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WATER ELECTROLYSIS AND HYDROGEN IN THE EUROPEAN UNION

2022

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

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Contents

Foreword

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.

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Executive Summary

Renewable and low carbon hydrogen is both *an energy carrier* able to produce other fuels and downstream products, such as the e-fuels, or e-ammonia, and *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 net zero emissions target in 2050.

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[2] (the Hydrogen Strategy)[3]. The REPowerEU Communication[4] has further addressed the joint EU and Member State actions needed in the context of the crisis triggered by the invasion of Ukraine in February 2022 and the necessity to phase out dependence on Russian supplies. The EC has strengthened the policy narrative around hydrogen and increased objectives for a pan European framework accelerating and upscaling the production of RES and low-carbon hydrogen. The main objectives and actions of the REPowerEU Plan, which build on the Hydrogen Strategy, are the deployment of several tens of GW of electrolyser capacity and the production and imports of 10 Mt and 10 Mt respectively of renewable hydrogen by 2030.

Currently the most mature and promising green hydrogen production technology is water electrolysis. The main technologies[5] considered in this report are: Alkaline electrolysis, Polymer Exchange Membrane (PEM) electrolysis, Solid Oxide electrolysis and Anion Exchange Membrane electrolysers (AEM).

The present EU generation capacity is around 10.3 Mt of hydrogen per year[6]. Water electrolysis accounts for a very limited amount of this. According to estimates from Hydrogen Europe, the total installed capacity in the EU, EFTA and UK grew from 90 MW (29% of capacity deployed via FCH JU projects) in 2019, to 100 MW (37% of capacity deployed via FCH JU projects) in 2020 and has reached 135 MW (43% of capacity deployed via FCH JU projects) of capacity installed as of August 2021[7]. IEA estimated a total worldwide installed electrolysers' capacity of around 300MW for 2020. Europe is the region with the highest installed capacity, even if China and Canada have been deploying a significant number of installations since 2019 and China in particular could surpass European capacity in 2022.

Given the constant stream of project announcements and pledges, forecasts of electrolyser deployment are difficult to keep track of. However all point towards growing prospects both in Europe and in the rest of the world[8]. In particular from 2030, if project announcements are followed through and respect the announced schedules, the acceleration in electrolyser field deployment will be very evident.

CAPEX is the main contributing factor to the final price of hydrogen only for very low utilization factors. As is increases, the relative weight of electricity cost increases and dominates the total hydrogen cost. In 2020 an estimate for the costs of 1kg of hydrogen produced in the EU through Steam Methane Reforming was 1.41 EUR/kgH_2[9]. According to estimates from Hydrogen Europe, the corresponding European hydrogen production costs using renewable sources varies from a median of 6.8 EUR kg/H_2 with solar PV, to a median of 5.5 EUR kg/H_2 in case of wind based production[10].

To date, the Clean Hydrogen Joint Undertaking and its predecessors have dedicated about EUR 150.5 million since 2008 to electrolyser technologies (EUR 74.7 million are for research actions and EUR 75.9 million for Innovation Actions (IA)). In addition, through Horizon 2020 (2014-2020) the EU has made available more than

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

[3] 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.

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

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

[6] Hydrogen Europe, CLEAN HYDROGEN MONITOR, 2021 and Fuel Cells and Hydrogen Observatory. This excludes the hydrogen contained in Coke Oven Gas (COG). If this is accounted for, the EU production capacity reaches 11 M tH_2 per year.

[7] Hydrogen Europe, CLEAN HYDROGEN MONITOR, 2021.

[8] Hydrogen Europe, CLEAN HYDROGEN MONITOR, 2021; BNEF, 1H 2022 hydrogen market outlook, 2022; IEA, Global Hydrogen Review, 2021 and The Future of Hydrogen, 2019.

[9] Hydrogen Europe, CLEAN HYDROGEN MONITOR, 2021.

[10] Clean Hydrogen Monitor, 2021, Hydrogen Europe.

EUR 130 million for developing water electrolysis. The ETS Innovation Fund has already supported four projects from h the two 2020 calls, and five further projects from the 2021 calls for small scale and large scale projects. The total budget provided by the Innovation Fund has been over EUR 240 million. From a Hydrogen Europe analysis[11] the total cumulative amount of funds available for hydrogen from all national recovery plans (RRPs) reaches over EUR 54 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.

For patents, an in-depth patent analysis by IRENA and EPO[12],confirms the trends of seeing China having the highest amount of patents overall and Europe having the largest amounts of international patents, as highlighted in previous years.

From the pledges made by electrolyser manufacturing companies, an increase in manufacturing capacity can surely be projected into the near future, also bearing in mind several on-going initiatives at European level such as the IPCEI and the Green Hydrogen Alliance. Estimates about the 2021 European manufacturing capacity vary, but it reasonable to assume a range between 2.5 GW[13] and 3 GW[14] per year. Worldwide capacity production in 2021 was expected to be 6.7 GW/y (of which about two third alkaline and one-third PEM)[15].

The electrolysis market is very dynamic with several mergers and acquisitions registered in recent years. Europe has a clear lead in terms of Solid Oxide and AEM electrolysers. The EU also hosts also a very large of number of companies producing entire electrolyser stacks or systems.

Manufacturing volumes of European companies for alkaline electrolysis are however lower than those of Asian companies (Chinese is particular). Estimates for 2021-2022[16] allocate around a half of the worldwide alkaline electrolyser capacity to Chinese companies, and most of the production capacity for PEM electrolysers to American companies.

According to available conservative estimates[17], shipments for 2022 will more than triple with respect to 2021, with a worldwide total of around 1.8 GW (0.5 GW in 2021). China accounts for about 70% of worldwide shipments, with Europe and America having shares of roughly 15% each. About three quarters of this capacity is alkaline, with the rest made up by PEM electrolysers.

From the analysis of available trade information it is clear that currently trade 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%[18]. Europe is strongly dependent on imported raw materials, but its share grows progressively for processed materials and components, reaching over 50% for electrolysers as a final product.

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

[11] Hydrogen Europe, CLEAN HYDROGEN MONITOR, 2021.
[12] IRENA and EPO, Innovation trends in electrolysers for hydrogen production, 2022.
[13] European Electrolyser Summit Brussels, 5 May 2022 Joint Declaration.
[14] Bloomberg NEF, 1H 2022 Hydrogen Market Outlook.
[15] Bloomberg NEF, 1H 2022 Hydrogen Market Outlook.
[16] Bloomberg NEF, 1H 2022 Hydrogen Market Outlook.
[17] Bloomberg NEF, 1H 2022 Hydrogen Market Outlook.
[18] JRC analysis for DG GROW.

Strengths • Strong European regulatory framework with funding and financing support schemes. • 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.	**Weaknesses** • Very high European reliance on imports of the critical raw materials. Lack of a recycling infrastructure. • Manufacturing costs of the electrolyser systems. • Lack of an international trade dimension. • Lack of mature European and international transport, storage and distribution networks. • Lack of fully mature markets for electrolysers and clean hydrogen.
Opportunities • 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. • Member States' coordination on the hydrogen proposals for the Important Projects of Common European Interest. • The increase of the cost of natural gas provides an opportunity for renewable hydrogen to achieve more easily cost competitiveness against fossil-based hydrogen. • Research and Innovation initiatives should pursuit opportunities to substitute CRMs and define recycling solutions.	**Threats** • Rising costs of electricity have an impact on the cost competitiveness of electrolyser technology and on the levelized cost of hydrogen. • Lack of international codes NACE for trade related to renewable and low carbon hydrogen, and electrolysers. • Costs of production and assembly of stacks against other economies seems not competitive.

1 Introduction

1.1 Scope

This report on hydrogen electrolysis is one of an annual series of reports from the Clean Energy Technology Observatory (CETO). It address technology maturity status, development and trends; value chain analysis and global market and EU positioning. It builds on previous Commission studies in this field[19].

1.1.1 Policy Context

Renewable and low carbon hydrogen, which is both *an energy carrier* able to produce other fuels and downstream products, such as the e-fuels, or e-ammonia, and *a decarbonised gas produced through renewable electricity*[20], has the potential to decarbonise hard to abate sectors which are difficult to directly electrify.

Amongst projected uses, hydrogen features in the industry processes, for the production of steel and cement, as feedstock for chemical processes, in the heavy duty and long distance transport (including solutions for e-fuels in aviation and maritime transport), as well as in support of energy storage.

Renewable and low carbon hydrogen can play a crucial role in achieving net zero emissions target in 2050 and contributing to the decarbonisation of hard to abate sectors.

The Staff working document accompanying the Communication - Stepping up Europe's 2030 climate ambition[21] - 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[22], thus amounting from about 80 up to 100 million tonnes of oil equivalent (Mtoe)[23] in 2050. In terms of installed electrolyser capacity a range between 528 and 581 GW in 2050 is given for the policy scenarios of the staff working document[24] accompanying the communication[25] 'Stepping up Europe's 2030 climate ambition'; whilst other studies suggest a 1 000 GW European market by 2050 [1].

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[26] (the Hydrogen Strategy)[27]. The Repower EU Communication[28] has further addressed the joint EU and Member States' actions needed in the context of the crisis triggered by the invasion of Ukraine in February 2022 and the necessity to phase out dependence on Russian supplies. The EC has strengthened the policy narrative and increased objectives for the pan European framework for accelerating and upscaling the production of RES and low carbon hydrogen.

The main objectives and actions of the Repower EU Plan which are building on the Hydrogen Strategy are:

— the initial targets of 6 GW of electrolysers in 2024 and of 40 GW of electrolysers in 2030 and a European production target of 10 Mt of renewable hydrogen have been set back in the Hydrogen Strategy in 2020[29];

[19] https://energy.ec.europa.eu/topics/research-and-technology/clean-energy-competitiveness_en#progress-reports

[20] 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.

[21] Stepping up Europe's 2030 climate ambition - SWD(2020) 176.

[22] Net total hydrogen consumption excludes hydrogen that is further processed to renewable fuels or liquids (see SWD(2020) 176).

[23] Equivalent to about 28-35 Mt of hydrogen.

[24] SWD(2020) 176.

[25] Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our people -

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

[27] 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.

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

[29] These electrolysers'deployent targets are expressed as hydrogen output, rather than as an electrical input power capacity. In the rest of the document, whenever possible, electrolysers' capacity will be expressed based on electrical input power. For producing 10Mt of hydrogen in a year, depending on assumptions, it is reasonable to expect an installed electrolysers capacity of 140GW based on electrical input.

- to import of 10 Mt (out of which 4 Mt in the form of ammonia[30]).
- in the amended proposal of the Renewable Energy Directive to use renewable hydrogen for consumption in each Member State:
  - in the industry processes the proposed target is set at 78% and
  - at 5.7% by MS in the transport sectors (the targets increased from the initially proposed target of 50% for the industry and 2.6% for transport).
- With regard to financing, the Repower EU Plan has also earmarked up to EUR 27 billion of European funds redeployed to support electrolyser production and distribution, including revisions of the national plans of the Recovery and Resilience Facility, as well as an increased EUR 200 million funding for the Clean Hydrogen Joint Undertaking and the creation of the Hydrogen Valleys in Europe.
- On the international scene, to increase the trade of renewable and low carbon hydrogen through strategic partnerships such as through the Mediterranean Partnership with Egypt. Other partnerships with Norway and with Ukraine, as soon as feasible, are also mentioned.
- It is exploring to set up the Global Hydrogen Facility to support EUR denominated hydrogen auctions, while securing compliance with EU internal market rules and the competition aspects.

If 10 Mt of renewable hydrogen were to be produced exclusively through the electrolysis process, the European hydrogen industry estimates a need for 120 GW of electrolyser capacity installed by 2030[31].

The illustrative demand for hydrogen uses in Europe in 2030, according to a PRIMES modelling exercise, can be summarized as in Figure 1. The PRIMES modelling exercise included in the Staff Working document addressing the implementation of the REPowerEU plan included 10 Mt of hydrogen imported, out of which 4 Mt in form of ammonia.

Other key policy initiatives have been launched in 2021, as part of the Fit-for-55 package, including in particular the revision of the Alternative Fuels Infrastructure Regulation, relevant for the deployment of the Hydrogen Refuelling Stations for light and heavy duty traffic on the main Trans-European Transport Network and the RefuelEU Aviation and FuelEU Maritime proposals aiming to boost the use of sustainable fuels by aviation and waterborne sectors, including hydrogen and synthetic fuels.

In this context the Commission has endorsed a creation of a Renewable and Low-Carbon Fuels Value Chain Industrial Alliance to support the creation of value chains for the supply of bio- and synthetic fuels for aviation and waterborne transports.

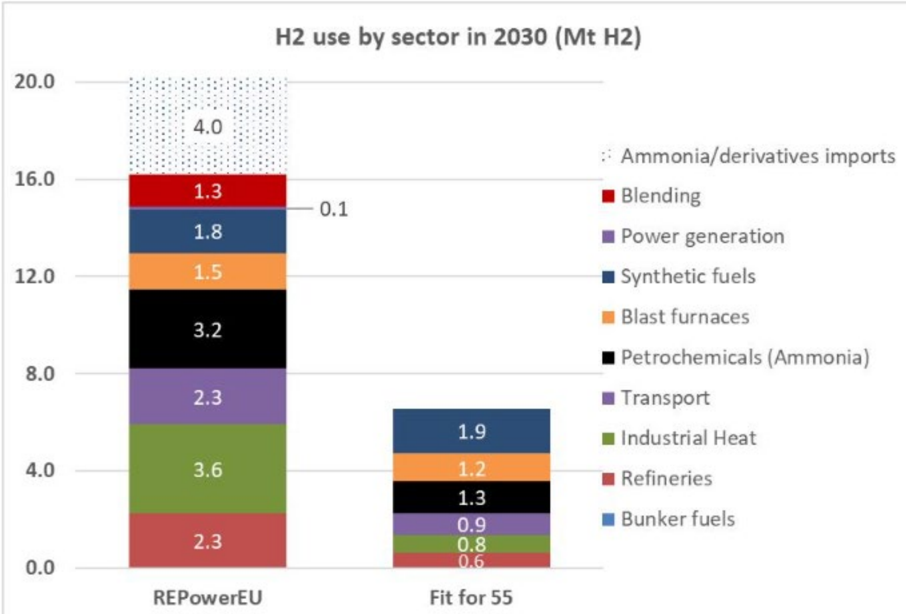
It is also worth mentioning, that the renewable and low carbon hydrogen are proposed by the EC to have least values of taxation in the proposal on the Energy Taxation Directive, as compared to other forms of fossil hydrogen.

In addition, the EC has recently published a consultation for the Delegated Act on the additionally supplementing the Renewable Energy Directive which aim is to incentivise production of hydrogen using renewable electricity at the times and in the geographical locations in the electricity bidding zones, where renewable resources are abundant and can be connected to electrolyser infrastructure.

[30] A conversion of ammonia to hydrogen is approximately 3:17, meaning that 4 Mt of hydrogen could approximately be used to synthesise 22.7 Mt of ammonia.

[31] IMPLEMENTING THE REPOWER EU ACTION PLAN: INVESTMENT NEEDS, HYDROGEN ACCELERATOR AND ACHIEVING THE BIO-METHANE TARGETS - SWD(2022) 230 and https://ec.europa.eu/commission/presscorner/detail/en/IP_22_2829

Figure 1. Hydrogen use by sector in 2030, Fit-fo-55 against REPowerEU (PRIMES modelling).



Source: European Commission, SWD(2022) 230.

1.1.2 Industrial commitment and leadership

The cooperation with industry has been launched by the EC 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.

In the joint Declaration of May 2022 signed by 20 industry CEO's of the European Clean Hydrogen Alliance and the Commissioner for Industry[32], Thierry Breton, have set aspirational targets to upscale the electrolyser industry in Europe and establish a total combined European electrolyser manufacturing capacity of 25 GW/y by 2025 (a tenfold increase from the current levels).

Additional investments in electrolysers and infrastructure have been notified to the EC and are being assessed in the notified proposal for the Important Project of Common European Interest.

Other activities in the international arena such as, for example, the Clean Hydrogen Mission initiated as the Cooperation of the Parties (COP) with the European Commission co-leading, the group of the Clean Energy Ministerial on Hydrogen and the Global Ports Coalition, all supplement EU and national efforts. The Clean Hydrogen Mission co-led by Australia, Chile, EU, UK and USA, aims at promoting and implementing Hydrogen Valleys across the world with the objective of producing renewable and low carbon hydrogen at a price of 1.5 EUR/kgH_2.

The Breakthrough Agenda led by the United Kingdom based on the process of the COP with developing economies has also emerged since the COP Glasgow summit in November 2021.

1.2 Methodology and Data Sources

The structure of report follows the CETO template, with three main sections:

a) Technology maturity status, development and trends

[32] https://ec.europa.eu/commission/presscorner/detail/en/IP_22_2829

b) Value chain analysis: this section aims to provide an analysis of the technology value chain
c) Global markets and EU positioning

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.

2 Technology State of the art and future developments and trends

2.1 Technology readiness level (TRL)

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

In short, it 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[33] (about 180-200 MJ) of electricity are needed to produce 1 kg of hydrogen from a stoichiometric minimum of 9 kg of water. The thermodynamic limit for dissociating water at room temperature through electrolysis is around 40 kWh/kgH2.

Solid Oxide Electrolysis (SOE) exploits the more favourable 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)[34]; extra heat requirements for maintaining the high temperature should also be factored in the efficiency[35].

The main electrolysis technologies[36], 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 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.
- Proton Exchange Membrane (PEM) electrolysers can reach high current and power density and can operate well under dynamic operations and partial load. Therefore, they are highly responsive, which makes coupling with RES 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.
- Solid Oxide electrolysers (SOE) must use materials capable of withstanding the higher temperatures involved with the use of this technology. 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 flexibility. 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.
- In addition to the two main low temperature electrolyser 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. This technology is currently at a relatively low Technology Readiness Level (TRL 3-5) and cannot presently achieve the performance and durability of other water electrolysis technologies.

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[33] SRIA (Strategic Research and Innovation Agenda 2021 – 2027) key performance indicators of the Clean Hydrogen Joint Undertaking point out at a SoA for 2020 which is 55 kWh/kgH_2 for both PEM and AEM, and 50kWh/kgH_2 for Alkaline electrolysis.

[34] SRIA (Strategic Research and Innovation Agenda 2021 – 2027) key performance indicators of the Clean Hydrogen Joint Undertaking.

[35] It is estimated that, in practice water consumption can reach up to around 17 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.

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

Alkaline and Proton Exchange Membrane are technologies that have achieved commercial maturity and have been, or will be, deployed in demonstrations reaching a power of tens of MW[37].

Solid Oxide Electrolysers have been already tested in real life environment and planned demonstrations should deploy several hundreds of kW up to MW scale soon[38].

Anion Exchange Membrane Electrolysers are at a much lower technical maturity level (TRL 3-5), with only one European supplier[39] and a product offer in the range of few kWs.

[37] Examples of projects: GREENH2ATLANTIC and GreenHyScale (Akaline) and REFHYNE II (PEM).
[38] MULTIPLHY project will demonstrate at MW scale (2.4 MW) https://www.green-industrial-hydrogen.com/
[39] Enapter

2.2 Installed energy Capacity, Generation/Production

Currently, the EU generation capacity can be estimated around 10.3 Mt of hydrogen per year [2] [3][40].

This hydrogen production capacity 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) totalling to about 3.6%.
- Reforming with carbon capture providing around 0.5% of total.
- Hydrogen produced via water electrolysis corresponding to only 0.1% of total hydrogen production capacity.

Water electrolysis is therefore accounting for a very limited amount of current hydrogen generation capacity. According to estimates from Hydrogen Europe, the total installed capacity in the EU, EFTA and UK grew from 90 MW (29% of capacity deployed via FCH JU projects) in 2019, to 100 MW (37% of capacity deployed via FCH JU projects) in 2020 and has reached 135 MW (43% of capacity deployed via FCH JU projects) of capacity installed as of August 2021 [2]. IEA estimated a total worldwide installed electrolyser capacity of around 300MW for 2020. Europe is the geographical area with the highest installed capacity, even if China and Canada have started deploying significant installations as of 2019 and each totalled around 50 MW in 2020.

Germany is the European country with the highest installed electrolyser capacity. From available data [2] it can be said that in terms of technology deployed on European territory, PEM seems to cover roughly 55% of capacity and alkaline 44%, with about 65% of capacity connected to the electrical grid and about 31% of capacity directly connected to renewable sources. The average project deployment size is around 1.3 MW for both alkaline and PEM.

As evidenced by several sources, if yearly evolutions following project announcements and pledges are taken into account, any deployment forecast for electrolyser constantly changes and shows a major growth forecast which is difficult to keep track of, but point towards an ever increasing deployment prospects both in Europe and in the rest of the world [2-6]. In particular from 2030, if project announcements follow through and respect initial schedules, it will be possible to significantly detect an acceleration in the field deployment of electrolysers.

As an example, a 2021 estimate by Hydrogen Europe [2] following announcements on power-to-hydrogen projects sees a forecasted deployment of more than 118 GW in EU, EFTA and UK combined by 2030. This is a 1 200% increase with respect to a similar exercise published in the previous year.

The European Clean Hydrogen Alliance alone identified a pipeline of over 750 project proposals deploying over 50 GW by 2030 across several EU sectors[41].

Today, the EU demand for hydrogen is about 7.8 million tonnes per year [2] [3][42], out of about a global demand of 120 Mt/y of hydrogen [5 [6][43]. Nowadays, overall hydrogen production processes are almost completely based on the use of fossil fuels and 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.

[40] This excludes the hydrogen contained in Coke Oven Gas (COG). If this is accounted for, the EU production capacity reaches 11 M tH_2 per year.
[41] RePower EU Plan - COM(2022) 230.
[42] This amounts excludes UK, Switzerland, Norway and Iceland.
[43] It includes 70 Mt H_2 in its 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.

- 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.
- Ca. 0.001% is currently used for transport applications.

Transport of hydrogen, its storage and its conversion in 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 Cost – Present and Potential Future Trends

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

1) Capital investment for electrolysers which depends on the technology used and its scale.
2) Operating costs, linked with the costs of electricity input (which are usually the biggest significant part of overall costs for both renewable and low-carbon hydrogen, and increasing their relative importance as CAPEX costs are driven down).
3) Other electricity-related, grid-related taxes and tariffs.
4) Load factor[44].
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.

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.

Cost of Electrolysers:

Table 1 summarizes the main Key Performance Indicators for 4 main categories of Electrolysers i) Alkaline; ii) PEM Proton Exchange Membrane; iii) AEM (Anion Exchange Membrane) and iv) Solid Oxide Electrolysers (SOE)

[44] Amount of hours a hydrogen production facility is able to run per year.

Table 1. 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.

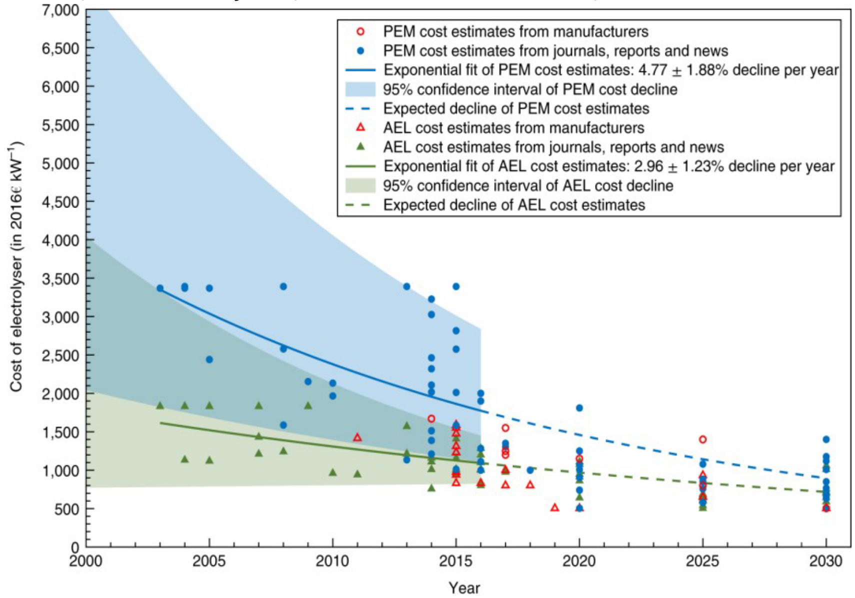
Learning curves:

Available learning curves for electrolyser manufacturing are usually based on information coming from wind, PV and battery historic data [7]. It is difficult to clearly express the total potential for electrolyser system cost reduction associated with increased manufacturing capacities since overall electrolyser manufacturing cost is also dependent on many different factors, including standardisation and specialisation and changes in system design. Moreover different components will be impacted differently by increased manufacturing capacities and using more efficient processes and automation possibilities. It seems however that, within the uncertainties intrinsic to the lack of actual data, the expected learning rates[45] for stack modules should be initially higher for SOE and PEM, and lower for alkaline electrolysers due to their higher maturity, their higher production volumes and their similarities with established electrolyser technologies used in the chlor-alkali process. For a 100 000 increase in cumulative production, learning rates should reach more or less the same levels for all technologies. It should also be noted that learning rates are expected to impact stack components production costs more than balance of plant components. For instance, for a PEM electrolysis system manufacturing line growing from 10 MW/y to 1 GW/y (tenfold increase), the relative share in system cost should move from about a 40%/60% split for stack components/balance of plant components to a 30%/70% split respectively [7].

Overall system CAPEX (in particular for PEM) have already been significantly reduced in the last ten years, and costs for alkaline and PEM electrolysers are expected to roughly halve in 2030 compared to today thanks to economies of scale and manufacturing expertise gains. Even higher CAPEX reductions are expected for SOE and AEM. Figure 2 and Figure 3 give an example of expected evolution based on available historic data (until 2017). It appears that the cost objectives for 2030 as expressed in Table 1, are already more optimistic that those expressed in Figure 2 and Figure 3 which have been published only few years earlier.

[45] The learning rate given as a constant percentage, expresses the decline of production costs for every cumulative doubling of production volume.

Figure 2. Extrapolated cost trajectory for PEM and alkaline electrolysers (AEL) based on historic data.



Source: Economics of converting renewable power to hydrogen, G. Glenk, S. Reichselstein, https://www.nature.com/articles/s41560-019-0326-1

Figure 3. Learning curves for electrolysis systems.

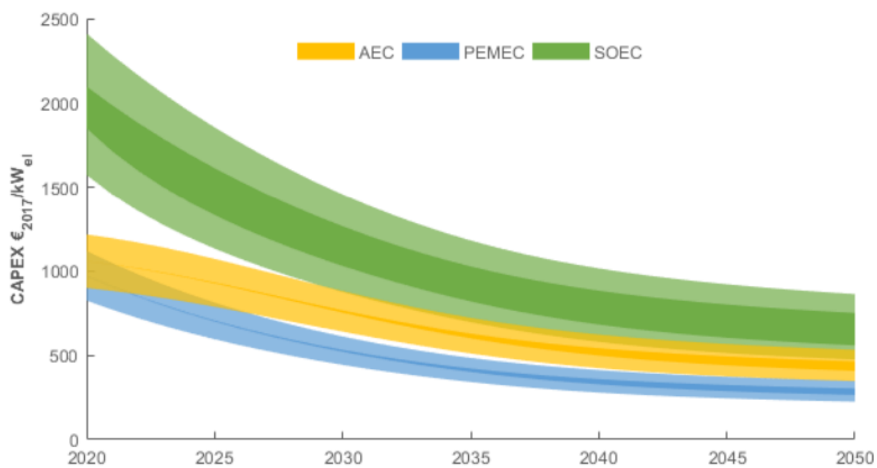


Figure 10-1: Resulting learning curves for electrolysis systems with an uncertainty of ±15% on initial CAPEX (light-colored areas)

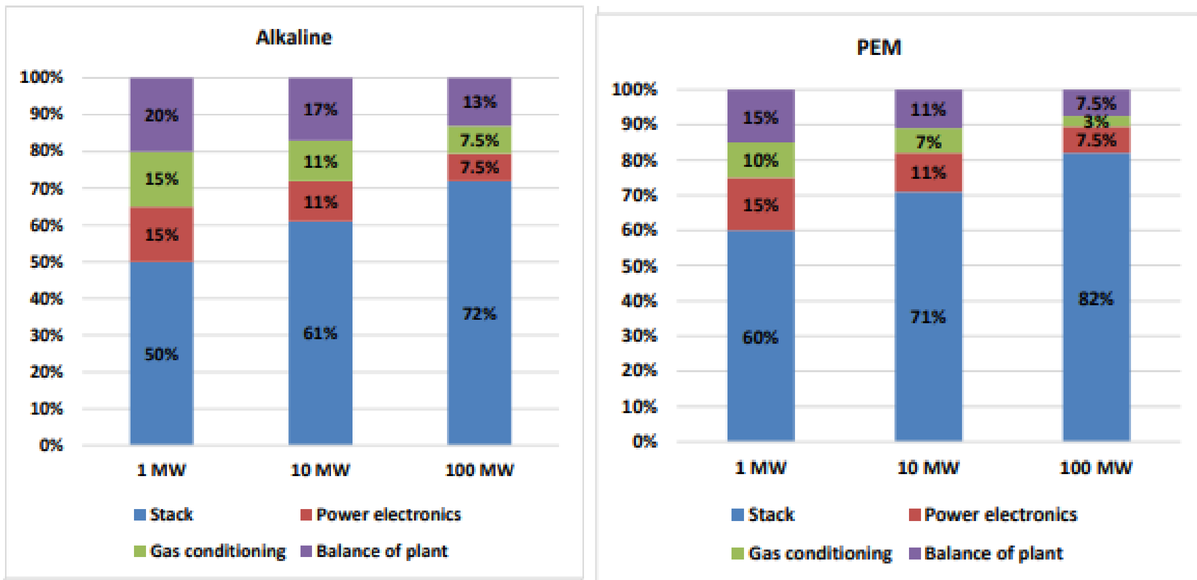
Source: STORE&GO – D7.5 Report on experience curves and economies of scale, Böhm et al., https://www.storeandgo.info/fileadmin/downloads/deliverables_2019/20190801-STOREandGO-D7.5-EIL Report_on_experience_curves_and_economies_of_scale.pdf

Notes: Uncertainty of ±15% on initial CAPEX (light-coloured areas). Alkaline (AEC), PEM (PEMEC) SOE (SOEC) are used in the figure instead of acronyms used in the rest of the document.

Impact of module size on costs:

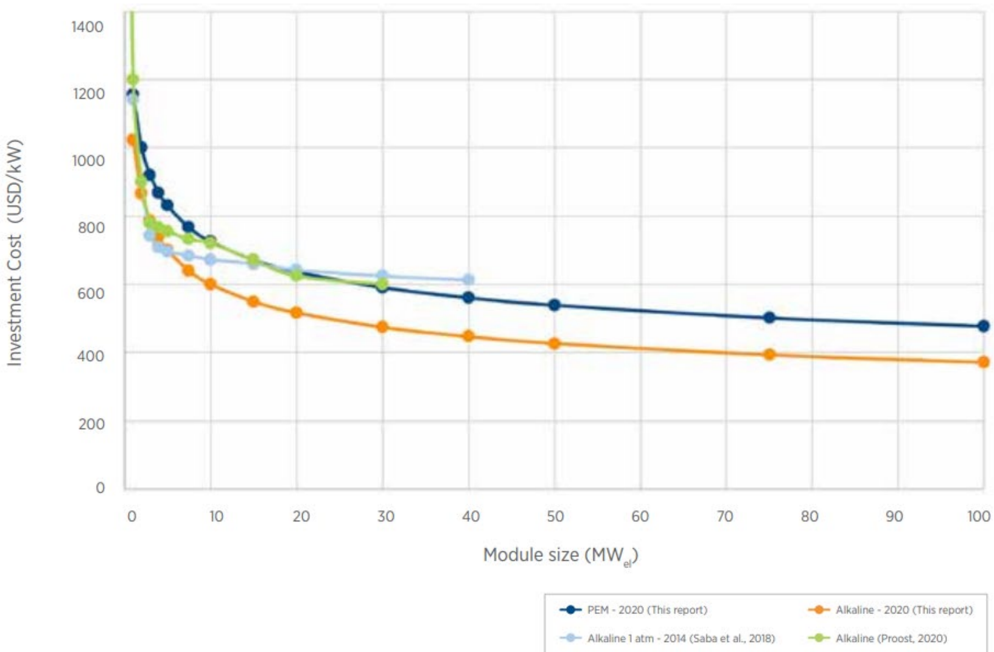
The total cost of electrolyser systems will also be impacted not only by increased manufacturing volumes, but also by producing larger and larger units. As can be seen in Figure 4 and Figure 5, an increase in system power is expected to decrease overall CAPEX (per unit of power), but will increase the relative share of stack components in overall CAPEX costs.

Figure 4. Estimated cost breakdown by major component for 1 MW, 10 MW, and 100 MW alkaline and PEM electrolysers based on current costs.



Source: The Oxford Institute for Energy Studies, Cost-competitive green hydrogen: how to lower the cost of electrolysers?, 2022 Elaborated from Green hydrogen cost reduction. Scaling up electrolysers to meet the 1.5C (2020) climate goal and Böhm et al. Applied Energy, 264 (1), pp. 1–13 (2020).

Figure 5. Electrolyser investment cost as a function of module size for various technologies.



Source: IRENA, Green hydrogen cost reduction. Scaling up electrolysers to meet the 1.5C (2020).

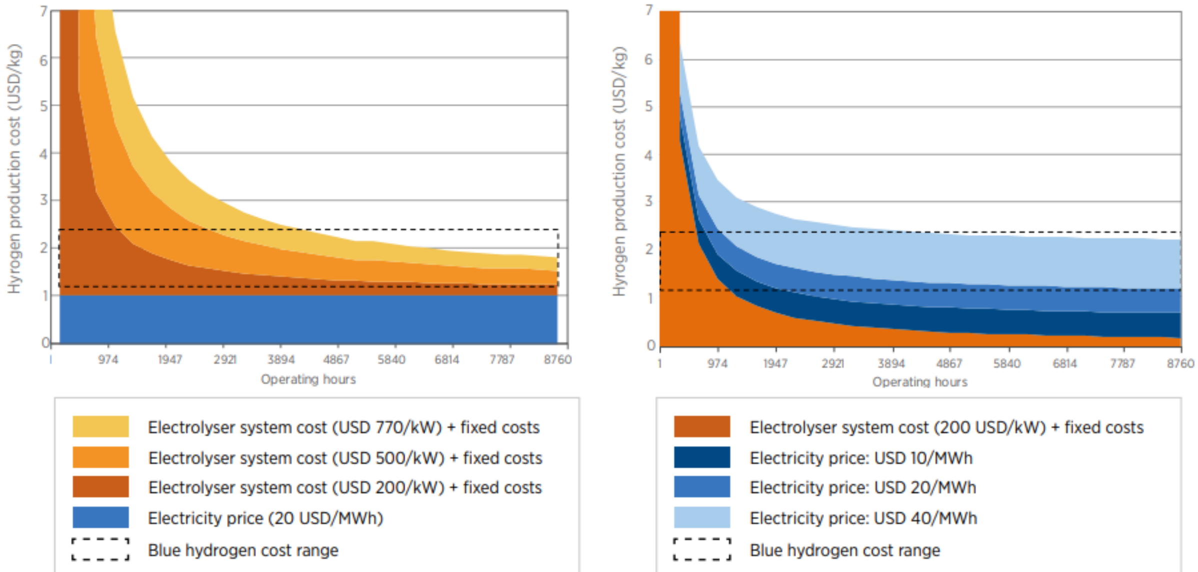
Impact of the Cost of Electricity on the viability of Electrolyser investment:

As can be seen in Figure 6, CAPEX is the main contributing factor to the final price of hydrogen only for very low utilization factors. As the electrolyser load factor increases, the relative weight of electricity cost dominates the total hydrogen cost with a relative weight which increases as utilization grows. 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% [7].

In European regions with suitable costs of renewable electricity, electrolysers are expected to produce hydrogen that will compete with fossil-based hydrogen already in 2030[46]. Locating electrolysers in areas with high access to cheap renewable electricity is likely to decrease overall costs and contribute to viable investments.

[46] Assuming current electricity and gas prices, low-carbon fossil-based hydrogen is projected to cost in 2030 between 2-2.5 EUR/kg in the EU, and renewable hydrogen are projected to cost between 1.1-2.4 EUR/kg (IEA, IRENA, BNEF). Costs linked with transport over long distances should be added on top of production costs.

Figure 6. 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, , or 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.

Projected costs of renewable based hydrogen production:

In countries relying on gas imports and characterised by good renewable resources, clean hydrogen production from renewable electricity can compete effectively with production that relies on natural gas [4] [6]. According to IRENA [7], '"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 6). Given the geopolitical situation and the instability in the wholesale prices in the wholesale European electricity market, the value of 20 USD/MWh[47] seems on the costs of electricity too optimistic for the European market in 2022 and would need to be verified periodically to factor in the market wholesale electricity prices.

In 2020 an estimate for the costs of 1kg of hydrogen produced in the EU through Steam Methane Reforming was 1.41 EUR/kgH_2 [2]. This drops to 1.16 EUR/kgH_2 excluding the impact of CAPEX amortisation[48]. More than 56% of the total cost of hydrogen production reported for 2020 is associated with the natural gas cost. With natural gas cost increasing the total cost of hydrogen coming from steam methane reforming is also going to increase.

[47] Roughly 19 EUR/MWh (June 2022).

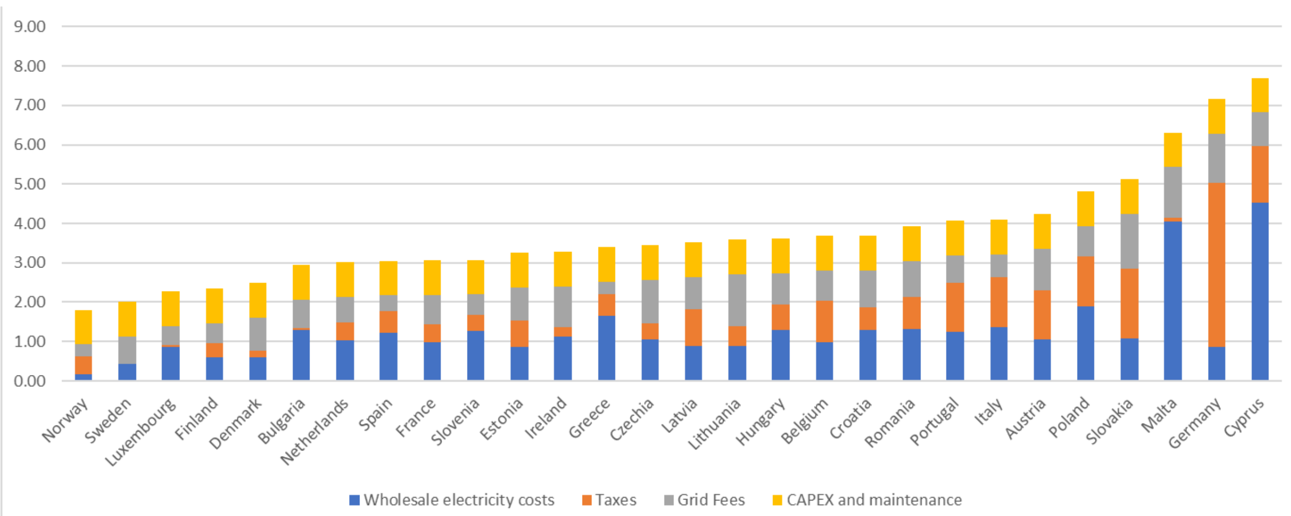
[48] This still includes a carbon allowance of 0.22 EUR/kgH_2.

There are two main options to calculate the levelised cost of hydrogen produced via electrolysis in Europe:

1) The hydrogen production costs using grid electricity in EU are in the range of 1.8 – 7.7 EUR/kgH_2 (2022) [3]. As it is shown in *Figure* 7, differences between the Member States are explained by differences in the wholesale electricity market prices and taxation levels. The EC proposal on the Energy Taxation Directive (fit for 55 package) would allocate the lowest taxation levels to the renewable and low carbon hydrogen. Hydrogen produced using grid electricity will have a carbon footprint which is directly proportional to the carbon footprint of the electricity used.

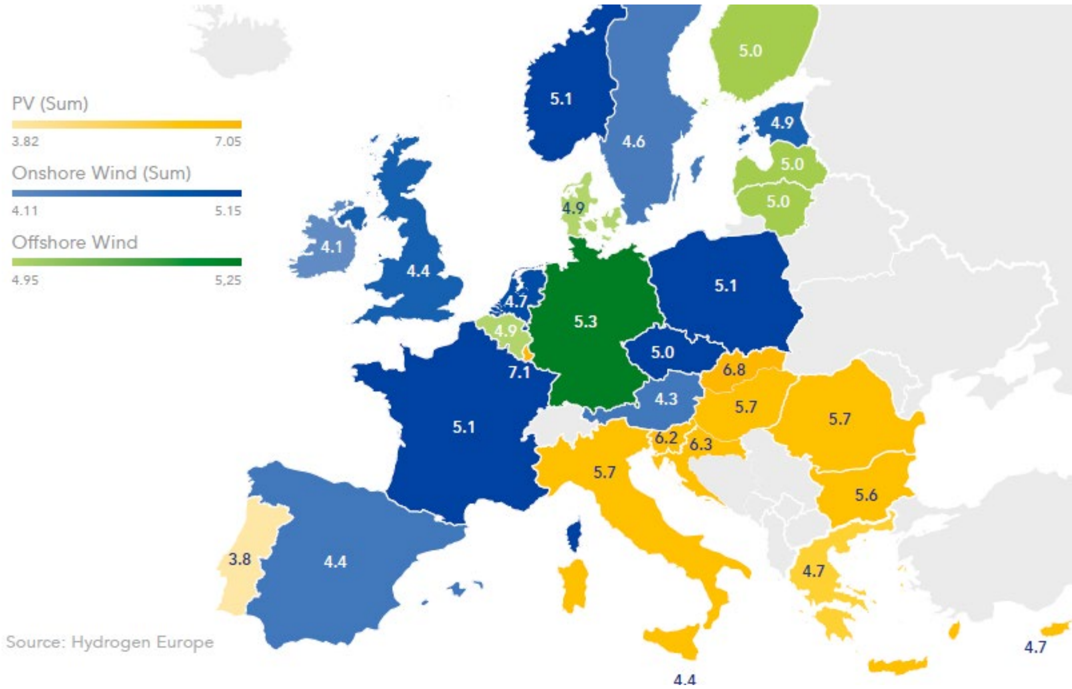
2) According to estimates from Hydrogen Europe, the European hydrogen production costs using directly renewable sources vary from a 2020 median of 6.8 EUR kg/H_2 if solar PVs are considered, to a 2020 median of 5.5 EUR kg/H_2 in case of wind based production [2] (see Figure 8). It has been shown before that the final cost of hydrogen produced using renewable electricity will be impacted by the load factor of the electrolysers and therefore 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.

Figure 7. Grid-connected electrolysis hydrogen production costs in the UE in 2020 (EUR/kgH_2).



Source: Fuel Cells and Hydrogen Observatory.

Figure 8. Average renewable hydrogen production costs in the EU (with UK and Norway) in 2020 (in EUR/kgH_2), using the lowest-cost RES technology for a given country.



Source: Clean Hydrogen Monitor, 2021, Hydrogen Europe

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 follow 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 variability of the renewable energy source. Especially for industrial processes, where hydrogen feedstock needs to remain relatively stable at large volumes, variability is an issue.

Table 2. The comparison of factors influencing both methods for the levelised cost of hydrogen.

Factors:	Grid connected electrolyser	Off grid- electrolyser connected directly to the source of the renewable energy	Commentary
Carbon contents of the grid	➢ Statistics of the carbon contents of the grid from the Environmental energy	➢ Accounted as 100% renewable if the conditions of the Delegated Act on	The Open Public Consultation on the draft Delegated Act supplementing Directive (EU) 2018/2001 of the European Parliament and of the

	Agency. National statistics. ➢ Flanking measures foreseen in the recast of the Renewable Energy Directive (2018/2001) refer to the possibility to purchase the direct Power Purchase Agreements with renewable electricity producers. ➢ Other flanking measures refer to the Guarantees of Origin to prove the renewable character of electricity. Grid connected electolysis to be accounted for a fully renewable.	additionally, supplementing the Directive (EU) 2018/2001 would apply (see the commentary).	Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin is open until 17 June 2022. The draft Additionally Delegated Act defines specific criteria for producing renewable hydrogen with renewable electricity and indicates the placement of electrolysers with the: ➢ The bidding zone correlation ➢ The price correlation if placed in an adjacent bidding zone ➢ The time correlation (with monthly accounting of renewables, going down to hourly accounting in 2027) And conditions to the connection of the electrolyser to the renewable source not longer than within 36 months
Electricity costs and tariffs and taxes	➢ Wholesale electricity prices and additional Taxes and Tariffs (Eurostat reporting bi-annually on the electricity costs to non-household consumers with and without taxes at https://ec.europa.eu/eurostat/web/main/search/)	➢ Some taxes would not be applicable to the electrolyser installation directly connected to the renewable source	➢ Note: The proposal on the Energy Taxation Directive refers to the lowest levels of taxation for renewable and low carbon hydrogen: ➢
Post production CO2 Scheme costs (Emission Trading System)	➢ ETS CO2 prices would be applicable in line with the rules of the Directive on ETS to the grid electricity	➢ N/A directly for fully renewable hydrogen. ➢ The carbon market reform within the fit for 55 package also proposes that all hydrogen manufacturing above a certain threshold would be covered by the ETS (previously it was only hydrogen manufacturing via	➢ Note: The World Bank Carbon Pricing Dashboard covers the main data on jurisdictions that have applied or have scheduled carbon pricing. https://carbonpricingdashboard.worldbank.org/map_data ➢ Some States have put in place Emission Trading Schemes, such as the UK, or some States of the USA. However the exact price correlation towards the EU

		thermal reforming). Green hydrogen producers could be eligible for free allowances which they could then sell improving the economic feasibility of renewable hydrogen production.	ETS is not established (the prices are not identical) Note: for carbon pricing
Expected performance of electrolysers in hours	➢ Estimated at 4.000 off peak hours. With increasing efficiency, the performance would increase.	➢ The RES available capacity is the limiting factor to directly connected electrolysers	

Source: European Commission, DG Energy, review of the Clean Hydrogen Monitor, 2021 by Hydrogen Europe, Eurostat data, World Bank Dashboard on carbon pricing, and EC legislation

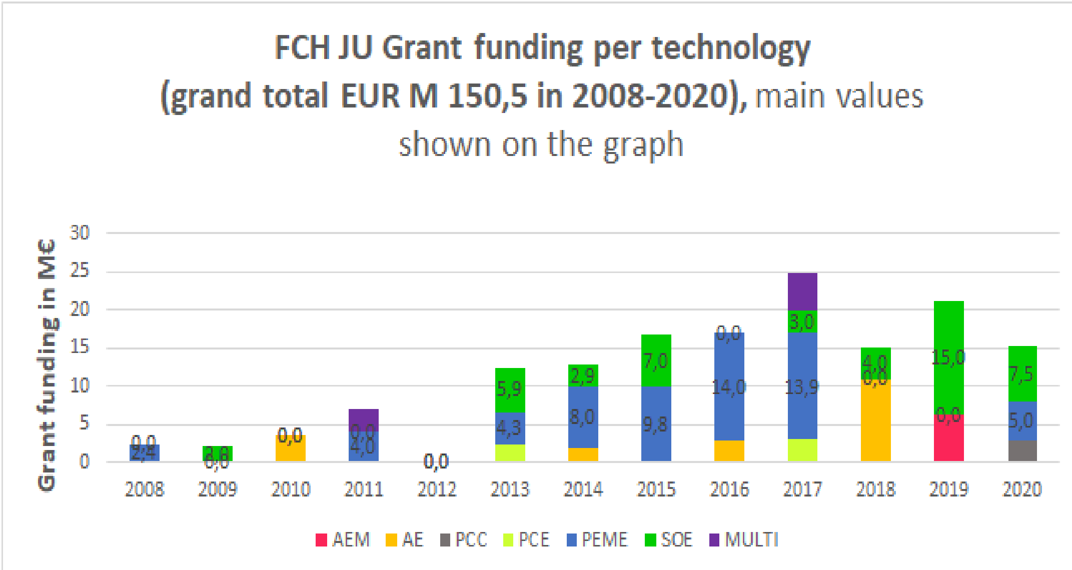
2.4 Public R&I funding

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 150.5 million since 2008 to electrolyser technologies (EUR 74.7 million are for research actions and EUR 75.9 million for Innovation Actions (IA)). 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 (Figure 9).

The main beneficiary countries are Germany, France and the UK with about EUR 31.4, 25.4 and 18.4 million respectively (Figure 10). Deployment of electrolyser capacity supported by the FCH JU has accelerated in recent years and went from average yearly deployment figures of 6.5 MW in the period 2016-2019 to 11.3 MW deployed in 2020 and 21 MW deployed in 2021.

Figure 9. Clean Hydrogen JU grant funding per technology in period 2008-2020.[49]

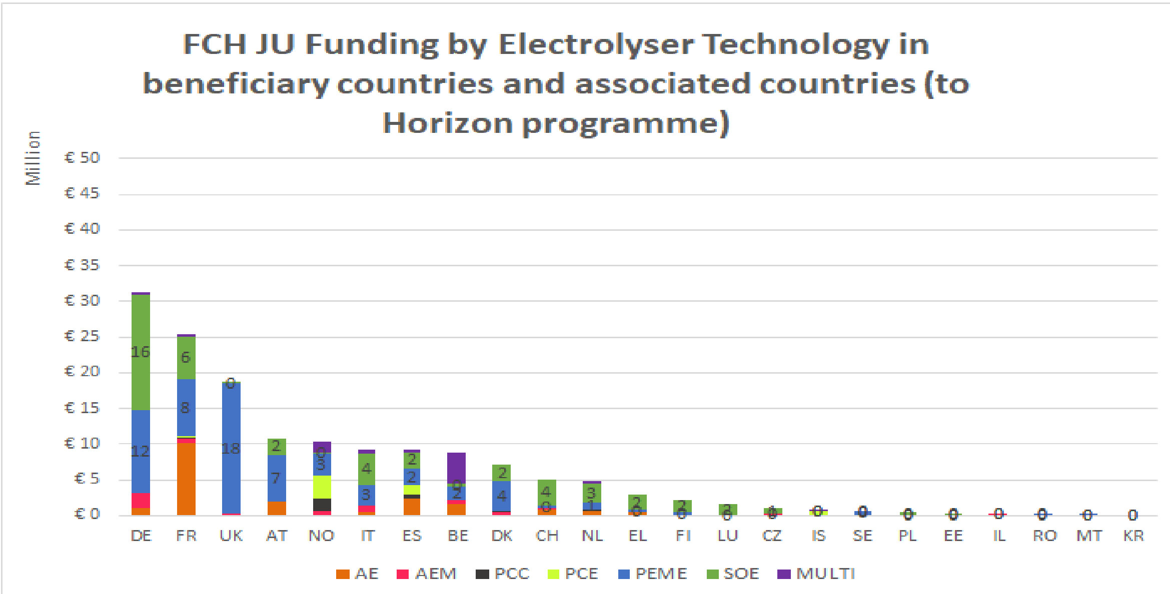


Source: Fuel Cell and Hydrogen JU, 2021

Notes: PCE is proton conducting electrolyser (a low technology readiness level version of the Solid Oxide) which conducts protons through the solid oxide membrane such is PCC is proton conducting ceramic. Multi- refers to multiple types of electrolyser technologies.

[49] The funding covers the period 2008-2020, as the last call of FCH JU was in 2020, while the Clean Hydrogen JU published its first Call in 31 March 2022.

Figure 10. Clean Hydrogen JU funding by country and associated country, and per technology.



Source: Fuel Cell Joint Undertaking, data 2021

Note: PCE is proton conducting electrolyser (a low technology readiness level version of the Solid Oxide) which conducts protons through the solid oxide membrane Multi- refers to multiple types of electrolyser technologies.

In addition to funding from 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. EU funding supporting water electrolysis amount to about EUR 56 million for PEM, about EUR 60.6 million for alkaline, about EUR 10.5 million for solid oxide electrolyte, and about EUR 3.5 million for AEM designs.

ETS Innovation Fund has already supported four projects with the first two 2020 closed calls over small scale and large scale projects. The total budget provided by the Innovation Fund has been over EUR 240 million. All these projects plan to deploy electrolysis capacity and target applications in both industrial settings and public transport applications with about 96% of this total budget is dedicated to two projects targeting introduction of large renewable hydrogen amounts into large-scale refinery operations and steelmaking.

Support from other large European initiatives such as the Important Projects of Common European Interest (IPCEI) is today not yet easily quantifiable since assessment of project proposal has just been finalised for the first waves of projects.

Recovery and Resilience Facility (RRF) and national recovery 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 [2] the total cumulative amount of funds available for hydrogen from all RRPs reaches over 54 billion euros, of which 42 are allocated to categories which include hydrogen technologies among investments in multiple other technologies and 12 dedicated exclusively to hydrogen technologies. It is not possible to easily extract dedicated funding for electrolysis from these funds, but initial estimates point out to a planned deployment of around 2 GW of electrolysers by 2026.

2.5 Private R&D funding

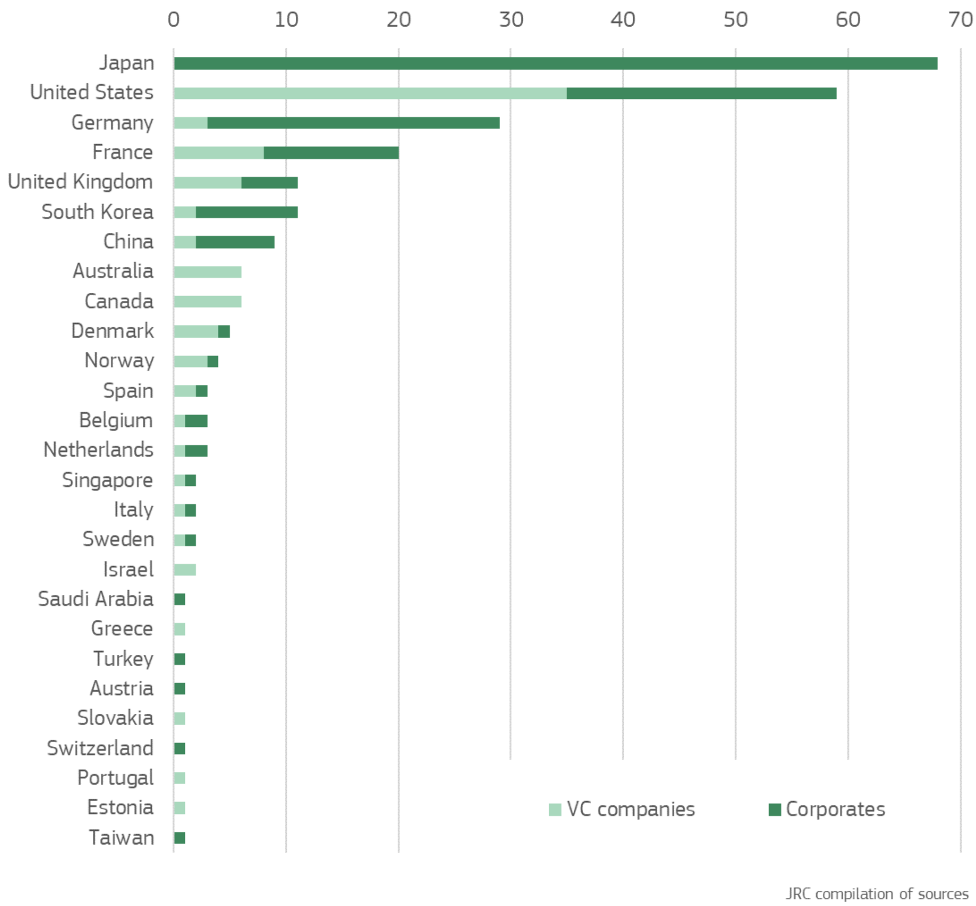
Five countries host 73 % of identified innovators but display various profiles (*Figure 11*). While Japan (1st) leads by the sole number of innovating corporates it hosts, the United States (2nd) follow closely, with start-ups accounting for more than half of the companies identified. Germany (3rd), France (4th) and the United Kingdom (5th) follow, the first with a very strong corporate innovator base, the latter two with almost equal splits between corporates and start-ups. Overall, the EU hosts around 30% of the innovating companies identified globally, both in terms of corporates and start-ups.

In 2021, global venture capital (VC) investments amount to EUR 385 million, more than doubling previous year's investments (+126 % as compared to 2020), an all-time high since 2010. This confirms a clear acceleration of investments in green hydrogen production companies over the current 2016-21 period, which have almost doubled as compared to the previous period (*Figure 12*).

Early ventures remain heavily subsidised, both in and outside of the EU, as grants represent 68 % of global early stage investments in identified companies. The EU accounts for 19% of the disclosed value of early stage transactions in the period 2016-2021, amounting to over EUR 58.2 million. Investments in the EU have steadily increased since 2017 and 73 % of them being concentrated over the past two years in Finland and France (and to a lesser extent in Denmark). The US, accounting for 64 % of investments, is responsible for the essential of investment growth over the current period.

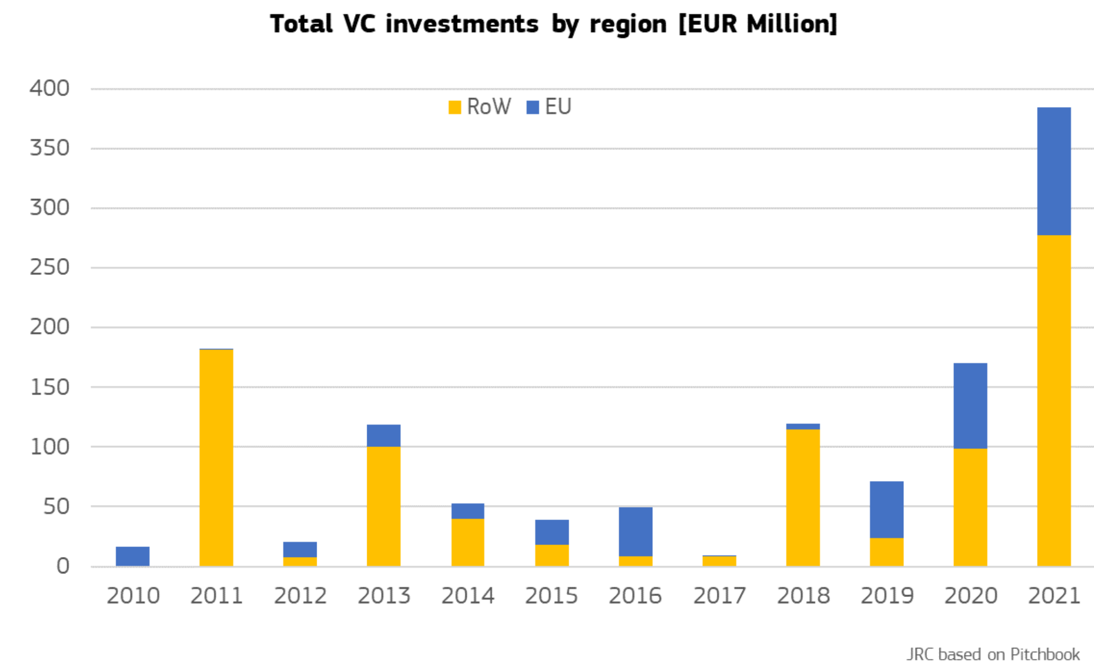
Over the 2016-21 period, global later stage investments amount to EUR 495 million (+ 30 % as compared to previous period). As seen in *Figure 13* later stages investments realised outside of the EU have quadrupled in 2021 and alone amount to as much as all EU later stages investments realised since 2016. The US remains the main destination of later stages investments (34 %) despite a sharp decrease as compared to the previous period. With growing investments, the EU accounts for 43 % of later stages investments over 2016-21 (in particular in France, Denmark and Italy.

Figure 11 Number of innovating companies (2016-21)



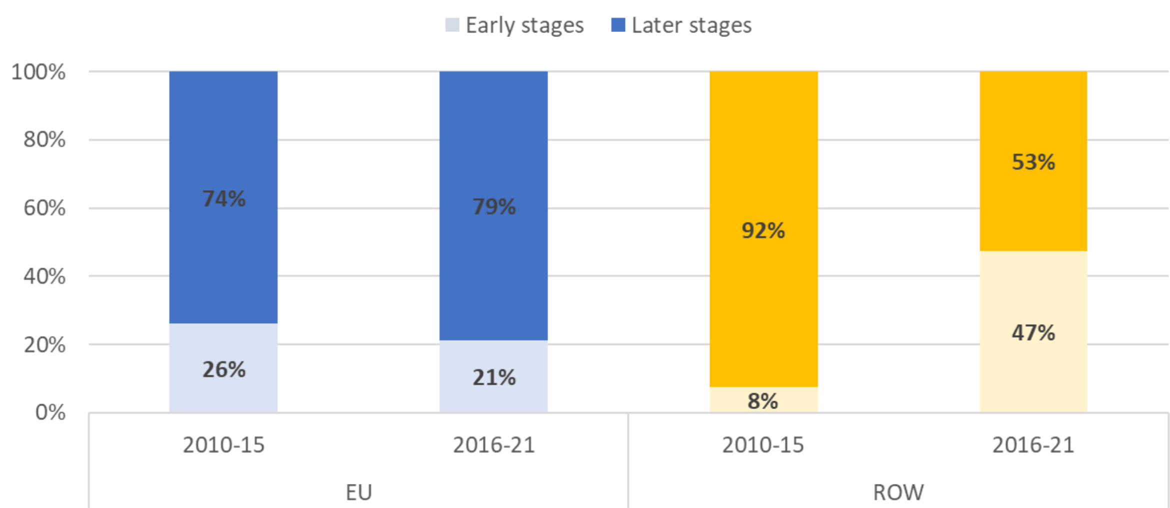
Source: JRC, 2022

Figure 12. Total VC investments by region [EUR Million].



Source: JRC, 2022

Figure 13. VC investments by stage and region (Share of capital invested).



Source: JRC, 2022

2.6 Patenting trends

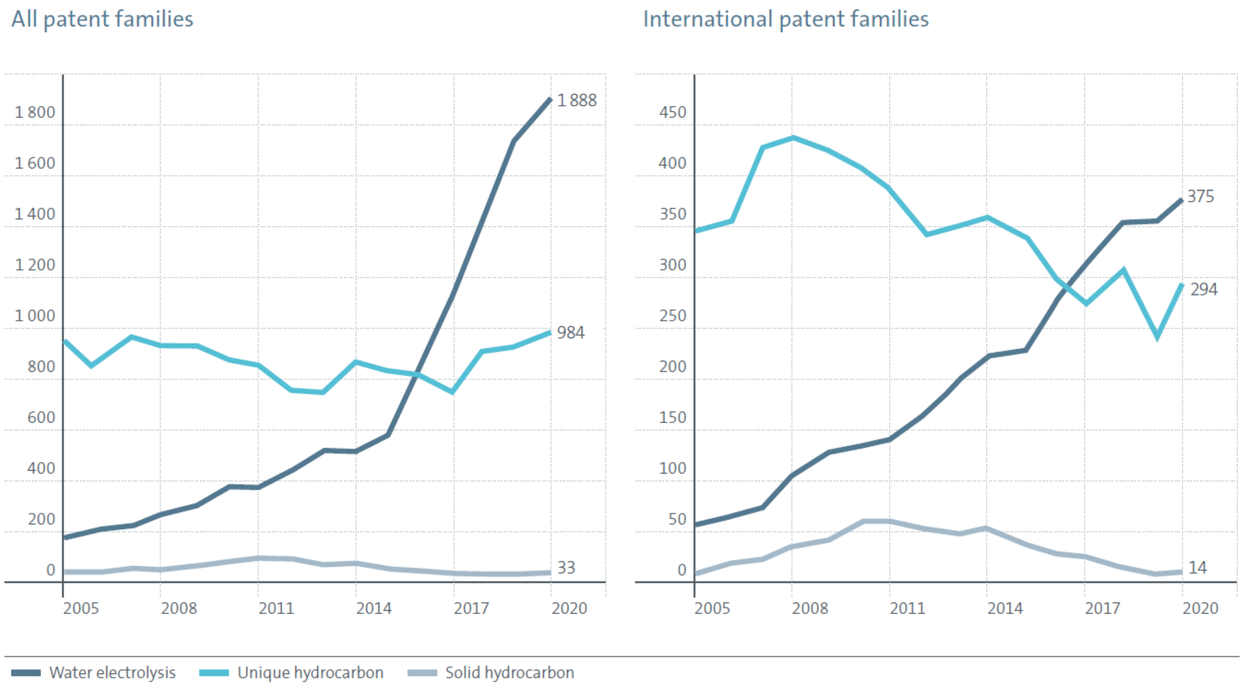
The trends highlighted in previous years are still valid and have been confirmed once again by in-depth patent analysis by IRENA and EPO [8]. As can be seen from Figure 14, 2017 the number of international patent families linked to hydrogen production processes based on water electrolysis surpassed the number of filings based on processes using liquid hydrocarbon sources; which has been higher than the number of filings based on solid hydrocarbons feedstock at least since 2005. The trend is similar also for national patent filings, with a takeover for water electrolysis technologies happening one year earlier.

As can be seen from the data presented in Figure 15, Japan, the USA and Germany are leading countries in terms of international filing. These three countries together account for about 52% of the total international patent families related to water electrolysis from 2005 to 2020. While all countries show an increasing trend of patenting internationally, Japan, after a significant acceleration in 2016, has been significantly reducing the amount of internationally filed patents since 2018 and now totals 731 international patents. Despite having the highest number of total patents, China has a very low fraction (about 3%) of international patents and reaches a total number of 179 international patents. EU member states together have more than 830 international patent applications on water electrolysis[50]. This number grows beyond 1 000 including UK, Norway, Switzerland and Iceland.

In 2018, overall patent filings related to non-noble metal electrocatalysis surpassed the number of inventions related to the use of noble metals, even if international patent filings associated with noble metals catalysts are still clearly dominant. Chinese national filings are responsible for the higher number of non-noble metal electrocatalysis patent filings since 2018.

[50] https://public.tableau.com/app/profile/irena.resource/viz/IRENA_Electrolysers_Patents_Insights/Electrolysers_patent_insight#2

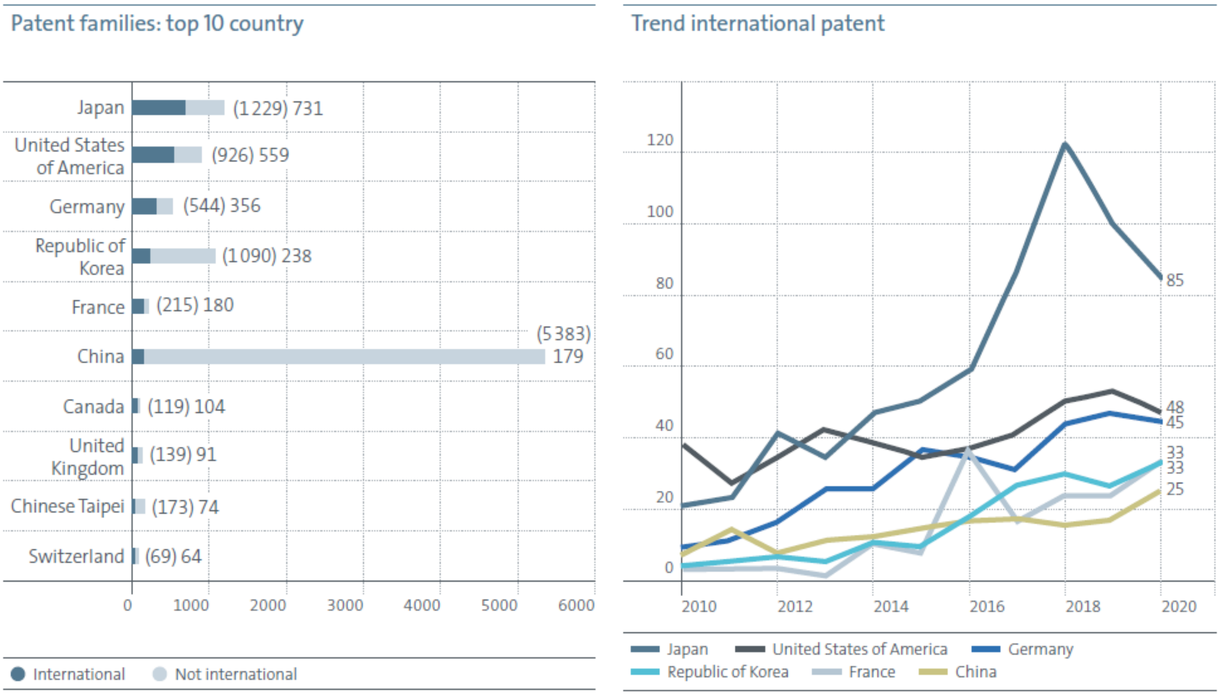
Figure 14. 2005-2020 trend of overall patent families (left-hand side) and international patent families (right-hand side).



Source: European Patent Office/IRENA [8]

The patent figures compare hydrogen production processes based on water electrolysis with processes using liquid or solid hydrocarbon feedstock. International patent families are patents that have more than one country in the list of publications, assignees, inventors or first priority countries. Using this concept excludes single national filings that have no family members.

Figure 15. Total number of patent families related to hydrogen production processes based on water electrolysis (2005-2020).



Source: European Patent Office/IRENA [8]

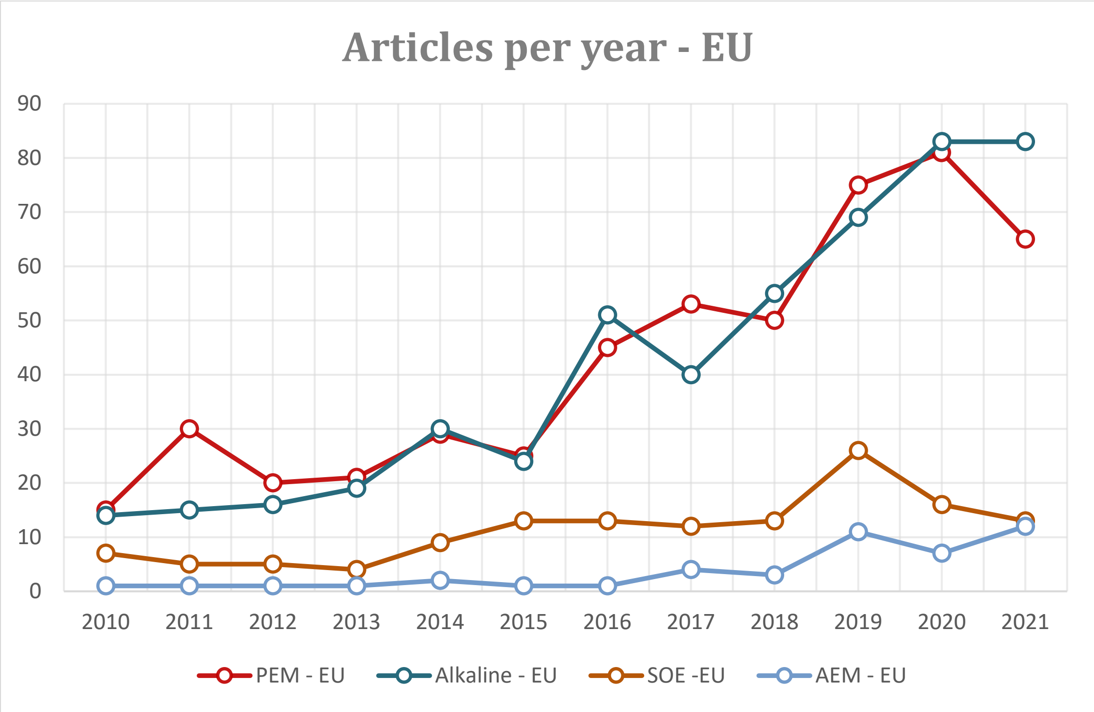
Notes: The top 10 countries are listed on the left-hand side (the number in brackets is the total; the number not in brackets refers to international patents only). Trends for international patent families for the top 6 countries is listed on the right-hand side. International patent families are patents that have more than one country in the list of publications, assignees, inventors or first priority countries. Using this concept excludes single national filings that have no family members.

2.7 Bibliometric trends/Level of scientific publications

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 and the US have a comparable amount of publications as Europe, with the exception of China clearly leading in terms of number of publications for alkaline 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.

Similar trends can be identified 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. European impact lead is matched by South Korea when AEM is considered.

2.8 Impact and Trends of EU-supported Research and Innovation (alternate years only)

This dimension is mostly covered by the annual Programme assessment performed by the JRC and provided to the Clean Hydrogen Joint Undertaking under the multiannual framework contract between the two parties. A public version is available in the Clean Hydrogen Joint Undertaking site[51].

[51] https://www.clean-hydrogen.europa.eu/knowledge-management/collaboration-jrc-0/programme-review-report_en

3 Value Chain Analysis

3.1 Turnover

Due to the lack of fully developed markets for electrolysers and the often commercially sensitive nature of the 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 electrolyser figures from overall financial information figures coming from large companies active in multiple technological field as well (e.g.: Siemens).

3.2 Gross value added

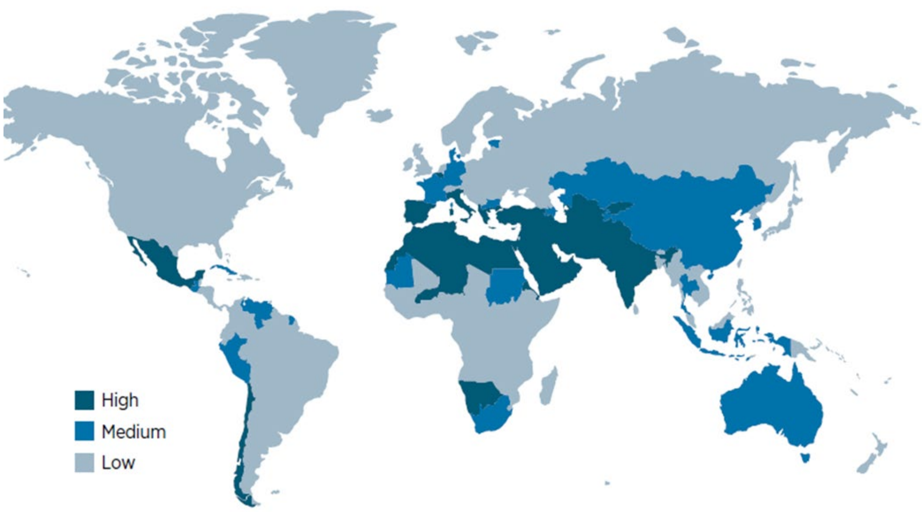
For the same reasons outlined for the category 'Turnover', retrieving information of gross added value it is extremely challenging.

3.3 Environmental and Socio-economic Sustainability

The main environmental impact of producing hydrogen through water electrolysis concerns: the sustainability and access to critical raw materials (discussed in section 4.3) water constraints the environmental impact associated with the source of electricity and the manufacturing of installations needed for producing renewable hydrogen (e.g.: renewable electricity generation and electrolysis). IRENA has issued a global water stress map (*Figure* 17) indicating regions with low, medium or high water stress[52].

When producing hydrogen through water electrolysis, due account should be taken on the impact of deionised water needed (estimated at a minimum level of 9 kg of water per 1 kg H_2).

Figure 17. Heat map of water stress levels.



Source: IRENA, Geopolitics of the energy transformation, the hydrogen factor (2022).

[52] 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.

A recent report from the Hydrogen Council[53] quantifies at least a tenfold reduction of carbon-equivalent GHG emissions if hydrogen is produced via electrolysis using renewable electricity coming from wind or solar, or nuclear energy, rather than via steam methane reforming.

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 [9] 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 low mass fraction of platinum (< 0.1% of the total mass of the stack). There are on-going social LCA studies on electrolysis the 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 Electorlysis Cell stack [10] found that stainless steel production is the main social hotspot of almost all the impact categories considered. This is due to the high mass ratio, which hides the effect 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

The electrolysis market is very dynamic with several mergers and acquisitions registered in recent years. An overview on the numbers of the manufacturers of medium to large scale electrolysis stacks and systems (Table 3), considering only manufacturers of commercial systems and not manufacturers of laboratory-scale electrolysers, shows that Europe has a clear lead in terms of Solid Oxide electrolysis and AEM. EU host also a very large of number of companies producing electrolyser stacks or systems.

Table 3. Location of electrolyser manufacturers, by technology.

Electrolyser technology	EU27	CH, NO, UK	USA	China	Others
Alkaline AEL	**10**	**2**	**3**	**5**	**3**
Proton Exchange Membrane PEM	**11**	3	7	2	3
Solid Oxide Electrolysis SOE	**3**		1		
Anion Exchange Membrane	**1**		1		

Source: Update of data extracted from A. Buttler, H. Spliethoff, Renewable and Sustainable Energy Reviews 82 (2018) 2440–2454 and IRENA, Green Hydrogen Cost Reduction, 2020.

It is recognised that current manufacturing volumes are not high enough if deployment ambitions, European ones in particular, have to be fulfilled. Nevertheless, it is difficult to keep track of the manufacturing capacity

[53] https://hydrogencouncil.com/wp-content/uploads/2021/01/Hydrogen-Council-Report_Decarbonization-Pathways_Part-1-Lifecycle-Assessment.pdf

actually available for electrolyser production due to the constantly evolving situation and due to a certain level of sensitivity this information can have in industrial environments.

Several pledges have been made by manufacturing companies and an increase in manufacturing capacity can surely be projected into the near future, as can be expected for instance by evaluating several on-going initiatives at European level such as the IPCEI and Green Hydrogen Alliance. Estimates about the 2021 European manufacturing capacity vary, but it reasonable to assume a range between 2.5 GW[54] and 3 GW [4] per year.

Worldwide capacity production in 2021 was expected to be 6.7 GW/y (of which about two third alkaline and one-third PEM) [4].

The manufacturing volumes of European companies are however lower than those of Asian companies (Chinese is particular). Estimates for 2021-2022 [4], allocate around a half of worldwide alkaline electrolysis capacity to Chinese companies, and most of the production capacity for PEM electrolysers to American companies. A significant amount of European and American manufacturing companies is forming joint ventures with Chines companies or having local production capacity in China [4]. This allows electrolyser producers to exploit significant lower production costs and have access to rapidly growing demand. Chinese manufacturing companies can offer installed system costs for alkaline which in 2021 were assessed to be four times lower than those of western companies [4].

Keeping track of projected future manufacturing capacity increase is not a simple task, due to an ever growing sequence of announcements and industry. For Europe, a joint declaration between the Commission and twenty manufactures has set the objective of a 25 GW manufacturing capacity to be reached by 2025[55]. Considering that worldwide manufacturing capacity in 2018 was estimated to be around 135 MW/y [11], it is expected that in the coming years announcements can credibly be followed by a massive increase in capacity and that significant growth will follow provided market demand and political support can sustain growth [11].

3.5 Employment in value chain incl. R&I employment (by segment)

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[56] 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).

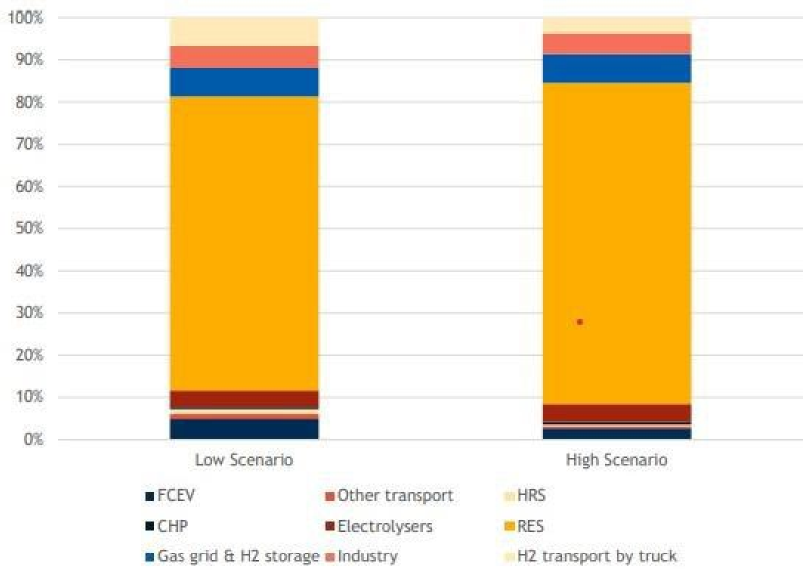
According to a study published by the Fuel Cell Joint Undertaking [12], hydrogen-related investments and operations are estimated to generate 29 270 – 106 980 direct jobs (in production and operations & maintenance) and contribute to further 74 790 – 250 650 indirect jobs, by 2030. Total job generated 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 job forecast fractions are highlighted in Figure 18 below. 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.

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

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

[56] 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.

Figure 18. 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).

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 /labour productivity

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

3.7 EU production Data (Annual production values)

On PRODCOM is not data available for 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 position and Global competitiveness

4.1 Global & EU market leaders (Market share)

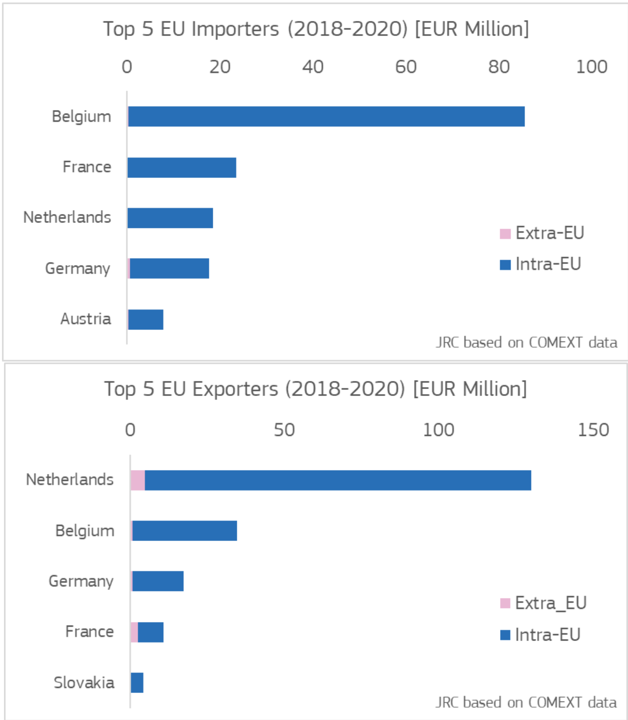
According to available conservative estimates [4], the expected shipments for 2022 will be more than tripled with respect to 2021, with a worldwide total of around 1.8 GW (0.5 GW in 2021). China accounts for about 70% of the worldwide shipments, with Europe and America having shares of roughly 15% each. About three quarters of this capacity is alkaline, with the rest made up by PEM electrolysers.

4.2 Trade (Import/export) and trade balance

From the analysis of available trade information it is clear that 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 seen from Figure 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 based on the information presented in section 2.2, it is however reasonable to assume that most, if not all the hydrogen traded, is of fossil origin, or obtained as by-product.

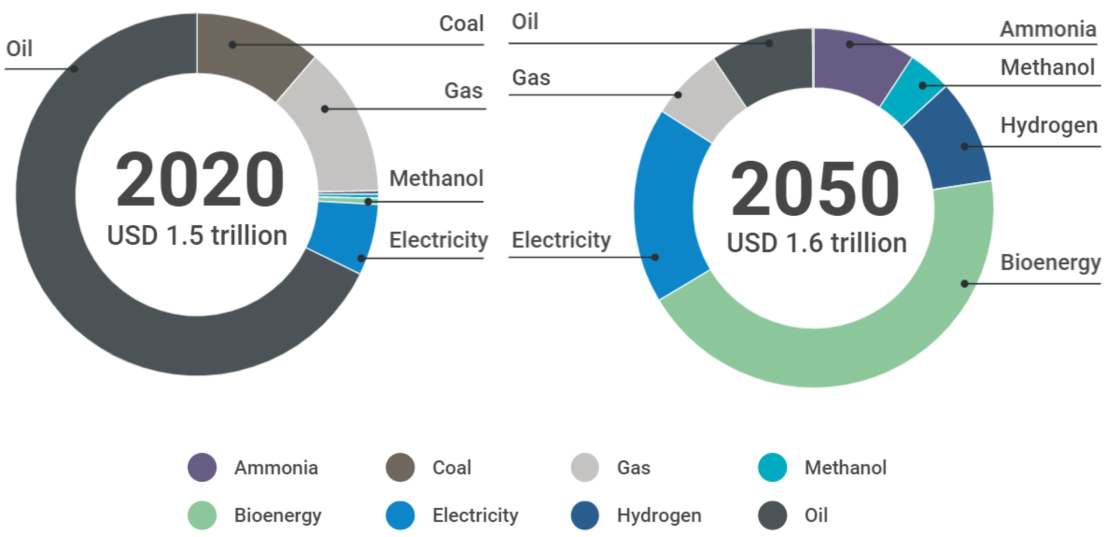
Figure 19. Value of hydrogen imports per country (right) and exports per country (left).



Source: JRC based on COMEXT data.

The market for renewable fuels is poised to grow and gradually replace the fossil fuel international trade. IRENA [13] 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 (Figure 20).

Figure 20. Projected shifts in the value of trade in energy commodities, 2020 to 2050.



Source: IRENA, Geopolitics of the Energy Transformation - The Hydrogen Factor, 2022.

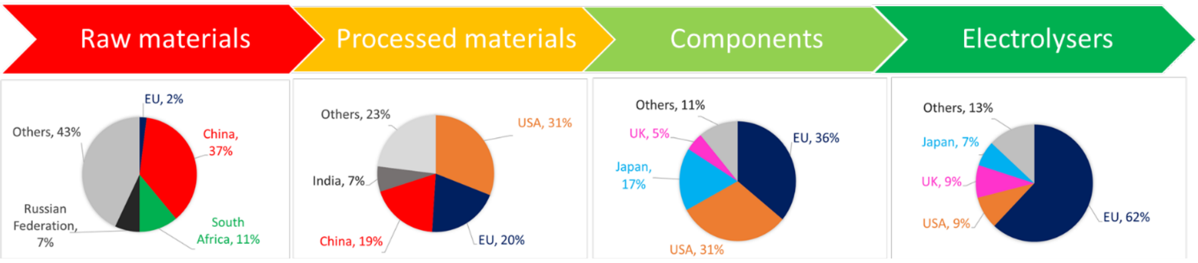
4.3 Resources efficiency and dependence in relation to EU competitiveness

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%[57]. As can be seen from Figure 21, Europe is strongly dependent on raw materials, with a global share growing progressively for processed materials and components and reaching a majority fraction for electrolysers.

The corrosive acidic regime employed by the PEM electrolyser, in particular, 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 [14].

[57] JRC analysis for DG GROW.

Figure 21. Supply chain for electrolysers.



Source: JRC analysis for DG GROW.

Notes: 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. 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. 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. 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

Current deployment of electrolysers on European territory is accelerating, but hydrogen produced using electrolysis is still less than 0.1% of current European (including UK, Norway, Switzerland and Iceland) hydrogen demand. Electrolyser deployment will reach significant volumes already by 2030 if the current strategies and pledges materialise into concrete follow-ups. Europe is in a good position to develop the manufacturing capacity required to reach the ambitious goals set in the REPowerEU Plan and the Hydrogen Strategy, but its competitiveness on global markets especially for alkaline technology is currently challenged, especially by China.

The EU's stronger position for PEM electrolysis risks being hampered by the supply the critical raw materials used for this technology. The EU industrial position is strong on SOE, but a dependence on Chinese critical raw materials is noted, together with mounting Chinese competition at a technological level. Europe has a strong position in terms of AEM electrolysis, but this technology is not at the same level of maturity of other commercially available water electrolysis options.

Indeed the EU's supply of critical raw materials, which are at the base of electrolyser value chains, depends almost completely on non-European sources and is concentrated in few geographical areas (especially China, South Africa and Russia). As a result, any action targeting significant deployment capacity will have to face supply challenges and put in place aggressive strategies for substitution and reduction of critical raw materials, for recycling and for diversification of supply.

The cost of renewable hydrogen will be strongly dependent on the price of electricity used for its production and on the availability of suitable amounts of dedicated renewable electricity production (solar and wind). A sustained increase on the cost of natural gas can improve the economic viability of renewable hydrogen.

International hydrogen markets are currently not well developed, do not move any significant amount of renewable hydrogen and tend to be localised on industrial clusters sitting close to national borders. If large amounts of renewable hydrogen will have to be transported across long distances, suitable markets structures and infrastructure will need to be established in the near future.

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

Provided a suitable market develops and political and economic support is available, European manufacturing capacity can receive benefits from increased automation, increased production volumes and larger stack capacities since all these can all help in reducing electrolysers system costs.

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List of abbreviations and definitions

AEM Anion Exchange Membrane
CAPEX Capital Expenditures
CH JU 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
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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