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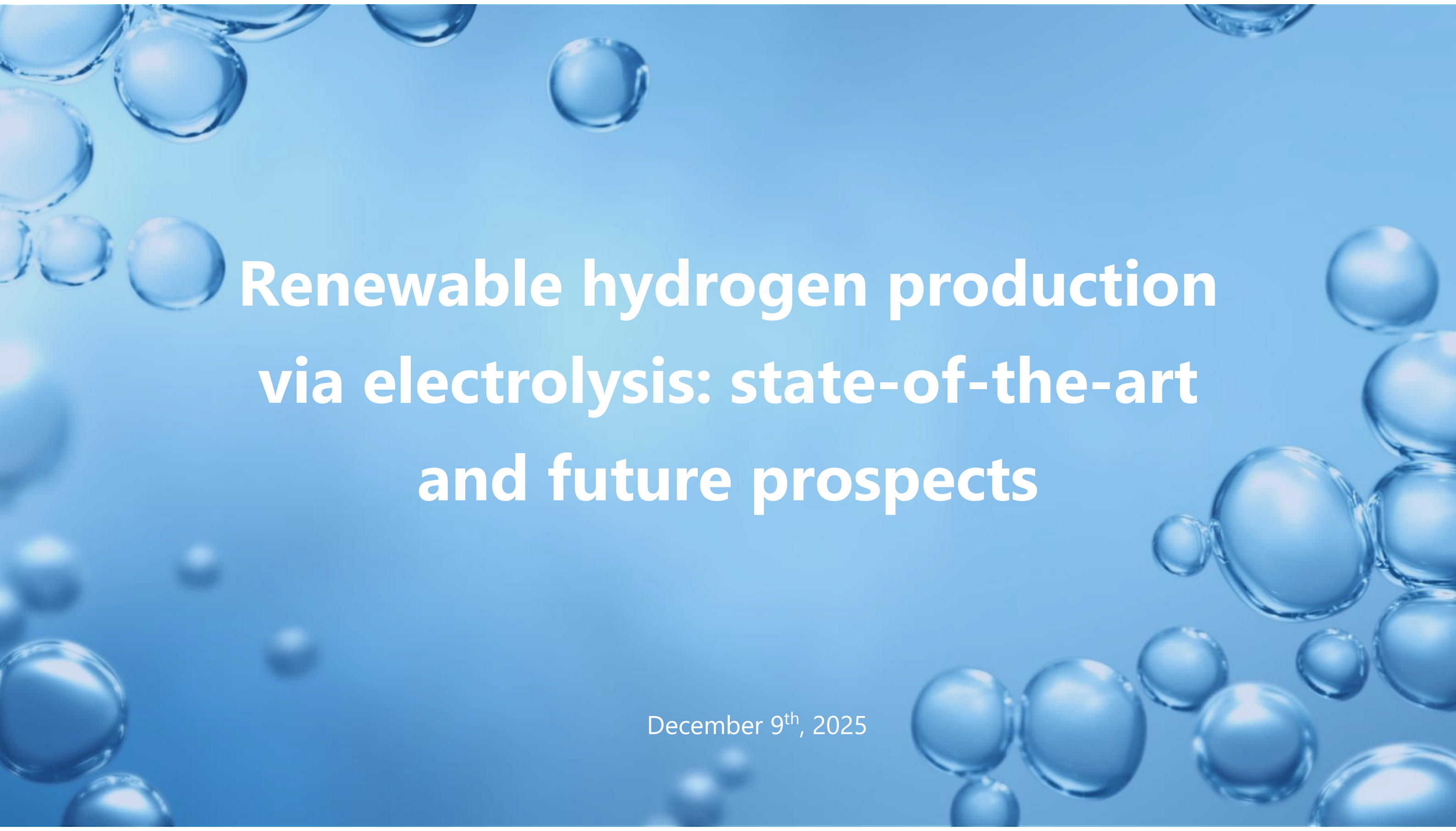

# Renewable hydrogen production via electrolysis: state-of-the-art and future prospects

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## Glossary

| | |
|---|---|
| **AEM** | Anion Exchange Membrane |
| **ALK** | Alkaline Electrolysis |
| **AaaS** | Auction-as-a-service |
| **Ba** | Barium |
| **BoP** | Balance of Plant |
| **AC** | Alternating Current |
| **CAPEX** | Capital Expenditure |
| **DC** | Direct Current |
| **CCUS** | Carbon Capture Utilisation and Storage |
| **CO** | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| **Co** | Cobalt |
| **Cu** | Copper |
| $e^-$ | Electron |
| **EBITDA** | Earnings Before Interest, Taxes, Depreciation and Amortisation |
| **EPC** | Engineering, Procurement and Construction |
| **Fe** | Iron |
| **GDC** | Gadolinium Doped in Ceria |
| **GDL** | Gas Diffusion Layer |
| $H^+$ | Hydrogen proton/ion |
| $H_2$ | Hydrogen |
| **HER** | Hydrogen Evolution Reaction |
| **HHV** | High Heating Value |
| **IEA** | International Energy Agency |
| **Ir** | Iridium |
| **IRENA** | International Renewable Energy Agency |
| **KOH** | Potassium hydroxide |
| **NaOH** | Sodium hydroxide |
| **La** | Lanthanum |
| **LCOE** | Levelised Cost of Energy |
| **LCOH** | Levelised Cost of Hydrogen |

| | |
|---|---|
| **LHV** | Low Heating Value |
| **MEA** | Membrane Electrode Assembly |
| **M** | Molar (concentration) |
| **Mo** | Molybdenum |
| **Ni** | Nickel |
| **$O_2$** | Oxygen |
| **$O^{2-}$** | Oxygen ion |
| **OER** | Oxygen Evolution Reaction |
| **OH-** | Hydroxide ion |
| **O&M** | Operation and Maintenance |
| **OPEX** | Operational Expenditure |
| **PGM** | Platinum Group Metals |
| **PPA** | Power Purchase Agreement |
| **PERTE** | Strategic Projects for Economic Recovery and Transformation |
| **PFAS** | Per- and Polyfluoroalkyl Substances |
| **PEM** | Proton Exchange Membrane |
| **Pt** | Platinum |
| **RFNBO** | Renewable Fuels of Non-Biological Origin |
| **Ru** | Ruthenium |
| **Sr** | Strontium |
| **Ti** | Titanium |
| **SCGZ** | Scandium, Ceria and Gadolinium doped in Zirconia |
| **SOEC** | Solid Oxide Electrolysis Cell |
| **IRR** | Internal Rate of Return |
| **TRL** | Technology Readiness Level |
| **EU** | European Union |
| **NPV** | Net Present Value |
| **WACC** | Weighted Average Cost of Capital |
| **YSZ** | Yttria-Stabilised Zirconia |

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## Executive summary

**Renewable hydrogen is establishing itself as an energy carrier which is key to achieving climate neutrality by 2050** and ensuring European energy security. It is doing so within a global context shaped by the climate urgency, the energy transition and the need to drastically reduce greenhouse gas emissions.

The different production options include **water electrolysis**, which is emerging as the most promising way of generating hydrogen from 100% renewable sources, transforming electricity from clean sources (solar, wind, hydraulic) into a versatile, storable and emission-free energy carrier.

This technical report, drawn up by the Hydrogen Technology Observatory, led by the **FHa (Aragon Hydrogen Foundation)** and developed in partnership with **Accelera by Cummins, ARIEMA, CNH2 (National Hydrogen Centre), CIDAUT (Foundation for Research and Development in Transport and Energy), CIIAE (Iberian Centre for Research in Energy Storage), CIEMAT (Energy, Environment and Technology Research Centre), EAG (Empresarios Agrupados - GHESA), Enagás, MIBGAS (Iberian Gas Market) and Navantia Seanergies**, provides a **comprehensive overview of the state of the art, the technical fundamentals and the prospects for the development of water electrolysis**.

The document offers in-depth analysis of the **physico-chemical principles** that govern electrolysis, the **structural components of the electrolysers** (stack and balance of plant (BoP)) and the associated **water consumption**, underlining that the **electrolytic process requires between 17 and 22 l/kg $H_2$** (a figure significantly lower than that needed for conventional fossil fuel-based processes, which stands at **32.2 l/kg for methane reforming with CCUS and 49.4 l/kg for coal gasification**), reinforcing its environmental viability. It also highlights the importance of developing advanced water purification and reuse technologies to enable large-scale sustainable production.

In the technological sphere, the report examines the **four main electrolysis technologies**:

- **Alkaline (ALK)**, mature and reliable, with decades of industrial experience;
- **Proton exchange membrane (PEM)**, compact and flexible, producing extremely pure hydrogen which is already commercially available;
- **Anion exchange membrane (AEM)**, an emerging technology that combines low cost and potential for scalability; and

- **Solid oxide electrolysis cell (SOEC)**, high thermal efficiency, geared towards large-scale industrial applications.

The **ALK and PEM** technologies currently dominate the market, accounting for over 95% of the installed capacity, while **AEM and SOEC** are rapidly advancing from their demonstration phases towards greater commercial maturity. The report compares their benefits, limitations and operational requirements and the main manufacturers, providing an overview of the technological landscape and the evolution that is expected as we approach 2030.

From an energy standpoint, **efficiencies** between 60% and 70% are currently identified for ALK, PEM and AEM, based on the Lower Heating Value (LHV), and up to 85% for SOEC. The determining factors for these efficiencies include the operating temperature, electrode and membrane materials, current density, thermal management and water purity.

| | Current state of the technology | TRL | Efficiency typical | No. of manufacturers identified | Strengths | Weaknesses | Development trends |
|---|---|---|---|---|---|---|---|
| **ALK** | Commercial | 9-10 | 60%-65% | 18 | Service life<br>CAPEX | Flexibility of the variation in the charge<br>Corrosive electrolyte<br>Pressure of the H2 | Increased operating pressure<br>Gain in efficiency |
| **PEM** | Commercial | 9-10 | 60%-70% | 16 | Flexibility of the variation in the charge<br>Compact design<br>Efficiency<br>High purity H2 > 99.9%<br>Operating pressure | CAPEX<br>Use of precious metals<br>PFAS use | Reduced use of precious metals<br>Increased service life<br>PFAS reduction |
| **AEL** | Development | 3-7 | 65%-70% | 3 | CAPEX<br>Low electrolyte corrosion<br>Compact design<br>Flexibility of the variation in the charge | Maturity of the technology<br>Duration of the membranes<br>Service life | Improved membranes<br>Increased service life |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **SOEC** | Pre-commercial | 6-8 | 85% | 7 | High efficiency if residual heat is used<br>Option of co-electrolysis | Maturity of the technology<br>CAPEX<br>Plant integration<br>Flexibility of the variation in the charge | Cost reduction<br>Operational strategies and integration into other equipment<br>Improved materials |

As for its **interaction with the electrical system**, the study explores the dual role of electrolysis, as a **flexible consumer** that can absorb surplus renewable generation and as a **network stability tool** which is capable of providing balancing services, a rapid response and chemical energy storage. This flexibility makes electrolysis a key component of the **coupling sector** concept, as it directly connects the electricity, gas and industrial systems.

From an economic point of view, a specific chapter is devoted to the **Levelised Cost of Hydrogen (LCOH)**, which is regarded as the main indicator for assessing the competitiveness of renewable hydrogen. It presents the calculation methodology, the variables with the greatest influence on its value (capital expenditure (CAPEX), operational expenditure (OPEX), utilisation factors, the electricity price and efficiency), as well as the cost reduction strategies that are underway, including economies of scale, technological learning, supply chain optimisation and component standardisation. The document also incorporates references to the **IBHYX index of MIBGAS**, a pioneering benchmark in Europe that provides a transparent price signal for renewable hydrogen in the Spanish market, as well as the **economic model of the European Hydrogen Observatory**, which compares scenarios and estimates the LCOH under different operating and financing hypotheses.

It also includes the **main projects and initiatives** that are driving the development of electrolysis in Europe and Spain: the **European Hydrogen Bank**, which channels the first large-scale financial support mechanisms, the **European Electrolyser Partnership**, which promotes industrial coordination to achieve European manufacturing capacity totalling 17.5 GW/year by 2030, and the **PERTE for Strategic Projects for Economic Recovery and Transformation (PERTE ERHA)** within the national framework.

The main **databases and platforms** that are identified (Hydrogen Tracker, Hydrogen Infrastructure Map, European Hydrogen Observatory, AEH2) are also presented as key tools for monitoring the technological and geographical deployment of projects in Spain and Europe and around the world.

Overall, the Hydrogen Technology Observatory report shows that water electrolysis constitutes a **strategic, cross-cutting and rapidly evolving technology** which is capable of articulating a new energy paradigm based on the integration of renewables, industrial decarbonisation and European energy autonomy. Its mass deployment will require **continuous technological innovation, stable regulatory frameworks, competitive access to renewable electricity and stable public-private partnerships** across the entire value chain.

The document concludes that **the advance of electrolysis** will not only **enable the production of competitive green hydrogen**, it will also **promote an industrial fabric** with high added value based on the design, manufacture and operation of electrolysers, generating qualified employment and consolidating Spain’s and Europe’s positions as technological leaders of the hydrogen economy.

# 1. INTRODUCTION

## 1.1. What is renewable hydrogen? Regulatory framework and classification

Renewable hydrogen is hydrogen produced from renewable energy sources. Unlike a primary source (such as the sun or wind), hydrogen is an **energy carrier**; it isn't directly available in nature in a useful form and it must be generated by consuming energy. Its value lies in the fact that it allows **clean energy** to be **stored and then used in a controlled manner** wherever it's needed.

The most widespread method for its production is **water electrolysis** (see chapter 2), using **electricity from 100% renewable sources**. Hydrogen obtained from **biogas reforming** or the **thermochemical conversion of biomass** can also be regarded as renewable, provided that the sustainability requirements of the European framework are met [1], although these pathways lie outside the scope of this document.

The European Union regulates the production and use of renewable hydrogen as part of its clean energy policy. **Directive (EU) 2018/2001 (RED II)** [2]incorporates hydrogen into the category of ***"renewable fuels of non-biological origin"* (RFNBO)** [3], i.e. gaseous fuels such as hydrogen produced from **renewable non-biological sources**.

RED II sets a target for the EU as a whole, stipulating that at **least 32% of the energy consumed in 2030** should come from renewable sources. Moreover, it sets specific **mandatory targets** for renewable hydrogen [4], including:

- that **at least 1% of the energy used in transport** should come from RFNBO by 2030;
- that **at least 42% of the hydrogen consumed in industry** should be of renewable origin by 2030, a figure **that must rise to 60% by 2035**.

The revision of this directive by means of **Directive (EU) 2023/2413 (RED III)** [5] raises the renewables target to **42.5% by 2030**, with an **additional indicative target of 45%**, and incorporates more accurate **targets and definitions** for renewable hydrogen and other green fuels that are only addressed to a limited extent in RED II. It also introduces **more streamlined administrative procedures** (one-stop shops, reduced deadlines) for the authorisation of renewable projects in order to facilitate their implementation. Ultimately, **RED III seeks to accelerate project deployment** and stimulate **large-scale investments in green hydrogen**.

In parallel to RED II, in February 2023, two **Delegated Regulations, (EU) 2023/1184** [6] **and 2023/1185** [7], were approved, complementing its content and specifying what can be regarded as **truly renewable hydrogen** [4] [8]:

- **Delegated Regulation (EU) 2023/1184** defines the conditions that **electricity used in hydrogen production** must fulfil in order to be certified as renewable. It establishes that it must be **100% renewable electricity** sourced from certified facilities, either via a **direct connection** to a renewable plant or by means of a **renewable power purchase agreement (PPA).** Moreover, it requires **additionality**; the electrolysers must be linked to new renewable electricity production and, from 2028 onwards, they may only use energy from assets that are **no more than 36 months old.** It also imposes **temporal and geographical correlation**; until 2030, the monthly match between hydrogen production and renewable generation will be sufficient, but an **hour-to-hour** match within the same geographical area will thereafter be required.
- **Delegated Regulation (EU) 2023/1185** establishes that, for hydrogen to be accepted as **renewable hydrogen** or a **recycled carbon fuel**, the production process must **reduce greenhouse gas emissions by at least 70%** compared to a fossil fuel, applying a **life-cycle calculation methodology**.

On this basis, the European regulation distinguishes between **five broad categories of hydrogen**, each associated with a production pathway with different implications in terms of sustainability and the market:

1. **Renewable non-biological hydrogen (RFNBO)**: This is the **strictest** category and it **sets the standard for sustainability** within the EU. It is obtained by means of **water electrolysis** using electricity from renewable sources (solar, wind), and it must fulfil the conditions of **additionality**, **temporal and geographical correlation** and **demonstration of renewable origin** set out in Delegated Regulations (EU) 2023/1184 and 2023/1185. In addition, it must demonstrate **a minimum 70% reduction in emissions** compared to fossil hydrogen.
2. **Bio-based renewable hydrogen**: This is produced using **biomass or biogenic waste** through sustainable processes, provided that the **sustainability and emission reduction criteria** of RED II and its updates are met. It includes, for example, hydrogen obtained from **biogas reforming** and **sustainable biomass gasification**. Its main benefit is its capacity to recover organic waste and by-products of agricultural, forestry and industrial origin, reducing

the environmental impact associated with waste management, particularly methane emissions resulting from its decomposition.

3. **Hypocarbon hydrogen**: This is hydrogen produced from **non-renewable sources** that achieves **significant emission reductions**, ensuring **at least 70% lower GHG emissions** compared to conventional fossil hydrogen. It can come, for example, from **natural gas reforming with $CO_2$ capture and storage** or **nuclear-powered electrolysis.**
4. **Renewable hydrogen (non-RFNBO)**: This includes hydrogen produced **using renewable sources** without **meeting one or more** of the RFNBO **requirements**.
    - It can use **existing renewable electricity**.
    - It doesn't necessarily require any **temporal or geographical correlation**.
    - It **may not achieve** the **70% emission** reduction.

    One example is an electrolyser connected to an **electrical grid with high renewable penetration** without demonstrating additionality or correlation.

5. **Fossil hydrogen**: This is hydrogen produced using **non-renewable fuels** (natural gas, coal, oil), usually by **reforming natural gas with steam**. It doesn't meet the **70% emission reduction** threshold and therefore it **doesn't qualify as clean hydrogen** within the meaning of the regulation.

**Spain** adopts the same definition of renewable hydrogen and incorporates it into its energy strategy. The **Hydrogen Roadmap** [9] and the **National Integrated Energy and Climate Plan (PNIEC 2021-2030)** [10] include the European criteria and set targets such as **reaching 12 GW of electrolysers by 2030**, chiefly aimed at supplying green hydrogen to **industry** and **heavy transport**.

## 1.2. Challenges and opportunities for renewable hydrogen

Green hydrogen currently constitutes one of the most promising pillars of the energy transition towards low-carbon systems. Its potential to decarbonise hard-to-electrify sectors, promote energy security and stimulate technological innovation is widely acknowledged [11] [12]. However, its development still faces significant economic, technological, regulatory and social challenges. These challenges shouldn't be interpreted as constraints, but rather as catalysts that drive innovative solutions and open up new opportunities for economic, industrial and social development.

From an economic point of view, the cost of producing green hydrogen remains higher than that of producing fossil hydrogen, limiting its competitiveness in the global energy markets. However, this apparent obstacle can become an opportunity for sectors that urgently require sustainable alternatives. The steel, cement and chemical industries, as well as long-distance transport, are paradigmatic examples of activities that need a clean energy carrier that doesn't rely on fossil fuels [13]. These industries are displaying a willingness to make higher upfront investments in order to significantly reduce their emissions. By positioning themselves as pioneering markets, they are contributing to the consolidation of the demand for green hydrogen, the generation of economies of scale and the acceleration of the technological learning curve, thus facilitating a progressive reduction of costs and the increased competitiveness of the sector. In this respect, this economic challenge is being transformed into a lever for innovation and a stimulus for the expansion of the global green hydrogen market.

In terms of the technology, the challenges relate to the efficiency of the electrolysers, the optimisation of the manufacturing, the operational and maintenance processes, the need for secure storage and transport infrastructures and, last but not least, limiting the loss of performance associated with degradation due to the inherently intermittent nature of the renewable energies that feed the process. These difficulties, in turn, can create fertile ground for innovation. Green hydrogen provides the possibility of harnessing renewable surpluses that would otherwise be wasted, converting them into a storable and transportable energy source. This will not only solve any generation variability problems, it will also make the energy systems more resilient and flexible[14]. In this regard, what initially appears to be a technological challenge can become an instrument to consolidate a more robust energy system, one that is capable of integrating increasing quotas of renewable energies.

In the regulatory sphere, the lack of uniform international standards for operating the technologies and specific use cases in terms of certification, safety and sustainability constitutes a challenge for the establishment of a global green hydrogen market. This regulatory vacuum has prompted multilateral initiatives seeking to build common governance frameworks. Achieving this regulatory maturity will foster transparency and investor confidence and contribute to the creation of a clean international hydrogen trade, with countries such as Spain, Chile, Morocco and Australia positioning themselves as potential strategic exporters [15]. The regulatory challenge will thus become the basis for an opportunity to develop new global value chains and enhance international energy cooperation.

In the social dimension, concerns still persist as to the safety of hydrogen and the competition for water resources for hydrogen production. However, these concerns can be addressed through technological innovation and inclusive communication and governance strategies. At the same time, the construction of electrolysis plants, transport infrastructures and green hydrogen projects offers clear opportunities for job creation, economic revitalisation and attracting investment to the regions that host these initiatives [11]. Consequently, the tangible benefits for the communities can reinforce the social acceptance of green hydrogen, turning a potential source of resistance into a driver of sustainable territorial development.

Finally, the conjunction of economic, technological, regulatory and social challenges can act as a catalyst for cross-cutting innovation. The search for green hydrogen solutions is promoting advances throughout the value chain, in electrolyser efficiency, storage systems, use of alternative water resources and participatory governance models. These advances will not only benefit this energy carrier, they will also generate positive synergies in other areas of the energy transition, promoting the development of the consortium’s industrial, scientific and technological fabric and accelerating the achievement of the global climate goals [13].

In conclusion, **green hydrogen has reached a point at which the challenges constitute a stimulus for change**. Each challenge opens up a window of opportunity; the high upfront costs drive pioneering markets, the intermittency of the renewables leads to flexible storage solutions, the incipient regulations encourage international cooperation and the social concerns are transformed into acceptance through tangible benefits. Green hydrogen is thus shaping up as an energy alternative and a real engine of comprehensive transformation that connects technological innovation, economic development and social progress.

# 2. FUNDAMENTALS OF WATER ELECTROLYSIS

This chapter outlines the basic principles of electrolysis, electrolyser components and water consumption, which are key to understanding the functioning, efficiency and impact of this technology.

## 2.1. Basic principles of the process

Water electrolysis consists of the splitting of the water molecule into hydrogen and oxygen by means of the application of a direct current of electricity, producing the following global reaction:

$$H_2O\ (liq) \rightarrow\ H_2(gas) + \tfrac{1}{2}\,O_2(gas) \qquad \text{(Equation 1)}$$

This electric current is generated from two electrodes connected to a power supply. The positive electrode is called the anode, in which the oxidation half-reaction when the oxygen is generated (also known as Oxygen Evolution Reaction or OER) takes place, while the negative electrode is called the cathode, in which the reduction half-reaction when the hydrogen is generated (known as Hydrogen Evolution Reaction or HER) takes place. The way in which these half-reactions develop, constituting processes that take place separately in each electrode, will depend on the electrolysis technology used, although the overall reaction is always the same: Equation 1 (for further details on these half-reactions, see each technology in chapter 3).

The water electrolysis is an endothermic reaction, in other words, it requires an energy input to take place. This energy input can come in the form of electricity or heat. The amount of energy required for this process can be quantified using the First Law of Thermodynamics:

$$\Delta H\ =\ \Delta G\ +\ T\ \cdot\ \Delta S \qquad \text{(Equation 2)}$$

Where $\Delta H$ shows the total energy (enthalpy) that must be supplied in order to split the water molecule. This energy may be of a thermal origin (entropy, $T \cdot \Delta S\ \equiv\ \dot{Q}$) that represents the irreversibilities of the system, or of an electrical origin (Gibbs free energy, $\Delta G$), given that, in an electrochemical process at a constant pressure and temperature, all the reversible work is electrical energy. Under standard conditions (25°C, 1 bar) these parameters have the following values: $\Delta H^0$ = 285.88 kJ/mol, $\Delta G^0$ = 237.23 kJ/mol and $T \cdot \Delta S^0$ = 48.65 kJ/mol.

### 2.1.1. Reversible and thermoneutral voltage and overpotentials

Reversible voltage ($U_{rev}$) is defined as the minimum voltage that needs to be applied between the anode and the cathode for the electrolysis to occur. From a thermodynamic point of view, the work that needs to be supplied to carry out this process, at a constant temperature and pressure, is equal to the increase in the Gibbs free energy (ΔG). If the electrolyser is only capable of exchanging work in the form of electricity and it doesn't provide any heat, the following occurs:

$$U_{rev} = \frac{\Delta g}{z \cdot F} \qquad \text{(Equation 3)}$$

Where $U_{rev}$ is the reversible or equilibrium voltage (V), $z$ *is* the number of electrons transferred in the water electrolysis ($2e^-$) and *F* is the Faraday constant (~96500 C/mol).

The reversible voltage at 25°C and 1 bar is 1.23V while for other conditions it is described by the Nernst equation, which establishes the relationship between the electrochemical potential and the partial pressure of the species involved.

When the electrolytic process is carried out under adiabatic conditions (without any heat exchange with the surrounding area), the total reaction enthalpy (ΔH) must be solely supplied by the electric current. Thus, in a similar way to the reversible voltage, the enthalpy variation can define the thermoneutral ($U_{tn}$) or enthalpic voltage:

$$U_{tn} = \frac{\Delta h}{z \cdot F} \qquad \text{(Equation 4)}$$

Under equilibrium conditions (25°C, 1 bar), the value of the thermoneutral voltage is 1.48V.

The difference between the reversible and thermoneutral voltage is known as thermal or entropic voltage and it represents the minimum overvoltage with respect to the reversible voltage that must be applied to the electrolysis cell to initiate the water decomposition reaction. Under standard conditions this potential is 0.25 V.

For practical purposes, when an electrolysis cell goes into operation, the voltage is always higher than the reversible voltage ($U_{rev}$) and even higher than the thermoneutral voltage ($U_{tn}$), due to the irreversibilities of the actual electrolysis process. These overpotentials can be classified as:

- **Activation or transfer overpotential ($\breve{\eta}_{act}$):** This is a loss caused by the fact that the charge transfer rate in the electrodes is limited.

- **Ohmic overpotential ($\breve{\eta}_{ohm}$):** This overpotential is associated with the sum total of the different electrical resistances of the process in accordance with Ohm’s law.
- **Concentration or diffusion overpotential ($\breve{\eta}_{conc}$):** This takes into consideration the limitations of the transmission of hydrogen and oxygen products that occurs, particularly with high current densities.

### 2.1.2. Volume of hydrogen produced: Faraday's laws of electrolysis

The current density used during the electrolysis directly determines the amount of hydrogen obtained by means of the following equation:

$$\dot{m}_{prod,teórico} = \left(\frac{M}{F \cdot z}\right) I \qquad \text{(Equation 5)}$$

Where $\dot{m}_{prod,teórico}$ is the mass of the substance produced in the electrode (g/s), $z$ is the number of electrons involved in the electron transfer (2e$^-$), $F$ is the Faraday constant (96,500 C/mol; 1 C ≡ 1 A·s), $M$ is the molecular weight of the substance (g/mol) and $I$ is the current intensity (A).

### 2.1.3. Process efficiency

Depending on the aspect of the process to be assessed, different kinds of efficiencies can be calculated.

The voltage efficiency ($\eta_U$) is defined as the ratio between the thermoneutral voltage ($U_{tn}$) and the actual voltage ($U$) applied to the electrolytic cell:

$$\eta_U = \frac{U_{tn}}{U} \qquad \text{(Equation 6)}$$

This efficiency quantifies the adequacy with which the electrolysis is carried out, given that the irreversibilities that arise in this process manifest themselves in the form of overpotentials, as indicated above.

The current or Faraday efficiency ($\eta_F$) relates the theoretical intensity ($I_{teórico}$) to carry out the electrolysis reaction to the actual current flowing through the cell ($I$). It is therefore a parameter that provides information on the fraction of current that flows through the cell without being involved in the electrolysis.

$$\eta_F = \frac{I_{teórico}}{I} \Longrightarrow \frac{\dot{m}_{prod,real}}{\dot{m}_{prod,teórico}} \qquad \text{(Equation 7)}$$

The overall efficiency ($\eta_{global}$) is defined as the relationship between the enthalpy variation of the process and the total energy supplied to the electrolysis cell per mole of hydrogen:

$$\eta_{global} = \frac{\Delta H}{energía\ eléctrica + energía\ térmica} \qquad \text{(Equation 8)}$$

If the only energy input comes from the electricity supplied to the cell's terminals, the thermal energy externally applied to the cell will be zero, and therefore the above expression will be equivalent to:

$$\eta_{global} = \eta_F \cdot \eta_U \qquad \text{(Equation 9)}$$

## 2.2. Components of an electrolyser

### 2.2.1. Stack of cells

Several electrolysis cells joined together form what is known as a stack. Depending on the connection of these cells, the stack may be single-pole or double-pole (see Figure 1).

In the single-pole configuration, the cells are electrically connected in parallel, in such a way that the cathodes of all the cells are connected to each other, as are the anodes. There is a physical gap between the anode and the cathode, facilitating their replacement in the event of a failure or breakdown. On the other hand, in the double-pole configuration the cells are connected in series, i.e. the anode is connected to the cathode of the next cell. Commercial electrolysers have a double-pole configuration.

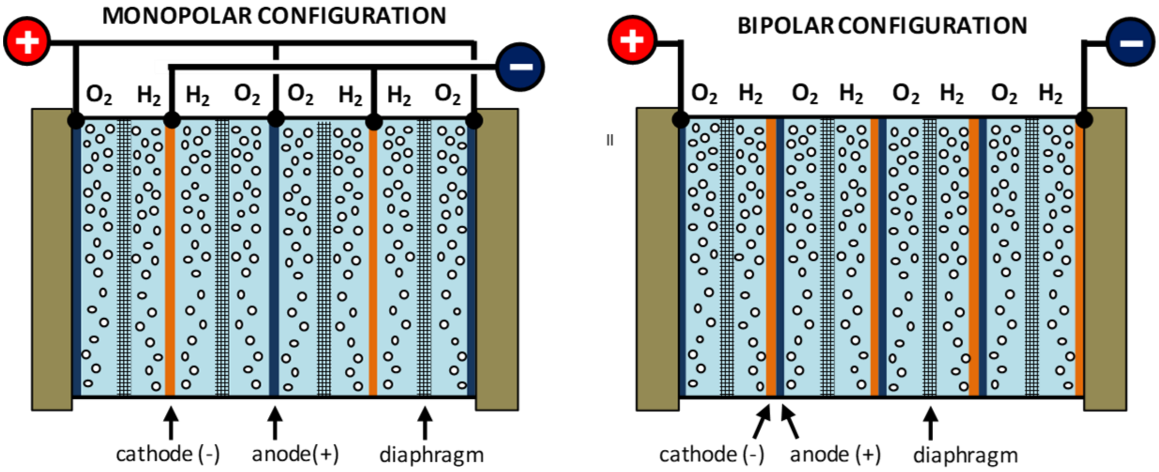


*Figure 1. Single-pole Configuration (left); Double-pole Configuration (right) [16].*

### 2.2.2. Balance of plant (BoP)

In an electrolyser, a series of devices and systems are required to allow the proper functioning of the cells and obtain the gases under the desired conditions. This set of ancillary systems is known as Balance of Plant (BoP) (see Figure 2).

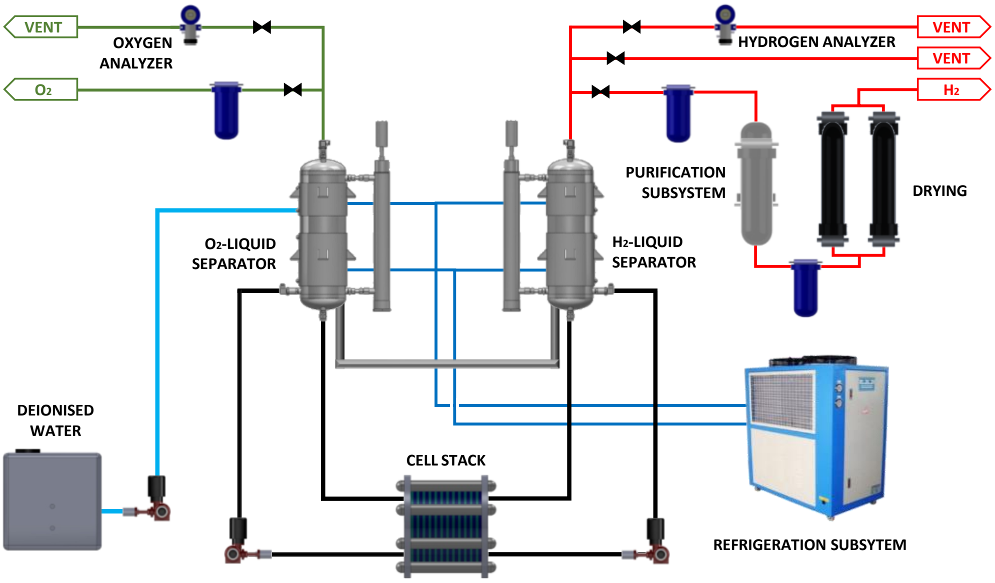


*Figure 2. Balance of plant of an ALK electrolysis system [16].*

- **Gas production subsystem:** This is where the water electrolysis process takes place. The oxygen and hydrogen bubbles that are generated are transported together with the electrolyte to the gas separation subsystem in two independent flumes.

- **Gas separation subsystem:** This consists of the separator tanks where the bubbling and separation of the gases and liquid takes place. The liquid is then recirculated to the stack.

- **Deionised water subsystem:** Because the water is consumed in the stack, it needs to be continually replenished. It is pumped from a supply tank to the hydrogen or oxygen separator. The water to be supplied is deionised water with the required purity and conductivity ($< 5\mu S/cm$), in order to prevent any potential contamination of the catalyst and diaphragm.

- **Thermal management subsystem:** A significant amount of the electrical energy supplied to the stack is transformed into heat due to the irreversibilities of the process, as a result of which a cooling system is required to keep the stack temperature below a certain value.

- **Pressure control subsystem:** The pressure is created by retaining the oxygen and hydrogen that are produced in the system in such a way that, as the gas accumulates, the pressure rises to the mark at which the pressure regulating valves are set. The pressure difference should be minimised as much as possible for the proper functioning of the system.

- **Subsystem for the elimination of electrolyte drag-out and the drying of the currents:** The gaseous streams that leave the separator tanks pass through a system of coalescing filters to remove as much of the electrolyte as possible; this is dragged by the gaseous streams through the desiccant filters to remove the remaining moisture.

- **Purification and drying subsystem:** Since the aim of the electrolysis is to obtain hydrogen with the highest possible purity, a deoxo reactor is usually installed to remove the oxygen impurities that are dragged along.

- **Subsystem for the analysis of the gases produced:** Small parts of the hydrogen and oxygen that are produced are sent to a trace analyser, one for each gaseous stream, in such a way that the proportions of oxygen and hydrogen in the piping equipment are always known, for safety reasons and so as to continuously quantify the purity of the gaseous streams.

- **Monitoring and control subsystem:** This aims to acquire all the information from the sensors and transducers and perform the actions required to enable the proper and safe functioning of the system.

- **Power electronics subsystem:** The electrical power that reaches the stack must be continuous, so it is necessary to incorporate the appropriate power electronics into the system for its integration into the available power supplies.

## 2.3. Water consumption during the process

Stoichiometrically, hydrogen production by means of electrolysis requires 9 litres per kg of hydrogen. However, due to the inefficiencies and water pre-treatments, the total consumption fluctuates at around 20 l/kg, depending on the technology [17]. According to the estimates of the International Renewable Energy Agency (IRENA), PEM electrolysis is the emission-free hydrogen production process with the lowest water consumption (17.5 l/kg $H_2$). It is followed by ALK electrolysis, which consumes 22.3 l/kg $H_2$. For an effective comparison with conventional production technologies, it is necessary to include the $CO_2$ capture systems. Thus, methane reforming with CCUS leads to consumption totalling 32.2 l/kg $H_2$, while in the case of coal gasification this value rises to 49.4 l/kg $H_2$ [18].

If we compare these data with the water consumption required for hydrogen production from current non-renewable sources, significant savings in water consumption can be observed (see Figure 3).

En España se consumen >0,5 millones de toneladas de hidrógeno ¿Cuántos hm$^3$ de agua son necesarios para producirlo?

La producción de combustibles convencionales para ir en coche de Barcelona a Madrid requiere **219 L** de agua, mientras que el **hidrógeno** solo **94 L**

Si en España se instalan **11 GW** de electrolizadores en 2030 (objetivo PNIEC) se podrían llegar a producir **1,75 Mtn de hidrógeno renovable**, que supondría un consumo de unos **26 hectómetros cúbicos de agua**

*Figure 3. Water consumption in hydrogen production [19].*

Given the importance of water availability in industrial processes, numerous efforts are being made to both reduce water consumption and ensure a sustainable source of this resource. In particular, due to the stringent purity requirements for water use in certain applications, developmental initiatives are also leading to significant breakthroughs in purification technologies such as reverse osmosis, electrodialysis, membrane distillation and advanced filtration systems using nanomaterials. These technologies can obtain high-purity water from a variety of sources, thus contributing to more efficient and responsible water management.

A recent analysis by the Spanish Hydrogen Association (AeH2)[19] shows that the production of the 1.75 Mton of hydrogen envisaged in Spain by 2030 will only require 0.07% of the water that can be stored in the available reservoirs or 0.1% of the water used for agricultural purposes (see Figure 3).

# 3. ELECTROLYSIS TECHNOLOGIES AND DEGREE OF COMMERCIAL MATURITY

This chapter analyses the four main electrolysis technologies, outlining their characteristics, benefits and limitations and their potential for green hydrogen production.

## 3.1. Introduction to electrolysis technologies

Water electrolysis is a technology which is key to the production of renewable hydrogen. As indicated in the previous chapter, electrolysis is the splitting of the water molecule into hydrogen and oxygen by means of the application of electrical energy. This process is carried out in devices called electrolysers that use different configurations and materials, depending on the technology used.

There are several electrolysis technologies, each with their specific characteristics, which make them more suitable for certain contexts and applications. The main technologies analysed in this document are:

- **Alkaline (ALK) electrolysis:** This is the most mature and widely-used technology, with over 100 years of presence in the industry. It uses alkaline liquid electrolytes and it is renowned for its reliability and low cost, although it has limitations in terms of its current density and dynamic response.
- **Proton exchange membrane (PEM) electrolysis:** This employs polymeric membranes to transport the protons, delivering high hydrogen purity, a compact design and a rapid operational response. It is ideal for integration into intermittent renewables, although its cost is currently penalised by the use of precious metals.
- **Anion exchange membrane (AEM) electrolysis:** This is an emerging technology that combines the benefits of ALK and PEM, using low-cost materials and anionic polymeric membranes. Although it is promising, it still faces challenges in terms of its durability and scalability.
- **Solid oxide electrolysis (SOEC):** This operates at high temperatures, making it possible to harness the waste heat and reduce the electricity consumption. It is particularly suitable for industrial applications and co-electrolysis processes, although it still has to overcome certain technical and economic challenges.

In market terms, **the ALK and PEM technologies are currently predominant, due to their maturity, reliability and large-scale availability.** On the other hand, emerging technologies such as **AEM and SOEC display high potential due to their theoretical efficiency and lower material costs**, although they have only reached their early development and pre-commercial phases and they have to overcome durability, scalability and cost-related challenges before they can enter the market in a significant manner.

In keeping with the above, Figure 4 shows the TRL (Technology Readiness Level) of the different electrolysis technologies, according to the estimates of the International Energy Agency (IEA) [20]. The ALK and PEM technologies have reached the market while AEM and SOEC are still in their demonstration phases.

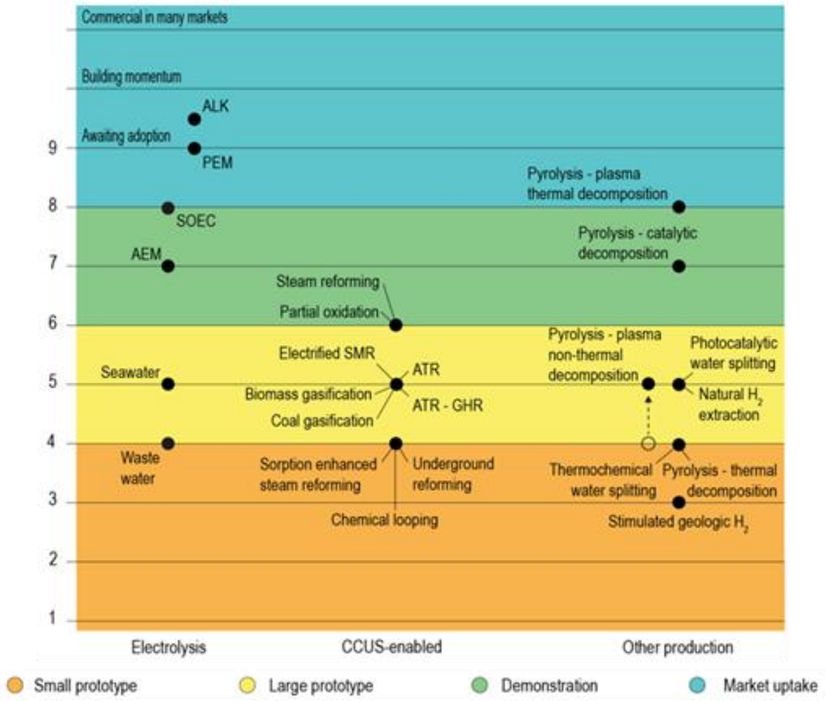


*Figure 4. TRL of low-carbon hydrogen production technologies [20].*

ALK technology remains the predominant choice, accounting for 75% of global electrolyser manufacturing in 2024, followed by PEM, with a share totalling about 22% worldwide (see Figure 5).

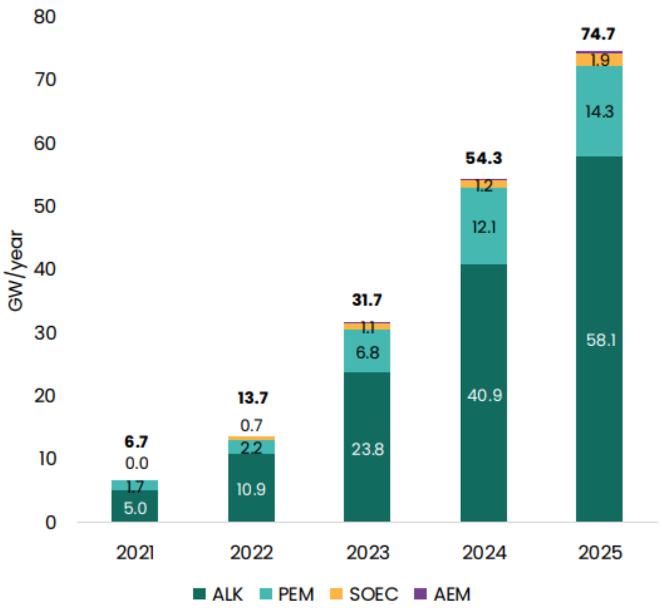


*Figure 5. Global electrolyser manufacturing capacity (estimated data for 2025) [21].*

According to the projections based on the announcements of global electrolyser manufacturing capacity, SOEC technology is expected to account for only 3% of the total by the end of 2025. However, SOEC manufacturers plan a significant expansion by 2030, with the aim of competing with regard to costs, even in the case of low-temperature electrolysis.

Each of the technologies have benefits and drawbacks that determine their suitability for different applications, from industrial hydrogen production to their integration into renewable energy sources. In the following sections, the characteristics, benefits, drawbacks and potential of each of these technologies are discussed in greater detail.

## 3.2. Alkaline (ALK) electrolysis

ALK technology is a highly mature hydrogen production technology going back over 100 years. The current commercial development of ALK electrolysis equipment lies on the MW power scale.

The operating conditions are as follows: temperatures between 60ºC and 85ºC, with an outlet pressure amounting to lower than 30 bar. Meanwhile, the overall efficiency lies at around 60%, depending on the commercial equipment. The purity of the hydrogen which is produced is about 99.5%, although after the purification systems it can reach 99.999% [16].

### 3.2.1. Concept

ALK electrolysis technology mainly consists of two electrodes that are immersed in a liquid electrolyte and a porous diaphragm that acts as a separating medium between the cathodic and anodic chambers, allowing the hydroxide ions ($OH^-$) to pass through (see Figure 6). The liquid electrolyte is an aqueous solution, usually based on potassium hydroxide (KOH) or sodium hydroxide (NaOH).

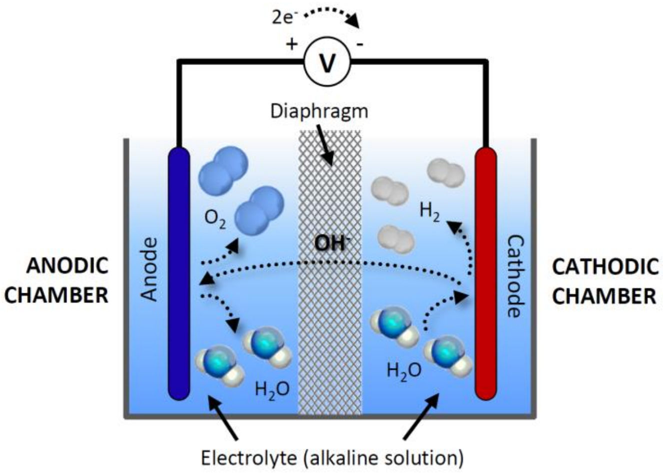


*Figure 6. General diagram of an ALK electrolysis cell [16].*

The functioning of ALK electrolysis begins with a potential difference between the electrodes, giving rise to the simultaneous half-reactions in the anode and cathode (see Equations 10 and 11). The reaction to reduce the water to hydrogen (HER) takes place in the cathode, generating $OH^-$ ions that advance towards the anode (oxidation half-reaction or OER), where they shed their electrons and generate oxygen [22].

Anode (OER): $2\,OH^- \rightarrow \frac{1}{2} O_2\,(gas) + H_2O(liq) + 2e^-$ (Equation 10)

Cathode (HER): $2\,H_2O(liq) + 2e^- \rightarrow H_2\,(gas) + 2\,OH^-$ (Equation 11)

An ALK electrolysis cell consists of the following elements:

- **Electrodes:** These are responsible for directing the electric current to the anode and cathode chambers. There are two distinct elements, the positive and negative electrodes. The positive electrode is called the anode and the gaseous oxygen formation half-reaction takes place in its interphase of separation with the electrolyte. On the other hand, the negative electrode is called the cathode and this is the place where the hydrogen gas formation half-reaction takes place.

  The electrodes must have specific characteristics to help the system to function properly, such as high resistance to corrosion, good electrical conductivity, a large active area and structural integrity. Stainless steel, Ni and Ni-Raney are used for the cathode, although Ru, Co or Mo alloys are also sometimes employed. On the other hand, the anode is made of Ni or Ni-coated steel [23] [24].

- **Diaphragm:** This is a separating medium tasked with dividing the electrolysis cell into two chambers (anodic and cathodic compartments), allowing only $OH^-$ ions to pass between the two electrolytic chambers, and it is impermeable to the gases. The most commonly used diaphragm material consists of a polysulphone network and zirconium oxide ($ZrO_2$) as an inorganic filler known as Zirfon® PERL and marketed by AGFA [23].
- **Electrolyte:** This is tasked with providing the ions responsible for the conduction inside the electrolytic cell. KOH solutions of around 30%-35% in weight are commonly used to minimise the resistance losses of the electrolyte, given that the conductivity falls if higher or lower concentrations are employed. Moreover, the conductivity of the electrolyte increases with the temperature, so it operates at around 60ºC-80°C, just below the boiling point of the aqueous solution.

Several cells joined together are called a stack. Once the main parts of the stack, the place where the electrochemical reactions take place, have been defined, it is also necessary to incorporate different devices and systems to enable the cells to function properly and obtain the gases under the desired conditions. The set of ancillary systems is referred to as BoP.

The BoP of an ALK electrolyser has been described in detail in section 2.2.2., so another diagram of an ALK electrolysis system is shown below, in which the main subsystems can once again be identified (Figure 7).

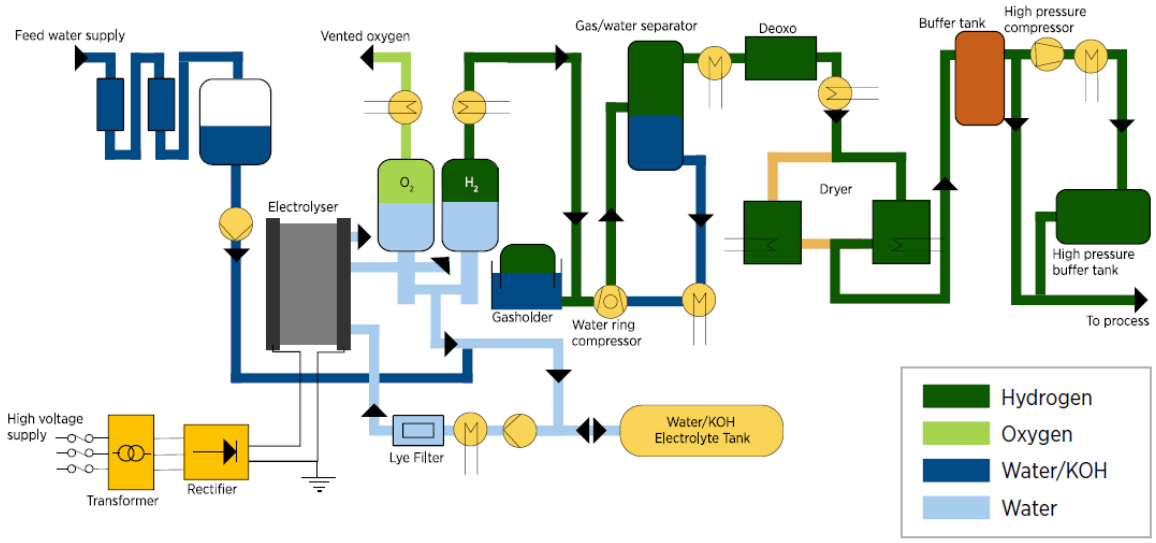


*Figure 7. BoP of an ALK electrolyser [25].*

### 3.2.2. Benefits and drawbacks of ALK electrolysis

The benefits include its proven durability and renowned behaviour, as it reaches the end of its service life after around 95,000 hours [26]. Furthermore, the cost is lower than that of other technologies with a similar maturity, as it doesn't contain any noble metals.

As for their limitations, ALK electrolysers have low current densities, within the 0.2-0.6 A/cm$^2$ range, they use highly corrosive electrolytes and they require stable power. To function properly they must operate at between 20% and 100% of their maximum capacity. Working in this range prevents the formation of flammable mixtures due to gas diffusion through the diaphragm, which usually occur with low current densities (<0.1A/cm$^2$). Therefore, when the electrolysers are integrated into a renewable energy plant, if the production isn't sufficient to use several electrolysers that are switched on and off in accordance with the plant's generation, it is necessary to connect them to an additional energy source, such as batteries or the electrical grid.

### 3.2.3. Innovation and future developments

The latest breakthroughs and innovations include the search for and development of advanced materials to optimise the catalytic activity of the electrodes with the aims of reducing overvoltages in both reactions and optimising the space between the electrodes to reduce the overpotential and increase the current density.

The application of improvements in the electrolyser's design have recently given rise to the development of zero-gap cell geometries[27]. The distance between the electrode and the diaphragm is minimised in this geometrical arrangement, optimising the cell's current distribution and reducing the voltage required. In the event that the above distance becomes zero, the geometry of the cell must also allow for easy release of the gases, which is hindered by the lack of space. The latest research is therefore focusing on innovative designs to improve the gas flow distribution.

Moreover, the 95,000-hour service life is reduced when the electrolyser operates with dynamic loads, as well as when it is frequently switched on and off, as a result of which the modifications and research are also geared towards improving this aspect [16].

### 3.2.4. Main players

There are currently a number of manufacturers that provide commercial ALK electrolysis equipment:

*Table 1. ALK electrolyser manufacturers (August 2025).*

| COMPANY | COUNTRY |
|---|---|
| John Cockerill - Jingli Hydrogen (Suzhou Jingli) | Belgium, China |
| Ener Blue | Switzerland |
| ErreDue | Italy |
| GreenHydrogen Systems | Denmark |
| Hydrogen Pro | Norway |
| Idroenergy | Italy |
| Sunfire (IHT Industrie Haute Tecnhology) | Germany |
| NEL Hydrogen | Norway |
| Sagim | France |
| Teledyne Energy Systems | USA |
| Tianjin Mainland Hydrogen | China |
| Hitachi Zosen | Japan |
| ThyssenKrupp Uhde Chlorine Engineers | Germany |
| LONGI | China |
| PH2 – Peric Hydrogen | China |
| Sungrow | China |
| Auyan | China |
| GuoFuHEE | China |

## 3.3. Proton exchange membrane (PEM) electrolysis

Water electrolysis using a proton exchange membrane (PEM) between the electrodes has its origins in the mid-20th century, with the development of the first Nafion membranes for aerospace fuel cell applications. Since then, the technology has progressed and established itself as a compact and highly efficient solution for the production of green hydrogen. PEM electrolysers are currently undergoing continuous improvements to the durability of their membranes and electrocatalysts and they are being used in commercial-scale industrial projects, with multiple initiatives ranging from 30MW to over 100 MW demonstrating their technical and economic viability.

### 3.3.1. Concept

In a PEM-type water electrolyser (see Figure 8), the water molecule is broken down into hydrogen and oxygen by passing an electric current through two electrodes separated by a solid electrolyte, consisting in this case of a proton exchange membrane or PEM. Thanks to the use of these membranes, the construction of these types of electrolysers is simpler than that of ALK electrolysers and their operational response is faster, making them more compact and smaller in volume, which is reflected in greater energy density. This means that they can store and generate more energy per unit of volume compared to other kinds of electrolysers. The higher energy density is a significant advantage, particularly in applications in which space is limited and high energy efficiency is required. Figure 8 shows the water electrolysis process in a PEM electrolyser.

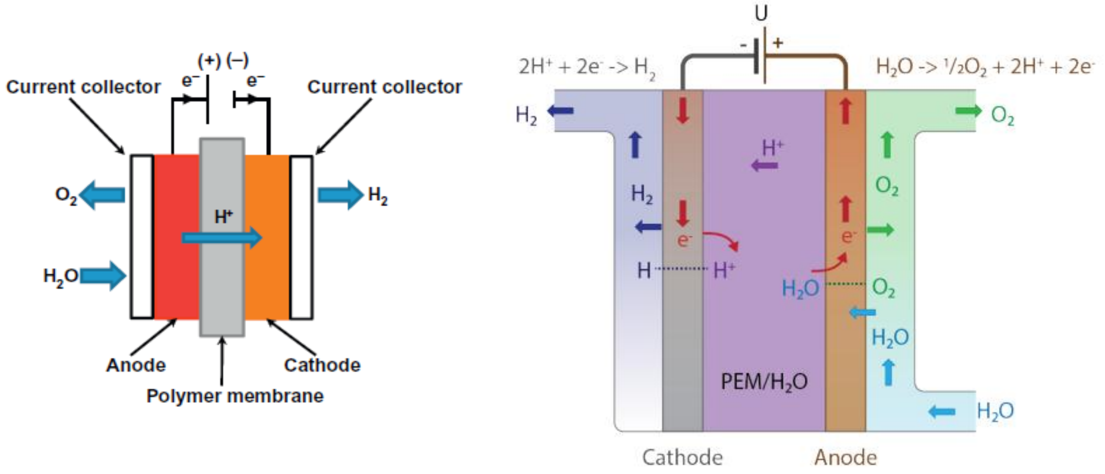


*Figure 8. PEM electrolysis diagrams [28] [29].*

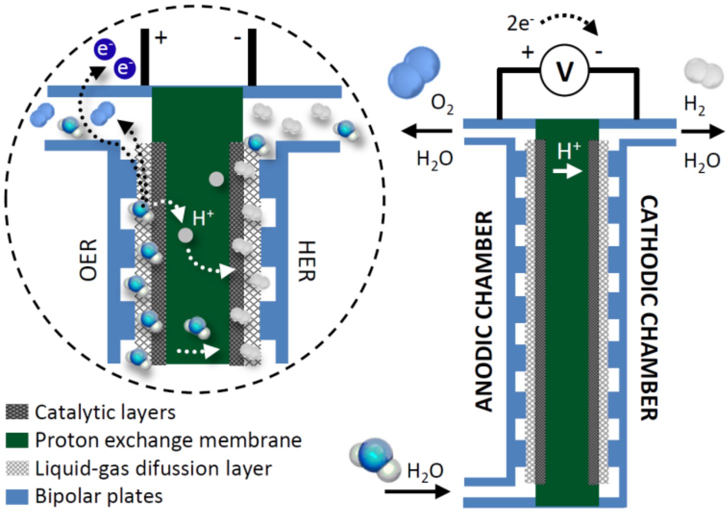


*Figure 9. General diagram of water electrolysis in a PEM electrolyser [16].*

As shown in Figure 9, the feed water flows through the flumes, undergoing oxidisation at the anode to release oxygen and protons ($H^+$). This reaction is known as OER (Equation 12). The protons that are formed then flow through the membrane, and the electrons circulate along the outer circuit to the cathode, closing the electrical circuit that supplies the power to carry out the process. In the cathode, the protons that arrive through the ion exchange membrane are chemisorbed into the electrocatalyst. These are recombined with the electrons that reach the cathodic electrode via the outer circuit to form the hydrogen molecules, which are released as a gas [30]. This reaction is known as HER (Equation 13).

Anode (OER): $$H_2O(liq) \rightarrow \frac{1}{2}O_2\,(gas) + 2H^+ + 2e^- \qquad \text{(Equation 12)}$$

Cathode (HER): $$2H^+ + 2e^- \rightarrow H_2\,(gas) \qquad \text{(Equation 13)}$$

As for its configuration, a PEM electrolysis cell consists of a polymeric membrane immersed in an aqueous solution that separates the cathodic and anodic half-cells. The electrodes supporting the catalytic layers, which can be directly deposited either on the membrane or on the current and flow distributors (a series of porous metal parts known as the Gas Diffusion Layer or GDL), come together with the membrane to form the Membrane Electrode Assembly (MEA), which lies at the heart of a PEM electrolyser. The water electrolysis takes place in this component, generating hydrogen on the one hand and oxygen on the other.

On both sides of the MEA and the current and flow (water/gas) distributors there are a series of metal plates (known as bipolar plates) where the flow distribution flumes are machined; these are responsible for distributing the water and carrying the hydrogen and oxygen that are generated to the outlet.

In a PEM electrolysis cell all these elements are mechanically supported by the end plates which, together with the seals and closure elements, allow the anode and cathode chambers to remain separate, preventing any contact between the oxygen and hydrogen that are generated.

Each of the main components that make up a PEM cell is outlined below:

- **MEA:** this consists of the membrane-electrode assembly (anode and cathode); the membrane is the central part of the assembly. It can be designed in different ways, although the difference is chiefly based on where the catalytic layer is deposited (on the membrane or on the GDLs), as shown in Figure 10:

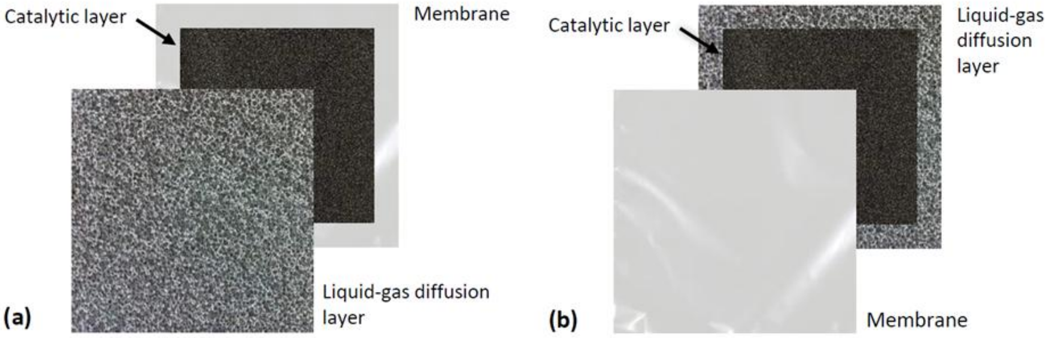


*Figure 10. Different types of electrode-membrane assemblies: (a) three-layer MEA with anodic and cathodic catalytic layers deposited on the membrane; (b) catalytic layer deposited on one side of the GDL [16].*

- **Electrodes:** their main function is to facilitate the contact between the reactants and catalytic sites, for which it is necessary to facilitate the conduction of the electrons and protons, the release of the gaseous products of the reaction and the arrival of the water at the catalytic points. The electrocatalytic function will be determined by the catalytic material, usually a metal oxide deposited on a medium with a large surface area (see Figure 10). Electrodes are highly complex structures and they are elements that are being actively researched to optimise them in terms of price and development [31].

  The anodic half-reaction promotes the OER, while the cathodic one promotes the HER. The OER reaction is the one with the slowest kinetics, and it is therefore the reaction that restricts the process. Therefore, stable electrocatalysts with high catalytic and selective activities are very much required to facilitate the OER. Thus, iridium and ruthenium are the elements that are most commonly used at the moment to synthesise the OER catalysts. Platinum has traditionally been used as a catalyst for the HER in the cathode.

- **GDL:** these are porous metallic grids that don't take part in the reactions and their function is to transport the current from the bipolar plates to the MEA while guaranteeing the homogeneous access of water to the membrane and the removal of the product gas. The porosity of this material is an important factor; if the pores are too small, they can cause problems in the water and gas transport, while an increase in the porosity facilitates the release of the gases, but significant ohmic losses are introduced into the contact points between the GDL and the MEA and between the GDL and the bipolar plate.

  Titanium, in the form of a mesh or sponge, is the material that is most widely used, as the pores between the particles allow the gas and water to flow through it and it provides a large contact surface with the electrodes, endowing it with greater conductivity.

- **Bipolar plates:** these constitute approximately 30% of the size and 50% of the total cost of a cell, so a good design for this component is essential. They are located at the ends of each of the cells and they have a series of mechanised flumes allowing the water to enter the MEA and the gases generated to exit it (see Figure 11). They are essential for the configuration of the stack, as they guarantee its proper functionality and connect the cells in series (the anode of one cell is connected to the cathode of the following one). Since materials with a large degree of resistance to corrosion and high electrical conductivity are required, noble metals with specific coatings are usually used. However, it is necessary to search for new alternatives for the manufacture of bipolar plates with improved corrosion resistance characteristics and high conductivity at lower prices [32].

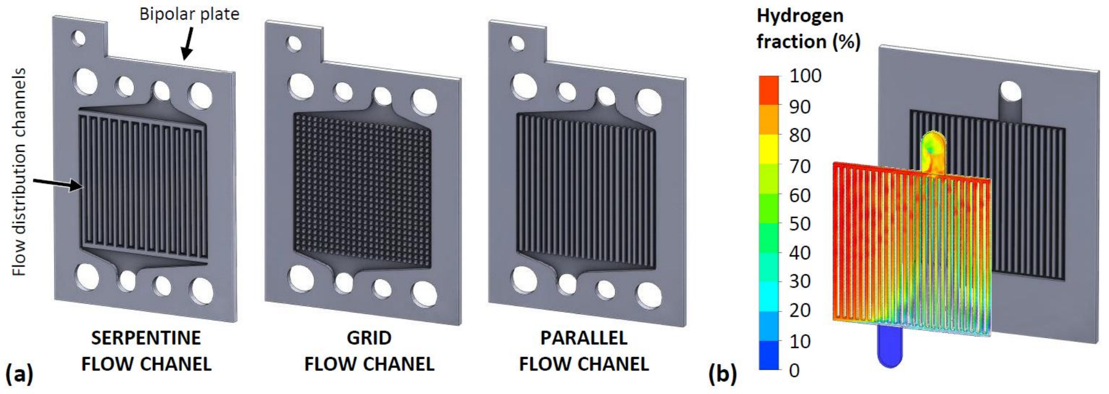


*Figure 11. Bipolar plates and flow distribution flumes in PEM electrolysis cells: (a) main types of flume designs (coil, grid, parallel); (b) flow distribution and hydrogen fraction when using straight parallel flumes [16].*

As in all the other electrolytic technologies, several cells can be linked together, usually in series (bipolar, as in the case of ALK electrolysers), to form a stack, thereby increasing the total amount of hydrogen produced (see Figure 12).

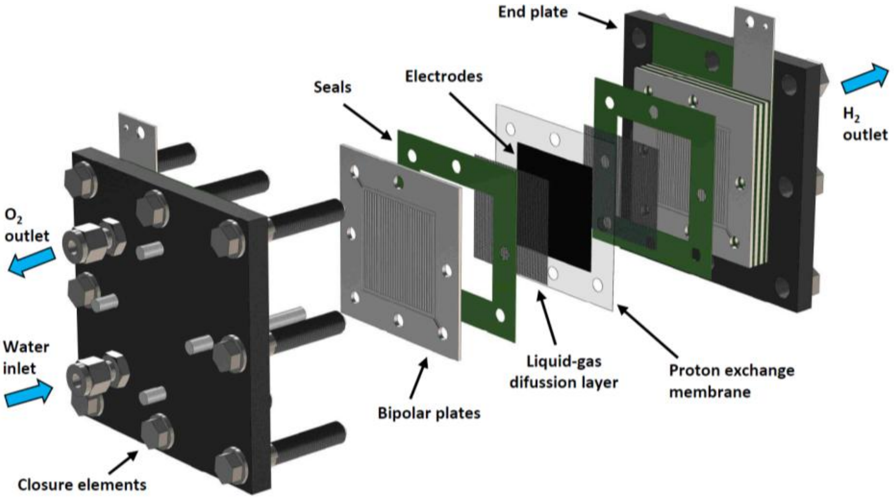


*Figure 12. Exploded drawing of a PEM electrolysis stack [16].*

In order to properly service the stack, a number of ancillary systems must be put in place to control the operating parameters, maximise its efficiency and allow it to function safely. As with an ALK electrolyser, these elements constitute the BoP.

PEM systems are considerably simpler than ALK systems. Generally, only circulation pumps, heat exchangers and pressure monitoring and control devices are required on the side of the anode (oxygen). However, on the side of the cathode, a gas separator, a deoxygenation module to remove the residual oxygen (usually unnecessary in a differential pressure system), a gas dryer and a final compression stage are required (see Figure 13).

PEM systems provide greater design flexibility; they can be configured to operate with an atmospheric, differential or balanced pressure (each system is specifically designed for one of these modes), helping to reduce costs, simplify the system's architecture and minimise the maintenance requirements.

In a balanced pressure operation, the anode and cathode operate with the same pressure level. The atmospheric pressure mode (< 1 atm standard) corresponds to a constant pressure regime. In addition, the proton exchange membrane allows work with a differential pressure, typically between 30 bar and 70 bar. However, this approach requires a thicker membrane to ensure mechanical stability and reduce the gas permeation, which has a negative impact on its efficiency. An additional catalyst may also be required to convert the hydrogen, which tends to permeate more easily due to the higher pressure, back into water.

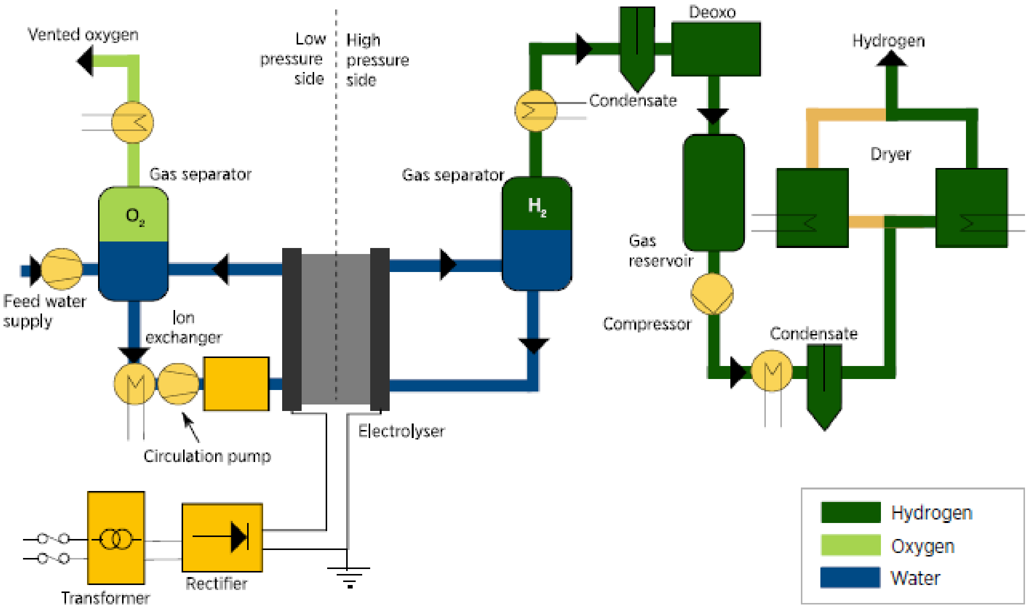


*Figure 13. Typical system design and balance of plant for a PEM electrolyser [25].*

NOTE: This configuration is for a generic system and it may not be representative of all manufacturers.

### 3.3.2. Benefits and drawbacks of PEM electrolysis

Water electrolysis based on PEM technology brings the following benefits for the electrolytic production of hydrogen and oxygen:

- The use of a corrosive electrolyte is avoided by using a PEM membrane, as occurs in ALK electrolysis.
- This allows for a compact system design and lower volume.
- It also allows for work with high current densities.
- The hydrogen which is produced is of great purity (> 99.99%) and it can be produced at a high pressure in the electrolyser, without the need for any additional energy input.
- It has faster dynamics (responses) to a variable power supply than ALK electrolysers, as a result of which it can be integrated into highly fluctuating energies such as renewables more easily.

The major drawback of these systems is their cost, due to the use of precious metals as catalysts, together with the strongly acidic environment to which the materials are exposed, which directly influences the material degradation processes and, ultimately, the system's service life. However, the industry is achieving significant reductions in the load of precious metals, while the membrane's durability and the stack's service life have been improved, as have the recycling technologies that contribute to further cost reductions.

### 3.3.3. Innovation and future developments

The development of alternative materials geared towards greater efficiency and cost reductions is a technological priority in the field of electrolysis. Improved membranes through the use of alternative polymers, reduced thickness, increased conductivity and less hydrogen crossover will make it possible to dispense with conventional fluoropolymers, optimise the overall energy efficiency and increase the purity of the hydrogen which is produced.

Hydrogen crossover refers to the phenomenon by means of which hydrogen molecules cross the electrolyser membrane from the side of the cathode to the side of the anode [16] [30]. This uncontrolled movement may have several negative effects:

- **Reduced energy efficiency:** Hydrogen that crosses without reacting constitutes a direct loss of energy.
- **Risk of gases mixing:** It may cause the hydrogen to mix with the oxygen, which is a safety risk due to the explosive potential.
- **Drop in hydrogen purity:** When it is mixed with other gases, the hydrogen which is produced loses quality for applications requiring high purity, such as fuel cells.

Therefore, an improved membrane that minimises this crossover will significantly contribute to improving the efficiency, safety and quality of the hydrogen generated.

Moreover, there is a need to develop non-fluorinated membranes that reduce the environmental impact of these systems due to the emission of the perfluoroalkyl and polyfluoroalkyl substances (PFAS) resulting from the use of Nafion as an electrolyte. For this reason they have recently been the subject of a position paper published by Hydrogen Europe, given the current importance of proton exchange membranes as key components of the development of fuel cells and electrolysers [33].

For the time being, the use of fluoropolymers in PEM technology is essential for the functioning of products in this industry, as there are no alternatives to replace them in the short term. In order to achieve the energy and climate goals envisaged for the coming years, it is proposed to postpone these restrictions, at least for the hydrogen industry, while work is carried out on the development of alternative modifications and compounds to minimise PFAS emissions. Graphene oxide is emerging as an option for use as a non-fluorinated proton exchange electrolyte, as interesting breakthroughs in this area are taking place [34] [35].

In parallel, research into alternative catalytic materials is seeking to replace or reduce the use of the expensive elements to be found in current PEM electrolysis models. Improvements in catalytic layer formation techniques to minimise the electrochemical losses, as well as the optimisation of membrane handling to prevent structural defects undermining the system’s performance, are also of great interest.

### 3.3.4. Main players

*Table 2. Major manufacturers of PEM electrolysers (August 2025).*

| COMPANY | COUNTRY |
|---|---|
| ACCELERA[1] | US A |
| ELOGEN[2] | France |
| ERREDUE | Italy |
| Giner Inc | US A |
| H2B2 | Spain |
| H2Greem Global Solutions | Spain |
| iGas Energy | Germany |
| ITM Power | United Kingdom |
| NEL | Norway |
| Ohmium | US A |
| PEAK SCIENTIFIC | United Kingdom |
| Plug Power Inc | US A |
| Protium Dynamics | Brazil |
| QUEST ONE[3] | Germany |
| Siemens Energy | Germany |
| Sungrow | China |

**NOTES Table 2**

1. In 2019, Cummins acquired a large part of Hydrogenics as part of its New Power division. Cummins currently owns 81% of Hydrogenics and 19% of Air Liquide. Since then, the name of the company has changed to Accelera.
2. ELOGEN is a member of GTT, which acquired the AREVA H2-Gen joint venture.
3. Founded as H-TEC Hydrogen Energy Systems, it was acquired by MAN Energy Solutions (now Everllence)

## 3.4. Anion exchange membrane (AEM) electrolysis

AEM electrolysis is an emerging technology that combines the benefits of ALK and PEM electrolysis, providing a more economical and sustainable solution for hydrogen generation. The first scientific paper on AEM was published in 2011 [36]. Since then, several research groups have promoted the study of this technology, contributing significantly to its development.

AEM electrolysis shares similarities with traditional ALK electrolysis. The main difference with respect to AEM lies in the use of a solid polymeric anion exchange membrane, which is similar to that used for PEM electrolysers instead of conventional diaphragms (such as asbestos or polyphenylene sulphide or PPS). The electrolyte concentration is also lower than the one used in ALK electrolysis.

### 3.4.1. Concept

AEM electrolysers constitute a hybrid technology merging conventional ALK systems and PEM electrolysers. They use anionic polymeric membranes that allow the transport of $OH^-$ anions in an alkaline environment, enabling the use of platinum group metal (PGM)-free catalysts and low-cost material components such as transition metals and opening the door to more sustainable and economically viable electrolysis.

As in the previous cases, the electrochemical process consists of two half-reactions (HER and OER).

In the cathode, the water molecules are reduced by means of the incorporation of two electrons from the outer circuit, generating hydrogen and $OH^-$ ions. Hydrogen is released onto the cathode's surface, while the $OH^-$ ions migrate towards the anode through the ion exchange membrane, attracted by the positive charge of the anode.

In the anode, the $OH^-$ ions lose electrons, which they shed to the outer circuit, and they are recombined to form water molecules and gaseous oxygen, which is released from the anode's surface.

Anode (OER): $$2OH^- \rightarrow H_2O + \frac{1}{2} O_2 + 2e^-$$ (Equation 14)

Cathode (HER): $$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$ (Equation 15)

The basic principle of AEM electrolysis is illustrated in Figure 14:

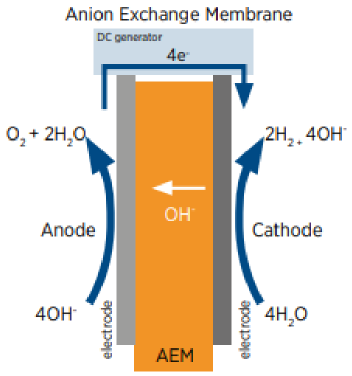


*Figure 14. Schematic view of the AEM electrolysis functioning principle [25].*

In general terms, the components of an AEM electrolyser include the MEA, consisting of the anion exchange membrane and the anionic and cathodic electrodes, which in turn are made up of the electrolyser and the ionomer, the PTL, bipolar plates, which in some designs are also used as current collectors, and the end plates (see Figure 15).

Several commercial anion exchange membranes (such as Sustanion®, Fumasep, Tokuyama and Aemion) are available on the market. The most common polymers used in their manufacture include polybenzimidazole (PBI), polyetheretheretherketone (PEEK) and polystyrene (PS). As for the cationic functional groups incorporated into the polymeric matrix, the ones most commonly used are quaternary ammonium salts, imidazole, pyridinium, etc.

The materials widely used as cathodic electrocatalysts are based on transition metals, particularly nickel (e.g. Ni-Raney), nickel-based alloys and certain nickel-iron-cobalt mixed oxides (NiFeCo). Mixed oxides of nickel, iron, cobalt and copper predominate in the case of the anodic electrocatalysts, For the PTLs in the anode and cathode, the most common material is nickel, which is used in the form of foam or sintered fibres. In individual cells, felt or carbon paper is also used solely on the cathode in some cases. Finally, the bipolar plates and end plates are usually made of nickel or nickel-plated stainless steel, although conventional stainless steel can be used.

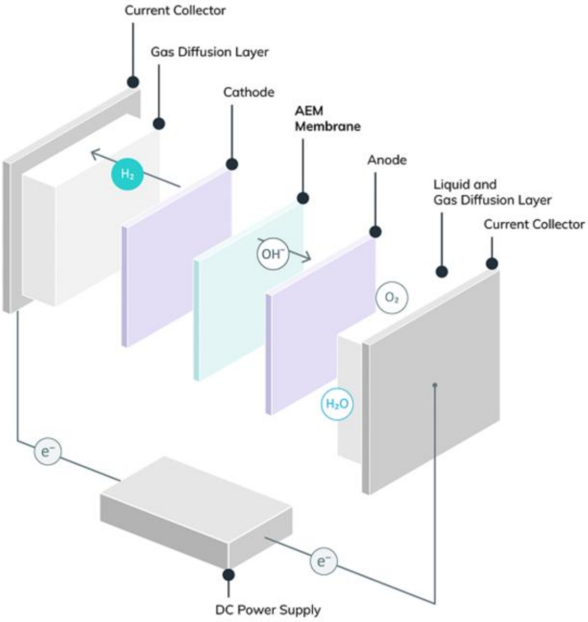


*Figure 15. Diagram of an AEM electrolysis stack [37].*

AEM electrolysers have a design configuration comparable to that of PEM electrolysers (see Figure 16). The current commercial electrolysers can operate at pressures of up to 30 bar. However, the main limitation of this technology lies in the chemical stability of the membrane, as $OH^-$ ions can neutralise the functional groups. This occurs because the $OH^-$ ions are species that are capable of breaking up the chemical bonds that form part of the polymeric membrane (e.g. quaternary ammonium groups), causing its degradation and a loss of ionic conductivity [38] [39] [40]. In addition to the above, the limited thermal and mechanical stability are factors that condition their service life. Another pending challenge is the development of more active electrocatalysts, which would allow work with higher current densities and, consequently, increase the efficiency and competitiveness of the process.

At this early stage of their development, it is anticipated that the improvements will concentrate on the stability of the AEM membranes, the purity of the gases generated, their ability to withstand higher pressure differentials than the present ones and an extension of the operating power range with respect to alkaline systems.

AEM electrolysers currently suffer from a significant restriction in their power input range compared to PEM electrolysers. This limitation is not due to the electrochemical stack itself, but rather to the configuration and sizing of the ancillary systems that make up the BoP.

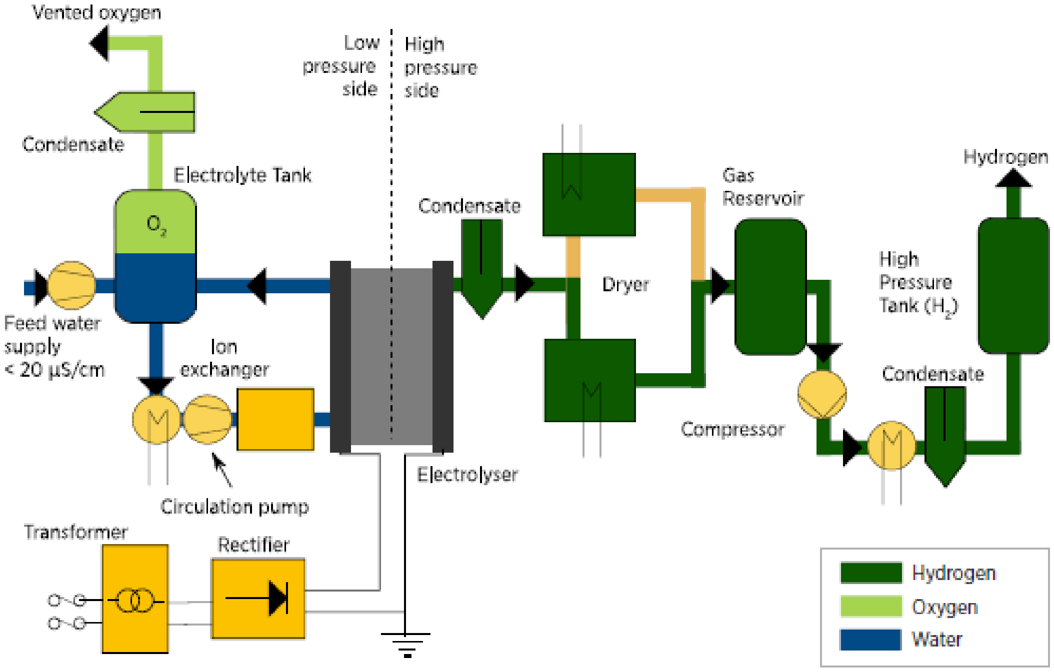


*Figure 16. Typical system design and balance of plant for a AEM electrolyser [25].*

NOTE: This configuration is for a generic system and it may not be representative of all manufacturers.

### 3.4.2. Benefits and drawbacks of AEM electrolysis

AEM electrolysers offer a combination of the benefits of both ALK and PEM technologies [41] [42] [43]:

- **Reduced cost:** They use components made of non-precious and more abundant materials (such as stainless steel and nickel instead of titanium) and employ catalysts made of non-precious metals (such as nickel, iron and cobalt), significantly reducing the manufacturing cost. However, both nickel and cobalt are regarded as strategic and critical raw materials under EU Regulation 2024/1252 [44].

- **Use of distilled water or low-concentration alkaline solutions** (e.g. 1M KOH) as an electrolyte, replacing the highly concentrated solutions (such as 5M KOH) used in ALK electrolysis. As in conventional ALK electrolysis, the electrodes in AEM electrolysis operate in an alkaline environment. Unlike PEM technology, the water purity requirements are less stringent, eliminating the need for de-ionised water purification systems. This feature helps to reduce both the risk of leakage and the problems associated with handling highly alkaline solutions.

- **Compatibility with renewable energies:** They operate efficiently even with variable power inputs, making them a suitable option for integration into sources such as solar or wind.
- **Modular and compact design:** Some models allow scalable and rapidly installable configurations (plug and play), facilitating their adoption in pilot projects and distributed applications [45].
- **Operational versatility:** They are suitable for small and medium-scale hydrogen production, such as on-site generation for industrial processes and refuelling stations.

However, this technology currently has the following drawbacks:

- **Limited technological maturity:** it is still under development, with a small number of pilot facilities and uncertainty regarding its large-scale performance.
- **Membrane durability and stability:** anion exchange membranes still pose challenges concerning their chemical and mechanical degradation over prolonged operations, with the reported service lives of the current prototypes far shorter than those of PEM and ALK electrolysers.
- **Poor commercial availability of optimised materials.**
- **Chemical compatibility between the membrane, ionomer and electrode still under development.**

### 3.4.3. Innovations and future developments

AEM electrolysis still faces a number of technical challenges for its development. The main ones include the chemical, thermal and mechanical degradation of the ionomer and membrane due to prolonged exposure to alkalis and thermal cycling (the operating temperature of commercial systems doesn't usually exceed 50°C). The variable load operation also has a negative impact on the stability of the MEA, as it induces thermal stresses, hydration changes and the progressive degradation of the components. In addition, the lower conductivity of the anionic membranes compared to PEM membranes leads to ohmic losses and resistance to transport that reduce their efficiency. Other significant issues include the adsorption of pollutants (e.g. carbonates), limiting the service life of the system, and the need for validation by means of medium-scale pilot projects (TRL 3-6) and the verification of their integration into renewable energies (photovoltaic or wind), in which operational flexibility is still limited.

The areas for improvement include increasing the membrane's stability, reducing the internal resistance and exploring more benign conditions, with the ultimate aim of using water instead of alkaline solutions, as well as the development of catalysts with higher electrochemical activity than the current ones and alternatives to precious metals (PGMs). The anion exchange membranes currently pose chemical stability problems in alkaline media and at moderate temperatures (≈70°C), due to the neutralisation of the cationic functional groups. The efforts in R&D are therefore geared towards increasing the density of the cationic groups without causing excessive expansion of the membranes, as this would compromise the mechanical stability. The incorporation of new functional groups that improve both the conductivity and the stability under alkaline and high temperature conditions is also being studied [42] [43].

With respect to the ionic conductivity, the current practice is to use small concentrations of KOH or NaOH to ensure sufficient conductivity in the cell, which partially mitigates the problems outlined above. However, the future trend is towards the use of pure water as the only reactant, which would simplify the operations and reduce costs [45]. Finally, in addition to the development of active and stable catalysts for the HER and OER, the optimisation of the cell design, flow distribution geometries and balance of plant are presented as a line key to achieving more efficient and durable systems.

### 3.4.4. Main players

**Industry:**

- Membranes: Versogen, Dioxide Materials, Ionomr, Fumatech
- Catalysts: Dioxide Materials, Matteco, Jolt

*Table 3. Major manufacturers of AEM electrolysers (August 2025).*

| COMPANY | COUNTRY |
|---|---|
| Enapter | Germany |
| Hygreen Energy | China |
| Hyter (Pietro Fiorentini Group) | Italy |

## 3.5. Solid oxide electrolysis (SOEC)

SOEC electrolysis is an emerging, research-phase technology that uses ceramic materials to operate at high temperatures. This promising firm of electrolysis achieves higher efficiencies than other electrolysis technologies, thanks to the combined use of electricity and heat.

### 3.5.1. Concept

SOEC electrolysis plays an important role in addressing the high cost of producing hydrogen and other synthetic fuels. The high operating temperatures reduce the different internal losses, increasing efficiency within the reactor. In addition, the thermodynamics of the reactions allows the waste heat from an industrial process such as any petrochemical or steel operation to be used to reduce electricity consumption, increasing efficiency at the plant by up to 20% [46]. Although the present work deals only with water electrolysis, it is worth mentioning the potential of this type of cell for work in co-electrolysis mode, which consists of feeding the system with water and carbon dioxide to produce synthesis gas (CO and $H_2$). This gas, together with the high operating temperatures, facilitates further integration into hydrocarbon synthesis processes to produce fuels and industrial products [47].

This technology involves the separation of water into hydrogen and oxygen at high temperatures (600ºC-900˚C), using a ceramic material as an ion-conducting solid electrolyte. It is therefore a technology of current interest for the production of hydrogen, as well as for the use of the electricity and waste heat that are generated.

SOEC cells consist of two electrodes, the anode or air electrode and the cathode or hydrogen electrode, separated by an ion-conducting electrolyte. Depending on the nature of the conducted ions, two categories can be distinguished: O-SOEC (oxide ion conducting) and H-SOEC (proton conducting) cells.

- **O-SOEC:** the water is supplied to the cathode and reduced to hydrogen and the oxide ion ($O^{2-}$), which is conducted to the anode to form oxygen:

$$\text{Anode (OER): } O^{2-} \rightarrow \frac{1}{2} O_2 + 2e^- \qquad \text{(Equation 16)}$$

$$\text{Cathode (HER): } H_2O\ (g) + 2e^- \rightarrow H_2\ (g) + O^{2-} \qquad \text{(Equation 17)}$$

$$\text{Global: } H_2O\ (g) \rightarrow H_2\ (g) + \frac{1}{2} O_2 \qquad \text{(Equation 18)}$$

- **H-SOEC:** water is supplied to the anode, where protons are formed and conducted to the cathode to produce hydrogen:

Anode (OER): $H_2O\ (g) \rightarrow \frac{1}{2}O_2\ (g)\ +\ 2\,H^+$ (Equation 19)

Cathode (HER): $2\,H^+ + 2e^- \rightarrow\ H_2$ (Equation 20)

Due to the enhanced proton transport facilitated by the electrolyte compared to their $O^{2-}$ ion conducting counterparts, in which the ionic transport is performed by less mobile oxygen anions, H-SOECs can operate effectively in lower temperature ranges (450ºC-700˚C), although they have reached a lower level of development than O-SOECs.

The typical layout of a SOEC cell is very similar to the concept used in all the electrochemical systems for energy conversion, in that it is made up of a series of functional and non-functional layers in close contact with each other [46] [48]**.** Specifically, a typical O-SOEC cell consists of:

- **Cathode:** Typically, this electrode is made of cermet-type materials (metal and ceramic composites), of which the state of the art is Ni-YSZ (yttria-stabilised zirconia or YSZ). This mixture gives the electrode conductive properties for both the electrons and oxygen ions in macroscopic terms, extending the reaction area along the thickness of the layer. The cathode electrode sometimes includes an initial layer of Ni-YSZ of greater thickness and porosity that acts both as a mechanical support and as a reactant buffer, improving the mass transport properties.
- **Electrolyte:** this layer usually consists of a highly densified ceramic material, the function of which is to support the conduction of ions from the cathode to the anode and isolate the two from each other, preventing the movement of gases and electric current between the compartments. The reference in this case is 8% YSZ, which is highly suitable for operations at temperatures above 750ºC-800°C. Below these temperatures, the conductivity of the material is drastically reduced and alternatives such as GDC (gadolinium-doped Ceria) and SCGZ (scandium, ceria and gadolinium doped in zirconia) have to be found.
- **Anode:** In SOEC electrolysis, the reaction of the evolution of the oxygen is highly conditioned by the transport of the oxygen ions across the electrode, as well as the migration and charge

transfer on the surface. This makes materials capable of conducting both the ions and the electrons (MIEC or Mixed Ionic-Electronic Conductors) the best alternatives in this case, as the effective reaction surface can be spread over the entire surface of the electrode. Some examples are LSCF ($La_{1-x}Sr_xCo_{1-\gamma}Fe_\gamma O_{3-\delta}$) and BSCF ($Ba_{0,5}Sr_{0,5}Co_{0,8}Fe_{0,2}O_{3-\delta}$).

The reason why SOEC electrolysis generates so much interest lies in the thermodynamics of the water separation reaction. In the Gibbs-Helmholtz equation:

$$\Delta H_{reac} \equiv \Delta G_{reac} + T\Delta S_{reac} \qquad \text{(Equation 21)}$$

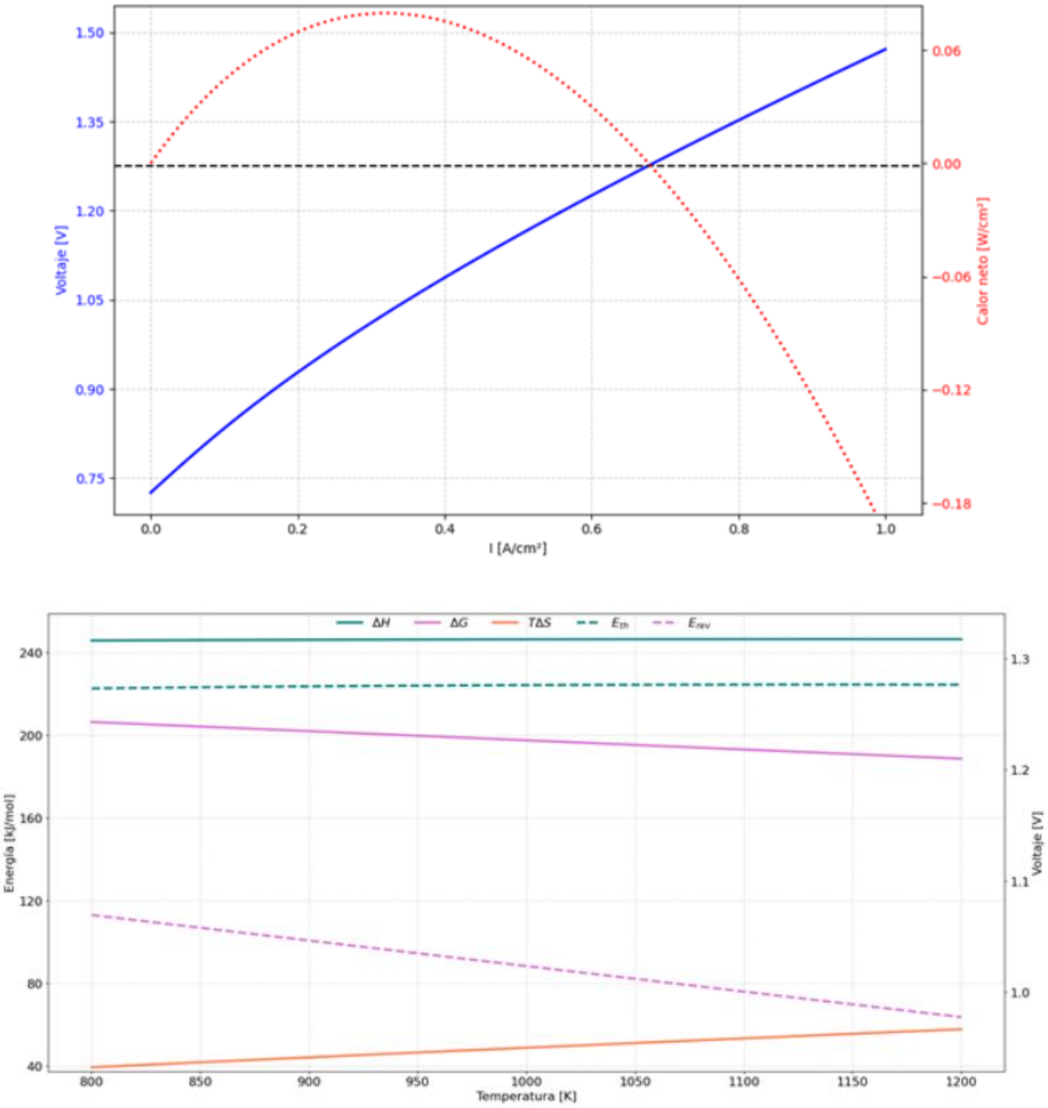


*Figure 17. (sup.) Net thermal demand and cell voltage as a function of current density (inf.) Variation of the thermodynamic properties in accordance with the temperature.*

The term $\Delta H_{reac}$ can be defined as the total energy required to carry out the water separation reaction, where $\Delta H_{reac}$ is the part representing the electrical work and $T\Delta S_{reac}$ is the thermal energy that needs to be supplied. The endothermic nature of this reaction means that, as the temperature increases, the thermal energy required becomes greater, reducing the electrical input required. Taking into account that $E_{rev} = \frac{\Delta G_{reac}}{nF}$ and $E_{tn} = \frac{\Delta H_{reac}}{nF}$, it follows that, once current is demanded from the system and both reactions take place, the internal losses generated will offset the losses until the so-called thermoneutral voltage or $E_{tn}$ is reached, above which the heat generated must be released outside to maintain the heat temperature (see Figure 17).

As far as the cell design is concerned, different options can be considered [48]**.** While small experimental cells have flat, button-shaped geometries, scaling up to larger sizes and powers opens up a wide range of possibilities, depending on the approach chosen. Generally speaking, a distinction can be made between flat cells and tubular cells, as well as cells supported on a cathode or electrolyte and on metal supports.

Firstly, a distinction is made between cells with a flat geometry and tubular cells. The former follow a more classical approach, similar to the filter-press type designs of traditional PEM batteries and ALK electrolysers. Piling them up to form a stack with higher power is achieved by alternating the different cells with intermediate elements, which normally have a defined flow pattern. These elements are called interconnectors or bipolar plates and, in addition to distributing the flow as evenly as possible, they are responsible for transporting the electrical current from cell to cell from one end to the other. Although it is complicated, this design can result in systems with very low total electrical resistivity and, given the flat and compact shape, they can generate high volumetric current densities. Conversely, achieving an airtight seal between the layers is complex, due to the large support surface and the rigid material of the joints. In addition, the different elements are less able to move in relation to each other when thermal gradients occur on their surface, which can generate internal stresses in the cell leading to accelerated degradation or premature failure.

Less explored alternatives include tubular and micro-tubular cells. These schemes are more similar to some thermochemical reactors and, unlike planar architectures, they don’t require any mechanical pressure to meet the sealing and electrical conductivity requirements. As a result, tubular cells excel in that they are more robust and, with some exceptions, easier to design. The sealing surface is usually significantly smaller, and high temperature adhesives are used, which, after curing, don’t require any tightening to insulate the anode and cathode compartments. In contrast, the electrical interconnection, both within the cell and between the cells in a set, is complex and still under study, and therefore they tend to have higher total resistivities. In addition, since the cylindrical geometry takes up more space, the system will have a lower volumetric current density.

Finally, mention should be made of the different approaches to the mechanical support of the cell's core. Because the functional layers of an SOEC cell are usually very thin (between 10 and 50 microns), the mechanical strength of the set can be compromised in the event of the slightest stress. For this reason, a non-reactive layer is usually implemented to support the others, often serving as a starting point for the manufacturing of the cell. In SOEC, the cell is most commonly supported on the cathode. This is due to the ease of generating thin but strong layers of Ni-YSZ on which the others can later be manufactured. This concept can be problematic in the presence of oxidising atmospheres, such as a pure water supply, as the nickel in the composite can re-oxidise to nickel oxide (NiO), generating expansions of the material that can crack the other layers. Alternatively, metallic supports such as mesh or nickel foams can be chosen, which pose fewer expansion problems in oxidising atmospheres. The only aspect to be taken into account in this case is the porosity of the support, which should not cause too much resistance to the transport of the reaction water. Finally, a decision can be made to support the cell in the electrolyte itself. This may be a good option given the high material density of this layer, as well as the option of implementing symmetrical cell concepts. However, the conductive properties of the electrolyte and the operating temperature must be taken into account to prevent work with excessive ion transport losses between the electrodes.

### 3.5.2. Benefits and drawbacks of SOEC electrolysis

The main benefits of SOEC technology lie in the operation at high temperatures. Firstly, in the 700ºC-900°C range the different processes taking place in electrochemical terms (activation of the reactions, charge transport and mass transfer) are facilitated, which considerably reduces the voltage required to overcome the losses [46]. This, in turn, increases the voltage efficiency of the cell/stack, which means that the power consumption can be reduced by up to 20%-25% [49].

This technology has great potential for reducing the cost of the hydrogen, as the energy consumption is the main factor contributing to its cost.

Furthermore, SOECs don't require any noble metals as materials for the electrodes and they can efficiently electrolyse the $CO_2$ to produce CO or generate synthesis gas by means of co-electrolysis of the water and carbon dioxide, which reduces $CO_2$ emissions and contributes to achieving the carbon neutralisation goals.

In addition, the capacity to reduce electricity consumption through the supply of waste thermal energy allows for its integration into processes in which such energy is a by-product to be disposed of. This benefit is particularly attractive on industrial sites where there is excess steam or heat (refineries, petrochemical plants, steel mills, cement plants, etc.) or in combination with sources such as advanced nuclear reactors and concentrating solar power plants. This makes SOEC the preferred alternative for cost-effective hydrogen production, enabling overall process efficiencies of up to 85% to be achieved.

The above points imply that, with the right plant design and integration, the levelised cost of hydrogen (LCOH) which is produced could be lower. Studies such as the one by Ramadan et al [50] indicate that, by overcoming the technical challenges affecting this technology, SOEC electrolysis could reduce the cost of production by 15%-20% compared to the current PEM or ALK alternatives.

However, for all these benefits to materialise through the implementation of SOEC electrolysis on an industrial scale, a number of challenges need to be overcome. The first and most obvious one is the high operating temperature, which places severe demands on the design, material selection and operation. In the work range (700ºC-900ºC), any mismatch between the thermal expansion coefficients of the different materials, added to the potential temperature gradients in the different areas and the succession of heating-cooling cycles, generates high mechanical stresses in the cell core, which end up creating delamination between the layers and, finally, the fracture of the cell. This challenge not only affects the design and operation, practically limiting the use of SOEC electrolysers to stationary applications with practically constant load degrees, it also constitutes a focus when it comes to developing cell materials that are resistant to accelerated degradation.

The operational strategies to mitigate the degradation also need to be defined. For example, maintain a reducing environment at the cathode through hydrogen recirculation, provide sealing air at the anode to reduce the oxygen partial pressure, prevent extreme electrochemical conditions and distribute the flow and current homogeneously, use slow thermal ramps (5°C/min as a guide) [51]) to limit gradients and shocks, choose a temperature that balances the kinetics and degradation, and work with excess water (moderate use factor) to prevent "starvation" (local water shortage), the occurrence of current non-uniformities, hot spots and delamination. Coordinated control of these aspects limits sintering, re-oxidation, parasitic phase formation, delamination and breakage, extending the system's service life.

Finally, there is one last aspect to be taken into account, namely the remarkable physical and operational complexity of the whole system. Much of this complexity comes from the need to incorporate the equipment and lines required to manage the energy flow, such as very high temperature heat exchangers and electric/gas heaters. In addition, it is necessary to implement a line diagram with its precise control to carry out the by-passes and purges required to maintain the composition and temperature conditions of the inlet and outlet currents of the stack suitable for each point of the operation.

Moving away from the purely technical aspect, the high manufacturing costs of SOEC stacks are one of the most important barriers. Overall, the current SOEC prototypes, which lie in kW scales with a low MW, are estimated to have an installed cost of around €4,000-5,000/kW [46], 3-4 times more than the ALK equivalent and twice the cost of a PEM electrolyser with the same power. To make such equipment commercially viable, it is hoped to overcome the various technical and production aspects at scale, with the aim of reaching €1,000-1,200/kW by 2030.

### 3.5.3. Innovation and future developments

Taking into account the state of the technology and the challenges to be overcome, the main lines of innovation and development of SOEC electrolysis are identified:

- **Improved materials and efficiency:** although the purely electrochemical performance of the cell materials is reasonably good, major efforts are being made to develop electrocatalysts and electrolytes that are capable of operating at lower temperatures with as little loss of performance as possible over time. This lower temperature, coupled with increased durability, would improve the overall efficiency and reduce both manufacturing and operating costs.
- **Development of operational strategies and schemes for integration with industry:** in addition to the development of operational strategies that simplify the system’s operation and improve durability, it is necessary to work on the implementation of these systems in industrial processes that emit heat, with the aim of maturing the schemes required for efficient operation and integration.
- **Reduced costs and industrial scaling-up:** “artisan” production must be replaced by automated large-scale manufacturing. In this respect, there exist several projects for the construction of plants to manufacture SOEC electrolysers with, volumes totalling up to 500 MW/year [52].

### 3.5.4. Main players

Table 4 shows the leading ones in the development and marketing of SOEC electrolysers.

*Table 4. Major manufacturers of SOEC electrolysers (August 2025).*

| COMPANY | COUNTRY |
|---|---|
| Bloom Energy | US A |
| Sunfire GmbH | Germany |
| Topsoe | Denmark |
| Ceres Power | United Kingdom |
| SolydEra | Italy |
| Elcogen | Estonia |
| Fraunhofer IKTS | Germany |

At present, H-SOEC electrolysers with proton electrolyte have only reached the research phase [53]. Business participation is limited and the use and development initiatives are focused on research and development centres within the framework of public-private projects.

## 3.6. Integration into uses

### 3.6.1. ALK electrolysis

ALK electrolysis is currently the most mature and widespread technology for hydrogen production, excelling in its reliability and lower investment costs compared to other alternatives [54]. It is mainly integrated into large-scale industrial projects that require a constant supply of hydrogen, such as ammonia, methanol and fertiliser production, and it is used in energy storage and power-to-gas schemes. Unlike PEM electrolysis, its slower response time makes it less suitable for integration into intermittent renewables, but it is well-suited to stable sources such as hydroelectric and continuously running solar energy [55]. ALK currently accounts for most of the world's installed capacity and it is expected to continue to play a key role in the energy transition, particularly in the decarbonisation of energy-intensive sectors such as chemicals and steel [56].

### 3.6.2. PEM electrolysis

In addition to the traditional uses of electrolysis, PEM technology is particularly suitable for projects requiring high-purity hydrogen and flexible operations. This technology is ideal in contexts within which intermittent renewable energy sources with a direct connection, such as solar or wind, are used, as it allows the hydrogen production to be rapidly adjusted to the energy availability. PEM electrolysis is therefore positioning itself as a strategic option for power-to-gas energy conversion applications, electrical grid balancing and hydrogen storage during periods with peak generation of renewables for their later use [57].

Due to its compact design, this technology is preferable in spatially constrained environments, such as refuelling stations, off-shore applications and on-site hydrogen generation systems for industrial processes. Its ability to operate with higher current densities compared to ALK electrolysis allows for faster hydrogen production, making it ideal for projects requiring rapid scalability.

PEM electrolysis is currently gaining prominence, particularly in view of the growing interest in green hydrogen in sectors such as transport, energy storage and industrial applications. Although its implementation isn't yet as widespread as that of ALK electrolysis, its adoption is expanding thanks to its operational flexibility, high degree of efficiency and compatibility with renewable energy sources. This technology has proven to be particularly valuable in projects in which it is essential to respond quickly to variations in the power supply and when high-purity hydrogen is required, as in the case of fuel cells.

### 3.6.3. AEM electrolysis

AEM electrolysers are an ideal solution for projects requiring higher operating pressures than those for ALK electrolysers, as well as more competitive capital costs compared to PEM systems [42]. As they are able to operate with high pressures, AEM electrolysers are beneficial for the direct production of pressurised hydrogen for storage or fuel cell use, reducing the need for additional compression equipment [58].

AEM electrolysis is particularly suitable for projects in which economic efficiency and sustainability constitute priorities but in which neither extremely high rates of hydrogen production nor ultra-high purity of the gas which is generated are required. This technology is suitable for small and medium-scale hydrogen production applications, such as on-site generation for industrial processes, power-to-gas electrical energy conversion systems and fuel supplies for hydrogen stations [59].

AEM technology displays remarkable adaptability within the context of projects that integrate renewable energy sources such as solar and wind power, due to its ability to provide an efficient performance under variable power input conditions.

This technology is also a practical option for initial-stage feasibility studies and pilot projects, as it enables developers to explore the potential of hydrogen production without the high costs associated with other kinds of electrolysers. In these cases, AEM electrolysis offers a solution that balances out performance and cost, leading to efficient production of green hydrogen focused on affordability.

Although AEM electrolysis is yet to be widely implemented in commercial production, recent developments point to growing interest in an industrial scale-up. By way of illustration, in March 2024, the Power to Hydrogen company collaborated with global leaders of the energy industry to showcase the first industrial-scale AEM electrolysis stack for low-cost green hydrogen production. In the field of energy research, the European Union-funded CHANNEL project is developing an innovative 2 kW stack based on AEM technology. This project is seeking to promote the generation of hydrogen by means of water electrolysis in an efficient and cost-effective manner.

### 3.6.4. SOEC electrolysis

As outlined in this document, integrating SOEC electrolysis systems into the waste heat of the different industrial processes minimises the stack's electrical energy needs and maximises the overall efficiency of the process. As might be expected, the most desirable heat sources will be those with the highest temperatures, as they will allow the steam and the other inlet gases to be conditioned as close to the operating temperature as possible, removing the importance of electric/gas heaters.

The processes in which such an integration is most attractive include:

- **Hydrogen production in refineries and the chemical industry:** one of the most attractive options is to incorporate electrolysis systems into refineries and e-fuel production plants. In this case, in addition to using the heat from the plant to offset the electrolyser's needs, the hydrogen produced by the latter can also be used for the different synthesis processes. Processes such as methanol synthesis, biomass gasification and methanation have been studied.

  One good example of the above is the MultiPLHY [60] project at the Neste refinery (Rotterdam, the Netherlands), where a 2.4 MW Sunfire SOEC electrolyser has been integrated into the plant, where the hydrogen that is generated will feed the biofuel production units. Using the steam from the refinery, the project aims to achieve 85% overall efficiency with respect to the LHV (lower heating value), producing around 60 kg/h of hydrogen. The completion of the project constitutes the implementation of the world's first multi-megawatt SOEC electrolysis at a real plant.

- **Steel industry:** steel manufacturing is a high $CO_2$-emitting industry and it also consumes hydrogen. This hydrogen is used both in the annealing processes and in the new direct slag reduction processes. This opens the door not only to the thermal integration, but also that of the hydrogen and oxygen produced.

  Several projects integrating SOEC into steel processes are currently under development. They include GrInHy (Sunfire SOEC) [61]SYRIUS (Elcogen) [62] and HySteel (FuelCell Energy) [63].

- **Coupling with nuclear energy and thermal renewables:** in order to store hydrogen during spikes in production or periods with low demand, the option of using the heat from advanced nuclear reactors or concentrated solar power plants to cover the demand for SOEC electrolysis can be considered. High-temperature gas-cooled reactors (HTGRs) use gases such as helium as a coolant, which rise to temperatures above 700°C, sufficient to condition the gases entering the electrolyser. Projects such as the HTTR-Hydrogen (Japan) and Euratom (Germany) seek to validate this concept.

In the area of solar energy, companies such as Heliocentric have begun to combine solar towers (whose molten salts reach temperatures of up to 800°C) and SOEC electrolysis, thus storing the surplus energy in the form of hydrogen.

# 4. FACTORS WITH AN INFLUENCE ON THE ELECTROLYSIS' EFFICIENCY

Firstly, this chapter analyses the main parameters that determine the efficiency of the operation of an electrolyser. The efficiency values currently achieved by the most representative commercial systems (ALK, PEM, AEM and SOEC) are reviewed below, providing a comparative view of their performances.

## 4.1. Main determining factors

The efficiency of an electrolyser is influenced by several physico-chemical and design factors. In practice, the overall efficiency of the system (see section 2.1.3 to find out how the different types of efficiency are calculated) may be conditioned by aspects such as the operating temperature, the current density, the materials used and the internal configuration [64] [65] [66]. Some key factors are outlined below:

- **Operating temperature:** This is one of the most influential variables in the electrical demand of an electrolyser. As the temperature increases, the electrolysis process becomes more efficient. This is because, firstly, the thermodynamic potential required to dissociate the water molecule decreases with the temperature and, secondly, both the kinetics of the surface reactions and the ionic conductivity of the electrolyte are favoured under higher thermal conditions.

- **Current density:** This has a direct effect on the overall efficiency of the electrolysis, as it influences the drops in voltage (overpotentials), the rate of hydrogen production and the durability of the system. A rise in the current density increases the rate of hydrogen generation, but, at the same time, it leads to greater overpotentials and faster wear of the materials, mainly due to the formation of bubbles and heat generation. Therefore, each technology has an optimal current density range for balancing the production and efficiency.

- **Electrode materials:** The selection of these materials is crucial, as it conditions the catalytic activity, the electrical resistance, the prevention of corrosion and, ultimately, the electrolyser's overall efficiency. The use of suitable catalysts can reduce the activation energy of the reactions and minimise the overpotentials, resulting in better use of the electrical power. Materials such as nickel, Ni-Raney and cobalt are common in ALK electrolysers, due to their cost-effectiveness, resistance to corrosion and chemical stability. Conversely, PEM systems require more active and acid-resistant catalysts, such as platinum, iridium and ruthenium, which explains their higher costs, although advances in electrode design are significantly reducing them. With emerging technologies such as AEM, alternatives based on non-noble metals and mixed oxides are being investigated to combine efficiency and low cost.

- **Features of the electrolyte:** The type of electrolyte and its concentration are factors that determine the efficiency of the electrolysis. In ALK electrolysis, for example, 25%-30% KOH solutions are used, as they provide good electrical conductivity without causing excessive wear to the components. Too low a concentration or the presence of impurities reduces the conductivity and, as a result, lessens the efficiency of the process.

  With the PEM and AEM technologies, the efficiency is highly dependent on the polymer membrane, which is highly sensitive to the purity of the water and the presence of contaminants. Moreover, the thickness of the membrane and the distance between the electrodes, as occurs in zero-gap designs, determine the system's internal resistance; the thinner the membrane and the smaller the gap, the lower the ohmic losses and the better the efficiency.

  With the SOEC electrolysers, the electrical conduction takes place through ceramic materials at high temperatures, and the efficiency depends on the quality of the material and the thermal conditions.

- **Gas and impurity management:** The hydrogen and oxygen bubbles that remain attached to the electrodes increase the ohmic resistance, reducing the usable current and, therefore, the efficiency. The size of the bubbles depends on the current density and pressure, as they are greater with higher current densities and lower pressures. In addition, the rate at which the bubbles become detached from the electrodes significantly influences the cell's electrical resistance.

  Furthermore, any impurities in the water and gases can cause parasitic currents and corrosion, reducing the efficiency. A proper electrolyte flow and degasification design, such as effective gas venting, helps to minimise these losses and maintain a stable performance.

- **Operating conditions and variable load:** Operating electrolysers powered by fluctuating renewable energies has an impact on their efficiency. The variable load operation entails frequent starts and stoppages, which can affect the system's stability and efficiency (due to spikes in the current and membrane degradation). Maintaining the optimal pressure and load conditions in the electrolysis equipment improves the overall efficiency of the process.

## 4.2. Current efficiency of commercial electrolysis systems

In practice, the most advanced commercial electrolysers achieve overall efficiencies totalling around 60%-70%, bearing in mind the hydrogen's Lower Heating Value (LHV). The LHV represents the amount of energy released by the combustion of one kg of hydrogen, without counting the heat from the condensation of the water produced during the reaction (≈33.3 kWh/kg $H_2$). In other words, only the energy that can be directly harnessed is taken into account, ignoring the energy contained in the water vapour generated.

To calculate the above efficiency, the amount of electricity supplied to the cell or electrolysis system to produce one kilogram of hydrogen is measured and compared with the hydrogen's usable chemical energy in accordance with its LHV. The efficiency thus reflects the fraction of electricity that has actually been converted into useful energy stored in the hydrogen. This procedure allows for a practical comparison of the performances of different electrolysers under similar operating conditions. In some cases, the efficiencies can also be calculated based on the Higher Heating Value or HHV, which includes the heat released by condensing the water vapour produced during the combustion (≈39.4 kWh/kg $H_2$).

In the commercial field, the current status of electrolysis technologies can be summarised as follows:

- **ALK electrolysis:** In large-scale facilities, ALK electrolysers can achieve typical overall efficiencies totalling 60%-65% (LHV), although, depending on the materials used and the maintenance of the equipment, higher values can be obtained [67] [68] [69] [70].

- **PEM electrolysis:** The current PEM electrolysers achieve slightly higher efficiencies than ALK ones, typically around 60%-70% (LHV), although, as above, higher values can be obtained [71] [72] [73] [74].

- **AEM electrolysis:** As an emerging technology, AEM electrolysers combine certain benefits of ALK and PEM ones. Recent commercial AEM electrolysers indicate efficiencies lying at around 65%-70% (LHV) [75] [76], reaching values of up to 80% in some laboratory studies [77]. This positions AEM electrolysers in a range similar to that of PEM ones but with cheaper materials, although there is still little commercial equipment available.

- **SOEC electrolysis:** During operations at a high temperature using external heat, the electrical efficiency can reach 90%. However, SOEC electrolysers have only reached the research phase; their efficiencies (~80%-90%) correspond to laboratory prototypes rather than commercial equipment. Even so, this technology offers the greatest efficiency potential if suitable heat sources become available [46].

# 5. POWER SUPPLY

The energy needed for the electrolysis process is supplied in the form of direct current (DC), and it is required by the electrolyser's stack (see section 2.2) to dissociate the water into hydrogen and oxygen. To supply this energy, industrial electrolysers use conversion systems (rectifiers), which transform the alternating current (AC) from the grid or renewable sources into DC.

In addition to the heart of the system (the stack), an electrolyser needs many other kinds of ancillary equipment: BoP (see section 2.2.2), which includes devices such as pumps, cooling systems, compressors and so on. These components are typically AC-powered and they can account for 10% to 15% of the total consumption of the electrolysis system, depending on the design and the electrolysis technology used.

Therefore, the electricity consumption of the stack and BoP is key to assessing the overall efficiency of the system, properly sizing the required electricity infrastructure and accurately estimating the operating costs associated with the hydrogen production.

This chapter analyses how to power an electrolyser with electricity, bearing in mind its connection to the grid and its integration into renewable energies.

## 5.1. Connection to the electrical grid

The direct connection of the electrolysers to the electrical grid raises a number of technical and regulatory considerations.

In Spain, the grid is interconnected with the European electricity system under the supervision of Red Eléctrica de España (REE) [78]. It operates in alignment with the standards laid down in Europe by the ENTSO-E (European Network of Transmission System Operators for Electricity) [79]. The system must maintain strict quality parameters, such as the frequency (50 Hz) and voltage, and it is governed by the European network codes, including the Demand Side Connection Code (EU Regulation 2016/1388 [80]; see RD 647/2020 in Spain [81]), which establishes specific requirements for major electricity consumers such as electrolysis plants.

Thus, the following sections analyse the two-way relationship between the electrolyser and the electrical grid: section 5.1.1 focuses on how the grid's characteristics may affect the operating of the electrolyser, while section 5.1.2 discusses the impact the electrolyser may have on the grid.

### 5.1.1. Effects of the grid on electrolysis equipment

The quality of the power supply is crucial for the proper functioning of an electrolyser. Although these systems are generally tolerant of some variations, severe disturbances can lead to safety shutdowns or damage sensitive components of the electrolyser. The most significant electrical grid disturbances include:

- **Variations in voltage**: Surges, reduced voltage (sags) and rapid fluctuations (flickers) can trigger protection systems and cause equipment resets.
- **Variations in frequency**: The normal operating range usually lies close to 50 Hz. The European connection regulations require continuous operation only between 49-51 Hz [80]; the unit must be switched off for safety reasons at below 47-48 Hz or above 51-52 Hz.
- **Harmonic distortions**: Current distortions in the form of a wave (harmonic distortions) can lead to the overheating of transformers and power electronics, thus reducing their efficiency and service life.

To mitigate these effects, electrolysers must be able to withstand electrical disturbances without their operation being interrupted. According to the Demand Side Connection Code [80], electrolysis plants must be able to maintain controlled operations during temporary grid failures ("fault-ride-through"). For this purpose, it is vital to have control systems that allow the electrolyser to continue operating safely or reconnect rapidly following brief periods of instability.

Electrolysers can also provide valuable services for the electrical grid. Thanks to their ability to modulate consumption quickly and accurately, they can act as flexible loads that help to absorb any surplus power, balance out the frequency of the grid and minimise any spikes in demand. As a result, their potential role in ancillary service markets is currently being explored, offering, for example:

- **Frequency control:** Rapidly adjusting their power consumption in the event of deviations from the nominal frequency to help to maintain the system's stability [82].
- **Voltage control:** Electrolysers can actively contribute to voltage control by injecting or absorbing reactive power, stabilising the grid's voltage when it deviates from the desired value.
- **Congestion management:** By consuming electricity in surplus areas, preventing overloads on transmission lines [83].

- **Network balancing:** Thanks to their remarkable ability to adjust the power consumption, and even production when they are integrated into fuel cells, electrolysers can operate in two directions. This allows them to absorb or inject energy in accordance with the grid conditions, helping to alleviate congestion, offset imbalances between supply and demand and promote the more stable and efficient operating of electrical grids [84].

### 5.1.2. Effects of electrolysis equipment on the electrical grid

As high-power loads, electrolysers can also affect the electrical grid. The most significant impacts include:

- **Local drops in voltage**: The high power consumption of an electrolyser can lower the voltage level of nearby grids, particularly weak or saturated grids, mainly during the start-up or sudden changes in power.
- **Reactive energy consumption**: If the rectifier isn’t properly compensated, it can disturb the electrical balance.
- **Generation of harmonic distortions**: AC/DC conversion without the proper filtering can introduce distortions into the network. To prevent disturbances for other users, facilities should include filters that minimise any harmonic distortions that are emitted.
- **Fluctuations in load**: If the power of the electrolyser changes rapidly, voltage fluctuations (“flickers”) may occur and affect any other connected equipment.

For this reason, electrolysis plants must meet the grid quality requirements set out in the regulation. This ensures that the operation of the plant doesn’t undermine either the quality or the stability of the electricity supply in the surrounding area.

## 5.2. Power supply with renewable energy

One of the major opportunities that electrolysis provides is its ability to directly harness renewable energy such as solar or wind power to produce green hydrogen. However, integrating an electrolyser into these energy sources poses technical challenges, due to their intermittent and variable nature; changes in the solar radiation and wind can cause energy fluctuations that prevent the electrolyser from operating stably, with frequent start/stop cycles or partial load conditions.

This may have consequences for the equipment, including reduced efficiency. Moving away from the ideal operating conditions increases electricity consumption for each kg of hydrogen produced.

The integration of renewable energies into the electrolysis therefore requires strategies to manage the fluctuations and keep the operation of the equipment stable. The options that can be considered include [85] [86]:

- **Use of batteries**: Storing surplus renewable energy in batteries allows the functioning of the electrolyser to remain stable during non-generation periods.
- **Flexible load control**: Dynamically adapting the operating power of the electrolyser to the energy available helps to reduce any unnecessary starts and stoppages. The consumption of modern electrolysers (especially PEM ones) can vary rapidly, making it easier to phase the hydrogen production in step with the renewable energy.
- **Predictive systems**: Meteorological models and forecasting algorithms can anticipate the availability of renewable energy. With reliable forecasts, the operation of the electrolyser can be planned, minimising any negative impacts on the equipment.
- **Other strategies**: In addition to the energy solutions, improvements can also be directly applied to the electrolysis system. For example, using more advanced rectifiers that transform alternating current into direct current better, preventing unwanted tiny fluctuations (“ripples”) that reduce efficiency and damage the components. The design of the electrolyser itself can be improved with more resistant materials, reinforced membranes and control systems that help to keep the temperature, pressure and flow conditions stable.

# 6. LEVELISED COST OF HYDROGEN (LCOH)

This chapter introduces the concept of LCOH, the existing public models to calculate it and the steps to be taken to achieve a reduction in the cost of hydrogen.

## 6.1. Concept and meaning of LCOH

The Levelised Cost of Hydrogen (LCOH) is a metric that quantifies the average cost, expressed in its present value, of producing one kilogram of hydrogen over the service life of a production plant. Its calculation includes the cost of the facility (CAPEX) associated with the design, construction and commissioning, together with the recurrent operational expenditure (OPEX) resulting from the operation and maintenance of the equipment, in addition to the energy and other associated costs.

The LCOH methodology thus provides a robust quantitative framework for assessing the economic viability of electrolysis projects, allowing the comparison of technologies, configurations and power supply scenarios under homogeneous criteria and helping to determine the variables with the greatest influence on the cost of hydrogen production.

The LCOH is usually expressed in euros or in kilowatt hours per kilogram of hydrogen (€/kg or €/kWh).

Expressed in mathematical terms, the most widespread equation takes the following form:

$$LCOH = \frac{I_0 + \sum_1^n \frac{C_t}{(1+i)^t}}{\sum_1^n \frac{M_t}{(1+i)^t}} \qquad \text{(Equation 22)}$$

Where:

- $I_0$: Initial investment in the hydrogen production plant, CAPEX
- $C_t$: Annual operating costs of the hydrogen production plant in year t
- i: target internal rate of return of the project.
- $M_t$: annual hydrogen production (kg or kWh)
- n: estimated life, in years, of the facility

### 6.1.1. Initial investment, CAPEX

Depending on the type of project, the initial investment or capital cost will include more or fewer factors with a direct effect on its value.

The main costs to be taken into account are:

- **Cost of the electrolysers:** These are the core of the plant and they account for its most important cost (between 30% and 50%). Their cost depends on the selected technology (ALK, PEM, SOEC), the origin of the equipment (Asian equipment is currently cheaper) and the installed capacity. They include the electrolysis cells and the ancillary equipment for their proper operation.
- **Cost of the BoP equipment:** This groups together the equipment that makes up the ancillary systems required for the plant to operate: tanks, pumps, cooling equipment, nitrogen supply, piping, valves, electrical panels and instrumentation. Equipment for water purification and treatment (reverse osmosis, demineralisation, desalination, as appropriate) which is essential for the electrolysis, is also included.
- **Cost of the hydrogen distribution system:** This system will depend on the way in which the hydrogen that is produced is dispatched (pipeline, lorry, hydrogen refuelling station, etc.). It includes the internal transmission of the gas at the plant, compressors, a storage system and the loading infrastructure for its distribution (filling stations). Its cost depends on the supply pressure, capacity and technology chosen.
- **Cost of the electricity infrastructure:** This includes the grid connection and the integration of the renewables, together with the substations, transformers, inverters and wiring. This section ensures a reliable and stable supply of electricity to the electrolysers.
- **Cost of the civil work:** This includes the main buildings (electrolysers, electrical building, administration building, etc.), ancillary buildings, foundations, structures, internal roads, buried networks, fencing, etc. Although they don’t generate hydrogen, they are essential for setting up and operating the plant safely. The cost varies, depending on the location of the plant and the size of the project.
- **Other costs:** These include the engineering costs (feasibility studies, basic and detailed design), commissioning, environmental licences, urban planning permits, industrial safety, consultancy and insurance. Although their influence on the CAPEX is minor, they are key to ensuring that the plant can be built and operated in compliance with the regulations, preventing delays and cost overruns.

In some projects, the cost of the construction of the electricity generation facilities using renewable sources (photovoltaic or wind) forms part of the calculation of the initial investment.

This initial investment can be reduced by any non-repayable subsidies that are received.

### 6.1.2. The plant’s operational expenditure, OPEX

The operating expenses include all the costs that are necessary for the proper functioning of the plant. Depending on the model used, they are more or less detailed and take into account more or fewer factors. Of course, the more details there are, the more accurate the calculation will be.

The main costs are as follows:

- **Cost of the electricity:** This constitutes by far the most decisive factor in the operating cost structure, especially when the electricity has to be purchased from third parties and it does not form part of the initial investment in the generation of renewables. To this cost we must add the charges associated with tolls and access to the high-voltage transmission or distribution network, unless they are already included in the price of the electricity in the contract.
- **Cost of auxiliary inputs:** This category includes water consumption, not only in relation to the electrolysis for hydrogen production, but also for consumption by ancillary services such as the cooling system. Other significant inputs are included, such as chemicals for the water conditioning and nitrogen, in the event that no internal generation is available.
- **Cost of replacing the electrolyser’s stack:** The stack undergoes degradation over its service life (operating hours), which has an impact on the efficiency of the plant and, as a result, the hydrogen production. When this loss of efficiency reaches a given value, the cost associated with changing the stack is offset by the avoidance of any loss of hydrogen production. The moment to change the stack will depend on the electrolyser’s technology/quality and the annual number of hours it has been used for.
- **Variable operating costs:** these are expenses directly linked to the operation of the plant, such as the annual maintenance of the equipment, including any consumables and spare parts for the equipment.
- **Fixed costs:** these are costs that remain constant, regardless of the level of production. They include personnel costs, land rentals, taxes, insurance and any other recurring overheads at the facility.

The way in which all these factors are taken into account will depend on the calculation methodology used.

Furthermore, additional income associated with the hydrogen production can be taken into account, such as the sale of the oxygen produced or the heat generated in the electrolysis, although is potential income is conditioned by the presence of a nearby customer. Similarly, any subsidy received on a regular basis should be regarded as income.

### 6.1.3. Annual hydrogen production

The hydrogen production is linked to the power (kW or MW) and efficiency of the electrolyser and the annual number of hours of use.

The efficiency of the electrolyser usually depends on the manufacturer, and it refers to the electrical energy required to produce one kilogram of hydrogen (kWh/kg$H_2$):

$$\text{Produción } (kg/h) = \frac{Potencia\ electrolizador(kW)}{Consumo\ por\ kg(kWh/kg)} \qquad \text{(Equation 23)}$$

This value, together with the number of hours of annual use, will provide us with the annual hydrogen production ($M_t$).

## 6.2. IBHYX index (MIBGAS)

The IBHYX index constitutes the benchmark for the levelised cost of the production of renewable non-biological hydrogen (RFNBO) in the Iberian Peninsula, in accordance with the European Delegated Acts 2023/1184 and 2023/1185. This indicator reflects the producer's minimum selling price to guarantee the expected profitability, and it is configured as an "ask" price signal for hydrogen production projects using electrolysis.

To obtain it, a representative template plant has been defined for a renewable hydrogen production project in the Iberian Peninsula, in compliance with the European regulations and, in particular, the European delegated acts that define renewable hydrogen (RFNBO). The plant in question (see Table 5) has been sized with a 50 MW electrolyser, based on a neutral technological configuration (50% PEM and 50% ALK), 25 years of service life and an operating regime with 4,500 equivalent hours per year. The electricity that powers the process comes from a hybrid system made up of dedicated renewable facilities (photovoltaic and wind) and renewable Power Purchase Agreements (PPAs), which are optimised to guarantee seasonal and hourly complementarity.

The LCOH calculation model is developed upon the basis of the above under a Project Finance type financial scheme. Unlike the simplified LCOH formulation based solely on the relationship between total costs and the hydrogen produced, the approach adopted by MIBGAS expressly incorporates the project's financial structure, the leverage, the debt amortisation, the taxation and the reinvestment in equipment.

For the initial investment (CAPEX), €1,600/kW is established for the electrolyser island, including the water treatment equipment, stacks, balance of plant, substation, electrical connection and engineering, procurement and construction (EPC). The land and licensing costs aren't taken into account at this stage and transferred to the operational expenditure (OPEX).

The OPEX is estimated as 2.5% of the annual CAPEX for consumables, access tolls, salaries, fees, concessions and licences. The insurance accounts for 1.5%.

The electricity cost is obtained by means of a parallel Project Finance model applied to dedicated renewable plants, which can calculate an LCOE for the electricity from this resource. The PPA contracts complement the model's operating hours. The LCOE of the dedicated plants and the price of the PPAs are incorporated as exogenous variables into the calculation of the LCOH. This procedure guarantees methodological consistency between the cost of the hydrogen and the cost of the electricity that supports it.

The model also envisages the replacement of the stacks in years 10 and 20, equivalent to 15% of the initial CAPEX in each case, and a progressive degradation of the efficiency of the electrolyser totalling 1% each year, leading to an increase in electricity consumption throughout the service life of the project.

The initial energy efficiency stands at 55.5 kWh/kg of the hydrogen produced (LHV reference). The annual hydrogen production remains constant under these hypotheses, although the electricity consumption increases over time due to the degradation of the equipment.

The income comes from the sale of renewable hydrogen, calculated as the annual production multiplied by the selling price. No additional income from by-products (such as oxygen and heat) is taken into account, except for EU Allowances (EUAs), which are integrated as a line of income in keeping with the European regulation.

The income minus the operating costs provides the EBITDA (Earnings Before Interest, Taxes, Depreciation and Amortisation), which represents the operating profitability before the financial effects are considered.

The model uses the free cash flow for the shareholder (the result of correcting the EBITDA by taking into account the debt service, taxes and new investments). This flow is discounted from the capital cost (the investor’s Internal Rate of Return or IRR) and compared with the initial investment. If the Net Present Value (NPV) is positive, the selling price is too high; if it is negative, it’s too low. The iteration converges when the NPV is equal to zero, resulting in the LCOH.

As for the financing, the MIBGAS model adopts a debt structure amortised by the French constant instalment method, which leads to regular payments including principal and interest. The interest rate which is applied depends on the project’s risk profile and the market conditions. Furthermore, the taxation is expressly introduced, in such a way that the cash flow reflects the net reality of the profit.

To ensure financial sustainability, each year the model monitors the Debt Service Coverage Ratio (DSCR), which relates the available cash flow to the debt service. A value greater than 1.35 in each year is required. If this condition isn’t met, the leverage is adjusted to reducing the proportion of debt in the financing.

The final result of the model is a representative value of the minimum price at which the RFNBO hydrogen produced at the plant in question can be sold. Given that its calculation encompasses technical and financial variables in a consistent manner, the IBHYX provides a reference aligned with the actual investment logic and the European regulatory requirements for the deployment of renewable hydrogen that guides producers, consumers and investors through the development of the renewable hydrogen market in the Iberian Peninsula.

*Table 5. Table of parameters. Source: MIBGAS.*

| | Parameter | Value | Units | Frequency | Confidential | Publication |
|---|---|---|---|---|---|---|
| **Price** | LCOH | - | €/kg | Weekly | No | Excel |
| | LCOH | - | €/MWh | Weekly | No | Excel |
| **ELECTROLYSER DATA** | Nominal power | 50 | MW | Fixed | No | PDF |
| | Service life | 25 | years | Fixed | No | PDF |
| | ELY Specific Consumption | 55,5 | kWh/kg | Fixed | No | PDF |
| | Higher heating value (HHV H2) | 39,41 | kWh/kg | Fixed | No | PDF |
| | Equivalent hours* (h.eq.) | 4500 | h/year | Fixed | No | PDF |
| | ETS allowances awarded | 6,84 | allowances/t H2 | Temporary | No | PDF |
| | Stack output pressure | 30 | bar | Fixed | No | PDF |
| | Stack degradation | 0,96 | %/year | Fixed | No | PDF |
| | Stack replacement period | 10 | years | | | |
| | OPEX | 2,5 | % of the CAPEX per year | Fixed | No | PDF |
| | Insurance costs | 1,5 | % of the CAPEX per year | Temporary | No | PDF |
| **POWER SUPPLY DATA** | Nominal electrical power | 50 | MW | Fixed | No | PDF |
| | Power of the solar plant | 75 | MW | Fixed | No | PDF |
| | Power of the wind plant | 25 | MW | Fixed | No | PDF |
| | H.eq. with dedicated solar | 2500 | h/year | Fixed | No | PDF |
| | H.eq. with dedicated wind | 1000 | h/year | Fixed | No | PDF |
| | H.eq. with wind PPA | 700 | h/year | Fixed | No | PDF |
| | H.eq. with solar PPA | 300 | h/year | Fixed | No | PDF |
| | Cost of the wind energy PPA | - | €/MWh | Weekly | Yes | Pexapark |
| | Cost of the solar energy PPA | - | €/MWh | Weekly | Yes | Pexapark |
| | Total cost of the energy PPA | - | €/MWh | Weekly | Yes | No |
| | Voltage at the connection point | 220 | kV | Fixed | No | PDF |
| | Direct line length | 5 | km | Fixed | No | PDF |
| | Distance to the connection point | 2 | km | Fixed | No | PDF |
| | LCOE dedicated solar plant | - | €/MWh | Temporary | Yes | No |
| | LCOE dedicated wind plant | - | €/MWh | Temporary | Yes | No |
| | LCOE joint dedicated renewable plant | 49.26- | €/MWh | Temporary | No | No |

| | | | | | | |
|---|---|---|---|---|---|---|
| **ECONOMIC DATA** | Service life dedicated solar plant | 25 | years | Fixed | No | PDF |
| | Service life dedicated wind plant | 25 | years | Fixed | No | PDF |
| | CAPEX dedicated solar plant | 500 | €/kW | Temporary | No | PDF |
| | CAPEX dedicated wind plant | 1100 | €/kW | Temporary | No | PDF |
| | O&M cost dedicated solar plant | 5 | €/kW-year | Temporary | No | PDF |
| | O&M cost dedicated wind plant | 50 | €/kW-year | Temporary | No | PDF |
| | Price of ETS allowances Y+2 | - | €/t CO2 eq | Weekly | Yes | ICE |
| | Cost of the debt (Euribor IRS + 300 p.p.) | - | % | Weekly | Yes | LSEG |
| | CAPEX subsidy (electrolyser only) | 0 | % of the CAPEX | Extraordinary | No | PDF |
| | OPEX subsidy (H2 production) | 0 | €/kg H2 | Extraordinary | No | PDF |
| | Electrolysis CAPEX | 1600 | €/kW | Extraordinary | No | PDF |
| | Stack replacement cost | 15 | % of the CAPEX | Extraordinary | No | PDF |

## 6.3. European Hydrogen Observatory model

The European Hydrogen Observatory, managed by the Clean Hydrogen Partnership, has developed a hydrogen levelised cost calculator [87], which is designed to estimate the cost of hydrogen production under different technical, financial and regulatory hypotheses.

The calculator allows users to enter the specific hypotheses of a hydrogen production project and obtain the resulting LCOH value.

The parameters that can be modifed by the calculator are as follows:

- **General parameters:** Capital cost, economic life.
- **Electrolysis unit:** Installed power, CAPEX, energy consumption, battery durability, battery degradation, battery replacement costs, other OPEX costs.
- **Electricity source:** Operating hours, average electricity cost, access/network tolls, electricity taxes.
- **Subsidies and additional income:** Subsidy to the CAPEX of the electrolyser, a green premium or regulated tariff for hydrogen injected into the grid, lower grid tolls and electricity taxes, oxygen selling price.

Its main asset lies in the possibility of comparing different project and country configurations, as well as the conducting of sensitivity studies to analyse how the different parameters can influence the final value of the LCOH.

## 6.4. Main factors that affect the LCOH

The LCOH depends on a complex set of technical, economic and financial factors that interact to determine the viability of electrolysis projects. Firstly, the cost of electricity constitutes the most crucial variable, as it accounts for 60%-70% of the cost of renewable hydrogen [88] [89] [90]. The reduction of this parameter is closely linked to the deployment of low-cost renewable sources (mainly photovoltaic solar and wind), as well as the availability of long-term power purchase agreements (PPAs) that guarantee price stability and comply with the conditions set out in the EU’s delegated acts for the definition and production of renewable hydrogen.

The geographical location plays a key role in the LCOH, as it determines the effective number of annual full load hours of the electrolyser if it relies on renewable sources and, therefore, the efficiency of use of the infrastructure which is installed [91]. Facilities with a low number of annual full load hours have a high LCOH, given that the fixed investment costs are spread over lower hydrogen production. Conversely, facilities located in regions with a high complementarity of renewable resources (such as a combination of solar and wind) can achieve a higher number of operating hours, contributing to a significant fall in the unit cost of the hydrogen produced [92].

Another core element is the CAPEX, which encompasses the initial investment in electrolysis equipment, balance of plant, electrical infrastructures and costs associated with engineering, procurement and construction.

In 2024, according to the IEA, the capital cost of an installed electrolyser (including the main equipment, gas treatment systems, balance of plant and engineering, procurement, construction and contingency costs) lay within the range between USD 2,000/kW and USD 2,600/kW [93]. In terms of the manufacturing location, electrolysers manufactured in China boast a significant cost advantage over those produced in Europe and North America, ranging from USD 600 to USD 1200/kW for an installed system. However, more than half of the total cost of an installed electrolyser is accounted for by EPC (engineering, procurement and construction) and contingency costs, which are entirely dependent on the location of the project. The higher EPC costs, coupled with the need to adapt the technology to local standards, mean that the capital cost of installing a Chinese-made electrolyser in other regions of the world ranges from USD 1,500 to USD 2,450/kW, significantly reducing the cost savings.

A breakdown of the CAPEX of an electrolysis system identifies several main components. Approximately 15%-20% of the total CAPEX is accounted for by the stack’s components, which constitute the greatest potential for cost reductions through technological innovation and the optimisation of the manufacturing processes. In contrast, 25%-30% is associated with the balance of plant (BoP), including the electrical power devices, piping, compressors and gas treatment systems, which are already commercially mature equipment with limited scope for cost reductions.

Finally, as indicated above, more than half of the total cost of an electrolyser is related to the engineering, procurement and construction (EPC) costs and contingencies, whose potential for reduction remains highly uncertain.

Finally, according to the IEA, the medium-term forecasts point to substantial cost reductions as a result of the industrialisation of the supply chain, mass production and economies of scale, particularly with regard to the stack. Under these conditions, the CAPEX is projected to fall by 40%-50% by the end of the decade.

However, it's not only the absolute magnitude of the CAPEX which is important, it's also the financing structure that accompanies it. In this regard, the cost of the financial capital, expressed through the weighted average cost of capital (WACC), decisively determines the profitability demanded by investors and, therefore, the minimum selling price of hydrogen to ensure the viability of the project. In the case of hydrogen produced using renewable electricity, for example, a three percentage point increase in the cost of the capital could increase the total cost of the project by almost one third [94].

In parallel, the OPEX, which includes maintenance, the replacement of equipment (particularly that of stacks over the plant's service life), insurance and indirect costs, accounts for a smaller but not negligible percentage of the cost structure. Technological efficiency plays a key role in this; an electrolyser with lower specific electricity consumption per kg of hydrogen can cumulatively reduce annual energy costs. However, the degradation of the equipment over its service life introduces a dynamic of progressively increasing electricity consumption, which must be offset by regular replacements or the initial oversizing of the installation.

Finally, it is vital to consider regulatory and market factors. The implementation of public support schemes such as CAPEX and OPEX subsidies, fiscal incentives and mechanisms linked to the EU Emissions Trading Scheme (EU Allowances or EUAs), together with the potential introduction of mandatory minimum consumption quotas in certain sectors, may significantly alter the competitiveness of renewable hydrogen vis-à-vis fossil alternatives [93].

In conclusion, the LCOH stems from the interaction of multiple factors: the cost of electricity as the dominant component, the evolution of the technology and economies of scale affecting the CAPEX, the operational efficiency and management of the OPEX, the capacity linked to the renewable resources available, and the regulatory framework that sets incentives and constraints. The right combination of these elements is crucial to enable renewable hydrogen to compete with fossil alternatives with regard to costs and establish itself as a key element in the energy transition.

## 6.5. Strategies to reduce the LCOH

Reducing the LCOH is essential if the competitiveness of renewable hydrogen in the market is to be achieved. The aspects whose optimisation can make a significant contribution to reducing the LCOH are listed below.

From a technical standpoint, improving the energy efficiency of the electrolysers (kWh/kg $H_2$) and mitigating electrode degradation are key factors, due to the high impact of the cost of electricity on the LCOH.

The use of waste heat by means of thermal recovery and the sale of by-products such as oxygen generates additional income and effectively reduces the LCOH. In particular, studies show that selling waste heat can reduce the LCOH by as much as €0.35 /kg $H_2$ [95].

From an industrial perspective, harnessing the economies of scale in the manufacture of electrolysers and furthering the industrialisation of the supply chain are determining factors, as they allow for significant reductions in the CAPEX and OPEX. Component standardisation, mass production and the technological maturity of the sector will facilitate a progressive fall in the LCOH, accelerating the competitiveness of renewable hydrogen in the market.

On the economic front, the signing of long-term renewable PPAs at stable prices ensures favourable electricity supply conditions; this is crucial at a time when the price of electricity accounts for up to two thirds of the LCOH [96].

Finally, from a regulatory standpoint, the reduction or elimination of tolls and taxes on electricity consumption for renewable hydrogen will lead to a direct fall in the OPEX. Moreover, tax incentives such as deductions for production or consumption can substantially improve the net profitability of a project.

In short, a combination of technological progress, economic mechanisms and the appropriate regulatory frameworks can create an environment conducive to enabling significant reductions in the LCOH.

# 7. LEADING PROJECTS AND INITIATIVES IN THE FIELD OF ELECTROLYSIS

The development of electrolysis in Spain and Europe is based on a growing series of strategic initiatives, support programmes and benchmark projects seeking to accelerate the transition towards a decarbonised energy system. This chapter lists the main initiatives promoted in Europe and throughout the country, as well as some of the most representative projects that are already underway.

## 7.1. European Hydrogen Bank

The European Hydrogen Bank (EHB) is one of the European Commission's strategic initiatives to accelerate the deployment of renewable hydrogen within the framework of the Green Deal, the Fit for 55 package and the REPowerEU plan.

The aim is to unlock private investments in the hydrogen value chains in the EU and third countries by connecting the renewable hydrogen supply with the emerging demand from European buyers, thereby establishing an initial market for renewable hydrogen. To achieve the above, the EHB has developed mechanisms that seek to close the gap between the current renewable hydrogen production costs and the price that demand is willing to pay, acting as economic support and a price signal.

The EHB's activities are based on four complementary pillars.

- **Domestic pillar:** This organises competitive auctions for the production of renewable hydrogen certified as RFNBO in the European Economic Area, remunerated by means of a fixed premium per kilogram, which is only paid after verified production and for a maximum period of ten years.
  The auctions seek to reduce the cost gap between renewable and fossil fuel-based hydrogen in the EU, help to create comparable price signals and reduce the investment risk in the initial phase of the projects.
- **International pillar:** This envisages a coordinated EU strategy to promote renewable hydrogen imports to the European market. For this purpose, the Commission is developing the design of joint European auctions.
- **Transparency and coordination pillar**: This is embodied in the Hydrogen Mechanism platform, aimed at promoting the market development of renewable and low-carbon

hydrogen and its derivatives (ammonia, methanol and electro-sustainable aviation fuel; eSAF). In practice, it compiles and processes the information on renewable and low-carbon hydrogen supply and demand provided by the agents and makes it available to the market. This increases transparency and allows European buyers to connect with both European and international suppliers.

- **Coordination of instrument pillar:** this aligns State aid, technical assistance and combined EU and member State funding.

Two auctions have been held until now, with the following results:

- **Pilot auction (IF23):** Launched in November 2023 and completed in February 2024, it received 132 bids from 17 countries and awarded almost 720 million euros to seven projects, six of which signed grant agreements in October 2024. The premiums that were offered ranged from €0.37 to €0.48/kg on a pay-as-bid basis, with obligations to start production within five years of signing the agreement.

- **Second auction (IF24):** It opened on 3 December 2024 and ended on 20 February 2025, incorporating a specific basket for maritime uses. The tender received 61 bids (eight of them in the maritime basket) for the 4.88 billion euros that were requested. On 20 May 2025, the Commission published the results; fifteen projects selected in five countries for a total of 992 million euros, with winning premiums for the general theme standing at between €0.20 and €0.60/kg and between €0.45 and €1.88/kg in the maritime theme. The projects as a whole undertake to achieve financial closure within a maximum of two and a half years and start production five years after they are signed. They will only receive the premium during the decade in which renewable production is proven.
  A new feature of IF24 has been the expansion of resources through the auction-as-a-service (AaaS) mechanism. On 18 November 2024, Spain, Lithuania and Austria announced national funding totalling over 700 million euros to support projects in their countries through AaaS, and on 15 April 2025 the Commission approved a Spanish state aid scheme for 400 million euros for the same purpose.

The Commission has announced a third auction in late 2025 with a budget of up to one billion euros, in keeping with the aim of consolidating a European market with increased liquidity and iterative regulatory learning. This announcement appears on the EHB's portal and in subsequent institutional communications.

A summary of the two auctions, highlighting the funds awarded to Spain, can be found in Table 6. It should be noted that the EHB recently reallocated part of the funds assigned in previous auctions by withdrawing the initial beneficiaries (or not signing the obligatory agreement) [97]. These funds have been allocated to 8 projects on the waiting list of the second auction (the reallocation is not included in Table 6).

*Table 6. Results of the EHB's auctions.*

| Indicator | First Auction (2023) | Second Auction (2025) |
|---|---|---|
| **Projects submitted** | 132 | 61 |
| **Projects selected** | 7 | 15 |
| **Spanish projects selected** | 3 (2 signed agreement) | 8 |
| **Total funding awarded (EU)** | €720 M | €992 M |
| **Funding for Spain** | €238 M (≈33%) | €292 M (≈30%) |
| **Total power awarded** | ~1,502 MW | 2,336 MW |
| **Power in Spain** | 595 MW | 891 MW |
| **Estimated renewable $H_2$ production** | 158,000 tonnes | 2.2 million tonnes |
| **Average price offered (Spain)** | €5.8/kg | €5.5/kg |
| **Fixed premium per kg $H_2$** | €0.37-€0.48/kg | €0.20-€0.60/kg |
| **Indicator** | PEM and ALK | PEM and ALK |
| **Projects submitted** | — | 38% of the projects |
| **Projects selected** | — | 75% of the aggregate capacity |
| **Spanish projects selected** | — | 64% of the projects (average 384 km) |
| **Total funding awarded (EU)** | Not applicable | Spain contributes an additional €400 M |

## 7.2. European Electrolyser Partnership

The European Electrolyser Partnership (EEP) was launched in 2022 as an initiative of the European Commission and the industry involved in hydrogen production as part of the European Clean Hydrogen Alliance (ECH2A), with the aim of developing electrolyser production capacity and the associated supply chain. The founding milestone was the Joint Declaration, signed at the Electrolyser Summit (Brussels, 5 May 2022), in which the industry undertook to raise annual manufacturing capacity from 1.75 GW to 17.5 GW_$H_2$/year by 2025.

In order to reinforce the competitiveness and scaling up of hydrogen within the EU, the EEP and the European Commission have agreed on four lines of action:

- Generate clear and additional demand for hydrogen and green products.
- Simplify the legislation on hydrogen, making it coherent and bolstering its implementation.
- Increase resilience and create conditions for fair and reciprocal competition for electrolysers and clean hydrogen products; EEP.
- Improve the financial support for the sector, providing clarity on the EU’s funding mechanisms to reduce the ecosystem risk.

## 7.3. National initiatives

The promotion of green hydrogen in Spain is being configured through a network of public policies, strategic plans and funding programmes seeking to position the country as one of the European benchmarks for this new energy economy. The initiatives that have been launched include two that excel in terms of their scope and transformational capacity: the PERTE ERHA (Strategic Project for the Recovery and Economic Transformation of Renewable Energies, Renewable Hydrogen and Storage) and the programme of the so-called "Hydrogen Valleys" or territorial clusters of renewable hydrogen. The two mechanisms, although their concepts are different, are closely linked and they form the core of Spain's strategy to make renewable hydrogen a pillar of the energy transition and industrial modernisation.

The PERTE ERHA, approved in 2021 as part of the Recovery, Transformation and Resilience Plan, constitutes the main industrial policy tool for channelling European NextGenerationEU funds into renewable energy, green hydrogen and energy storage projects [98]. This strategic project is conceived as a country initiative geared towards meeting the decarbonisation targets set by the European Union and transforming the national productive fabric. Overall, it is estimated that it will mobilise over 16 billion euros of public and private investment, a significant part of which will be specifically devoted to developing renewable hydrogen [9].

The PERTE's objectives are multiple: to promote research and technological development, to reinforce the Spanish industrial value chain, to attract private investment, to create quality employment and to consolidate the country's leadership of an emerging sector. Furthermore, it is hoped that the deployment of green hydrogen will have a balanced territorial impact, reaching both the major industrial hubs and the regions affected by depopulation and energy reconversion processes. With the above in mind, the lines of action include pioneering projects to demonstrate the viability of new technologies in real conditions, the development of the domestic value chain with the manufacture of electrolysers and proprietary components, collaboration with SMEs and technology centres to promote innovation, and territorial integration through the creation of ecosystems combining hydrogen production, transport and consumption. The latter measure is directly linked to the "Hydrogen Valleys" programme, which represents the PERTE's most ambitious territorial concretisation.

This programme's initiative is based on the idea of creating integrated energy and industrial ecosystems in which the production, storage, distribution and use of renewable hydrogen are concentrated in a single geographical area. This approach will be able to reduce logistical costs, harness economies of scale and encourage cooperation between companies, administrations and innovation centres. In 2025, the Ministry for the Ecological Transition and the Demographic Challenge (MITECO) awarded over 1.2 billion euros of aid from the PERTE ERHA to finance seven large hydrogen cluster projects in different autonomous communities [99]. These projects, located in regions such as Aragón, Andalusia, Castile and Leon, Catalonia and Galicia, boast a combined total of around 2,300 megawatts of electrolysis power, with their estimated production capacity amounting to over 260,000 tonnes of renewable hydrogen per year.

The scale of these figures demonstrates the ambition of the programme, involving a shift from pilot projects to large-scale industrial facilities capable of supplying energy-intensive sectors such as iron and steel, the chemical industry and heavy mobility. Moreover, the expected impact of the "Hydrogen Valleys" goes far beyond energy, as a major impact on employment and territorial development is envisaged. Thousands of direct and indirect jobs are expected to be created, particularly in regions affected by the energy transition, including former mining basins and areas in industrial decline. In this regard, the clusters will become a tool for decarbonisation, but also one for economic revitalisation and social cohesion.

Another key aspect of these initiatives is their strategic international dimension. Spain, thanks to its high potential for renewable energy and its privileged geographical location, aspires to become a hub for exports of green hydrogen to the rest of Europe. The valleys are fundamental parts of this scheme, as they will act as production nodes that can be connected to cross-border infrastructures such as the H2med corridor, which is designed to transmit hydrogen from the Iberian Peninsula to the rest of Europe [100].

In short, the expansion of green hydrogen in Spain is based not only on the abundance of renewable resources, but also on the articulation of a comprehensive strategy. The PERTE ERHA provides the financial, strategic and industrial framework required to drive investment and innovation, while the hydrogen valleys can turn this framework into large-scale projects with tangible economic, social and territorial effects. The combination of the two instruments places Spain in a privileged position when it comes to consolidating its position as a European benchmark for renewable hydrogen, integrating the challenge of decarbonisation into an opportunity to create a sustainable, innovative and competitive industry.

## 7.4. Relevant projects: databases

In the field of renewable hydrogen, numerous projects of varying degrees of maturity (from industrial pilots and demonstrators to commercial-scale facilities) covering production by means of electrolysis powered by electricity from renewable sources are being developed.

In order to obtain constantly updated information on the most representative projects, it has been deemed most appropriate to make use of regularly updated sectoral databases and observatories rather than cite specific cases.

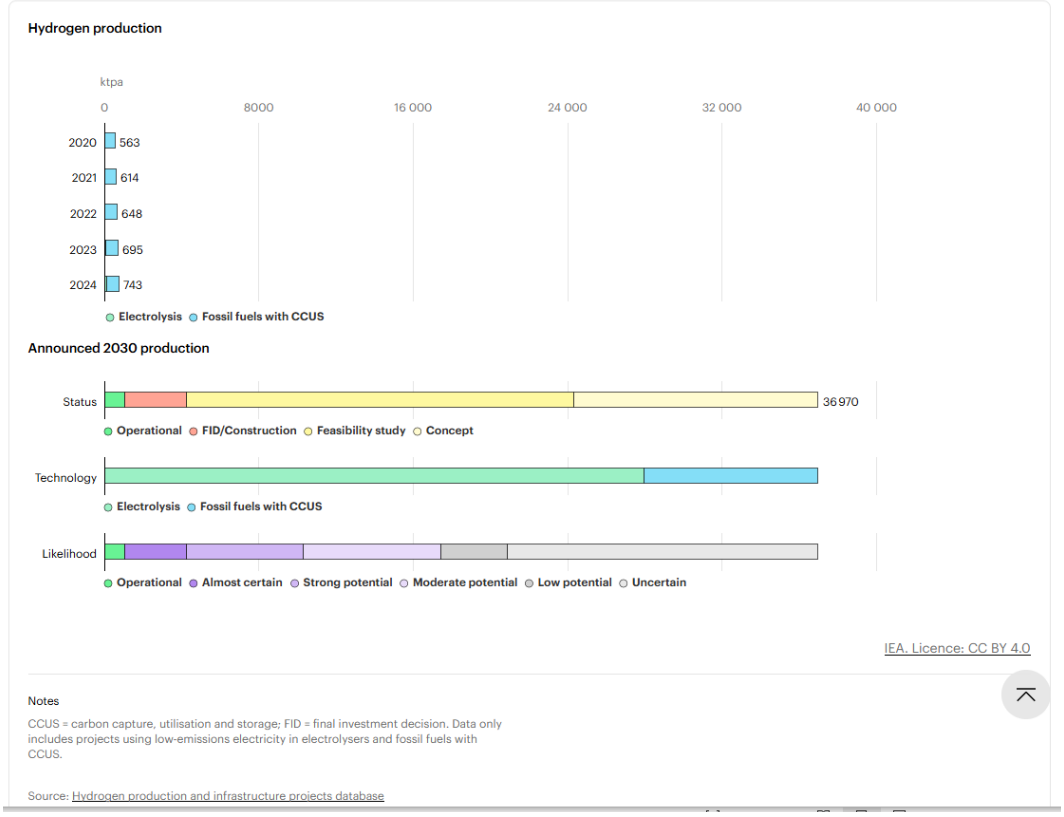
Upon the basis of the above, four sources of information have been identified, as listed below.

### 7.4.1. Hydrogen Tracker

The IEA's Hydrogen Tracker [101] is a public and interactive tool that can explore historical data on low-emission hydrogen production, as well as the deployment of dedicated pipelines and underground storage and projects that have been announced around the world.

The tracker is based on the IEA's Hydrogen Production and Infrastructure Projects Database and it complements the annual Global Hydrogen Review. Figure 18 displays the graph with the low-emission hydrogen production data. It is also possible to navigate over a map, which includes a general search screen, to select and filter by multiple fields.

It also includes estimates of the production costs by region and technology pathway with a 2030 time frame and incorporates a national policy tracker with over 1,000 measures announced or implemented since 2020, making it a useful resource for regulatory and market analysis.



Notes

CCUS = carbon capture, utilisation and storage; FID = final investment decision. Data only includes projects using low-emissions electricity in electrolysers and fossil fuels with CCUS.

Source: Hydrogen production and infrastructure projects database

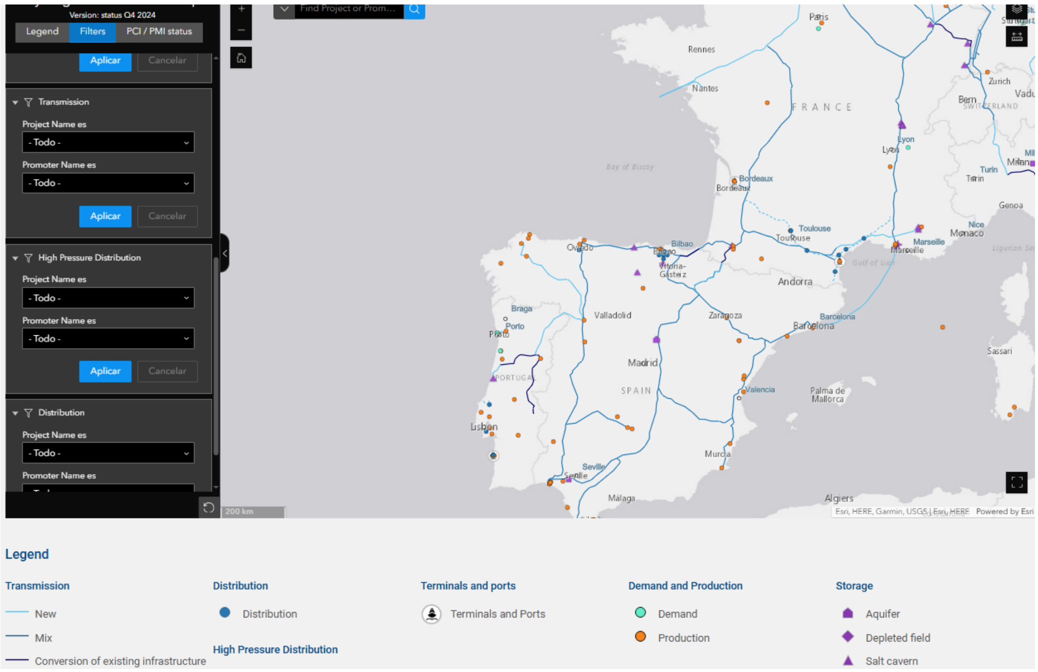
*Figure 18. Low-emission hydrogen production data provided by the IEA's Hydrogen Tracker [101].*

### 7.4.2. Hydrogen Infrastructure Map

The Hydrogen Infrastructure Map [102] is a joint initiative of ENTSOG, GIE, Eurogas, CEDEC, GD4S and GEODE, in cooperation with the European Hydrogen Backbone (EHB), which, based on the findings of the 36th European Gas Regulatory Forum (Madrid Forum), launched a bottom-up process to compile all the relevant hydrogen infrastructure projects in Europe and present them on an accessible and user-friendly map for the players in the industry and public officials.

The map integrates the perspective and projects of operators involved in natural gas transmission (TSOs), distribution (DSOs) and storage (SSOs) and LNG terminals (LSOs), as well as third-party developers that conduct initiatives across the entire value chain (see Figure 19).

The tool shows the development of the projects until 2050 and divides the information into six categories: transmission (pipelines), distribution, terminals and ports, storage, demand and production. It is possible to browse by country or region, activate and deactivate layers by category, search for projects by name or promoter and filter by projects of the European Commission with PCI/PMI status and so on.



Transmission
Project Name es: - Todo -
Promoter Name es: - Todo -

High Pressure Distribution
Project Name es: - Todo -
Promoter Name es: - Todo -

Distribution
Project Name es: - Todo -
Promoter Name es

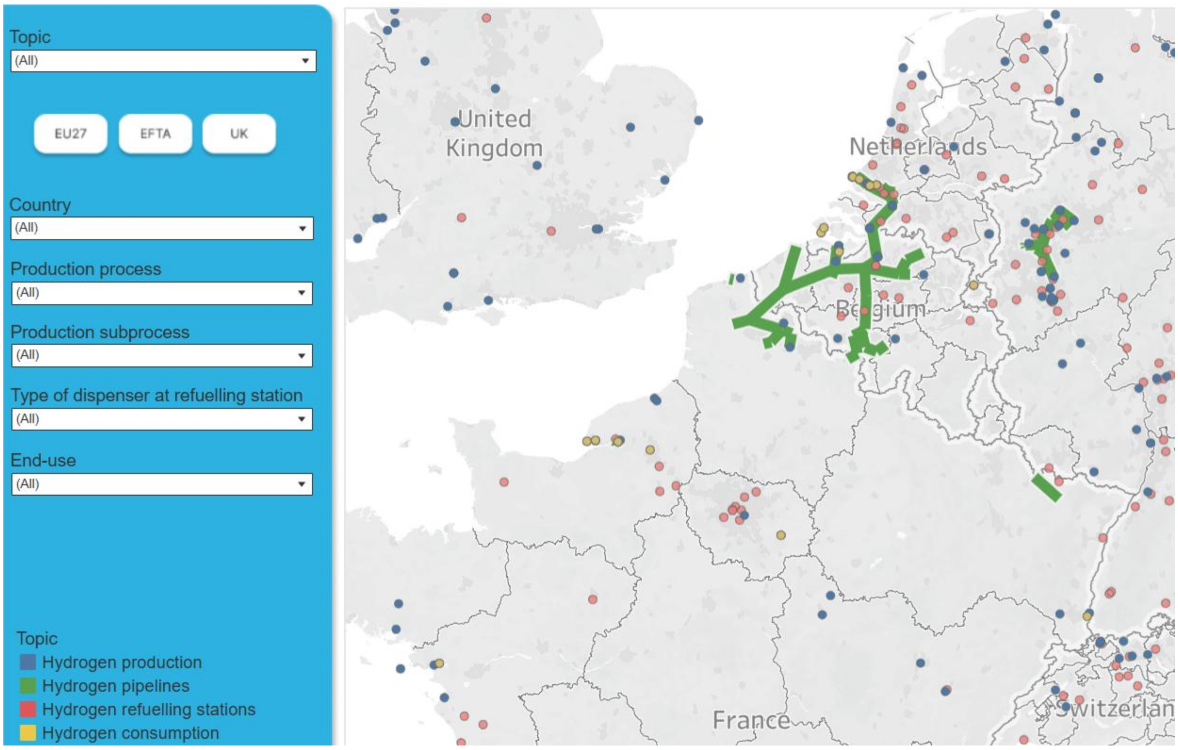
*Figure 19. Screen of the Hydrogen Infrastructure Map. Source [102]: H2 infrastructure map: "Hydrogen Infrastructure Map (ENTSOG, GIE, CEDEC, Eurogas, GEODE, GD4S) https://www.h2inframap.eu/".*

### 7.4.3. European Hydrogen Observatory

The European Hydrogen Observatory also provides a public, customisable and interactive tool that can visually explore the European hydrogen market [103].

In a single view, the map (see Figure 20) includes data on:

- The locations and main attributes of hydrogen production plants (all the technological pathways).
- The locations and types of dispensers of hydrogen refuelling stations.
- The locations and features of operational dedicated hydrogen pipelines.
- The locations and attributes of hydrogen consuming plants (ammonia, methanol, refined and "other" chemicals) in six countries (France, Italy, the Netherlands, Norway, Poland and Spain).



Topic: (All)

Country: (All)

Production process: (All)

Production subprocess: (All)

Type of dispenser at refuelling station: (All)

End-use: (All)

*Figure 20. Screen of the European Hydrogen Observatory map [103].*

### 7.4.4. Spanish Hydrogen Association

The Spanish Hydrogen Association (AeH2) has compiled a census of the hydrogen projects of its members, constituting a reference for the monitoring of hydrogen deployment in Spain [104].

This is an interactive map that includes projects (production, transmission, storage and final use) led by or involving AeH2 partners, with a minimum TRL threshold above 3 (see Figure 21).

The above page displays the relevant information for each project related to, among other details:

- **Identification of the project:** name/title of the project and promoter/coordinator (and, as appropriate, partners).
- **Type of project/TRL:** classification by nature (TRL 3-4 research, TRL 5-6 demonstration in the relevant environment, TRL 7-8 demonstration in a real commercial environment) and the degree of maturity.
- **Value chain:** production, storage, transmission/distribution, uses/applications (mobility, industry, derivatives such as ammonia/methanol/e-SAF, residential, etc.).

- **Core technology:** E.g. electrolysis (ALK, PEM, SOEC, AEM) and other pathways (steam/autothermal reforming, gasification, LCOH, etc.).
- **Location:** Geographical scope of the project (autonomous community/province/municipality or approximate location in early stages).
- **Status/progress:** Concept, feasibility study, FEED, FID/under construction, in operation (whenever applicable to demonstrators/commercial projects).
- **Capacities/scale (if applicable):** E.g. MW of electrolysis or planned hydrogen production in demonstrators/commercial projects, whenever publicly declared.
- **Funding (whenever public and non-confidential):** Main programmes/entities providing support (AEI, CDTI, Renewable $H_2$ Complementary Plan, IDAE, Clean Hydrogen Partnership, etc.).
- **Timeline/milestones (if available):** target for start-up or project horizon.

*Figure 21. Screen of the hydrogen project census map of the AeH2 [104].*

# 8. CONCLUSIONS

The main findings of this report are as follows:

- **Water electrolysis is consolidating its position as a technology that is key** to achieving the goals of climate neutrality and the deep decarbonisation of the energy system. Its ability to transform renewable electricity into clean hydrogen can connect the electricity, gas and industrial sectors, creating a more flexible and integrated energy system.

- **Electrolysis technologies are evolving rapidly**, moving from the demonstration phase to full-scale marketing.

  - **Alkaline (ALK)** Alkaline technology remains the most mature and widespread option, with over a century of development, a typical 60ºC-85°C operating temperature, usually at atmospheric pressure, overall efficiencies standing at around 60% and approximately 95.5% purities.

    Its industrial leadership is clear; around 75% of global manufacturing capacity by 2024, accounting for the majority of large-scale commercial projects. Overall, it remains the benchmark in terms of reliability, manufacturer availability and cost, lying in the 60%-65% (LHV) efficiency range reported for low-temperature technologies.
  - **Proton exchange membrane (PEM)** A technology which is already commercially available, it excels in terms of its compact size, dynamic response and high hydrogen purity (99.99%). Its market share stands at about 22% of estimated global manufacturing in 2025. It can be found in numerous large-scale projects. Its current efficiencies lie in the 60%-70% range (LHV). It's a well-established and flexible alternative for integration into renewables and purity-demanding applications.
  - **Anion exchange membrane (AEM)** AEM technology is emerging as an option under development that combines operations with higher pressures than ALK and cheaper materials than PEM, making its CAPEX potentially more competitive than the latter. It's suitable for small-medium scale operations and integration into variable power renewables and it doesn't require ultra-high water purities. Its efficiency lies

  at 60%-70% (LHV). The challenges remain its durability and scalability, but its cost potential and adaptability make it a relevant candidate for the next generation.
- ➢ **Solid oxide electrolysis cell (SOEC)** SOEC technology capitalises on operations at a a high temperature (≈ 600ºC-900°C) and waste heat to reduce electricity consumption, achieving extremely high efficiencies totalling up to 85% and a LCOH potential 15%-20% lower than ALK/PEM if specific technical challenges are overcome. It is particularly attractive in industrial environments with available steam/heat and in co-electrolysis, but it currently faces barriers involving its operational complexity and sensitivity to thermal gradients and degradation, as a result of which its current deployment is limited (≈ 3% of estimated manufacturing by the end of 2025) and geared towards stationary applications with stable loads.

- **The current efficiencies** reach values between **60% and 70% (LHV)** for ALK, PEM and AEM and up to **85% for SOEC**, reflecting remarkable progress in the performance and durability of the systems.

- The **water consumption** associated with electrolysis is low compared with conventional processes, standing at between **17 and 22 l/kg $H_2$**, reinforcing its environmental sustainability and its compatibility with responsible water resource management. In particular, in the case of Spain, the water needed to meet the 2030 targets would account for 0.1% of the water used for agricultural purposes.

- From an economic point of view, the **levelised cost of hydrogen (LCOH)** remains the main indicator for estimating the competitiveness of renewable hydrogen.

  - ➢ Its value depends essentially on the **CAPEX**, the **price of electricity**, **system efficiency** and **utilisation factors**.

    The report highlights the relevance of the **IBHYX (MIBGAS) index** as a market reference and the **European Hydrogen Observatory model** for benchmarking projects.

  - Cutting the LCOH will require **economies of scale, the industrialisation of manufacturing, innovation in materials and reduced EPC costs**, together with stable access to renewable electricity at competitive prices.

- The **integration of electrolysers into the electricity system** brings a dual benefit:

  - It enables the **use of renewable surpluses** by means of chemical energy storage.
  - It acts as an **element of grid flexibility and stability**, facilitating sectoral coupling and efficient management of energy resources.

- The development of electrolysis is accompanied by **strategic national and European initiatives** to accelerate its deployment and reinforce the value chain:

  - The **European Hydrogen Bank** as a tool for financial support and production incentives.
  - The **European Electrolyser Partnership** as a public-private partnership aimed at securing **17.5 GW/year of European manufacturing capacity by 2030**.
  - The national **PERTE** and regional programmes that position Spain as one of the **leading countries for renewable hydrogen projects**.

- Spain has **unique structural advantages** - an abundance of renewable resources, a well-developed gas network and industrial capacity - that make it a **natural candidate to become a hub for renewable hydrogen production and exports** in southern Europe.

- The **main challenges in the short and medium terms** focus on:

  - Accelerating **cost reductions and technological scalability**.
  - Developing **transmission, storage and distribution infrastructures** suited to hydrogen.
  - Establishing **clear, stable and harmonised regulatory frameworks** that foster investment and market certainty.
  - Promoting **education and training** in new professional skills linked to hydrogen.

- Beyond its technological role, electrolysis represents a **strategic opportunity for energy sovereignty**; it can reduce dependence on imported fossil fuels, stabilise the electricity system and move towards a decarbonised and competitive industrial model.

- The deployment of electrolysis will drive **a new European industrial value chain** with the capacity to generate **skilled employment, innovation and technological leadership and attract foreign investment.**

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