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Water electrolysis and hydrogen in the European Union

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

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Contents

Abstract

This report is an output of the Clean Energy Technology Observatory (CETO). 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 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 Green Deal Industrial Plan classifies water electrolysis 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 through, while reducing EU dependency for the supply of Critical Raw Materials through the Critical Raw Materials Act[6].

The European Hydrogen Bank, expected to be operational in 2023, aims at long-term "offtake agreements" between producers and buyers with a first auction of EUR 800 million in Q3 2023 and a maximum support of 4.5 EUR/kgH_2[7].

The EU has made available more than EUR 130 million for research activities on water electrolysis through Horizon 2020 (2014-2020). By 2022 the Clean Hydrogen Joint Undertaking has awarded ca. additional EUR 150 million for electrolysers development and an additional EUR 35 million to projects forming Hydrogen Valleys. The ETS Innovation Fund is also supporting projects deploying hydrogen technologies, especially in industrial settings. Nine projects were granted a total of EUR 406.6 million (2020 – 2022 calls). From all national Recovery and Resilience Plans (RRPs), EUR 42 billion are allocated to categories which include hydrogen technologies among other technologies, and EUR 12 billion dedicated exclusively to hydrogen technologies.

As of October 2023, two sets of Important Projects of Common European Interests (IPCEIs) dedicated to hydrogen have been officially launched. A total of EUR 10.6 billion of state aid were approved, supposedly unlocking another EUR 15.8 billion in private investments.

With regard 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[8]: 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 11.5 Mt per year[9] [1]. Water electrolysis accounted for about 0.25% of this total. According to estimates from Hydrogen Europe, the total installed power-to-hydrogen capacity in the EU, EFTA and UK grew from 85 MW in 2019, to 95 MW in 2020 and has reached a cumulated 162 MW as of August 2022. By the end of 2023, short-term estimates point to a capacity reaching at least 191 MW and up to an optimistic 500 MW[10]. By the end of 2025, 1 371 MW are planned to enter operation in Europe.

[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] European Commission. Innovation Fund Auction – Terms and Conditions. August 2023.

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

[9] 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.

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

Estimates of global installed electrolysers' capacity stand in the range of 600-700 MW for 2022, -up from about 500 MW in 2021- and are expecting to approximately reach 2 GW by the end of 2023[11]. 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 2022 are around 200 MW and is expected to enter the gigawatt range (1.1 GW) in 2023. 2022 estimates of installed capacities in the U.S. are around 19 MW of which 16 MW is PEM; 291 MW of electrolysis capacity are expected to come online by the end of 2023. Global acceleration in electrolyser deployment would increase significantly from 2030 if project announcements are followed through and respect the announced timelines.

Global manufacturing capacity of electrolysers was estimated between 13 and 14 GW/y at the end of 2022. These capacities are expected to more than double at the end of 2023, reaching more than 40 GW/y, with around 3.3 GW/y in Europe [1]. In Europe, industry-led initiatives such as the European Clean Hydrogen Alliance[12] and the Electrolyser Partnership[13] have made concrete commitments to reach 25 GW of annual electrolysers manufacturing capacity by 2025. China is the region with the largest manufacturing capacity, covering at least the half of global volumes and focussing almost exclusively on alkaline. North America has a manufacturing capacity close to the European one but focussing currently more on PEM electrolysis.

Given the constant stream of project announcements and pledges both for hydrogen production capacities and electrolyser manufacturing capabilities, forecasts are highly unstable. However, all indicators point towards growing deployment prospects both in Europe and in the rest of the world, despite an associated expected maturation of the market with related delays and techno-economic recalibration of projects.

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 utilization 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 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.

A 2021 estimate for the costs of 1kg of hydrogen produced in Europe through Steam Methane Reforming was 2.65 EUR/kgH_2. According to estimates for 2021 from Hydrogen Europe, the European hydrogen production costs using directly renewable sources and in the best locations can be as low as 2.9 EUR/kgH_2 for southern European countries using solar PVs and 2.2 EUR/kgH_2 in case of generation capacity using wind in northern European countries. The European median is around 6.3 EUR/kgH_2 [1].

Concerning patenting trends, 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 (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%). The EU share is only 2%. Europe is strongly dependent on imported raw materials, but its global share grows progressively for processed materials and components, reaching a significant fraction when final products are considered.

The following SWOT table summarises the factors relating to the EU's competitiveness in the hydrogen electrolysis sector.

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

[12] European Clean Hydrogen Alliance

[13] Electrolyser Partnership - Hydrogen Europe

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

Strengths	**Weaknesses**
– Strong European regulatory framework with funding and financing support schemes. – The proposal for the Net Zero Industry Act identified water electrolysis, and the fuel cells technology as strategic ones. They would enjoy a faster permitting and access to funding. – The development of the financing scheme via the Hydrogen Bank (financing facility) to guarantee purchase of produced hydrogen between the producers the offtakes, which should be launched in 2023. – The Delegated Regulation on Additionality C(2023)1087 of renewable electricity to produce renewable hydrogen. – European companies have a strong presence as international patent holders. – Europe's (EU, EFTA and UK) cumulative deployments are accelerating. Deployment plans are growing year after year. – Significant number of European manufacturers.	– Very high European reliance on imports of critical raw materials, which is partly addressed through the proposal on the Critical Raw Materials Act. – Lack of a recycling infrastructure. – Manufacturing costs of the electrolyser systems. – Lack of long-term, large-scale operational experience (e.g., on performance degradation, scale effects, optimization strategies for balance-of-plants components and on-site infrastructure, etc.) – Additional emerging challenges for Research and Innovation, such as related to the replacement or substitution of materials in the membranes of electrolysers, some of which contain the PFAS. – Lack of mature European and international transport, storage, and distribution networks. – Lack of fully mature markets for electrolysers and clean hydrogen, especially on the demand side.
Opportunities	**Threats**
– Completion of the EU regulatory framework for renewable and low carbon hydrogen and gasses. – Momentum reached with manufacturing industry announcing the establishment of gigawatt factories in Europe. – The implementation of the Important Projects of Common European Interest approved in 2022 with effects on creating economies of scale and manufacturing capacities in Europe. A first set of projects "Hy2Tech" supports the development of hydrogen technologies across the value chain. The second set of projects "Hy2Use" supports infrastructure and industrial integration. – The increase of the cost of natural gas provides an opportunity for renewable hydrogen to achieve more easily cost competitiveness against fossil-based hydrogen. On the other hand, the spikes in prices of electricity in European markets have shown this as a hurdle to competitiveness. – Research and Innovation initiatives should pursuit opportunities to substitute PFAS, CRMs and define recycling solutions.	– Rising costs of electricity in the context of European economies have an impact on the cost competitiveness of electrolyser technology and on the levelized cost of hydrogen. – The 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. – Costs of production and assembly of stacks against other economies seem not competitive. – US and China maintain or accelerate their public efforts in advancing the deployment of low-carbon and renewable hydrogen production capacities as well as manufacturing capacities of hydrogen technologies.

Source: EC, 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 2022 report on the same topic [2].

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*[14]. It holds a significant potential for decarbonizing 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.

Therefore, renewable and low carbon hydrogen is set to play a crucial role in achieving the objectives of the European Green Deal, the REPowerEU plan (COM(2022) 230) and the net-zero emissions targets by 2030 and beyond [3]. 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 of electrolysers in 2024 and of 40 GW of electrolysers in 2030 and a European domestic production target of 10 Mt of renewable hydrogen;
- to import 10 Mt (out of which 4 Mt in the form of ammonia).

If 10 Mt of renewable hydrogen were to be produced exclusively through water electrolysis, the European hydrogen industry estimates a need for 140 GW of electrolysis capacity installed by 2030 [4].

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 revisions of the Renewable Energy Directive (REDIII) (2021/0218(COD)) set a target of 42% for renewable hydrogen in total hydrogen consumption in industry by 2030. 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.

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 Communication on the Hydrogen Bank C(2023)156 aims at setting up a framework for green premium schemes between hydrogen producers and offtakers for long term (up to 10 years) investment contracts. The financing is expected to come from the European Emissions Trading System allowances and the first auction is planned to take place in Q3 2023 with a budget of EUR 800 million with a maximum support of 4.5 EUR/kgH_2[15].

Political agreement on the Carbon Border Adjustment Mechanism has emerged in 2022, awaiting finalisation of the legislative process, where both hydrogen and ammonia would be subject to specific taxation rules when being shipped to European markets.

[14] 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.

[15] European Commission. Innovation Fund Auction – Terms and Conditions. August 2023.

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[16], thus amounting from about 80 up to 100 million tonnes of oil equivalent (Mtoe)[17] in 2050[18]. 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 [5].

The cooperation with industry has been fostered by the European Commission through the establishment of the European Clean Hydrogen Alliance gathering industry, public authorities, academia to discuss key challenges, including regulatory barriers and facilitation of access to finance.

At the international level, the Inflation Reduction Act (2022) adopted by the United States of America in 2022 and aiming at promoting support to renewable and low carbon technologies including hydrogen, has led to considerable discussions within industry groups and politically. 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 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 recognizes hydrogen's key role in the modernization of its energy systems, as stated in its 14th Five-Year Plan of Modern Energy System (2022)[19] and its 14th Five-Year Plan of Renewable Energy Development[20] (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 and 100 000-200 000 tonnes per year by 2025 of renewable hydrogen.[21]

As of 2023, more than 50 countries had released at least a national hydrogen strategy or roadmap[22], 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.

[16] Net total hydrogen consumption excludes hydrogen that is further processed to renewable fuels or liquids (see SWD(2020) 176).
[17] Equivalent to about 28-35 Mt of hydrogen.
[18] More than 20% in Fit-for-55 scenarios, summing together hydrogen and e-fuels.
[19] 国家发展改革委 国家能源局 – 关于印发《"十四五"现代能源体系规划》的通知, 2022
[20] 十四五"可再生能源发展规划（发布稿）, 2022
[21] NDRC, & NEA. Medium and Long Term Plan for the Development of Hydrogen Energy Industry (2021-2035). March 2022
[22] 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[23] [6]. The thermodynamic limit for dissociating water at room temperature through electrolysis is around 40 kWh/kgH_2.

The main electrolysis technologies [7], 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.
- 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.
- 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) [6]; 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.
- 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.

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 demonstrations reaching a power of hundreds of MW[24].

[23] 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.

[24] Examples of projects: GREENH2ATLANTIC, GreenHyScale (Akaline), REFHYNE II (PEM), and a 150 MW project developed by Ningxia Baofeng Energy Group in the autonomous region of Ningxia, central China.

Solid Oxide Electrolysers have been already tested in real life environment and planned demonstrations should deploy in the range of multi-MW scale soon[25]. 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[26].

Anion Exchange Membrane Electrolysers emerges now in small-scale commercial applications, as first deliveries of 1-MW AEM electrolysis systems are expected to take place in 2023. These electrolysers are today produced by only one European supplier[27].

2.2 Installed Capacity and Production

2.2.1 Current situation and short-term forecasts

In 2022, the hydrogen production capacity in Europe (EU + UK, NO, CH) could be estimated around 11.5 Mt/y [1] [9][28], against a global production capacity of around 124 Mt/y of hydrogen [8][29].

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 95.8% of total capacity.
- By-product electrolysis (i.e., hydrogen from chlor-alkali and sodium chlorate processes) totaling to about 3.6%.
- Reforming with carbon capture providing around 0.5% of total.
- Hydrogen produced via water electrolysis corresponding to only about 0.2% 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 162 MW (43% of this capacity deployed via FCH JU projects) as of August 2022 [1]. By the end of 2023, short-term estimates point to a capacity in Europe to reach at least 191 MW and up to an optimistic 500 MW[30]. Around 1.4 GW are planned to enter operation in Europe by the end of 2025 [10]. In Europe, Germany is the country with the highest installed electrolysis capacity (65 MW) [10]. From available data in 2022, PEM seems to be the technological choice for almost 60% of European capacity (84 MW) and alkaline 40% (57 MW) [1]. Regarding the source of electricity, around 60% of the installed electrolysis capacity is connected to the electrical grid, 23% to dedicated renewable sources and 17% is both connected to a dedicated source and the grid. The average project deployment size is around 1.3 MW alkaline and 1.5 MW for PEM. The average size of projects is expected to grow significantly in the coming years, from a few MW to more than 200 MW by 2025, even reaching multi-GW scale projects by 2028 according to project developer's announcements [1]. This has yet to be materialized.

Beyond Europe, estimations of global installed electrolysis capacity are in the range of 600 - 700 MW at the end of 2022 [11] [12]. Latest available information suggests a global capacity reaching the 2 GW mark by the end of 2023 [13].

China is now the geographical area where most of the growth in electrolysers deployment is expected to happen. Estimations of electrolysis capacity in China in 2022 are around 200 MW and is expected to reach 1.1 GW capacity installed in 2023 [11][14]. Estimates for the United States electrolysis capacity at the end of 2022 are around 19 MW of which 16 MW are using PEM technology [14]. In addition, 291 MW of electrolysis capacity are expected to come online in the US by the end of 2023 [14].

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

[26] 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.

[27] Enapter

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

[29] It includes 74 Mt H_2 in pure form and about 20 Mt H_2 mixed with carbon-containing gases used in industrial applications. It includes also around 30 Mt H_2 present in residual gases from industrial processes used for heat and electricity generation.

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

According to available estimates, shipments of electrolysers almost doubled for 2022 with respect to 2021, with a worldwide total of around 0.8 GW (0.5 GW in 2021) [11]. Global deployment started to accelerate in 2021-2022 and shipments are expected to be in the range of 2-3 GW at the end of 2023 [11]. Alkaline technology is the main technology choice, with a global share consistently above 70-75% in the last five years. China accounts for about 80% of worldwide shipments, with Europe and America having shares of roughly 10% each. About 84% of this capacity is alkaline, with the rest made up by PEM electrolysers.

2.2.2 Long-term perspectives

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 [1;8;9;11;15]. Recalibration for long-term forecasts have to be expected in every region of the world.

In particular for 2030, if project announcements follow through and respect current pledges, it will be possible in principle to reach the REPowerEU targets. As an example, an optimistic 2022 estimate by Hydrogen Europe [1] following announcements on power-to-hydrogen projects sees a forecasted deployment of more than 138 GW in EU, EFTA and UK combined by 2030. This is more than a fourteen-fold increase with respect to a 2021 projection. The European Clean Hydrogen Alliance alone identified a pipeline of over 840 project proposals across several EU sectors[31]. Other forecasts range between 5 GW to 60 GW of installed capacity in Europe by 2030 [11][14], demonstrating the volatile dynamics of the market.

In addition, based on recent announcements, analysts estimate, China is to reach between 5.4 GW [11] and 9.2 GW [14] by 2030, which seems underappreciated and will probably be recalibrated in the coming years. In the US, announcements summed up to a total of 4.8 GW installed by 2030 [11]. It is expected that the Inflation Reduction Act will increase the shipments of electrolysers to the U.S. to a level bigger than the shipments to European market [11]. Here again, a recalibration for 2030 forecasts is to be expected.

2.2.3 Hydrogen demand

With regards to the demand volume for hydrogen, the EU consumed in 2020 around 8.7 million tonnes per year [1] [9][32], out of about a 2021 global demand of 94 million tonnes per year of hydrogen [8] [15][33]. Nowadays, overall hydrogen production processes are almost completely based on the use of fossil fuels and are associated with large industrial processes.

The demand in the EU can be broken down as:

- ca. 50.5% as chemical feedstock for oil refining;
- ca. 29.5% for ammonia production;
- ca. 4.3% for methanol synthesis.
- ca. 7.3% for other chemical synthesis.
- ca. 4.7% for other uses (such as uses in the food industry, glass manufacturing, or power generation cooling).
- ca. 3.7% for energy production (mostly in industrial applications where hydrogen is combusted for its energy content).
- ca. 0.001% is currently used for transport applications.

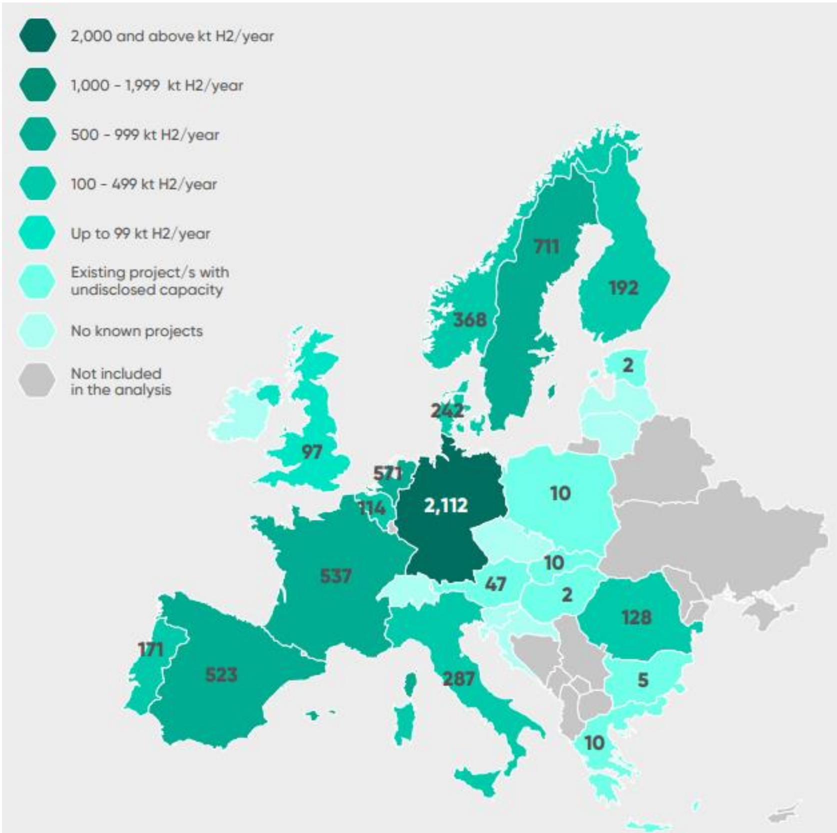
Based on current information, the 2030 planned industrial consumption of renewable hydrogen in Europe (EU, EFTA and UK) is estimated to be 5.4 MtH_2/y, raising to 6.1 MtH2/y by including projects with a non-disclosed operational date (see **Figure 1**) [1]. This would presuppose a yearly renewable hydrogen supply increase of about 600-750 kt H_2/year from 2023 in order to meet the planned demand by 2030. Germany is expected to become the main European driver for future renewable hydrogen demand amounting to 38% of the total clean hydrogen consumption [1]. More than half of the planned demand is expected to come from the steel industry (53%), 17% of the consumption should be to be used for the production of ammonia and 13% for refining processes [1].

[31] https://single-market-economy.ec.europa.eu/industry/strategy/industrial-alliances/european-clean-hydrogen-alliance/project-pipeline_en

[32] This amount excludes UK, Switzerland, Norway and Iceland.

[33] 38 MtH2/y for refining, 34 MtH_2/y for ammonia synthesis, 15 MtH_2/y for methanol synthesis and 5 MtH_2/y for DRI based steelmaking.

Figure 1. Map of total planned clean hydrogen consumption in industry by 2030 (including non-disclosed date of operation projects) in the EU, EFTA, UK region, in ktH_2/year



Source: Hydrogen Europe, Clean Hydrogen monitor 2022

The hydrogen transport, storage and conversion for end-use applications (e.g., industry, mobility, or buildings) are not part of the focus of the analysis performed in this report and related information will not be provided here.

2.3 Technology Costs

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

1. Capital investment (CAPEX) for electrolysers which depends on the technology used and its scale.
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[34].
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.

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. For lower rates (below 25-30%), 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.

[34] 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.

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).

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.

Table 2 summarizes the main Key Performance Indicators, including CAPEX, for 4 main categories of electrolysers: alkaline, PEM electrolysers, AEM electrolysers and SO electrolysers.

Installed fully functioning electrolysers system costs, also including site preparation, can easily be 2-3 times higher if not more, than those of **Table 2** [12].

Table 2. Key Performance Indicators for the four main Water Electrolysis technologies in 2020 and projected in 2030.

	2020	2030	2020	2030	2020	2030	2020	2030
	Alkaline		PEM Polymer Electrolyte Membrane		AEM = Anion Exchange Membrane		SO Solid Oxide Electrolysers	
Chracteristic Temperature [°C]	70-90	-	50-80	-	40-60	-	700-850	-
Cell Pressure [bar]	<30	-	<70	-	<35	-	<10	-
Electricity consumption (system) at nominal capacity [kWh/kgH2]	50	48	55	48	55	48	40 (+ 9.9 heat)	37 (+ 8 heat)
Degradation [%/1,000h]	0.12	0.1	0.19	0.12	> 1	0.5	1.9	0.5
Key Performance Indicators: economic performance								
Capital Cost Range (€/kW - based on 100 MW production)	**600**	**400**	**900**	**500**	**1000**	**300**	**2130**	**520**
Estimated Operational and Maintenance Costs in Euros/(kg/d)/y	**50**	**35**	**41**	**21**	**34**	**21**	**410**	**45**

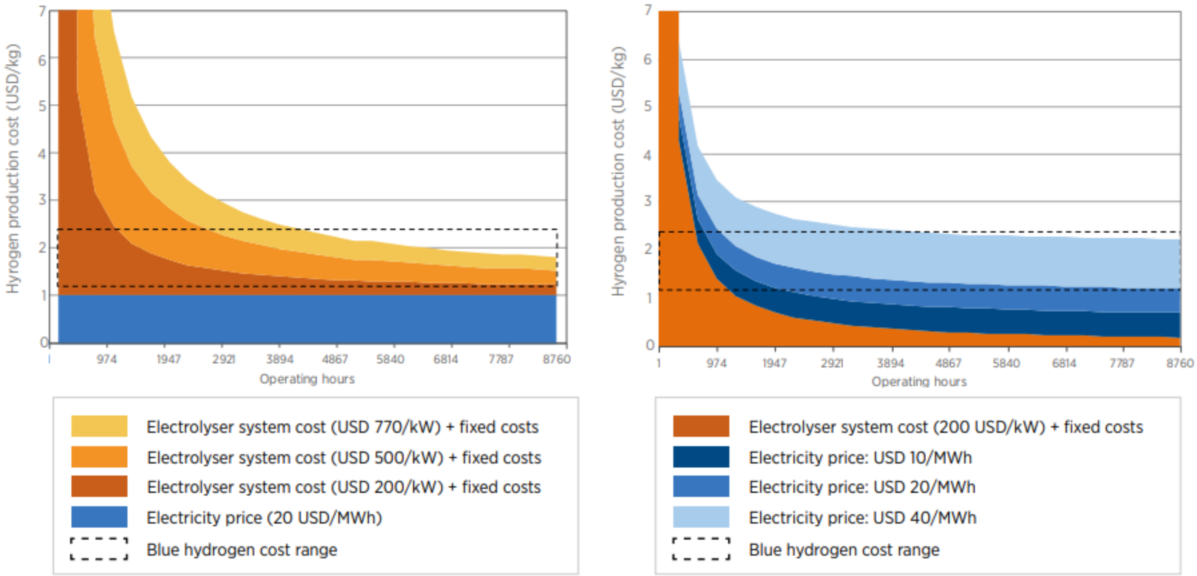
Source: Clean Hydrogen joint Undertaking, key performance indicators targets from Strategic Research and Innovation Agenda 2021 – 2027, 2022 and DG ENERGY/JRC (European Commission) elaboration based on IRENA data from the "Green Hydrogen Cost Reduction" report", 2020.

Since manufacturing capacity is expected to significantly expand in the coming years, learning curves for electrolysers should benefit from the higher production volumes and equipment costs should drop. The relative share of Balance of Plants components may then increase in the final CAPEX figures. However, deploying larger systems could also counterbalance this trend. [2].

2.3.1 Impact of the Cost of Electricity on the viability of Electrolyser investment:

As can be seen in **Figure 2**, CAPEX is the main contributing factor to the final price of hydrogen only for utilization factors up to less than 50%. As the electrolyser load factor increases beyond this threshold, the relative weight of electricity cost dominates the total hydrogen cost. The higher the load factor, the higher the share of electricity cost in total cost of hydrogen. At the same time, all analyses highlight that the price of hydrogen produced via electrolysis is reduced by increasing the number of operational hours and decreasing electricity prices. IRENA estimates that these factors have the capacity to decrease the cost of hydrogen by 80% [16].

Figure 2. Hydrogen production cost as a function of investment, electricity price and operating hours.



Source: IRENA, Green Hydrogen Cost Reduction, 2020

Notes: Assumptions are efficiency at nominal capacity is 65% (with an LHV of 51.2 kWh/kg H2), the discount rate 8% and the stack lifetime of 80 000 hours.

Other factors that will influence the economic viability of an investment on electrolysis are:

- increasing system lifetime – therefore decreasing CAPEX impact on levelised cost of hydrogen;
- increasing operational efficiency of the system – therefore reducing OPEX impact because of a reduced electricity consumption.

They will all be key drivers for the progressive development of hydrogen across the EU economy.

2.3.2 Projected costs of renewable based hydrogen production:

In countries relying on gas imports and characterized by large potential of renewable resources, clean hydrogen production from renewable electricity can compete effectively with production that relies on natural gas [11] [15]. According to IRENA [16], '"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 (see **Figure 2**).

Hydrogen Europe estimates that the cost of 1 kg of hydrogen produced in the EU through steam methane reforming (SMR) in 2021 was 2.65 EUR/kgH_2 [1]. This drops to 2.42 EUR/kgH_2 excluding the impact of CAPEX amortisation[35]. More than 67% of the total cost of hydrogen production reported for 2021 is associated with the natural gas cost. With natural gas cost increasing, the total cost of hydrogen coming from SMR is also going to increase, and because of this in 2022 has reached values as high as 10 EUR/kgH_2 significantly impacting the economic viability of several industries processes using hydrogen [1].

Hydrogen Europe estimates that for 2021, the European hydrogen production costs using directly renewable sources and in the best locations were as low as 2.9 EUR kg/H_2 for southern European countries using solar PVs and 2.2 EUR kg/H_2 in case of generation capacity using wind in northern European countries [1]. The median for European countries was around 6.3 EUR kg/H_2.

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

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

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.

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. 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 Clean Hydrogen Joint Undertaking was established in 2021 as a Public Private Partnership (PPP). To date, the Clean Hydrogen Joint Undertaking and its predecessors have dedicated about EUR 150 million since 2008 to electrolyser technologies. Alkaline electrolysis was supported with EUR 23.4 million, PEM electrolysis with around EUR 63 million, solid oxide electrolysis designs (including proton conducting membranes) with around EUR 53 million and AEM electrolysis with EUR 6.2 million [17]. In addition, EUR 35 million were dedicated to fund the deployment of Hydrogen Valleys.

In addition to the Joint Undertaking, through Horizon 2020 (2014-2020) the EU has made available more than EUR 130 million of funding for developing water electrolysis. The Green Deal Call of 2020 alone has supported the development of three 100 MW electrolysers through more than EUR 90 million funding.

The ETS Innovation Fund is also supporting projects deploying hydrogen technologies, especially in industrial settings. Nine projects were granted a total of EUR 406.6 million [18] in 3 Innovation Fund calls (two calls for large-scale projects in 2020[36], 2022[37] and one call for small-scale projects in 2020[38]) (see **Annex 3** for a detailed list of the projects).

Two sets of Important Project of Common European Interest (IPCEIs) dedicated to hydrogen have been already approved in 2022, for a total of 76 projects with Member States providing up to €10.6 billion in public funding, which is expected to unlock additional EUR 15.8 billion in private investments. Two new sets of IPCEIs are in preparation. These investments are however not simply dedicated to water electrolysis deployment and hydrogen production but will support the development of manufacturing capacities of electrolysers, the transport and storage infrastructure as well as applications.

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 [1] 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 (**Figure 3**). 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

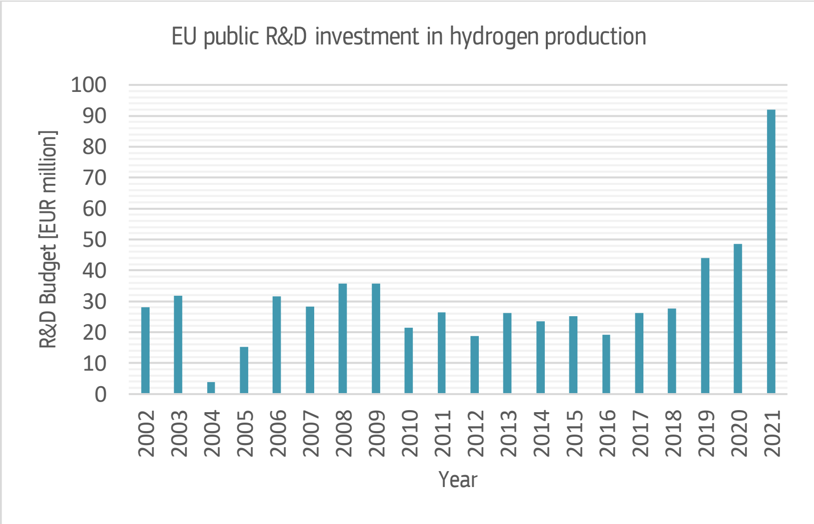
36 https://climate.ec.europa.eu/news-your-voice/news/first-innovation-fund-call-large-scale-projects-311-applications-eur-1-billion-eu-funding-clean-tech-2020-11-05_en

37 https://climate.ec.europa.eu/news-your-voice/news/eu15-billion-clean-tech-138-projects-apply-eu-innovation-funds-second-call-large-scale-projects-2022-03-11_en

38 https://climate.ec.europa.eu/eu-action/funding-climate-action/innovation-fund/small-scale-calls_en

to quantify the actual expenditure in hydrogen production technologies in general, and electrolysers in particular, both in the EU and in other major economies.

Figure 3. EU public R&D investment in hydrogen production [EUR million]



Source: JRC based on IEA data

2.5 Private RD&I funding

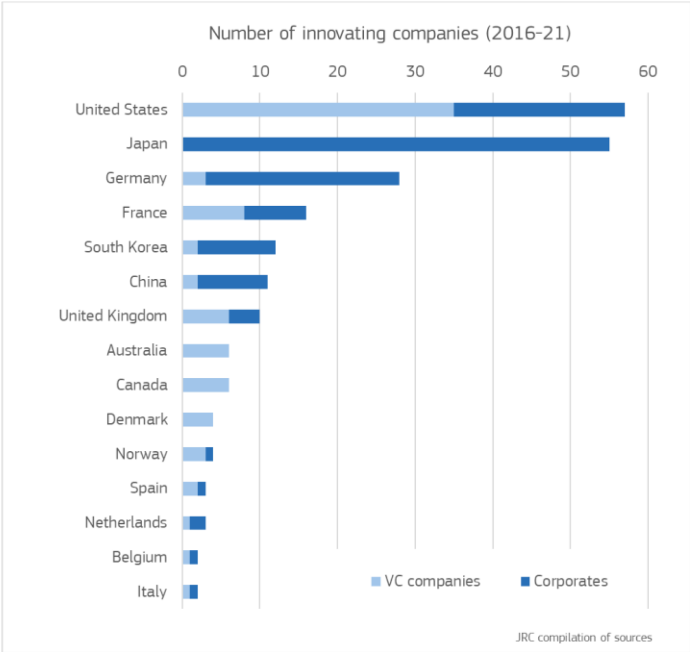
Five countries host 73 % of identified innovators but display various profiles (**Figure 4**). While USA (1st) leads with start-ups accounting for more than half of the companies identified, Japan (2nd) has corporations as sole contributors. Germany (3rd), France (4th) and the South Korea (5th) follow, 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 5**).

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.

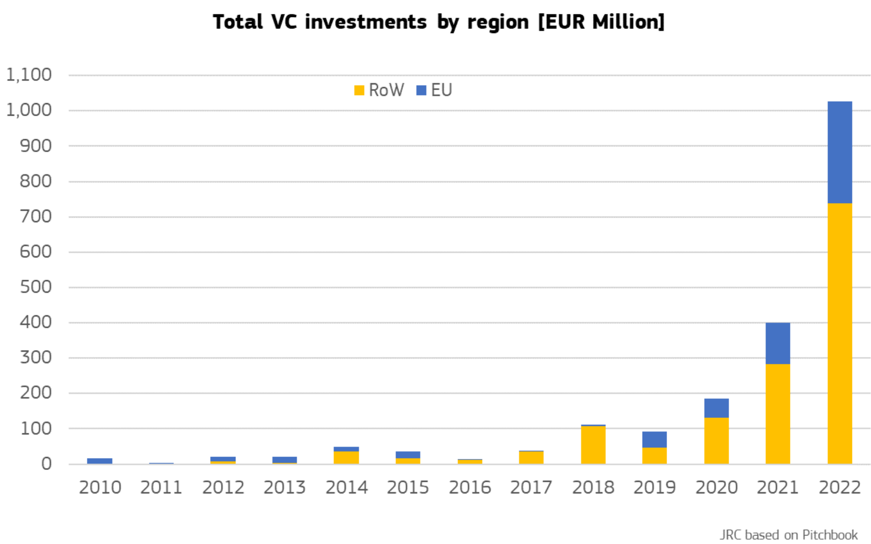
Over the 2010-22 period, global investments amount to a total of EUR 1 045 million. As seen in **Figure 6** later stages investments are the overwhelming majority of European investments, with the rest of the world having more or less a 50-50 split between early and late-stage investments. While the 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 4 Number of innovating companies (2016-21)



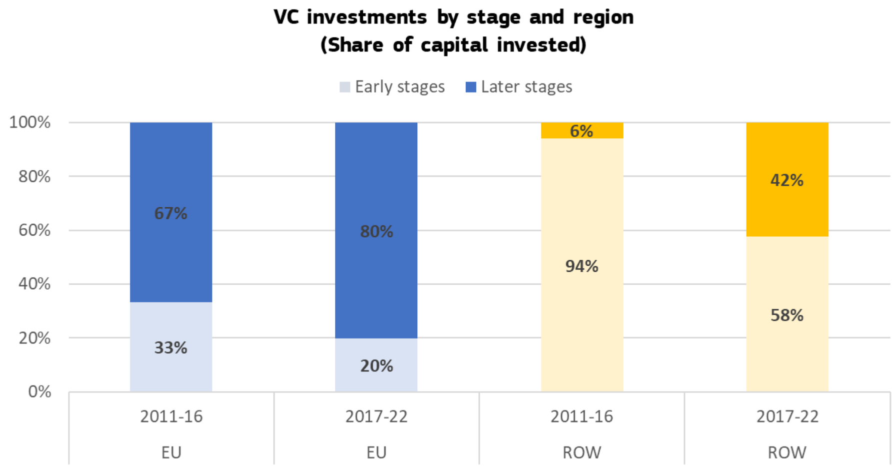
Source: JRC, 2023

Figure 5. Total VC investments by region [EUR Million].



Source: JRC, 2023

Figure 6. VC investments by stage and region (Share of capital invested).

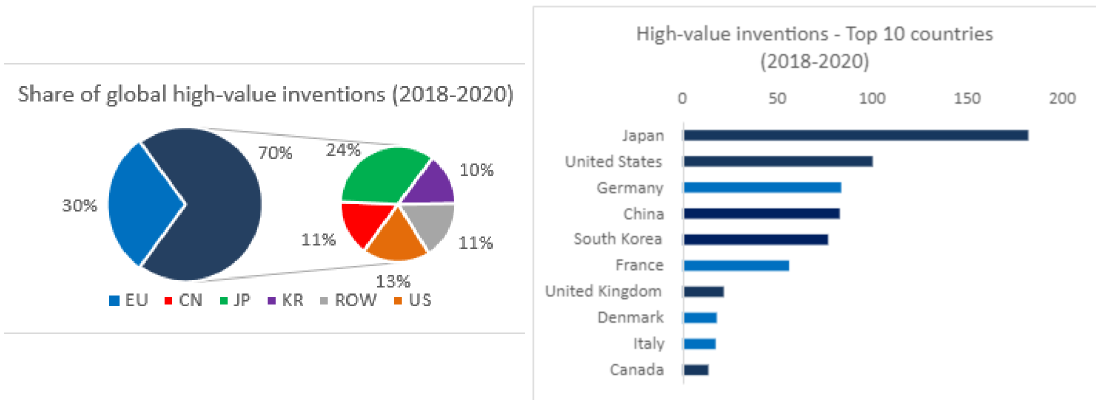


Source: JRC, 2023

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 [19]. When it comes to high value inventions, EU is still leading (with 31% of total share) alongside Japan. Germany is the best performing Member States 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 7**, 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 7: Share in high-value inventions for the major economies (left) and top 10 countries in high-value inventions (right) for the period 2018-2020



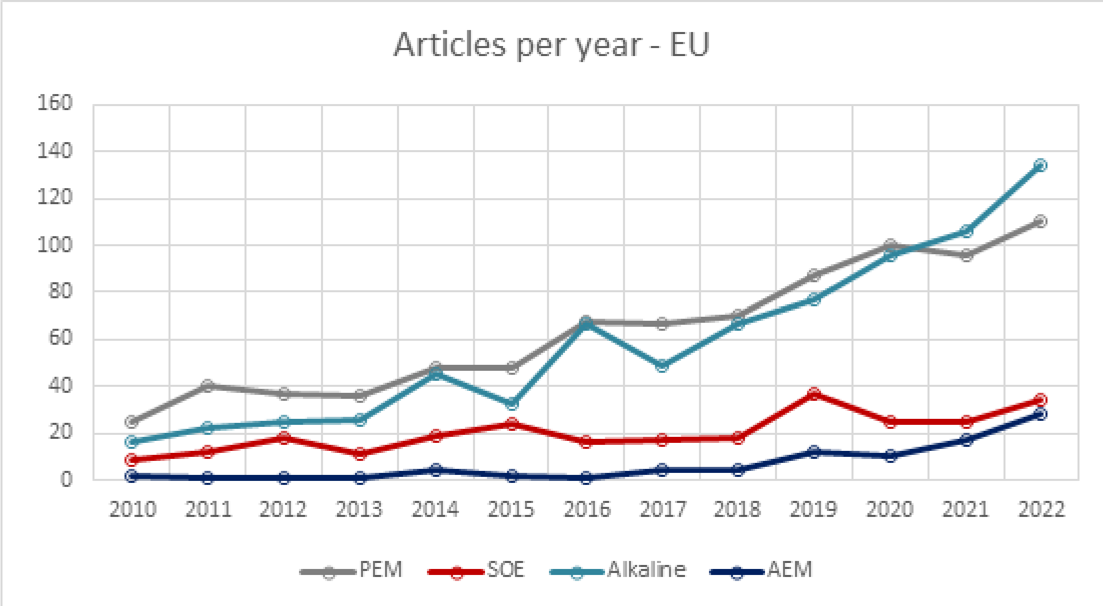
Source: JRC based on EPO Patstat

2.7 Scientific publication trends

As can be seen in **Figure 8**, 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 8. 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 [20].

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.

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).

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) [21]. 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 [22] 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 $kgCO_2/kgH_2$ [1].

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 estimate 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 [23].

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 electrolytic process requires itself 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 [24].

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 [25].

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 [26][39].

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.

As regard of a 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 [27] 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 [28] 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

Global electrolysers manufacturing capacity at the end of 2022 was estimated between 13 and 14 GW/y [11][29], which is almost doubling a 2021 estimate of 6.7 GW/y (of which about two third alkaline and one-third PEM) [11]. Global manufacturing capacity is expected again to more than double at the end of 2023, reaching beyond 40 GW/y [11].

As of August 2022, European electrolysers manufacturing capacity amounts to about 3.3 GW/y (60% alkaline, 40% PEM and less than 1% solid oxide electrolysis). Germany and the United Kingdom have about 1 GW/year of production capacity each. Norway has over 0.5 GW/year, Italy 0.3 GW/year, and France almost 0.2 GW/year [1]. Europe therefore accounts for around 25-30% of current world manufacturing capacity, with China undisputedly dominating the current production market for alkaline and having the highest worldwide

[39] 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.

production capacity [11]. Estimates for 2022-2023 allocate 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 [11]. At the moment, Europe has strong position in SOE, followed closely by the US.

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 [12][29].

Under an extremely optimistic scenario where all the announced plants are realised and exploited at full capacity, European manufacturing capacity could reach 53 GW/y by 2030 (31% alkaline, 25% PEM and 21% solid oxide electrolysis) [1]. Already more than 50% of this capacity is planned before 2025, enabling Europe to reach the targets set in a joint declaration between the Commission and twenty manufactures[40]. However, almost 80% of the expected future capacity expansion planned between 2023 - 2030 is still in the initial stages of development without having received definite funding allocations or having begun preparatory works. If all facilities planned are managing to become fully operational with the expected timing, 104 GW of electrolysers could in principle already be deployed in 2026 and the EU production target of 10 million tonnes of hydrogen per year could in principle be achieved by then [1].

More conservative estimates expect Europe to catch up in terms of market shares for electrolysers manufacturing capacity to reach around 25% (31.25 GW/y), more or less equalling the share of Chinese manufacturers and be closely followed by the US with a 20% share (27.2 GW/y) [29]. This does not consider the effect of initiatives such as the incentives granted under the USA IRA, which could significantly change the weight of the American market share.

According to some analysts, shipping of full electrolysers systems across long distances is not expected to be economically viable. Electrolysers manufacturing is expected to be in relative proximity to deployment sites, since large electrolysers installations will have to be tailored to the needs of a specific project; especially for deployments with relatively larger footprints. This does not imply that smaller components could be traded and distributed towards assembly lines.

The electrolysers' manufacturing market is currently going through a tumultuous growth process, characterized 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 [11][12]. This allows electrolyser producers to exploit significant lower production costs and have access to rapidly growing demand in areas which have abundant renewable electricity production potential.

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, development times for new electrolysers manufacturing sites are estimated to take between 2 and 3 years [12]. 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 [1], 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. Based on very limited data available, solid oxide electrolysers manufacturing seems to be more expensive than PEM and alkaline for example. Although some projects seem to require a CAPEX of more than EUR 150 million/GW for installed manufacturing capacity, an average of EUR 50 million can be considered a reasonable approximation for setting up, or upgrading a plant with a capacity of 1 GW/y in Europe. Expansion plans for already existing large-scale manufacturing plants should be a more economically attractive option. The required CAPEX seems to be lower for manufacturing facilities in China, in the range of EUR 30 million/GW [11].

Overall, there seems to be the risk of an overabundance of electrolyser manufacturing capacity in every region if demand and supply are not matched. Shipment forecasts based on demand are in the range of several GW for the following years (see Section 2.2) whereas planned increase for manufacturing capacity can reach dozens of GW per year by 2024. In addition, analysts underline a highly possible discrepancy between the announced

[40] European Electrolyser Summit Brussels, 5 May 2022 Joint Declaration.

manufacturing capacity volumes for full systems and the actual capacity that the factory will be able to produce when constraints on the supply chain will likely appear [1].

It is generally recognised that current manufacturing volumes are not high enough to achieve the full ambitions for future electrolysis deployment globally and at European level. Nevertheless, it is difficult to keep track of the manufacturing capacity actually available for the production of electrolysers due to the constantly evolving situation and the likelihood of overstated manufacturing capacities which are usually given only as a final stack production capability. This underestimates upstream bottlenecks such as components manufacturing, supply of critical raw materials. It seems likely that the current expected manufacturing capabilities based on announcements could be downsized down to a third of the stated volumes [11].

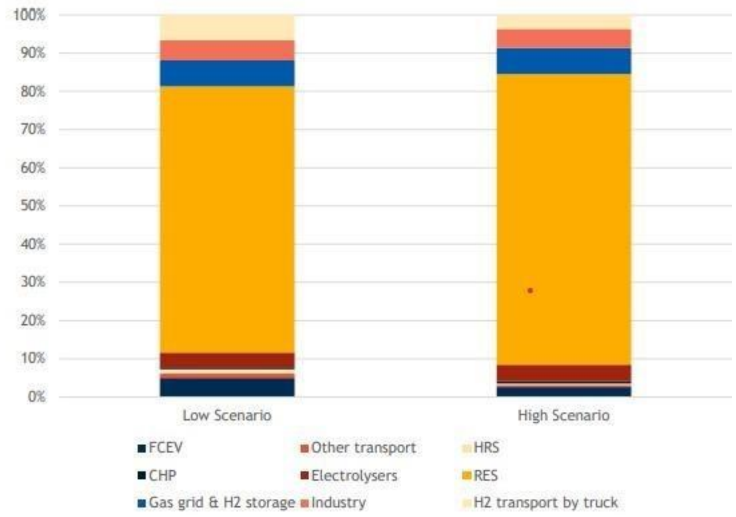
3.5 Employment

As regards to employment in the 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[41] 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 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 [30], 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 9. 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).

[41] 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.

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 [11], the expected shipments for 2023 will be more tripled with respect to 2022, with a worldwide total of around 2-3 GW. China is expected to remain by far the biggest market in terms of capacity even if it is consisting almost completely of alkaline water electrolysis.

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 [19], 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 [31] 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 [8]. Best case estimates range between 12 MtH_2/y [8] up to 24 MtH_2/y [11] 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%[42]. As can be seen from

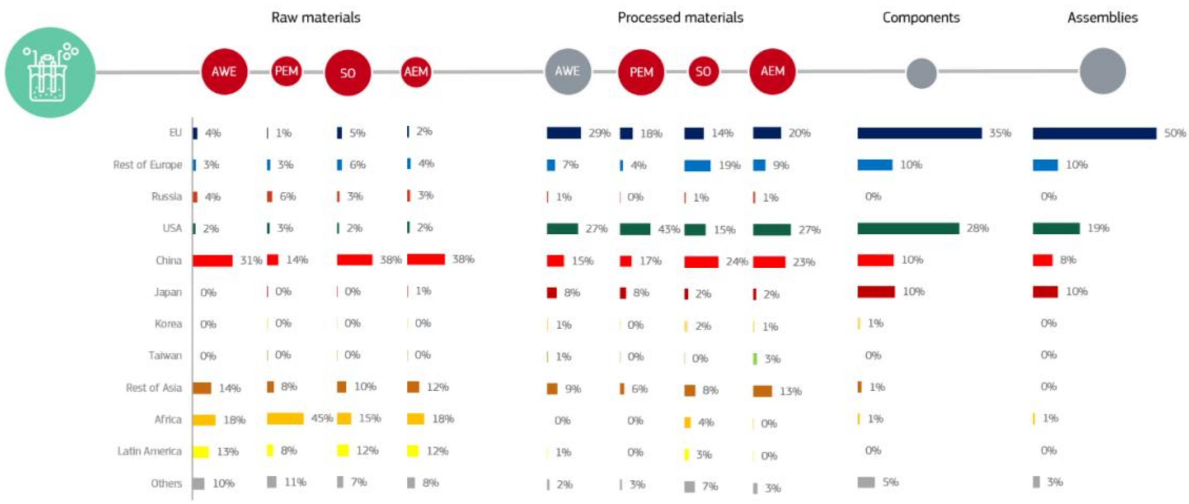
Figure 10, Europe is strongly dependent on raw materials, with its global share growing progressively for processed materials and components and reaching a majority fraction for electrolysers [32].

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 at large scale, if the current catalyst loading and lack of recycling options are going to remain unchanged [33] [34]. While rare earths, which are critical for manufacturing oxide conducting membranes for SOE, are mainly supplied by China.

[42] JRC analysis for DG GROW.

Figure 10. Supply chain for electrolysers.



Source: JRC, Foresight study 2023.

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 green 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 [34].

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 CO2 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 [35]. 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 [35]. 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, which should accelerate even more in 2023, the volumes of renewable hydrogen currently produced are still negligible. 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, IEA and ISO.

Renewable hydrogen production costs are highly dependent on electricity prices. With natural gas bills decreasing from the highs reached in 2022, the competitiveness of renewable hydrogen production against fossil fuels based production is significantly decreased.

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 demand will play a critical role in the coming years. Another major perceived challenge will be the deployment of an adequate supply of renewable electricity, which can be a crucial bottleneck towards the path of achieving European strategic production goals for renewable hydrogen.

Now that some projects are into the first steps of their realisation, concrete insights can be drawn. Some delays in supplying the necessary equipment, and volatility for electricity prices are hampering the viability of such projects. This is a crucial moment where large dissemination efforts must be undertaken in order to put to good use the lesson learned in this first attempts and improve the efficacy of future actions.

Despite several initiatives trying to fully assess 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 doesn't allow drawing accurate conclusions at this point.

European dependency on critical raw materials and processed materials remains. 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.

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

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

IPCEI Important Projects of Common European Interest

IRENA International Renewable Energy Agency

LHV Lower Heating Value

NO Norway

O&M Operation and Maintenance

OPEX operational Expenses

PCC Proton Conducting Ceramic

PCE Proton Conducting Electrolyser

PCI Projects of Common Interest

PEM Proton Exchange Membrane

PGM Platinum group metal

RES Renewable Energy Source(s)

SOE Solid Oxide electrolysers

TRL Technology Readiness Level

UK United Kingdom

USA United States of America

VC Venture Capital

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Annexes

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
	– Employment	– See References
	– Energy intensity and labour productivity	–
	– EU industrial production	– See References
– 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 Sustainability Assessment Framework

Parameter/Indicator
Environmental
LCA standards, PEFCR or best practice, LCI databases
GHG emissions
Energy balance
Ecosystem and biodiversity impact
Water use
Air quality
Land use
Soil health
Hazardous materials
Economic
LCC standards or best practices
Cost of energy
Critical raw materials
Resource efficiency and recycling
Industry viability and expansion potential
Trade impacts
Market demand
Technology lock-in/innovation lock-out
Tech-specific permitting requirements
Sustainability certification schemes
Social
S-LCA standard or best practice
Health
Public acceptance
Education opportunities and needs
Employment and conditions
Contribution to GDP
Rural development impact
Industrial transition impact
Affordable energy access (SDG7)
Safety and (cyber)security
Energy security
Food security
Responsible material sourcing

Annex 3 List of projects funded under the Innovation Fund

Project	Innovation Fund Grant	Reference
GreenH2: Small-scale green hydrogen production facility	EUR 4 492 131.00	https://ec.europa.eu/assets/cinea/project_fiches/innovation_fund/101102990.pdf
HH - Holland Hydrogen	EUR 89 000 000.00	https://climate.ec.europa.eu/system/files/2022-12/if_pf_2022_hh_en.pdf
FUREC - FUse, REuse, ReCycle	EUR 108 000 000.00	https://climate.ec.europa.eu/system/files/2022-12/if_pf_2022_furec_en.pdf
ELYgator - Kick-starting a renewable hydrogen value chain for industry and mobility: highly integrated, flexible large-scale 200MW water electrolyser producing renewable hydrogen and oxygen	EUR 99 000 000.00	https://climate.ec.europa.eu/system/files/2023-03/if_pf_2022_elygator_en.pdf
SHARC: Sustainable Hydrogen and Recovery of Carbon	EUR 88 286 266.00	https://climate.ec.europa.eu/system/files/2022-07/if_pf_2022_sharc_en.pdf
H2 Valcamonica: Green hydrogen for the decarbonisation of Valcamonica valley	EUR 4 430 421.00	https://climate.ec.europa.eu/system/files/2022-07/if_pf_2021_h2valcamonica_en.pdf
HYVALUE: Novel upcycling production process, based on an innovative circular business model, for high-quality hydrogen production through urban waste streams valorisation	EUR 4 458 000.00	https://climate.ec.europa.eu/system/files/2022-07/if_pf_2021_hyvalue_en.pdf
SUN2HY: First Small-Scale Deployment of a Pre-Commercial Plant Based on Photoelectrocatalytic Technology for Hydrogen Production	EUR 4 484 293.00	https://climate.ec.europa.eu/system/files/2022-07/if_pf_2021_sun2hy_en.pdf
ZE PAK green H2: 5 MW pilot green hydrogen production facility	EUR 4 460 000.00	https://climate.ec.europa.eu/system/files/2022-07/if_pf_2021_zepak_en.pdf
Total	**EUR 406,611,111.00**	

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