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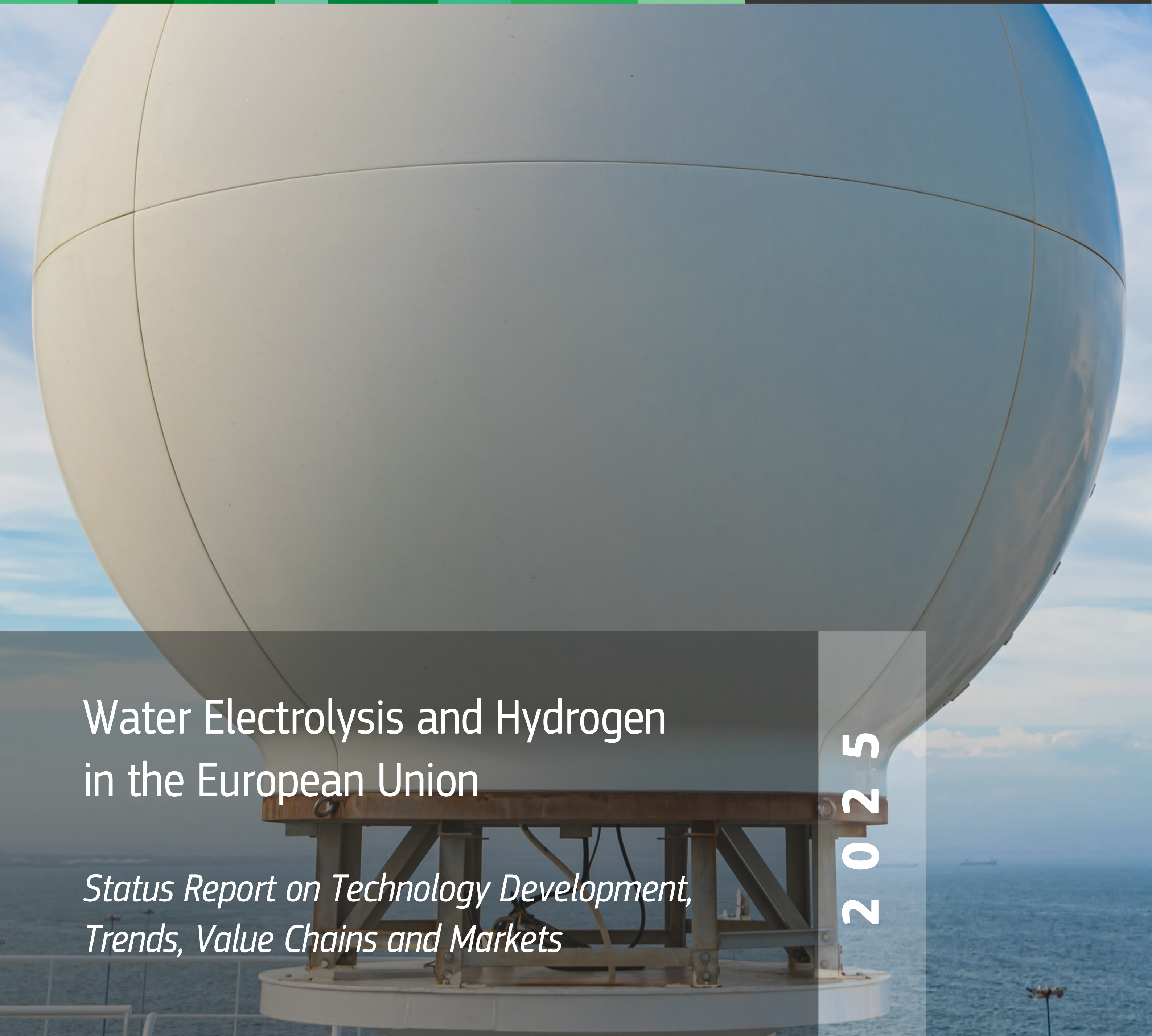


Water Electrolysis and Hydrogen in the European Union

Status Report on Technology Development, Trends, Value Chains and Markets

2025

Contact information
Name: Julien BOLARD
Address: European Commission - Joint Research Centre, Westerduinweg 3, 1755 LE, Petten, the Netherlands
Email: julien.bolard@ec.europa.eu
Tel.: +31 22456-5225

The Joint Research Centre: EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC144106
EUR 40607

PDF ISBN 978-92-68-35392-9 ISSN 1831-9424 doi:10.2760/7797181 KJ-01-26-025-EN-N

Luxembourg: Publications Office of the European Union, 2026

Generative AI based on Mistral.ai's models was used to generate scripts for data analysis purposes.

How to cite this report: Bolard, J., Dolci, F., Weidner, E., Gryc, K., Eynard, U. et al., *Clean Energy Technology Observatory: Water Electrolysis and Hydrogen in the European Union - 2025 Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg, 2026, https://data.europa.eu/doi/10.2760/7797181, JRC144106.

Contents

Abstract

This report from the Clean Energy Technology Observatory (CETO) updates the status of water electrolysers and hydrogen in the EU. The EU's cumulative electrolysis capacity is projected to range between 514 MW_{el} and 800 MW_{el} by the end of 2025. The EU's operational manufacturing capacity is estimated at approximately 8.9 GW_{el}/year by the end of 2025, with a potential to reach 41.7 GW_{el}/year by 2030 considering all companies' announcements. While the EU leads in patenting activities, it faces challenges from state-backed competition, higher capital expenditure costs than anticipated, and critical dependence on imported raw materials. The European sector is supported by significant public funding, with instruments like the Innovation Fund and European Hydrogen Bank.

CETO is being implemented by the Joint Research Centre for DG Research and Innovation Energy, in coordination with DG Energy.

Foreword on the Clean Energy Technology Observatory

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-faceted character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognizing the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), who run the observatory, and Directorate Generals Research and Innovation (R&I) and Energy (ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal
- assess the competitiveness of the EU clean energy sector and its positioning in the global energy market
- build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020)
- publish reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and inventive technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation of and development of EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore).
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy system, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport.
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis
- Clean Energy Outlooks: Analysis and Critical Review
- System Modelling for Clean Energy Technology Scenarios
- Overall Strategic Analysis of Clean Energy Technology Sector

More details are available on the CETO web pages

Acknowledgements

The authors are very grateful for the contributions and reviews received from:

- JRC colleagues Nigel TAYLOR (CETO project leader) and Krzysztof PIELA for coordination, support, review and comments.
- Siobhan MCGARRY (European Commission - DG GROW)
- Jacopo TATINI (European Commission - DG GROW)
- Leonidas MANTZOS (European Commission – JRC)
- Markus NOHL (European Commission – JRC)
- Matthijs SOEDE (European Commission – DG RTD)
- TIM team (JRC.T.5) for their support in providing scientific publication trends data: Michela BERGAMINI, Marcelina GRABOWSKA, Geraldine JOANNY and Olivier EULAERTS.
- Lorena IGLESIAS (CINEA) for her assessment on electrolyser projects funded by CINEA.

The JRC.C.6 energy system modelling teams for providing energy scenarios:

- from POTEnCIA: Gea Bermudez J., Jaxa-Rozen M., Sikora P., Neuwahl F., Salvucci R.
- from POLES-JRC: Schade B., Keramidas, K., Fosse, F., Dowling, P, Russ, P., Aycart J.

Authors

- Julien BOLARD, Joint Research Centre, Unit C.1 - Technology expert
- Francesco DOLCI, Joint Research Centre, Unit C.1 - Technology expert
- Eveline WEIDNER, Joint Research Centre, Unit C.1 – Technology expert
- Katarzyna GRYC, DG Energy, Unit B.4 – Policy officer
- Umberto EYNARD, Joint Research Centre, Unit D.3 – Sustainability assessment
- The ERIC Team (Joint Research Centre, Unit C.7): Aliki GEORGAKAKI, Simon LETOUT, Aikaterini MOUNTRAKI and Ela INCE, for R&D funding, production, trade and patent analysis.
- Máté ROZSAI, Moritz WEGENER, Joint Research Centre, Unit C.6 – POTEnCIA model experts
- Andreas SCHMITZ, Joint Research Centre, Unit C.6 – POLES-JRC model expert

Executive summary

EU objectives and challenges / policy context

Water electrolysers are central to the European Union's strategy for decarbonisation, underpinning the objectives of the European Green Deal, Clean Industrial Deal, REPowerEU, and the Net Zero Industry Act. The EU has established a comprehensive regulatory framework to stimulate both the production and consumption of Renewable Fuels of Non-Biological Origin, such as electrolytic renewable hydrogen. However, significant challenges persist. The implementation of renewable sub-targets for RFNBOs in transport and in the industrial sectors, such as those in the Renewable Energy Directive (REDIII), is heterogeneous across Member States, creating market uncertainty. Furthermore, the European manufacturing base faces intense, state-backed competition, particularly from China, while also navigating complex and lengthy permitting procedures for infrastructure projects which can delay project execution. A notable gap between project announcements and final investment decisions (FIDs) further complicates the landscape for manufacturers, and uncertainty about the off taking customers also remains.

Technology status

The report refers to the water electrolysis technology and does not cover chlor-alkali electrolysis technology. Other hydrogen production routes based on thermal or electrochemical decomposition of waste is also out of the scope of this report.

Alkaline and Proton Exchange Membrane (PEM) electrolysis technologies have reached commercial maturity and are starting to being deployed in large-scale projects, with the largest operational electrolyser in Europe more than doubling in capacity to 54 MW_{el} in Germany, up from the 24 MW_{el} electrolyser located in Norway described in the previous report. Anion Exchange Membrane (AEM) and Solid Oxide (SOE) electrolysis technologies are now being deployed in industrial setting, with initial commercial applications and large-scale demonstrations planned of up to several megawatts being commissioned this year.

Consolidated estimates shows that the EU27's total installed electrolysis capacity should range between 514 and 800 MW_{el} by the end of 2025. Estimates for global electrolysis capacity deployment range between 4.0 and 6.3 GW_{el}, with China leading with capacities estimated between 2.0 and 4.4 $GW_{el,}$ highlighting significant discrepancies between available datasets. While the EU leads in patenting activities, indicating a strong innovation ecosystem, China now leads in the volume of scientific publications.

Project costs (measured in terms of EUR per kW of electrolysis capacity) in Europe are proving higher than previously estimated, with recent data showing capital expenditures for large-scale projects, beyond 100-MW_{el}, ranging from EUR 2630/kW_{el} to over EUR 3050/kW_{el}, influenced by inflation, underestimation of installation and connection to the grid costs, other indirect costs such as overheads, engineering, and a lack of manufacturing economies of scale**.**

Investment and funding

The EU is channelling significant public funds to de-risk investments and stimulate the electrolyser market. Key instruments include the Innovation Fund, which has supported projects planning to install over 4.2 GW_{el} of electrolysis capacity, and the European Hydrogen Bank, which has conducted 3 auctions with a total funding of approximately EUR 3 billion to bridge the cost gap for renewable hydrogen production. Additionally, four Important Projects of Common European Interest (IPCEIs) have been approved, with the ambition to mobilise approximately EUR 35 billion in public and private funding to support the entire hydrogen value chain, from R&D to infrastructure and industrial deployment. Venture capital investment in EU-based ventures has also shown resilience, reaching an all-time high of EUR 450 million in 2024.

Value chain

European companies play a prominent role in the global electrolyser market, with manufacturers like Siemens Energy and Thyssenkrupp Nucera supplying equipment for the largest projects both within the EU and globally. However, the value chain exhibits critical dependencies, particularly for raw and processed materials. Analysis shows that for key raw materials needed in electrolyser production, 37% are supplied by China, while the EU's share is only 2%. This dependency becomes less pronounced further up the value chain in components and final assemblies, where European manufacturing is strong. A potential risk to the domestic market is the observed decline in hydrogen consumption as a feedstock in the EU's ammonia and methanol sectors, which could limit opportunities for replacing fossil-based hydrogen.

Sustainability

The greenhouse gas intensity of renewable hydrogen production is highly dependent on the carbon intensity of the electricity grid, with renewable-powered electrolysis offering a near-zero emission pathway. Large-scale deployment also raises concerns about water resource management, requiring careful site selection and technology choices to minimise local impact. The supply chain for electrolysers, particularly for PEM and SOE technologies, relies on critical raw materials such as platinum, iridium, and rare-earth metals, sourced from regions with potential social and geopolitical risks.

EU positioning and global competitiveness

The EU is a major player in the global electrolyser market, but its position is under pressure. In 2025, EU factories in operation (of both EU-headquartered companies and the foreign direct investments in Europe from Cummins) represented over 8.9 GW_{el}/year of announced nameplate manufacturing capacity of electrolysers' stacks, second only to China's nearly 34.7 GW_{el}/year. The manufacturing of PEM stack represented 4.2 GW_{el}/year, alkaline stacks represented 3.8 GW_{el}/year. SOE electrolysers represented 0.9 GW_{el}/year of capacity.

While the EU's announced manufacturing capacity is projected to reach nearly 41.7 GW_{el}/year by 2030. The combined EU + EFTA + UK bloc could reach 50.2 GW_{el}/year, rivaling that of Chinese manufacturing capacity planned to reach 51.9 GW_{el}/year. However, EU's global share has seen a relative decline, due to the faster pace of announcements elsewhere, and other factors affecting the overall cost competitiveness of hydrogen.

European-made electrolysers often carry a higher price tag than Chinese alternatives, attributed to higher labour and energy costs. Some analysts indicates that this price tag is due to the manufacturing of more efficient systems in the EU, however the lack of globally harmonised testing protocols cannot confirm these claims. The EU's robust regulatory framework and strong support for innovation are key strengths, but maintaining competitiveness will require addressing cost disparities, securing supply chains both on materials and manufacturing equipment, and accelerating the pace of project deployment to ensure demand for its growing manufacturing base. Electricity cost remains of the key factors influencing the end price of hydrogen. The European Commission has provided a response to mid- and long-term projections via the Affordable Energy Action Plan; however currently, access to affordable energy to operate electrolysers and produce RFNBOs remains high.

SWOT analysis

Table 1. CETO SWOT analysis for the competitiveness of water electrolysers.

Strengths	**Weaknesses**
– Industrial scale projects are growing in production capacity with the largest European operational electrolyser more than doubled in size since last year report from 24 MW_{el} to 54 MW_{el}, securing industrial know-how necessary to continue the deployment of larger projects and reach the 100-MW_{el} mark. – The EU benefits from an established regulatory framework spanning across the entire value chain including hydrogen demand (REDIII), manufacturing capacities with the Net Zero Industry Act under the Clean Industrial Deal and financial capabilities, and financial support with the European Hydrogen Bank. – Europe benefits from a continued Research, development and deployment pipeline of projects, spread across several agencies and bodies such as the Clean Hydrogen Joint Undertaking and CINEA. – The largest projects are using European electrolysers (such as ThyssenKrupp, Siemens Energy, ITM Power, NEL), with the resilience criteria implemented in the latest regulations (NZIA and EU Hydrogen Bank) creating demand for systems manufactured in Europe.	– Uneven speed of implementation of the REDIII hydrogen targets creates disparities between member states, potentially leading to market fragmentation, business uncertainty and delays despite a common EU policy framework. – The production of key electrolyser components, particularly for PEM technology, relies on critical raw materials like titanium, platinum and iridium, for which the EU has a high import dependency. – European-made electrolysers often come with a higher price tag compared to their Chinese counterparts, likely due to higher labour and energy costs and to not having yet achieved economies of scale. – While downstream project deployment is increasing, it lags behind previously announced ambitious deployment targets. There is a notable gap between project announcements and final investment decisions (FIDs), creating uncertainty for manufacturers. – Although four groups of important projects of common European interest (IPCEI) have been approved, the funding allocation and disbursement is highly uneven across member states, creating uncertainties and delays in hydrogen project implementation.
Opportunities	**Threats**
– Following the four IPCEIs schemes and two EU Hydrogen Bank auctions, the renewable hydrogen production and consumption sector continues to benefit from strong European and national public funding support with a 3rd EU H_2 Bank auction with budget of EUR 1.3 billion launched end of 2025. – The deployment of larger-scale projects in the 50-MW_{el} range will yield highly valuable industrial experience and allow to further improve concepts and integration for plants in the 100-MW_{el} range. – The EU leads in patenting activities and start-up creation thanks to a highly active innovation ecosystem, a positive signal of commitment from the private sector in R&D and technological knowledge retention. – The stability of the EU demand-side regulations also provides support to potential foreign exporters to the EU and catalyses the development of international delivery infrastructures.	– Aggressive industrial policies and state-backed competition, particularly from China, pose a significant threat to the European manufacturing base. – Increasing import of ammonia reduce the European demand of hydrogen. – Several legacy manufacturers filed for bankruptcy this year, likely due to a lack of cash inflows because of oversized manufacturing capacities and deployment projects lagging behind targets. – Support and incentives for demand do not yet match what is in place for production. – Europe still lacks access to raw materials. – Delays in hydrogen transport infrastructure put the deployment of larger electrolyser projects at risk. – Too ambitious aspirational targets set by the European Union is leading to the multiplication of negative signals and sentiment as the industry is going through a recalibration phase towards market and industrial reality.

Source: JRC 2025

1. Introduction

1.1. Scope and context

This report on water electrolysers and hydrogen in the European Union is part of the annual series of reports from the Clean Energy Technology Observatory (CETO). This report builds on previous EU studies in this field and updates the previous CETO report on water electrolysers (European Commission, Bolard, Dolci et al., 2024). It provides an overview of the current state of water electrolysers, including the main electrolysis technologies development and trends, a value chain analysis, and an assessment of global manufacturing capacities, including the EU's position in relation to other regions.

Water electrolysers play a crucial role in achieving the objectives of the European Green Deal, the European hydrogen strategy and REPowerEU, the Net Zero Industry Act, and the Clean Industrial Deal. The EU has set ambitious consumption targets of Renewable Fuels of Non-Biological Origin (RFNBO) in the share of final energy demand; renewable or low-carbon hydrogen produced by water electrolysers is expected to contribute significantly to meeting these targets.

The report is organised into five main chapters. **Chapter 2** examines the state of the art and future developments of water electrolysers, focusing on advancements in technology readiness, energy capacity, costs, and research funding. **Chapter 3** focuses on the value chain analysis, covering economic contributions, sustainability, and the role of EU companies in the market. **Chapter 4** provides an overview of the EU's global position and competitiveness in the water electrolysers industry, analysing market status and resource efficiency. **Chapter 5** concludes the report by synthesising key findings and highlighting strategic opportunities and challenges.

1.2. Methodology and data sources

The present report follows the general structure of all CETO technology reports and is divided into four sections with several indicators used to evaluate the EU water electrolyser technology along its value chain:

- Technology State of the art and future developments and trends;
- Value chain analysis;
- EU position and global competitiveness.

The report uses the following information sources:

- Eurostat data;
- Existing studies and reviews published by the European Commission and international organisations;
- Information from EU-funded research projects;
- EU and international databases;
- EU trade data, trade reports, market research reports and others;
- JRC own review and data compilation;

— Stakeholders’ input.

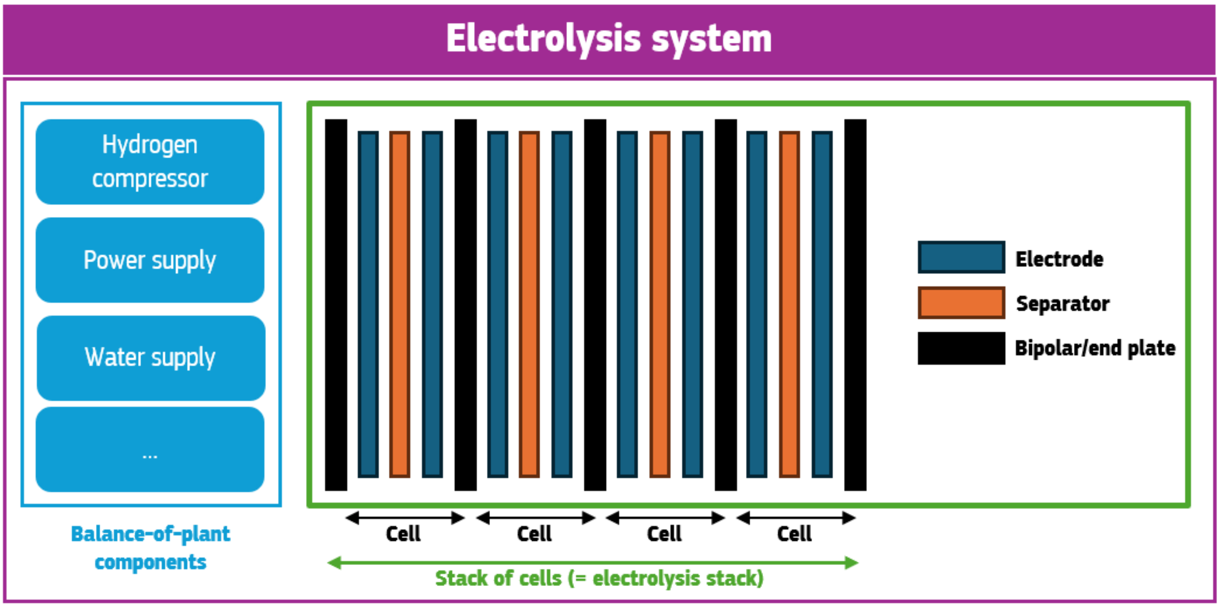
Details of specific sources can be found in the corresponding sections and Annex 1 provides a summary of the indicators for each aspect, together with the main data sources.

2. Technology status and development trends

2.1. Technology overview

Water electrolysis is currently the most mature and promising hydrogen production technology that can be coupled with renewable electricity. The electrolysis of water requires the application of an electrical field to force the dissociation of water molecules into hydrogen and oxygen. Depending on the technology, the use of a membrane or separator allows the migration of molecules, and the extraction and storage of hydrogen. An electrolyser system is composed of the electrolyser stack where the reaction takes places and auxiliary components used to properly manage the water, heat, electrical current or the hydrogen and oxygen gases created during the reaction. **Figure 1** provides an overview of an electrolyser system and its components.

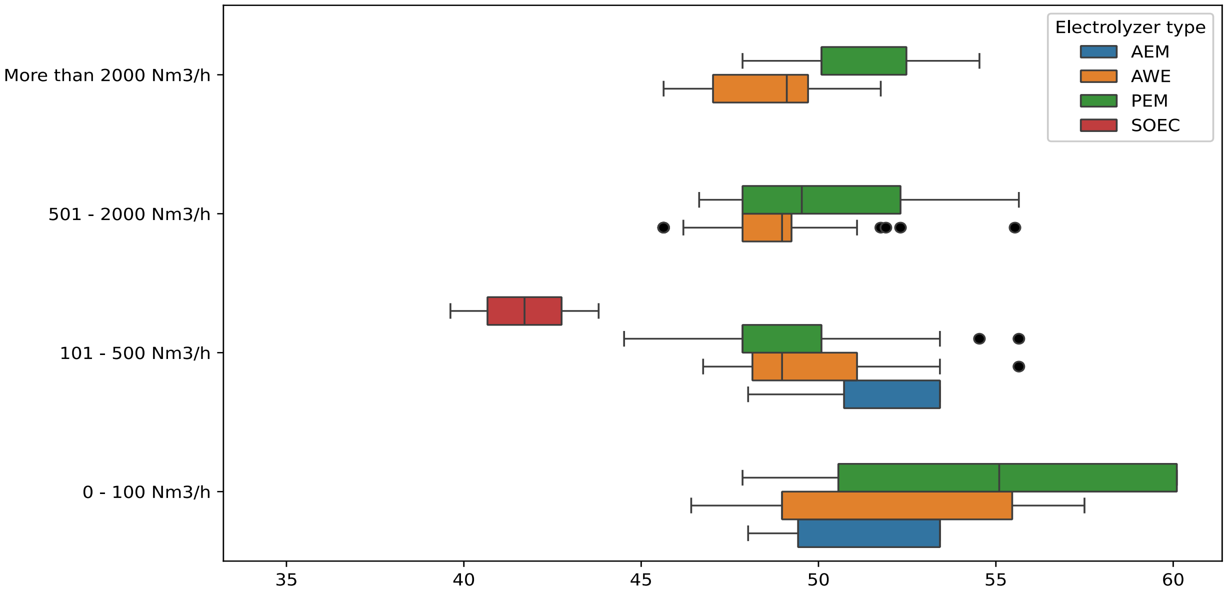
Figure 1. Overview of an electrolyser system



Source: Joint Research Centre (Bolard, Pilenga and Malkow, 2024)

Figure 2 shows a breakdown of the available stack energy consumption (in kWh/kg(H_2) produced) as reported by manufacturers by type and size of the stack. For low-temperature electrolysis, around 48-55 kWh (about 180-200 MJ) of electricity is needed to produce 1 kg of hydrogen depending on the technology used. Higher temperature electrolysers require less electricity but need to be supplied with high-grade heat. The thermodynamic limit for dissociating water at room temperature through electrolysis is around 39.39 kWh/kgH_2.

Figure 2. Reported energy consumption at stack level of commercial systems by type and size category



Energy consumption (kWh/kgH₂)

Source: Joint Research Centre analysis based on public system specifications collected by Rystad Energy (2024)

The main electrolyser stack technologies, as well as their added values and drawbacks, are summarised below:

— Alkaline electrolysis is a well-established low-temperature water electrolysis technology for hydrogen production, with relatively cost-effective stacks already available in the megawatt range. Alkaline electrolysers do not use noble metal catalysts and are stable, with a very long lifetime. Their main drawbacks are that alkaline electrolysers can only operate at relatively low current densities and their potential lack of operational flexibility. Historically, alkaline electrolysers systems have shown poor dynamic behaviour, with limited load flexibility as low loads may present a safety issue. However, progress is being made on adapting this technology for flexible operation required for a more efficient coupling with renewable electricity sources.

— Proton Exchange Membrane (PEM) electrolysers can reach high current and power density and can operate well under dynamic conditions and partial load. Therefore, they are highly responsive, which makes coupling with renewable energy sources easier. Their main drawbacks are associated with durability, related to catalyst loss and membrane lifetime, and cost, partly due to their catalysts containing expensive and rare platinum group metals such as platinum and iridium.

Alkaline and Proton Exchange Membrane are the two main technologies that have achieved commercial maturity for large-scale applications and have been, or will be, deployed in large-scale systems in the range of several hundreds of megawatts[1] as nominal power input.

[1] Examples of projects: GREENH2ATLANTIC, GreenHyScale (Akaline), REFHYNE II (PEM), Ningxia Baofeng Energy Group or Kuqa – Sinopec in China.

— In addition to the two main low-temperature electrolysis technologies (alkaline and PEM electrolysis), recent years have also seen the development of Anion Exchange Membrane electrolysers (AEM). This technology operates in alkaline media but using a solid electrolyte. In principle, this means they can combine the use of non-platinum group metal catalysts with the production of high-purity hydrogen due to the presence of the solid electrolyte. Anion Exchange Membrane Electrolysers emerge now in small-scale commercial applications, with the first deliveries of 1-MW_{el} AEM electrolysis systems in 2023, with 5-MW_{el} systems possibly being commissionned by the end of 2025 (Hydrogen Tech World, 2025).

— Solid Oxide electrolysers (SOEL) exploit the more favourable thermodynamics of water splitting to circulate negatively-charged ions across the ceramics at higher temperatures (usually above 800ºC) and can have electrical consumptions around 40 kWh/kgH_2, provided a suitable heat source is available (around 10 kWh/kgH_2 of heat) (Clean Hydrogen Joint Undertaking, 2022); extra heat requirements for maintaining the high temperature should also be factored in the efficiency. They have slow ramp rates from cold-start due to the necessity to reach high temperatures and the necessity to avoid thermal shocks for the ceramic materials constituting the electrochemical cell. Therefore, they also have limited operational flexibility. They must use materials capable of withstanding the higher temperatures involved with the use of this technology and they also contain critical raw materials such as rare-earth metals. Despite having reached a technological level able to support large demonstration plants, R&I actions are still necessary, and materials- related challenges must be addressed to deploy the technology at large scale. Solid Oxide electrolysers have been already tested in real-life environment and planned demonstrations in the range of multi-MW_{el} scale have started, such as the 2.6-MW_{el} SO electrolyser of the EU-funded MULTIPLHY project commissioned in October 2025 (Sunfire, 2025).

— An even lower TRL technology which offers significant development potential is Proton Conductive Ceramic electrolysis (PCC). This electrolysis technique has similarities to SOE, but here the ceramic membrane is used to transport protons. The temperature range of PCC is around 500-700ºC. Despite the promising features of this technology, its scale-up is still difficult and several research breakthroughs are needed for its full commercialisation.

2.2. Technology readiness level

Table 2 provides a quantitative assessment of the different electrolyser technologies. This assessment considers the current deployment of alkaline and PEM technologies for large-scale applications in industrial settings (more than 20MW_{el}).

Table 2. Current TRL of the different electrolyser technologies.

	TRL (Technology Readiness Level)								
Sub-Technology	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Alkaline									■
PEM									■
AEM								■	
SOE								■	
PCC			■	■					

Source: JRC analysis, 2025.

The upscaling of electrolyser systems from several megawatts to gigawatt systems brings new technical challenges in regards to performance, safety, designs and manufacturing.

Large electrolyser systems are a modular technology, where several electrolyser stacks are installed according to the needs of a specific project. Although a lot of R&D efforts are focussing on the performance of individual stacks, the ambition of deploying large scale systems is also driving innovation at the whole system level. In addition, since some large-scale projects require the production of hydrogen directly on site of consumption, engineering efforts of project developers also focus on the complete integration of the electrolyser into the offtaking industrial processes, such as the ammonia production process for example.

To cope with this, some manufacturers are starting to develop modular full system designs based on standardized 100-MWe electrolysis modules. This is the case of Rely, a JV between two historical hydrogen players, Technip (EPC and BOP) and John Cockerill (stacks)) (Rely, 2023). Another example is Electric Hydrogen, which is also developing an integrated 100-MWe electrolytic system (Electric Hydrogen, 2025). Lastly, Samsung E&A acquired 9% of Nel ASA in order to develop integrated hydrogen production systems (Samsung E&A, 2025).

Some analyst reported major differences in efficiency measurements across regions, mostly between electrolysers manufactured in Europe and these imported from China (BNEF, 2024). As of today, it is difficult to fully benchmark the performance of electrolyser in a robust way. Standardised comparisons can actually be made only when the performances are measured under the same testing protocols, such as ISO-22734/2019 or the JRC harmonised protocols for low-temperature and high-temperature electrolysis (European Commission. Joint Research Centre., 2023a; Tsotridis and Pilenga, 2021; European Commission. Joint Research Centre., 2024a). It is not clear from the systems specifications provided by manufacturers how the data is collected and under which protocols. This uncertainty also increases when it comes to the performance of larger systems, including their balance-of-plant components or their integration into larger industrial hub (Bolard, Pilenga and Malkow, 2024).

2.3. Installed energy capacity and production/generation

The evolving hydrogen market, and the electrolyser sector specifically, is experiencing wild variations making the precise assessment of future developments challenging. The following chapter provides an overview of the best trends' estimates at European and global level. Five sources of data were used and compared as described in **Table 3**.

Table 3. Sources used for the electrolysis deployment analysis.

Organisation	Document	Release date	Acronym	Reference
International Energy Agency	Hydrogen Production and Infrastructure Projects Database	September 2025	IEA	(IEA, 2025e)
European Hydrogen Observatory	Public datasets	2025	EHO	(European Hydrogen Observatory, 2025a)

Organisation	Document	Release date	Acronym	Reference
Rystad Energy	Hydrogen Solutions	September 2025	-	(Rystad Energy, 2025)
BloombergNEF	Clean Hydrogen Production Assets	September 2025	BNEF	(BloombergNEF, 2025)
Hydrogen Europe	Clean Hydrogen Monitor 2025	September 2025	CHM	(Hydrogen Europe, 2025a)

Source: Joint Research Centre analysis (2025)

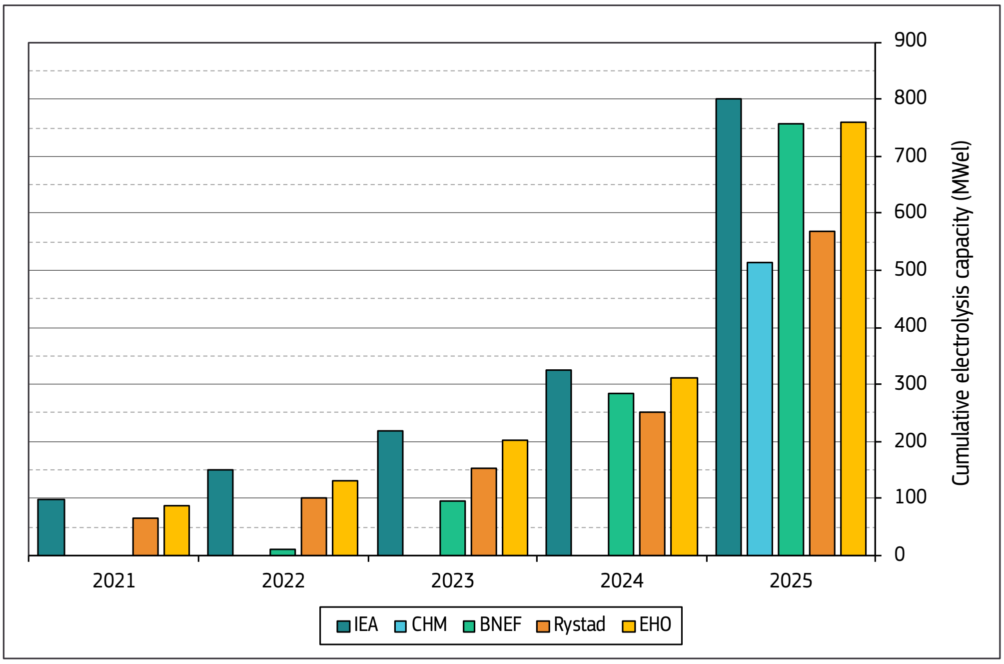
2.3.1. Current and projected European electrolysis capacity

2.3.1.1. Deployment at the level of the European Union

Figure 3 shows the aggregated cumulative deployment for the European Union. Estimates from the abovementioned 5 sources are compared to reflect the most realistic ranges. This data suggests that the forecast of electrolysis capacity entering operation by the end of 2025 should range between 514 MW_{el} (CHM) and 800 MW_{el} (IEA).

The divergence highlights the considerable uncertainty even for short-term projections of electrolysis capacity. These differences seem to arise due to discrepancies in the reported starting date of large-scale projects across the datasets. As an example, the Get H2 Nukleus project (100 MW_{el}) (RWE, 2025) has a reported starting date of 2025 in the IEA dataset, and 2028 in the Rystad dataset. Due the unavailability of vetted reliable information from public sources, the reconciliation of these datasets is out of the scope of this report.

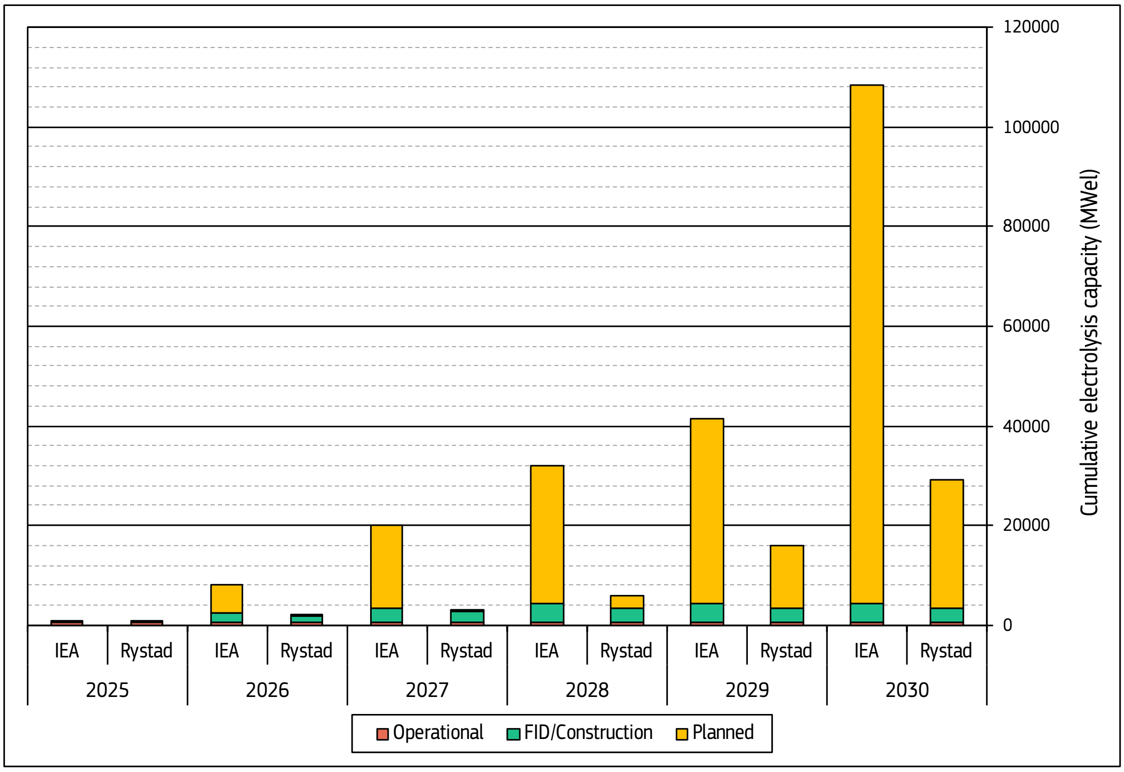
Figure 3. Estimations of cumulative electrolysis capacity in operations, under construction or FID in the EU27



Source: JRC analysis based on data from the International Energy Agency, BloombergNEF, Hydrogen Europe, Rystad Energy, and the European Hydrogen Observatory (2025)

The gap is also explained by the difference in reported status of projects. **Figure 4** below shows the gap between electrolysis deployment across sources. **Figure 4** also shows how this gap widens for projected capacities, especially when projects only reported as “planned” are considered. The IEA projections show up to 20 GW_{el} being deployed in 2027 in Europe, where Rystad’s analysis passes the 20 GW_{el} threshold only in 2030. The European electrolysis capacity might reach between 1.9 GW_{el} (Rystad) and 8.1 GW_{el} (IEA) by the end of 2026, and between 29 GW_{el} (Rystad) or 108 GW_{el} (IEA) by 2030. However, some listed projects such as the very large-scale project *Høst - Esbjerg green ammonia plant* (DNK, 1 GW_{el}) reported with a commissioning date of 2026 in the IEA dataset might enter commercial operations by 2030 only (HØST PtX Esbjerg, 2025). This shows the current high degree of uncertainty with regards to the deployment of electrolysers in Europe.

Figure 4. Cumulative electrolysis capacity of the pipeline of projects in EU27 by status

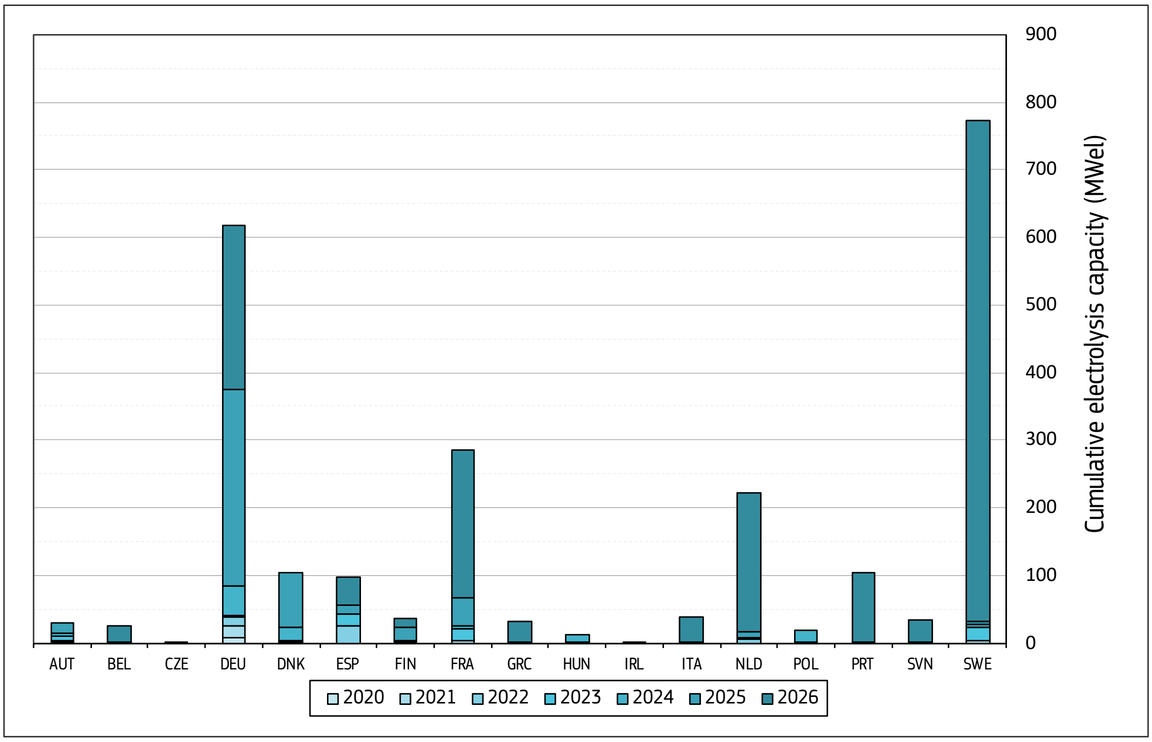


Source: JRC analysis based on data from the International Energy Agency and Rystad Energy (2025)

2.3.1.2. Deployment at the level of EU member states

At the level of EU member states, Germany plans to install more than 1.4 GW_{el} of electrolysis capacity by 2028, only considering projects currently in operation, under construction or with FID taken according to the two datasets provided by IEA and Rystad Energy. Sweden projects an electrolysis deployment between 750 and 1 300 MW_{el} by 2028. The detailed capacity currently in operations, under construction or with FID taken across Member States is presented in **Figure 5**.

Figure 5. Cumulated electrolysis capacity currently in operation, under construction, or with FID taken in EU member states with starting date from 2020 to 2026



Source: JRC analysis based on IEA and Rystad Energy (2025)

2.3.1.3. Largest projects currently in operation or under construction in the EU

In the first half of 2025, four large-scale projects were commissioned for a combined capacity of more than 100 MW_{el} of electrolysis capacity in the European Union (Hydrogen Europe, 2025c). Two projects above 50 MW_{el} were commissioned, which more than doubled the capacity of the 24-MW_{el} electrolyser system of Yara Herøya Green Ammonia plan (NO), identified as the largest project in Europe (outside the EU27) in the previous CETO report.

The largest European project - the 54-MW_{el} Hy4Chem project owned by BASF in Ludwigshafen, Germany, entered into operation in August 2025. The electrolyser system is fully integrated into BASF's chemical production complex to produce renewable hydrogen for use as a feedstock for chemical processes. A share of the hydrogen is distributed to local off-takers for mobility applications. The electrolyser is composed of 72 stacks manufactured by Siemens Energy. It received up to EUR 124.3 million in public funding from the German federal government and the state of Rhineland-Palatinate, provided under the Important Projects of Common European Interest (IPCEI) framework. This public contribution dwarfs BASF's direct investment of around EUR 25 million, underlining the essential role of government support in launching first-of-a-kind projects (BASF, 2025).

The second largest electrolyser project has been deployed by European Energy and is located within the Kassø E-Methanol Facility, Denmark. The facility uses renewable hydrogen produced using the 52.5 MW_{el} electrolyser manufactured by Siemens Energy and biogenic CO_2 to produce e-methanol for the shipping and plastics industries (with off-takers such as A.P. Moller – Maersk, LEGO Group, Novo Nordisk). The annual e-methanol production is expected to reach 42 000 tonnes. (European

Energy, 2025). The total investment was not disclosed, but the project received a direct EUR 53 million grant from the Danish Green Investment Fund (DGIF) in 2022 (Offshore Energy, 2022).

In its quarterly forecast, Hydrogen Europe reports a list of projects which entered into operation in Q1 and Q2 2025:

Table 4. Projects which entered into operation in Q1-Q2 2025

Project Name	**Location**	**Lead / Company**	**Capacity (MW_{el})**	**Start Date**
Hy4Chem	Ludwigshafen, Germany	BASF	54	March 2025
Kassø e-methanol plant	Aabenraa, Denmark	European Energy	52.5	Q2 2025
P2X Harjavalta	Harjavalta, Finland	P2X Solutions	20	Feb 2025
HySynergy	Fredericia, Denmark	Everfuel	20	Feb 2025
OMV's UpHy project	Austria	OMV	10	Q2 2025
Ineratec's e-fuels facility	Frankfurt, Germany	Ineratec	10	Q2 2025
Schwäbisch Gmünd	Schwäbisch Gmünd, Germany	Lhyfe	10	Feb 2025

Source: Data collected and reported by Hydrogen Europe (Hydrogen Europe, 2025c)

2.3.1.4. Future of large-scale projects in Europe

Several of Europe's largest electrolysers now under construction are concentrated in industrial clusters and heavy-industry offtake hubs.

As of November 2025, the largest planned European project remains the 740-MW_{el} Stegra DRI green steel plant in Boden, SE among which 200-MW_{el} composed of ten 20-MW_{el} modules produced by Thyssenkrupp (in Tarragona, Spain) have been installed in August 2025 (Stegra, 2025; Hydrogen Insight, 2025b). Analysts report that the company raised EUR 4.2 billion in debt and EUR 2.1 billion in equity for the project, in addition to a more than EUR 500 million public grant from the EU and the Swedish government (Hydrogen Insight, 2025a), totalling more than EUR 6.8 billion for the entire project. This means to an approximative investment of EUR 9 100/kW_{el} which comprises the electrolysers and steel production system.

EWE's "Clean Hydrogen Coastline" (Emden, DE) is an integrated hydrogen hub which plans to install an 320-MW_{el} industrial electrolyser manufactured by Siemens Energy. The project might start hydrogen production at scale from 2027 for regional industrial users and acts as the production hub for storage, transport and downstream offtake within the North-German hydrogen corridor (EWE, 2025; Siemens Energy, 2024).

TotalEnergies and Air Liquide recently announced their partnership to build a 250-MW_{el} electrolyser in Zeeland, the Netherlands, to supply the TotalEnergies's Zeeland refinery by 2029 (Total Energies, 2025), a few months before Air Liquide took the final investment decision on the ELYgator 200-MW_{el} electrolyser project to be deployed in the port of Rotterdam (Air Liquide, 2025b).

The Normand'Hy project is being developed by Air Liquide and aims at deploying a 200-MW_{el} PEM electrolyser to produce renewable and low-carbon hydrogen in the Port-Jérôme, FR industrial zone. The electrolyser supplier is Siemens Energy (via a joint venture with Air Liquide) which will deliver the PEM stacks and modules. One half of the output is committed to supplying the nearby TotalEnergies refinery at Gonfreville-l'Orcher, FR under a long-term offtake agreement; the remaining capacity will serve local industrial customers and decarbonised mobility (notably hydrogen trucks and bus fleets along the Seine industrial corridor) (Air Liquide, 2025a).

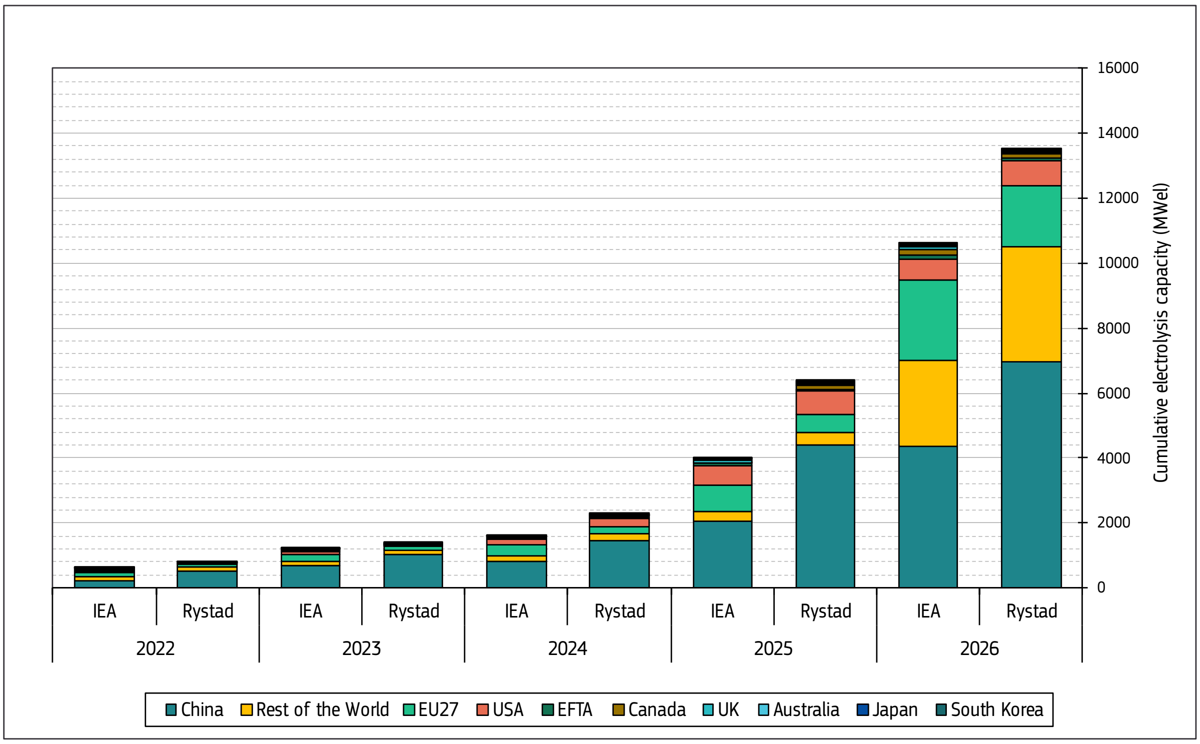
The Holland Hydrogen I project, led by Shell in the Netherlands, plans to deploy a 200-MW_{el} alkaline using standard 20-MW_{el} modules manufactured by Thyssenkrupp (Shell, 2025; thyssenkrupp, 2022). The renewable hydrogen output will be delivered via pipeline to Shell's Energy & Chemicals Park in Pernis (Port of Rotterdam, NL) to decarbonise hydrogen consumption in refining and chemicals operations. Construction work has already begun with grid/connection agreements signed with the Dutch grid operator TenneT (Hydrogen Insight, 2024).

2.3.2. Electrolysis capacity deployed at global level

As of November 2025, estimates for global electrolysis capacity deployment range between 4.0 and 6.3 GW_{el}. It is extremely difficult to provide precise estimations of global electrolyser capacity deployment due to significant discrepancies in available datasets, which often stem from different tracking methodologies and rapidly changing project pipelines. This is illustrated in **Figure 6** where the IEA and Rystad data on projects currently in operation, under construction, or with FID taken reveal significant electrolysis deployment trends, though absolute values and projections differ notably between the sources. In 2023, China already led deployment, with IEA data showing 695.2 MW_{el} and Rystad showing 1029.6 MW_{el}, compared to the EU's 218.7 MW_{el} (IEA) and 152.3 MW_{el} (Rystad). This divergence accelerates dramatically in forecasts for 2025, where the IEA projects China at 2.07 GW_{el} and the EU at 800.3 MW_{el}, while Rystad forecasts a much larger 4.41 GW_{el} for China and only 567.1 MW_{el} for the EU. Both datasets project strong continued growth for China, forecasting 4.37 GW_{el} (IEA) or 6.95 GW_{el} (Rystad) by 2026. As seen above in **Figure 4**, projections for the EU are also positive, though the sources disagree on the 2026 outcome, forecasting 2.49 GW_{el} (IEA) versus 1.86 GW_{el} (Rystad).

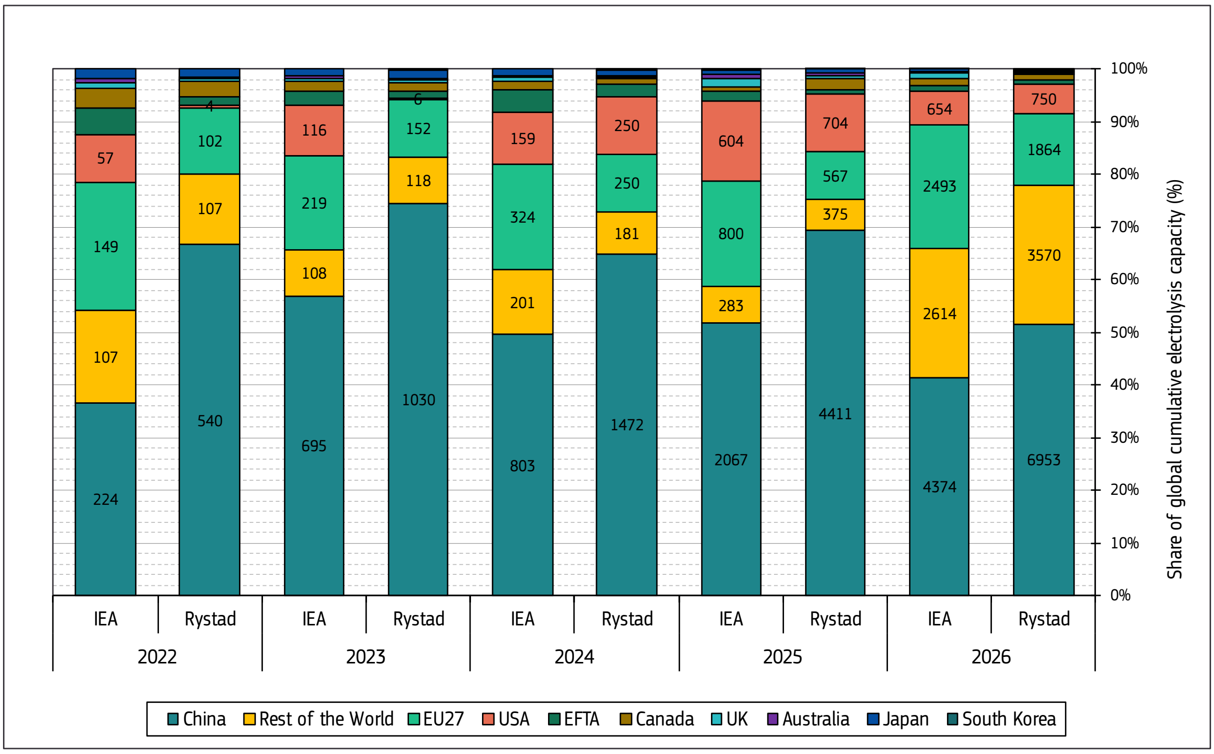
These diverging forecasts lead to different conclusions about regional gaps: the IEA data suggests the gap between China and the EU will grow to 1.88 GW_{el} by 2026, whereas Rystad's data implies a much wider gap of 5.09 GW_{el}, primarily due to the different growth trajectories projected for China. In both datasets, other key regions lag significantly; by 2026, the US is projected to reach 654.2 MW_{el} (IEA) or 749.5 MW_{el} (Rystad), and Japan is projected at 34.8 MW_{el} (IEA) or 41.6 MW_{el} (Rystad), both well behind China and Europe.

Figure 6. Global electrolysis capacity currently in operation, under construction, or with FID taken per region



Source: JRC analysis based on data from Rystad, IEA (2025)

Figure 7. Regional breakdown by shares of global electrolysis capacity

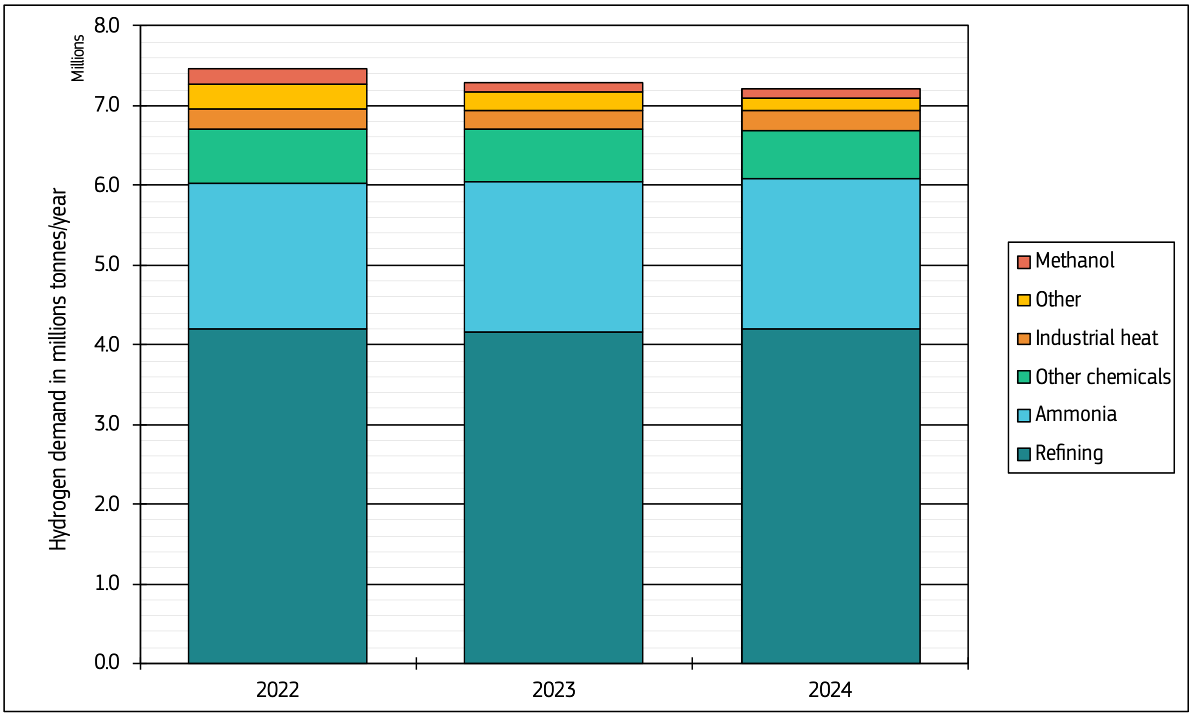


Source: JRC analysis based on data from Rystad, IEA For clarity, cumulative capacity are displayed within the bar charts (in MW_{el}) (2025)

2.3.3. Hydrogen demand in the European Union

The EU27's hydrogen demand from 2022 to 2024 slightly declined from 7.47 million to 7.21 million tonnes of hydrogen per year, according to data from EHO (European Hydrogen Observatory, 2025a). As shown in **Figure 8**, the market remains overwhelmingly dominated by its two traditional pillars: refining (around 4.2 million tonnes of hydrogen demand in 2024) and ammonia production (around 1.9 million tonnes of hydrogen demand in 2024). However, the methanol production sectors required half as much hydrogen, down from 200 000 tonnes in 2022 to 116 000 tonnes in 2024.

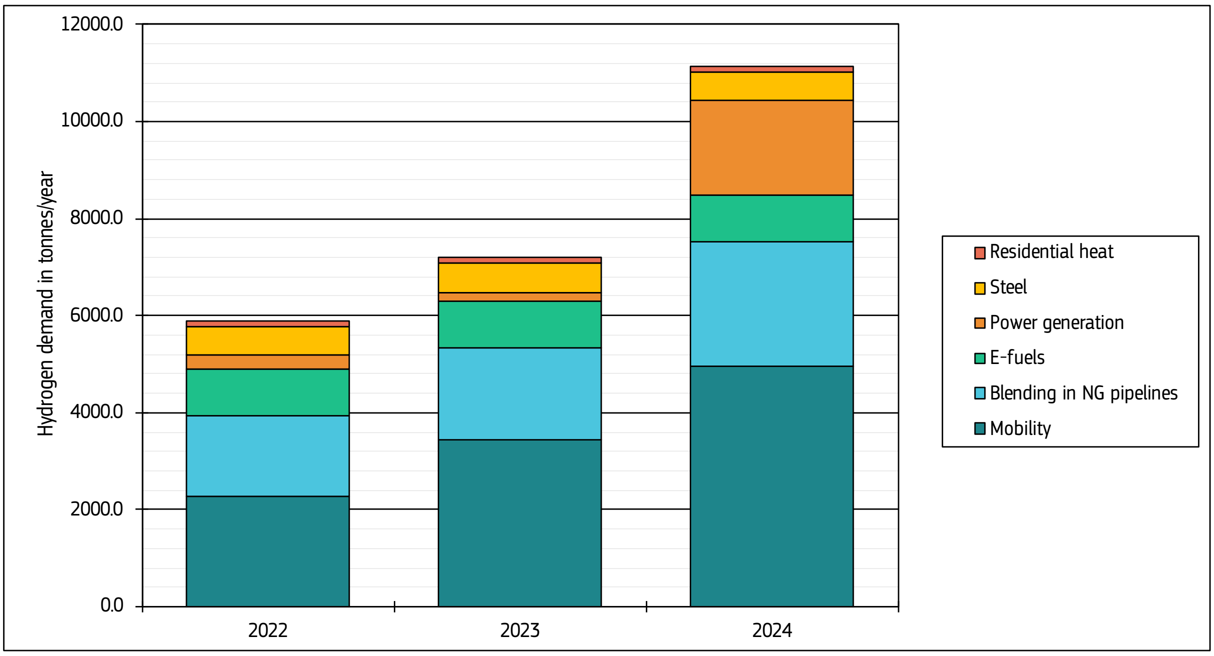
Figure 8. Hydrogen demand in the EU27 by major end-use sectors, excluding emerging applications such as mobility, power generation and grid blending.



Source: JRC analysis based on Clean Hydrogen Observatory data (2025)

As shown in **Figure 9**, emerging applications show upward momentum such as mobility applications (rising to 4 956 tonnes of hydrogen demand per year in 2024 from 2 283 tonnes in 2022), blending in natural gas pipelines (2 557 tonnes of hydrogen in 2024 up from 1 660 in 2022), and power generation (jumping to 1 967 tonnes of hydrogen demand per year from 281 in 2022).

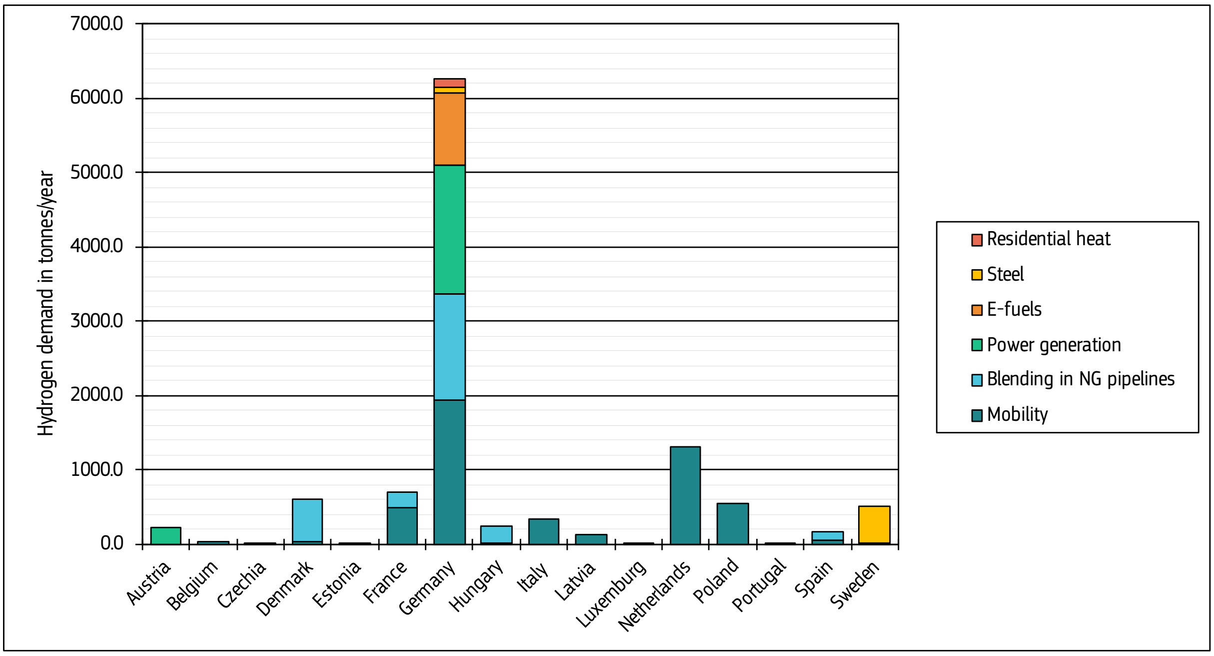
Figure 9. Hydrogen demand in the EU27 by emerging end-use sectors.



Source: JRC analysis based on Clean Hydrogen Observatory data (2025)

This demand is largely driven by Germany, representing 56% of the total EU27's demand, followed by the Netherlands (11.78% of total demand). However, these figures are still negligible in the context of the total market, and while their growth is apparent, the trends should be considered with caution given their very low starting base.

Figure 10. Hydrogen demand in emerging sectors by EU country in 2024



Source: JRC analysis based on Clean Hydrogen Observatory data (2025)

2.4. Technology costs

This chapter describes the capital cost structure related to electrolyser projects then address the cost of renewable hydrogen production systems and projects.

2.4.1. Capital Expenditure for electrolyser projects

2.4.1.1. Cost of electrolyser stacks

Commercial electrolysers are not sold off-the-shelf and there are no publicly-available catalogue prices of electrolyser stacks from manufacturers. The EHO published cost data collected from industry for PEM and alkaline electrolysers deployed in Europe (European Hydrogen Observatory, 2025a). This survey found an average cost of EUR 323.4/kW_{el} for alkaline and EUR 563/kW_{el} for PEM electrolysers.

The electrolysis stack being the core component of electrolyser systems, it received greater attention when it comes to modelling their cost reduction potential. A 2024 study estimates that future stack manufacturing costs could decrease from 242 - 388 EUR/kW_{el} for alkaline and 384 – 1071 EUR/kW_{el} for PEM to 52 – 79 EUR/kW_{el} and 62 – 234 EUR/kW_{el} respectively by 2030 (Krishnan, Koning, Theodorus De Groot et al., 2023). NREL conducted an analysis of the cost reduction potential of electrolyser systems, with an in-depth focus on PEM stack cost reduction and concluded there is a cost reduction potential from 316 USD/kW_{el} to 31 USD/kW_{el} by 2030 if all cost reduction strategies are put in place (Badgett, Brauch, Thatte et al., 2024). However, the capacity of OEMs to reach these values remains highly dependent on the economies of scale driven by higher capacity deployment.

2.4.1.2. Cost of electrolyser systems

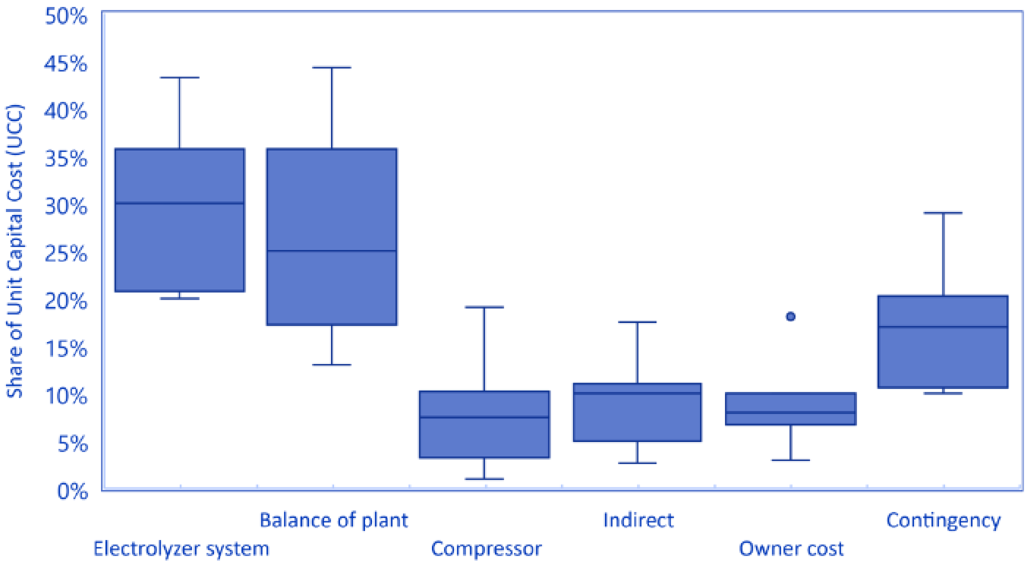
The total cost of an electrolyser system is composed of the electrolyser stack and the balance of plant (BoP), which includes all auxiliary equipment. The aforementioned survey from the EHO refers to CAPEX cost for alkaline systems of EUR 1016/kW_{el} and EUR 1209/kW_{el} for PEM systems.

The development of learning curves for electrolysers, as a key technology for green hydrogen production, has been hindered by a lack of detailed data, particularly in niche markets. A paper by (Galletti, Pasimeni, Melideo et al., 2025) addresses this gap by presenting a novel European dataset of 165 electrolyser projects from 2005-2031, providing complete information on capacity, investment costs, and other key factors. The analysis of this dataset reveals a positive learning effect for certain types of electrolysers, with cost reductions driven by scaling effects and technological advancements, and estimates that significant investment will be required to achieve the EU's 2030 targets, including approximately EUR 2.3 billion/year over the next six years.

2.4.1.3. Cost envelope of deploying electrolyser projects

A 2024 cost analysis study based on Dutch projects funded under the Sustainable Energy Production and Climate Transition Incentive Scheme (SDE++) shows a CAPEX range from more than 3 050 EUR/kW_{el} to 2 630 EUR/kW_{el} for 100-MW_{el} and 200-MW_{el} full projects respectively (TNO, 2024). According to the TNO report, the projects reported that between 20% and 45% of this CAPEX is required for the electrolysis stack, and 15%-40% for balance-of-plant components, the rest being allocated to hydrogen compressors, contingency costs, or other indirect costs borne by the project owners as described in **Figure 11**. Bloomberg ran a survey on electrolyser cost in 2024 which confirm these ranges for European and American manufacturers, while Asian systems are 4-6 times cheaper (BloombergNEF, 2024a). The IEA also provides estimates on the costs of electrolysers in the range of 1 700 – 2 000 USD/kW$_{el}$ at least (including stack, balance-of-plant and engineering, procurement, construction costs), with possible higher costs for projects in Europe (International Energy Agency, 2023).

Figure 11. Cost breakdown of the Unit Capital Cost (UCC) based on survey of projects funded under the SDE++ scheme.



Source:. Box limits indicate the range of the central 50% of the data, with a central line marking the median value. Whiskers indicate the overall range of the data. Data points further than 1.5 times the Interquartile range (box limits) from the bottom and top whiskers are considered outliers and are shown as single point. (TNO, 2024)

Although expected to decrease over the years, the latest available data show that the cost of installing electrolysis projects in Europe is higher than anticipated by analysts (BloombergNEF, 2024b; IRENA, 2020). This is the case for both PEM and alkaline technologies and according to several institutions, this trend is due to:

- An underestimation of previous cost studies which mostly focused on the cost of manufacturing stacks and balance-of-plants (BloombergNEF, 2024b; IRENA, 2020). Costs such as installing power connections, engineering costs, and the weighted average cost of capital (WACC) were not available or properly assessed since no large-scale projects were yet deployed.
- According to the IEA, inflation and the increase of the WACC explained more than half the cost increase between 2021 and 2023 systems.
- An overestimation of stack cost reduction. The maturation and upscaling of stack assembling capacities was expected to drive costs down. However, this has not yet happened for Western original equipment manufacturers (OEMs) due to a lack of orders, which in turn is hindering economies of scale. The IEA reports an utilisation rate of today's factories of about 10% (International Energy Agency, 2024). Sections 3 and 4 give more information about the current status of electrolyser manufacturing capacities.

2.4.2. Cost of renewable hydrogen

The cost of renewable hydrogen production is generally expressed in terms of Levelised Cost of Hydrogen (LCOH) as this allows for comparison with different production processes or electrolyser designs.

The cost of producing renewable and low carbon hydrogen through electrolysis depends on multiple factors which are specific to each project.

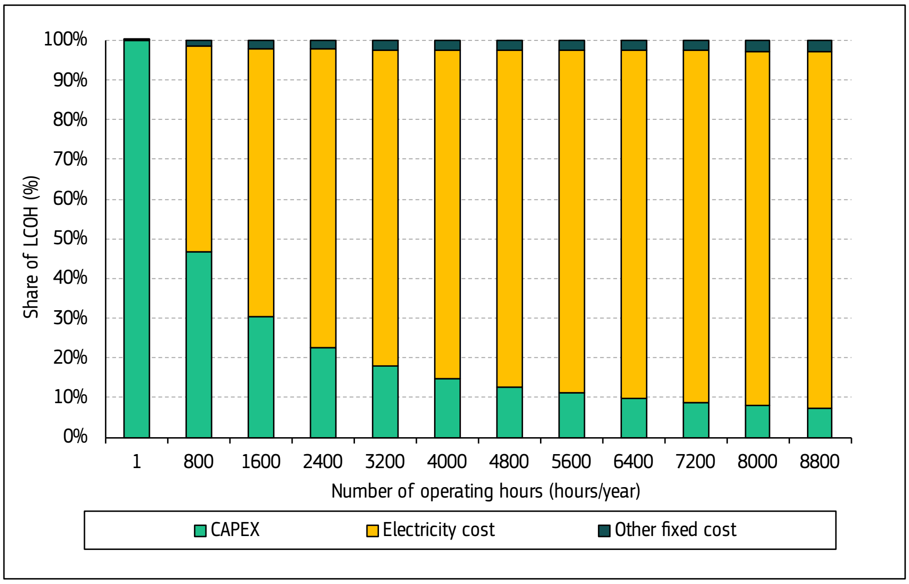
1. Capital investment (CAPEX) for electrolysers system which depends on the technology used and its scale as describe above, but also the CAPEX required for land procurement and the engineering, procurement and construction.
2. Operating expenditure (OPEX), largely impacted by the cost of electricity provided to the electrolyser.
3. Other electricity-related costs such as grid-related taxes and tariffs.
4. Load or utilisation factor[2].
5. Other OPEX costs such as water costs and operation and maintenance (O&M) costs. These are not important as the other listed above but can still impact the final hydrogen cost.
6. Cost of capital needed for financing electrolyser deployment.

2.4.2.1. Cost at system level

At electrolyser system level, the two most important factors impacting the LCOH are (1) the electrolysis system cost and (2) the electricity price. Their respective final share in the LCOH varies accordingly to the utilisation factor of the electrolyser as theoretically illustrated in **Figure 13.** When the utilisation factor of the electrolyser increases, the relative weight of electricity cost – a large part of the OPEX- increases and dominates the total hydrogen cost.

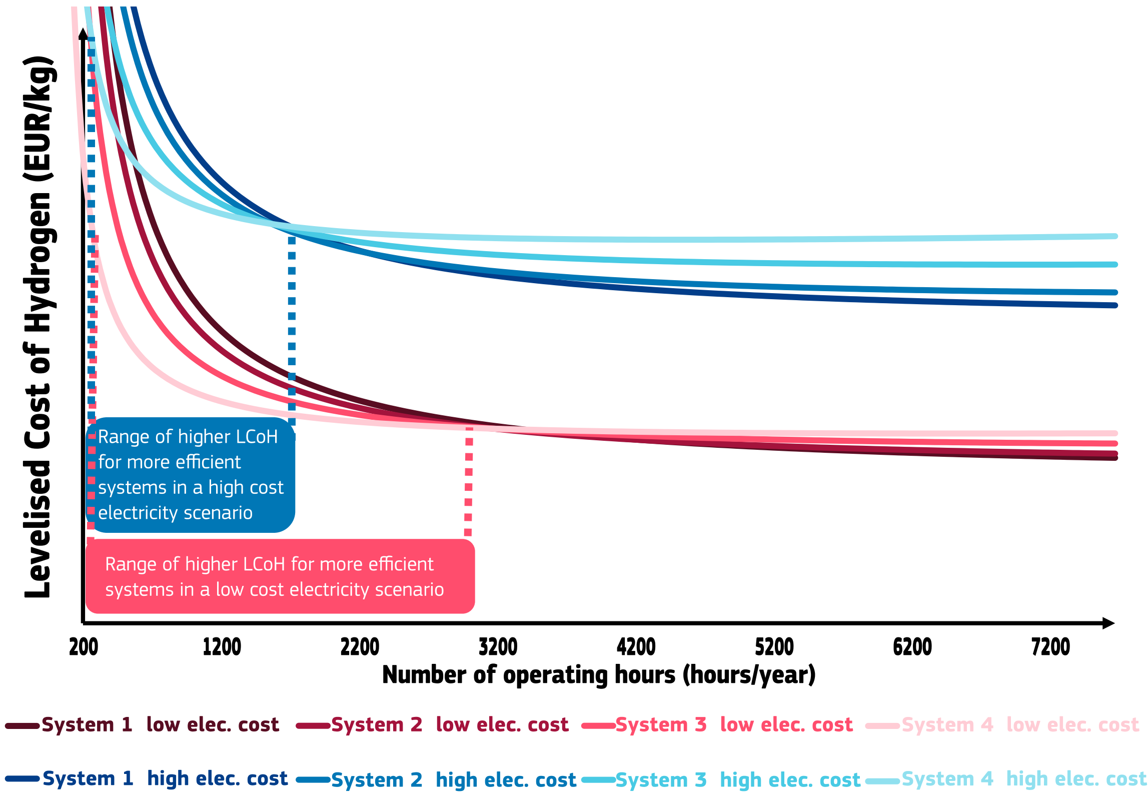
[2] Number of hours a hydrogen production facility is able to run per year. Usually expressed as full-load-hours, meaning equivalent hours the system can run at full capacity.

Figure 12. Theoretical illustration of the variation of the share of CAPEX, electricity and other costs in the Levelised Cost of Hydrogen (LCoH) depending on the number of operating hours.



Source: Modelling activity without calibration to real-world data, Degradation ranges from 0.05%/kilohour, 4% depreciation rate, 15 years operation time. Electricity price is EUR 0.25/kWh Joint Research Centre (2025)

Figure 13. Theoretical illustration of the levelised cost of hydrogen (LCoH) versus the number of operating hours for different systems.



Source: Joint Research Centre analysis (Bolard, Pilenga and Malkow, 2024). Baseline system size is 100 MW_{el}. Efficiency range is 48-60 kWh/kg with System 1 being the most efficient. CAPEX range is EUR 500-2000/kW_{el}, with System 4 being the cheapest. Degradation ranges from 0.05%/kilohours for System 1 to 0.12%/kilohours for System 4. Low electricity price is EUR 0.12/kWh, high is EUR 0.25/kWh.

Models and calculators such as the one developed by the European Hydrogen Observatory are getting more sophisticated, encompassing more aspects of newly installed systems installations (such as the renewable electricity source profile, local regulations and tariffs). In addition, cost models benefit now from real-world electrolyser plants' development costs, thus allowing for the modelling of more accurate costs for future larger projects (Forschungszentrum Jülich, 2025; European Hydrogen Observatory, 2025c; IEA, 2025f).

2.4.2.2. Cost at plant level

At the level of a fully integrated hydrogen plant, the cost of large-scale electrolysis plants can be broken down into several distinct categories:

1. The CAPEX is a significant component, encompassing the upfront costs of purchasing and installing the electrolyser equipment (electrolysis stacks, hydrogen compressors), as well as associated infrastructure for power supply and/or on-site hydrogen storage. CAPEX is also sensitive to the materials used and the characteristics of the components for a given stack. Stacks with less degradation and therefore a higher lifetime might be more expensive.
2. OPEX is another key category, covering the ongoing costs of running the facility, including non-electrolysis related energy consumption, maintenance, and labour. OPEX is highly affected by system-specific parameters such as efficiency, as less efficient systems drive up the electricity consumption and OPEX cost for a given system. Additionally, there are costs associated with the production of hydrogen itself, including the cost of electricity and water.
3. Other expenses such as the costs related to financing, land acquisition, insurance and contingency financing, permitting, grid connection fees, hydrogen transportation infrastructure also contribute to the overall cost of a large-scale hydrogen project.

These factors may have a considerable impact on the final price of hydrogen production, sometimes even greater than the CAPEX of the electrolyser. As example, the IEA estimated the cost gap between hydrogen produced by an electrolyser plant built with a European or a Chinese stack based on industry survey (IEA, 2025c). The assessment concluded that a system built with a Chinese stack and BoP would only provide a LCoH reduction of 3%-13%, depending on the electricity sourcing design. The 13% cost difference refers to projects sourcing electricity from solar PV and located in the Southern European region. In addition, the partial offsetting of the CAPEX cost is compensated by a higher share of electricity due to the still lower efficiency and underperformance of Chinese electrolysers as reported by analysts.

The detailed analysis of these factors is out of scope of this report and further details and explanations on cost dynamics are available in the IEA or Hydrogen Europe's reports (IEA, 2025d; Hydrogen Europe, 2025a). (Shafiee and Schrag, 2024) also provides a list of recent analysis of levelised costs of hydrogen storage and distribution from various sources.

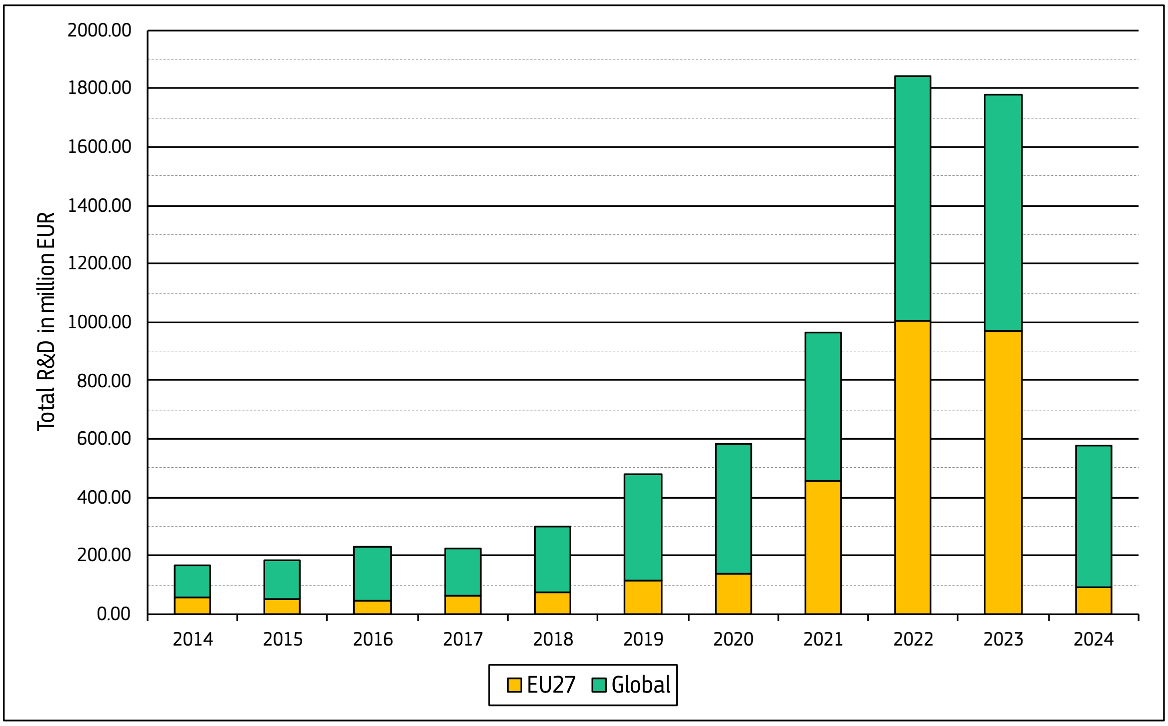
2.5. Public RD&I funding

2.5.1. Public RD&I funding at global level

According to data from the International Energy Agency (IEA) shown in **Figure 14**, public R&D investment in hydrogen technologies shows a significant upward trend, both globally and within the EU. It is important to note that these figures specifically track budgets reported under categories for hydrogen production, storage, transport, infrastructure, certain end-uses (excluding fuel cells and vehicles), and unallocated hydrogen projects[3]. Within this defined scope, the data shows that global funding grew from EUR 170.17 million in 2014 to a peak of over EUR 1.84 billion in 2022. The EU27's investment mirrored this trajectory, climbing from EUR 54.96 million to over EUR 1 billion in the same period. This highlights the EU's growing leadership, with its share of the reported total rising from under a third to over 55% by 2022.

Given that hydrogen is a cross-cutting energy carrier with applications across numerous sectors, these figures may not represent the entire scope of public funding. Investment in hydrogen-related innovations could also be accounted for within broader R&D budgets for transport, industry, or power generation, making complete accounting challenging. **Figure 15** shows that 62 % of the cumulative public R&D funding over the period 2014-2024 was unallocated. This illustrates the difficulty in effectively tracking funding across programs.

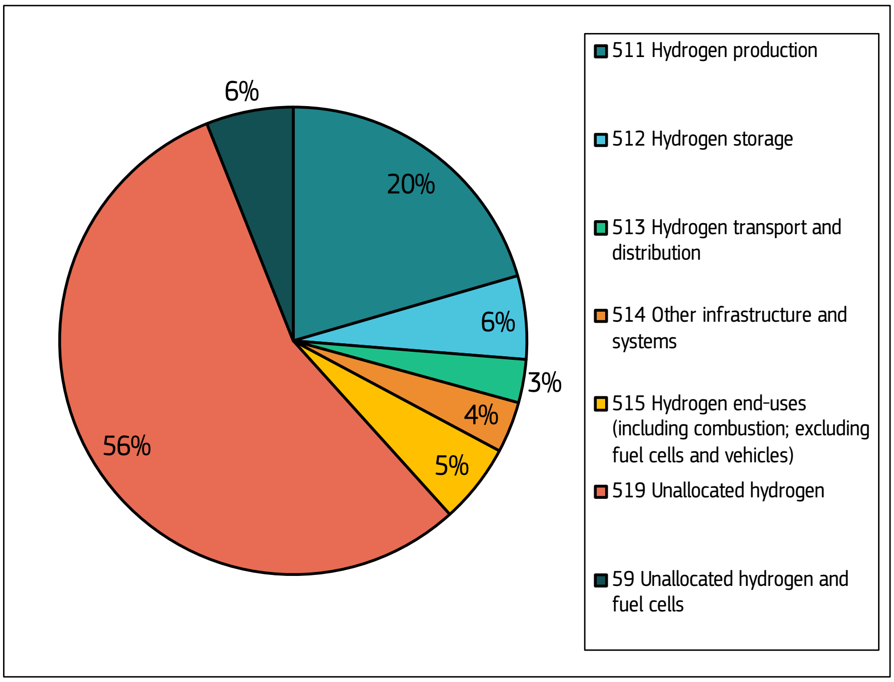
Figure 14. Public R&D investment in hydrogen technologies



Source: JRC analysis based on IEA data (IEA, 2025a). 2023 and 2024 data are provisional (2025)

[3] The related IEA documentation provides detailed descriptions of topics considered in these categories (IEA, 2025a).

Figure 15. Cumulative share of reported funding categories over the period 2014-2024

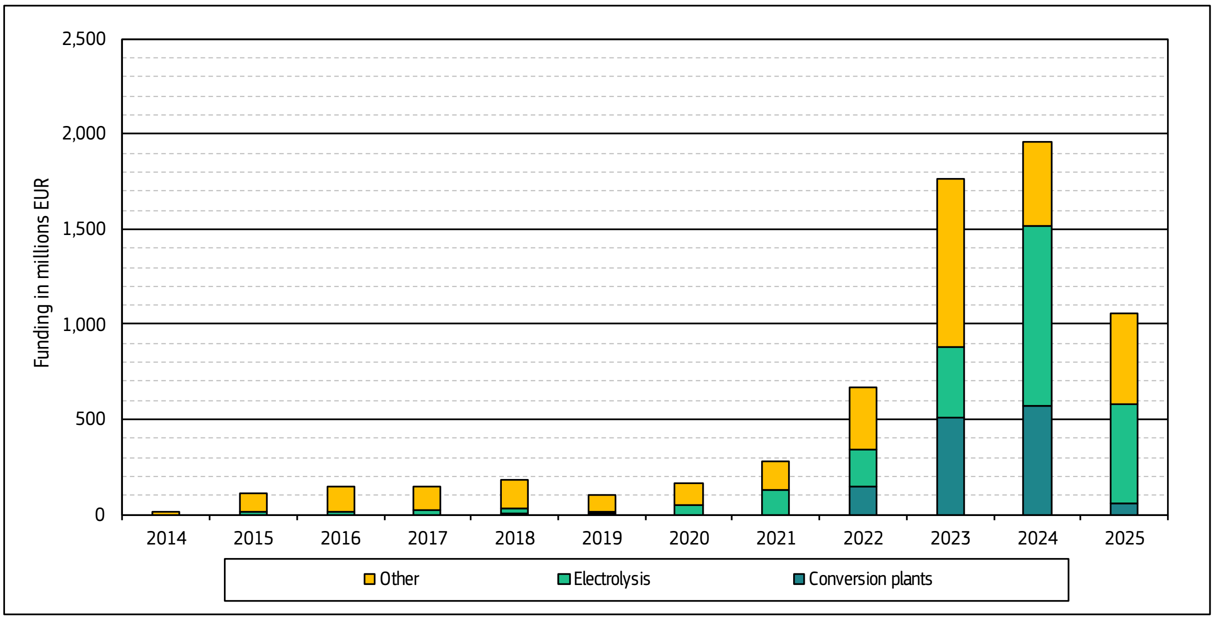


Source: JRC analysis based on IEA data (IEA, 2025a), (2025)

2.5.2. Public RD&I funding at European level

An analysis of EU hydrogen project funding from 2014 through 2025 from the CORDIS and CINEA databases shows that electrolysers technologies benefit from a large share of European public funding from programmes such as Horizon Europe, Horizon 2020 and the Innovation Fund. Out of a total of EUR 6.6 billion allocated, nearly EUR 3.6 billion has been channelled directly into projects installing electrolysers, either as their core focus of the projects or as a key component of projects integrating electrolysers within broader conversion plants (e.g. systems producing sustainable aviation fuels), as indicated in **Figure 16**.

Figure 16. Share of funding of electrolyser-related projects against non-electrolyser projects from EU programmes managed by CINEA and the Clean Hydrogen Joint Undertaking by starting year from 2014 to 2025 (estimates)[4]



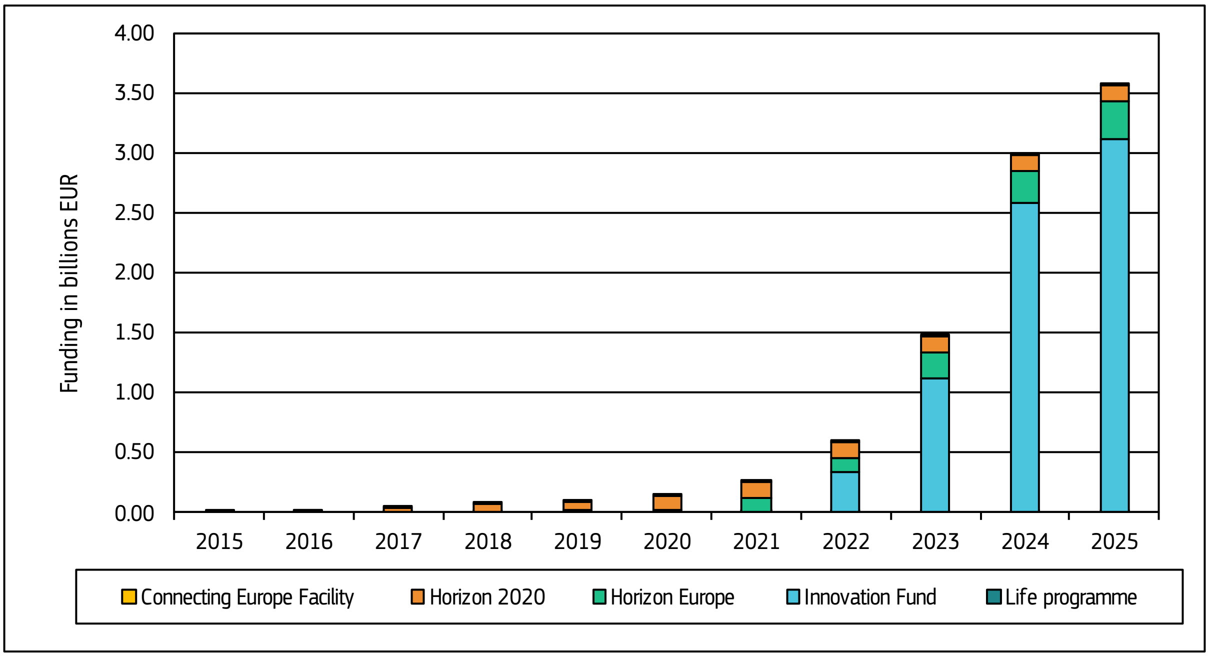
Source: Joint Research Centre analysis based on data from CORDIS and CINEA project dataset (European Climate, Infrastructure and Environment Executive Agency (CINEA), 2025) (2025)

The cumulative funding over the period 2014 to 2025 reached more than EUR 3.5 billion with 131 projects specifically related to electrolysers out of 537 related to hydrogen technologies in general. As indicated in **Figure 17**, the Innovation Fund[5] is the main funding instruments for project deployment or researching electrolyser technologies with cumulative funding of more than EUR 3 billion from 2014 to 2025.

[4] The analysis based on CORDIS/CINEA databases presented in Figure 16 includes projects from the Connecting Europe Facility funds which are deployment-related projects and do not necessarily conduct R&D activities. The aggregated funding is therefore higher than the R&D budgets presented in Figure 14 where the EU share is limited to Horizon 2020, Horizon Europe and the Innovation Fund fundings.

[5] The Innovation Fund uses funds collected from the European Union's Emissions Trading System (ETS) to support the deployment of innovative net-zero technologies in various sectors, including hydrogen technologies. Projects are usually demonstrating technologies at pre-industrial or industrial scale or deploy clean technology manufacturing capacities.

Figure 17. Cumulative funding of projects related to electrolyser or conversion plants by source of European programme funds from 2014 to 2025 (estimates)



Source: Joint Research Centre analysis based on data from CORDIS and CINEA project database (2025)

2.5.3. Member State public funding

2.5.3.1. Recovery and Resilience Facility

Recovery and Resilience Facility (RRF) and national Recovery and Resilience Plans (RRPs) presented by the EU countries to repair damages from the pandemic are also a significant source of financing for hydrogen technologies. From a Hydrogen Europe analysis (Hydrogen Europe, Muron, Pawelec et al., 2022) the total cumulative amount of funds available for hydrogen from all RRPs reaches over EUR 55 billion, of which EUR 42 billion are allocated to categories which include hydrogen technologies among investments in multiple other technologies and EUR 12 billion dedicated exclusively to hydrogen technologies. It is not possible to extract dedicated funding for electrolysis out of these figures.

2.5.3.2. Important Projects of Common European Interest (IPCEI)

The Important Projects of Common European Interest (IPCEI) framework is a state-aid mechanism allowing MS to fund large-scale innovative projects deemed to be essential for Europe's interest. The IPCEI scheme complements other State aid rules such as the Climate, Energy and Environment Aid Guidelines, the General Block Exemption Regulation and the Framework for State aid for research and development and innovation. Although not considered as traditional R&D funding, IPCEI mechanism allow Member States to support innovative projects, while ensuring that potential competition distortions are limited. Moreover, these investments are however not simply dedicated to water electrolysis deployment and hydrogen production but expected foster innovation and drive demand for electrolysers.

As of October 2025, four groups of projects[6] dedicated to hydrogen have been approved:

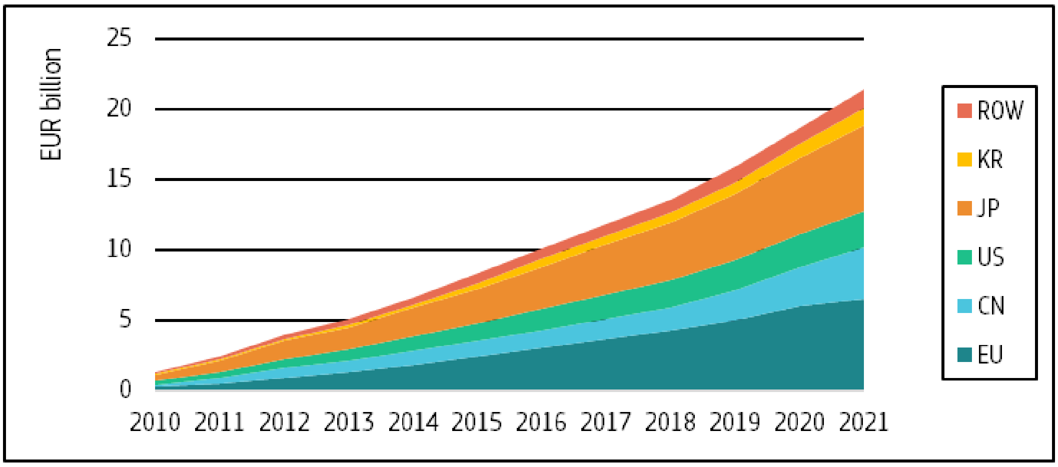
- Hy2Tech, approved in July 2022, for a total of EUR 5.4 billion in public funding. The objective of Hy2Tech is to support research and innovation and first industrial deployment in the hydrogen technology value chain, including the generation of hydrogen, fuel cells, storage, transportation and distribution of hydrogen, as well as end-use applications, in particular in the mobility sector. It has an innovation-centric approach and is expected to contribute to the development of important technological breakthroughs.
- Hy2Use, approved in September 2022, for a total of EUR 5.2 billion in public funding with EUR 7 billion in private investments. The objective to Hy2Use is to support the construction of hydrogen-related infrastructure, such as large-scale electrolysers and transport infrastructure; and the development of innovative and more sustainable technologies for the integration of hydrogen into the industrial processes of multiple sectors, such as steel, cement, and glass.
- Hy2Infra, approved in February 2024, for a total of EUR 6.9 billion in public funding with EUR 5.4 billion in private investments. The objective of Hy2Infra is to support hydrogen infrastructure including 3.2 GW_{el} of large-scale electrolysers, approximately 2 700 km of new and repurposed hydrogen transmission and distribution pipelines, 370 GWh of large-scale hydrogen storage facilities, terminals and related port infrastructure for liquid organic hydrogen carriers ('LOHC') with a capacity to handle 6 000 tonnes of hydrogen per year.
- Hy2Move, approved in May 2024, for a total of EUR 1.4 billion with EUR 3.3 billion in private investments. Hy2Move covers a wide part of the hydrogen technology value chain, including the development of mobility and transport applications, development of high-performance fuel cell technologies, the development of next generation on-board storage solutions, as well as the development of technologies to produce hydrogen for mobility and transport applications.

2.6. Private RD&I funding

An analysis of cumulative Research and Innovation (R&I) funding for hydrogen technologies from 2010 to 2021 shows significant global growth, with total investment increasing from EUR 1 275 million to EUR 21 404 million. By 2021, the European Union (EUR 6 522 million) and Japan (EUR 6 099 million) registered the highest cumulative funding totals, establishing them as the leading investors over this period. During the same timeframe, China's cumulative investment grew to EUR 3 611 million, above the estimated United States' investment of EUR 2 615 million. A breakdown of the EU's investments reveals a high degree of internal concentration; Germany's cumulative funding of EUR 4 193.9 million accounts for approximately 64% of the EU's total. France is the second-largest contributor with EUR 993.2 M, representing about 15% of the bloc's investment. Combined, these two member states constitute nearly 80% of the EU's cumulative R&I funding in this sector, indicating that the global trend of investment concentration is also prominent within the European Union itself.

[6] https://ipcei-hydrogen.eu/

Figure 18. Private R&I funding in hydrogen technologies.



Source: The dataset used The dataset includes hydrogen production, distribution and storage technologies for the energy sector and transport applications of hydrogen technologies tagged under the Climate Change Mitigation Technologies. Joint Research Centre analysis (2025)

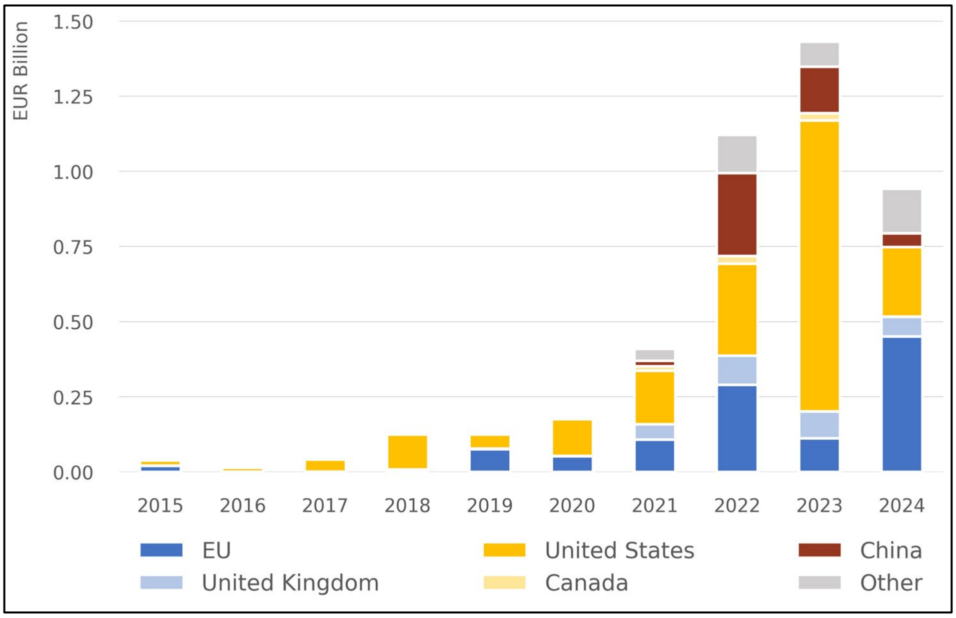
2.6.1. Venture capital and early and later-stage investments

This chapter provides an overview on the latest VC trends related to companies involved in the supply chain of electrolysers.

Global VC investment peaked in 2023 driven by a series of larger deals in US ventures including Electric Hydrogen (EUR 345 million), Ohmium (EUR 231 million) and Ambient Fuels (EUR 227 million). With a 34 % decrease in 2024 compared to 2023, global VC investment sets back to EUR 942 million, below 2022 level but still 2.3 times larger than in 2021 (**Figure 19** and **Figure 20**).

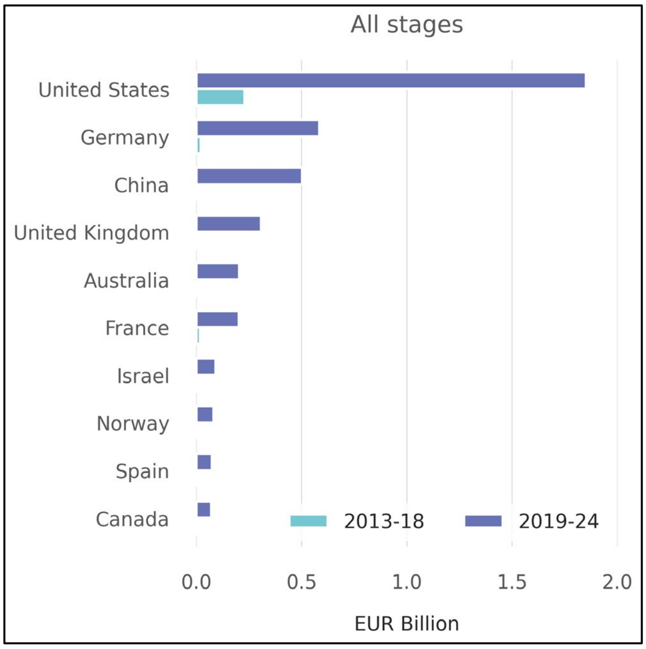
VC investment in China-based ventures dropped in 2024 after a series of larger deals in SynoHy Energy (CN, EUR 106 million in 2022), NextGenH2 (CN, EUR 88 million in 2022) or Sungrow Hydrogen Energy (CN, EUR 85 Million in 2023).

Figure 19. Global VC/PE EU investment in the water electrolyser sector, by region for all deals.



Source: JRC based on Pitchbook (2024)

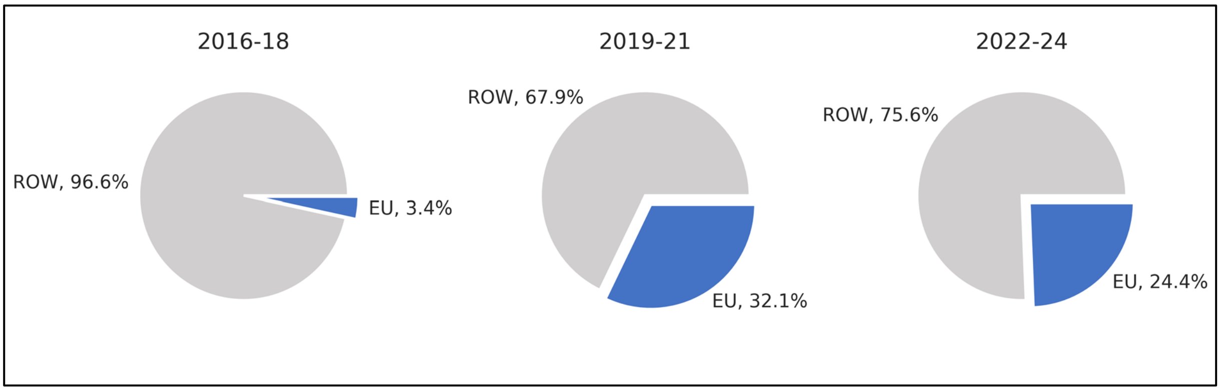
Figure 20. VC/PE investment in water electrolysers companies for the top 10 beneficiary countries, by period for all deals.



Source: JRC based on Pitchbook (2024)

In 2024, VC investment in EU ventures bounced back to an all-time high after a drop in 2023 (a four-fold increase compared to 2023) and reached EUR 450 million (**Figure 19**). In 2024, the EU took back the lead and accounted for 48 % of the total (after only 17 % over 2021-2023 period), driven by successful financing rounds of Sunfire (DE, EUR 315 and 210 million in 2024 and 2022 respectively) (**Figure 21**).

Figure 21. Share of VC/PE investment in the electrolyser sector, either in the EU and in the ROW for all deals over the 9 years, by period of 3 years

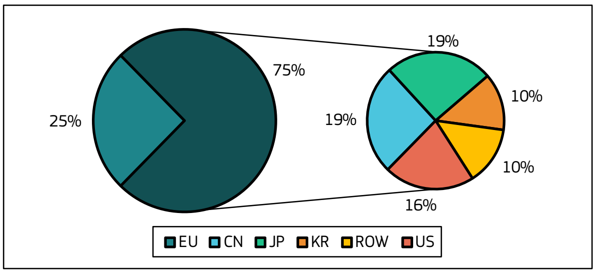


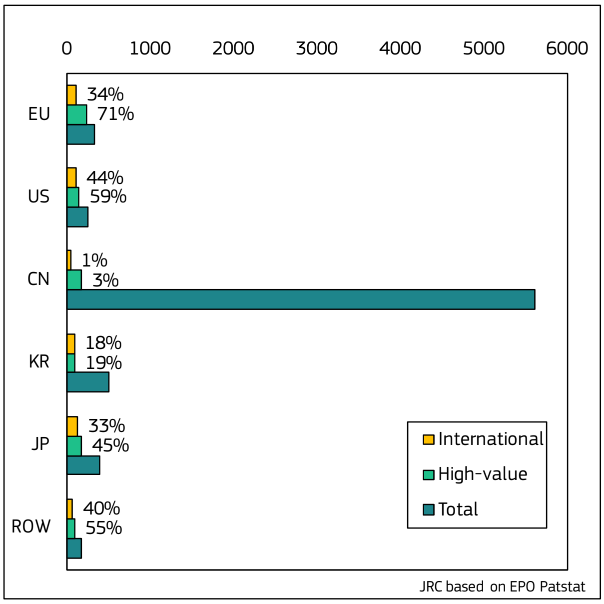
Source: JRC based on Pitchbook, (2025)

2.7. Patenting trends

This chapter provides the provisional results of an analysis conducted by the JRC based on the European Patent Office data available until 2022, with the 2022 data still in consolidating phase at the time of publication of the report. Thus, the results of this assessment should be considered with care. The available data summarised in **Figure 22** shows that the EU is leading in term of total high-value inventions' patents licensed between 2020 and 2022, although EU's share of total high-value inventions declined from 29 % over 2019 – 2021 to 25 % from 2020-2022. China represents the largest count in term of patenting activity (n = 5061 innovations), which have been mostly protected in their domestic market.

Figure 22. Share of global high-value inventions (2020-2022) (Left) – Number of inventions and share of high-value and international activity (2020-2022) (Right)

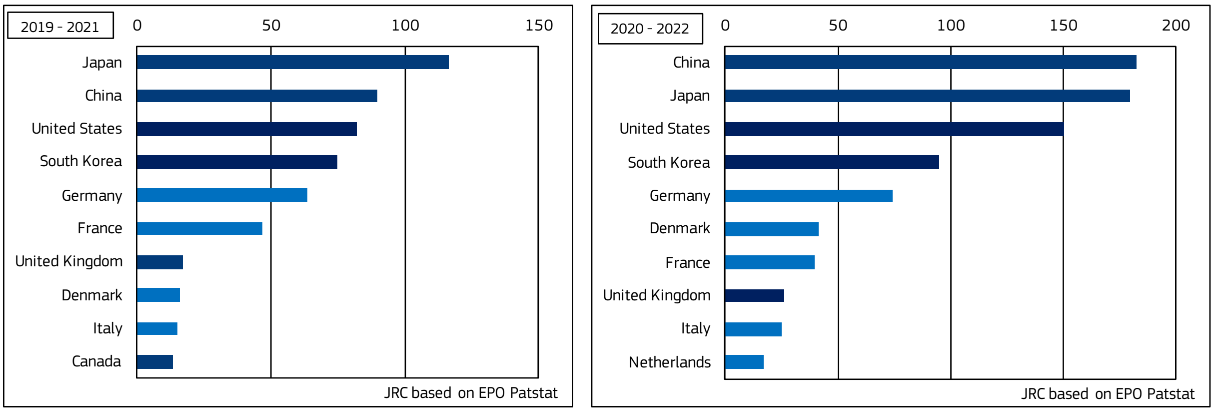




Source: Data for 2022 is not complete. Joint Research Centre (JRC) based on data from the European Patent Office (EPO) (2025)

Looking at country level (see **Figure 23**), the abovementioned trend confirmed the increasing dominance of China which ranked first over 2020 – 2022 in terms of total count of High-value inventions. It overtook Japan and is followed by the United States, Korea, and Germany stands as the highest ranked European nation.

Figure 23. High-value inventions - Top 10 countries 2019-2021 (left) and 2020-2022 (right).

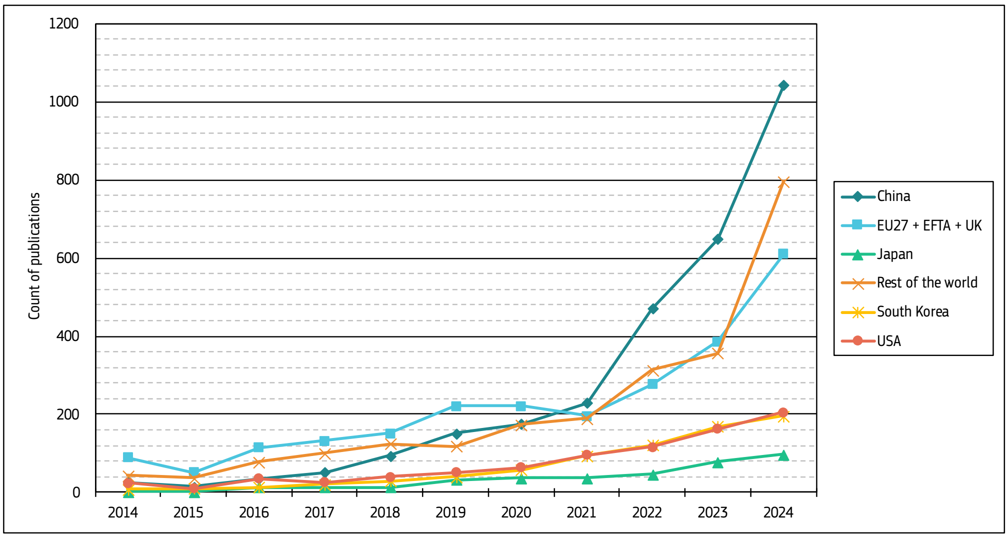


Source: Data for 2022 is not complete. Joint Research Centre (JRC) based on data from the European Patent Office (EPO) (2025)

2.8. Scientific publication trends

Based on the publications data from the Scopus database analysed by the JRC's TIM team, **Figure 24** indicates a continuous increase in scientific literature on electrolyser technologies from 2014 to 2024. Between 2014 and 2021, the European region (EU27 together with the EFTA and the UK) region consistently produced the highest annual number of publications. In the same period, output from China showed a sustained increase, which accelerated after 2021. In 2022, the number of publications from China exceeded that of the European bloc for the first time. By 2024, China's publication count reached 1 042, compared to 610 for the European bloc. The grand total of publications from 2014 to 2024 shows China with the highest number at 2 940, followed by the European bloc with 2 453.

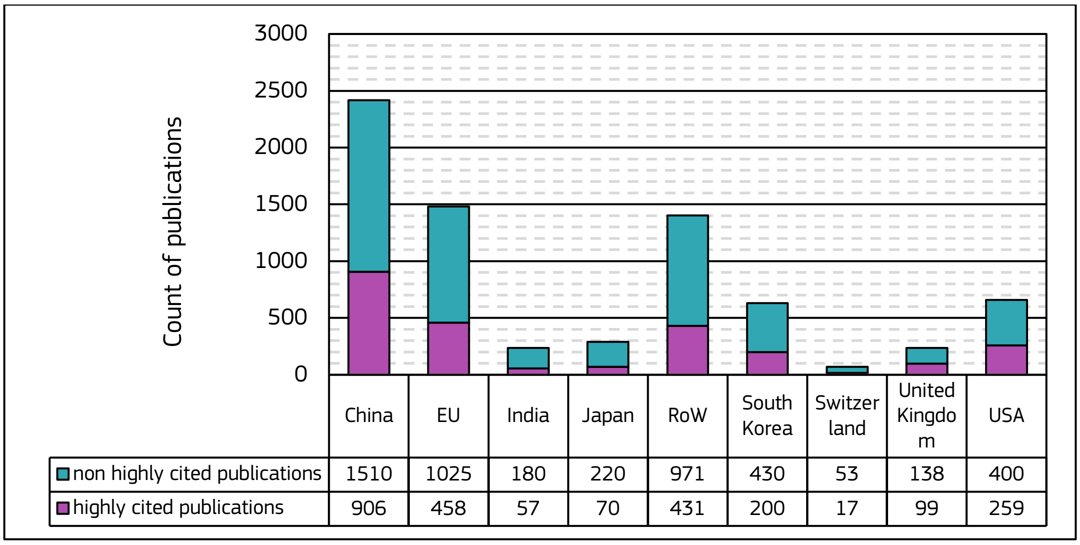
Figure 24. Count of publications across all electrolyser technologies from 2014 to 2024 per region.



Source: JRC TIM analysis based on Scopus data (2025)

Regarding citation impact, China dominates with the highest numbers of publications related to water electrolysers according to Scopus dataset, reaching 2416 publications from 2010 to 2024, including 906 highly cited publications. EU27 countries follow with a total of publications of 1483 and 458 highly-cited over the same period.

Figure 25. Count of highly and non-highly cited publications related to electrolysers per region from 2010 to 2024



	China	EU	India	Japan	RoW	South Korea	Switzer land	United Kingdo m	USA
non highly cited publications	1510	1025	180	220	971	430	53	138	400
highly cited publications	906	458	57	70	431	200	17	99	259

Source: JRC TIM analysis based on Scopus data (2025)

2.9. Assessment of R&I project developments

At European level, this dimension is currently mostly covered by the Annual Programme Technical Assessment Review performed by the JRC and provided to the Clean Hydrogen Joint Undertaking under the multiannual framework contract between the two parties (Clean Hydrogen Joint Undertaking, 2024).

3. Value chain analysis

3.1. Turnover and Gross Value Added

Due to the lack of fully developed markets for electrolysers and the often commercially sensitive nature of relevant information, it is difficult to have a clear vision on European and global market turnover.

Complete and aggregated financial information is offered commercially by several analyst groups, but it is not clear how accurate this is and how well it represents a business landscape that is evolving at a very high pace and changes in the span of a few months. It is also difficult to disentangle electrolysis figures from overall financial information figures coming from large companies active in multiple technological fields as well (e.g.: Bosch).

3.2. Environmental and socio-economic sustainability

The main environmental impact of producing hydrogen through water electrolysis concerns: the greenhouse gas emission intensity of water electrolysis and potential global warming impact of hydrogen, the sustainability and access to critical raw materials, the local impact of large-scale water electrolysis on water resources, the environmental impact associated with the source of electricity and the manufacturing of installations needed for producing renewable electricity.

3.2.1. Greenhouse gas emission intensity of water electrolysis and global warming impact of hydrogen

Intense international efforts are underway for the development of a working methodology for assessing the greenhouse gas emission intensity of hydrogen production, such as the work performed by the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) (International Partnership for Hydrogen and Fuel Cells in the Economy, 2023). According to the IPHE methodology, the carbon intensity of an electrolyser connected to dedicated renewable energy sources can be considered 0 $kgCO_2/kgH_2$ and the carbon intensity of a grid-connected electrolyser will depend on many factors such as the carbon intensity of the grid itself. A recent report from the Hydrogen Council (Hydrogen Council, 2021) quantifies as at least a tenfold reduction of carbon dioxide equivalent emissions if hydrogen is produced via electrolysis using renewable electricity coming from wind or solar, or nuclear energy, rather than via steam methane reforming. According to estimates from Hydrogen Europe, only 12 European countries would have an electrical grid with a carbon intensity low enough to produce hydrogen via water electrolysis below the benchmark carbon intensity of hydrogen produced via steam-methane reforming of 9 $kgCO_2/kgH_2$; 4 countries would be below the EU Taxonomy threshold of 3 $kgCO_2/kgH_2$ (Hydrogen Europe, Muron, Pawelec et al., 2022).

Another carbon-related aspect to consider is hydrogen emissions. Hydrogen is not a greenhouse gas per se but is considered as an indirect greenhouse gas because of its interaction with hydroxyl radicals, a naturally occurring compound in the atmosphere and a natural sink for methane. An increased concentration of hydrogen in the atmosphere will lead to an extended lifespan of methane, thus having an indirect radiative forcing. Some estimates report that 46% of the radiative effect of hydrogen emissions is due to the increased lifetime of methane, and 28% to the production of water vapour in the stratosphere. Attempts have been made to evaluate the Global Warming Potential of hydrogen and the best estimates are in the range of 5±1 and 11±5 kg

CO_2e/kg H_2 over a 100-year time horizon (GWP_{100}), and 12-33 kg CO_2e/kg H2 over 20 years (GWP_{20}), but results are subject to a very high level of uncertainty (European Commission. Joint Research Centre., 2022).

3.2.2. Impact of large-scale water electrolysis on water resources

When producing hydrogen through water electrolysis, due account should be taken on the impact of the quantity of water needed. The water electrolysis process itself requires a stoichiometric minimum level of 9 kg of ultrapure water per 1 kg H_2 produced. Information available from PEM electrolyser manufacturers gives a range from 10 to 22 L/kg H_2 of purified water processed within the electrolyser because of losses in purifying/deionising water down to 1-10µS (Simoes, Catarino, Picado et al., 2021).

Water is also used as a cooling agent in most industrial settings to safely manage the heat produced by the electrolysis stack and balance-of-plant components and prevent overheating. The water consumption depends on the cooling technology used on site, ranging from lower water-intensive technologies (air-cooled heat exchangers) to highly water-intensive technologies (cooling towers).

The amount of water required to produce hydrogen will also depend on the source of water (sea water, wastewater, or freshwater) and the technology used to desalinate and/or purify it to reach electrolyser requirements. Using sea water and desalination systems will abstract around 3.3 times the minimum amount of pure water required but will release a large part of it as brine. While there are attempts to develop systems able to directly electrolyser seawater, coupling industrial desalination plants to traditional electrolysers seems to be privileged by project developers at the moment (Serafini, Weidner, Bolard et al., 2025).

According to some estimates on the whole life-cycle water consumption of hydrogen production via electrolysis, the choice of electricity source has the highest impact on the overall water footprint. Fossil-based electricity could increase the total water footprint of hydrogen by more than 180 L/kg $H_{2,}$ while using renewable electricity does not seem to have a significant additional impact on the total life-cycle water consumption (Elgowainy, 2016).

In conclusion, the water consumption to produce hydrogen varies greatly and depends on installation-specific parameters. Across all hydrogen production technologies, IRENA estimates that steam methane reforming has the lowest impact on water resources with an estimated abstraction level of 20 L/kgH_2 and a consumption of 17.5 L/kgH_2, while alkaline electrolyser and PEM electrolyser technologies abstract on average 32.2 and 25.5 L/kgH_2 respectively (with 22.3 and 17.5 L/kgH_2 water consumed on average for these technologies) (IRENA, 2023)[7].

There seems to be considerable uncertainties about the local environmental impact of this water release, such as the impact of large quantity of brine on coastal ecosystems, or the potential release of per- and polyfluoroalkyl substances due to the degradation of PFAS-containing membranes.

[7] The same analysis estimates that water consumption for hydrogen production in 2050 will be less than 1% of water demand for agriculture and about 3% of water demand for industrial processes.

3.2.3. Social impact and sustainability of the supply of raw materials

Besides technical, environmental, and economic aspects, it is also crucial to consider social implications linked to the expected wide deployment of these technologies. A few studies have been conducted to screen relevant potential social risks of hydrogen technologies.

Regarding Proton Exchange Membrane Fuel Cells, which share several critical raw materials with PEM electrolysers and therefore could be used as a proxy for impact coming from activities such as mining, a recent study (Bargiacchi, Campos-Carriedo, Iribarren et al., 2022) has identified platinum production in South Africa as the main social hotspot for the social impact categories considered in the study. This is mainly linked to the high specific cost of platinum and the high sector-specific risk level in the relevant manufacturing country (South Africa), despite the low relative mass fraction of the used platinum (< 0.1% of the total mass of the stack). There are ongoing social LCA studies on electrolysis which will provide a good basis to evaluate potential social risks in the value chain of these technologies. However, similar and preliminary assumptions could be made for the life cycle stage of platinum group metals mining which are used in the manufacturing of electrolysers (e.g., iridium and platinum).

In a recent social LCA of a Solid Oxide Electrolysis Cell stack (Bargiacchi, Campos-Carriedo, Iribarren et al., 2022) it was found that stainless steel production is the main social hotspot among almost all the impact categories considered. This is due to the high mass ratio, which hides the effects of lower economic flows allocated to countries with higher social risk. Mining activities were found relevant in terms of social risks and very dependent on the addressed impact category.

3.3. Role of EU companies

Siemens Energy provided the electrolysers to the two largest electrolyser plants currently in operation in Europe (54-MW_{el} Hy4Chem project and 52-MW_{el} European Energy), developing industrial knowledge in projects above the 50-MW_{el} mark (BASF, 2025; European Energy, 2025). It will also be involved in several large-scale projects currently under construction, such as the 320-MW_{el} EWE's "Clean Hydrogen Coastline" (Emden, DE) project, or the 200-MW_{el} Normand'Hy project with Air Liquide (France).

Thyssenkrupp Nucera is also executing several large-scale projects, including the 2.2 GW NEOM complex in Saudi Arabia and Shell's 200 MW Holland Hydrogen I, while recently being selected as the preferred supplier for a 1.4 GW green iron project in Australia. To enhance its technological capabilities the company has opened a pilot plant for SOEC technology with Fraunhofer IKTS (Thyssenkrupp nucera, 2025b, 2025a; Hydrogen Insight, 2023).

Two European manufacturers filed for bankruptcy this year: McPhy and Green Hydrogen Systems (John Cockerill, 2025; Thyssenkrupp nucera, 2025c). This shows difficulties for smaller-scale manufacturers to sustain financially within a slower-than-anticipated market deployment. Their assets were however bought by other European manufacturers, such as John Cockerill (McPhy) and Thyssenkrupp Nucera (Green Hydrogen Systems).

3.4. Employment

Unfortunately, there are no reliable estimates available for the electrolyser sector.

3.5. Energy intensity and labour productivity

Unfortunately, there are no reliable estimates available for the electrolyser sector.

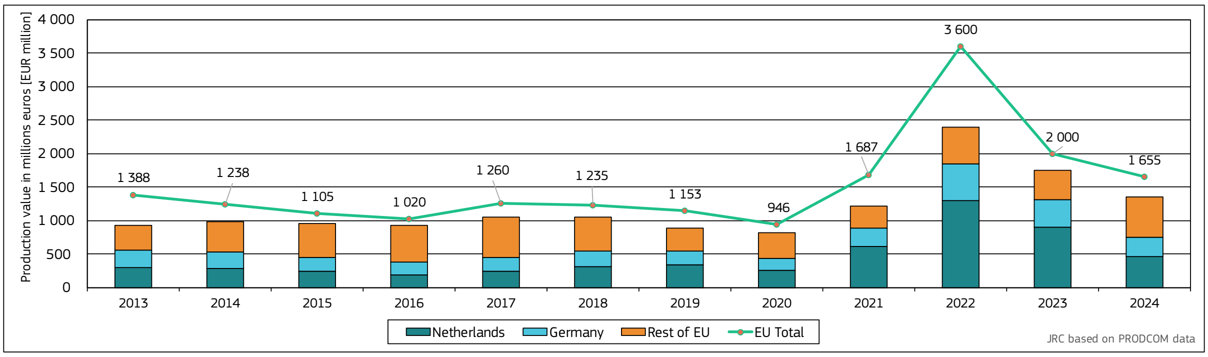
3.6. EU production data[89]

Prodcom code 20111150 (Manufacture of industrial gases - Hydrogen) is used to monitor hydrogen production and sold to consumer, excluding hydrogen produced and consumed on the same site. It does not distinguish between renewable or low carbon hydrogen and hydrogen produced via conventional fossil fuel-based methods, leading to inflated absolute production values. As a result, this code serves only as a proxy for understanding the production trends.

Figure 26 illustrates EU merchant hydrogen production in monetary value. The sum of countries' production (boxes) is lower than the 'EU Total' (line) because some Member States keep their production data confidential. However, Eurostat includes confidential data in the 'EU Total' estimates.

In 2024, EU hydrogen production declined by 17% compared to 2023, falling to under EUR 1.7 billion. Over the past decade (2015-2024), total EU hydrogen production value increased by 50%, with an annual compound growth rate of 4% and an average annual value of EUR 1.6 billion. Netherlands and Germany were the leading EU producers, accounting for 28% and 17% of the total EU 2024 production, respectively.

Figure 26. EU production value of hydrogen and top producers among the Member States disclosing data [EUR million]



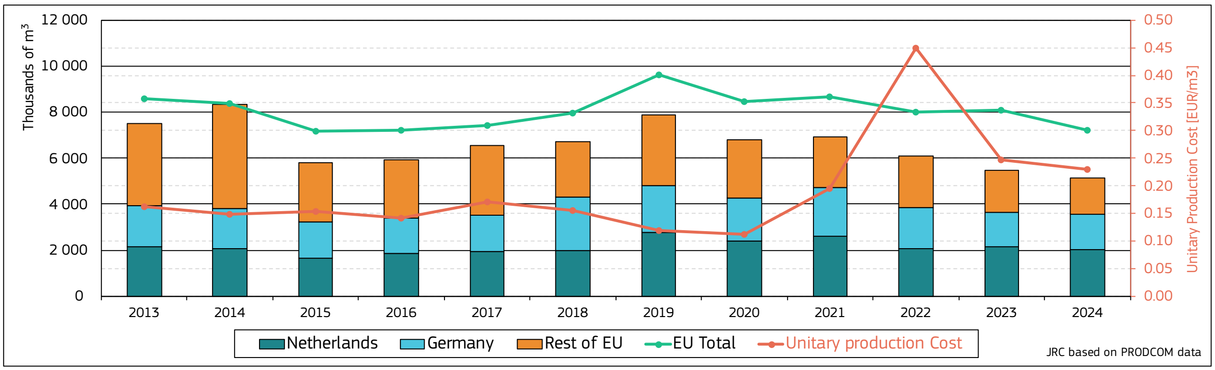
Source: JRC based on PRODCOM data (2025)

EU hydrogen production volumes also declined in 2024, dropping by 11% compared to 2023 to around 7.2 million m3. The Netherlands and Germany remained the largest producers, accounting for 28% and 21% of the total EU 2024 production (as seen in Figure 27). This is likely driven by the

8 *This sub-chapter is authored by Aikaterini.Mountraki@ec.europa.eu as part of the project "Energy Research Innovation and Competitiveness For the Green Transition" (ERIC4GT) within the unit "Energy Transition Insights for Policy" (JRC.C7) to support Clean Energy Technology Observatory (CETO) studies 2025.*

refining and chemical sectors, both two main hydrogen consumers, as seen in Figure 8 which are producing hydrogen on-site for captive consumption.

Figure 27. EU production of merchant hydrogen [thousands of m^3] (left axis) and EU production unitary value of hydrogen [EUR per m^3] (right axis)

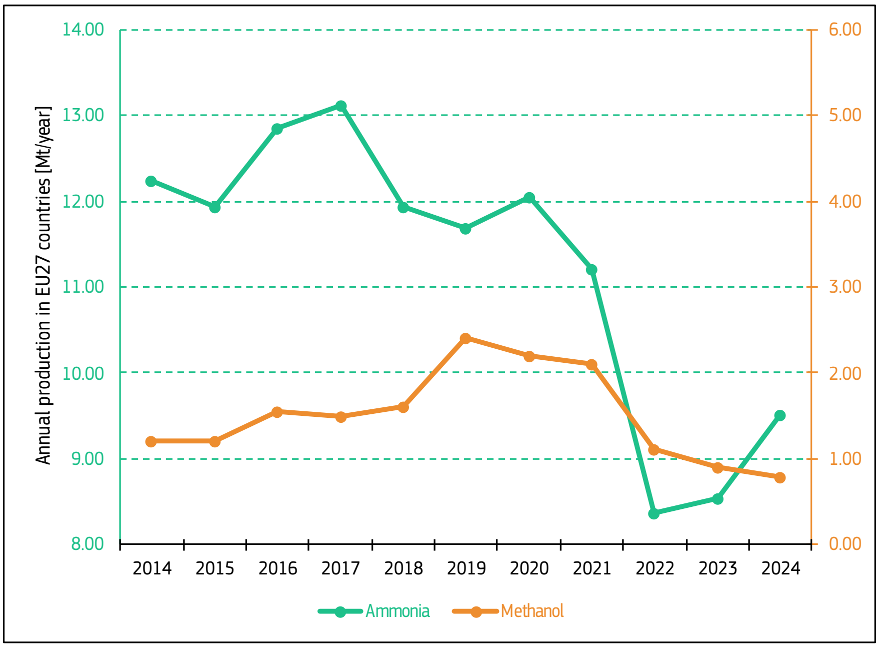


Source: JRC based on PRODCOM data (2025)

While hydrogen production volumes remained stable over the past decade (2015-2024), the average unitary production value increased by nearly 50%, rising from EUR 0.15 per m^3 in 2015 to EUR 0.23 per m^3 in 2024 (**Figure 27**). This rise in unitary cost gives the signal of a hydrogen market growing after 2020 when expressed in monetary values, where it actually has decreased in term of total production volumes since 2020.

It is worth noting that the production of key industrial sectors consuming hydrogen such as ammonia and methanol production appears to be progressively decreasing and has not fully recovered from the 2022 shocks. The overall dynamics of these sectors seems to follow a downward trend (see **Figure 28**). This trend might illustrate than large consumers of hydrogen for methanol and ammonia production are now importing more methanol and ammonia to produce their final products (like fertilisers), instead of producing these feedstocks directly on-site from hydrogen. If these trends continue and less hydrogen is consumed by these large-offtakers, the market for renewable hydrogen will also shrink, making the substitution of fossil-based hydrogen with renewable hydrogen even more difficult. However, this trend still need to be confirmed in the medium-run with future releases of statistics.

Figure 28. Annual production of anhydrous ammonia and methanol



Source: JRC analysis based on Eurostat data (2025)

4. EU market position and global competitiveness

4.1. Global markets and growth prospects

4.1.1. Current EU positioning in the global market

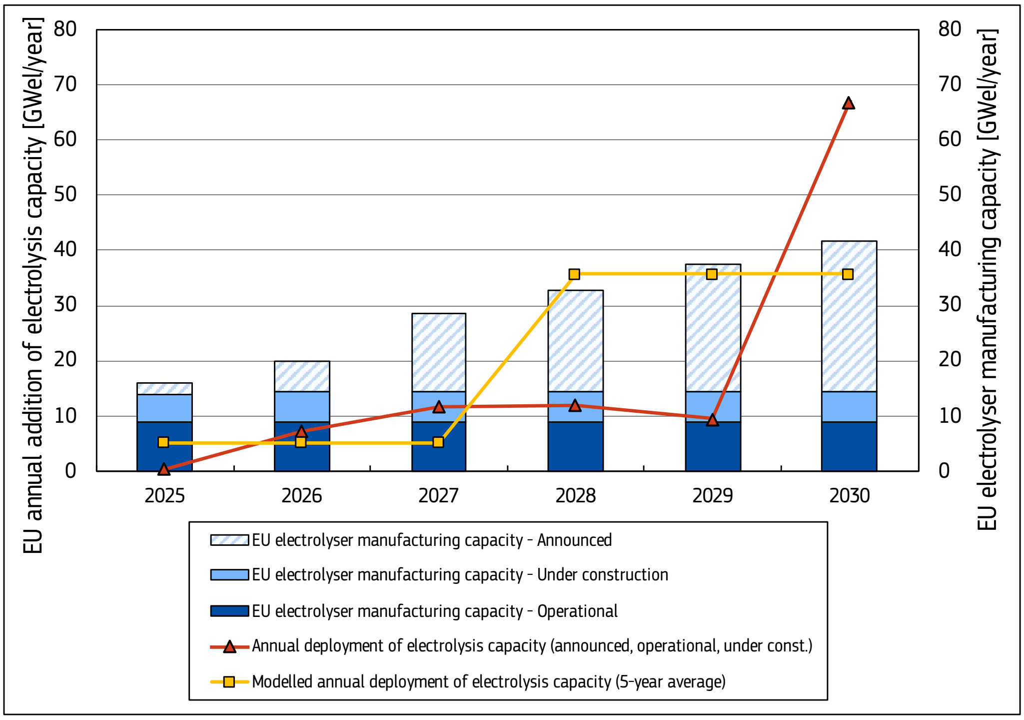
Conservative estimates based on publicly confirmed data indicates an EU operational manufacturing capacity of water electrolysers of approximately 8.9 GW_{el}/year as of November 2025. Most of EU's manufacturing capacity is dedicated to PEM electrolysis, with approximately 4.2 GW_{el}/year, followed by alkaline (3.8 GW_{el}/year), SOEC (0.9 GW_{el}/year), and AEMEL[10] (0.03 GW_{el}/year). In addition to this operational capacity, 5.4 GW_{el}/year of capacity are currently under construction and were to start by the end of 2025. Manufacturing capacity could reach approximately 41.7 GW_{el}/year by 2030 considering all announcements from companies. These estimates represent the processed of assembling cells to produce electrolyser stacks but does not necessarily consider the manufacturing of all BoP components. Most importantly, these estimates are based on announced nameplate capacities and do not represent the actual production of factories.

All factories within the EU are accounted, independently of the headquarter location of the owning company. This is a conservative estimate compared to other analyses, particularly those from Hydrogen Europe, which predict an operational manufacturing capacity of around 12 GW_{el}/year (EU27, EFTA, UK) (Hydrogen Europe, 2025b). The discrepancy can be attributed to assumptions regarding the actual starting dates and whether the full scale of announced capacities, such as Siemens Energy's projected 3 GW_{el}/year (Siemens Energy, 2023), is accurately accounted for.

Figure 29 illustrates the EU's manufacturing capacity relative to the projected annual increase of water electrolysers based on estimates from the IEA. This highlights the disparity in utilisation rates, ranging from a low-capacity factor of 5% (if all EU projects deploy EU-made electrolysers) to a potential shortage in manufacturing capacity, should all announced projects become operational by 2030 under optimistic projections and if they deploy only EU-made electrolysers.

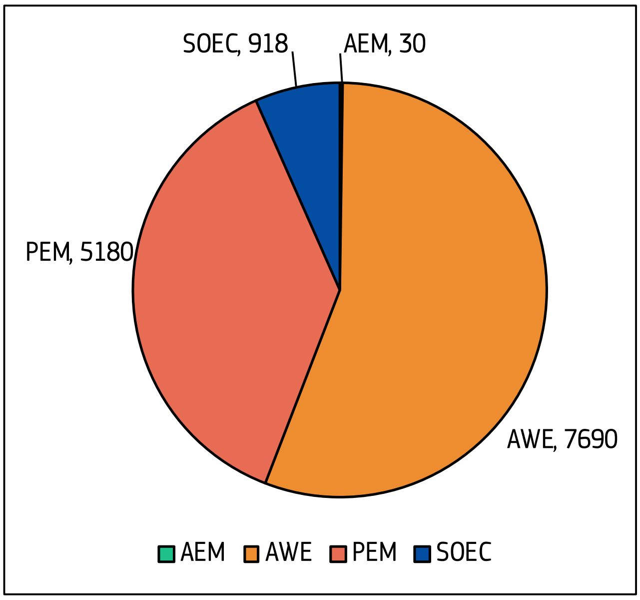
[10] The manufacturing capacity for AEMEL technology is unclear, as Enapter moved the preparation of the electrolyser skid to China via a JV with Wolong, and kept the stack manufacturing capacities in Europe (Enapter, 2024). More optimistic estimate could consider approximately 0.3 GWel/year of AEM manufacturing capacity.

Figure 29. Manufacturing capacity versus annual added electrolysis capacity in the European Union



Source: Joint Research Centre analysis based on manufacturing capacity data from Rystad Energy, Enerdata, manufacturer websites. Modelled capacity based on POTEnCIA CETO 2025 Scenario as a 5-year average centered around 2025 and 2030. Annual added capacity based on IEA data. (2025)

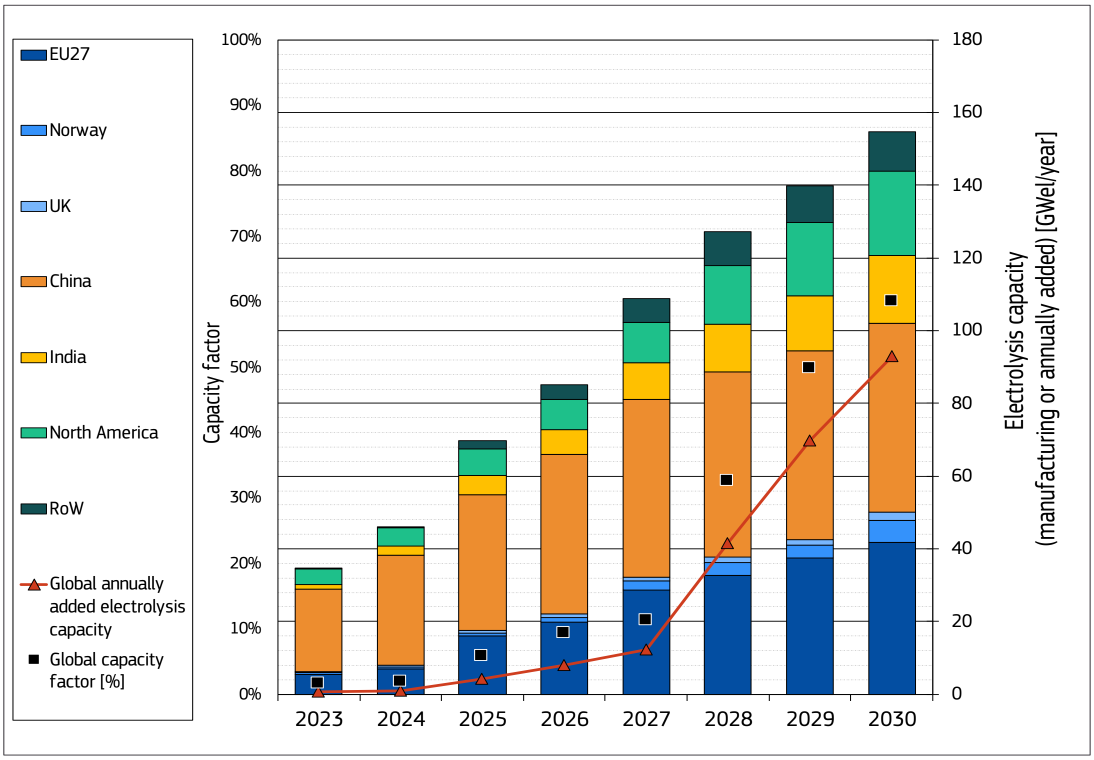
Figure 30. Breakdown of EU manufacturing capacity by 2025 (operational and under construction, factories located in the EU)



Source: Rystad Energy and Enerdata (2025)

Global electrolyser manufacturing capacity in operation or under construction by the end of 2025 is estimated to reach approximately 63 GW_{el}/year, as shown in **Figure 31**. Most of the capacity (34.7 GW_{el}/year, 55.1 %) belongs to factories located in China. The EU capacity (in operation and under construction) represents approximately a quarter (13.9 GW_{el}/year, 22.1 %) of the global capacity.

Figure 31. Cumulative manufacturing capacities in operation or under construction over the period 2020-2030 by factory region against global annual deployment capacity.

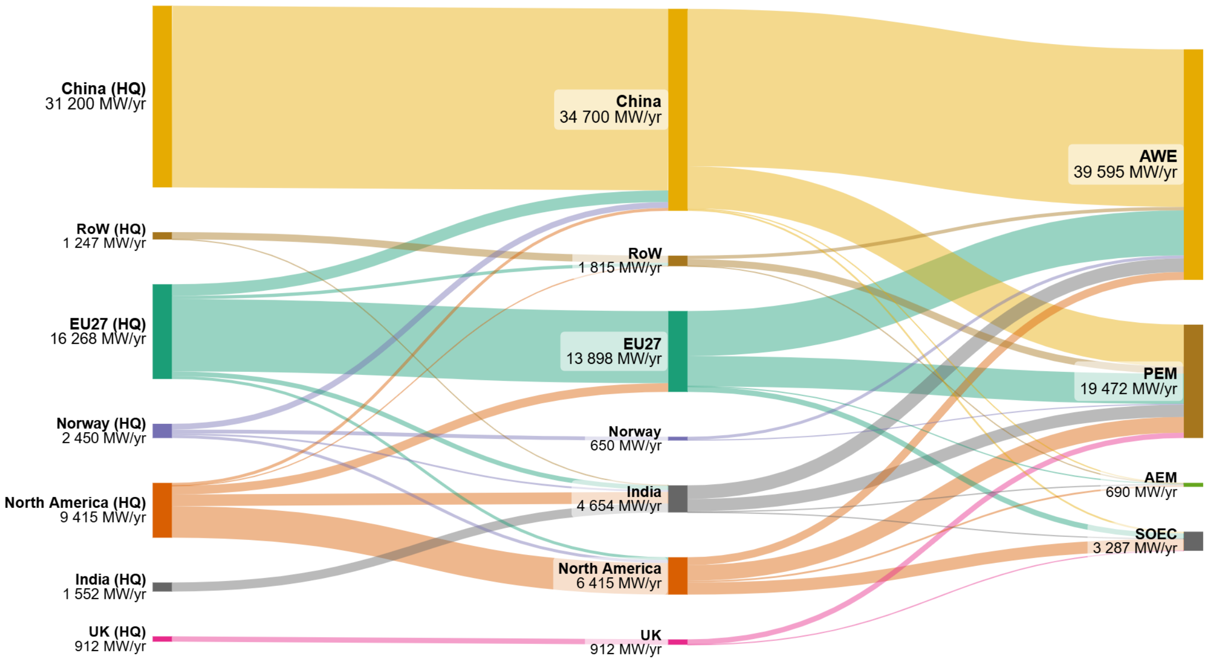


Source: JRC analysis based on data on manufacturing capacities from Rystad Energy, Enerdata and manufacturers websites, data on annual deployment from Rystad Energy with projects in operations, under construction, planned (2025)

The most optimistic range of capacity deployment considers the total announced capacity across all tracked regions and is projected to reach approximately 155 GW_{el}/year by 2030 according to Rystad Energy data. The combined EU27, Norway, and UK bloc demonstrates an increasing growth trajectory, with announced capacity expected to reach nearly 50.2 GW_{el}/year by 2030, eventually rivalling the capacity of China (estimated to grow to approximately 51.9 GW_{el}/year by 2030). North America also shows a substantial planned expansion, though on a different scale, with projections increasing to over 23.2 GW_{el}/year by 2030.

All the abovementioned manufacturing capacity currently refer to factories located in a given region. However, the picture is slightly readjusted when looking at the location of the headquarters of the manufacturing companies. **Figure 32** below shows the relationship between the location of manufacturer headquarter and factories as of November 2025. It seems that all Chinese companies deploy manufacturing capacity in China, where approximately 2 GW_{el}/year of capacity from European companies are actually located in China.

Figure 32. Headquarters (left) versus factory locations (middle) and technology breakdown (right) of electrolysers manufacturers in 2025.



Source: JRC analysis based on data from Rystad Energy and Enerdata (2025)

Note: manufacturing capacities are expressed in MW_{el}/year and include factories with status labelled as "Under construction" and "Operational". Sankey produced with sankeymatic.com

4.1.1.1. Policy context

The EU Energy and Raw Materials Platform has launched a Hydrogen Mechanism, a digital platform designed to accelerate the market for renewable and low-carbon hydrogen and its derivatives. This mechanism, part of the European Hydrogen Bank, aims to connect hydrogen producers with buyers, facilitating investment and infrastructure development. Two auctions were conducted so far with a budget of EUR 1.7 billion (European Commission, 2025c). A 3rd European Hydrogen Bank auction opened in December 2025 with a budget of EUR 1.3 billion (European Commission, 2025a). The platform is intended to support the EU's decarbonisation goals by scaling up hydrogen production and usage in sectors like heavy industry and transport. Despite the stimulus provided by the consumption targets set in the Renewable Energy Directive (2023/2413)[11], the delayed implementation at a national level is jeopardising the possibility of having a faster and more solid uptake of renewable hydrogen (European Commission, 2025b).

In the United States of America, the "One Big Beautiful Bill Act", passed into law in July 2025, significantly modifies energy tax provisions, including those related to hydrogen, from the Inflation Reduction Act (IRA). The bill moves forward the expiration of the clean hydrogen production tax

[11] RED III mandates a 42% consumption goal for renewable fuels of non-biological origin in industrial processes by 2030, growing up to 60% by 2030. The directive also mandates a 1% target for RNFBO used as transport fuels.

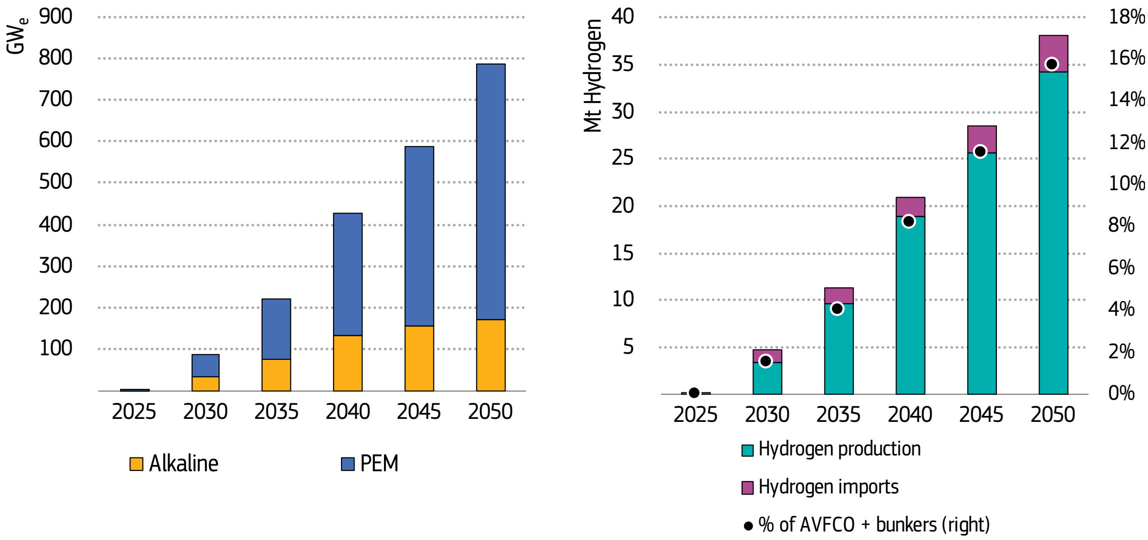
credit (Section 45V) to the end of 2027 for projects starting construction. This accelerated timeline is expected to impact around 75% of the existing renewable and low-carbon hydrogen pipeline, making these projects unlikely to qualify for the tax credit.

4.1.2. Market prospects

For the European Union, the JRC-in-house POTEnCIA model has been used to project the deployment of renewable hydrogen and the required electrolyser capacity. According to the latest *POTEnCIA CETO 2025 Scenario* results, illustrated in **Figure 33**, the EU production of renewable hydrogen is projected to be 3.5 MtH_2/year by 2030, with additional imports of 1.3 MtH_2/year. By 2040, these figures are estimated to grow to 18.9 MtH_2/year for domestic production and 2.0 MtH_2 /y for imports, respectively. In 2050, EU production is calculated to be 34.2 MtH_2/year with imports reaching 3.9 MtH_2/year.

To achieve this level of domestic production, a significant ramp-up of installed electrolyser capacity is required. The model projects a total capacity of approximately 86.1 GW_{el} by 2030, growing to nearly 788 GW_{el} by 2050[12], considering around 2000 h/year of full load equivalent. The scenario results suggest a larger adoption of PEM technology, which is expected to account for over 618 GW_{el} of the total capacity in 2050, compared to 170 GW_{el} for alkaline electrolysers.

Figure 33. Estimated future electrolyser deployment and hydrogen production/imports in the European Union



Source: Hydrogen production and electrolyser deployment results of the POTEnCIA CETO 2025 Scenario, Joint Research Centre (2025)

Note: AVFCO = Available energy for final consumption (final energy consumption + final non-energy consumption). The denominator of the reported share includes energy consumed by international aviation and shipping.

[12] The estimated electrolyser capacity, higher than in some other sources (e.g. other modelling exercise projects 40 GW_{el} electrolysis capacity by 2030 (European Commission, 2024)), reflects the low capacity factor in countries where VREs are dominated by solar power, and the lack of explicit consideration, in the *POTEnCIA CETO 2025 Scenario,* of coupling electrolysers with dedicated battery storage (Neuwahl, Wegener, Salvucci et al., 2025).

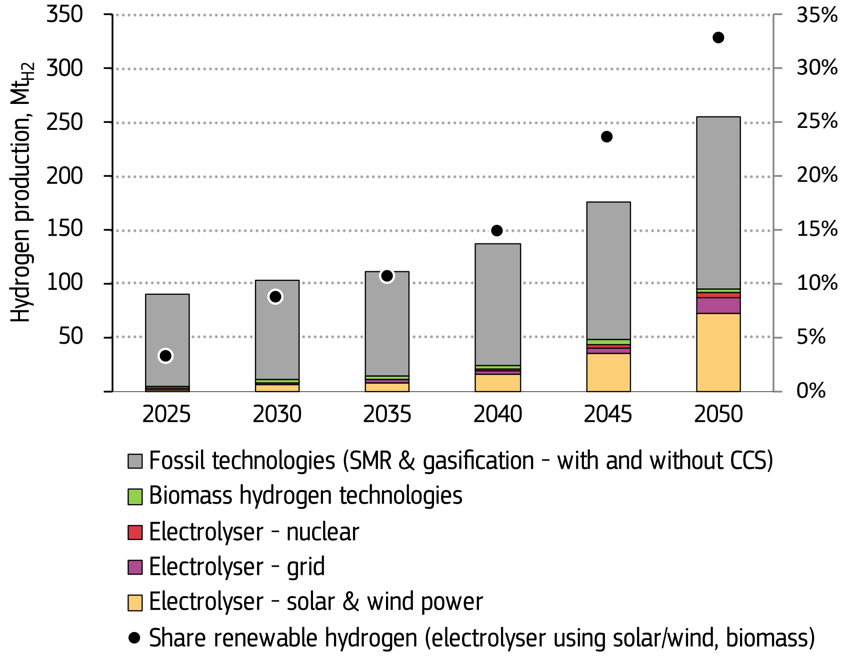
Several demand-side policies are considered in the model that stimulate demand for hydrogen and hydrogen-derivatives: RED III, FuelEU Maritime, ReFuelEU Aviation, and the Alternative Fuels Infrastructure Regulation (AFIR). The demand is initially driven by refineries and the chemicals sector, where hydrogen supply chains and transformation processes are already established. However, in the mid- to long-term, demand becomes more diverse. Major demand comes from the aviation and maritime sectors, predominantly by using hydrogen-derivatives such as synthetic kerosene and ammonia to meet emission and clean fuel targets. Additionally, hydrogen becomes essential for decarbonising industry, specifically the iron and steel sector, where hydrogen direct reduced iron (DRI) has the potential to replace coal- and coke-based iron making, as well as the chemicals sector, where hydrogen replaces large shares of oil products as a more sustainable feedstock[13].

Compared to the previous year's report (European Commission, Bolard, Dolci et al., 2024), the *POTEnCIA CETO 2025 Scenario* shows a notable shift in the projected timeline and sourcing of renewable hydrogen for the EU. The short-term outlook for 2030 is now more ambitious, with projected domestic production increasing from approximately 2 MtH_2/year to 3.5 MtH_2/year, and imports rising from 0.8 MtH_2/year to 1.3 MtH_2/year. Conversely, the mid- to long-term projections are more conservative regarding total supply. By 2040, domestic production is now projected at 18.9 MtH_2/year (down from 21 MtH_2/year), while imports are significantly lower at 2.0 MtH_2/year (down from 4 MtH_2/year). This trend continues to 2050, where domestic production is projected at 34.2 MtH_2/year (slightly down from 36 MtH_2/year), and reliance on imports is reduced to 3.9 MtH_2 /year compared to the 6 MtH_2/year previously anticipated.

The POLES-JRC model was also used to provide a global-scale energy scenario as described in **Annex 3**. The *Global CETO 2°C Scenario 2025* investigates the uptake capacity of 13 different hydrogen production pathways (fossil, electrolytic, or biomass-based). Although the scenario projects a growing consumption of hydrogen at global level, the share of fossil-based technologies remains the largest as seen in **Figure 34**.

[13] The intermediate demand of fossil-fuel derived hydrogen of oil refineries, used for conventional upgrade of fossil fuels, is not reported in the model. However, the demand of refined oil is expected to drastically decrease towards 2050 according to POTEnCIA results.

Figure 34. *Global CETO 2° C Scenario 2025* projection of annual hydrogen production per technological pathways



Source: Global CETO 2°C Scenario 2025 (POLES-JRC) (2025)

The differences in hydrogen uptake across those two models emerge from their core assumptions. On one hand, the *POTEnCIA CETO 2025 Scenario*, is heavily driven by targets resulting from EU policies as well as from each Member State's NECPs. On the other hand, the *Global CETO 2°C Scenario 2025* is driven by a single global carbon value aiming to limit global warming to 2° C and global economic development. Further information about the models is provided in Annex 3.

4.2. Trade (Import/export) and trade balance[14][15]

There is no available trade data of water electrolysers. For an analysis of the location of manufacturing factories versus companies' headquarters, see **Section 4.1**. The development of CN codes specific to water electrolysis would allow to monitor the trade and supply concentration of such systems.

This chapter provides information on the trade of hydrogen solely. The HS code 280410 (Hydrogen) is used for monitoring hydrogen trade. However, the code does not distinguish between renewable or low carbon hydrogen and hydrogen produced via conventional fossil fuel-based methods, leading to inflated absolute production values. As a result, this code serves only as a proxy for understanding the trade trends.

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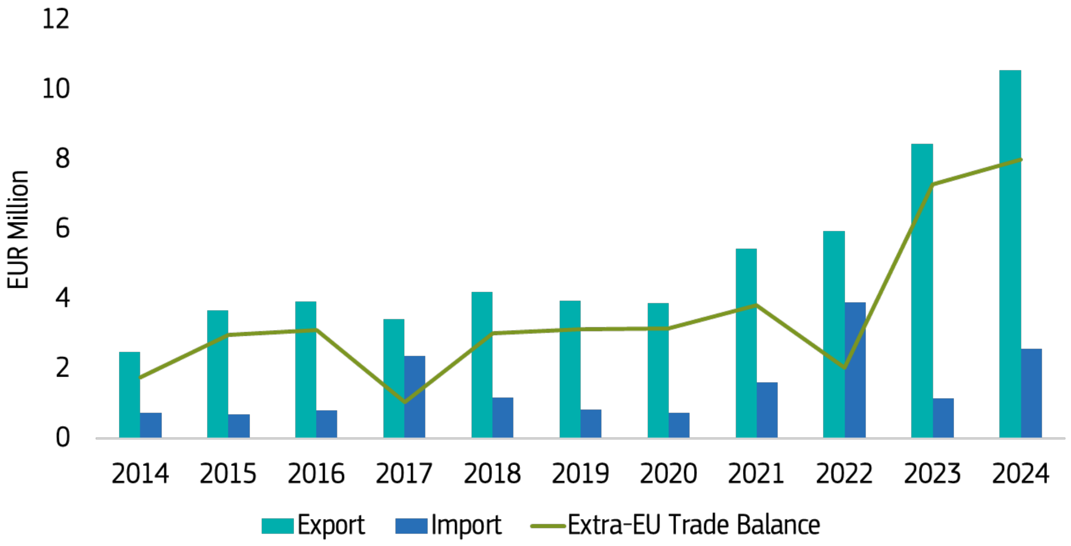
[14] This sub-chapter is authored by Aikaterini.Mountraki@ec.europa.eu as part of the project "Energy Research Innovation and Competitiveness For the Green Transition" (ERIC4GT) within the unit "Energy Transition Insights for Policy" (JRC.C7) to support Clean Energy Technology Observatory (CETO) studies 2025.

Figure 35 illustrates that the EU has maintained a positive trade balance between 2014 and 2024, averaging approximately at EUR 4 million. In 2024, extra-EU exports increased by 25% compared to 2023 to EUR 11 million, while extra-EU imports tripled, reaching EUR 3 million, yielding a trade surplus of EUR 8 million.

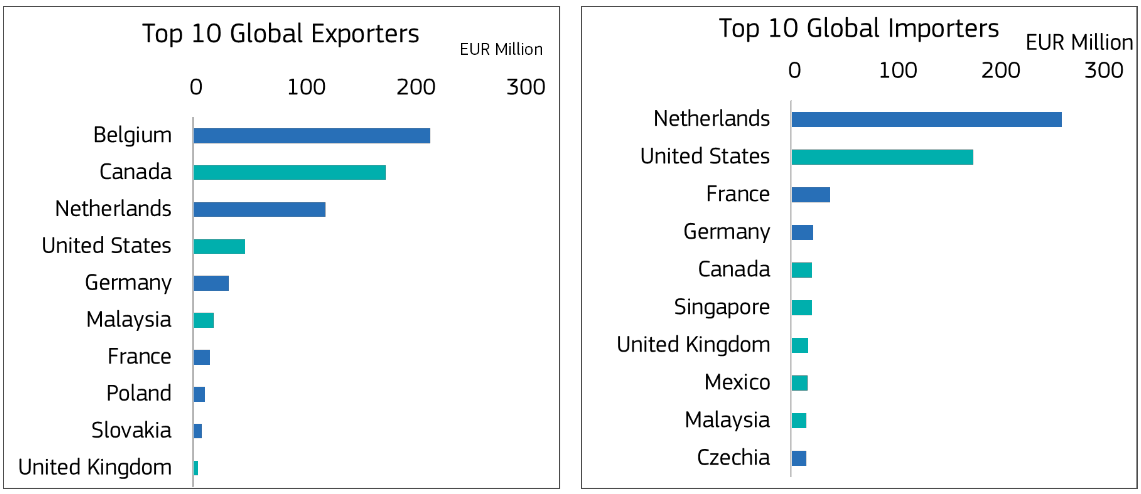
Figure 35. Extra-EU trade in hydrogen for 2014-2024



Source: JRC based on COMEXT data (2025)

Global exports decreased from EUR 200 million in 2023 to EUR 152 million in 2024. EU exports (including intra-EU trade) decreased from EUR 110 million to EUR 64 million. Over 2022–2024, the EU accounted for 62% of global exports (including intra-EU trade), while extra-EU exports (excluding intra-EU trade) represented 8% of global transactions. The EU met 98% of its import needs through intra-EU trade. Belgium was the leading global exporter, accounting for 32% of global exports, followed by Canada (26%%) and Netherlands (18%) (**Figure 36**, left). Netherlands, the US and France were the largest global importers (**Figure 36**, right).

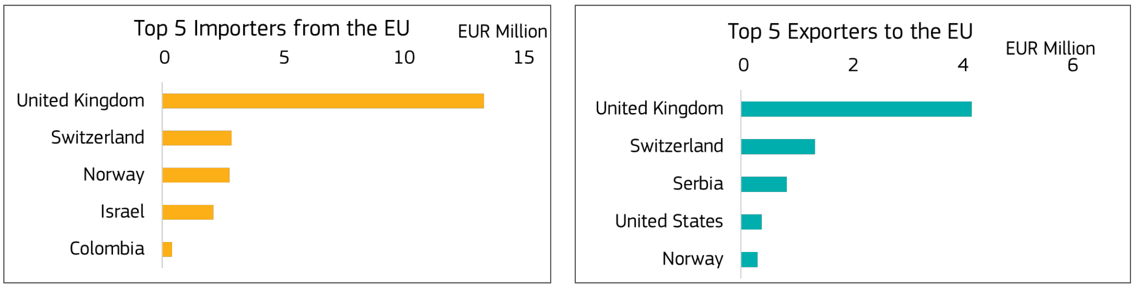
Figure 36. Top ten global hydrogen (left) exporters and (right) importers for 2022-2024



Source: JRC based on COMTRADE data (2025)

During the same period (2022-2024), the UK was the largest importer from the EU, receiving 54% of the extra-EU exports, followed by Switzerland (12%) and Norway (11%). The UK was also the largest exporter to the EU, accounting for 55% of extra-EU imports, followed by Switzerland (18%) and Serbia (11%) (**Figure 37**).

Figure 37. Top five countries (left) importing from and (right) exporting to the EU for 2022-2024



Source: JRC based on COMEXT data (2025)

Table 5 shows the growing markets[16] of hydrogen during 2021-2023[17]. The US had the largest net import increase, followed by Mexico and Malaysia, where the EU captured 0%, 0% and 1% of each country's growing market, respectively. The EU secured the expanding markets in the UK (99%).

Table 5. Growing markets of hydrogen based on a two-year average of net import change

Country	Total import (2021-2023) [EUR Million]	% import from the EU	2-year average of net import change
United States	163	0%	14
Mexico	13	0%	3
Malaysia	12	1%	3
Canada	16	1%	3
United Kingdom	12	99%	1
Indonesia	3	0%	1

Source: JRC based on COMTRADE data (2025)

4.3. Status of net zero technology systems and components in the EU

4.3.1. Relevant final products and primarily used components

The availability of data for primarily used components (PUC) in the context of the Net Zero Industry Act benchmark analysis is uneven. While electrolyser stack manufacturing capacities are tracked by several data providers, data on sub-stack component manufacturing are more limited. Data on components other than electrolyser stacks are not reported in a consistent manner from manufacturers; therefore, it is impossible to trace the flow of components being used for

[16] Calculated as $net\ import\ change = [(import_{2022} - import_{2021}) + (import_{2023} - import_{2022})]/2$

[17] Latest year data (2024) is incomplete for comtrade, because it does not provide estimates for the missing values as comext does.

electrolysers specifically. This is the case for components such as membranes or catalysts which are used in many different applications beyond electrolysers.

Some data points are nonetheless available for a selection of PUCs, notably for the alkaline electrolyser technology, and are listed below. They overall represent conservative estimates since that for most PUC, other factories were identified without manufacturing capacities available to our data providers. Although these numbers are nonetheless used for calculating the NZIA benchmarks, they remain subject to substantial changes as the industry undergoes consolidation.

Table 6 below provides the exhaustive list of PUCs and the number of datapoints available for each component.

Table 6. Count of datapoints per PUC available for the estimation of NZIA benchmarks

Final products	PUC	Total data points on # of identified sites	Total data points on # sites with validated capacities	Sources
Alkaline electrolysers (AEL)	Stacks	33	32	European Hydrogen Observatory, Rystad Energy, Enerdata
Alkaline electrolysers (AEL)	Separators (diaphragm or membranes tailored for water electrolysis)	2	1	Enerdata
Alkaline electrolysers (AEL)	Bipolar plates	1	0	Enerdata
Alkaline electrolysers (AEL)	Electrodes	4	2	Enerdata
Alkaline electrolysers (AEL)	Frames	0	0	Enerdata
Alkaline electrolysers (AEL)	Gaskets / sealants	0	0	Enerdata
Proton exchange membrane electrolysers (PEMEL)	Stacks	31	31	European Hydrogen Observatory, Rystad Energy, Enerdata
Proton exchange membrane electrolysers (PEMEL)	Membrane electrode assemblies (3-layer) / catalyst coated membranes	2	0	Enerdata
Proton exchange membrane electrolysers (PEMEL)	Porous transport layers / gas diffusion layers	1	1	Enerdata
Proton exchange membrane electrolysers (PEMEL)	Bipolar plates	4	0	Enerdata
Proton exchange membrane electrolysers (PEMEL)	Gaskets / sealants	0	0	Enerdata
Anion exchange membrane electrolysers (AEMEL)	Stacks	7	7	European Hydrogen Observatory, Rystad Energy, Enerdata
Anion exchange membrane electrolysers (AEMEL)	Membrane electrode assemblies (3-layer) /	0	0	Enerdata

	catalyst coated membranes			
Anion exchange membrane electrolysers (AEMEL)	Porous transport layers / gas diffusion layers	0	0	Enerdata
Anion exchange membrane electrolysers (AEMEL)	Bipolar plates	0	0	Enerdata
Anion exchange membrane electrolysers (AEMEL)	Gaskets / sealants	0	0	Enerdata
Solid-oxide electrolysers (SOEL)	Stacks	11	11	European Hydrogen Observatory, Rystad Energy, Enerdata
Solid-oxide electrolysers (SOEL)	Electrolytes & electrodes	0	0	Enerdata
Solid-oxide electrolysers (SOEL)	High-temperature gaskets / sealings	0	0	Enerdata
Solid-oxide electrolysers (SOEL)	Interconnectors	0	0	Enerdata
Solid-oxide electrolysers (SOEL)	Meshes	0	0	Enerdata

Note: For the purpose of NZIA benchmarking, only factories in operations or under construction with a commissioning date planned by the end of 2025 are considered.

Source: JRC analysis based on data from Rystad Energy, Enerdata, BloombergNEF (2025)

4.3.2. EU Manufacturing Benchmark

The EU manufacturing benchmark is estimated for several PUCs based on consolidated data from Rystad Energy, BloombergNEF, and Enerdata.

According to the CETO methodology developed for estimating the NZIA benchmark, EU manufacturing capacities are calculated against the annual deployment need capacities derived from the NZIA (Regulation (EU) 2024/1735) and the JRC POTEnCIA model projections. As described in **Section 4.1.2.**, POTEnCIA projects a total electrolysis deployed capacity of 86.1 GW_{el} by 2030, of which 32.4 GW_{el} is alkaline stacks and 53.7 GW_{el} is PEM (SOEC and AEM technologies are not considered in the *POTEnCIA CETO 2025 Scenario* and, thus, are not considered for calculating the benchmark). The annual deployment capacities are then derived based on a linear extrapolation over a five-year period of 2025-2030. All PUCs deployment needs are expressed in final product deployment capacities (GW_{el}/annum).

Table 7. EU manufacturing benchmark for 2030

Final products	PUC	Production Capacity Units	EU Manufacturing Capacity	EU annual Deployment needs 2030	2030 EU Manufacturing Capacity Benchmark [%]	Notes
AEL	Stacks	GW_{el}/annum	3.8	6.5	58%	

AEL	Separators	GW_{el}/annum equivalent	20	6.5	308%	Conservative estimates as two manufacturing sites have been identified but only one with manufacturing capacities.
AEL	Electrodes	GW_{el}/annum equivalent	2.35	6.5	36%	Conservative estimates as four manufacturing sites have been identified but only two with manufacturing capacities.
PEMEL	Stacks	GW_{el}/annum	4.25	10.7	40%	
PEMEL	PTL/GDL	GW_{el}/annum equivalent	1	10.7	9%	

Note: for PUC other than stack, the production capacity is given equivalent to the final electrolysis capacity. It should be recalled that the 2030 and 2040 benchmark exercises both rely on highly uncertain assumptions. These results should be considered as rough estimations of potential bottlenecks, but further monitoring and refinement of the data and models will improve the accuracy of this assessment in subsequent years.

Source: JRC analysis based on data from Rystad Energy, Enerdata, BloombergNEF (2025)

4.3.3. EU share in Global Manufacturing Benchmark

The second overall benchmark is assessed according to the Article 5 of the NZIA (Regulation (EU) 2024/1735). The *Global CETO 2°C Scenario 2025* (POLES-JRC) projects a global electrolyser deployment (PEM and alkaline) of approximately 60 GW_{el}/annum by 2040. Notably, this global figure is at the same level as the projected electrolyser deployment for the EU alone, which is also estimated to be around 28.5 GWel/annum according to POTEnCIA[18]. The discrepancies between these model projections are briefly described in Section 4.1.2 but a detailed analysis is out of the scope of this report. The NZIA regulation stipulates that the 2040 EU Production Capacity Benchmark should be the minimum of either 15% of global deployment needs by 2040 (9.1 GW_{el} from POLES-JRC projections) or the EU deployment needs by 2040 (28.5 GW_{el} from POTEnCIA). Therefore, the 2040 manufacturing target is set at 9.1 GW_{el}/annum for our assessment as described in **Table 8**.

Table 8. EU manufacturing benchmark for 2040

Final products	**PUC**	**Production Capacity Units**	**EU Manufacturing Capacity**	**Production Target 2040**	**2040 EU Production Capacity Benchmark, %**
Low-temperature electrolysers	AEL/PEM stacks	GWel/annum	8.1	9.1	89%

[18] Considering a linear extrapolation over 15-years to reach the 427 GW_{el} capacity projected in the POTEnCIA model.

(AEL/PEM combined)					

Note: the POLES-JRC model refers to a generic electrolyser technology, making it difficult to estimate the benchmark for PEM or alkaline technology similarly to the first benchmark as well as the related sub-stack components. It should be recalled that the 2030 and 2040 benchmark exercises both rely on highly uncertain assumptions. These results should be considered as rough estimations of potential bottlenecks, but further monitoring and refinement of the data and models could improve the accuracy of this assessment in subsequent years.

Source: Joint Research Centre analysis (2025)

4.4. Resource efficiency and dependence in relation to EU competitiveness

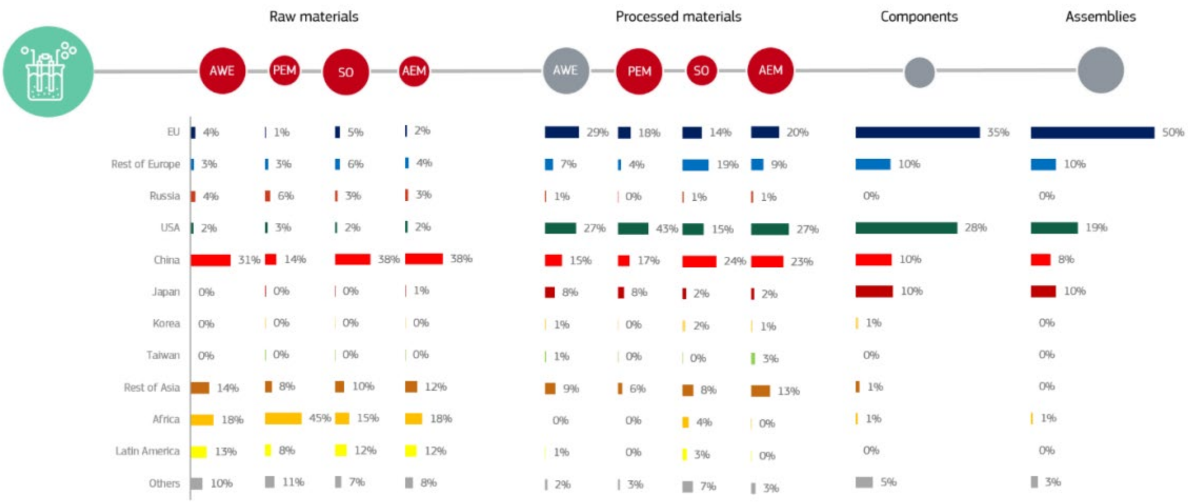
More than 40 raw materials and 60 processed materials are required in electrolyser production. Major suppliers of raw materials for electrolysers are China (37%), South Africa (11%) and Russia (7%). The EU share is only 2%[19]. As can be seen from **Figure 38**, Europe is strongly dependent on raw materials, with its global share growing progressively for processed materials and components and reaching a majority fraction for electrolysers (European Commission. Joint Research Centre., 2023c).

Nickel, manganese, chromium and iron are common materials for all electrolysers. Aluminium, cobalt, copper, lanthanum, molybdenum, natural graphite and zirconium are also used, but to a lesser extent. Other key materials which are more specific for some electrolyser technologies can also be identified, such as PGMs for PEM electrolysis and rare earths for SOE.

For instance, the corrosive acidic regime employed by the PEM electrolyser requires the use of precious metal catalysts like iridium for the anode and platinum for the cathode, both of which are mainly sourced from South Africa (which according to Raw Materials Dashboard has 94% of the global production of primary iridium), followed by Russia and Zimbabwe. Iridium supply is a significant bottleneck for deployment of this technology at large scale, if the current catalyst loading and lack of recycling options are going to remain unchanged (Clapp, Zalitis and Ryan, 2023; Minke, Suermann, Bensmann et al., 2021). Rare earths, which are critical for manufacturing oxide conducting electrolytes for SOEC and are also used in PCC, are mainly supplied by China.

[19] JRC analysis for DG GROW.

Figure 38. Supply chain for electrolysers



Source: JRC, Foresight study 2023 (European Commission. Joint Research Centre., 2023c).

Notes: The colour shows whether the step should be considered as critical (red) or non-critical (grey). One step is considered critical if at least 30% of its elements are critical, or if at least 20% of its elements are critical and at least one of them shows a very high level of criticality. The size of the bubble is a proxy of the complexity of the supply chain step. Bubbles can be small, medium, or large, depending on the number of elements appearing in the supply chain step. Shares for raw materials, processed materials, components and electrolyser stacks (Alkaline Electrolysers, Proton Exchange Membrane (PEM) Electrolysers, Anion Exchange Membrane (AEM) Electrolyser and Solid Oxide (SO) Electrolysers are considered together). Electrolysers and components are counted as a share in the number of manufacturers headquartered in a geographical location.

For renewable hydrogen production, electrolysers will need to use electricity from renewable energy sources such as wind, solar power, hydropower and other renewable sources. This adds pressure on the availability of materials required for these technologies, as well as other limitations, such as high land usage requirements. If several tenths of GW of electrolysers are to be installed in the EU by 2030 and fed by renewable electricity coming predominantly from wind and solar energy sources, dependency on critical raw materials required for these two technologies should be carefully analysed.

Recycling potential will only be available in a time-horizon compatible with the lifetime of the electrolysers being deployed. Recycling will be particularly relevant for Platinum Group Metals (PGMs) used in electrolysers such as iridium and platinum; reduction of PGM loadings is also necessary to achieve global scale deployment compatible with the expected scenarios (Clapp, Zalitis and Ryan, 2023).

Nevertheless, recycling infrastructure for the collection, dismantling and processing of the relevant products, components and materials needs to be put in place in good time to harvest the highest possible benefit from recycling activities. R&D should be supported to develop innovative recycling methods offering high yield-rates and high-quality secondary materials. The fast uptake of electric vehicles in Europe is phasing out conventional vehicles (with internal combustion engine) to cut CO_2 emissions by 2035. Platinum used in auto catalysts could therefore be an interesting source of secondary raw materials for electrolyser manufacturing as early as 2030 (European Commission. Joint Research Centre., 2023b). Indeed, closed loop recycling of spent autocatalysts to recover materials such as Platinum is a well-established practice, and these flows could be channelled to the electrolyser industry. On the other hand, platinum's availability for recycling from domestic end-of-life vehicles are predicted to gradually decline (European Commission. Joint Research Centre., 2023b). To be able to confirm the secondary raw materials potential, the EU will need to develop recycling infrastructure for Platinum and Iridium catalysts, develop and maintain data on secondary raw materials relevant for electrolysers, and check material stocks and flows as well as competition between sectors.

5. Conclusions

The European water electrolyser industry is at a critical juncture, transitioning from research and demonstration to industrial-scale deployment. The sector deployment is supported by a comprehensive policy framework at the EU level, designed to stimulate a complete value chain, from manufacturing to end-use. This has fostered a growing innovation ecosystem where the EU continues to lead in patents. The recent commissioning of projects in the 50 MW-plus range, supplied by European manufacturers, marks a significant milestone, demonstrating the technological maturity and growing industrial know-how within the Union.

Despite this progress, the pace of deployment is not yet aligned with the EU's ambitious targets. A persistent gap between the large pipeline of announced projects and final investment decisions creates uncertainty and hinders the ability of manufacturers to achieve economies of scale, keeping costs high. Capital expenditure for new projects in Europe has proven to be higher than anticipated, reflecting the real-world complexities of deploying first-of-a-kind industrial installations.

Globally, the EU stands as a leader alongside China. However, it faces intense competition from state-supported international players who can often offer lower-cost systems. Furthermore, the EU's manufacturing ambitions are exposed to significant supply chain vulnerabilities, particularly its high dependency on imported critical raw materials like platinum group metals.

Sustained and targeted public support through instruments like the Innovation Fund and the European Hydrogen Bank remains essential to de-risk pioneering projects and close the viability gap. To secure its strategic objectives, the EU must focus on accelerating permitting, ensuring the swift and harmonised implementation of demand-side regulations across Member States, and fostering strategic partnerships to diversify its raw material supply chains.

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List of abbreviations and definitions

Abbreviations	Definitions
AEM, AEMEL	Anion Exchange Membrane electrolyser
CAPEX	Capital Expenditures
CHJU	Clean Hydrogen Joint Undertaking
CH	Switzerland
EC	European Commission
EPO	European Patent Office
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
IEA	International Energy Agency
ETS	Emission Trading System
IPCEI	Important Project of Common European Interest
IRENA	International Renewable Energy Agency
LHV	Lower Heating Value
NG	Natural gas
NO	Norway
O&M	Operation and Maintenance
OEM	Original Equipment Manufacturer
OPEX	Operational expenses
PCC	Proton Conducting Ceramic
PCE	Proton Conducting Electrolyser
PCI	Project of Common Interest
PEM	Proton Exchange Membrane

Abbreviations	Definitions
PGM	Platinum Group Metal
RES	Renewable Energy Source
SOEL	Solid Oxide Electrolyser
TRL	Technology Readiness Level
UK	United Kingdom
USA	United States of America
VC	Venture Capital

List of figures

List of tables

Annexes

Annex 1 Sustainability assessment framework

Sustainability aspect	Method/approach	Indicators	Technology assessment
Market trend	No specific guidance is available in the context of sustainability assessment. Assessment based on energy statistics and literature review for insights on forecasts.	Evolution of demand for a certain technology over time	
Trade and trade balance	No specific guidance is available in the context of sustainability assessment. Assessment based on energy statistics and literature review for insights on forecasts.	EU share in global export Extra EU trade balance	
Cost of energy	No specific guidance is available in the context of sustainability assessment. Assessment based on energy statistics and literature review for insights on forecasts.	For power generation technologies: Levelized Cost Of Electricity (LCOE) For storage technologies: Levelized Cost of Storage (LCOS) For heating technologies: Levelized Cost of Heating (LCOH)	
Critical Raw Materials (CRMs)	The periodical EC list of CRMs should be use as a reference to describe the potential supply chain bottlenecks.		
Technology-specific permitting requirements	These requirements are based on RED II, EIA, Water Framework, Alternative Fuels Infrastructure, Mining Waste, Geological Storage of Carbon Dioxide and Industrial Emissions Directives. Assessment is based on current legislation about critical points for small and large projects, either commercial or residential	Some general examples: Transportation infrastructure Visual impact Reservoir management (Hydropower) Navigation and Shipping Corrosion and Biofouling Risk of fire Fuel Source Leakage risk (CCUS)	
Skills and technology development	**Skill development** concerns four categories: 1. Skills gap, the distance between the skill level in society and the skills required for the technology development and deployment; 2. Skill obsolescence, the loss of skills due to the lack of use, or the risk the skills become irrelevant;		

	3. Skill shortages, when there are jobs, but no qualified staff in the community; 4. Over and under skilling, when people have skills above or below the requirements. **Technology transfer and development** is the process for converting research into economic development, or for using technology, expertise or know-how for a purpose not originally intended by the developing organization. It is fundamental for the improvement of social conditions and to prevent further environmental damage related to old technology use.		
Resilience		Energy production redundance	
Resource efficiency and recycling		Minimum recycle efficiency Recycling increase growth	
Energy balance	Quantitative indicators	Energy Pay Back Time (EPBT) Energy Return on Energy Invested (EROI)	
Climate change	LCA / Product Environmental Footprint (PEF)	Global warming potential (GWP100)	
Ozone depletion			
Particulate matter/Respiratory inorganics			
Ionising radiation, human health			
Photochemical ozone formation			
Acidification			
Eutrophication, terrestrial			
Eutrophication, aquatic freshwater			
Eutrophication, aquatic marine			
Land use	LCA / Product Environmental Footprint (PEF)	Units (km^2/TWh)	
Water use	LCA / Product Environmental Footprint (PEF)	Units (m^3/kWh)	
Resource use, minerals and metals			

Resource use, energy carriers			
Biodiversity			
Child labour			
Forced labour			
Equal opportunities/discrimination	Social Life Cycle Impact Assessment (Type I).	Gender wage gap (%) – EU/country level Women in the labour force (ratio) – country/sector level	Gender gap exhibit 14 10.2777/8283
Freedom of association and collective bargaining			
Working hours			
Fair salary			
Health and safety		Global deaths per terawatt https://ourworldindata.org/safest-sources-of-energy	
Responsible material sourcing			
Competition for material resources, (incl. Water, land, food) and indigenous right	Literature review about the outcomes between the energy projects deployment and the effects in endangered communities	Additional investment cost linked to environmental and social risk mitigation (https://media.odi.org/documents/ODI_RE2.PDF)	
Contribution to economic development (including employment)			
Affordable energy access			
Public acceptance			
Rural development			

Annex 2 Geographical classification

This annex details the regional classification used for plotting the graphs.

Table 9. Regional classification for **Figure 32**

Factory region	**Factory country**
East Asia	China
	Japan
	South Korea
EU27 + EFTA + UK	Belgium
	Denmark
	Estonia
	France
	Germany
	Greece
	Ireland
	Italy
	Netherlands
	Norway
	Portugal
	Spain
	Sweden
	United Kingdom
Middle East	UAE
North Africa	Egypt
	Morocco
North America	Canada
	United States
Oceania	Australia
	New Zealand
South America	Brazil
South Asia	India
South East Asia	Singapore

Annex 3 Energy System Models and Scenarios: POTEnCIA and POLES-JRC

Annex 3.1 The POTEnCIA model

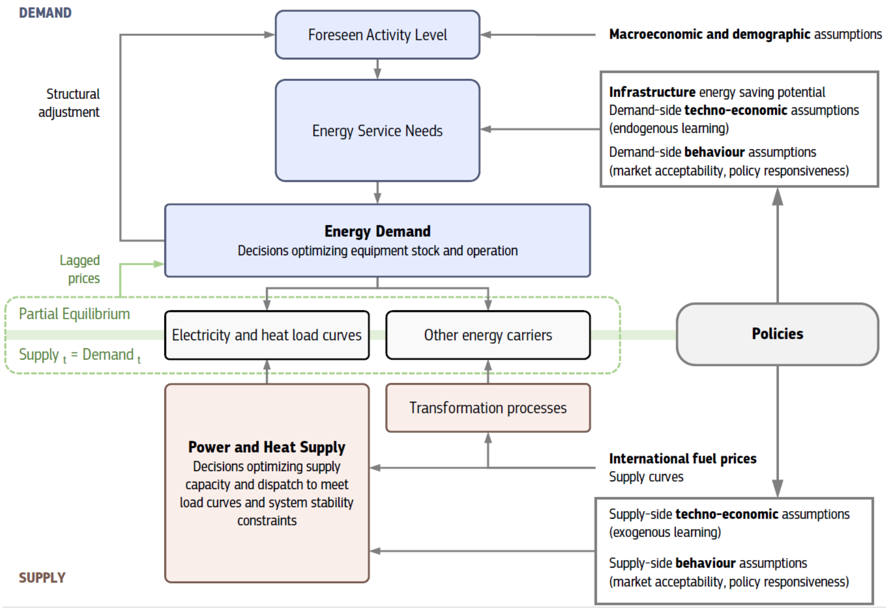
AN 3.1.1 Model Overview

The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed in-house by the European Commission's Joint Research Centre (JRC) to support EU policy analysis, POTEnCIA allows for the joint evaluation of technology-focused policies, combined with policies addressing the decision-making of energy users. To this end:

- By simulating decision-making under imperfect foresight at a high level of techno-economic detail, POTEnCIA realistically captures the adoption and operation of new energy technologies under different policy regimes;
- By combining yearly time steps for demand-side planning and investment with hourly resolution for the power sector, POTEnCIA provides high temporal detail to suitably assess rapid structural changes in the EU's energy system;
- By tracking yearly capital stock vintages for energy supply and demand, POTEnCIA accurately represents the age and performance of installed energy equipment, and enables the assessment of path dependencies, retrofitting or retirement strategies, and stranded asset risks.

The core modelling approach of POTEnCIA (**Figure 39**; detailed in (Mantzos, Matei, Rózsai et al., 2017; Mantzos, Wiesenthal, Neuwahl et al., 2019)) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method. As such, for each sector of energy supply and demand, this approach assumes a representative agent seeking to maximize its benefit or minimize its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies.

Figure 39. The POTEnCIA model at a glance



Source: JRC adapted from ((Mantzos, Wiesenthal, Neuwahl et al., 2019))

This modelling approach is implemented individually for each EU Member State to capture differences in macroeconomic and energy system structures, technology assumptions, and resource constraints. The national model implementation is supported by spatially-explicit analyses to realistically define renewable energy potentials and infrastructure costs for hydrogen and CO_2 transport. Typical model output is provided in annual time steps over a horizon of 2000-2070; historical data (2000-2021) are calibrated to Eurostat and other official EU statistics to provide accurate initial conditions, using an updated version of the JRC Integrated Database of the European Energy System (European Commission. Joint Research Centre., 2024b).

Annex 3.1.2 POTEnCIA CETO 2025 Scenario

The technology projections provided in the *POTEnCIA CETO 2025 Scenario* are obtained under a climate neutrality scenario aligned with the broad GHG reduction objectives of the European Green Deal. As such, this scenario reduces net EU GHG emissions by 55% by 2030 and 90% by 2040, both compared to 1990, and reaches net zero EU emissions by 2050. To model suitably the uptake of different technologies under this decarbonisation trajectory, the scenario includes a representation at EU level of general climate and energy policies such as emissions pricing under the Emissions Trading System, as well as key policy instruments that have a crucial impact on the uptake of specific technologies. For instance, the 2030 energy consumption and renewable energy shares reflect the targets of the EU's Renewable Energy Directive and of the Energy Efficiency Directive. Similarly, the adoption of alternative powertrains and fuels in transport is consistent with the updated CO_2 emission standards in road transport and with the targets of the ReFuelEU Aviation and FuelEU Maritime regulations.

Compared to the *POTEnCIA CETO 2024 Scenario* ((Neuwahl, Wegener, Mortiz, Jaxa-Rozen, M et al., 2024)), the *POTEnCIA CETO 2025 Scenario* incorporates many model enhancements and scenario-specific data updates, most notably:

— The usage of the more recent JRC-IDEES 2023 data ((Rozsai, Jaxa-Rozen, M, Salvucci, R et al., Forthcoming))

— Closer alignment to the National Energy and Climate Plans (NECPs) of the individual MS, which have been published in recent months

A more detailed description of the *POTEnCIA CETO 2025 Scenario* will be available in the forthcoming report ((Neuwahl, Wegener, Mortiz, Jaxa-Rozen, M et al., Forthcoming)).

Annex 3.2 POLES-JRC model

AN 3.2.1 Model Overview

POLES-JRC (Prospective Outlook for the Long-term Energy System) is a global energy model well suited to evaluate the evolution of energy demand and supply in the main world economies with a representation of international energy markets. It is a simulation model that follows a recursive dynamic partial equilibrium method. POLES-JRC is hosted at the JRC and was designed to assess global and national climate and energy policies.

POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables) to transformation (power, biofuels, hydrogen and hydrogen-derived fuels such as e-fuels and ammonia) and final consumption sectoral demand (industry, buildings, transport) (see

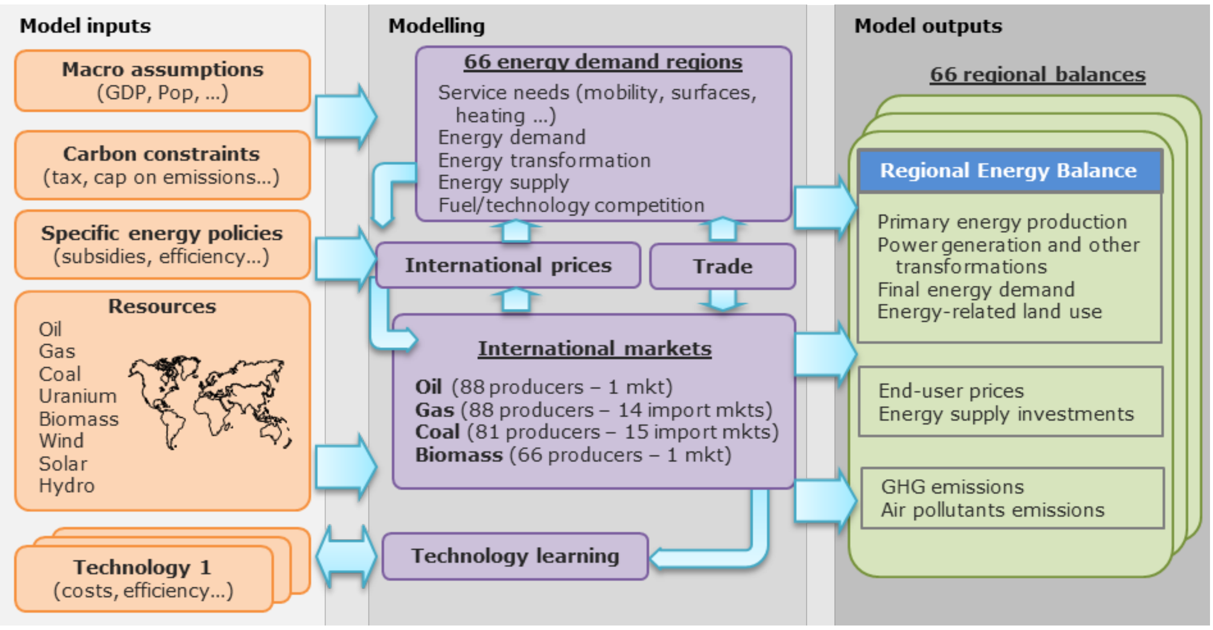
Figure 40). International markets and prices of energy fuels are calculated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global frame: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2100 and is updated yearly with recent information.

The POLES-JRC model comprises a comprehensive portfolio of technologies and dynamic interaction between technologies and across sectors. Therefore, POLES-JRC is well suited to describe technology evolutions for a technology focused project such as CETO.

POLES-JRC results are published within the annual report "Global Climate and Energy Outlooks" (GECO). The GECO reports along with detailed country energy and GHG balances and an on-line visualisation interface can be found at: https://joint-research-centre.ec.europa.eu/scientific-activities-z/geco_en

Detailed documentation of the POLES-JRC model is provided in (Despres, Keramidas, Schmitz et al., 2018). The techno-economic assumptions used in the current version of the model are provided in (Schmitz et al, 2025). The latter report provides also a comprehensive overview of the evolution and interaction of various groups of clean energy technologies until the end of the century.

Figure 40. Schematic representation of the POLES-JRC model architecture.



Source: POLES-JRC model (2025)

AN 3.2.2 POLES-JRC Model description

Power system

The power system considers all relevant power generating technologies including fossil, nuclear and renewable power technologies. Each technology is modelled based on its current capacities and techno-economic characteristics. The evolution of cost and efficiencies are modelled through technology learning.

With regard to the power technologies covered by CETO, the model includes solar power (utility-scale and residential PV, concentrated solar power), wind power (on-shore and off-shore), hydropower and ocean power. Moreover, clean thermal power technologies are taken into account with steam turbines fuelled by biomass, biomass gasification, CCS power technologies and geothermal power. Furthermore, electricity storage technologies such as pumped hydropower storage and batteries are also included.

For solar and wind power, variable generation is considered with hourly profiles. For all renewables, regional resource potentials are considered.

Electricity demand
Electricity demand is calculated for all sectors taking into account hourly demand fluctuations. Clean energy technologies using electricity include heat pumps (heating and cooling), electric vehicles, electrolysers, and direct air capture.

Power system operation and planning
Power system operation allocates generation by technology each hour, ensuring that supply and storage technologies meet overall demand, including grid imports and exports. Capacity planning considers the existing power mix, the expected evolution of electricity demand as well as the techno-economic characteristics of the power technologies.

Hydrogen

POLES-JRC takes into account several hydrogen production routes: (i) low temperature electrolysers using power from dedicated solar, wind and nuclear plants as well as from the grid, (ii) steam reforming of natural gas (with and without CCS), (iii) gasification of coal and biomass (with and without CCS), (iv) pyrolysis of gas and biomass as well as (v) high temperature electrolysis using nuclear power.

Hydrogen is used as fuel in all sectors including industry, transport, power generation and as well as feedstock for the production of synfuels (gaseous and liquid synfuels) and ammonia. Moreover, hydrogen trade is modelled, considering hydrogen transport with various means (pipeline, ship, truck) and forms (pressurised, liquid, converted into ammonia) (Schade, Keramidas, Schmitz et al., 2025).

Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM-G4M model (IIASA, 2024). This approach allows to model bioenergy demand and supply by taking into account biomass-for-energy potential, production costs and reactivity to carbon pricing.

Biomass is used for power generation, hydrogen production and for the production of 1st and 2nd generation of liquid biofuels.

Carbon Capture Utilization and Storage (CCUS)

POLES-JRC uses CCUS technologies in:

- Power generation: advanced coal using CCS, coal and biomass gasification with CCS, and gas combined cycle with CCS.
- Hydrogen production: Steam reforming with CCS, coal and biomass gasification with CCS, and gas and biomass pyrolysis.
- Direct air capture (DAC) where the CO_2 is either stored or used for the production of synfuels (gaseous or liquid).
- Steel and cement production in the industrial sector.
- Second generation biofuels production.

The deployment of CCS technologies considers region-specific geological storage potentials.

Endogenous technology learning

Endogenous technology learning is a key feature of the POLES-JRC model, which describes the evolution of technology costs using a one-factor learning-by-doing approach. This approach is applied to all technologies in the comprehensive portfolio, modeling overnight investment costs, operation and maintenance costs, and efficiencies with technology-specific learning rates.

Notably, the model uses a component-based learning-by-doing approach to capture spillover effects across technologies and sectors. For example, components of CCS technologies are used in power generation, hydrogen production, and DAC, while battery learning effects can be modeled across transport and power sectors. This approach also enables estimating cost evolutions for emerging technologies with limited historical data. Moreover, floor costs for each component set a minimum investment cost, limiting cost reductions through endogenous learning. As investment costs approach these floor costs, learning-driven cost reductions slow down. The POLES-JRC model's technology learning dynamics are further described in (Schmitz et al., 2025).

AN 3.2.3 Global CETO 2°C Scenario 2025

Scenario Description

The global scenario data presented in the CETO technology reports 2025 refers to a 2°C scenario modelled by the POLES-JRC model in a modified and enhanced version to address the specific issues relevant for the CETO project.

The *Global CETO 2°C scenario 2025* is designed to limit global temperature increase to 2°C at the end of the century. It is driven by a single global carbon price for all regions that reduces emissions sufficiently so as to limit global warming to 2°C. This scenario is therefore a stylised representation of a pathway to the temperature targets. This scenario does not consider financial transfers between countries to implement mitigation measures. This is a simplified representation of an ideal case where strong international cooperation results in concerted effort to reduce emissions globally; it is not meant to replicate the result of announced targets and pledges, which differ greatly in ambition across countries.

As a starting point, for all regions, it considers already legislated energy and climate policies (as of June 2024), but climate policy pledges and targets formulated in Nationally Determined Contributions (NDCs) and Long-Term Strategies (LTSs) are not explicitly taken into account. In particular, the EU Fit for 55 and RePowerEU packages are included in the policy setup for the EU. Announced emissions targets for 2040 and 2050 for the EU are not considered.

Model Enhancements

The *Global CETO 2°C scenario 2025 builds on the POLES version of GECO 2024* (European Commission. Joint Research Centre., 2025). Additionally, to the GECO 2024 model version following enhancements have been implemented:

- Electrolyser's overnight investment costs have been increased substantially reflecting recent cost revisions as provided in (TNO, 2024), (U.S. Department of Energy, 2024) and (European Hydrogen Observatory, 2025b).
- Cost optimisation for producing hydrogen by PV and wind powered electrolysers has been implemented. The optimisation considers an over-sizing of PV and wind capacities relative to the electrolyser's capacity. As a result, lower cost hydrogen production can be achieved as full load hours of the electrolyser operation increase. Moreover, the optimisation considers the potential to add batteries to balance intermittent PV and wind power generation.
- Updated investment costs for renewable power generating technologies and utility battery costs according to (IRENA, 2025).
- Updated installed capacities for power generating technologies.
- Revised global wind profiles (off-shore and on-shore).
- Recent data on new vehicles and vehicle stock by transport mode (battery and fuel cell vehicles, ICE, hybrid) and vehicle type (passenger cars, light and heavy trucks, buses)(Acea, 2025) (Acea, 2025), (IEA, 2025b).
- Update of hydrogen infrastructure cost related to passenger and freight transport on road.

Annex 3.3 Distinctions for the CETO 2025 Scenarios - POLES-JRC vs. POTEnCIA

The results of both models are driven by national as well as international techno-economic assumptions, fuel costs, as well as policy incentives such as carbon prices. However, on one side these two JRC energy system models differ in scope and level of detail, on the other side the definitions of the POTEnCIA and POLES-JRC scenarios presented in this document follow distinct logics, leading to different scenario results:

- The *Global CETO 2°C scenario 2025* (POLES-JRC) scenario is driven by a global carbon price trajectory to limit global warming to 2°C, where enacted climate policies are modelled, but long-term climate policy pledges and targets are not explicitly considered. Scenario results are presented for the global total until 2050.
- The *POTEnCIA CETO 2025 scenario* is a decarbonisation scenario that follows a trajectory for EU27's net GHG emissions aligned with the general objectives of the European Climate Law (ECL) taking into consideration many sector-specific pieces of legislation and national energy and climate plans (NECPs). Scenario results are presented for the EU27 until 2050

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