VS Alkaline Hydrogen Generator.* Available at: https://senzahydrogen.com/pem-hydrogen-generator-vs-alkaline-hydrogen-generator/
18. Stargate Hydrogen. (n.d.). *Alkaline Electrolysers 101: Everything You Need to Know About the Most Reliable Hydrogen Production Technology*. Available at: https://stargatehydrogen.com/blog/alkaline-electrolysers-101/
19. Sood, S., Prakash, O., Boukerdja, M., Dieulot, J.-Y., Ould-Bouamama, B., Bressel, M., & Gehin, A.-L. (2020). Generic Dynamical Model of PEM Electrolyser under Intermittent Sources. *Energies*, *13* (24), 6556. https://doi.org/10.3390/en13246556
20. Stargate Hydrogen. (n.d.). *Exploring the Basics of Hydrogen Electrolysis / Water Electrolysis*. Available at: https://stargatehydrogen.com/blog/basics-of-hydrogen-electrolysis/
21. FH2R. (n.d.). *Fukushima Hydrogen Energy Research Field (F H2R).* Available at: https://www.bdi.fr/wp-content/uploads/2020/03/Fukushima-Hydrogen-Energy-Research-FieldFH2R.pdf

22. Toshiba. (n.d.). *The World's Largest-Class Hydrogen Production, Fukushima Hydrogen Energy Research Field (FH2R) now is Completed at Namie Town in Fukushima.* Available at: https://www.global.toshiba/ww/news/energy/2020/03/news-20200307-01.html
23. Thyssenkrupp Nucera. (n.d.). *Industrial-Scale Water Electrolysis for Green Hydrogen Production.* Available at: https://www.thyssenkrupp-nucera.com/wp-content/uploads/2023/11/thyssenkrupp-nucera_green-hydrogen_brochure_web.pdf
24. Thyssenkrupp Nucera. (n.d.). *Cepsa Selects Thyssenkrupp Nucera as Preferred Supplier of a 300-MW Electrolyzer for Green Hydrogen Plant in Spain.* Available at: https://www.thyssenkrupp-nucera.com/cepsa-selects-thyssenkrupp-nucera-as-preferred-supplier-of-a300-mw-electrolyzer-for-green-hydrogen-plant-in-spain/
25. ETN. (n.d.). Siemens Energy to Set Up 280 MW Electrolyzer for EWE's Clean Hydrogen Coastline Project. Available at: https://etn.news/buzz/siemens-energy-to-set-up-280-mw-electrolyzer-for-ewes-clean-hydrogen-coastline-project
26. Yara. (n.d.). Yara's Renewable Hydrogen Plant in Porsgrunn, Norway. Available at: https://www.yara.com/siteassets/news-and-media/press-kit/renewable-hydrogen-plant-heroya/yaras-renewable-hydrogen-plant-fact-sheet.pdf?_gl=1*1ct2kxq*_up*MQ..*_ga*OTM2ODIzODM3LjE3NDg4OTc3OTA.*_ga_W5MJZ2GTWV*czE3NDg4OTc3OTAkbzEkZzAkdDE3NDg4OTc3OTAkajYwJGww
27. H2E Power. (n.d.). *Solid Oxide Electrolyser Cell.* Available at: https://www.h2epower.net/solid-oxide-electrolyser-cell/
28. Afroze, S., Sofri, A. N. S. B., Reza, M. S., Iskakova, Z. B., Kabyshev, A., Kuterbekov, K. A., … & Azad, A. K. (2023). Solar-Powered Water Electrolysis Using Hybrid Solid Oxide Electrolyzer Cell (SOEC) for Green Hydrogen – A Review. *Energies, 16* (23), 7794. https://doi.org/10.3390/en16237794
29. Aravindan, M, & Praveen Kumar, G. (2023). Hydrogen towards Sustainable Transition: A Review of Production, Economic, Environmental Impact and Scaling Factors. *Results in Engineering*, *20*. https://doi.org/10.1016/j.rineng.2023.101456
30. GrInHy2.0. (n.d.). *GrInHy2.0 – Green Industrial Hydrogen.* Available at: https://salcos.salzgitter-ag.com/fileadmin/footage/MEDIA/SZAG_microsites/salcos/2022/grinhy-20/downloads/flyer/220413_GrInHy2.0_Flyer_v6.pdf
31. Salcos. (n.d.). *Green Industrial Hydrogen.* Available at: https://salcos.salzgitter-ag.com/en/grinhy-20.html
32. Ahmad, M., Hussain, F., Qazi, A., Selvaraj, J., Zainul, R., K., Abd R., … & Benti, N. E. (2024). Recent Advances in Anion Exchange Membrane Technology for Water Electrolysis: A Review of Progress and Challenges. *Energy Science & Engineering.* http://doi.org/12. 5328-5352. 10.1002/ese3.1938
33. Łosiewicz, B. (2024). Technology for Green Hydrogen Production: Desk Analysis. *Energies*, *17* (17), 4514. https://doi.org/10.3390/en17174514
34. Faid, A., & Sunde, S. (2022). Anion Exchange Membrane Water Electrolysis from Catalyst Design to the Membrane Electrode Assembly. *Energy Technology.* http://doi.org/10. 10.1002/ente.202200506
35. Enapter. (n.d.). *Hydrogen Terminal MW-scale Research Hub.* Available at: https://www.enapter.com/en/application/hydrogen-terminal-mw-scale-research-hub/
36. TUB. (n.d.). *Opening and Open Day of the Hydrogen Terminal Braunschweig.* Available at: https://magazin.tu-braunschweig.de/en/pi-post/opening-and-open-day-of-the-hydrogen-terminal-braunschweig
37. SIZ Energieplus. (n.d.). *H2-Terminal Braunschweig.* Available at: https://siz-energieplus.de/en/projects/h2-terminal-braunschweig
38. Vibhu, V., Vinke, I. C., Eichel, R.-A., & de Haart, L. G. J. (2023). $La_{0.6}Sr_{0.4}MnO_3$-Based Fuel Electrode Materials for Solid Oxide Electrolysis Cells Operating under Steam, CO_2, and Co-Electrolysis Conditions. *Energies*, *16* (20), 7115. https://doi.org/10.3390/en16207115

39. Uecker, J., Unachukwu, I.D., Vibhu, V., Vinke, I.C., Eichel, R.-A., & de Haart, L.G.J. (2023). Performance, Electrochemical Process Analysis and Degradation of Gadolinium Doped Ceria as Fuel Electrode Material for Solid Oxide Electrolysis Cells. *Electrochimica Acta*, *452*. https://doi.org/10.1016/j.electacta.2023.142320
40. Yuan, J., Li, Z., Yuan, B., Xiao, G., Li, T., & Wang, J.-Q. (2023). Optimization of High-Temperature Electrolysis System for Hydrogen Production Considering High-Temperature Degradation. *Energies*, *16* (6), 2616. https://doi.org/10.3390/en16062616
41. Wolf, S. E., Vibhu, V., Tröster, E., Vinke, I. C., Eichel, R.-A., & de Haart, L. G. J. (2022). Steam Electrolysis vs. Co-Electrolysis: Mechanistic Studies of Long-Term Solid Oxide Electrolysis Cells. *Energies*, *15* (15), 5449. https://doi.org/10.3390/en15155449
42. López-Fernández, E., Sacedón, C. G., Gil-Rostra, J., Yubero, F., González-Elipe, A. R., & de Lucas-Consuegra, A. (2021). Recent Advances in Alkaline Exchange Membrane Water Electrolysis and Electrode Manufacturing. *Molecules*, *26* (21), 6326. https://doi.org/10.3390/molecules26216326
43. Noor Azam, A. M. I., Li, N. K., Zulkefli, N. N., Masdar, M. S., Majlan, E. H., Baharuddin, N. A., … & Shaffee, S. N. A. (2023). Parametric Study and Electrocatalyst of Polymer Electrolyte Membrane (PEM) Electrolysis Performance. *Polymers*, *15* (3), 560. https://doi.org/10.3390/polym15030560
44. Pérez-Viramontes, N. J., Collins-Martínez, V. H., Escalante-García, I. L., Flores-Hernández, J. R., Galván-Valencia, M., & Durón-Torres, S. M. (2020). Ir-Sn-Sb-O Electrocatalyst for Oxygen Evolution Reaction: Physicochemical Characterization and Performance in Water Electrolysis Single Cell with Solid Polymer Electrolyte. *Catalysts*, *10* (5), 524. https://doi.org/10.3390/catal10050524