Observatorio Tecnológico del Hidrógeno

Renewable hydrogen production via electrolysis:

state-of-the-art and future prospects

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IN COLLABORATION:

Observatorio
Tecnológico
del **Hidrógeno**

Renewable hydrogen production via electrolysis:
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Water electrolysis is emerging as the most promising pathway for renewable hydrogen production, as it enables the conversion of renewable electricity into a versatile, storable energy carrier with no direct emissions.

Electrolysis technologies are evolving rapidly, achieving efficiencies in the range of 60% to 85%.

Alkaline electrolysis (ALK) remains the most mature and widely deployed option – in 2024 it accounted for around 75% of global manufacturing capacity – with overall **efficiencies in the range of 60–65% (LHV) and hydrogen purities of approximately 95.5%. It is followed by proton exchange membrane (PEM) technology, which delivers higher hydrogen purity (99.99%) and efficiencies of around 60–70% (LHV).**

By contrast, **anion exchange membrane (AEM) technology**, still under development, **combines operation at higher pressures than ALK with lower-cost materials than PEM**; whereas solid **oxide electrolysis cell (SOEC) technology**, currently at a pre-commercial stage, **can achieve efficiencies of up to 85%.**

Beyond its technological role, **electrolysis represents a strategic opportunity for energy sovereignty** and will drive the emergence of a new European industrial value chain, with the potential to generate skilled employment, foster innovation, strengthen technological leadership and attract foreign investment.

This executive summary sets out the main conclusions of the report prepared by the Hydrogen Technology Observatory (OTH), and specifically by its members: FHa (Fundación Hidrógeno Aragón), Accelera by Cummins, ARIEMA, CNH2 (Centro Nacional del Hidrógeno), CIDAUT (Fundación para la Investigación y Desarrollo en Transporte y Energía), CIIAE (Centro Ibérico de Investigación en Almacenamiento Energético), CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas), EAG (Empresarios Agrupados – GHESA), Enagás, MIBGAS (Mercado Ibérico del Gas) and Navantia Seanergies.

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Fundamentals of water electrolysis: principles of hydrogen production from water

Electrolysis processes are carried out in an electrolyser, which consists of **two main parts:** the **stack**, or cell stack, which forms the core where the electrolysis reaction takes place, and the **Balance of Plant (BoP)**, comprising the auxiliary equipment and systems that ensure the proper operation of the cells and enable the safe and reliable operation of the overall system.

Water electrolysis consists of **splitting the water molecule into hydrogen and oxygen by applying a direct electric current**, resulting in the following overall reaction:

$$H_2O\ (liq) \rightarrow H_2\ (gas) + \frac{1}{2}\ O_2\ (gas)$$

The electric current is applied through **two electrodes** connected to a power supply. At the **positive electrode**, known as the anode, **the oxidation half-reaction takes place, in which oxygen is generated** (Oxygen Evolution Reaction, OER). At the **negative electrode**, known as the cathode, **the reduction half-reaction occurs, in which hydrogen is generated** (Hydrogen Evolution Reaction, HER). **The specific form these half-reactions take**, representing the processes occurring separately at each electrode, **depends on the electrolysis technology employed**.

The **performance of the electrolysis process** can be described using different efficiency metrics that characterise it from various perspectives. Among the most relevant are **voltage efficiency, current efficiency or Faradaic efficiency, and overall efficiency**. The combined analysis of these indicators provides an integrated view of the electrolyser's behaviour and of how effectively the supplied electrical energy is utilised for hydrogen production.

The efficiency achieved in the operation of an electrolyser is conditioned by various design and operating factors. These include the operating temperature, the applied current density, the electrode materials, and the characteristics and purity of the electrolyte. Gas and impurity management is also a critical aspect, as are the operating conditions under variable load scenarios, particularly when the system is integrated with renewable energy sources.

Electrolysis technologies: types, evolution and current applications

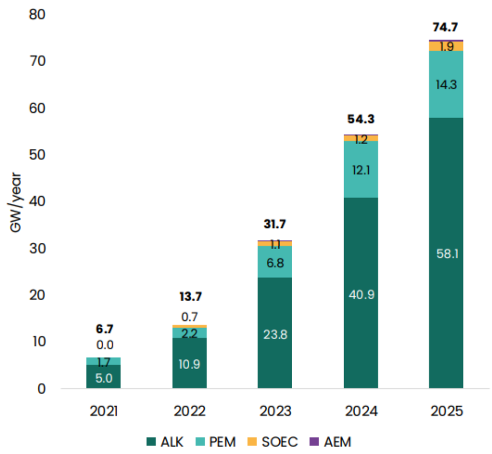
Several electrolysis technologies exist, each with specific characteristics that make them more suitable for certain contexts and applications. The main water electrolysis technologies are:

- Alkaline (ALK) electrolysis
- Proton exchange membrane (PEM) electrolysis
- Anion exchange membrane (AEM) electrolysis
- Solid oxide (SOEC) electrolysis

Electrolysis technologies are evolving rapidly, driven by decarbonisation targets and it is expected an important cost reductions towards 2030.

In market terms, **ALK and PEM technologies currently dominate** due to their maturity, reliability and large-scale availability. Their level of development and industrial consolidation positions them as the reference options for commercial hydrogen production projects based on electrolysis, accounting for the vast majority of installed capacity.

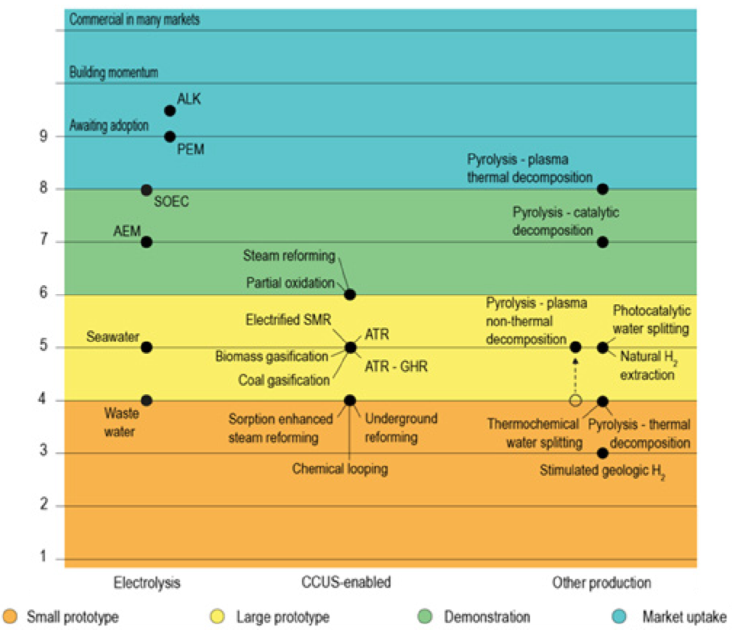
Global electrolyser manufacturing capacity (estimated 2025 data)



SOURCE: Hydrogen Europe, «Clean Hydrogen Production Pathways» 2024

On the other hand, **emerging technologies such as AEM and SOEC offer attractive potential linked to their higher theoretical efficiency and the possibility of reducing material costs**. Nevertheless, they are still at early development stages or in pre-commercial phases, and must overcome significant challenges in terms of durability, scalability and costs before achieving widespread commercial deployment.

TRL of low-carbon hydrogen production technologies



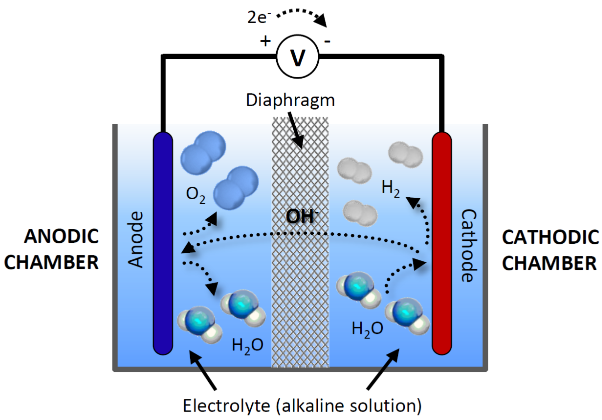
Source: International Energy Agency (IEA), «Global Hydrogen Review 2025»

The main characteristics of each technology are detailed below.:

- **Alkaline technology (ALK)**, with over a century of development, is the most mature one. It **typically operates at temperatures of 60–85 °C** and usually at atmospheric pressure, with **overall efficiencies of around 60–65% (LHV) and hydrogen purities of approximately 95.5%.**

  Its industrial leadership is clear: in 2024 it accounted for around 75% of global manufacturing capacity, dominating most **large-scale commercial projects that require a continuous hydrogen supply**.

General schematic of an alkaline (ALK) electrolysis cell

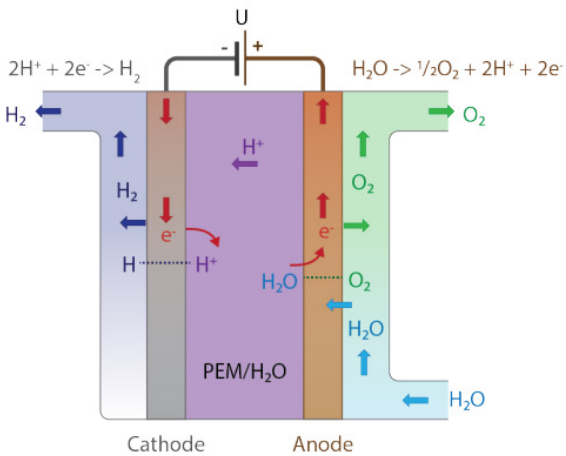


Source: Sustainable Fuel Technologies Handbook., London: Dutta S, Hussain CM. Academic Press, 2021

- **Proton exchange membrane (PEM)** technology is already commercially available and is characterised by its **compact size, dynamic response and high hydrogen purity (99.99%)**. It is expected to account for around 22% of global manufacturing capacity in 2025.

  Current efficiencies are in the range of 60–70% (LHV). It is a consolidated and flexible option for **integration with renewables, due to its capability for dynamic operation and its suitability for applications requiring high hydrogen purity**.

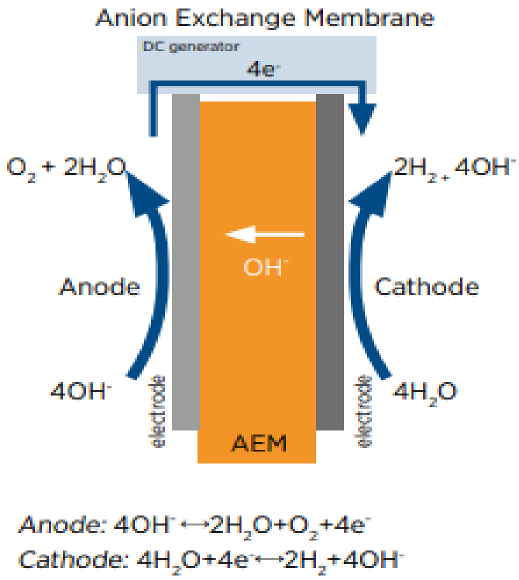
PEM electrolysis diagrams



Source: Journal of Power and Energy Engineering, vol. 5, pp. 34-49, 2017

- **Anion exchange membrane (AEM)** technology is emerging as an option, still under development, that **combines operation at higher pressures than ALK with lower-cost materials than PEM**, making its CAPEX potentially more competitive. This technology is suitable for small- to medium-scale applications and for integration with variable-output renewable power, and it does not require ultra-high water purity. Its **efficiency lies in the 60–70% (LHV) range**. The main challenges are durability and scalability, but its cost potential and adaptability position it as a relevant next-generation candidate.

Schematic view of the operating principle of AEM electrolysis



IRENA, «Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal»
International Renewable Energy Agency, Abu Dhabi, 2020

- **Solid oxide electrolysis (SOEC) technology takes advantage of high-temperature operation (≈ 600–900 °C)** and utilization of any waste heat source to reduce electrical consumption. This technology can achieve **very high efficiencies of up to 85%**. It **is particularly attractive in industrial environments with available steam and for co-electrolysis applications**, but it currently faces barriers related to operational complexity, sensitivity to thermal gradients and degradation. As a result, its current deployment is limited (≈ 3% of estimated manufacturing capacity by the end of 2025) and is mainly oriented towards stationary applications with stable load profiles.

Comparison of electrolysis technologies

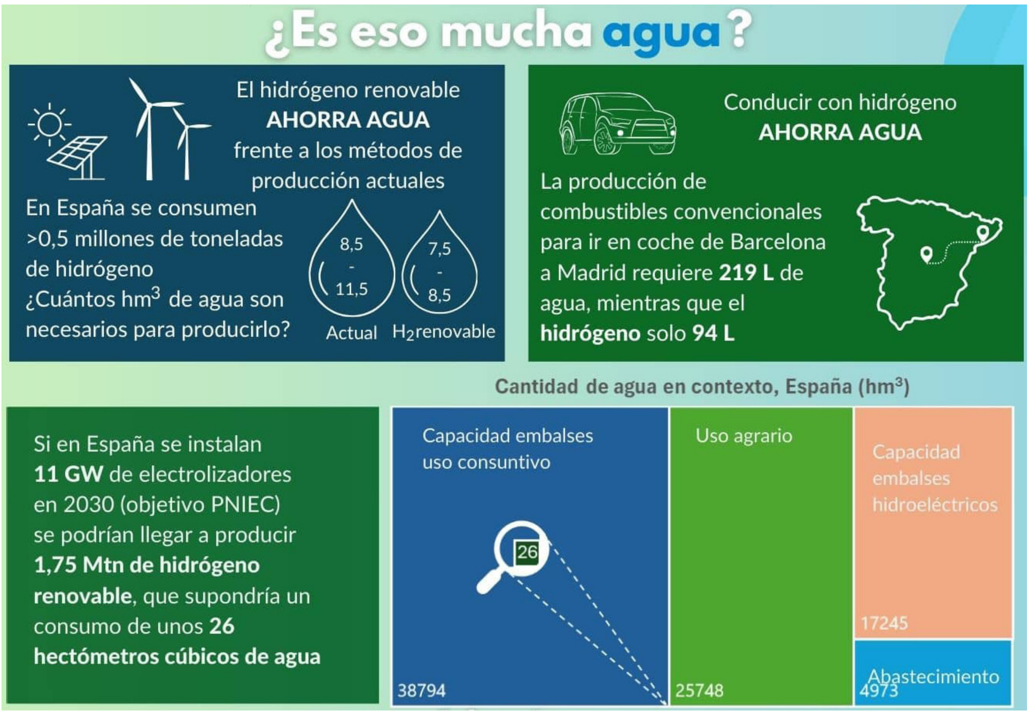
	Current technology status	TRL	Typical efficiency	No. of identified manufacturers	Strengths	Weaknesses	Development trends
ALK	Commercial	9 - 10	60 - 65%	18	• CAPEX • Lifetime	• Flexibility to load variation • Corrosive electrolyte • H2 pressure	• Increased operating pressure • Increased efficiency
PEM	Commercial	9 - 10	60 - 70%	16	• Load flexibility • Compact design • Efficiency • High-purity H_2 > 99.9% • Operating pressure	• CAPEX • Use of precious metals • Use of PFAS	• Reduction in the use of precious metals • Increased service life • Reduction in PFAS
AEL	Development	3 - 7	65 - 70%	3	• CAPEX • Low electrolyte corrosivity • Compact design • Load flexibility	• Maturity of the technology • Membrane lifespan • Useful life	• Improved membranes • Increased service life
SOEC	Pre-Commercial	6 - 8	85%	7	• High efficiency when waste heat is utilised • Possibility of co-electrolysis	• Technology maturity • CAPEX • Plant integration • Flexibility to load variation	• Cost reduction • Operating strategies and integration with other equipment • Improvement of materials

Source: Own elaboration based on data as of December 2025

Water resources and integration of electrolysis into the power system

Water consumption in electrolysis processes **is low and fully compatible with other uses, even under scenarios of extensive technology deployment**. From a stoichiometric perspective, approximately 9 litres of water are required per kilogram of hydrogen produced. When inefficiencies and pretreatment requirements are taken into account, actual consumption lies in the range of 17–22 l/kg of hydrogen. According to an analysis by Asociación Española del Hidrógeno (AeH_2), even with the projected development of electrolysis projects in Spain by 2030, the associated water volume would represent only around 0.1% of the water allocated to agricultural uses.

Water consumption in hydrogen production



Source: the Spanish Hydrogen Association (AeH_2)

Beyond the mere production of hydrogen, the use of electrolysers offers two additional benefits when they are integrated into the power grid. On the one hand, it makes it possible to **utilise renewable generation surpluses** by converting them into stored chemical energy; on the other, it **acts as a source of flexibility and stability for the grid**, facilitating coupling between energy systems (sector coupling) and contributing to a more efficient management of energy resources.

What are the Levelised Cost of Hydrogen (LCOH) and the IBHYX index?

The Levelised Cost of Hydrogen (LCOH) **has become the key indicator for comparing renewable hydrogen with other energy alternatives and for assessing project viability under different scenarios**. In practice, the LCOH aggregates into a single metric the combined impact of technological, economic and operational decisions associated with hydrogen production.

The LCOH is essentially **determined by several factors**: **the price of electricity, which is usually the dominant component**; the CAPEX associated with the electrolyser and the Balance of Plant (BoP); utilisation factors, linked to the annual operating hours; system efficiency; and the fixed and variable operation and maintenance costs.

Considering the scenario in Spain, it is worth highlighting that MIBGAS has developed the IBHYX Index, which is established as the reference levelised cost of production for renewable fuels of non-biological origin (RFNBO) hydrogen in the Iberian Peninsula.

Databases for analysing hydrogen market developments.

The market currently offers **multiple databases that provide access to structured information on the main projects and their most relevant characteristics**.

Among these tools, the most notable are the European Hydrogen Observatory's, the IEA's Hydrogen Tracker, the Hydrogen Infrastructure Map and AeH_2's (Spanish Hydrogen Association) project registry, all of which facilitate comparative analysis and monitoring of the deployment of renewable hydrogen.

Spain as a potential hub for renewable hydrogen production and export

Spain has **distinctive structural advantages** —abundant renewable resources, a well-developed gas network and a strong industrial base— that position it as a **natural candidate to become a hub for renewable hydrogen production and export in Southern Europe**. These strengths enable the country to occupy a differentiated position in the hydrogen economy, both at EU level and internationally.

The development of this energy carrier faces several **short- and medium-term challenges**. Key priorities include accelerating **cost reductions and technological scalability, deploying transport, storage and distribution infrastructures adapted to hydrogen, and establishing clear, stable and harmonised regulatory frameworks** that stimulate investment and provide certainty to the market. In addition, it is essential to promote training and skills development in new professional competencies linked to hydrogen, as a prerequisite for sustaining the sector's growth.

Beyond its purely technological dimension**, electrolysis represents a strategic opportunity in terms of energy sovereignty**: it helps to reduce dependence on imported fossil fuels, supports the stabilisation of the power system and enables progress towards a decarbonised and competitive industrial model.

In this context, **the deployment of electrolysis is set to drive the development of a new European industrial value chain**, with the capacity to create skilled jobs, foster innovation, strengthen technological leadership and attract foreign investment.

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