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Water electrolysis and hydrogen in the European Union

STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS & MARKETS

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Contents

Abstract

This report is an output of the Clean Energy Technology Observatory (CETO) and is an update of the "Water electrolysis and hydrogen in the European Union" 2023 CETO report. CETO's objective is to provide an evidence-based analysis feeding the policy making process and hence increasing the effectiveness of R&I policies for clean energy technologies and solutions. It monitors EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal; and assesses the competitiveness of the EU clean energy sector and its positioning in the global energy market.

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-faced 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

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Executive Summary

Hydrogen is both *an energy carrier* able to produce other fuels and downstream products, such as the electricity-based fuels and their derivatives (e-fuels or e-ammonia), and it can be *a decarbonised gas produced through renewable electricity*[1]. It has the potential to decarbonise hard to abate sectors which are difficult to directly electrify and play a crucial role in achieving the net zero emissions target in 2050.

The European Commission has outlined the policy context and key actions for the development and the deployment of renewable hydrogen[2] within the 2030 time horizon with the Hydrogen Strategy for a Climate Neutral Europe Communication[3] (the Hydrogen Strategy). The REPowerEU Communication[4] reiterates the objectives of a yearly production of up to 10 million tonnes and envisages the same quantity as imports by 2030. The revised Renewable Energy Directive refers to the final consumption targets for the Renewable Fuels of Non Biological Origin (RFNBOs) of 1% in transport and 42% in industry by 2030. The Green Deal Industrial Plan classifies water electrolysers and fuel cell technologies as one of strategic decarbonisation technologies able to achieve European climate ambition. The associated Net Zero Industry Act[5] advocates for faster permitting procedures and quicker access to funding, while reducing EU dependency for the supply of Critical Raw Materials through the Critical Raw Materials Act[6].

European financing mechanisms are in place both at EU and Member state level. The 3rd Important Projects of Common European Interests project (IPCEI) on hydrogen infrastructure and the 4th IPCEI supporting the development of the hydrogen and fuel cells-based mobility were approved in 2024. This brings the total of state aid support through the 4 IPCEIs scheme to EUR 18.9 billion of public funding, channelling an expected EUR 15.7 billion of private investment. Innovation Funds projects are planning to install approximately 4 270 MWe of electrolysis capacities with a total public support of EUR 2.27 billion. The first auction of European Hydrogen Bank successfully awarded 7 projects in 2024, matching long-term offtake agreements between producers and buyers with a first auction of EUR 720 million for the production of 1.58 million tonnes over 10 years. A second auction of EUR 1.2 billion is planned for the end of 2024. With the Clean Hydrogen Joint Undertaking, the EU has made available more than EUR 213 million for research activities on electrolyser technologies, deploying an additional 40 MWe of electrolysis capacity specifically for joint public-private R&D activities.

With regards to technology aspects, water electrolysis remains the most mature and promising technology for producing renewable hydrogen from non-carbon sources. Five main electrolysers technologies are identified[7]: alkaline electrolysis, Polymer Exchange Membrane (PEM) electrolysis, Solid Oxide (SOEC) electrolysis, Anion Exchange Membrane (AEM) electrolysis, and Proton Conducting Ceramic (PCC) electrolysis. Alkaline and PEM are the most mature and well-established technologies, with SOEC and AEM slowly emerging and PCC at a much earlier development stage. SOEC and PCC electrolysis work at higher temperature, can recover high grade waste heat from other industrial processes and intrinsically operate at higher electrical efficiencies.

In 2021, European (EU+UK, NO, CH) hydrogen production capacity was around 11.4 Mt per year[8] [1]. Water electrolysis accounted for about 0.3% of this total. According to estimates from several analysts, the total installed power-to-hydrogen capacity in the EU, EFTA and UK grew from 85 MWe in 2019, to approximately 228 MWe in August 2023. By the end of 2024, short-term estimates point to an installed capacity reaching between 500 MWe and 812 MWe[9]. By the end of 2025, between 950 MWe and 3.4 GWe are planned to enter in operation in Europe. The largest project in operation has a nominal electrolysis capacity of 24 MWe (Yara,

[1] Renewable hydrogen can also be derived from low carbon biomass sources meeting a 70% CO_2 reduction target as defined by the European Taxonomy. This is however not relevant for the current report on electrolysis and in the following report 'renewable hydrogen' will refer to hydrogen produced by electrolysis powered by renewable electricity.

[2] Renewable hydrogen, as defined in the Hydrogen Strategy, is hydrogen produced through the electrolysis of water (in an electrolyser, powered by electricity), and with the electricity stemming from renewable sources.

[3] A hydrogen strategy for a climate-neutral Europe, COM(2020) 301 final.

[4] REPOWEREU Plan - COM(2022) 230 final.

[5] Proposal for a Regulation of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act) (COM(2023) 161 final)

[6] Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020 (2023/0079(COD))

[7] Historical Analysis of FCH 2 JU Electrolyser Projects, JRC (European Commission) Technical Report, 2021.

[8] This excludes the hydrogen contained in Coke Oven Gas (COG). If this is accounted for, the European production capacity reaches 12.2 MtH_2 per year.

[9] [1], [2]If projects currently under construction respect the planned commissioning date.

Norway), spearheading the up-scaling of electrolysis systems and the direct integration into industrial processes.

Estimates of global installed electrolysers' capacity stand in the range of 1.4-1.7 GWe at the end of 2023, up from 600 - 700 MWe in 2022. According to analysts, up to 5 GWe of electrolysis capacity should enter operations by the end of 2024, and between 10.9 and 17.8 GWe at the end of 2025[10]. China is now the geographical area where most of the growth in electrolysis deployment is expected to happen. Estimations of installed electrolysis capacity in China in end 2023 are in the range of 718 – 1056 MWe, expected to reach 3.3 – 3.6 GWe by the end of 2024. In the U.S., updated estimations point to an installed capacity of reaching between 176 and 300 MWe by the end of 2024, up from approximately 80 MWe at the end of 2023, and 19 MWe in 2022. Global acceleration in electrolyser deployment would increase significantly from 2030 if project announcements are followed through and respect the announced timelines.

By the end of 2024, the global estimated stack assembling capacity is projected to reach 40 - 54 GWe/year based on analysts' estimates (up from around 25 GWe/year in 2023 and 13-14 GWe/year in 2022). Based on the manufacturers' headquarters locations, Europe represents at least 25 % of this market share, with estimates of manufacturing capacity reaching the range of 7 – 15.7 GWe/year by the end of 2024, a significant increase from the 3.9 GWe/year capacity estimated in September 2023. According to data collected following manufacturers' announcements -implying a high degree of uncertainty- this share could fall to 20 % by 2030.

China is the region with the largest manufacturing capacity with at least 20 GWe/year planned to enter in operation by the end of 2024 based on OEMs' headquarters locations, and focussing almost exclusively on alkaline technology (16.4 GWe/year by the end of 2024). The U.S. has a manufacturing capacity close to the European one with approximately 11.2 GWe/year posed to be commissioned in the end of 2024, with a focus on PEM electrolysis (8.2 GWe/year)[11]. However, these values refer mostly to the OEMs' headquarter locations, that can be distinct from the actual locations of the factories outside Europe.

Despite a promising pipeline of announced projects in Europe, only a fraction of these have reached an advanced stage and have a secured deployment timeline ahead (60% for projects starting in 2025, 48% for 2026). Securing offtakers and having a well-defined business case appears to be one of the main obstacles of new projects. In other geographical areas, such as Asia, demand for large scale electrolysers' deployment appears to be granted by a strong intervention of public resources.

Regarding the cost of hydrogen, the two most impacting factors on the Levelised Cost of Hydrogen (LCoH) are (1) the electrolysis system cost and (2) the price of the consumed electricity. Their respective final share in the LCoH varies accordingly to the utilisation factor of the electrolyser. For lower rates (below 25-30%), the Capital Expenditure (CAPEX) contributes the most to the final price of hydrogen. 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.

The cost of 1 kg of hydrogen produced in the EU through steam methane reforming (SMR) in 2022 averaged 5.7 EUR/kgH2 (up from 2.65 EUR/kgH_2 in 2021). According to estimates for 2022 from Hydrogen Europe, the European hydrogen production costs using directly renewable sources and in the best locations can be as low as 4.4 EUR/kgH_2 for southern European countries using solar PVs and 3.1 EUR/kgH_2 in case of generation capacity using wind in northern European countries. The European average is around 7 EUR/kgH_2. An overall increase in costs estimates from previous years has been driven up by higher inflation and higher costs of capital. The LCOH is confirmed to experience significant variations depending on the project designs, locations and operation conditions.

Although expected to decrease over the years, the latest available data and analysis are showing that the cost of developing and installing electrolysis projects in Europe is higher than anticipated. This is the case for both PEM and alkaline technologies and according to several institutions, this trend upwards is due to (1) the under-appreciation of related costs for the deployment of large-scale systems (such as permitting, power grid connections), an overestimation of the stack cost reduction which has not yet materialised, and inflation. A recent 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/kWe to 2 630 EUR/kWe for 100-MWe and 200-MWe full projects respectively [3].

[10] If projects currently under construction respect the planned commissioning date.

[11] Based on data collected in June 2024. Delays might differ the commissioning date of an unknown share of manufacturing capacities.

Concerning patenting trends, the ones highlighted in previous years are still valid and have been confirmed once again by the 2023 Edition of the European Climate-neutral industry competitiveness scoreboard (CIndECS). When it comes to high value inventions, EU is still leading with (31% of total share) alongside Japan.

Based on available information, international trade of hydrogen (both fossil and renewable) does not play any major role in hydrogen markets.

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%). Europe is strongly dependent on imported raw materials as between 1-5% Critical Raw Materials are sourced domestically, but its global share grows progressively for processed materials and components, reaching a significant fraction when final products are considered.

The following Strength Weaknesses Threats and Opportunities table summarises the factors relating to the EU's competitiveness in the hydrogen electrolysis sector.

Table 1. CETO SWOT analysis for the competitiveness of water electrolysis technologies.

Strengths	**Weaknesses**
– Established EU regulatory framework with legally binding targets securing the demand for RFNBOs and support for the deployment of manufacturing capacities (Net Zero Industry Act). – Success of the 1st auction of the European hydrogen bank, supporting the uptake of renewable hydrogen production and consumption, with a 2nd auction in preparation to be launched by the end of 2024. – Approval of 4 Important Project of Common European Interest (Hy2Tech, Hy2Use, Hy2Infra, Hy2Move) for a total of EUR 18.9 billion of state aid exemption, supporting research, innovation and infrastructure development across the whole hydrogen value chain and catalyzing coordination between European industrial stakeholders. – Europe's deployment of electrolysis capacity is accelerating with higher numbers of large-scale systems (largest site operates a 24 MW-electrolyser). – Some European companies aims to deploy gigawatt scale factories for manufacturing electrolysers.	– Largest system currently in operation in Europe is 24 MW, 10 times smaller than the largest installation out of Europe. – European electrolysers systems including stack and balance-of-plant components can be up to 3-4 more expensive than non-European systems. – The designs of full electrolysis systems are still specific to projects and suppliers, slowing down the reduction of cost for auxiliary and balance-of-plant components. – Significantly longer lead times of European stacks comparatively to non-European economies. – Very high European reliance on imports of critical raw materials and processed materials, which is partly addressed by the Critical Raw Materials Act and lack of a recycling infrastructure for electrolysis stacks. – Lack of mature European and international hydrogen transport, storage, and distribution networks. – Additional emerging challenges related to the replacement or substitution of PFAS or critical raw materials in the electrolyser stack.
Opportunities	**Threats**
– Completion of the EU regulatory framework for renewable and low carbon fuels – Several very large projects (more than 100 MWe) have reached Final Investment Decisions. – Europe involvement in international standardisation committees. – Increasing coordination between industrial stakeholders in the context of Important Projects of Common European Interest could foster innovation and accelerate the uptake of technological development from lab to industrial-scale and the development of a coordinate infrastructure framework at European level. – New opportunities for business cases able to exploit intermittent renewable electricity prices in the most effective way are emerging. – Research and Innovation initiatives should pursue opportunities to substitute the PFAS, CRMs and define recycling solutions.	– Lack of secured demand for electrolysers and consequently a lack of secured and contractualised renewable hydrogen offtake still seem to be main obstacles for projects in Europe compared to other regions. – Rising costs of electricity in the context of European economies have an impact on the levelised cost of hydrogen, weakening the business case for electrolysis technologies. Recent analysis point out to a much higher cost renewable hydrogen production than previously reported. – Cost reduction strategies of European manufacturers do not seem to have yet yielded results, leaving an increasing gap against some non-European manufacturers. – Manufacturing capacity for PEM electrolysers in non-European regions has overtaken European capacity. – Harmonised certification schemes at international level will have to be put in place, requiring an agreement or consensus with regard to the criteria applied to the imported hydrogen, so as to avoid "greenwashing" or inappropriate treatment of imported hydrogen.

Source: European Commission, DG Energy and JRC analysis

1 Introduction

1.1 Scope and context

This report on hydrogen electrolysis is one of an annual series of reports from the Clean Energy Technology Observatory (CETO). It addresses technology maturity status, development and trends; value chain analysis and global market and EU positioning. It builds on previous Commission studies in this field and it updates the 2023 report on the same topic [4].

Renewable and low carbon hydrogen is both *an energy carrier* able to produce other fuels and downstream products, such as e-fuels, or e-ammonia, and *a decarbonised gas produced through renewable electricity*[12]. It holds a significant potential for decarbonising hard-to-abate sectors which are difficult to directly electrify. Amongst projected uses, hydrogen can have a prominent role in industrial processes, such as the production of steel and cement, ammonia and fertilisers, or can be used as fuel in the heavy duty and long-distance transport (including solutions for e-fuels in aviation and maritime transport). Finally, it can be used in support of energy storage systems, especially for seasonal applications.

1.1.1 Policy context in the European Union

Therefore, renewable and low carbon hydrogen is set to play a crucial role in achieving the objectives of the European Green Deal [5], the REPowerEU plan (COM(2022) 230) and the net-zero emissions targets of the European Climate Law ((EU) 2021/1119) by 2030 and beyond. The European Commission has recently outlined the policy context and necessary actions for the development and deployment of renewable and low carbon hydrogen within the 2030 time horizon with the Hydrogen Strategy for a Climate Neutral Europe Communication (COM(2020) 301). The main objectives and actions of the REPowerEU Plan and the Hydrogen Strategy are:

- the initial targets as defined in the Hydrogen Strategy in 2020, of deploying 6 GW (expressed in hydrogen output) of electrolysers in 2024 and of 40 GW (expressed in hydrogen output) of electrolysers in 2030 and a European domestic production target of 10 million tonnes of renewable hydrogen;
- to import 10 million tonnes (out of which 4 million tonnes in the form of ammonia).

If 10 million tonnes of renewable hydrogen were to be produced exclusively through water electrolysis, the European hydrogen industry estimates a need for 140 GWe of electrolysis capacity installed by 2030 [6].

The strategic role of water electrolysis technology and fuel cell technologies in achieving European ambitions is also highlighted by the fact that they have been included in the Green Deal Industrial Plan (COM(2023) 62) and the Net Zero Industry Act (COM(2023) 161). The revision of the Renewable Energy Directive (REDIII) (EU/2023/2413) sets a target of at least 42 % of the hydrogen used for final energy and non-energy purposes in industry by 2030, and 60 % by 2035. In the transport sector, the REDIII sets a binding combined sub-target of 5.5% for advanced biofuels and renewable fuels of non-biological origin (RFNBOs), with a minimum of 1% of RFNBOs in this sub-target. The Alternative Fuels Infrastructure Regulation (AFIR), Fuel EU Maritime Regulation and ReFuelEU Aviation Regulation also support the uptake of renewable hydrogen by forcing minimal adoption shares of RFNBOs in the maritime and aviation sectors.

Two associated Delegated Acts setting out detailed rules for the production of renewable hydrogen (C(2023) 1086 and C(2023) 1087). While a methodology for accounting greenhouse gas emissions savings from clean hydrogen is detailed in the first act C(2023) 1086, the second act C(2023)1087 also at reinforcing the additional and renewable character of the electricity used to power the production of hydrogen and encourages the installation of (water) electrolysers in areas with abundant renewable sources. Some criteria allow producers of hydrogen using nuclear electricity to recognise its renewable character namely through the purchase of the Power Purchase Agreements.

The Carbon Border Adjustment Mechanism (CBAM), published in the Official Journal on 16 May 2023, is a European Union instrument that aims to ensure a fair pricing of carbon emissions generated during the production of carbon-intensive goods imported into the EU and promote cleaner industrial production in non-EU nations. The mechanism is designed to align the carbon price of imports with that of domestic production, thereby safeguarding the EU's climate objectives. In accordance with World Trade Organization (WTO) rules,

[12] Renewable hydrogen can also be derived from low carbon biomass sources meeting a 70% CO_2 reduction target as defined by the European Taxonomy. This is however not relevant for the current report on electrolysis and in the following report 'renewable hydrogen' will refer to hydrogen produced by electrolysis powered by renewable electricity. In a European context 'clean' and 'renewable' are to be considered synonyms.

CBAM will be implemented on a definitive basis from 2026, following a transitional phase taking place between 2023 and 2025. During this transition period, EU importers will be required to report greenhouse gas emissions embedded in their imports without the obligation to purchase and surrender certificates. Initially, the CBAM will apply to goods such as cement, iron and steel, aluminium, fertilisers, electricity, and hydrogen, which will collectively account for more than 50% of the emissions in sectors covered by the EU Emissions Trading System (ETS) upon full implementation.

The European Hydrogen Bank is a funding mechanism to support the deployment of renewable hydrogen within the European Economic Area (EEA) using resources collected from the EU – Emission Trading System. The scheme connects renewable hydrogen suppliers with consumers and fills the financing gaps on a competitive bidding principle. The first auction under the Innovation fund closed in February 2024 and awarded EUR 720 million to 7 projects planning to produce 1.58 million tonnes of renewable hydrogen over 10 years.

The Commission plans to launch a second European Hydrogen Bank auction by the end of 2024 with a budget of EUR 1.2 billion. It will draw on the lessons learned from this pilot auction and involve further consultation with stakeholders before launching. Individual grant agreements will be prepared between each selected project and CINEA and are expected to be signed by November 2024. After this, the projects must start producing renewable hydrogen within a maximum of 5 years. They will receive the awarded fixed premium subsidy for up to 10 years for certified and verified renewable hydrogen production.

In this auction-based mechanism, projects bid on the amount of funding in EUR/kg(H_2) required to come to an agreement with an off-taker and eventually launch the project. The lower the bid, the higher the chances for a project to win. In addition to this bid, the projects are also evaluated against non-price criteria.

Long-term strategy

The latest 2040 scenarios (SWD(2024) 63 final) foresees an expected renewable hydrogen production of 3.13 million tonnes per year as of 2030, primarily reflecting the impact of RFNBO targets, and associated hydrogen production, as per the revision of the Renewable Energy Directive under the Fit-for-55 package. This production capacity is set to grow in 2040 and reach between 20.9 and 34.9 million tonnes per year, depending on the scenario and subsequent role played in supporting demand for e-fuels. In 2050 production should be almost 65 million tonnes per year, almost doubling previous estimates (SWD/2020/176).

The Staff Working Document (SWD/2020/176) accompanying the Communication - Stepping up Europe's 2030 climate ambition (COM/2020/562) - thereafter referred to as the Long Term Strategy (LTS) - foresees that the share of hydrogen in Europe's total energy demand will grow from the current level of less than 2% up to estimates reaching 13% by 2050[13], thus amounting from about 80 up to 100 million tonnes of oil equivalent (Mtoe)[14] in 2050[15]. In terms of installed electrolysis capacity, a range between 528 and 581 GW in 2050 is given for the policy scenarios of the abovementioned Staff Working Document, whilst other studies suggest a 1 000 GW European market by 2050 [7].

1.1.2 Policy context beyond the European Union

In the United States, the Inflation Reduction Act (2022) adopted in 2022 aims to support renewable and low carbon technologies including hydrogen and has led to considerable discussions within industry groups and politically. In December 2023, The U.S. Department of the Treasury and Internal Revenue Service (IRS) have released proposed rules for the Clean Hydrogen Production Credit, part of the Inflation Reduction Act [8]. This credit offers four technology-neutral tiers based on emission rates, ranging from USD 0.60 to USD 3 per kg of hydrogen produced, contingent on lifecycle emissions, prevailing wage, and apprenticeship requirements. The credit is valid for 10 years, starting when a hydrogen facility is operational, and requires hourly matching of power and hydrogen production from 2028 onwards. The EU currently permits aligning renewable power generation with electrolyser operation within a monthly timeframe until 2030, after which they must be synchronised within an hour. In contrast, the US Treasury mandates annual alignment until 2027, followed by hourly correlation from 2028 onwards, resulting in stricter rules compared to Europe.

The "Infrastructure Investment and Jobs Act" (2021) provisioned USD 9.5 billion for clean hydrogen technologies with the objective to reduce the cost of electrolytic hydrogen to 2 USD/kg by 2026 and to develop the U.S. manufacturing capacity and recycling initiatives for key components. The "U.S. National Clean Hydrogen Strategy and Roadmap" (June 2023) sets an objective of 10 million tonnes of clean hydrogen annually produced from

[13] Net total hydrogen consumption excludes hydrogen that is further processed to renewable fuels or liquids (see SWD(2020) 176).
[14] Equivalent to about 28-35 Mt of hydrogen.
[15] More than 20% in Fit-for-55 scenarios, summing together hydrogen and e-fuels.

2030 and considers as 'clean' the production of hydrogen from various sources: renewables, hydropower, biomass and waste feedstock, low-cost power through nuclear electricity, fossil based SMR or auto thermal reforming ATR with CCS or methane pyrolysis. American support is mainly targeted at the development of Region Clean Hydrogen Hubs perceived as the main driver of the development of clean hydrogen technologies while delivering the highest social benefits. In this regard, a share of the tax credit under the IRA will be conditioned to socially inclusive job policies.

China recognises hydrogen's key role in the modernisation of its energy systems, as stated in its 14th Five-Year Plan of Modern Energy System (2022)[16] and its 14th Five-Year Plan of Renewable Energy Development[17] (2022). In its 2021-2035 plan for the development of hydrogen industry published in March 2022, China set the objective to build and deploy 50 000 hydrogen fuel-cell vehicles by 2025, 1 million by 2030. The country is also investing heavily in hydrogen infrastructure, with plans to build over 1,000 hydrogen refueling stations by 2025. China ambitions to produce 100 000-200 000 tonnes per year by 2025 of renewable hydrogen.[18]

As of 2023, more than 50 countries had released at least a national hydrogen strategy or roadmap[19], demonstrating the growing interest worldwide.

1.2 Methodology and Data Sources

Each of these uses a series of specific topics or indicators common to all the CETO technology reports. There are addressed to the extent that data is currently available.
The report uses the following information sources:

- Existing studies and reviews published by the European Commission;
- Information from EU-funded research projects;
- EU trade data, trade association reports, market research provider reports and others as appropriate;
- JRC own review and data compilation.

Details of specific sources are given in the corresponding sections.

Reliable and complete datasets about electrolysers manufacturing and shipments are not available, although some analysts provide partial information and indication on present and future market trends. This report intends to provide a summary of the ranges found in publicly available documents and commercial sources, for which the underlying raw datasets were not always available.

[16] Notice on the issuance of the "14th Five-Year Plan for Modern Energy System" - National Development and Reform Commission, National Energy Administration - 2022, 2022
[17] "14th Five-Year Plan" Renewable Energy Development Plan, 2022
[18] NDRC, & NEA. Medium and Long Term Plan for the Development of Hydrogen Energy Industry (2021-2035). March 2022
[19] https://www.taskforcehydrogene.fr/work/strategies-hydrogene

2 Technology status and development trends

2.1 Technology readiness level

Currently water electrolysis is the most mature and promising hydrogen production technology that can be coupled with renewable electricity.

Water electrolysis involves the dissociation of water molecules into hydrogen and oxygen and requires large amounts of electrical energy. For low temperature electrolysis, around 50-55 kWh (about 180-200 MJ) of electricity are needed to produce 1 kg of hydrogen from a stoichiometric minimum of 9 kg of water[20] [9]. The thermodynamic limit for dissociating water at room temperature through electrolysis is around 40 kWh/kgH_2.

The main electrolysis technologies [10], 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 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 consisting of 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[21] as nominal power input.

- 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, as first deliveries of 1-MW AEM electrolysis systems took place in 2023.
- Solid Oxide electrolysers (SOE) exploit the more favorable thermodynamics of water splitting 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) [9]; 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, they also contain critical raw materials such as rare-earth metals. Despite having reached a technological level able to support large demos, R&I actions are still necessary, and materials related challenges have to be tackled in order to guarantee the possibility of deploying the technology at large scale. Solid Oxide Electrolysers have been already tested in real life environment and planned demonstrations should deploy in the range of multi-MW scale soon[22]. There are recently announced projects aiming at having SOE deployed at a scale comparable with that of PEM and Alkaline. Large-scale manufacturing plants should come online soon also for SOE[23].

[20] It is estimated that, in practice water consumption can reach up to around 22 kg of water for the production of 1 kg of hydrogen. The reason for this assessment is linked to losses in purifying/deionising water down to 1-10μS before feeding it to the electrolyser. See Section 3.3.2)

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

[22] MULTIPLHY project will demonstrate at MW scale (2.4 MW) https://multiplhy-project.eu/

[23] Topsøe announced the development of a 500-MW factory in Denmark with a possible extension to 5 GW of manufacturing capacity. Bloom Energy built a 1 GW solid oxide fuel-cell manufacturing facility in US.

– An even lower TRL technology which offers significant development potential is Proton Conductive Ceramic electrolysis (PCCEL). This electrolysis technique has similarities to SOE, but here the ceramic membrane is used to transport protons. The temperature range of PCCEL 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 commercialization.

Table 2: 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 estimates (2024)

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)). Another example is Electric Hydrogen, which is also developing an integrated 100-MWe electrolytic system.

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 [11], [12], [13]. 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.

2.2 Installed Capacity and Production

In 2022, the total hydrogen production capacity in Europe (EU + UK, NO, CH) is estimated around 11.4 Mt/y (stable from the 11.5 Mt/y estimated in 2020) [14], [15], against a global production capacity of around 95 Mt/y of hydrogen [8]. According to the Clean Hydrogen Observatory [15], around 72% capacity (production was 8.2 Mt/y in 2022), which is lower than an utilisation rate of around 76% for 2020.

The hydrogen production capacity of the EU can be divided into:

– ”Thermal” production methods (reforming, mainly– 90.8% and other production methods such as partial oxidation, by-product production from refining operations, and by-product production from ethylene and styrene) amounting to about 95.6% of total capacity.

– By-product electrolysis (i.e., hydrogen from chlor-alkali and sodium chlorate processes) totaling to about 3.7%.

– Reforming with carbon capture providing around 0.5% of total.

– Hydrogen produced via water electrolysis corresponding to only about 0.3% of total hydrogen production capacity.

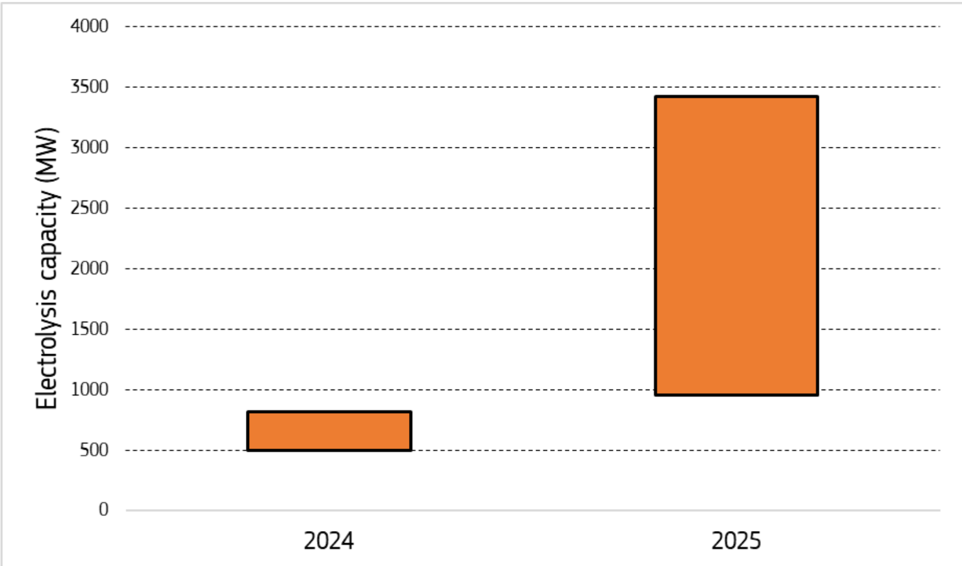
Water electrolysis is therefore accounting for a very limited amount of current hydrogen generation capacity.

In the EU, EFTA and UK, estimates from Hydrogen Europe show that the total installed capacity grew from 85 MW in 2019 to 228 MW as of September 2023 [14]. By the end of 2024, short-term estimates point to a capacity in Europe to reach between 500 MW[24] and 812 MW [1], depending on the actual date of entry of operation of the considered projects (only projects operational/under construction or with a FID taken are considered). Between 950 MW and 3.4 GW of electrolysis capacities are planned to enter operation in Europe by the end of 2025 [1], [2], [15], the gap being explained by the same reason as above. In Europe, Germany is the country with the highest electrolysis capacity planned to be installed by the end of 2024 with a range of 159 MW and 207 MW [1], [2], [15]. According to Hydrogen Europe, 60% of the capacity planned to be installed in 2025 was under construction or in a preparatory stage in 2023 and had a secured deployment timeline ahead [14].

In the EU, electrolyser technology distribution as of 2023 comprises approximately 58% alkaline technology, 41% PEM technology, with AEM and SO technologies being comparatively less mature and deployed. However, by 2030, Hydrogen Europe estimates that PEM technology will lead with 60% of manufacturing capacity, followed by ALK at 32%, and increased market shares for AEM and SO at 2% and 6%, respectively [14].

According to Hydrogen Europe, by 2030, more than 52% of the installed electrolyser projects will be in the range of 100 MWe to 1 GWe. Today, 118 MWe of the electrolysis capacity in Europe is spread across project smaller than 5 MWe [14]. Overall, the average size of projects is expected to grow significantly in the coming years, even reaching the gigawatt scale by 2025 according to project developer's announcements[25]. This has yet to materialise.

Figure 1 - Ranges of planned deployment of electrolysis capacities in Europe for 2024 and 2025 (EU+CH, NO, UK)



Source: JRC analysis based on various sources including the IEA, Clean Hydrogen Observatory, Rystad Energy. Only projects already operational, under construction or at FID stage are considered. Most of the discrepancy is explained by the difference in the commissioning date of the projects. (2024)

The two largest electrolysis projects identified as FID or already Under Construction in the IEA hydrogen project database with a planned date of entry into operation before 2030 are the Stegra[26] project and HYBRIT (Hydrogen Breakthrough Ironmaking Technology) Demonstration. Both projects are described further in addition to the H2 Energy Europe's project, which did not reach FID but recently received environmental approval from the Danish authorities:

- The H2 Energy Europe's project in Esbjerg, Denmark which plans to install 1 GWe of electrolysis capacity that will enter into operation in late-2025. The project will use 50 proton exchange membrane (PEM) electrolysers supplied by US manufacturer Plug Power with a production target of approximately 90 000

[24] If projects currently under construction respect the planned commissioning date.
[25] https://h2eeurope.com/denmarks-1gw-green-hydrogen-production-facility-receives-important-environmental-approval-from-authorities/
[26] https://stegra.com/

tonnes of renewable hydrogen annually. The project did not reach FID yet but received the environmental approval in January 2024. The facility will provide hydrogen to several offtakers and support the decarbonisation of heavy industries and road transportation.

- The Stegra project in Boden, Sweden plans to install a total of 700 MWe of alkaline electrolysis capacity provided by Thyssenkrupp Nucera based on standardized 20-MW modules. The electrolysers will be integrated within a low-carbon steel factory facility. Operations are planned to start in 2025 with an upscale to the full capacity of 700 MWe by 2030, producing up to 5 millions tonnes of low-carbon steel. The total funding raised by the project is approximately EUR 6.5 billion, of which EUR 4.2 billion as debt financing and EUR 200 million from Innovation Fund.[27] This project will be integrated within a steel production plant.
- The HYBRIT Demonstration project in Gällivare, Sweden will deploy 500 MWe of electrolysis capacity producing renewable hydrogen to replace coal-based blast furnaces in the ironmaking process. The project will use hydrogen in an innovative direct iron ore reduction process and produce 1.2 million tonnes of crude steel annually.[28] This project will also be integrated within a steel production plant.

Estimations of global installed electrolysis capacity were in the range of 600 - 700 MWe at the end of 2022 and between 1.4 and 1.7 GWe at the end of 2023 [14], [16]. According to analysts, approximately 5 GWe of electrolysis capacity should enter in operations by the end of 2024 [1] and between 10.9 and 17.8 GWe by the end of 2025 [1], [2].

China is still the geographical area where most of the growth in electrolysers' deployment is expected to happen. Estimates for Chinese electrolysis capacity are in the range of 718 MWe and 1 056 MWe installed and operational at the end of 2023 [1], [2]. The Chinese electrolysis capacity is expected to reach between 3.3 GWe and 3.6 GWe by the end of 2024 [1], [2].

In the United States, electrolysis capacity in operation at the end of 2022 was estimated to be around 19 MW [2] and 80 MWe at the end of 2023 (these are below the 291 MWe estimated to come online in last year CETO [4]). By the end of 2024, latest estimates point to an electrolysis capacity up to between 176 MWe - 300 MWe in the United States [1], [2].

According to long-term forecasts, the deployment of electrolysis capacity shows an expected major growth which is difficult to keep track of. However, this growth points towards an ever-increasing deployment prospect both in Europe and in the rest of the world [17], [18], [19]. Recalibration for long-term forecasts have to be expected in every region of the world.

2.2.1 Hydrogen demand

According to Hydrogen Europe, Europe (EU, EFTA + UK) consumed in 2022 around 8.2 million tonnes per year[29]. This demand decreased from 9.2 million tonnes of hydrogen in 2020[30]. The global demand for hydrogen grew in 2022 from 93 million tonnes to 95 million tonnes, with Europe representing 8% of this demand, down from 8.5% in 2021.[31]

In 2022, the hydrogen demand in Europe was mostly broken down as:

- ca. 56% as chemical feedstock for oil refining;
- ca. 24.5% for ammonia production;
- ca. 11.5% for methanol and other chemical synthesis.
- ca. 3.7% for other uses (such as uses in the food industry, glass manufacturing, or power generation cooling).
- ca. 3.4% for energy production (mostly in industrial applications where hydrogen is combusted for its energy content).

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27 https://www.thyssenkrupp.com/en/newsroom/press-releases/pressdetailpage/thyssenkrupp-nucera-supplies-the-electrolyzers-for-h2-green-steel-to-build-one-of-the-largest-integrated-green-steel-plants-in-europe-224050
28 https://www.hybritdevelopment.se/en/hybrit-demonstration/
29 This amount excludes UK, Switzerland, Norway and Iceland.
30 The difference between the 2023 CETO report reflects the adjustment of hydrogen demand from the Clean Hydrogen monitor 2023.
31 Hydrogen Europe. "Clean Hydrogen Monitor 2023," October 2023. https://hydrogeneurope.eu/wp-content/uploads/2023/10/Clean_Hydrogen_Monitor_11-2023_DIGITAL.pdf.

– ca. 0.04% for the transport sector.

By 2030, European industrial buyers plan to use 7.1 million tonnes of renewable hydrogen per year across 268 projects according to their announcements.[32] If projects without starting date are included, the total demand could reach 7.4 million tonnes per year. According to these announcements, the largest users will be the ammonia and steel industries, each accounting for around 2 million tonnes per year.[33] The refining sector would use 1.2 million tonnes per year by 2030.

The development of renewable hydrogen projects in various countries is influenced by several factors, including:

– Existing hydrogen demand (e.g. Germany and Netherlands)

– Low-carbon grid electricity (e.g. France, Finland, Sweden, Norway)

– Access to abundant and affordable renewable energy (e.g. Spain and Portugal)

– Availability of subsidies and support programs (e.g. Netherlands, France, Germany, Denmark)

These factors drive the location and development of renewable hydrogen projects, with countries with existing demand and low-carbon energy sources being more likely to invest in renewable hydrogen production.

For the European Union, the JRC-in-house POTEnCIA model has been employed to project the deployment of renewable electrolyser deployment. In the context of the wider CETO 2024 exercise, the POTEnCIA CETO 2024 Scenario has been modelled. More details on the model and the scenario are provided in **Annex 4**. According to the POTEnCIA CETO 2024 Scenario, the EU production of renewable hydrogen would be in the order of 2 MtH_2/y by 2030, with additional imports of 0.8 MtH_2/y; by 2040 they are estimated to grow up to 21 MtH_2/y and 4 MtH_2/y respectively. In 2050 EU production is calculated to be 36 MtH_2/y with imports around 6 MtH_2/y. In the POTEnCIA CETO 2024 Scenario, various policies are considered, which foster the demand of hydrogen and hydrogen-derivatives: RED III, FuelEU Maritime, REFuelEU Aviation, and the Alternative Fuels Infrastructure Regulation (AFIR). In this model, the demand is driven by the chemicals sector, where hydrogen supply chains and transformation processes are already established. However, in the mid- to long-term, demand structures would be more diverse. Major demand could come 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 could become essential for decarbonizing 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 will replace large shares of oil products as a more sustainable feedstock. In the transport sector, hydrogen-fuelled FCEV trucks could be used to satisfy long-distance freight demand.

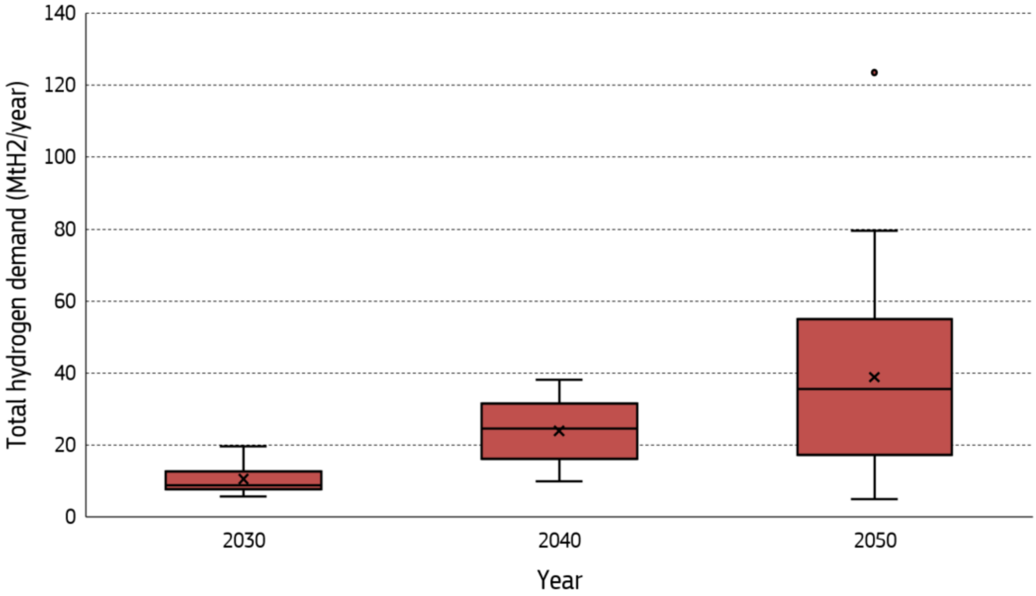
The Clean Hydrogen Observatory collected information on the hydrogen demand forecast from 34 different scenarios modelled between 2018 and 2023[34]. The complete list of scenarios is available in Annex 3 and **Figure 3** provides a statistical analysis of the outputs of the different models for 2030, 2040, 2050. The total hydrogen demand is aggregated between the industry, transport, building and power sectors.

[32] Hydrogen Europe. "Clean Hydrogen Monitor 2023," October 2023. https://hydrogeneurope.eu/wp-content/uploads/2023/10/Clean_Hydrogen_Monitor_11-2023_DIGITAL.pdf.

[33] Hydrogen Hydrogen Europe. "Clean Hydrogen Monitor 2023," October 2023. https://hydrogeneurope.eu/wp-content/uploads/2023/10/Clean_Hydrogen_Monitor_11-2023_DIGITAL.pdf.

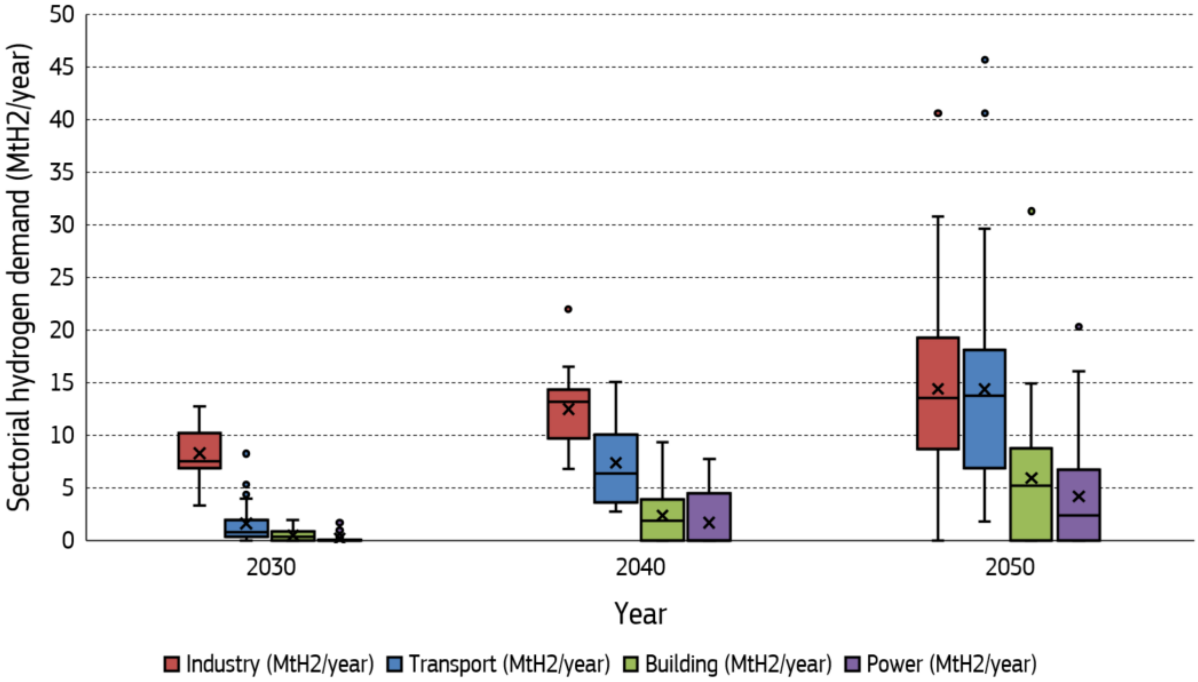
[34] European Hydrogen Observatory. "Hydrogen Demand Forecast," 2024. https://observatory.clean-hydrogen.europa.eu/tools-reports/datasets.

Figure 2 – Statistical summary of the estimations of hydrogen aggregated demand from industry, transport, building, and power sectors across 34 different scenarios



Source: JRC analysis based on data available on the European Hydrogen Observatory (2024). 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. Crosses indicate the mean value. 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.

Figure 3 – Statistical summary of estimations of hydrogen demand from different sectors (industry, transport, building, and power) across 34 scenarios



Source: JRC analysis based on data available on the European Hydrogen Observatory (2024). 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. Crosses indicate the mean value. 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.

The technology and competitive aspects of hydrogen transport, storage and conversion for end-use applications (e.g., power, industry, mobility, or buildings) are not part of the focus of the analysis performed in this report.

On a global scale, the *Global CETO 2°C scenario 2024* developed by the JRC-POLES model (s. Annex 4 for more info on the model and the scenario) projects hydrogen production via electrolysis to rise to 12 MtH2/y by 2030 and 112 MTH2/y by 2050. However, when considering electrolysis driven only by renewable energies, the projected production reaches only 9 MtH2/y by 2030 and 96 MtH2/y by 2050.

2.3 Technology Costs

2.3.1 Cost of large-scale electrolysis projects.

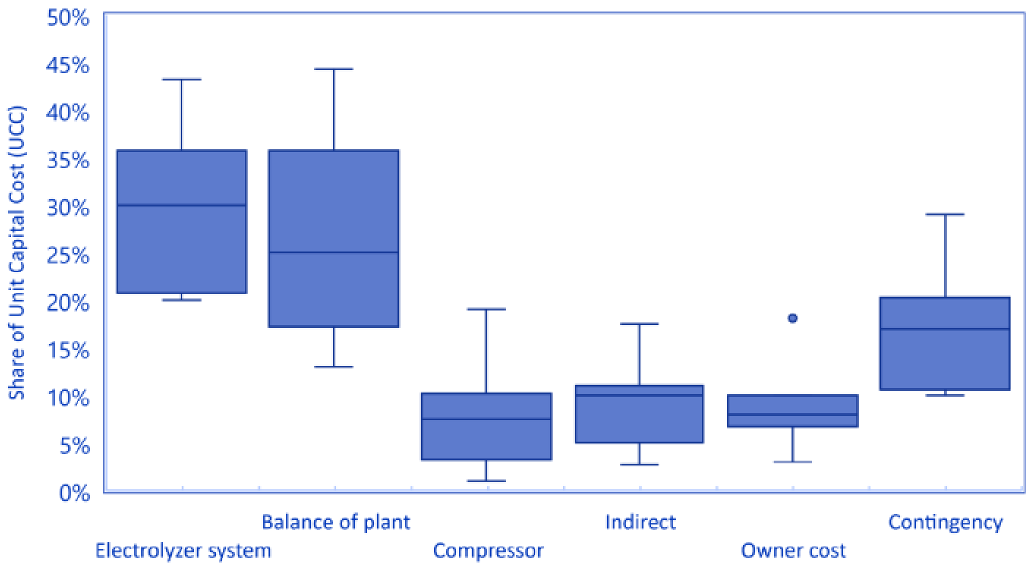
The cost of large-scale electrolysis projects can be broken down into several distinct categories:

- The capital expenditure (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.
- Operating expenditure (OPEX) is another key category, covering the ongoing costs of running the facility, including non-electrolysis related energy consumption, maintenance, and labour. Additionally, there are costs associated with the production of hydrogen itself, including the cost of electricity and water.
- Finally, other expenses such as the costs related to financing, land acquisition, insurance and contingency financing, permitting, and grid connection fees also contribute to the overall cost of a large-scale electrolysis project.

As larger projects are now being deployed across the world, modellers have now access to more accurate and factual data. This contributed to improve cost estimations of projects in the range of tens and hundreds of megawatts, reducing uncertainty embedded when estimating the cost of such complex industrial projects.

A recent 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/kWe to 2 630 EUR/kWe for 100-MWe and 200-MWe full projects respectively [3]. 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 the balance-of-plant components. 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 [20]. The IEA also provides estimate on the cost of electrolysers in the range of 1 700 – 2 000 USD/kWe at least (including stack, balance-of-plant and engineering, procurement, construction costs), with possible higher cost for projects in Europe [21].

Figure 4 - Cost breakdown of the Unit Capital Cost (UCC) based on survey of projects funded under the SDE++ scheme.



Source: TNO. "Evaluation of the Levelised Cost of Hydrogen Based on Proposed Electrolyser Projects in the Netherlands. Renewable Hydrogen Cost Element Evaluation Tool (RHyCEET[35])," May 13, 2024. 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.

Although expected to decrease over the years, the latest available data and analysis are showing that the cost of developing installing electrolysis projects in Europe is higher than anticipated. This is the case for both PEM and alkaline technologies and according to several institutions, this trend upwards is due to:

- An underestimation of previous cost studies which mostly focused on the cost of manufacturing stacks and balance-of-plants [22], [23]. Such costs as installing power connections, engineering costs, and the WACC were not available or properly assessed since no large-scale projects were actually deployed yet.
- According to the IEA, the inflation and the increase of the weighted average cost of capital (WACC) explained more than half the cost increase between 2021 and 2023 systems.
- An overestimation of stack cost reduction. The maturation and the upscale of stack assembling capacities were expected to drive costs down. However, this is not yet happening for Western original equipment manufacturers (OEMs) due to a lack of orders hindering economies of scale. The IEA reports an utilisation rate of today's factories of about 10% [24]. Section 3 and 4 give more information about the current status of electrolyser manufacturing capacities.

The electrolysis stack being the core component of electrolyser systems, it received greater attention in regard to manufacturing cost reduction. A 2024 study estimates that future stack manufacturing cost could decrease from 242 - 388 EUR/kWe for alkaline and 384 – 1071 EUR/kWe for PEM to 52 – 79 EUR/kWe and 62 – 234 EUR/kWe respectively [25]. NREL conducted an analysis of the cost reduction potential of electrolyser systems, with an in-depth focus on PEM stack cost reduction and concluded to a cost reduction potential from 316 USD/kWe to 31 USD/kWe by 2030 if all cost reduction strategies are put in place [26].

2.3.2 Cost of hydrogen produced by water electrolysers

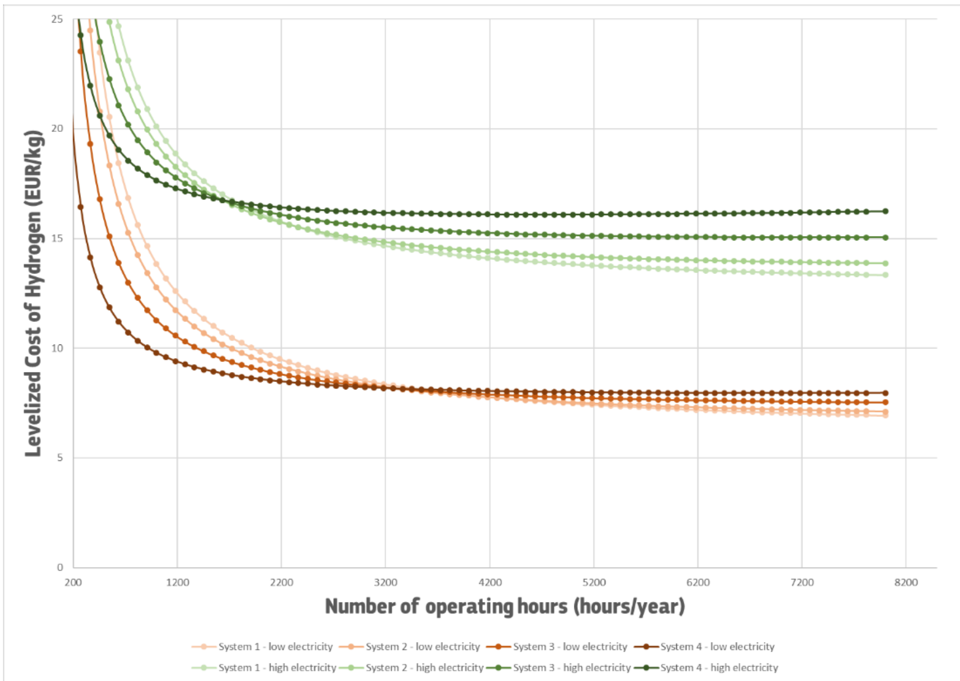
The cost of renewable hydrogen production is generally expressed in Levelised Cost of Hydrogen (LCOH) as this allows for comparison with different production processes or electrolyser designs. Models and calculators such as the one developed by the European Hydrogen Observatory are getting more sophisticated, encompassing more aspects of installations (such as the electricity profile, local regulations and tariffs) external factors (solar and wind energy potential and cost). They are more integrated (cost of storage and hydrogen transport). In addition, cost models are now fed with more accurate data and assumptions from industrial stakeholders.

The cost of producing renewable and low carbon hydrogen through electrolysis depends on several factors:

[35] RHyCEET to be pronounced like "Receipt"

1. Capital investment (CAPEX) for electrolysers which depends on the technology used and its scale as describe above.
2. Operating expenditure (OPEX), largely impacted by the cost of electricity provided to the electrolyser.
3. Other electricity-related, grid-related taxes and tariffs.
4. Load or utilization factor[36].
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.

Figure 5 - Illustration of LCOH variation for different systems



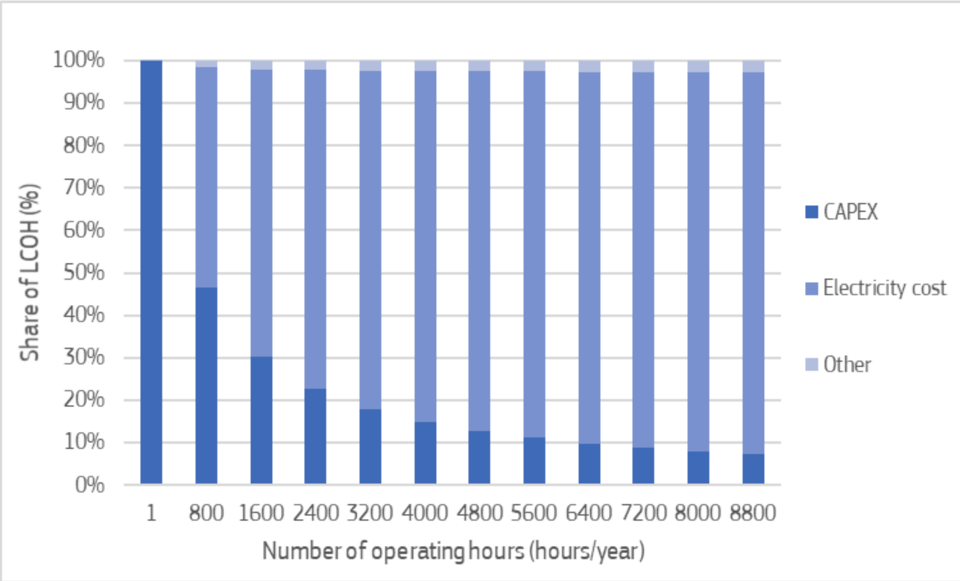
Source: Joint Research Centre analysis (2024)

Note: Baseline system size is 100 MWe. Efficiency range is 48-60 kWh/kg with System 1 being the most efficient. CAPEX range is EUR 500-2000/kWe, 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.

The two most impacting factors on the Levelised Cost of Hydrogen (LCoH) are (1) the electrolysis system cost and (2) the electricity price. Their respective final share in the LCOH varies accordingly to the utilization factor of the electrolyser as described in **Figure 6**..

[36] 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 6 - Share of CAPEX and electricity cost in the Levelised Cost of Hydrogen depending on the number of operating hours.



Source: JRC analysis (2024). Assumptions: Baseline system size is 100 MWe. Stack CAPEX of 1000 EUR/kW, Cost of electricity 0.12 EUR/kWh, degradation of 0.12%/kilohours, Energy consumption of 60 kWh/kg(H_2)

For lower rates, the Capital Expenditure (CAPEX) contributes the most to the final price of hydrogen. When the utilization factor of the electrolyser increases, the relative weight of electricity cost – a large part of the OPEX- increases and dominates the total hydrogen cost.

Other factors impacting economic viability of hydrogen produced via electrolysis versus other production pathways which emit CO_2, depend on regulatory environment features such as the price of carbon emissions (e.g., in the Emission Trading System). In addition, the system lifetime will influence the frequency of stack replacement or the system efficiency all have a direct impact on the LCOH.

Other infrastructure or transportation cost elements such as availability and cost of transport and storage should also be considered. These factors may have a considerable impact on the final price of hydrogen; however, the analysis of these factors is out of scope in this assessment. [27] provides a list of recent levelized costs of hydrogen storage and distribution from various sources.

2.3.3 Projected costs of renewable based hydrogen production:

In countries relying on gas imports and characterised by large potential of renewable resources, clean hydrogen production from renewable electricity can compete effectively with production that relies on natural gas [28]. According to IRENA [23], '"in the best-case scenario," using low-cost renewable electricity at USD 20/MWh, "large, cost-competitive electrolyser facilities" could produce green hydrogen at a competitive cost with hydrogen produced using fossil fuels already today. However, this depends on the availability of required volumes of competitively priced renewable electricity.

Hydrogen Europe estimated that the cost of 1 kg of hydrogen produced in the EU through steam methane reforming (SMR) in 2022 averaged 5.7 EUR/kgH_2 (up from 2.65 EUR/kgH_2 in 2021) [14]. This dropped to 5.5 EUR/kgH_2 when excluding the impact of CAPEX amortisation[37]. More than 85% of the total cost of hydrogen production reported for 2022 is associated with the natural gas cost. New estimations based on lower gas prices in 2023 are leading to a 3.5 EUR/kgH_2 on average in Europe [14].

Hydrogen Europe estimates that for 2022, the European hydrogen production costs using directly renewable sources and in the best locations averaged 5.2 EUR/kgH_2 for southern European countries using solar PVs (lowest estimate at 4.4 EUR/kgH_2) and 5.5 EUR/kgH_2 in case of generation capacity using wind in northern European countries (lowest estimate at 3.1 EUR/kgH_2) [17]. The average for European countries was around 7 EUR/kgH_2.

[37] This still includes a carbon allowance of 0.22 EUR/kgH_2.

An increase with respect to previous year estimates was justified by the higher inflation and higher cost of capital, impacting both CAPEX and OPEX.

It has been already shown before that the final cost of hydrogen produced using renewable electricity will be impacted by the load factor of the electrolysers. Therefore, the cost of hydrogen will be ultimately impacted by the intrinsic geographical availability of the renewable source used and by how much electricity produced by a renewable source installation will be dedicated to the production of hydrogen. Renewable hydrogen production costs have historically decreased, and it is reasonable to expect a further drop, although it could happen at a slower pace than in the last 10 years. Availability of large amounts of cheap renewable electricity able to maximise electrolyser full load hours will be the main driver for renewable hydrogen cost reduction.

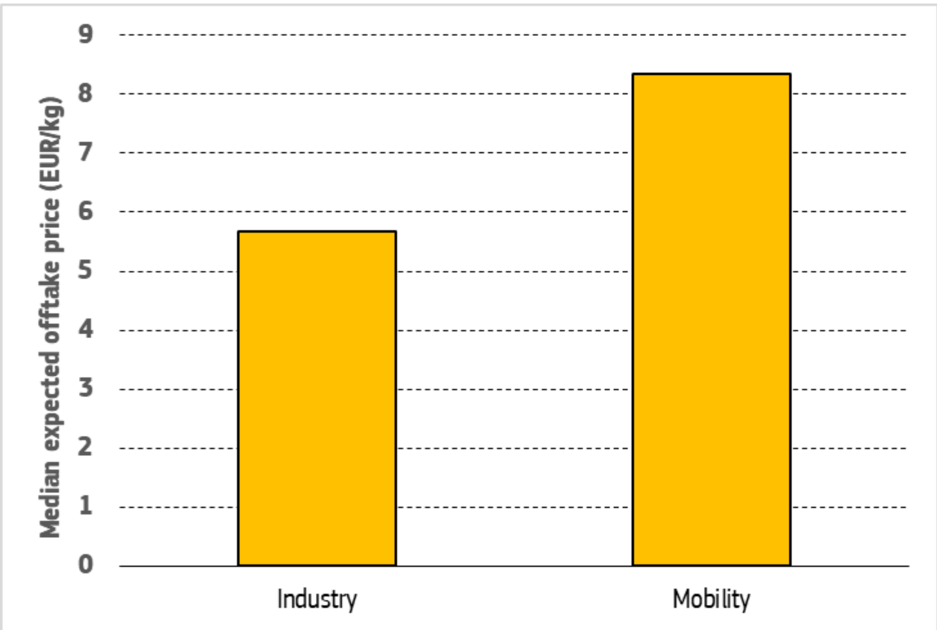
2.3.4 Sectorial differences in hydrogen offtake price

Reducing the price of renewable hydrogen can allow an increasing penetration of hydrogen into different sectors and applications. Usually, system boundaries for hydrogen production calculations are defined by the production side, but actual competitiveness for hydrogen uses comes from the opportunity offered by business cases outside the production boundaries, which likely include steps such as transport and storage.

Industrial competitiveness could allow certain industrial processes to become affordable earlier than others which have to face more challenging economic competition against conventional fossil-based hydrogen (e.g., ammonia). As an additional advantage, renewable hydrogen may have a lower price volatility against hydrogen produced from fossil fuels, which follows natural gas prices. Its price will depend on the volatility of the (renewable) electricity used for electrolysis.

As very large-scale projects (more than 100 MWe) approach final investments decisions, more information about the hydrogen price premia that different sectors can afford start to be available. This is illustrated in **Figure 7** which shows the two median off-take prices agreed upon by projects funded under the first auction of the European Hydrogen Bank. The median of the expected off-take prices for projects with industrial applications is 5.67 EUR/kg, versus 8.34 EUR/kg for projects with mobility-related offtakers.

Figure 7 - The first auction of the Hydrogen Bank resulted in different levels of willingness-to-pay depending on the sector.



Source: European Commission DG CLIMA ([Competitive bidding - European Commission (europa.eu)](#))

The main drawback of a hydrogen supply based on renewable electricity is linked with the intrinsic irregularity in the supply of the renewable energy source. Especially for industrial processes, where hydrogen feedstock needs to remain relatively stable at large volumes, uncertainty and variability are issues which can be tackled by deployment storage systems.

2.4 Public RD&I Funding and Investments

The funding ecosystem at European and Member States levels on electrolysers technologies is broad and complex. Different programs will fund different type of projects, from basic research to large-scale infrastructure development across the whole value. Therefore, it is not clear exactly which amount of funding goes to activities specifically targeting RD&I activities. The Clean Hydrogen Monitor 2023 provides an extensive overview of the funding instruments available and their respective scope, source and budget[38]. The following section provides more details about a selection of funding instruments.

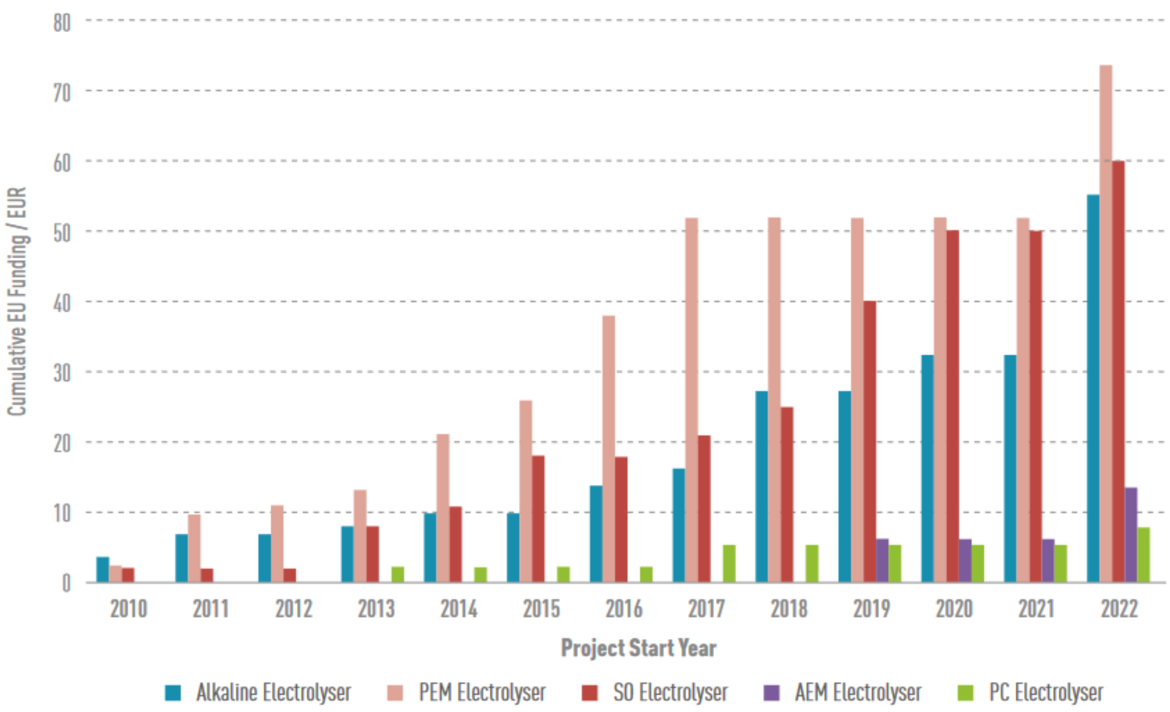
2.4.1 Horizon Europe and the Clean Hydrogen Joint Undertaking

The Clean Hydrogen Joint Undertaking (CHJU) was established in 2021 as a Public Private Partnership (PPP) following the Council Regulation (2021/2085) establishing the Joint Undertakings under Horizon Europe. The CHJU is the successor of the Fuel Cells and Hydrogen joint undertaking (FCHJU) and manages a budget of originally EUR 2 billion (from which EUR 1 billion stems from Horizon Europe and EUR 1 billion from private partners) attributed to the funding of R&I activities. This was topped up by EUR 200 million as part of the RePowerEU Plan from 2022, aiming to double the number of hydrogen valleys in the EU by 2025 (and also to be matched by the same amount by private partners).

From 2008 to 2022, the Clean Hydrogen Joint Undertaking and its predecessors have dedicated about EUR 213.17 million to electrolyser technologies. From 2010 to 2022, research on alkaline electrolysis was supported with a total of around EUR 55 million, PEM electrolysis with around EUR 75 million, SOEC electrolysis with around EUR 60 million, AEM electrolysis with EUR 13 million[29] , and PCC electrolysis with EUR 8 million. In addition, EUR 35 million were dedicated to fund the deployment of Hydrogen Valleys.

In 2022, the Clean Hydrogen Joint Undertaking deployed almost 40 MW of electrolysis capacities, up from 25 MW deployed in 2021.

Figure 8 - Cumulative funding from the Clean Hydrogen Joint Undertaking to electrolysis projects



Source: Clean Hydrogen Joint Undertaking Programme Review report (2023) (PC electrolyser refers to Proton Conducting Ceramic electrolyser (PCC))

[38] Hydrogen Europe. "Clean Hydrogen Monitor 2023," October 2023. https://hydrogeneurope.eu/wp-content/uploads/2023/10/Clean_Hydrogen_Monitor_11-2023_DIGITAL.pdf.

Outside of the scope of the Clean Hydrogen Joint Undertaking but stemming from Horizon Europe budget, the Green Deal Call of 2020 alone has supported the development of three 100 MW electrolysers through more than EUR 90 million funding. Some of these projects have experienced challenges with implementation and could be delayed, suspended or terminated.

2.4.2 Innovation Fund

One of the main public instrument existing at European level which fosters innovation in the Innovation Fund. The Innovation Funds 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 aiming at demonstrating technologies at pre-industrial or industrial scale or develop clean technology manufacturing capacities

From 2020 to 2024, the Innovation Funds launched a total of 8 calls for projects for a total of about EUR 40 billion from 2020 to 2030 which depends on the price of carbon in the ETS. From 2020 to 2024, 7 calls consisted of 6 regular large-scale calls[39] and small-scale calls[40] as well as one aggregated call which closed in April 2024 and for which results are expected to be published at the end of 2024[41].

As of June 2024, a total of 38 projects have been granted a total of EUR 2.27 billion under the traditional Innovation Fund calls and are planning to install a total of 4 270 MWe of electrolysis capacities. Some projects are developing manufacturing capacities of electrolyser components (PEM or SOEC stacks, membrane, electrodes). The planned date for entry in operation is not known, but according to the Innovation Fund regulation, financial closing must happen within 4 years from the Grant agreement.

In addition to these 7 regular calls, the Innovation Fund also funds projects under a competitive bidding process in the context of the European Hydrogen bank for a total of EUR 800 million made available via the first auction[42]. A second auction is planned to be launch by the end of 2024 with a total budget of EUR 1.2 billion. Contrary to the regular calls, these auction-based call specifically targets hydrogen production projects. Under the European hydrogen bank calls, 7 projects are planning to install a total of 1 502 MWe of electrolysis capacity. According to the auction's Terms and Conditions, projects must enter into operations within 5 years after signing the grant agreement.[43]

A complete list of projects funded under the Innovation fund including regular and auction-based calls is available in **Annex 2**.

2.4.3 Important Project of Common European Interest (IPCEI)

Important Project of Common European Interest (IPCEI) is a state-aid exemption mechanism allowing Member States to fund projects identified as of strategic interest for achieving the European Union climate ambitions. 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, which allow supporting innovative and green projects whilst ensuring that potential competition distortions are limited.

As of October 2024, a total of 4 Important Project of Common European Interest (IPCEIs)[44] dedicated to hydrogen have been approved:

- Hy2Tech[45], 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-users applications, in particular in the mobility sector. It has an innovation-centric approach and expect to contribute to the development of important technological breakthroughs.

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39 https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/calls-proposals/large-scale-calls_en
40 https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/calls-proposals/small-scale-calls_en
41 https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/calls-proposals_en
42 https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/competitive-bidding_en#ref-2023-auction-for-renewable-hydrogen-production
43 https://climate.ec.europa.eu/document/download/cedaacd0-6be5-49e6-81a9-adcafdb25e4c_en?filename=innovationfund_pilotauction_termsandconditions_en.pdf
44 https://ipcei-hydrogen.eu/
45 https://ec.europa.eu/commission/presscorner/detail/en/IP_22_4544

- Hy2Use[46], 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[47], 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 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[48], approved in May 2024, for a total of EUR 1.4 billion with EUR 3.3 billion in private investments. Hy2Move will cover 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.

These investments are however not simply dedicated to water electrolysis deployment and hydrogen production but are expecting to foster innovation and drive the demand for electrolysers.

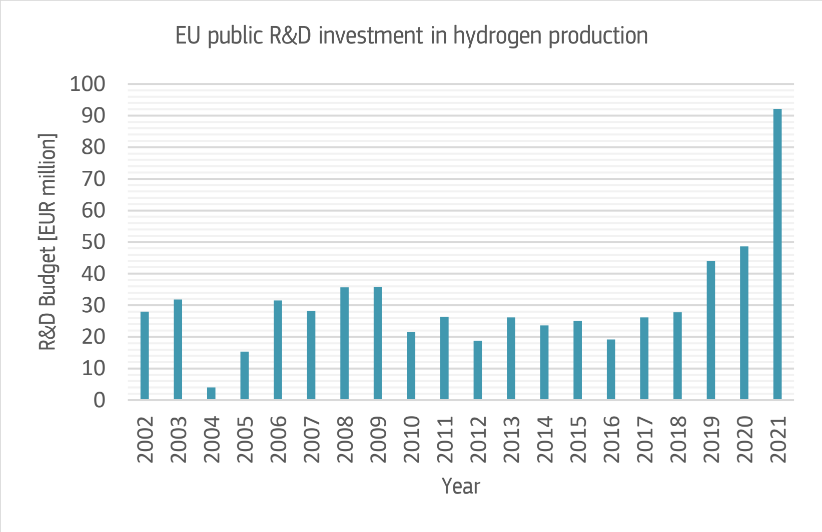
2.4.4 Public RD&I funding at national level

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 [17] 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.

Public R&D investment in hydrogen production has been increasing in EU Member States). Unfortunately, available data is not granular enough to draw insights on how much funding addresses exclusively electrolysis or green hydrogen production; it is very likely that support for conventional technologies is included in this figure. France accounts for nearly half of the tracked EU investment. The Netherlands, Czechia, Germany, Belgium and Denmark have also invested over EUR 6 million in hydrogen production R&D in the period 2018-2020 and are in the top 10 IEA members reporting R&D expenditure in this area. It is almost impossible to quantify the actual expenditure in hydrogen production technologies in general, and electrolysers in particular, both in the EU and in other major economies.

[46] https://ec.europa.eu/commission/presscorner/detail/en/ip_22_5676
[47] https://ec.europa.eu/commission/presscorner/detail/en/IP_24_789
[48] https://ec.europa.eu/commission/presscorner/detail/en/ip_24_2851

Figure 9 - EU public R&D investment in hydrogen production [EUR million]



Source: JRC based on IEA data

2.4.5 Other funding

The 27 revised National Recovery and Resilience plans (RRPs) include the update of more than EUR 2.5 billion in investments to renewable hydrogen production. [30]

2.5 Private RD&I funding

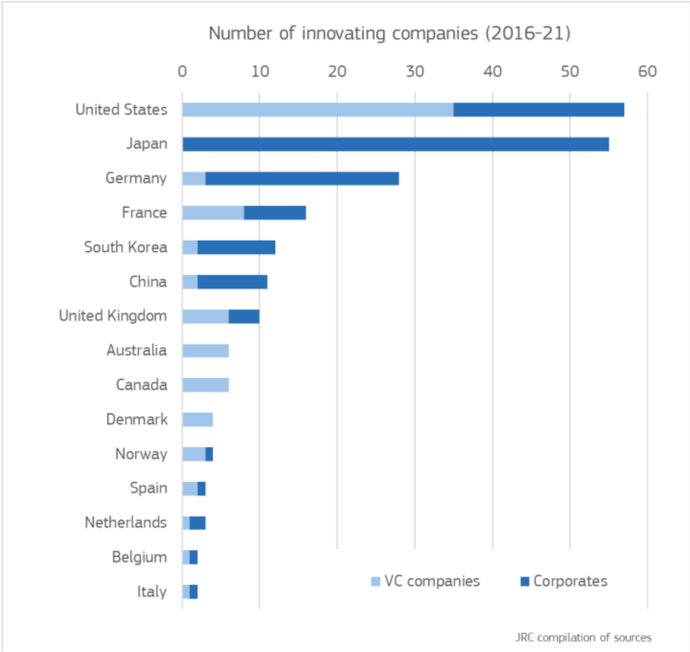
Five countries host 73 % of identified innovators but display various profiles (**Figure 10**). While USA (1st) leads with start-ups accounting for more than half of the companies identified, Japan (2nd) has corporations as sole contributors. Germany (3rd), France (4th) and the South Korea (5th) follow, with Germany and South Korea relying on a very strong corporate innovator base, while France relying both on start-ups as well as corporates. Overall, the EU hosts around 28% of the innovating companies identified globally, both in terms of corporates and start-ups.

In 2022, global venture capital (VC) investments amount to more than EUR 1 billion, showing strong signs of acceleration lasting since at least three years: more than one and a half time the global funds of 2021, more than four and a half time global values for 2020 (**Figure 11**).

Total investments are dominated by USA, China and Germany, which are also the three leading countries for later stage investments. USA, Israel and the UK are leading early-stage investments.

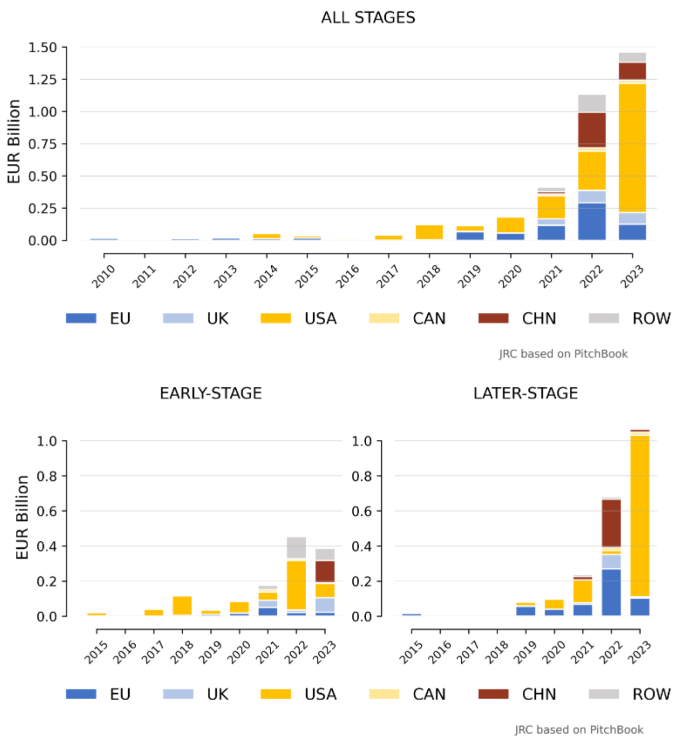
Over the 2010-22 period, global investments amount to a total of EUR 1 045 million. As seen in **Figure 13** later stages investments are the overwhelming majority of European investments, with the rest of the world having more or less a 50-50 split between early and late-stage investments. While the European ratio between early and late-stage investments has not changed much historically, the share of later stage investments in the rest of the world has increased remarkably in the last five years.

Figure 10 - Number of innovating companies (2016-21)



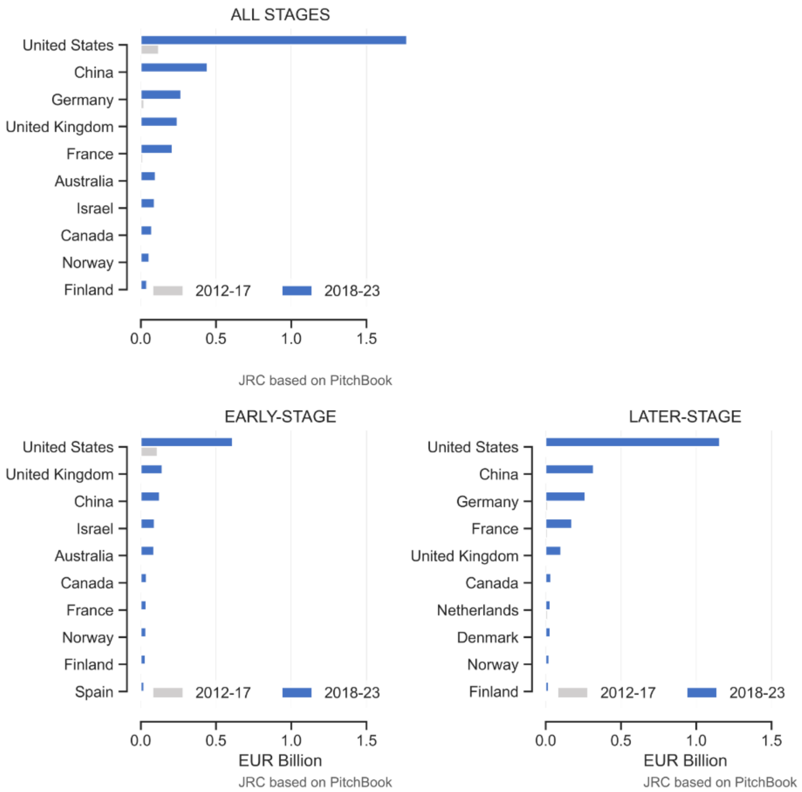
Source: JRC, 2023

Figure 11 - Global VC/PE investment, by region for all deals (top), early-stage deals (bottom left) and later-stage deals (bottom right).



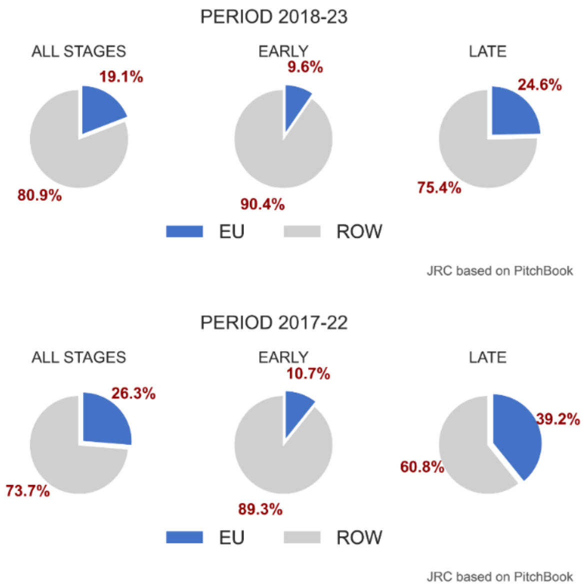
Source: JRC, 2024

Figure 12 - VC/PE investment in top 10 beneficiary countries, by period for all deals (top), early-stage deals (bottom left) and later-stage deals (bottom right) [EUR billion]



Source: JRC, 2024

Figure 13 - VC/PE investment share in the EU and in the ROW, by region for all deals (left), early-stage deals (center) and later-stage deals (right) - 6 year period comparison between current ceto edition (top) and previous (bottom).

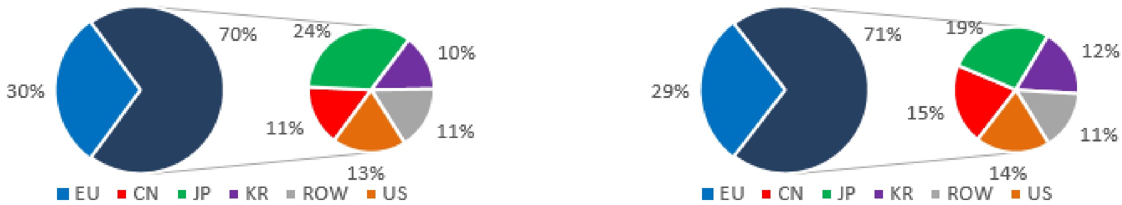


Source: JRC, 2024

2.6 Patenting trends

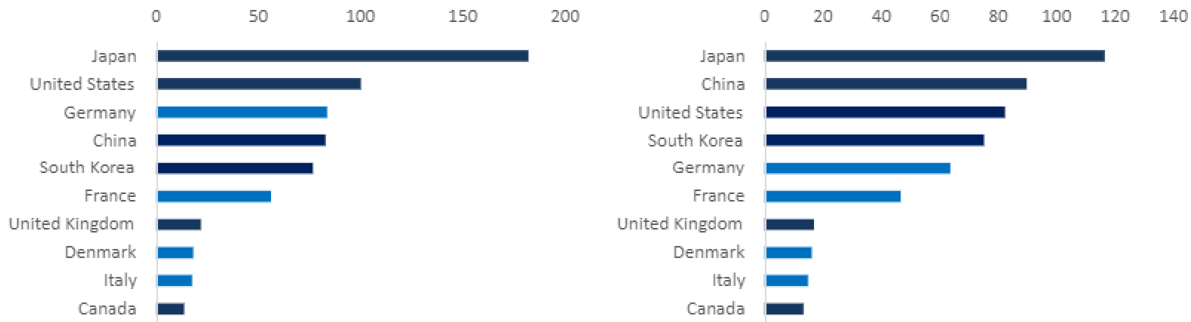
The trends highlighted in previous years are still valid and have been confirmed once again by the 2023 Edition of the European Climate-neutral industry competitiveness scoreboard [31]. When it comes to high value inventions, EU is still leading (with 31% of total share) alongside Japan. Germany is the best performing Member State thanks to the effort of Siemens (2nd worldwide behind Toshiba). Haldor Topsoe (Denmark) also plays a major role (top 10) while Hymeth (Denmark) and Bosch (Germany) fell a bit behind. As can be seen in **Figure 14**, EU innovations activities are undertaken by many different actors rather than a few highly innovative multinationals. Over the 2016-2019 period, EU companies mainly protected their innovations in the US (31%) and China (22%), as well as other jurisdictions outside major economics (39%).

Figure 14 - Share of global high value inventions (left: 2018-2020; right: 2019-2021)



Source: Joint Research Centre (JRC) based on data from the European Patent Office (EPO)

Figure 15 - Top 10 countries with high-value inventions (left: 2018-2020; right: 2019-2021)



Source: Joint Research Centre (JRC) based on data from the European Patent Office (EPO)

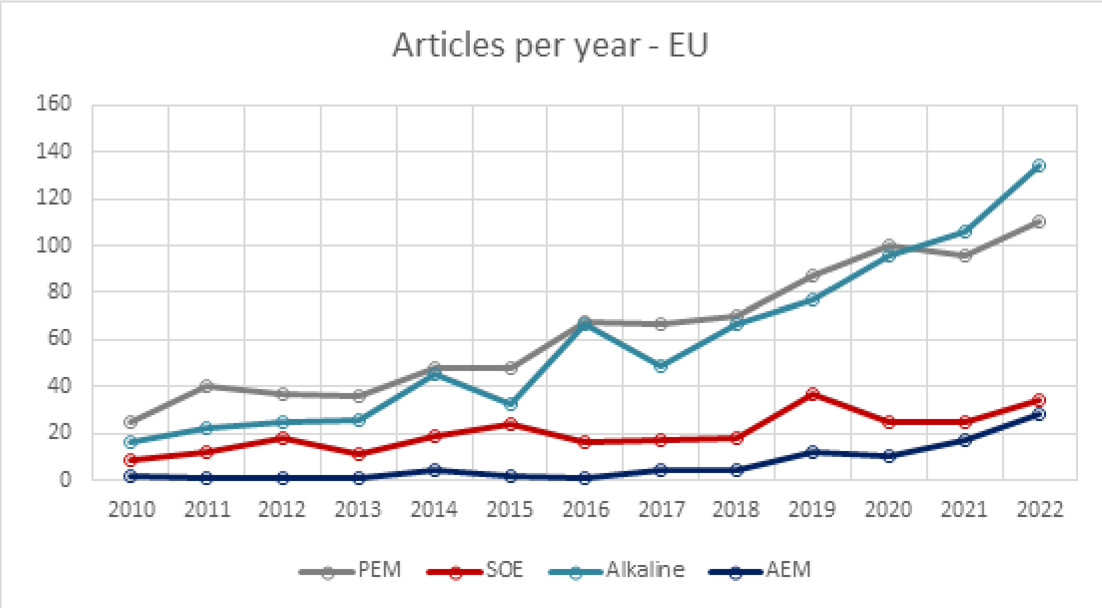
2.7 Scientific publication trends

As can be seen in

Figure 16, PEM and alkaline electrolysis are dominating the number of publications, with SOE and AEM more or less constant and significantly below in numbers. Both PEM and Alkaline electrolysis related publications from European institutions are steadily growing year after year since 2015. Germany is the most represented European country for each technology.

China is clearly leading in terms of number of publications for all types of electrolysis.

Figure 16 - Historical evolution of European number of publications on PEM, alkaline solid oxide and alkaline membrane electrolysis.



Source: JRC using TIM from Scopus database.

When appraising impact of the publications considered, Europe has a clear lead for PEM electrolyser technology and slight lead for solid oxide electrolysis, but clearly falls behind China when alkaline electrolysis is considered.

2.8 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 [29].

3 Value Chain Analysis

The scope of this chapter mainly covers the production stage of the clean hydrogen value chain with a focus on the manufacturing of electrolysis systems. The employment chapter covers a broader range of the value chain mainly due to a lack of disaggregated data.

3.1 Turnover

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.: Siemens).

However, some publicly traded manufacturers do provide financial data on their websites. The reported incomes for a selection of electrolyser manufacturers shows great discrepancies. For example, Thyssenkrupp Nucera AG reported a net income of EUR 22 million in 2023 [32]. ITM Power, a UK-based electrolyser manufacturer, has reported a reduction in its losses for the year ending April 2024, with a forecasted loss of GBP 39-44 million, down from its initial guidance of GBP 45-55 million. The company's revenue is expected to be between GBP 16-16.5 million, which is triple its 2022 revenue of GBP 5.2 million [33].

3.2 Gross value added

For the same reasons outlined for the category 'Turnover', retrieving information of gross added value it is extremely challenging.

3.3 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 (discussed in section **4.3**), 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.

3.3.1 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) [34]. 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 [35] 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 $kgCO_2/kgH_2$ [17].

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 [36].

3.3.2 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 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 [37].

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.

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 [38].

In conclusion, the water consumption to produce hydrogen varies greatly and depends on installation-specific parameters. In addition, water losses in industrial settings must also be accounted for. IRENA provides an overview of global water stress map indicating regions with low, medium or high water stress [39][49].

However, not all water will be consumed, and a large part will also be released locally or evaporated. 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.

3.3.3 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 [40] 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 on-going social LCA studies on electrolysis which will provide a good basis to evaluate potential social risks in the value chain of this 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 [40] 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 in particular, were found relevant in terms of social risks and very dependent on the addressed impact category.

3.4 Role of EU Companies

By the end of 2024, recent estimates based on 2024 announcements foresee a European electrolyser manufacturing capacity between 7.4 and 16.2 GWe/year based on OEM's headquarters location[2], [41].

[49] 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.

According to Hydrogen Europe, as of September 2023, European electrolysers manufacturing capacity amounted to about 3.9 GW/y (60% alkaline, 40% PEM and less than 1% solid oxide electrolysis) [14]. In the European Union, alkaline electrolysis technology accounts for approximately 58% of the total electrolyser manufacturing capacity. PEM technology makes up 41% of the overall capacity. Solid oxide and anion-exchange membranes technologies production capacity represented a negligible share of production capacity in 2023, but manufacturer announcements pose for an increase approaching the gigawatt scale in the following years driven by Genvia and Topsoe for SO (950 MWe/year by 2025) and Enapter for AEM [2].

In 2023, Germany was the European country with the largest manufacturing capacity (4.1 GWe/year, up from approximately 1.5 GWe/year in 2022) followed by Belgium (2 GWe/year) and Norway (1.1 GWe/year) according to some estimates [2].

By 2030, the European manufacturing capacity could reach between 27.8 and 31 GWe/year [2], [14].

Electrolysers are currently mostly produced with manual and/or semi-automated processes suited for small volume production. Perceived as an important leverage for driving down electrolysers cost, there is a strong push from companies towards a higher degree of automation of the whole manufacturing processes. Based on the few examples currently available, lead times for new electrolysers manufacturing sites are estimated to take between 1 and 3 years [41]. Most manufacturers are currently in the design/pre-operation phases and expect entering full scale operation of their manufacturing capacities between 2025-2030. According to Hydrogen Europe [17], the most cited reasons for recent delays in deployment of European capacities include "regulatory uncertainty", "lack of financial incentives", and "supply chain/ pandemic delays". Estimated costs for setting up a new manufacturing facility, or upgrading an already established one for Europe is a difficult exercise, since it depends on the targeted technology, the adopted system design and the amount of process automation.

3.4.1 Perceived overcapacity

Based on available estimates, there seems to be approximately between 12.4 and 16.2 GW/year of nameplate manufacturing capacity in Europe, where up to an optimistic 500 MWe of electrolysis capacity is expected to be installed in 2024 and 2 GWe to be installed by the end of 2025 (see **Section 2.2**). If all the electrolysers to be installed in Europe would actually be assembled in Europe, European factories would run at barely 15% of their announced capacity. This gap between the maximum theoretical production capacity and the actual production of the plant is often referred to as overcapacity by analysts. However, this perceived overcapacity fails to consider two main aspects:

1. Although large giga-factories are being built, manufacturers do not necessarily invest in the machines nor hire/train the required workforce to operate these machines in order to run the factory at its full capacity.
2. "Electrolyser manufacturing" usually means the activities related to the assembly of sub-components into an electrolysis stack. Most of the OEMs are actually not manufacturing all of the required sub-components themselves. This raises then the issue of the constraints from the upstream supply chain. As of today, there is no consolidated information about the European supply network and its capacity to produce the required sub-components at the cost, speed and quality required to follow any potential increase of stack assembly activities.

It seems likely that the current expected manufacturing capabilities based on announcements could be downsized. It is expected that, should larger orders be contracted in the near-future, workforce would be hired, trained and the supply chain would mature both in Europe and globally.

3.5 Employment

As regards to employment across the whole value chain, various studies show different results, due to the different methodology and assumptions adopted (for example: direct versus indirect jobs, sectors of employment including manufacturing of fuel cell vehicles, etc.).

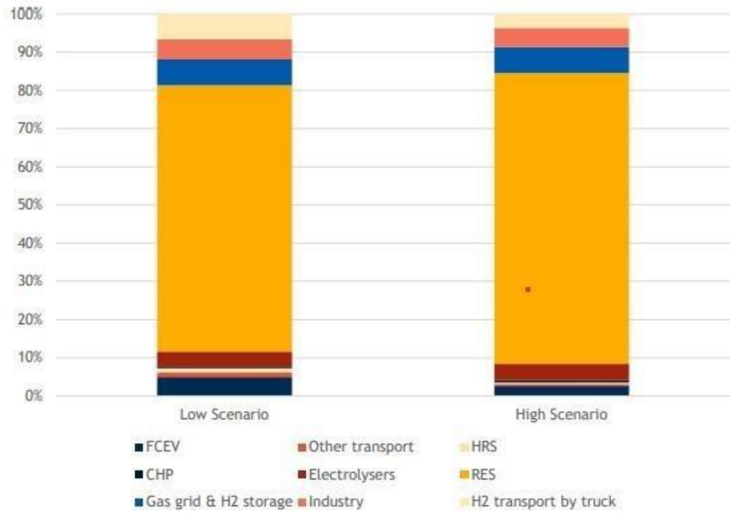
A study commissioned by the EC DG Energy[50] does not single out clear figures for electrolyser value chains but evidences a significantly larger fraction of jobs located in sectors linked with the production of renewable electricity than in sectors linked with hydrogen technologies. The electricity sector is expected to be the largest

[50] Hydrogen generation in Europe: Overview of costs and key benefits, ASSET study, 2020 Investment projections assume 40 GW of renewable hydrogen as well as 5 MT of low-carbon hydrogen by 2030, and 500 GW of renewable electrolysers by 2050.

sector of employment linked with large scale renewable hydrogen deployment in Europe (Electricity production would account for 5.9 million jobs created for each billion euros of investment and an estimated 7 million jobs in the electricity sector for each billion euros of investment).

According to a study published by the Fuel Cell Joint Undertaking [42], hydrogen-related investments and operations are estimated to generate 29 270 – 106 980 direct jobs (in production and operations & maintenance) and contribute to further 74 790 – 250 650 indirect jobs, by 2030. Total job generated by 2030 could be in the range 104 060 – 357 630 jobs. These numbers are based on two different demand scenarios for hydrogen demand: 1.2 MtH_2/y for the lower boundary and 5.4 MtH_2/y for the upper boundary. The study considered assumes that as hydrogen demand grows the number of fulltime jobs created for unit of hydrogen demand will grow marginally smaller. If the figure provided in the study are extrapolated up to a yearly 10 Mt hydrogen demand total job creation should grow up to roughly 440 000 jobs.

Figure 17 - Value Added Share per Value Chain Segment – EU + UK.



Source: Fuel Cell Joint Undertaking, Opportunities for Hydrogen Energy Technologies and NECPs, 2020

Notes: Fuel Cells Electric Vehicles (FCEV), combined heat and Power (CHP), Hydrogen Refuelling Stations (HRS), Renewable Electricity Sources (RES).

Although no aggregated information is available so far, the recent development in electrolyser manufacturing might give a first indication of the direct jobs required in the factories. ITM 1-GW electrolyser manufacturing plant employing 320 people in August 2021 [43]. Cummins' 500-MW electrolyser manufacturing plant, starting operation in 2024, will employ at least 65 direct jobs on the manufacturing site [44]. Nel's Heroya-based manufacturing plant targets approximately 70 direct jobs creation for running the two factory lines for a total of 1 GW production capacity by the end of 2024 [45].

Investments in electrolysers would represent a minor part of the overall value of the employment, with the main sector being the job creation in RES production.

3.6 Energy intensity and labour productivity

It is difficult to defined figures for these categories since they are not officially tracked.

3.6.1 Energy intensity

3.6.2 Labour productivity

3.7 EU Production Data

No PRODCOM data is available for water electrolysis systems, renewable hydrogen, or hydrogen produced by water electrolysis. The available PRODCOM code does not distinguish between different production methods and therefore does not allow to provide relevant information on hydrogen produced via water electrolysis.

4 EU Market Position and Global Competitiveness

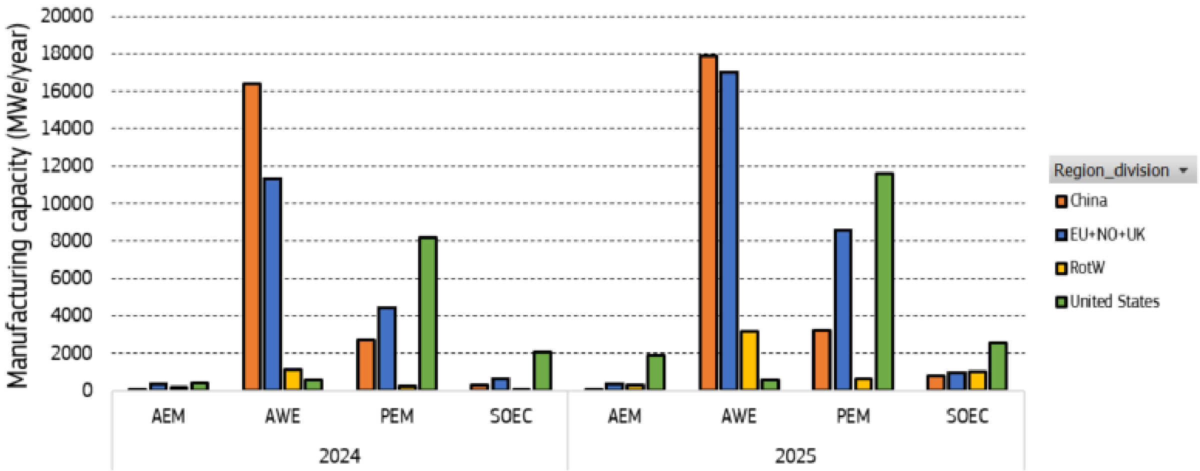
4.1 Global & EU market leaders

According to available estimates, global shipments likely surpassed 1 GWe in 2023, with expected shipments for 2024 likely to more than double with respect to 2023, up to 3-4.5 GWe [46] and [2]. China is expected to remain by far the biggest market in terms of capacity.

As described in Section 3.4, European stack assembly capacity ranges is estimated to reach 7 – 15.7 GWe/year by the end of 2024 [2], [16], up from an estimation of operational manufacturing capacity of 3.9 GWe/year in September 2023 [14], [16]. In 2023, alkaline manufacturing capacity represented 58% of the manufacturing capacity, where PEM represented 41% [14].

In 2024, the global estimated manufacturing capacity would likely reach between 40 - 54 GWe/year based on analysts' estimates [2], [16], [41] (up from around 25 GWe/year [16], [41] in 2023, and 13-14 GWe/year in 2022)[41]. A breakdown of the global manufacturing capacity according to the location of the OEMs' headquarters is shown in **Figure 18**.

Figure 18 – 2024-2025 manufacturing capacity per electrolyser type and per region of OEMs' headquarters.



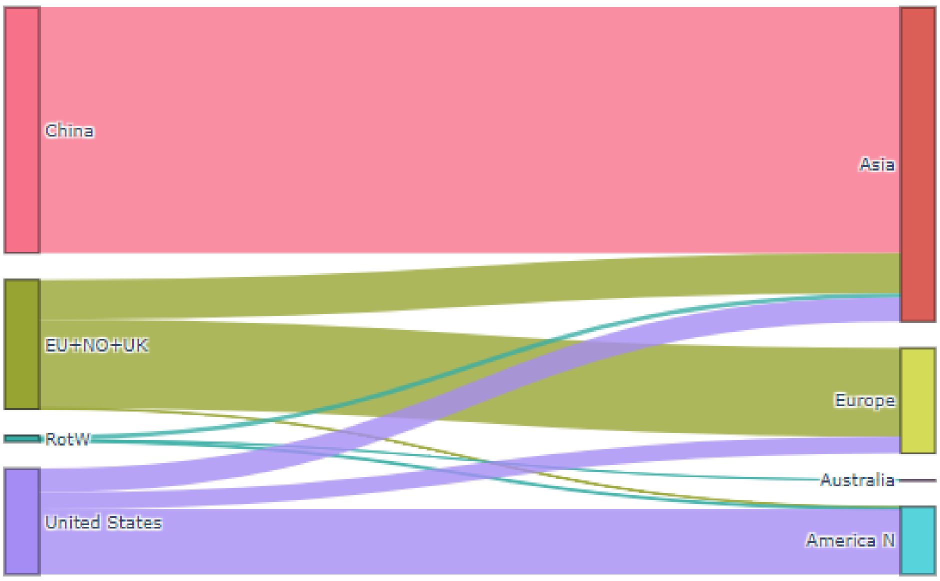
Source : JRC analysis based on various public and commercial sources (Rystad Energy, OEMs websites). (2024). Announced projects and projects in operations or under construction are shown, with a high uncertainty embedded in the actual commissioning year of the factory. The results differ across analysts and commercial data sources and the variability is not reflected in this plot. AWE refers to Alkaline water electrolyser

This means Europe could represent at least 25 % of the global manufacturing capacity in 2024. However, these values refer mostly to the headquarter locations of the manufacturers, without considering the factory locations. **Figure 19** and **Figure 20** illustrates the relationship between regions of the OEMs headquarters and the actual location of the factory, based on 2023 and 2024 data from [2].

China is the region with the largest manufacturing capacity with at least 20 GWe/year planned to enter in operation by the end of 2024 based on OEMs' headquarters locations, and focussing almost exclusively on alkaline technology (16.4 GWe/year by the end of 2024). This is line with previous estimates for 2022-2023 which allocated more than half of worldwide alkaline electrolysis manufacturing capacity to Chinese companies, and more than half of the production capacity for PEM electrolysers to American companies [19].

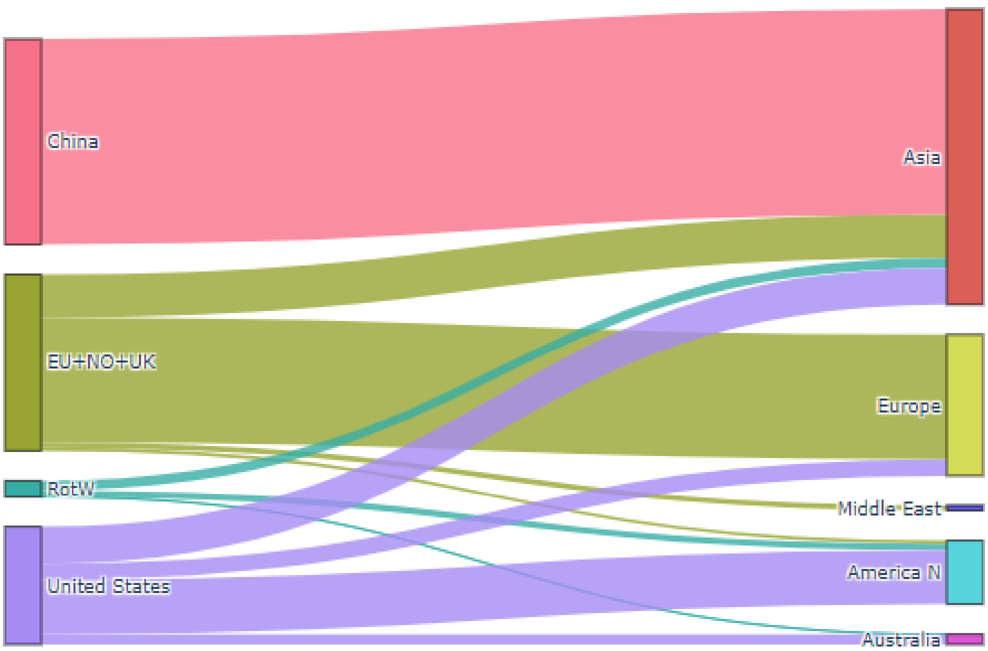
However, estimates for 2024-2025 foresees a rapid uptake of US manufacturing capacity for PEM electrolysers, as shown in Figure 18**.** According to some analysts, the U.S. has a manufacturing capacity close to the European with approximately 11.2 GWe/year (according to OEM's headquarters locations) posed to be commissioned in the end of 2024, with a focus on PEM electrolysis (8.2 GWe/year).

Figure 19 - Headquarter versus factory locations of electrolysers manufacturers (factory in operations in 2023)



Source: JRC analysis based on data from multiple public and commercial sources (2024). The size of the source and target rectangles show the relative share of manufacturing capacity against global capacity.

Figure 20 - Headquarter versus factory locations of electrolysers manufacturers (factory planned to enter operations in 2024)



Source: JRC analysis based on data from multiple public and commercial sources (Bloomberg, Rystad Energy, OEMs websites (2024) The size of the source and target rectangles show the relative share of manufacturing capacity of each region against global capacity.

Based on company announcements, IEA estimates the global manufacturing capacity to reach between 100-136 GW/y by 2030 if all planned and announced production plants become operational by then [47] [48]. Hydrogen Europe estimates that the European share of manufacturing capacity by 2030 could reach 27.8 GWe/year, or 20 % of a total global installed capacity of approximately 137 GWe/year [14].

Europe therefore may reduce its global market share down to 20% with China undisputedly dominating the current production market for alkaline and having the highest worldwide production capacity [46].

In addition, most of the locations of future manufacturing capacities are not chosen or revealed yet, adding large uncertainty when it comes to estimates long-term market shares trends.

The electrolysers' manufacturing market is currently going through a tumultuous growth process, characterised by vertical integrations and announcements concerning new players. This occurs especially on the Chinese market with joint ventures between European and American manufacturing companies forming partnerships with Chinese, Australian or Indian companies on mature and less mature technologies [49] [46]. This allows electrolyser producers to exploit significant lower production costs and have access to rapidly growing demand in areas which have abundant and cheap renewable electricity production potential.

Because of the lack of complete, up-to-date and reliable data, a very high degree of uncertainty is embedded into these analysis. The values are however plotted to show short-term trends expected to take place in the next couple of years.

4.2 Trade (Import/export) and trade balance

From the analysis of available trade information, currently hydrogen trade does not play any major role in hydrogen markets. In 2020, the total amount of hydrogen exported by EU countries both to other EU member states and to other countries can be estimated as 0.013 Mt; which is less than 0.2% of total European hydrogen consumption. Most of this trade occurred across the Netherlands, Belgium, and France, with only 696 tonnes (5%) exported to non-EU countries.

As can be derived from available data [31], the amount of hydrogen traded across borders in Europe does not have a significant economic weight, with around EUR 200 million mobilized in four years across few countries. From the information available it is not possible to ascertain the origin of the hydrogen traded, but it is reasonable to assume that most, if not all the hydrogen traded, is of fossil origin, or obtained as by-product.

The market for renewable fuels is poised to grow and gradually replace the fossil fuel international trade. IRENA [50] estimates a 2050 international market which is of the same magnitude of current fossil fuel market, but more diversified and in which hydrogen and hydrogen-derived fuels add up to about 25% of international trade market.

Announcements for large-scale hydrogen production processes dedicated to export are growing at a fast pace. Estimates for a 2030 timeframe vary wildly and only a significant minority of these projects have reached final investment decision status[18]. Best case estimates range between 12 MtH_2/y [18]up to 24 MtH_2/y [19] available for international trade. Only about a third of planned production capacity is already located close to a port which have suitable infrastructure, even if there are plans to expand relevant maritime infrastructure. Ammonia seems to be the carrier of choice with more than 90% of announcements expected to deliver hydrogen in the form of ammonia. There is however a significant fraction of projects which have not yet announced any hydrogen carrier of choice.

4.3 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%[51]. As can be seen from **Figure 21**, 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 [51].

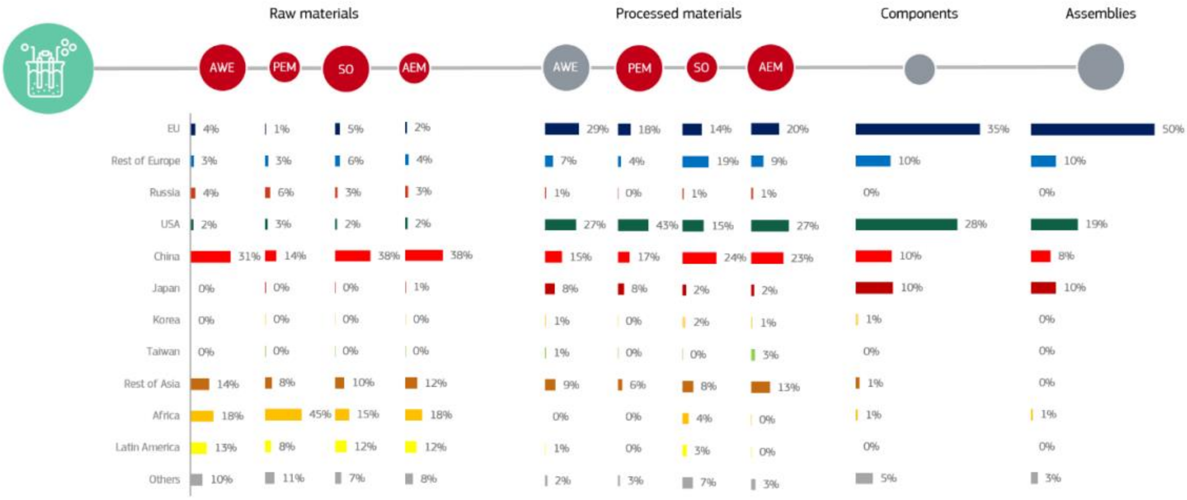
Nickel, manganese, chromium and iron are common materials for all electrolysers. Aluminium, cobalt, copper, lanthanum, molybdenum, natural graphite and zirconium are also used, but to a lesser extent. Other key materials which are more specific for some electrolyser technology can also be identified, 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

[51] JRC analysis for DG GROW.

at large scale, if the current catalyst loading and lack of recycling options are going to remain unchanged [52], [53]. While rare earths, which are critical for manufacturing oxide conducting electrolytes for SOEC and are also used in PCC, are mainly supplied by China.

Figure 21 - Supply chain for electrolysers.



Source: JRC, Foresight study 2023 [51].

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 introduces additional 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 in order to achieve global scale deployment compatible with the expected scenarios [52].

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 in order 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 electrolysers manufacturing as early as 2030 [54] . 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 I predicted to gradually decline [54]. 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 market for renewable hydrogen and water electrolysis is once more growing with respect to the previous year, both in Europe and globally. Despite clear signs of growth and increased policy support, which should accelerate even more in the coming years, the volumes of renewable hydrogen currently produced are still negligible and do not reach the ambition of the European hydrogen strategy and REPowerEU plan. International trade of renewable hydrogen is not yet a reality anywhere in the world even if the number of announced projects is also growing. Adequate standardised approaches to certification for renewable hydrogen at international level are yet to bear fruit, despite positive examples of international collaboration on the matter such as for International Partnership for a Hydrogen Economy (IPHE), the International Energy Agency (IEA), and the International Organization for Standardization (ISO). With regard to trade of the stacks and electrolysers currently there are no developed NACE trade codes.

Recent assessments point at renewable hydrogen production costs and larger electrolysers system (multi-MW) costs being higher than what was considered in previous estimates. With natural gas bills reducing from the highs reached in 2022, the competitiveness of renewable hydrogen production against fossil fuels based production is significantly decreased. For sectors where profit margins are relatively small the use of expensive hydrogen feedstock can jeopardise the viability of a business case currently based on a cheaper supply of natural gas. The willingness to pay depends on the sector and final use of the hydrogen, with higher willingness-to-pay for mobility applications rather than industry (based on the results of the European hydrogen bank first auction).

Manufacturing capacity of electrolysers is also poised to accelerate everywhere globally with the concrete risk of not matching the current market appetite for electrolyser deployment, which is driven by demand for renewable hydrogen. It seems that matching the public support for renewable hydrogen production and creating demand will play a critical role in shaping markets in the coming years. Another major challenge will be the deployment of an adequate supply of renewable and affordable electricity, which could be a crucial bottleneck towards the path of achieving European strategic production goals for renewable hydrogen.

The fact that current manufacturing capacity is underutilised points out at possible chokepoints in the supply of necessary components, or materials for stack manufacturing and in insufficient demand for renewable hydrogen, hindering the acceleration of the deployment of full-scale electrolysers. An overproduction capacity for system manufacturers can also be a driver for increased international competition, potentially exacerbated by the lower lead times and lower costs offered by Asian producers which are in the order of 6-7 months, while the European and Western manufacturers deliver them on average within 22 months.

Despite a promising pipeline of announced projects in Europe, only a fraction of these have reached an advanced stage and have a secured deployment timeline ahead. Securing offtakers and having a well-defined business case appears to be one of the main obstacles of new projects. In other geographical areas, such as Asia, demand for large scale electrolysers deployment is granted by a strong intervention of public resources.

Despite several initiatives aiming at fully assessing the environmental and social impacts of large-scale deployment of hydrogen technologies (e.g.: hydrogen emissions, pressure on water resources and the social implications of raw materials extraction), the lack of mature models and enough field data do not allow drawing accurate conclusions at this point. However, for regions already under water-stress, water consumption for water electrolysis could add additional pressure on these resources.

European dependency on critical raw materials and processed materials remains, with an estimated range of 1%-5% of CRM being sourced domestically. It seems that actions aimed at reducing the use of critical raw materials and incentivise recycling are not yet impactful enough and no improvement have been observed with respect to the previous year. Finding substitutes to the “forever chemicals” PFAS substances used in some of the membranes of electrolysers will remain a research challenge until suitable and cost effective solutions are available.

Europe continues to have a strong presence as an international patenting actor. Europe is also active in R&D actions spanning the whole continent and has a leading global scientific publication record together with China and the US.

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List of abbreviations and definitions

Abbreviations	Definitions
AEM	Anion Exchange Membrane
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
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
PGM	Platinum Group Metal

Abbreviations	Definitions
RES	Renewable Energy Source
SOE	Solid Oxide Electrolyser
TRL	Technology Readiness Level
UK	United Kingdom
USA	United States of America
VC	Venture Capital

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Annex 1 Summary Table of Data Sources for the CETO Indicators

– Theme	– Indicator	– Main data source
– Technology maturity status, development and trends	– Technology readiness level	– JRC analysis
	– Installed capacity & energy production	– IEA Hydrogen Project Database
	– Technology costs	– Commercial specifications
	– Public and private RD&I funding	– JRC analysis (ERIC team)
	– Patenting trends	– JRC analysis (ERIC team)
	– Scientific publication trends	– JRC analysis (TIM team)
	– Assessment of R&I project developments	– See References
– Value chain analysis	– Turnover	–
	– Gross Value Added	–
	– Environmental and socio-economic sustainability	– See References
	– EU companies and roles	– See References
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– Global markets and EU positioning	– Global market growth and relevant short-to-medium term projections	– See References
	– EU market share vs third countries share, including EU market leaders and global market leaders	– See References
	– EU trade (imports, exports) and trade balance	–
	– Resource efficiency and dependencies (in relation EU competitiveness)	– JRC analysis

Annex 2 List of projects funded under the Innovation Fund

Project name	Calls	EU Grant [EUR]	Electrolysis capacities	Sector
AIR	2021 Large-scale	97,000,000.00	N/C	Chemicals
ASTURIAS H2 VALLEY	2022 Large-scale	18,072,962.00	N/C	Hydrogen
BioOstrand	2022 Large-scale	166,648,512.00	N/C	Biofuels and bio-refineries
Columbus	2022 Large-scale	68,600,000.00	N/C	Hydrogen
E-fuel Pilot	2022 Large-scale	40,000,000.00	N/C	Refineries
ELYAS	2022 Large-scale	51,926,000.00	N/C	Manufacturing of components for production of renewable energy or energy storage
ELYgator	2021 Large-scale	99,000,000.00	N/C	Hydrogen
eM-Rhone	2022 Large-scale	115,190,750.00	N/C	Chemicals
EnergHys	2022 Large-scale	75,000,000.00	N/C	Hydrogen
GAP	2022 Large-scale	203,766,000.00	N/C	Chemicals
GIGA-SCALES	2022 Large-scale	11,031,000.00	N/C	Manufacturing of components for production of renewable energy or energy storage
GRAMLI	2022 Large-scale	48,500,000.00	N/C	Chemicals
GreenH2	2021 Small-scale	4,492,131.00	N/C	Hydrogen
GreenH2CY	2021 Small-scale	4,499,877.00	N/C	Refineries
GREEN MEIGA	2022 Large-scale	122,917,845.00	N/C	Chemicals
H2GS H2 Green Steel	2022 Large-scale	250,000,000.00	700	Iron and steel
H2 Valcamonica	2020 Small-scale	4,430,421.00	N/C	Hydrogen
HH	2021 Large-scale	89,000,000.00	N/C	Hydrogen
HYBRIT demonstration	2020 Large-scale	143,000,000.00	N/C	Iron and steel
HydrOxy	2022 Large-scale	49,212,730.00	N/C	Hydrogen
HySkies	2021 Large-scale	80,200,000.00	N/C	Refineries

HyNCREASE	2022 Large-scale	5,224,360.00	N/C	Manufacturing of components for production of renewable energy or energy storage
N2OWF	2021 Large-scale	95,876,645.00	N/C	Wind energy
SEAWORTHY	2022 Large-scale	26,000,000.00	N/C	Hydro/Ocean energy
SHARC	2020 Large-scale	88,286,266.00	N/C	Hydrogen
T-HYNET	2022 Large-scale	62,491,697.00	N/C	Hydrogen
TopSOEC	2022 Large-scale	94,000,000.00	N/C	Manufacturing of components for production of renewable energy or energy storage
TRISKELION	2022 Large-scale	48,846,672.00	N/C	Refineries
VOZARTEK	2021 Small-scale	4,470,000.00	N/C	Hydrogen
ZE PAK green H2	2020 Small-scale	4,460,000.00	N/C	Hydrogen
GH2A	2022 Large-scale	61,987,272.00	N/C	Hydrogen
GreenH2LaRobla	2022 Large-scale	42,424,204.00	N/C	Hydrogen
eNRG Lahti	EU hydrogen bank auction	N/C	90	N/C
El Alamillo H_2	EU hydrogen bank auction	N/C	60	N/C
Grey2Green-II	EU hydrogen bank auction	N/C	200	N/C
HYSENCIA	EU hydrogen bank auction	N/C	35	N/C
SKIGA	EU hydrogen bank auction	N/C	117	N/C
Catalina	EU hydrogen bank auction	N/C	500	N/C
MP2X	EU hydrogen bank auction	N/C	500	N/C

Annex 3 List of scenarios considered in the statistical analysis of the aggregated forecast of hydrogen demand

- Aurora - Central (2021)
- Aurora - High (2021)
- Aurora - Low (2021)
- BP - Net-zero (2020)
- CAN - 1.5°C (2020)
- CHJU Roadmap - Ambitious (2019)
- CHJU Roadmap - BAU (2019)
- Deloitte/CHJU - Ambitious (2023)
- Deloitte/CHJU - Conservative (2023)
- Deloitte/CHJU - Moderate (2023)
- DNV - Net-zero (2021)
- EC - 1.5LIFE (2018)
- EC - 1.5TECH (2018)
- EC - Baseline (2018)
- EC - Circularity (2018)
- EC - COMBO (2018)
- EC - Electrification (2018)
- EC - Energy Efficiency (2018)
- EC - Fit-for-55 (2021)
- EC - Fit-for-55 (2022)
- EC - Hydrogen (2018)
- EC - MIX (2020)
- EC - PtoX (2018)
- EC - REPowerEU (2022)
- ENTSOG - Distributed (2022)
- ENTSOG - Global Ambition (2022)
- EUCalc - Tech (2020)
- Guidehouse - EHB (2021)
- IFS - 1.5 scenario (2019)
- JRC - GECO (2021)
- JRC - LCEO Net Zero (2020)
- JRC TIMES - Net-zero (2021)
- McKinsey - Breakthrough (2020)
- McKinsey - Cost Optimal (2020)

Annex 4 Energy System Models and Scenarios: POTEnCIA and POLES-JRC

AN 4.1 POTEnCIA Model

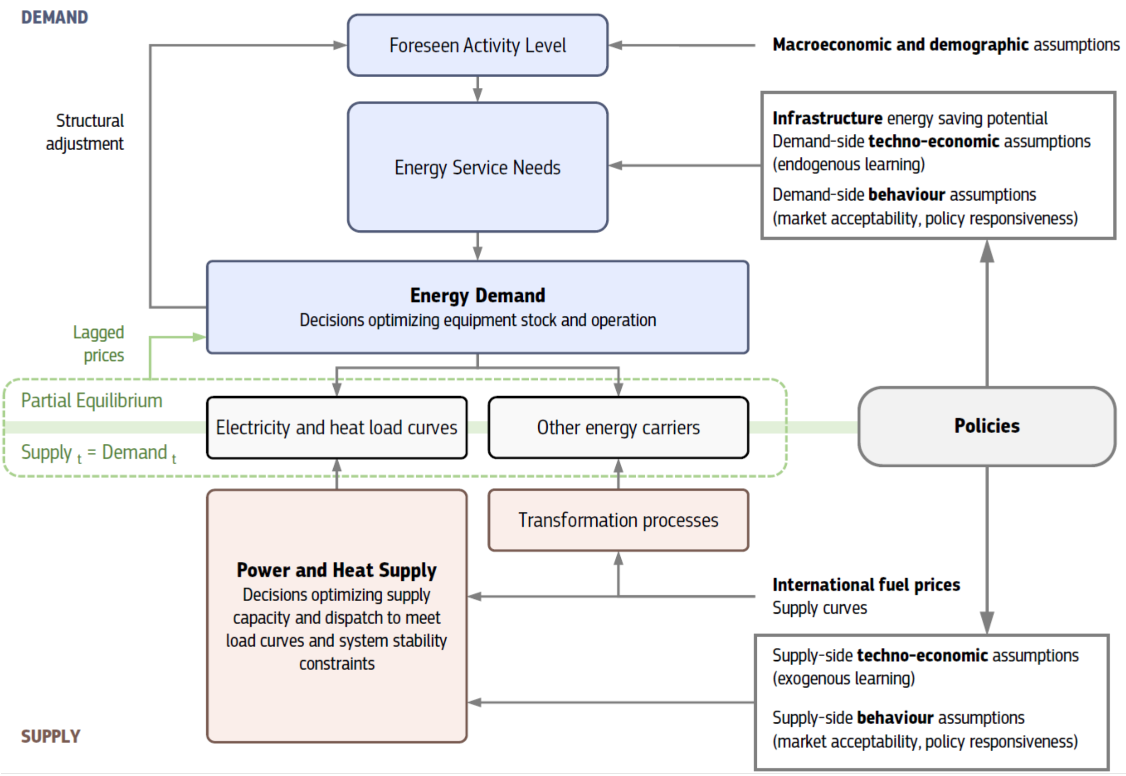
AN 4.1.1 Model Overview

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 (**Error! Reference source not found.**; detailed in [55], [56]) focuses o n 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 22 - The POTEnCIA model at a glance



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

This core 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 ([57]).

AN 4.1.2 POTEnCIA CETO 2024 Scenario

The technology projections provided by the POTEnCIA model 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. A more detailed description of the POTEnCIA CETO 2024 Scenario will be available in the forthcoming report ([58]).

AN 4.2 POLES-JRC model

AN 4.2.1 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.

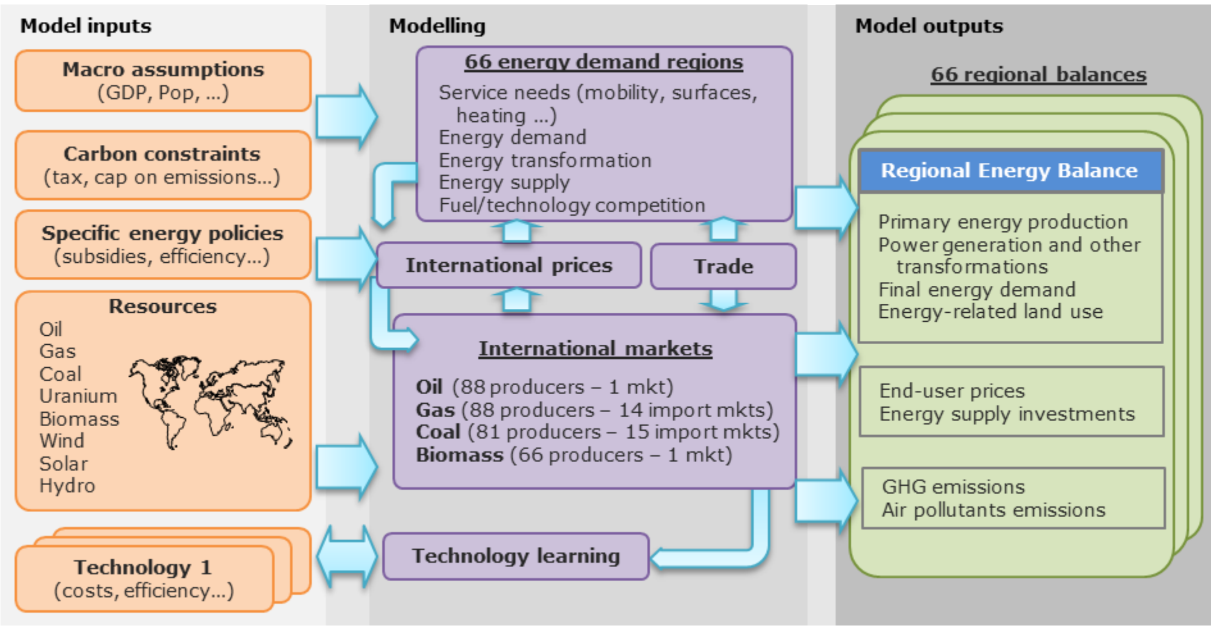
POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables) to transformation (power, biofuels, hydrogen and hydrogen-derived fuels such as synfuels) and final sectoral demand (industry, buildings, transport). International markets and prices of energy fuels are calculated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all detailed 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 applied for the CETO project is specifically enhanced and modified to capture learning effects of clean energy technologies.

POLES-JRC results are published within the series of yearly publications "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

A detailed documentation of the POLES-JRC model is provided in ([59]).

Figure 23 - Schematic representation of the POLES-JRC model architecture.



Source: POLES-JRC model

AN 4.2.2 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 by representative days with hourly profiles. For all renewables, regional resource potentials are considered.

Electricity demand
Electricity demand is calculated for all sectors taking into account hourly fluctuations through the use of representative days. Clean energy technologies using electricity consist of heat pumps (heating and cooling), batteries and fuel cells in transport, and electrolysers.

Power system operation and planning
Power system operation allocates generation by technology to each hour of representative days, ensuring that supplying 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. Moroever, hydrogen trade is modelled, considering hydrogen transport with various means (pipeline, ship, truck) and forms (pressurised, liquid, converted into ammonia).

Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM-G4M model ([60]). This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass-for-energy potential, production cost 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

The POLES-JRC model was enhanced to capture effects of learning of clean energy technologies. To capture these effects, a one-factor learning-by-doing (LBD) approach was applied to technologies and technology sub-components, aiming at endogenising the evolution of technology costs.

POLES-JRC considers historical statistics and assumptions on the evolution of cost and capacities of energy technologies until the most recent year available (this report: 2022/2023). Based on the year and a capacities threshold, the model switches from the default time series to the endogeneous modelling with the one-factor LBD approach. Within the LBD, the learning rate represents the percentage change of the cost of energy technology based on a doubling of the capacity of the energy technology.

This generic approach is applied on a component level to capture spillover effects as well. For instance, a gasifier unit is used as component for several power generating technologies (e.g. integrated gasification combined cycle, IGCC) as well as for several hydrogen production technologies (e.g. gasification of coal and biomass). Therefore, the component-based LBD approach allows to model spillover effects not only across technologies, but also across sectors. Also, it allows to estimate costs for emerging technologies for which historical experience does not yet exist.

Moreover, for each component a floor cost is specified which marks the minimum for the component's investment cost and serves as limitation for the cost reduction by endogenous learning. Cost reductions by learning in POLES-JRC slow down when the investment cost approaches the floor cost.

The described method above applies not only for the overnight investment cost of energy technologies, but as well for operation and maintenance (OM) costs, which also decrease as technologies improve, and for efficiencies. In the model, OM costs diminish synchronously to the decrease of total investment cost of the technology. The efficiency of renewables is implicitly taken into account in the investment cost learning and the considered renewable potentials. For most technologies the efficiencies are endogenously modelled.

AN 4.2.3 Global CETO 2°C scenario 2024

The global scenario data presented in the CETO technology reports 2024 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 2024* and its specific POLES-JRC model configuration is described in detail in the forthcoming report "*Impacts of enhanced learning for clean energy technologies on global energy system scenario*" ([61]).

The *Global CETO 2°C scenario 2024* 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 2023), 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.

The *Global CETO 2°C scenario 2024* differs fundamentally from the *Global CETO 2°C scenario 2023* used in the CETO technology reports in 2023 in various aspects[52]:

- The version of the POLES-JRC model used for the Global CETO 2°C scenario has been further enhanced and modified to capture effects of endogenous learning of clean energy technologies and, furthermore, several technology representations were further detailed, e.g. DAC (composition of renewable technologies, batteries and DAC unit), fuel conversion technologies (for hydrogen transport) and batteries in transport.
- The techno-economic parameters have been thoroughly revised and updated taking into account the expertise of the authors of the CETO technology reports.

As a result, major scenario differences occur in the *Global CETO 2°C scenario 2024* regarding DAC, synfuels, CCS power technologies, wind power and ocean power.

AN 4.3 Distinctions for the CETO 2024 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 2024* (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 2100.
- The *POTEnCIA CETO 2024 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. Scenario results are presented for the EU27 until 2050.

[52] A description of the *Global CETO 2°C scenario 2023* can be found in Annex 3 of (Chatzipanagi et al., 2023).

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