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EUROPEAN CLIMATE NEUTRAL INDUSTRY COMPETITIVENESS SCOREBOARD (CINDECS)

Annual Report 2021

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Abstract

This report builds on the findings and framework developed in the study, 'Climate neutral market opportunities and EU competitiveness', conducted by the ICF and Cleantech Group for DG GROW in 2019-2020. The objective is to establish a scoreboard to assess the EU's competitive position in carbon-neutral solutions across important industrial ecosystems related to the energy transition. The 2021 annual report of the European Climate Neutral Industry Competitiveness Scoreboard (CIndECS) provides an assessment of 20 climate-neutral solutions, in the ecosystems of renewable energy, energy-intensive industry, mobility-transport-automotive, construction and electronics. The scoreboard is based on ten key indicators: public R&D investment, early and later stage private investment, patenting activity, number of innovating companies, employment, production, turnover, imports & exports and trade balance. The analysis for each indicator is presented through a number of supporting sub-indicators, described in the summary of the assessment methodology, data collection and sources. For more details on the methodology, readers should consult the respective CIndECS technical document, on the protocol of the assessment methodology.

Foreword

This document is part of the Administrative Arrangement (AA) N° SI2.836914, JRC 35853, between DG GROW and JRC: European Climate Neutral Industry Competitiveness Scoreboard (CIndECS).

It fulfils Task 5: Producing an annual report for the year 2021.

It also contains as Annex to the report:

- Final $D2_{2021}$ Datasets of the 20 climate neutral solutions;
- Final $D3_{2021}$ Scoreboard of the 20 climate neutral solutions;

The report is accompanied by:

- A PowerPoint presentation on methodology, analysis and main conclusions, with relevant graphs to display the results and key findings that can be used for communication purposes ;
- A summary in the form of a policy brief, including a short description of the scope of the study, a synthesis of the findings, summary scoreboards for the climate neutral solutions assessed and a summary of messages relevant for policy making.
- Three of the solutions: wind rotors, offshore operations for RE installation, and decarbonisation of steel through H-DRI and electrification have received greater focus and analysis, the latter two also being the subject of dedicated expert workshops.

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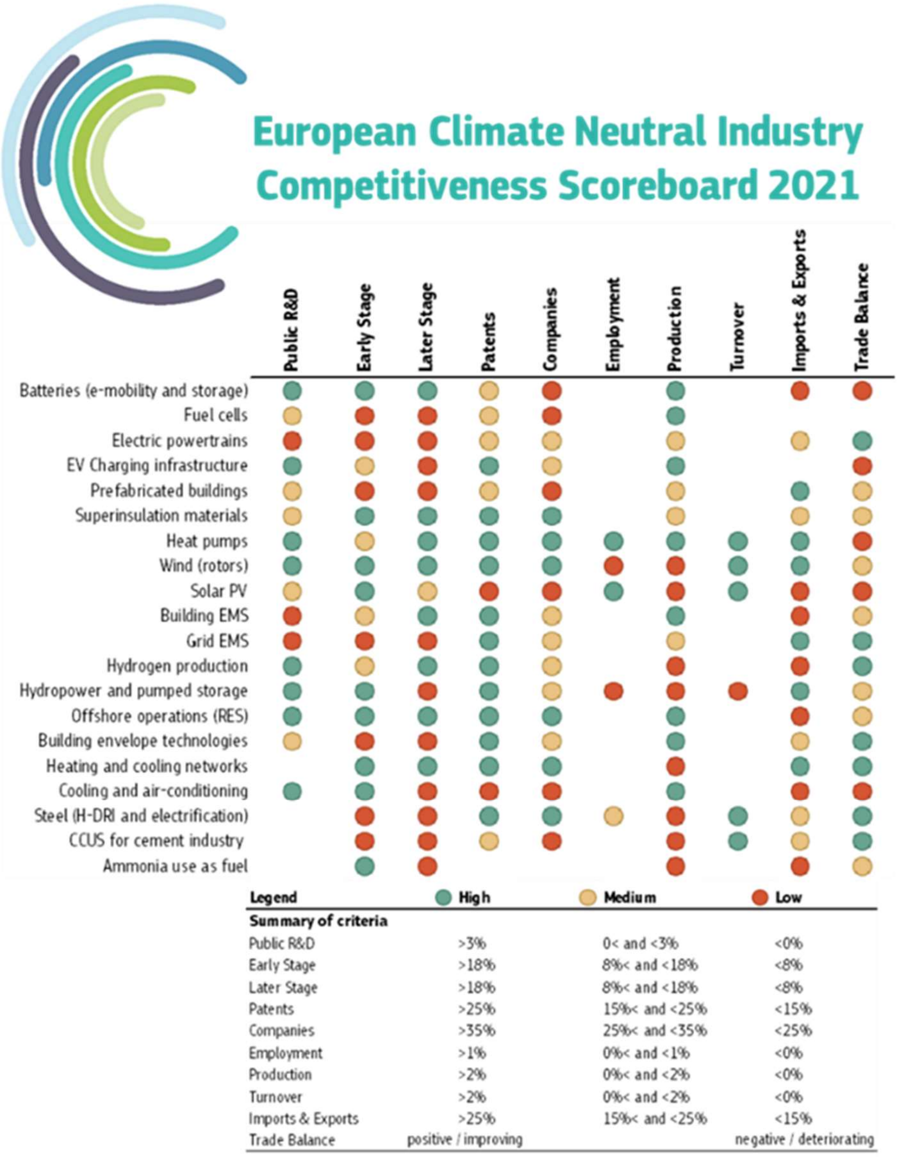
Executive summary

The 2021 annual report of the European Climate Neutral Industry Competitiveness Scoreboard (CIndECS) presents an assessment of key climate-neutral solutions (listed in the figure below) that have high potential to support the competitiveness of European industry, while also benefiting Europe's socio-economic development, aligned with the European Green Deal and the objective of climate neutrality by 2050.

The summary scoreboard for 2021 provides a snapshot of the EU's competitive position and performance across 20 key climate-neutral solutions, 12 of which are carried over from a previous assessment and eight of which have been added in 2021. The scoring criteria benchmark the value or trend in the indicator for each solution against the performance of the EU economy and its relative share in the global economy. In addition to the ten key competitiveness indicators, which provide the basis for the annual scoreboard, a number of sub-indicators support and underpin the competitiveness analysis and are made available in comprehensive datasets.



Source: JRC

Policy context

The European Green Deal ([1]), and the "new Industrial Strategy for Europe" ([2])([3]) place industry in a leading role to deliver the transformational change needed across European economy, society and industry to achieve

([1]) COM(2019) 640 final, 11th December 2019, The European Green Deal and a comprehensive package of proposals COM(2021) 550 final, 14th July 2021, 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality.

climate neutrality. Faced with challenge of energy dependence and rising energy prices, REPowerEU ([4]) has accelerated the urgency of this change. In order to succeed, EU industry needs to remain competitive and continue to innovate. This new scoreboard measures EU progress on climate neutral solutions key to achieving these goals.

This work contributes to the annual Clean Energy Competitiveness Progress Report, accompanying the State of the Energy Union Report. The solutions assessed feature in Member State's National Climate and Energy Plans and Recovery and Resilience Plans, and are aligned with the long-term decarbonisation needs. REPowerEU ([5]), proposed in the time of writing to address EU dependency on energy imports and rising energy prices, seeks to accelerate adoption of several technologies assessed here.

Key conclusions

EU public R&D investment in climate-neutral solutions is growing in all but three solutions in 2015-2019. In regards to venture capital investment, the EU performs better at early stage investment, financing start-ups, than at later stages, financing scale-ups. The EU performs very well in patenting activity, holding a significant share of high-value filings in 12 solutions. The EU hosts over 35% - the threshold of strong performance – of identified innovating companies in 6 solutions.

EU production, as an indication of EU manufacturing capacity, grew in 12 solutions in 2015-2020. In regards to EU external trade, the EU performs strongly, accounting for over 25% of extra-EU exports, in 6 solutions. At the same time, a big share of EU imports are EU internal trade, illustrating the importance and strength of the European single market. The EU has a positive trade balance in 11 solutions and trade deficit in 7 solutions. In all solutions, where the EU has negative trade balance, China is the main exporter to the EU, with the exception of ammonia, which is primarily imported from Russia.

In the 2015-2020 period, employment and turnover in solar PV and heat pumps increased faster than EU employment and GDP overall. By contrast, wind experienced no employment growth, but still generated a 4% increase in turnover. There are significant difficulties in consolidating employment and turnover figures, and data is therefore unavailable for majority of solutions.

The impact of the pandemic was mixed. Venture capital investment was practically unaffected by the pandemic, with investments continuing to rise in 2020. By contrast, the production of most solutions experienced some contraction in 2020, amounting to a 4% overall decline on 2019 values. Nevertheless, there were exceptions. The production of batteries and fuel cells continued to grow by 52% and 64% respectively in 2020 compared to 2019. Extra-EU exports declined by 3% in 2020 compared to 2019, whereas EU imports from outside the EU increased by 3%. For example, in heat pumps, 2020 was the first year in which the EU trade surplus turned into a deficit, due to increasing imports from China.

Main findings

The report confirms EU areas of strength: wind (rotors), heat pumps, hydropower, offshore operations (for installation of renewables) and heating and cooling networks, where EU performs well on most indicators. There are signs of improvement in some key technologies, such as batteries, solar PV and hydrogen production. The report reveals also areas of weaknesses and potential threats. EU performance is more often weak in transport-related solutions such as fuel cells, electric powertrains and EV charging infrastructure, and in building-related solutions such as prefabricated buildings, building envelope technologies and building EMS.

Related and future JRC work

Future work will focus on addressing data gaps where possible, expanding the scoreboard to cover more solutions and monitoring the evolution of the indicators to provide insights on the change in EU competitiveness across the relevant ecosystems.

Quick guide

For more details on the methodology, readers should consult the respective CIndECS technical document, on the protocol of the assessment methodology.

([2]) COM(2020) 102 final, 10 March 2020, the "New Industrial Strategy for Europe".
([3]) COM(2021) 350 final, 5 May 2021.
([4]) COM(2022) 108 final, 8th March 2022.
([5]) COM(2022) 108 final, 8th March, REPowerEU: Joint European Action for more affordable, secure and sustainable energy.

1 Introduction

The European Green Deal (European Commission 2019) is Europe's new growth strategy ([6]). At the heart of it is the goal of becoming the world's first climate-neutral continent by 2050. In 2021, climate neutrality by 2050 was enacted as a legally binding target in the European Climate Law ([7]), which also included the target of reducing greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. In addition, the Commission adopted a comprehensive package, 'Fit for 55', which included a series of proposals to revise all relevant policy instruments to deliver the additional emissions reductions for 2030 ([8]). Achieving the higher climate target requires additional annual investment of some EUR 355 billion over the next decade, from both private and public sources, according to Executive Vice-President Dombrovskis ([9]).

The new Industrial Strategy for Europe published in 2020 ([10]), and its recent update in 2021 ([11]), gives industry a leading role in making this transformation, while remaining competitive on the global stage. A central element of the renewed strategy is that EU industry can only succeed globally if it is competitive and continues to innovate. This is also crucial to the success of the EU's expanded energy and climate ambition.

In response to the pandemic, the EU adopted a comprehensive recovery plan, NextGeneration EU, to mitigate the economic and social impact of the pandemic and to make European economies and societies more sustainable, resilient and better prepared for the challenges and opportunities of the green and digital transitions. Under the Recovery and Resilience Facility, Member States will implement reforms and investment in line with the EU's priorities. Member States have allocated almost 40% of the spending in their plans on climate measures and more than 26% on the digital transition across the 22 Recovery and Resilience Plans approved so far (European Commission 2022).

At the time of writing, the European Commission has put forward a plan, REPowerEU ([12]), to address energy dependency and rising energy prices in the fast evolving geopolitical situation. The plan seeks to accelerate adoption of several of the assessed solutions by, for instance, frontloading deployment targets of heat pumps, wind power, solar energy, and boosting green hydrogen production and uptake in the energy-intensive industries.

In this context, quantitative datasets on EU industry competitiveness are instrumental in providing the EU with evidence on how climate-neutral solutions and components of industrial ecosystems are evolving. Industrial ecosystems of interest include those related to construction, low-carbon energy-intensive industries, the mobility, transport & automotive industry, renewable energies and hydrogen, civil, mechanical, electric and electronic engineering, as wells as solutions for energy systems integration.

The study assesses key climate-neutral solutions that have significant potential to support the competitiveness of European industry, and to be of great benefit to Europe's socio-economic development, in line with the European Green Deal and its 2050 climate-neutrality objective.

1.1 The purpose of the study

The present study builds on the findings and the framework developed in the study, 'Climate neutral market opportunities and EU competitiveness' (European Commission, 2020a). The main objective is to compile a scoreboard to assess the EU's competitive position in important industrial ecosystems related to the energy transition. The study builds on previous JRC work on competitiveness in the low-carbon energy industries (Asensio Bermejo and Georgakaki 2020, Fiorini, et al. 2017), which also steered the previous study, for which the JRC provided data and guidance on indicators. The study takes advantage of the established in-house expertise within the JRC, enabling consistency, coherence and continuity with other EC initiatives and data sources.

The assessment framework includes ten competitiveness indicators that cover a number of aspects of competitiveness. For the indicators to be useful, it is essential that they support continuous monitoring and

(6) COM(2019) 640 final, 11th December 2019: The European Green Deal.
(7) Regulation (EU) 2021/1119: European Climate Law
(8) COM(2021) 550 final, 14th July 2021.
(9) Speech by Executive Vice-President Dombrovskis at the EU Sustainable Investment Summit. Available at: https://ec.europa.eu/commission/commissioners/2019-2024/dombrovskis/announcements/speech-executive-vice-president-dombrovskis-eu-sustainable-investment-summit_en
(10) COM(2020) 102 final, Brussels 10.3.2020
(11) COM(2021) 350 final, Brussels 5.5.2021
(12) COM(2022) 108 final, 8th March 2022, REPowerEU: Joint European Action for more affordable, secure and sustainable energy: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0108&qid=1647269978089

tracking of long-term trends. They should be replicable across a number of climate-neutral solutions and allow comparison of the performance of the EU and EU businesses to that of other major economies and businesses located in other regions in the world. They should also be based on transparent, robust and reproducible data and accessible data sources. The geographical scope is the EU and all Member States, and major global competitors. The indicators are summarised in the form of a scoreboard to provide a snapshot of the EU position in comparison with its major global competitors.

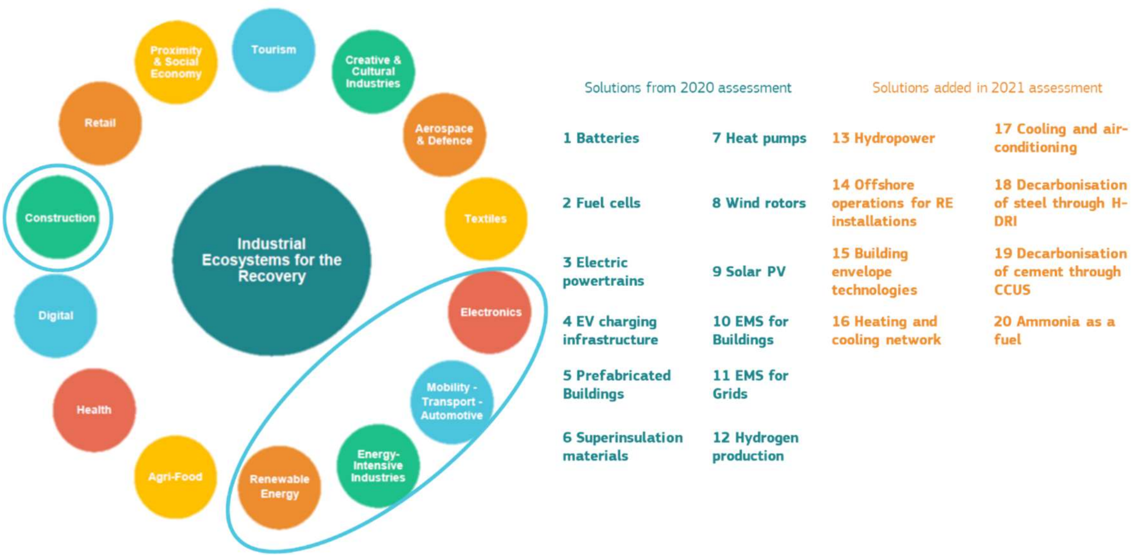
To ensure this, the JRC carried out a comprehensive revision of the assessment framework. A detailed protocol of data collection and methodology is available as a separate technical report. Technology experts were consulted as much as possible, to validate the information collected and the scope of the solutions, to identify appropriate proxies, where needed, and to highlight potential caveats in the data. At the same time, it is important to acknowledge that the industries and solutions assessed are evolving fast, together with the existing data classifications, such as recent consolidation in Cooperative Patent Classification (CPC) codes for Climate Change Mitigation Technologies from EPO and UPSTO, and the forthcoming update of Harmonised System (HS) codes used for international trade. This affects reproducibility of previous analysis and necessitates frequent updates to the data collection protocol.

1.2 Scope and climate neutral solutions covered

The selection of climate-neutral solutions in addition to the 12 already analysed in the 2020 assessment took into account the strategic priorities of a climate-neutral transition, digitalisation and building resilience, notably in those industrial ecosystems which are key to European recovery. A long list of climate-neutral solutions from existing literature and policy documents was screened using several criteria: (1) technologies with the largest potential to contribute to EU decarbonisation ambitions and relevant policy actions; (2) technologies highlighted in Member States' National Energy and Climate Plans (NECPs) and anticipated in the Recovery and Resilience Plans (RRPs); and (3) market relevance in terms of existing or expected European market growth. The final decision of the eight new solutions was taken in consultation with experts in two workshops.

Figure 1 depicts the climate-neutral solutions assessed in this report and the EU industrial ecosystems to which these solutions are most relevant. The first 12 solutions, shown on the left, were included in the previous study (European Commission, 2020a) and updated in this report. The eight solutions on the right were first included in the 2021 assessment. In 2022, a further eight solutions will be added to the assessment and scoreboard. A more detailed overview of the scope of the solutions and the codes which are used to identify and collect relevant data can be found in the Annex 1.

Figure 1: EU Industrial Ecosystems (left) and climate-neutral solutions assessed ([13]) (right)



Source: JRC

([13]) A more detailed description of each solution can be found in the Annex.

2 The assessment approach and methodology

The assessment framework, on which the annual competitiveness scoreboard builds, includes ten main indicators. The first five relate to innovation and competitiveness in future markets, while the latter five address competitiveness in markets today. These indicators provide a range of information about the climate-neutral solutions in question:

— **Public R&D ([14]) investment** shows whether the climate-neutral solution benefits from sustained and/or increasing levels of public RD&D investment;

— **Early and late stage investment** (mainly venture capital (VC) investment) indicates whether the market recognises the potential of the solution to invest in innovation and generate growth and financial returns in the future;

— **Patents** are used as a measure of innovation in the targeted sectors and solutions;

— **Innovating companies** are counted and compared with the global trend;

— **Employment** shows whether the climate-neutral solution has an established labour market in the EU and whether it is expanding or contracting;

— **Production** gives an indication of the EU production competence and capability;

— **Turnover** monitors EU firms' ability to generate turnover;

— **Imports and Exports** gives an indication of the EU's capacity to generate exports to non-EU countries and to meet demand inside the EU market;

— **Trade balance** monitors whether the EU can sustain a strong and positive trade balance or whether it is reliant on non-EU imports.

In addition, the datasets that underpin the report include a number of sub-indicators under each main indicator. More detailed descriptions of changes to the sub-indicators and new additions are detailed in the technical report on the protocol of the assessment methodology. **Table 1** summarises the data sources used for each main indicator and for sub-indicators.

Table 1: Competitiveness assessment indicators and sub-indicators

#	Quantitative indicator	Source	Sub-indicators
1	Public R&D investment	IEA	Top 10 investing countries
			EU investment trend
2	Early stage investment (Venture Capital)	Pitchbook	Top countries by raised capital
			EU share of investment deals, EU vs RoW
			EU share of total investment value, EU vs RoW
			Evolution of investment by region, EU vs RoW
			Evolution of capital raised by deal type, EU vs RoW
3	Later stage investment (Venture Capital)	Pitchbook	Top countries by raised capital
			EU share of investment deals, EU vs RoW
			EU share of total investment value, EU vs RoW
			Evolution of investment by region, EU vs RoW
			Evolution of capital raised by deal type, EU vs RoW
4	Patenting trends	JRC based on Patstat	Top patenting leaders and distribution of invention types
			Evolution of high-value inventions by region
			Top 10 countries with high value inventions
			Flow of high value inventions
			Top patenting entities – top 10 in the World and top 10 in the EU
5	Innovating companies	Pitchbook, CTG and other sources (e.g. BloombergNEF) for VC companies ([15]) and JRC based on Patstat for patenting corporates	EU share of active VC companies and innovative corporates
			EU share of total raised capital by VC-backed companies
			Top countries with VC-backed companies and innovative corporates
			Top countries by raised VC capital

([14]) Research, development and demonstration.
([15]) VC companies refer to companies that have received venture capital investment, mainly comprising start-ups and scale-ups.

			Evolution of capital raised by investment stage, EU vs RoW
6	Employment	EurObserv'ER	Top 10 countries by employment
			EU employment trend
			Growth rate for EU
7	Production	PRODCOM	Production per year over time for EU total
			Top producing countries' share of the total
8	Turnover	EurObserv'ER	Top 10 countries in turnover
			EU27 turnover trend
			Growth rate for EU
9	Imports & Exports	COMTRADE and COMEXT	Top 5 EU importers and exporters, intra-EU and extra-EU trade
			Evolution of total extra-EU imports and exports
			Evolution of global exports with EU total and share of total global exports, EU-total and extra-EU
			Top 10 global exporters and importers
			EU capture of growing non-EU markets – EU share of biggest global importers and growing or shrinking position of EU exports in growing markets
10	Trade balance	COMEXT	Evolution of extra-EU trade balance
			Top EU countries with positive trade balances
			Top EU countries with negative trade balances
			Top 10 trading partners for the 3 countries identified in the previous step (major exporter and major importer)
			Relative trade balance for EU Member States

Source: JRC

This study maintains the structure used in the previous assessment, while revising the scoring criteria. For the scoring criteria of indicators that look at the EU trend, namely public R&D investment, employment, production, turnover and trade balance, the change in the indicator over time was benchmarked against the broader socio-economic context, namely the growth in EU GDP and total employment over the same period of time. The remaining indicators, namely early and late stage investment, patents, innovating companies and extra-EU trade, assess the EU share of the global total. For some of these, key performance indicators defined by European Round Table for Industry (ERT) provided guidance as to the benchmark that could be adopted to indicate strong competitive performance (European Round Table for Industry 2020). **Table 2** summarises the scoring criteria and benchmark for each indicator and **Figure 2** shows the scoring thresholds used in 2021.

Table 2: Scoring criteria and benchmarks of EU performance for the scoreboard

	Scoring criteria	Benchmark	
Public RD&D investment	EU trend	EU GDP growth	Growth higher than that of EU GDP qualifies as high performance. Contraction implies low performance.
Early stage investment	EU global share	EU's economic size and the average performance in VC investments	To close the gap to competitors the EU should receive at least the share that reflects its economic size (European Round Table for Industry 2020), which qualifies as high performance. The EU average in all climate tech venture capital investment was 8% (2015-2020), which qualifies as medium performance.
Late stage investment	EU global share	EU's economic size and the average performance in VC investments	To close the gap to competitors the EU should receive at least the share that reflects its economic size (European Round Table for Industry 2020), which qualifies as high performance. The EU average in all climate tech venture capital investments was 8% (2015-2020), which qualifies as medium performance.
Patents (high-value)	EU global share	1.5 x EU's economic size ([16])	To close the gap with the competitors in industrial R&D investment and reflect the EU's technological leadership, the EU should outperform its share in the global economy by 50% (European Round Table for Industry 2020), i.e. 1.5 times its economic size.
Innovating companies	EU global share	The US average and the EU average performance	The US, historically the leading location of start-ups, is at 35%, which is used to derive the upper threshold for high performance. The EU average share of innovating companies is about 25% which qualifies

([16]) EU's economic size i.e. share of the global economy stands at around 18%.

			for medium performance.
Employment	EU trend	EU total employment growth	Growth higher than that of EU GDP qualifies as high performance. Contraction implies low performance.
Production	EU trend	EU GDP growth	Growth higher than that of EU GDP qualifies as high performance. Contraction implies low performance.
Turnover	EU trend	EU GDP growth	Growth higher than that of EU GDP qualifies as high performance. Contraction implies low performance.
Imports and Exports	EU global share (extra-EU exports)	1.3 x EU's economic size	The EU should capture a market share in high technology exports larger than its share in the global economy by at least 30% (European Round Table for Industry 2020), to qualify as high performance.
Trade balance	EU trend		Growing surplus qualifies as high performance, whereas growing deficit as low performance. Improving deficit or decreasing surplus qualify as medium performance.

Source: JRC

Figure 2: Scoring criteria thresholds in 2021

Legend	**High**	**Medium**	**Low**
Summary of criteria			
Public R&D	>3%	0< and <3%	<0%
Early Stage	>18%	8%< and <18%	<8%
Later Stage	>18%	8%< and <18%	<8%
Patents	>25%	15%< and <25%	<15%
Companies	>35%	25%< and <35%	<25%
Employment	>1%	0%< and <1%	<0%
Production	>2%	0%< and <2%	<0%
Turnover	>2%	0%< and <2%	<0%
Imports & Exports	>25%	15%< and <25%	<15%
Trade Balance	positive / improving		negative / deteriorating

Source: JRC

2.1 Data collection and validation

A major change compared to the previous assessment relates to identification of venture capital companies and the data provider of venture capital investment. Companies in the present study are identified through keywords (detailed in the protocol of the assessment methodology), and validated by expert screening. This has led to changes in the number of companies and the associated investments. However, company lists are now more robust and the selection criteria is more transparent and reproducible in the future. More details about all changes can be found in the protocol of the assessment methodology ([17]).

Reliability of data

The data for seven out of ten indicators comes from publicly available sources that are regularly updated and monitored. While the data is validated by the respective authority, its quality and reliability is subject to the quality, coherence and completeness of the reporting from the initial data provider such as Member States and their national statistical offices. In addition, data from these sources is subject to different classifications, which do not lend themselves well to monitoring of individual solutions and technologies in all cases. Key points of uncertainty regarding each database are listed below:

— Public R&D investments from IEA: the geographical coverage of the data is limited to IEA member countries only. There are gaps in the reporting for a number of countries and/or years. Countries report to a varying degree flows at a granular level of detail (such as 3-digit and 4-digit levels), which is often the necessary level for monitoring individual solutions;

— Patent data from EPO Patstat: there are several shortcomings associated with the quality of the data extracted directly from PATSTAT that are addressed through the JRC methodology (Fiorini, et al., 2017). To assess patenting trends in climate neutral solutions, the Y code classification system is used. While some strategic components are readily ranked as clean technologies, others are not. In addition, recent consolidation of the patent classification reduced the level of detail available.

([17]) European Climate Neutral Industry Competitiveness Scoreboard (CINDECS) – Protocol of the assessment methodology, JRC129397 (not yet published).

— Employment and turnover from EurObserv'ER: EurObserv'ER covers only renewable energy solutions. Employment and turnover are estimated using 'follow-the-money' approach based on the capital investments made and the associated employment & turnover intensities at each stage of the value chain. The effect is reported for the year of commissioning of the project and not distributed over time as it would be the case in reality, creating sharp statistical peaks in the data.

— Production from Eurostat Prodcom: Production data is based on sales as reported by EU countries, thus, not accounting for stocks and the total production. The Member States may choose to keep production values confidential, limiting the analysis. There may be also underreporting from the Member States.

— Imports and exports, and trade balance from Eurostat Comext and UN Comtrade: Comext covers only European countries in EUR, while Comtrade covers global flows in USD. The data does not always match exactly between the two databases. Some countries may choose to keep their values confidential at a national level, limiting the sample for the analysis. Global reporting of flows is harmonised only until the 6-digit level, which is not always specific enough to track individual solutions and technologies.

Early and later stage investments are based on Pitchbook database, which is behind the paywall but provides a better coverage of the investment flows globally than the previously used provider. Still, it is impossible to determine the completeness of the data. Reliability and reproducibility has been improved by transparent company identification using solution relevant keywords and relevant industry categories, both of which are screened by technology experts, who also validate the final company selection. The so-called incumbents or patenting corporates are identified based on their patenting activity.

More detailed description of data uncertainty can be found in a separate methodology report ([18]). In addition to more general issues mentioned above, each solution may pose solution-specific limitations and shortcomings, which are addressed under the respective technology chapters.

2.2 Updates

Assessment of the previously examined 12 solutions included a revision of classification codes and data sources used, which is detailed in the protocol of the assessment methodology, and an update of datasets used in the previous study.

Covid-19 impact

The impact of Covid-19 can be particularly seen in production and trade figures. By contrast, venture capital investment had a record year globally and in Europe in 2020. Battery and fuel cell production was also unaffected by the pandemic, continuing to grow by 52% and 64% in 2020 compared to 2019. Production of nearly all other solutions experienced some decrease in 2020. The biggest decline was seen in wind ([19]), where production dropped by 30% in 2020 compared to 2019. The drop was associated mainly with manufacturing in Denmark, where production dropped by nearly 50% in 2020. Production also declined in solar PV, however this reflected a long-term declining trend in EU production ([20]).

In 2020, extra-EU exports also decreased, while imports from outside the EU increased. Extra-EU exports grew particularly in offshore operations and batteries, where growth compared to 2019 was 92% and 74% respectively. The biggest decrease was seen in solutions for decarbonisation of steel, and energy management systems for buildings, with a decrease of exports by 27% and 23% respectively. Imports from outside the EU increased in offshore operations, wind and heat pumps. In heat pumps, a trade surplus turned to a trade deficit for the first time in the period 2011-2020.

Change from EU28 to EU27

The previous study of 12 climate-neutral solutions (European Commission, 2020a) included the UK in EU totals. In the present study, all indicators cover the EU27. This has caused some reductions in EU totals, particularly in public R&D investment, as the UK is a big public R&D investor.

Major changes due to methodological update

([18]) European Climate Neutral Industry Competitiveness Scoreboard (CINDECS) – Protocol of the assessment methodology, JRC129397 (not yet published).

([19]) Decline was also seen in solutions for the decarbonisation of steel, where production dropped by 42% in 2020. However, production was already in decline in previous years, related to graphite electrodes.

([20]) Production has declined throughout the period of 2011-2020.

Validation of key words and company lists by experts led to changes in the final number of VC companies (and consequently on early and later stage investment volumes). The major reason was the exclusion of digital and service-oriented companies that are not specific to the climate-neutral solution in question. In addition, in contrast to the previous assessment, innovating companies include incumbents that are identified via their patenting activity and not through expert judgement. The scoreboard threshold for high performance changed from 45% to 35%, as data available in Pitchbook is more representative globally ([21]). Major changes in the EU share of innovating companies occurred in prefabricated buildings (from 55% to 21%) ([22]), in EV charging infrastructure (from 47% to 29%), in heat pumps (from 59% to 44%), and in fuel cells (from 34% to 22%).

Following the change in the VC company list, the EU share of early and later stage investment was affected in some solutions. The most affected were fuel cells (the share dropped from 47% and 50% respectively, to 2% and 5%), prefabricated buildings (the share of early stage investments dropped from 40% to 2%), hydrogen production (the share of later stage investments increased from 9% to 70%), and heat pumps (the share of later stage investments increased from 23% to 51%).

The revision of production and trade codes also affected some solutions significantly. In production, new data was added for fuel cells, EV charging infrastructure and building energy management systems. The extra-EU export share of the EU increased slightly in all solutions, but more markedly in heat pumps (from 1% to 43%) and in wind (rotors) (from 39% to 70%). This was mainly due to the exclusion of four-digit HS-codes, which can lead to double-counting and are often too broad a trade category to capture insights specific to certain solutions.

([21]) In the previous assessment, the 45% threshold was due to the Cleantech Group database being more representative of North American and European VC companies.

([22]) Some companies previously included under prefabricated buildings were moved to building envelope technologies as they were related to building envelope rather than off-site modal manufacturing.

3 Batteries

Batteries are a key enabling technology, allowing us to reap the benefits of electrification and opening up the possibilities for far more energy-efficient transport modes ([23]) (SWD(2021)307 final ([24])). As electrified transport is the primary market for batteries, the focus here is on Li-ion batteries ([25]) and next generation batteries ([26]). The scope includes, however, all kinds of grid-connected electrochemical batteries used for energy storage and digital control systems. Activities linked to material extraction (e.g. sourcing and excavating), batteries for small-scale electronics (<160 Wh), hydrogen-related energy storage, flywheels, ultracapacitors, thermal storage, and mechanical storage are excluded.

3.1 Overview of the solution and current status

Various battery chemistries exist and are being further developed. Lithium-based chemistries are dominant in e-mobility and there is further room for improvement in their energy density, essential especially for heavier transport and aviation. The average energy density of electric vehicles (EVs) is rising by 7% per year, according to the BNEF 2021 EV outlook ([27]).

Over 90% of additions to battery capacity in the EU are related to e-mobility (SWD(2021)307 final). EVs hit historic growth in 2020, representing over 10% of sales in the EU, making Europe the biggest EV market ahead of China (IEA, 2021a). Stationary battery capacity ([28]) in Europe, albeit growing, reached only about 1.7 GWh in 2020 (EASE, 2021). An interesting case in this regard is Germany, which represents two thirds of the EU residential battery storage market, as households are incentivised to install batteries together with residential PV installations to encourage self-consumption ((SWD(2021)307 final) and (Weniger, et al., 2021)).

Historically, Europe has a large chemical industry cluster and a large ecosystem around batteries, such as lead-acid batteries, of which EU is a net exporter (SWD(2021)307 final). In Li-ion batteries and other modern applications, the EU is catching up fast, with a significant number of EU cell manufacturing projects due to be online by 2025 (Fleet Europe, 2021). By 2030, European production capacity should have increased sufficiently to meet EU demand (Avicenne energy, 2021).

The global market of Li-ion batteries was estimated at EUR 41 billion ([29]) in 2020 (Avicenne energy, 2021). The market is forecast to experience a compound annual growth rate (CAGR) of up to 16%, reaching EUR 112 billion by 2027 (ReportLinker, 2021). According to the same study, the EU market is forecast to reach EUR 26 billion by the year 2027, with Germany driving the growth at approximately 12% CAGR.

3.2 EU positioning in innovation

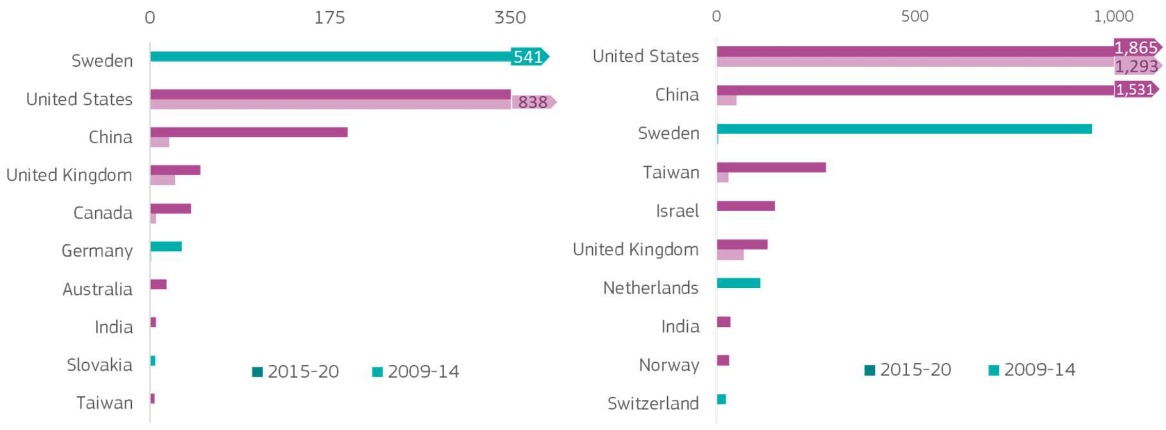
The EU-wide strategic research agenda has stimulated public R&D investment in recent years. In 2019, EU public R&D investment rose to over EUR 90 million, as Germany reported its figures for the first time at this level. Canada is the biggest public investor globally, followed by France, Belgium and Austria, all of which increased their funding since 2019. The data is subject to member countries reporting to the IEA. The US, previously the biggest investor, and South Korea, having strong patenting activity in batteries, have not reported at this level in recent years. Also, China, having the third biggest patent portfolio in the area and being one of the top spenders globally in energy R&D (IEA, 2022), does not report at the sufficient level of granularity.

Early stage investment enjoyed a record year in 2020, reaching nearly EUR 700 million, with the EU capturing 47% of all disclosed early stage investment in 2015-2020 (**Figure 3**). Sweden alone attracted over EUR 500 million (92% of the EU total), largely thanks to investment associated with Northvolt. Later stage investment peaked in 2018 and 2019, reaching over EUR 5 billion globally from 2015 to 2020. The EU saw a record year in 2019, capturing 21% of all disclosed later stage investment in 2015-2020. The US and China dominate, attracting EUR 1.9 billion and EUR 1.5 billion of late stage investment respectively during the 2015-

([23]) EVs convert over 77% of the electrical energy from the grid to power at the wheels compared to 12-30% that conventional gasoline vehicles convert from the energy stored in gasoline to power at the wheels.
([24]) European Commission SWD(2021) 307 final, Brussels 26.10.2021
([25]) Li-ion batteries are leading in electrification of transport thanks to their superior energy density.
([26]) Lead acid batteries are excluded as these are mainly batteries used in conventional cars or to provide a backup for uninterrupted electricity supply in case of unforeseen outages.
([27]) BloombergNEF, Electrical Vehicle Outlook 2021, 2021.
([28]) Li-ion batteries make up about 90% of stationary battery storage capacity (SWD(2021)307 final).
([29]) For comparison, lead-acid batteries stood at EUR 33 billion in 2020. Converted from USD to EUR using 2020 exchange rate.

2020 period. Sweden is again the top performing EU country, capturing 86% of EU later stage investment. At both early and later stage, but particularly at early stage, the EU has attracted significantly bigger deals.

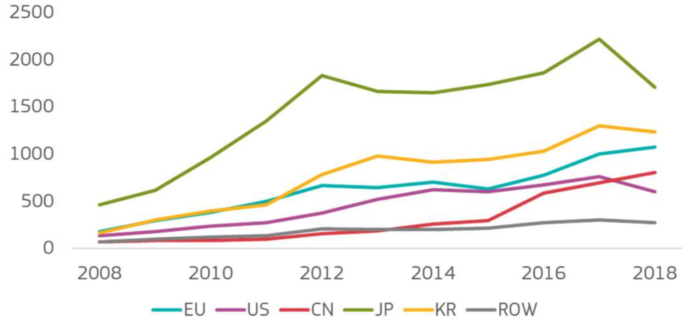
Figure 3: Top countries in early (left) and later (right) stage investment [EUR Million]



Source: JRC based on Pitchbook

EU patenting activity is increasing steadily and catching up with the leaders (**Figure 4**), Japan and Korea, who hold 34% and 21% of all high-value inventions respectively. The EU holds 17% of all high-value inventions. Germany, France and Sweden are the leading patenting countries in the EU. Globally, it is mainly Korean and Japanese companies who stand out in terms of patenting activity, with one German company (Robert Bosch Gmbh) in the top 10. Lg Chem Ltd (KR), followed by Toyota (JP) and Samsung (KR) are the leading patenting companies.

Figure 4: Trend in high-value inventions for the major economies



Source: JRC based on EPO Patstat

The US and Japan host the biggest number of innovating companies, followed by Germany. The US has the biggest ecosystem of VC companies, with over 200, while Japan has the biggest number of innovating corporates, with nearly 350. The EU has the second biggest pool of VC companies after the US and the second biggest pool of corporates after Japan. Overall, the global number of VC companies and corporates indicates that this is a dynamic and growing innovation ecosystem.

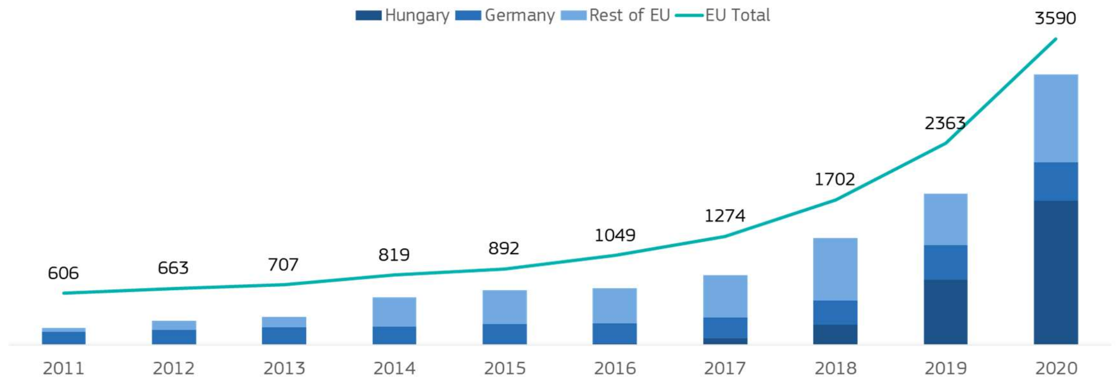
Innovation is focused on advanced materials for Li-ion technology, such the use of graphene, silicon anodes, solid-state electrolytes, room-temperature polymer electrolytes and big-data-driven component recycling and repurposing (SWD(2021)307 final). Solid-state batteries (Generation 4) can be made thinner and more flexible, while containing more energy per unit weight than Li-ion and being safer at the same time (SWD(2021)307 final).

For stationary battery storage, as the share of batteries in all-in system costs is expected to shrink, more focus will be placed on the balance of system cost reductions, including the cost of electronic and hardware components (SWD(2021)307 final).

3.3 EU positioning in current market

EU production value of batteries ([30]) has increased by an average 32% annually since 2015, reaching EUR 3.6 billion in 2020 (**Figure 5**). Production did not even slow down in 2020. Based on the reported data, the biggest producers are Hungary and Germany, where many non-European companies have already established their manufacturing plants. Many Member States keep their data confidential – hence the gap in the chart.

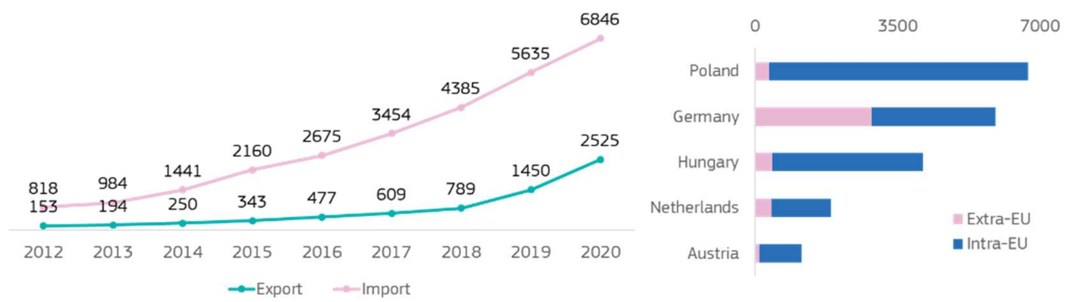
Figure 5: EU production value and top producers disclosing data among the Member States [EUR Million]



Source: JRC based on PRODCOM

Extra-EU imports have grown steadily since 2012, reaching nearly EUR 7 billion in 2020. Extra-EU exports only really started growing after 2018, when EU production increased, and reached EUR 2.5 billion in 2020. Exports increased by 220% over the 2018 to 2020 period, whereas imports increased only by 56% in the same period. Poland, where LG Chem plant came online in 2018, is the biggest EU exporter, but with the majority of trade staying inside the EU. Germany is the biggest EU exporter to outside the EU. Globally, China is by far the biggest exporter, accounting for over a third of all global exports, and the biggest exporter to the EU. The EU captures only 6% of global exports, and only 45% of EU imports are covered internally.

Figure 6: Extra-EU import & export (left) and top 5 EU exporters in 2018-2020 (right) [EUR Million]



Source: JRC based on Comext data

The EU has a negative trade balance, which is still degrading, reaching over EUR 4 billion in 2020. However, in 2020, the rate of change slowed down, showing potential signs of plateauing. Poland and Hungary, supplying almost exclusively the EU market ([31]), had the biggest trade surpluses, which seem to grow exponentially from 2017 onwards. In contrast, Germany, France and Belgium have the biggest and increasing trade deficits. Nearly 60% of German imports come from outside the EU, mainly from China and South Korea.

([30]) Prodcom code associated to Li-ion batteries is only available as of 2019. Due to reclassification also other than Li-ion batteries are thus included, but the share of Li-ion from total is growing from 74% in 2019 to 84% 2020, constituting the majority of reported production value.

([31]) Poland and Hungary export 95% and 90% respectively of their exports within the EU.

3.4 Future outlook

The European Commission launched the European Battery Alliance to address the gap in industrial capacity in 2017. This was followed by a Strategic Action Plan covering the whole value chain in 2018. The European Battery Alliance has proven to be a catalyst in sparking the battery ecosystem across the entire EU value chain (SWD(2021)307 final). In addition, the European Commission has adopted decisions on the provision of State Aid for highly innovative investments under the instrument, Important Projects of Common European Interest (IPCEI). The European Investment Bank also announced in 2020 that it would increase the financing of battery-related projects to more than EUR 1 billion (European Commission, 2020a).

In 2020, the European Commission proposed a new Batteries Regulation (COM(2020) 798 final ([32])), to ensure that batteries in the EU market are sustainable and safe throughout their entire life cycle. This would replace the previous Batteries Directive 2006/66/EC and amend Regulation (EU) No 2019/1020. The European Raw Materials Alliance was also launched to ensure reliable, secure and sustainable access to raw materials.

The cost reduction of Li-ion batteries has been, and continues to be, the main driver of EU battery market expansion, both in mobility and in stationary use. The European electrochemical battery market could reach EUR 250 billion annually by 2025, according to the European Battery Alliance (European Battery Alliance, 2022). This presents an enormous market growth, which European industry cannot afford to lose. In recent years, there have been signs that EU production and exports are picking up, as a result of manufacturing capacity investments present and future. However, these mainly involve subsidiaries of Korean companies (SWD(2021)307 final). The EU industry should still strive for mass production capacity in order to avoid a reliance on third countries.

Battery technology also offers further opportunities for cost reduction, efficiency gains, lifespan improvements and safety gains (European Commission, 2020a). Improving trends in investments and patents indicate that the EU is strengthening its positioning in next-generation batteries. Future EU regulation on batteries and waste batteries can help make it a world leader in clean batteries with a low-CO_2 footprint. It can also incentivise the EU circular economy in batteries, as for the moment, all used batteries are exported to Asia for end-of-life recycling (SWD(2021)307 final) .

The EU has been severely lagging in key segments of the battery supply chain, from raw materials (1% share of production) all the way to assemblies (0% share). In processed materials, the EU share of production is 8%, and in components, 9% (European Commission, 2020). Several raw materials in the 2020 Critical Raw Materials list are used in battery chemistry today, namely cobalt, natural graphite and lithium. The EU has no lithium refining capacity (SWD(2021)307 final), and is extremely dependent on imports of raw materials, processed materials and components. The EU also relies on imports of the majority of battery cell production equipment, mainly from Asia (China, Japan and South Korea), which supplies 86% of all processed materials and components for Li-ion batteries globally (European Commission, 2020b). Even more critically, the EU is fully dependent on imports of battery cells, exposing the industry to supply uncertainties and potential high costs, with China (at 66% of global cell manufacturing) being the major player in manufacturing Li-ion cells (European Commission, 2020b). Nevertheless, as already mentioned, the EU has invested in developing and ramping up its own battery manufacturing capacity, which should ease dependency in the near future.

EU activity in sodium-ion battery development is relatively low, which may be a lost opportunity to reduce dependence on critical lithium and cobalt (SWD(2021)307 final). Despite all the effort and progress in recent years, the EU is still catching up with its competitors, and remains highly dependent on third countries for raw materials and some active materials. This makes it hard for EU-headquartered companies to be able to mass-produce battery cells at competitive prices. EU cell manufacturers should also be able to embrace the cell standardisation challenge (SWD(2021)307 final). To improve access to raw materials, the social acceptance of mining inside the EU would need to improve significantly. And even if it does improve, the permitting of mining sites is an extremely time-consuming process.

Box 1: Transforming automotive sector jobs in the EU

The automotive sector is a key strategic sector in Europe. It provides 12.6 million jobs along the supply chain (including direct and indirect manufacturing, automobile use, transport and construction), accounting for about 7% of total EU employment. Of these, 2.6 million are direct jobs in automotive manufacturing, accounting for 9% of EU manufacturing employment. Direct and indirect jobs in automotive manufacturing alone amount to 3.5 million in Europe (ACEA, 2021b).

([32]) COM(2020) 798 final, 2020/0353(COD), Brussels 10.12.2020

The automotive sector is currently undergoing transformation, and faces substantial disruption in the EU and worldwide. This stems, on the one hand, from process optimisation, and on the other, from product innovation related to the transition towards electric, autonomous and connected transport. More advanced manufacturing, robotics, new materials, increased digitalisation and AI to optimise the process of production entail potential jobs losses along the value chain. The move towards vehicle electrification brings with it a similar impact on employment, due to fewer moving parts, longer lifespan, fewer manufacturing hours per vehicle and less maintenance and repair (International Labour Organization, 2021).

Suppliers (often SMEs) are more vulnerable to the shift towards electromobility than original equipment manufacturers, as they produce specialised parts for combustion engines. Member States with a higher than EU-average share of direct automotive employment within manufacturing (e.g. Slovakia, Romania, Sweden Czechia, Hungary and Germany) will be particularly sensitive to the shift away from the production of internal combustion engines. In Germany alone, by 2025, the switch to electric motors will affect at least 178 000 employees, with 137 000 of them employed directly by the automotive industry (Falck, et al., 2021). Natural, age-dependent job fluctuation will not offset this change. In terms of geographic concentration, the production sites of powertrains are particularly badly affected, with estimated job losses reaching 10-46% (Thielmann, et al., 2020).

Europe is currently experiencing a boom in battery cell production, with 50 GWh/y capacity in 2020. Central European automotive manufacturing countries, including Hungary, Slovakia and Poland, were among the first movers in the battery industry within Europe. Further facilities have been announced and are gradually commencing operation in Sweden, Germany and France (Thielmann, et al., 2020).

For each GWh of battery capacity, about 40 jobs are created in battery cell manufacturing and another 200 in upstream sectors such as research and development or machine and plant construction (Thielmann, et al., 2020). Based on planned and announced facilities, the total annual Li-ion cell production capacity in Europe could reach around 591 GWh as early as 2025 (Coelho, 2021). This translates to nearly 142 000 jobs.

Moving towards electromobility (see also Chapter 5 and Chapter 6) can create jobs beyond battery production for automotive manufacturing, in the energy sector, in EV charging infrastructure and in recycling. There is no statistical data available for the employment generated by EV charging infrastructure. However, one study has estimated that by 2030, assuming that EV uptake reaches 35%, 200 000 new jobs will be created along the EV charging infrastructure deployment, both public and private ([33]) (Alyssa Pek, et al., 2020). The most job-intensive segment is the maintenance of chargers, accounting for nearly 40% of new jobs by 2030, followed by battery cell manufacturing with 17%, and the installation of chargers with 11%. Operation of the charging points and manufacturing of the charging equipment each represent 7% of total new jobs, according to the study (Alyssa Pek, et al., 2020).

Several European initiatives have been launched in recent years to address battery industry-related skills challenges. The EC's Strategic Action Plan for Batteries was adopted in 2018 and includes, among its six priority areas, the securing of a highly skilled workforce along the whole battery value chain. The EU-supported Automotive Skills Alliance, launched in 2020, is an industry-led initiative aiming to address skills-related bottlenecks in the sector. EU-funded projects within this ecosystem (including DRIVES (Drives, 2022), ALBATTS (ALBATTS, 2022), and the COSME project Automotive skills (European Commission, 2021b)) investigate skills gaps, deliver human capital-related solutions, and design blueprints for competences and training schemes.

3.5 Scoreboard and key insights

EU positioning in batteries shows promising signs, although the EU is still catching up to its competitors, particularly in Asia. Both public R&I and private venture capital investments have seen an increasing trend in the EU. Sweden attracted the largest proportion of early stage investments, and came third only to the US and China in later stage investments. The success story of Northvolt in Sweden should not be seen as a one-off, and should inspire similar successes around the continent from an emerging battery ecosystem sparked by the European Battery Alliance and supported by several EU initiatives. With regard to patents, the EU is on

([33]) Job creation considered includes 10 sectors: battery manufacturing, charger manufacturing, wholesales, installation of the chargers, grid connection, grid reinforcement, civil and road work, charge point operation, charge point maintenance and electricity generation. Job creation from manufacturing of electrical equipment and power electronics for vehicles is excluded, as well as replacement of chargers. Jobs derived from the installation, operation and maintenance of complementary technologies, such as solar PV and battery systems, are also excluded.

an upward trajectory, indicating the strengthened position of the EU innovation landscape, although it hosts only 22% of innovating companies globally. The EU still captures only 6% of global exports and has a trade deficit of over EUR 4 billion. However, there are some weak signals of improvement, as EU exports have grown for the first time more than imports, by 220% from 2018. Also, EU production has increased by an average of 32% annually since 2015.

Figure 7: Scoreboard for batteries

Scoreboard	**Batteries**	EU performance in the reference period		
Public R&D		28%	2015-2019	EU CAGR
Early Stage		47%	2015-2020	EU share of global total value
Later Stage		21%	2015-2020	EU share of global total value
Patents		17%	2016-2018	EU share of global total HVI
Companies		22%	2015-2020	EU share of innovating companies
Employment			2015-2020	EU CAGR
Production		32%	2015-2020	EU CAGR
Turnover			2015-2020	EU CAGR
Imports & Exports		6%	2018-2020	EU share of global exports
Trade Balance		Low	2015-2020	EU trade balance trend

Source: JRC

4 Fuel cells

The scope of the solution covers hydrogen fuel cells, irrespective of their application (e.g. stationary or transport). This differs from the previous study (European Commission, 2020a), and reflects the fact that, while there are differences and adaptation to the technology per application, many aspects of hydrogen fuel cell technology are common to all. Thus, the competitiveness of the industry in one area can have spillover effects to another. Moreover, and in part because of this fact, there is often an overlap – or no distinction – in the datasets, which makes information difficult to attribute to a specific market segment.

The main changes in methodology compared to the previous study are the reduction in the number of codes considered for the construction of the patenting trends and the change in data source and methodology for the early and late stage investments and selection of companies.

4.1 Overview of the solution and current status

Table 3 lists the main fuel cell technologies according to the main electrolytes used, with their key characteristics and principal areas of application. PEMFC is the type predominantly used for mobility; HT-PEMFC is not as developed as low temperature PEMFC. DMFC is mainly used for portable, smaller size, applications. All are commercialised in some way apart from PCFC, which is at a lower TRL.

Table 3: Main fuel cell technologies, applications and characteristics.

Fuel Cell Type	Applications	Advantages	Challenges
Polymer Electrolyte Membrane or Proton Exchange Membrane (PEMFC) or Solid Polymer (SPFC)	Back-up power, portable power, distributed generation, residential CHP, transportation	Solid electrolyte reduces corrosion & electrolyte management problems; low temperature; quick start-up and load following	Expensive catalysts Sensitive to fuel impurities
High temperature Polymer Electrolyte Membrane (HT-PEM)	Auxiliary power, back-up power, residential CHP	Higher tolerance to impurities such as CO; easier water management; no humidification needed; possible use of produced heat	High Pt loading Lower power density than LT PEM Degradation
Direct Methanol (DMFC)	Portable power, back-up power, off-grid power supply, military	Fuel storage and delivery; thermal management	Power density; slow kinetics; fuel cross-over; flooding; fuel toxicity; water management
Alkaline (AFC)	Military; space; back-up power; off-grid power	Wider range of stable materials allows lower cost components; low temperature; quick start-up	Sensitive to CO_2 in fuel and air (carbonate precipitation) Electrolyte management
Phosphoric Acid (PAFC)	Distributed generation	Suitable for CHP; Increased tolerance to fuel impurities	Low efficiency; low power density; expensive catalysts; long start-up time; sulphur sensitivity
Molten Carbonate (MCFC)	Electric utility; distributed generation; auxiliary power	High efficiency; fuel flexibility; suitable for CHP; suitable for hybrid/gas turbine cycle; suitable for carbon capture	High temperature corrosion and breakdown of cell components; long start-up time; low power density
Solid Oxide (SOFC)	Auxiliary power; electric utility; distributed generation; residential CHP	High efficiency, fuel flexibility; solid electrolyte; suitable for CHP; potential for reversible operation; suitable for hybrid/gas turbine cycle	High temperature corrosion and breakdown of cell components; long start-up time; limited number of shutdowns
Proton Ceramic (PCFC)	Auxiliary power; CHP ; distributed generation;	Lower temperature than SOFC	Materials issues; Sensitive to CO_2

Source: Adapted from JRC (Bednarek, et al., 2021)

Given the wide range of applications, the fuel cell sector is affected by a broad range of legislation. The legislation and initiatives listed in connection to hydrogen production (see Chapter 14) are also applicable for fuel cells. In addition, the Alternative Fuels Infrastructure Regulation ([34]), has as one of its goals that a hydrogen refuelling station will be available at least every 150 km along the TEN-T core network and in every urban node, by the end of 2030. Other complementary regulations and packages include Regulation (EU) 2019/1242, setting CO_2 emissions standards for vehicles, the 2016 Clean Energy Package, the 2016 European Strategy for low-emission mobility, and the Clean Vehicles Directive (2019) (Seemungal, et al.,

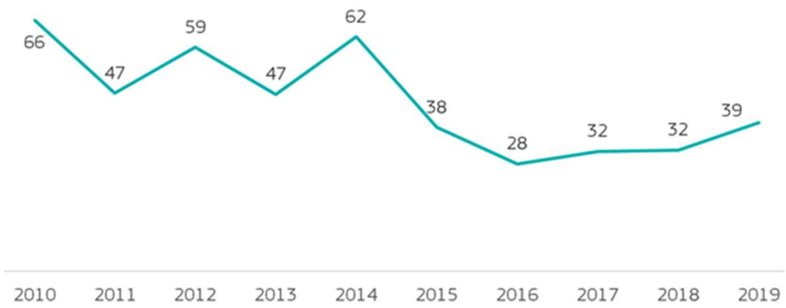
([34]) COM(2021) 559 final Proposal for a Regulation of the European Parliament and of the Council on the deployment of alternative fuels infrastructure

2021). The Fuel Cell and Hydrogen Observatory (FCHO) policy module presents an overview of EU and national policies (Fuel Cells and Hydrogen Observatory, 2021a). According to its mapping, at national level, 24 EU/EEA/UK countries have at least one policy in place to support the use of hydrogen fuel cell electric vehicles in transport, 21 of them also having at least a policy in place for refuelling infrastructure. However, only 12 EU/EEA/UK countries have at least one policy to support the use of stationary fuel cells for power.

4.2 EU positioning in innovation

The previous study found that public R&D investment decreased in hydrogen fuel cells, potentially because of the existing high level of investment in these solutions, and a shift in focus to deployment now that they are becoming more established.

Figure 8: EU Member States public R&D investment in fuel cells [EUR million]

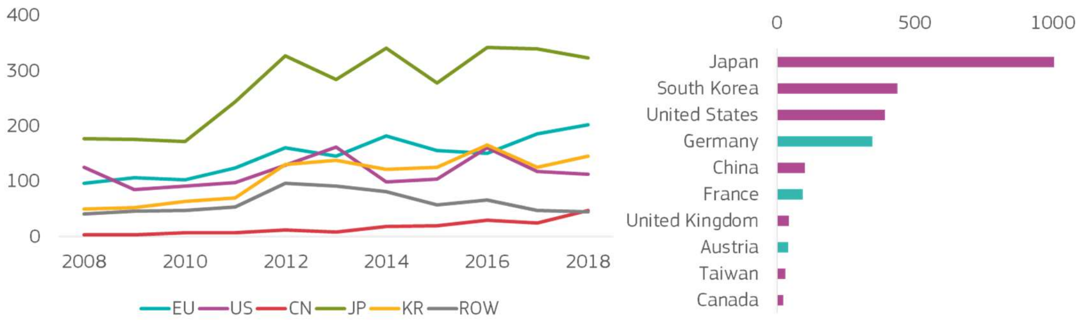


Source: JRC based on IEA data

Public investment has been relatively stable over the last five years, but approximately half of what it was over the previous five-year period (**Figure 8**). The slight increase in Member States' R&D budgets is below the EU GDP. However, in the period 2014-2020, EU Framework Programmes have contributed in excess of EUR 295 million to fuel cell R&D. The two combined outperform R&D investments from other major economies, such as the lead investors Japan and South Korea. However, as in the case of hydrogen technologies (see Chapter 14) the reporting is not always clear in the area of R&D funding. In the period 2016-2018, Germany, which has the second largest Member State R&D budget dedicated to fuel cells, also declared an average EUR 14 million of R&D under the 'unallocated fuels cells and hydrogen' heading. The United States, also a big R&D investor in the technology, only reports expenditure under the same heading, making it difficult to distinguish between R&D priorities. At EU level, between 2008 and 2020, the Fuel Cells and Hydrogen Joint Undertaking (FCH 2 JU) funded projects to a total budget of just over EUR 1 billion, matched by an almost equal amount from other sources (FCH 2 JU, 2021). However, this covers the whole hydrogen value chain (production, storage and distribution, and end-uses, as well as cross-cutting activities).

Consistent with the support from public R&D funding, the EU performs well in terms of patenting output, behind Japan, who is the clear technology leader (**Figure 9**). The patenting trends presented here monitor filings in fuel cell technology as part of climate change mitigation technologies. While collectively ahead of other major economies, the EU share in high-value filings, at 20%, is just over its economic size, but not quite up to the level set for a strong performance. Along with Japan, South Korea and the United States also host a large number of innovators, ahead of individual EU Member States. Germany, France and Austria represent the EU in the top 10. Companies from Japan and South Korea also dominate the top 10 of innovators, with the exception of Bosch (Germany) and a subsidiary of General Motors (United States). The automotive industry has a very strong presence in both the global and EU top 10 of fuel cell innovators. Audi, Volkswagen and BMW are in the EU top 10, which consists of companies headquartered in Germany, with the exception of AVL (Austria) and Safran Power Units (France).

Figure 9: Trend in high-value inventions for the major economies (left) and top 10 countries in 2016-2018 (right)

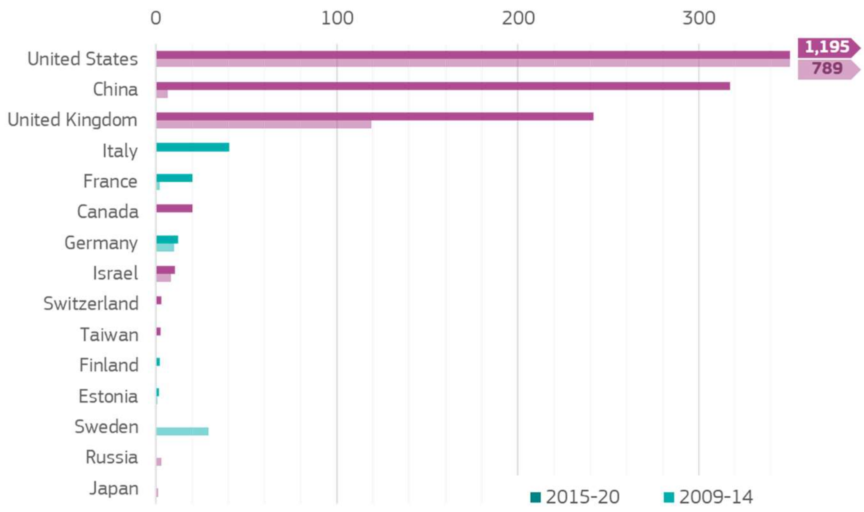


Source: JRC based on EPO Patstat

The EU attracts a small share of venture capital, both in early and later stage investments, with relatively few transactions and a small share of the total value on the global scale. In the period 2015-2020, EU-based companies were recipients in 10% of early stage transactions, amounting to 2% of the disclosed value. The respective figures for later stage investment were 16% of transactions and 5% of disclosed value. Even though there has been an increase of over 70% in investment from the period 2009-2014, attracting funds for start-ups is a weak area for this solution, indicating a gap between funding for research and commercialisation. For the EU Member States hosting start-ups, notable examples include Italy, France, and Germany, followed by Finland, Estonia and Sweden.

The United States and the United Kingdom perform very well in attracting both early and later stage investment, though the majority of investment is later stage. Since 2015, there has also been a significant flow of venture capital for the latter in China.

Figure 10: Top countries in early and later stage investment in 2015-2020



Source: JRC based on Pitchbook

The challenges listed in **Table 3** constitute areas for improvement and further development.

In its programme review, the FCH 2 JU sets out areas of research and development that need further attention (FCH 2 JU, 2021). In transport, additional focus is needed in making sure that there are enough manufacturers of fuel cell parts and systems to ensure an adequate supply of spare parts throughout the vehicle lifecycle. Future activities are also suggested towards a common product design for compact, modular, and flexible components and integrated systems, as well as smart and cost-effective quality control techniques. In energy applications, the products developed in the EU might have potential in non-EU markets, and further development of large-scale solutions can have positive effects in maritime and aviation applications, for example. Existing efforts have assisted European producers in improving production and quality at lower cost and with a smaller environmental burden. However, more effort is needed to reduce material costs, increase durability and reliability, and scale up the range of products and manufacturing capacity (as well as the pool of manufacturers) to achieve a competitive market presence.

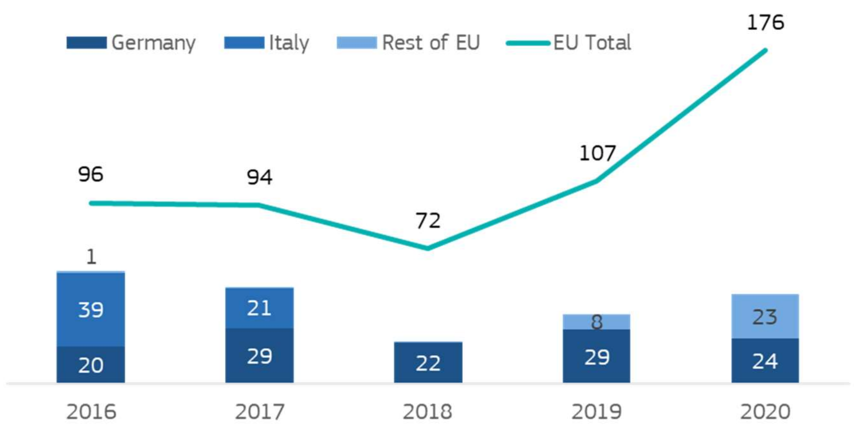
Scaling up PEM fuel cell stacks to required power, while maintaining low weight and dimensions at a low cost, as well as addressing lifetime, performance and reliability issues, are also challenges for the deployment of heavy duty vehicles. The durability currently achieved for passenger vehicles would need to be six times higher for heavy-duty applications (Seemungal, et al., 2021).

Recyclability and circularity, as well as material substitution, are important areas of research, given the cost, dependence and criticality issues related to some of the materials involved.

4.3 EU positioning in current market

PRODCOM contains data under a dedicated code from 2016 onwards. Statistics show a significant increase in production over the last five years. Statistics are not disclosed for all Member States, but the reported EU total is increasing, thus competitiveness is marked as strong. Due to the data aggregation, there is limited possibility for analysis. Germany, Italy and Finland are the only Member States reporting figures, while entries are empty for other hosts of relevant companies, such as France, Belgium and the Netherlands.

Figure 11: EU production value and top producers disclosing data among the Member States [EUR Million]



Source: JRC based on PRODCOM

The major producers of fuel cells and components are Asia (mainly Japan and South Korea) and North America (Canada and USA). However, fuel cells and components are traded under a number of different codes (parts and accessories, AC/DC generators, primary cells) which are not specific enough to monitor. The descriptive codes introduced in the US are not applied elsewhere, so trade statistics are not available.

Statistics on shipments by region of deployment or system integration (Fuel Cells and Hydrogen Observatory, 2021b; E4tech, 2021)(**Figure 12**) show that, while gaining ground, production (and deployment) in Europe is low compared with other regions, and Asia in particular. Fuel cell shipments are dominated by PEMFC and SOFC. While numbers were up compared to previous years, shipment volume has been curtailed, both at the production and demand side, as an effect of the pandemic.

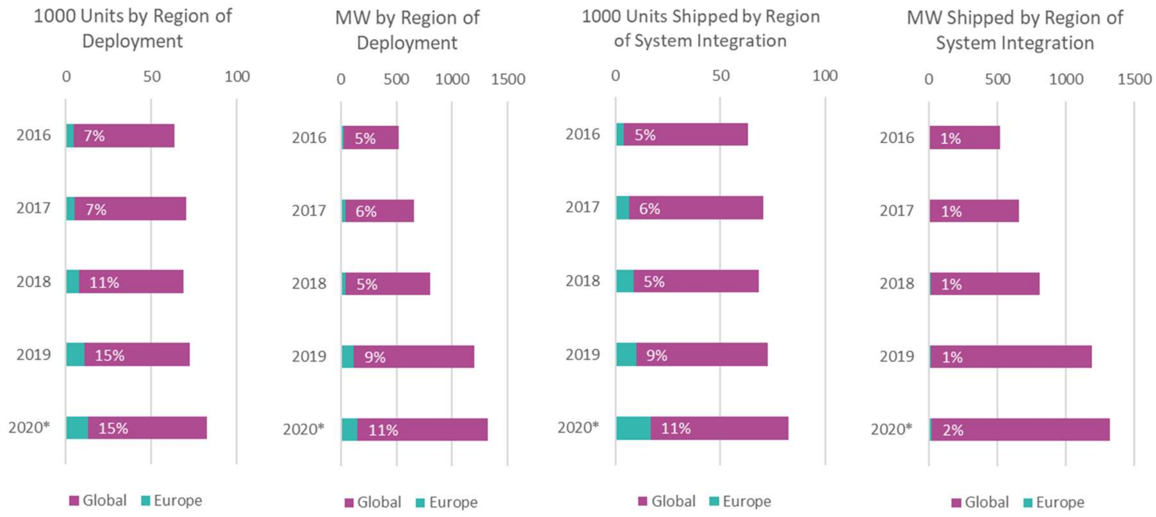
South Korea (Hyundai) and Japan (Toyota) are the clear leaders in fuel cell cars, with vibrant markets in road transport in general. China's support policies also drive a very large and expanding market, especially for buses and trucks. Despite the restrictions and changes in public transport brought on by the pandemic, there is a lot of ambition for deployment of fuel cell buses in Europe, as well as movement in the rail and shipping sectors, which are driving the establishment of production and assembly lines in the EU (Fuel Cells and Hydrogen Observatory, 2021b; E4tech, 2021).

The main actors in the global deployment of large-scale stationary fuel cells (>250 kW) are the US and South Korea. Three technologies are prevalent for this size of unit: MCFC, SOFC and PAFC, with one dominant company specialising in the production of each type (e.g. FuelCell Energy for MCFC, Bloom Energy for SOFC and Doosan Fuel Cells for PAFC) (Weidner, et al., 2019). Competition on cost and supply chain is thus mostly among alternative fuel cell technologies. Some European manufacturers also offer PEMFC in the MW range (e.g. Ballard, Hydrogenics, Nedstack and Powercell).

Japan and Europe have both focused heavily on micro-CHP (< 5 kW). In Europe, the main PEMFC suppliers for micro-CHP systems have been BDR Thermea Group (Senertec/Panasonic) and Viessmann (Panasonic fuel cell). European SOFC manufacturers are SolidPower, Sunfire, Elcogen, Bosch, Wärtsila/Convion, Hexis/mPower and Ceres Power, again mainly developing products for the residential and small building sectors (Bednarek, et al., 2021).

While European fuel cell system manufacturing remains low and spread across a number of companies and fuel cell technologies, it does include several leading fuel cell technology suppliers globally, such as Bosch, Ceres, Nedstack, Elcogen and others, which participate in market growth elsewhere (Fuel Cells and Hydrogen Observatory, 2021b).

Figure 12: Europe's share in fuel cell shipments by area of deployment and system integration (final manufacturer)



*2020 figures include projections for the 4th quarter

Source: JRC adapted from FCHO (Fuel Cells and Hydrogen Observatory, 2021b)

Similarly to trade, there are no statistics readily available on employment or turnover for the sector. Manufacturing and deploying fuel cell technology at scale will present a challenge in training and up-skilling personnel to fulfil the needs of production, installation and maintenance. Though learning material will be made available through the FCH 2 JU, existing EU training programmes have had difficulty in maintaining and updating training tools, so more effort is needed to ensure continuity and to overcome challenges introduced by the pandemic (FCH 2 JU, 2021).

4.4 Future outlook

While the trajectory of global economies after the pandemic is not clear, the green economic recovery plans pursued globally should offer an opportunity for the sector to reverse the curtailment in growth brought about by Covid-19. In heavy-duty transport, in conjunction with other solutions, fuel cell trucks may be needed for long-range, heavy load haulage to remote locations in view of the 2050 goals. Increased uptake is also expected in stationary units, especially for micro-CHP. Increased focus on these units operating on green hydrogen rather than on internally or externally reformed natural gas will be necessary. Overall, the market potential for equipment manufacturing in the fuel cell sector is estimated at EUR 19-23 billion by 2050 (Ludwig, et al., 2021).

The ambition of Member State policy frameworks ([35]) could lead to the deployment of 300 000 hydrogen fuel cell vehicles by 2030. This only reflects estimates provided by half of the Member States, while a number did

([35]) SWD(2021) 49 final. Detailed Assessment of the Member States Implementation Reports on the National Policy Frameworks for the development of the market as regards alternative fuels in the transport sector and the deployment of the relevant infrastructure. Implementation of Art 10 (3) of Directive 2014/94/EU not have a strategy in place. Nonetheless, it would still require a considerable effort, given the current levels of annual fuel cell vehicle registration in Europe (2 750 in 2020 (Fuel Cells and Hydrogen Observatory, 2021b)). By the same assessment, the number of hydrogen refuelling stations in the EU would increase from 125 in 2020, to around 600 by 2030, which would still provide a rather limited network. A study for the FCH 2 JU analysing the role of hydrogen in the National Energy and Climate Plans (NECPs) (FCH 2 JU, 2020) developed two (high and low) scenarios for the deployment of fuel cells in the transport and energy sectors by 2030. These projections run to over 2.5 million vehicles and 178 000 CHP units by 2030 and would appear difficult to achieve under current deployment levels. In the same assessment, while the share of the value added for the fuel cell sector in the hydrogen economy value chain modelled was low (under 5%), the share of the projected job creation was substantial (between 12% and 22% for the low and high scenarios respectively). Another estimate of employment impacts from investments in the EU green hydrogen value chain estimates that 1 700 to 2 000 jobs could be created per EUR 1 billion invested per year between 2030 and 2050 in the machinery and equipment sector (European Commission, 2020d).

In terms of vulnerabilities, the fuel cell supply chain runs its highest risk at the stage of assemblies (where the EU share of production is less than 1%), followed by raw materials (the EU share of production is 5%); though the supply of raw materials required is diversified among many suppliers. The risk is lower in components (the EU share of production is 25%) and in processed materials (EU has a 40% share of production). Fuel cells use around 30 different key raw materials, 13 of which are considered critical (European Commission, 2020b). The high cost of platinum is one of the major challenges in PEM fuel cell production, as it represents about half of the cost of a stack. The platinum loading on the electrocatalyst is closely related to durability and, as previously mentioned, its reduction is a main point of research and innovation, along with recycling and circularity options by design.

4.5 Scoreboard and key insights

The EU performs reasonably well in the area of innovation, but does not attract investment for start-ups, and levels of manufacturing and deployment are low compared to other regions. Nonetheless, production is increasing and a number of worldwide suppliers of components and stacks are based in Europe. Historically, the EU was not faced with some of the drivers spurring the growth of the sector in other regions, such as high levels of air pollution or an unreliable electricity grid (Weidner, et al., 2019). There is a policy framework in place to continue the significant support provided to date in research and innovation, as well as to foster higher levels of deployment. While manufacturing is not at the scale needed, and large scale deployment would need to use technology produced outside the EU, there is a foundation to develop from in the longer term towards a domestic supply chain or manufacturing base.

Figure 13: Scoreboard for fuel cells

Scoreboard	**Fuel Cells**	EU performance in the reference period		
Public R&D		1%	2015-2019	EU CAGR
Early Stage		2%	2015-2020	EU share of global total value
Later Stage		5%	2015-2020	EU share of global total value
Patents		20%	2016-2018	EU share of global total HVI
Companies		22%	2015-2020	EU share of innovating companies
Employment			2015-2020	EU CAGR
Production		16%	2016-2020	EU CAGR
Turnover			2015-2020	EU CAGR
Imports & Exports			2018-2020	EU share of global exports
Trade Balance			2015-2020	EU trade balance trend

Source: JRC

5 Electric powertrains

Decarbonisation of transport, especially the light vehicle segments, relies largely on electrification. Electric powertrain, in addition to battery, is an essential component of fully electrical and hybrid electrical vehicle. The EV market has been stimulated by EU policies that have gradually tightened the emissions performance standards of vehicles. In 2020, the emissions standards were 95 gCO_2 for cars and 147 gCO_2/km for vans ([36]). In 2021, the European Commission proposed to extend the EU Emissions Trading System to road transport as part of its comprehensive climate package, Fit for 55 ([37]). Various subsidy schemes put in place by Member States as part of pandemic recovery measures have also stimulated market growth (Boston, 2021), which is expected to continue. European EV sales overtook China for the first time in 2020, and the EU became the biggest market.

The scope of the solution focuses on the electric components responsible for propulsion of road vehicles fuelled solely or partially by electric power (European Commission, 2020a). It includes electric traction motors and power electronics (motor controllers, internal chargers and converters) for battery electric vehicles (EVs), but excludes activities associated with the axles and the batteries themselves as these are addressed separately (see Chapter 3). It is difficult to separate investment in powertrains from other activities in EV companies.

5.1 Overview of the solution and current status

EV sales have seen near-exponential growth, from 125 000 units sold in 2012 to a forecast 6.4 million units globally in 2021 (EVVolumes.com, 2021). For the first time since 2015, Europe overtook China in 2020 as the region with the most new EV registrations, at 1.4 million. China followed with 1.2 million registrations and the US with 295 000 (IEA, 2021a). The sales share of new electric cars stood at 10% in Europe, followed by China with a 6% market share (IEA, 2021a). Nevertheless, the total number of EVs on the road is still low, representing less than 4% of all vehicles in the EU in 2019 (EEA, 2021). There are also vast regional differences in EV penetration among EU Member States. EVs are still too expensive for most consumers, especially in lower income countries, for example in eastern and southern Europe.

Electrification of other transport segments lags behind ([38]). China and Europe lead in electric light-commercial vehicle (LCV) registrations, but their cumulative stock is only about 435 000 units globally, with one third in Europe (IEA, 2021a). Electric buses and heavy-duty vehicles also saw an increase in registrations in 2020, with cumulative stock of 600 000 e-buses and 31 000 electric heavy-duty vehicles on the roads globally (IEA, 2021a). Electrification of heavy-duty vehicles still faces some technical and development challenges, e.g. megacharging needs (see Chapter 6). While adoption of EVs in Europe is driven by economic incentives and CO_2 standards, the current emissions standards for LCVs and heavy duty vehicles are less stringent.

More than 50 million EVs are expected on EU roads by 2030 ([39]). EV market development creates increasing demand for electric powertrains. According to BNEF, in 2020, the electric powertrain represented only about 5% of the total cost of an EV, while the battery accounted for nearly 30% of the total cost (BNEF, 2021c).

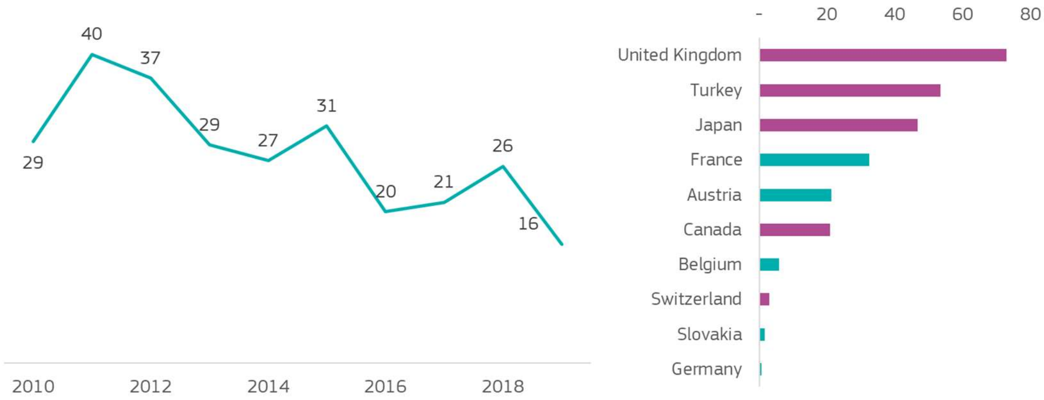
The automotive sector is well-established in the EU, but the value chain of electric powertrains remains relatively small. European manufacturers have a strong dependence on components and raw materials from third countries, especially China (European Commission, 2020b).

5.2 EU positioning in innovation

The EU public investment trend is decreasing (**Figure 14**). The departure of the UK, the biggest public investor, could further affect publicly funded R&D projects. The data should be treated with caution, as the IEA only includes its own members, and some countries either do not report at all (e.g. the US) or under-report (e.g. Germany). France is the biggest investor among EU Member States, followed by Austria.

([36]) Until 2020 Regulations (EC) No 443/2009 and (EU) No 510/2011, and post-2020 Regulation (EU) 2019/631.
([37]) COM(2021) 550 final, 14th July 2021.
([38]) See more information on new registrations by segments in EU SWD(2021) 307.
([39]) According to central MIX scenario for the Fit for 55 proposals (COM(2021) 550 final).

Figure 14: EU Member States public R&D investment (left) and top 10 IEA Members in 2017-2019 (right) [EUR million]



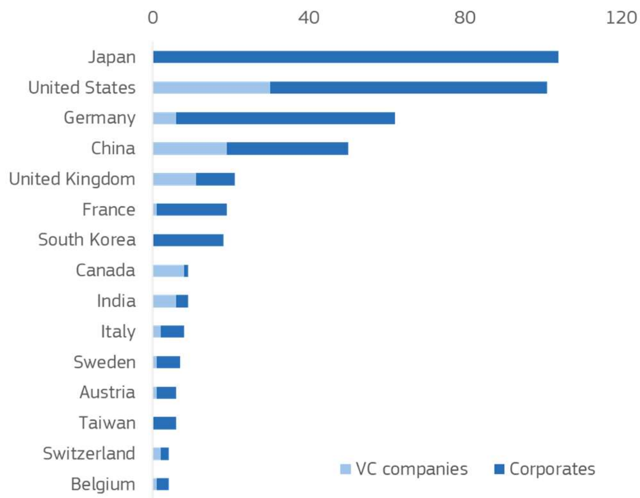
Source: JRC based on IEA data

In terms of venture capital investment globally, electric powertrain companies attracted significant amounts of both early (EUR 2.5 billion) and later stage (nearly EUR 11 billion) investment during the 2015-2020 period. However, the EU share of this is negligible, representing only 2% of early stage investment and nearly 1% of late stage investment. China is the leader by far, with over EUR 2 billion of early stage investment, followed by the US and UK. Belgium, Germany, Netherlands, Italy and Finland are the best performing EU countries. The US and China also lead in later stage investment, where they attracted nearly EUR 6 billion and EUR 4.5 billion respectively in 2015-2020. Finland, Germany, Slovenia, Netherlands and France are the best performing EU countries. In both early and later stage investment, the EU attracts a higher share of deals, which implies that deal values in the EU are significantly smaller than those in China and the US.

Patenting activity increased until 2012 but has largely plateaued since. Japan is by far the leader in patents with a 44% share of high value inventions, followed by the EU with 19%. Germany, along with France, Italy and Sweden with smaller shares, are among the top 10 patenting countries. Japanese, US and South Korean companies dominate patenting, with only one European company in the top 10. The leading three companies are in the automotive sector: Toyota, Ford and Honda. The European top-10 is exclusively made up of German companies, with the exception of the French Alstom. The absence of European automotive companies in the global top-10 reflects their late entrance into the EV race.

For this solution, innovating companies are predominantly corporates (**Figure 15**). Japan is a host to the largest pool of innovating companies, with no VC companies included. The US and China host the biggest number of start-ups and scale-ups. The EU hosts about a quarter of all innovating companies, with more corporates than VC companies.

Figure 15: Number of innovating companies in 2015-2020



Source: JRC compilation of sources

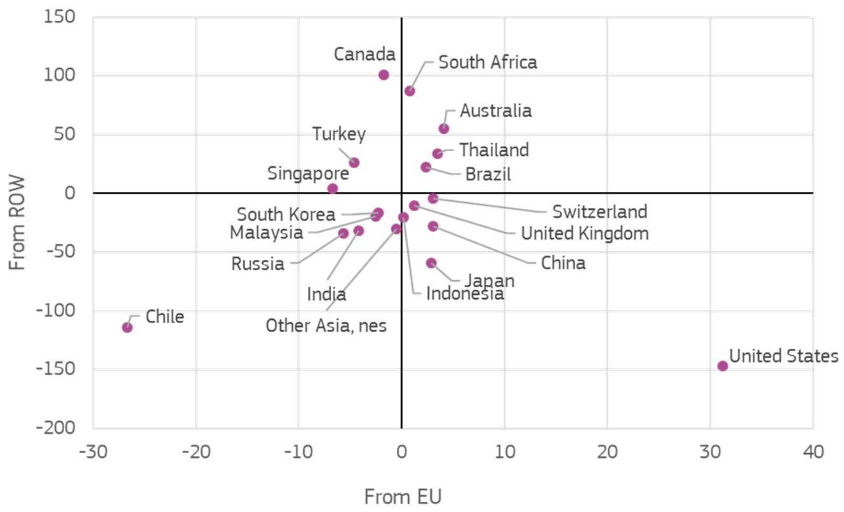
The primary aims of innovation are to optimise size and weight, enable new vehicle concepts and improve the overall efficiency and performance of the vehicle. Key areas of innovation are the integration of motor and power electronics, innovative software controls, skateboard platforms, in-wheel motors and innovation in motor design and materials to improve power density and efficiency (European Commission, 2020a). Major European players recently announced a partnership to develop an electric motor without the use of permanent magnets and therefore the need of rare earths (Fleet Europe, 2022).

5.3 EU positioning in current market

EU production value ([40]) has remained stable at about EUR 4 billion per year. Production seems to have been largely unaffected by the pandemic in 2020, except for a decrease in Germany, Italy, Czechia and Poland. Italy's production has decreased since 2011, and in 2020, France overtook it as the second biggest producer after Germany. Some Member States keep their data confidential.

Extra-EU exports have grown steadily to over EUR 3 billion. However, imports have also grown during the same period, reaching EUR 1.8 billion. The EU accounts for 23% of global exports, which increases to 42% if intra-EU trade is taken into account. Nearly 70% of EU imports are internal. Germany, Italy, France, Czechia and Finland are the top EU exporters, all featuring in the top-10 exporters globally. The main destinations of EU exports are the US, China, Russia, Switzerland and the UK. China is by far the biggest exporter to the EU, and the biggest exporter overall. The EU is capturing the growing markets of South Africa, Australia, Thailand and Brazil, but losing ground in Canada and Turkey (**Figure 16**). The biggest import market globally, the US, is contracting in terms of overall imports but not in terms of those from the EU. The Chinese import market is largely stable and the EU has captured over half of it.

Figure 16: EU positioning in different markets: change in import from the EU and RoW in 2019-2020 [EUR million]

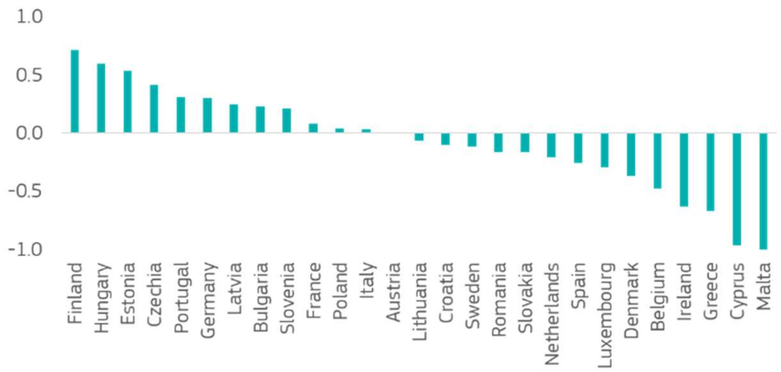


Source: JRC based on Comtrade data

The EU trade surplus peaked in 2013 at EUR 1.6 billion, after which it dropped to EUR 1.3 billion in 2020. As the world's second biggest exporter, Germany has the strongest positive trade balance, and growing, reaching EUR 1.4 billion in 2020, followed by Finland and Czechia. Belgium, the Netherlands and Spain have the biggest trade deficits. In relative terms, Finland, Hungary, Estonia and Czechia have the highest trade surpluses (**Figure 17**).

([40]) Production and trade figures track electric motors, which is a broad category and includes a diverse range of applications, not only electric motors used in vehicles.

Figure 17: Relative trade balance in 2018-2020



Source: JRC based on COMEXT data

5.4 Future outlook

The automotive sector is well-established in Europe, but it has not yet fully tapped into the emerging opportunities of transport electrification. The European automotive sector appears finally to be catching up with its rivals in transforming its product offering and manufacturing capabilities. Investment in European battery manufacturing will increase opportunities to capture a higher share of value chain segments (see Chapter 3).

The overall production of electric powertrains in the EU has remained stable and has not been affected by the pandemic. Similarly, EU exports and the positive trade balance have remained stable and largely unaffected. This implies that the EU has a strong manufacturing base and a good position in the value chain to obtain value creation in the electrification of mobility. However, to maintain that good position and capture a greater proportion of growing markets in the EU and globally, more will need to be done on the innovation side.

The UK is home to many European companies and is one of the biggest public R&D investors in this area. Post-Brexit relations and agreements with the EU could affect European competitiveness. EU countries are also far behind their competitors, namely China, the US and the UK, in attracting venture capital. This creates the risk of falling behind in cutting-edge technology and growing markets. The EU still hosts 19% of all high-value inventions and is home to 27% of all innovators, but more needs to be done to avoid losing this advantage.

The Chinese EV industry is consolidating to be more competitive and to curb overcapacity (BNEF, 2021b). Chinese companies are also looking at Europe for potential export growth opportunities, which have so far been very low (BNEF, 2021a). This creates competition for the European automotive sector, which is already catching up in the electrification race. Venture capital funding for electric powertrains has been limited in the EU, especially in comparison with the US and China, which puts European industry at a competitive disadvantage.

As with the wind industry, the supply risks related to the rare earth elements in permanent magnets are of most concern for electric powertrains. The manufacturing of permanent magnets is increasingly concentrated in China (European Commission, 2020b). This creates risk for the future, as permanent magnet technology is expected to dominate the growing market and determine the design of motors and vehicles (European Commission, 2020).

The EV supply chain also suffers from severe shortages of semiconductors that control most of the EV functions (ECB, 2021). The effect of this shortage can already be seen in the declining sales reported in September 2021 (ACEA, 2021b).

5.5 Scoreboard and key insights

EU score is a cause for concern, particularly in the innovation-related indicators, such as public R&D and venture capital investments. The number of patents and innovating companies gives more hope, although the activity is concentrated to Germany with traditionally strong automotive industry. The EU has the second biggest pool of innovating corporates behind Japan, but less than a fifth of EU innovators are VC companies, reflecting late entrance to the EV race. Current market-related indicators show that the EU still has a strong manufacturing base of electric motors, but production and exports are largely stagnating despite a growing market. This indicates that the EU needs to catch up to stay competitive and capture the growing EU market.

Figure 18: Scoreboard for electric powertrains

Scoreboard	**Electric powertrains**	EU performance in the reference period		
Public R&D	🔴	-16%	2015-2019	EU CAGR
Early Stage	🔴	2%	2015-2020	EU share of global total value
Later Stage	🔴	1%	2015-2020	EU share of global total value
Patents	🟡	19%	2016-2018	EU share of global total HVI
Companies	🟡	27%	2015-2020	EU share of innovating companies
Employment			2015-2020	EU CAGR
Production	🟡	1%	2015-2020	EU CAGR
Turnover			2015-2020	EU CAGR
Imports & Exports	🟡	23%	2018-2020	EU share of global exports
Trade Balance	🟢	High	2015-2020	EU trade balance trend

Source: JRC

6 Electrical vehicle charging infrastructure

By 2025, the European Green Deal (COM(2019) 640 final)([41]), foresees the need for 1 million public recharging points by 2025, to serve 13 million EVs. Public EV charging infrastructure is key to the uptake of EVs as it tackles range anxiety and ensures a sufficient network for clean mobility. By 2030, there should be 3 million public charging points serving at least 30 million zero-emission vehicles, according to Sustainable and Smart Mobility Strategy (2020)([42]). The recent 'Fit for 55' package included the tightening of CO_2 emission performance standards for new passenger cars, light commercial vehicles and heavy-duty vehicles ([43]). In addition, a growing number of Member States (including Denmark, Ireland, Netherlands, Slovenia and Sweden) have announced plans to ban the sale of fossil fuel cars from 2030 (European Court of Auditors, 2021). This creates a strong push for the deployment of EVs (about 2 million at present), and consequently an increasing need for public charging points (about 300 000 at present).

6.1 Overview of the solution and current status

The scope of electric vehicle (EV) charging infrastructure covers the equipment and services used to deliver power to EVs, and the accompanying software, charging stations, chargers and charging equipment accessible to the general public ([44]) or to fleets for EVs and plug-in hybrid vehicles (PHEVs). EV charging infrastructure has two key components: the charging hardware and the charging management platforms. There are five major categories of charging hardware technology distinguished by technical variations in how electricity is delivered to the EV: (1) AC chargers; (2) DC chargers; (3) wireless chargers; (4) pantographs and (5) battery swap systems. Another characteristic is charging power: slow (single-phase AC) 3-7kW, normal (three-way AC) 11-22kW, fast (DC) 50-100kW and ultra-fast (DC) beyond 100kW (T&E, 2020). Deployment of hardware is often supported by software tools to manage metering, billing and charging optimisation and can enable the provision of ancillary services to the grid. Based in the cloud, charging platforms manage the interaction between grid operator and vehicle supply equipment (European Commission, 2021c).

Publicly accessible chargers ([45]) reached 1.3 million units in 2020, of which 30% were fast chargers (IEA, 2021a). Between 2012 and 2020, public charging deployment grew on average by 34% per year globally (BNEF, 2021d). According to the IEA (2021), China leads in terms of the number of EV chargers installed, with over 310 000 fast chargers and 500 000 ([46]) slow chargers in 2020. Europe is in second place with 38 000 fast public chargers and 250 000 slow chargers in 2020. Fast chargers are being rolled out at a higher pace in Europe than slow chargers. The US is trailing China and Europe in public charging points, with 17 000 fast chargers deployed by 2020, of which 60% were Tesla superchargers, and 82 000 slow chargers. South Korea deployed 9 800 fast and 54 000 slow chargers by 2020.

In 2020, Europe hit the new record with over 110 000 new connectors installed, but this needs to increase to 160 000 connectors a year, to hit the target of 1 million chargers by 2025 (BNEF, 2021d). Moreover, EV infrastructure is distributed unevenly: just a few countries account for majority of charging points (European Court of Auditors, 2021) ([47]). The Netherlands leads with more than 63 000 slow chargers and 2 000 fast chargers. Germany and France each has over 40 000 public chargers, including nearly 7 500 and 4 000 fast chargers respectively. Sweden, Finland and Iceland doubled their stock of slow chargers in 2020. Meanwhile, charging infrastructure lags behind in 10 Member States, including Lithuania, Greece, Poland, Latvia and Romania, with less than one public charger per 100 kilometres (ACEA, 2021a).

Globally, in 2020, the total investment in public charging hardware reached EUR 1.3 billion, and a further EUR 1.7 billion was spent on associated installation costs. Installation costs are estimated to be approximately 1.3 times the hardware costs (BNEF, 2021d). In 2020, European market size was about EUR 500 million in charging hardware and EUR 130 million in charging platforms, growing to over EUR 5 billion and EUR 1.5 billion respectively by 2030. Public infrastructure accounts for 65% of the hardware market and nearly 50% of the charging platform market (European Commission, 2021c).

([41]) COM(2019) 640 final, 11th December 2019.
([42]) COM(2020) 789 final, 9th December 2020.
([43]) COM(2021) 556 final, Brussels 14.7.2021. Procedure 2021/0197/COD.
([44]) Separating public charging infrastructure from private in the various datasets, is, however, challenging.
([45]) Chargers can be distinguished based on charging power. The most common division is into: (1) slow chargers with power below 22 kW and (2) fast chargers exceeding 22 kW. They can also be classified into four categories by charge speed and type: (1) slow (single-phase AC) 3-7 kW; (2) normal (three-phase AC) 11-22 kW; (3) fast (DC) 50-100 kW; and (4) ultra-fast (DC) beyond 100 kW (T&E, 2020).
([46]) This is more than half of the world's stock of slow chargers.
([47]) Home charging accounted for 75% of charging in 2020.

The European charging market is very diverse ([48]) and competitive, especially in comparison with the US, which has limited public charging infrastructure in general, with Tesla dominating the market ([49]). In Europe there are 22 large operators with ownership of more than 3 000 public connectors, whereas in China there are 16 and in the US only five. As a result, just three operators in China ([50]) and the US ([51]) account for a 70% market share, whereas in Europe ([52]), the three biggest operators have a combined market share of less than 30%. Tesla has the biggest market share in the US (55%) and Europe ([53]) (16%) in fast and ultra-fast public charging, with the exception of the German market (BNEF, 2021d). In 2020, Allego – the pure play operator – installed the most new capacity with 12 000 connectors, followed by Vattenfall (9 400) and E.ON (9 100). Tesla dominates, with more than twice the number of fast connectors than any other operator, and these are primarily ultra-fast (over 100 kW) compared to mostly 50 kW for most other operators (BNEF, 2021d).

According to Bloomberg NEF, European and US operators have further to go before making profits than China, due to low utilisation and higher costs. The average public charger in Chinese networks delivered more than double the daily amount of energy than in US and European networks ([54]) in 2020-2021. In general, DC chargers tend to distribute more energy than AC chargers. Utilisation is expected to increase, across Europe, China and the US with the energy delivered outpacing the growth of the network in the next decade, thus improving the business case for operators (BNEF, 2021d).

Europe has a strong, competitive industry in both charging hardware and charging platforms, which have grown annually by 26% and 28% respectively (European Commission, 2021c). Supply chains of EV charging hardware are mainly local and/or regional, in particular for EU-based vendors, yet basic electronic parts are purchased from Asia. Leading European hardware vendors are ABB, EVBox, Enel X, NewMotion, Efacec, Alfen. Tritium is a leading non-European vendor. There is significant investment from established power and automation suppliers, oil and gas companies and electricity suppliers in Europe. Leading European charging platform companies include Virta, Fortum, Charge &Drive, has.to.be, Green Flux, and Last Mile Solutions. For the moment, the market is driven by innovation and the focus is on research and development, with manufacturing mostly in-house. As the market becomes more mature, outsourcing and contract manufacturing may become more viable. There is also a variety of business models, from pure hardware providers to pure software-based operators, full-service providers, asset owners, and fully integrated players (European Commission, 2021c).

One of the main challenges facing the development of EV charging infrastructure is the cost and financing required. There is a need to strike the right balance, with adequate charging infrastructure deployment and appropriate investment to encourage EV uptake, but without underutilised and obsolete assets ([55]) (European Commission, 2020a). Local and legal requirements for charging points differ across Member States, creating legal and regulatory barriers when building cross-state networks, creating uncertainties for end-users. According to the European Court of Auditors, despite common minimum EU plug standards and improved access to different charging networks, the availability of charging stations varies between countries, payment schemes are not harmonised and information for users is inadequate (European Court of Auditors, 2021).

The public charging infrastructure deployed so far has focused on serving electric light-duty vehicles, while heavy freight trucks will require even higher power charging. Megachargers are still at demonstration level, with efforts underway to achieve international standardisation. The rollout of megachargers will require long-term planning to avoid negative impacts on the electrical grid (IEA, 2021a).

6.2 EU positioning in innovation

The data on public investment is available for a limited group of countries covered by the IEA, with some major economies, such as Germany, Italy, the US and South Korea not reporting. During 2017-2019, EU investment totalled EUR 40 million and the trend seems to be increasing slightly. France was the biggest investor among the reporting countries.

([48]) The European market has a diversity of operators, namely four utilities, two oil and gas companies, two pure-play operators and one automaker in the top ten of largest operators

([49]) Tesla dominates the EV market in the US with 79% of the BEV sales in 2020 (in Europe and China, Tesla's share was 14%), which provides its own exclusive charging network

([50]) The three biggest operators in China: TGood, Star Charge, State Grid.

([51]) The three biggest operators in the US: ChargePoint, Tesla, Semacharge.

([52]) The three biggest operators in Europe: French syndicats, Allego and Engie.

([53]) The next biggest operators are BP with 7% market share, and E.ON with 5% share.

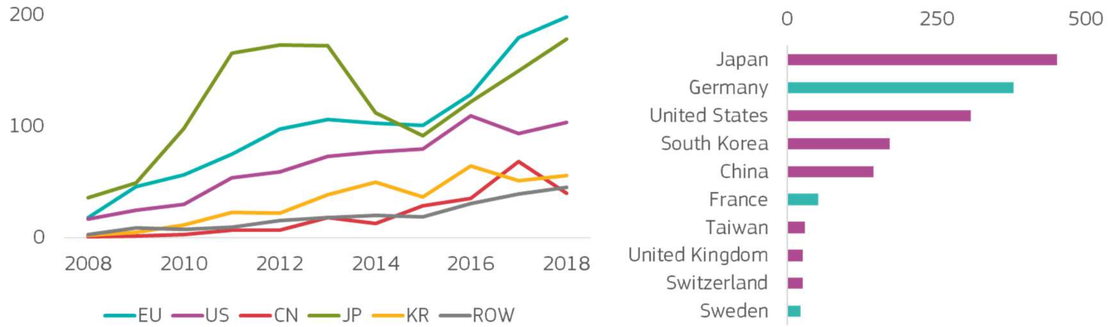
([54]) 46 kWh per charger per day in China against 19 kWh per charger in the US and Europe.

([55]) With evolving technologies and standards, there is a risk that EV infrastructure will become rapidly outdated, creating investor uncertainty.

Venture capital investment has increased globally, particularly later stage investment which saw a record year in 2020. The EU is attracting relatively more early stage investment and captured 15% of the global total during 2015-20. EU companies attracted only 4% of later-stage investment during the same period. Overall, Germany, Spain and the Netherlands attracted the most venture capital from EU countries. Globally, the US is the leader by far, followed by China and Australia.

Globally, patenting activity soared in 2015, and especially strongly in the EU, which overtook Japan as the leading patenting economy, see **Figure 19**. The EU holds 30% of high-value inventions, followed by Japan with 27% and the US with 18%. Germany, France and Sweden rank among the top 10 countries globally.

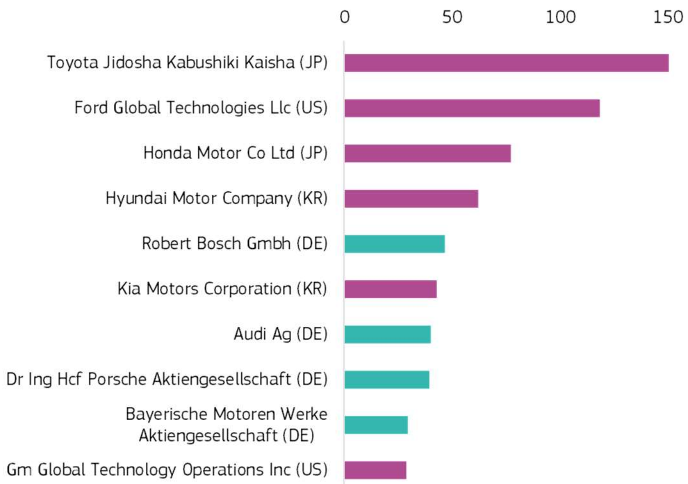
Figure 19: Trend in high-value inventions for major economies (left) and top 10 countries in 2016-2018 (right)



Source: JRC based on PATSTAT

The automotive sector is very active and well represented in patenting activity. Toyota and Ford are the top two patenting corporates, with four German corporates ranking among the global top 10, see **Figure 20**. Among the EU-based corporates, German companies are the most active in patenting, with only one French company among the top 10.

Figure 20: Top 10 global companies in high-value inventions in 2016-2018



Source: JRC based on EPO Patstat

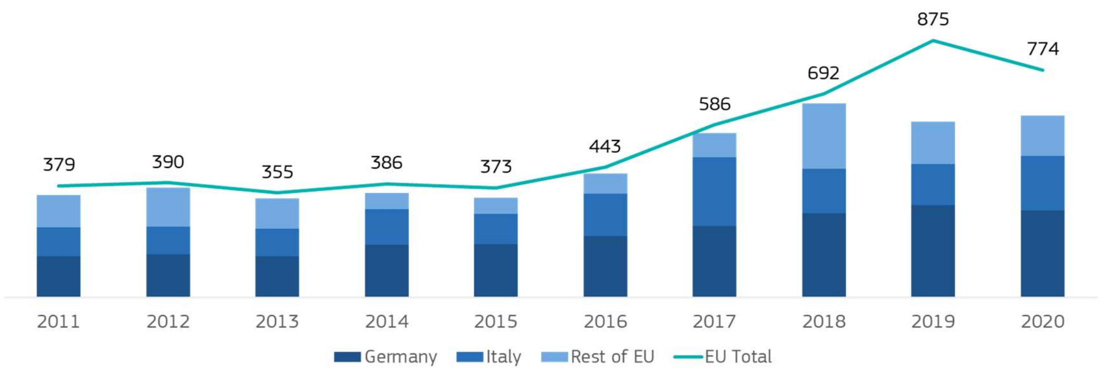
EV charging is an emerging, yet dynamic market, with more innovating corporates than VC companies. The majority of VC companies received investments in the past five years. The EU hosts 26% of all VC companies and 30% of all innovating corporates, thus accounting for the second biggest pool of VC companies and the biggest pool of corporates. The US hosts the largest total number of innovating companies and VC companies.

Areas of innovation include predictive maintenance, smart charging, vehicle-to-grid solutions, peer-to-peer energy trading and autonomous payments using blockchain. For instance, innovative charging stations such as robotic chargers (Mob-Energy), battery swapping stations (Zeway) and wireless charging (Magment and Blue Inductive) have all received investment in the past five years (European Commission, 2020b).

6.3 EU positioning in current market

Since 2015, production value ([56]) has increased annually, but dropped slightly in 2020, to less than EUR 800 million, due to the pandemic. **Figure 21** shows that Germany and Italy are the biggest producers, but significant amounts of EU production are not disclosed in recent years.

Figure 21: EU production value and top producers disclosing data among the Member States [EUR Million]



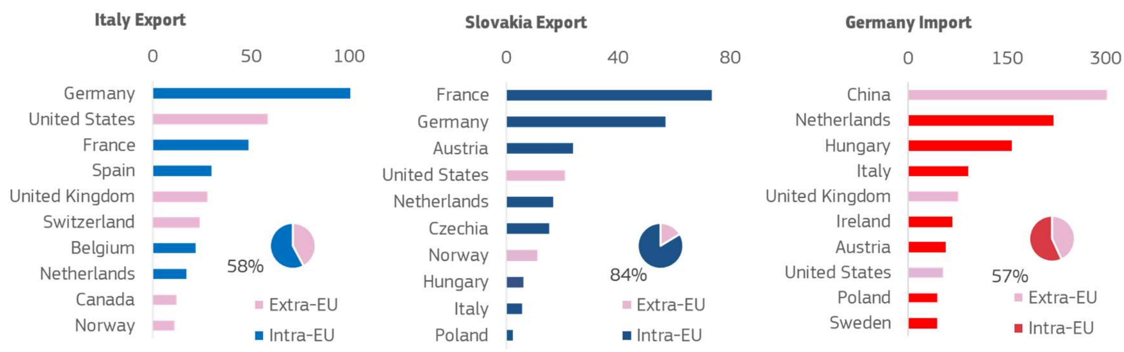
Source: JRC based on PRODCOM data

There is no statistical data available for employment, however, see **Box 1** for more information on the impacts of electrification on employment. While there is no data on turnover from public charging infrastructure, it is expected to grow massively by 2030 as more EVs are deployed. In terms of public charging infrastructure, asset ownership is expected to be the main source of revenues, followed by one-time revenues from hardware. Recurring revenues are also expected from operation, platform, mobility services and electricity and grid (European Commission, 2021c).

Both exports from and imports to the EU are growing ([57]). As with EU production in 2020, imports and exports were not affected by the pandemic. The biggest exporter to the EU by far was China, with nearly EUR 1.3 billion in 2017-19. The main destinations of EU exports are the US, at EUR 270 million, and the UK at EUR 260 million. EU internal trade accounts for well over half (56%) of all EU imports. The Netherlands is a major re-exporter within the EU, while nearly all of Hungary's exports are to EU countries. Germany is the biggest exporter outside the EU.

The EU trade balance deficit was over EUR 270 million in 2020, and is slightly increasing. Italy and Slovakia are among the EU countries with the biggest positive trade balance, with Italy exporting nearly 60% and Slovakia over 80% internally (**Figure 22**). Germany, France and Spain have the biggest trade deficits. Germany imports nearly 60% internally.

Figure 22: Top 10 partners of Italy, Slovakia and Germany in 2018-2020 [EUR Million]



Source: JRC based on COMEXT data

([56]) There has been reclassification of codes and the specific code for accumulator chargers is available only after 2019.

([57]) Accumulator charger is available only at 8-digit level, therefore, it was not possible to determine overall global exports and consequently EU share of global exports.

6.4 Future outlook

In its comprehensive package, the Commission proposed to revise the Alternative Fuels Infrastructure Regulation ([58]),([59]), which is a key policy tool to develop publicly accessible infrastructure and overcome the 'chicken and egg' problem with EV uptake. Revised regulation requires charging points at regular intervals on major highways, namely every 60 kilometres for electric charging.

The Connecting Europe Facility (CEF), directly managed by the Commission, awarded approximately EUR 343 million to electrical charging infrastructure between 2014 and 2020. The Action plan on alternative fuels infrastructure (2017) estimated that EUR 2.7 billion to EUR 3.8 billion is required per year for EV charging infrastructure as of 2021, depending on the share of fast chargers deployed by 2020 (European Court of Auditors, 2021). Several Member States have included investments in charging infrastructure in their Recovery and Resilience Plans under NextGenerationEU; these include Italy (EUR 32 billion ([60])), Austria (EUR 256 million ([61])), Belgium (EUR 920 million ([62])) and Lithuania (EUR 341 million ([63])). Germany plans to incentivise the uptake of electric cars with EUR 2.5 billion, creating a stimulus for private investments in infrastructure.

Home charging will remain the dominant method of charging, accounting for 87% of installed connectors compared to just 1% of public fast connectors. However, public fast connectors and bus and truck chargers will make up 48% of all investment[64] (BNEF, 2021g), and account for 24% of electricity demand (BNEF, 2021e). The EU market for public EV charging hardware will surpass EUR 3.4 billion by 2030, with a compound annual growth rate of 26% (European Commission, 2021c). The charging platforms segment is expected to grow to EUR 1.3 billion by 2030, with a compound average growth rate of 28%.

Globally, the installation rate slowed from an 85% increase in 2019 to a 45% increase in 2020, which the IEA attributed to interruptions in key markets as the likely effect of the pandemic (IEA, 2021a). However, the impact can be expected to be short-lived in Europe, where EV registrations more than doubled to 1.4 million, representing a sales share of 10% in 2020 (IEA, 2021a). As EV uptake and the rollout of charging infrastructure is a central plank of the stimulus package, it is likely that the installation rate will increase again.

The European EV charging infrastructure market is relatively new, but a promising and growing sector. Stimulated by regulatory push, European EV sales overtook China, becoming the biggest EV market in 2020 (IEA, 2021a), and that strong growth is expected to continue. Combined with public investment plans under NextGenerationEU, EV charging development and deployment in Europe is experiencing significant push and pull dynamics. Market growth provides vast opportunities for EU industry, which, based on patenting activity, is well positioned to develop competitive technology for the future.

The EU charging market is very competitive, with many large companies setting high-level charging targets, including BP, Shell, Enel, EDF, Iberdrola and Volkswagen. There are over 40 000 installed and announced ultra-fast connectors from 88 companies in Europe, which, if delivered, would surpass the TEN-T regulation target of one charger every 60 km along the TEN-T network by 2035 (BNEF, 2021f). In 2020, four pure-play companies, ChargePoint, EVBox, Volta and EVgo, went public via SPACs (BNEF, 2021d).

The market is still young and innovation-led. The low share of private investment raises doubts about whether there is enough private financing in Europe to support the growth of European start-ups. Europe is home to fierce competition and can be characterised by a 'land grab' of leading companies. Moreover, the next phase will focus on value-adding services such as smart charging and innovative payment methods, but deployment will also move from support-driven to profit-seeking, squeezing the market further.

([58]) The Alternative Fuels Infrastructure Directive 2014/94/EU, in force since 2014, introduced a minimum level of EV charging across the EU.

([59]) COM(2021) 559 final, Brussels 14.7.2021. Procedure 2021/0223/COD.

([60]) Italy will invest EUR 32.1 billion in sustainable mobility, including the high-speed rail network, rail freight corridors, local transport, hydrogen refueling points and electric charging stations.

([61]) Austria will support large rollout of electric vehicles and installing charging stations with EUR 256 million.

([62]) Belgium will invest EUR 920 million in sustainable finance for 356 green buses and over 78,000 electric charging stations. Investments will also go to improving railway infrastructure and intermodal platforms in ports across the country, and refurbishing 1500 km of cycling pathways.

([63]) Lithuania will invest EUR 341 million to sustainable mobility by phasing out most polluting vehicles and increasing the share of renewable energy in the transport sector.

([64]) Bloomberg NEF forecasts that just over EUR 500 Billion will be needed to deploy 309 million EV charging connectors globally by 2040

EV charging shares similar supply chain risks to those of other digital technologies. The EU is a net importer of electronic boards, semiconductors and microprocessors, which exposes it to vulnerabilities and disruptions (European Commission, 2021d). Also, the widescale adoption of charging, and especially smart charging, increases that systemic risk (European Commission, 2021d).

6.5 Scoreboard and key insights

Figure 23 depicts a two-fold picture of EU positioning in EV charging. EU score is high in public R&D funding and patents. EU patenting activity has surged and overtaken Japan in recent years.. The EU share of innovating companies is average, at 29%. Nevertheless, the EU has the biggest pools of both innovating corporates and VC companies, reflecting the very dynamic and competitive nature of EU market. At the same time, lower scores in venture capital investments, especially at the later stage, may pose a challenge for growth of EU scale-ups as the market matures. EU production and exports are growing, but imports are also growing, resulting in a slightly increasing trade deficit. This exposes the threat that non-EU producers may capture the growing EU markets.

Figure 23: Scoreboard for EV charging infrastructure

Scoreboard	**EV charging infrastructure**	EU performance in the reference period		
Public R&D	🟢	16%	2015-2019	EU CAGR
Early Stage	🟡	15%	2015-2020	EU share of global total value
Later Stage	🔴	4%	2015-2020	EU share of global total value
Patents	🟢	30%	2016-2018	EU share of global total HVI
Companies	🟡	29%	2015-2020	EU share of innovating companies
Employment			2015-2020	EU CAGR
Production	🟢	16%	2015-2020	EU CAGR
Turnover			2015-2020	EU CAGR
Imports & Exports			2018-2020	EU share of global exports
Trade Balance	🔴	Low	2015-2020	EU trade balance trend

Source: JRC

7 Prefabricated buildings

The Fit for 55 climate package ([65]) has set a target of 40% emissions reduction by 2030 for the buildings sector, compared to 2005 levels. Moreover, the proposal to extend the EU Emissions Trading Scheme (ETS) to buildings and the Social Climate Fund are to support investment in renovations to increase the energy performance of buildings. In force since 2010, the Energy Performance of Buildings Directive (EPBD)([66]) seeks to achieve a highly energy-efficient and decarbonised building stock by 2050, to provide investment stability, and to empower both consumers and businesses to understand how to cut energy consumption and save money. The Energy Efficiency Directive (EED)([67]) seeks to increase the national annual energy savings obligations.

7.1 Overview of the solution and current status

The scope of the prefabricated buildings solution covers elements and technologies that enable the production of modular and offsite construction of residential, commercial, or industrial buildings and components related to their installation, both permanent and relocatable. Prefabricated components are seen as an effective alternative to conventional construction techniques due to their lower emissions (Jiang et al., 2019; Karlsson et al., 2020; EASAC and DANL, 2021). Thus, this report postulates that prefabricated buildings are de facto mitigating climate change and takes into account all prefabricated solutions. Insulation and envelope materials, such as windows and doors, are covered in other solutions, while services related to transportation, installation, and assembly are excluded.

Innovative construction methods do not share a common definition. In 2019, UK government established a cross-industry working group to come up with a definition framework for modern methods of construction (GOV.UK, 2019). This framework identified the following categories:

1) Pre-Manufacturing - 3D primary structural systems
2) Pre-Manufacturing - 2D primary structural systems
3) Pre-Manufacturing - Non systemised structural components
4) Pre-Manufacturing - Additive Manufacturing
5) Pre-Manufacturing – Non-structural assemblies and sub-assemblies
6) Traditional building product led site labour reduction/productivity improvements
7) Site process led labour reduction/productivity improvements

Prefabricated solutions span over five categories in the UK working group classification, indicating the level of market fractionation. Apart from the different construction methods, the market segments differentiate the construction materials (i.e. wood, steel), the type (i.e. permanent, relocatable), and the application (i.e. commercial, hospitality). The European Federation of Premanufactured Buildings (EFV) promotes the competitiveness of prefabricated construction in Europe ([68]). The European PropTech Association – PropTech House (PROTECH)([69]) has, as its mission, to harmonise the fragmented European market and to help create a legal framework adapted to new technologies, fostering innovations in the property market.

GMI (2022), estimated the global market at nearly EUR 114 billion ([70]) in 2020. The European market was estimated at about EUR 44 billion and North American at EUR 35 billion for the same year. The market was balanced regarding the type (around 55% relocatable vs. 45% permanent). Steel was the most preferred construction material (around 46%), followed by wood (around 38%). A 2020 report released by Dodge Data & Analytics forecasted an increased use of prefabrication and permanent modular construction globally in 2021-2024, especially for healthcare facilities and hotels (DODGE, 2020).

([65]) COM (2021) 550 final 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0550

([66]) Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (OJ L 153 18.6.2010, p. 13)

([67]) Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC (OJ L 315 14.11.2012, p. 1)

([68]) Link to the website: http://e-f-v.eu/eng/index.html

([69]) Link to the website: https://www.proptechhouse.eu/

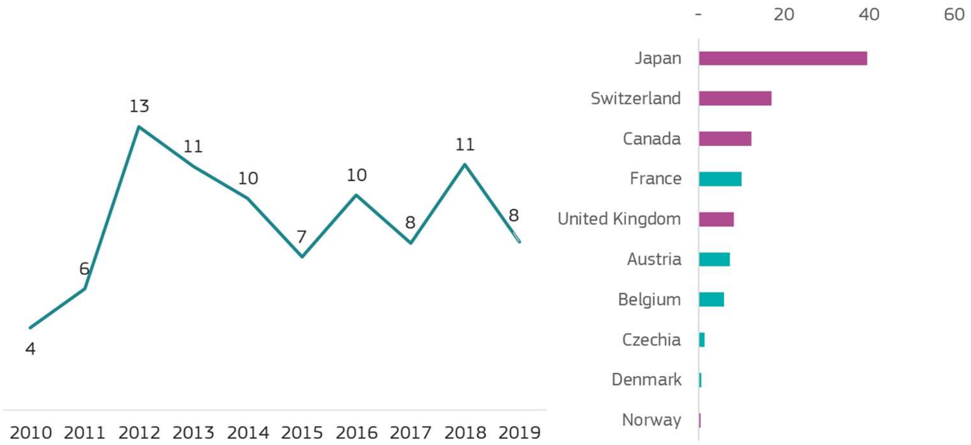
([70]) Foreign currencies are converted to EUR based on the annual averages published by the European Central Bank

The low uptake of prefabricated solutions in the housing sector reflects the high investment cost and the lack of a demand pipeline large and stable enough to ensure the market absorption of new homes and the financial viability of offsite factories. Consumers and investors are often sceptical, due to cases where prefabricated buildings have been found to be defective or have even collapsed. The lessons of the UK housing crisis, show that challenges include labour shortages, low productivity, lack of collaboration, and a failure to embrace new technologies (Maslova et al., 2021).

7.2 EU positioning in innovation

The total public R&D investment for 2017-2019 was EUR 105 million, with Japan and Switzerland the top investors among the reporting countries. With EUR 27 million and an increasing trend, the EU holds around 25% of total investment during 2017-2019, while five Member States are among the top investors (**Figure 24**).

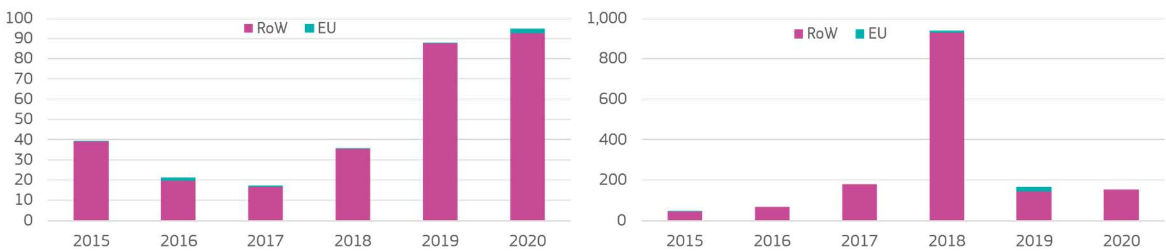
Figure 24: EU Member States public R&D investment (left) and top 10 IEA Members in 2017-2019 (right) [EUR Million]



Source: JRC based on IEA data

Later stage investment peaked in 2018, at more than five times that of the previous and following year (**Figure 25**). Trends in the construction industry in 2018 included the integration of digital technologies and software, the incorporation of green technologies with a focus on sustainability, and a rise in safety standards (Novotny, 2018). However, the EU share is negligible in both cases, representing less than 2% of early and later stage investment. Angel & seed investment is more prominent in early stage funding in the EU than in the rest of the world, while later stage venture capital (VC) is the only later stage investment type worldwide.

Figure 25: Early (left) and later (right) stage investment by region [EUR Million]



Source: JRC based on Pitchbook

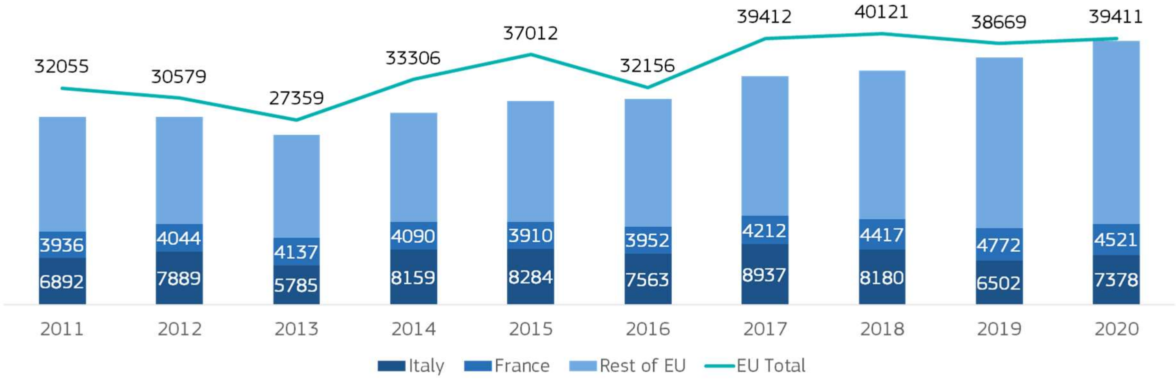
Patenting activity in prefabricated buildings is low. The US became more active after 2015, and China after 2017, after releasing its 13th Five-Year Plan. China and Russia are the top high-value invention holders, followed by Germany. Europe has some patenting activity, but no rising trends. Prefabricated and modular construction is an emerging market, mainly consisting of innovative VC companies. During 2015-2020, the US hosted most of the innovating companies, having almost three times that of the UK. Only 21% of all innovating companies had their headquarters in the EU.

ICF and Cleantech group have noted that innovation in component design enables faster and more efficient logistics and assembly, while advanced assembly technologies, like 3D printing, have the potential to reduce cost and increase replicability. Moreover, the integration of different and innovative materials and the use of artificial intelligence can increase the energy efficiency and functionality of the final construction (European Commission, 2020a).

7.3 EU positioning in current market

Over the period 2011-2020, EU production grew slightly (**Figure 26**). There was a drop in 2013, which was a year of political instability in Italy (Dinmore and Segreti, 2013), which held approximately one-fifth of European production. Another drop was in 2016, while the pandemic in 2020 does not seem to have made a significant impact. Germany overtook France, as the second biggest EU producer in 2018-2020.

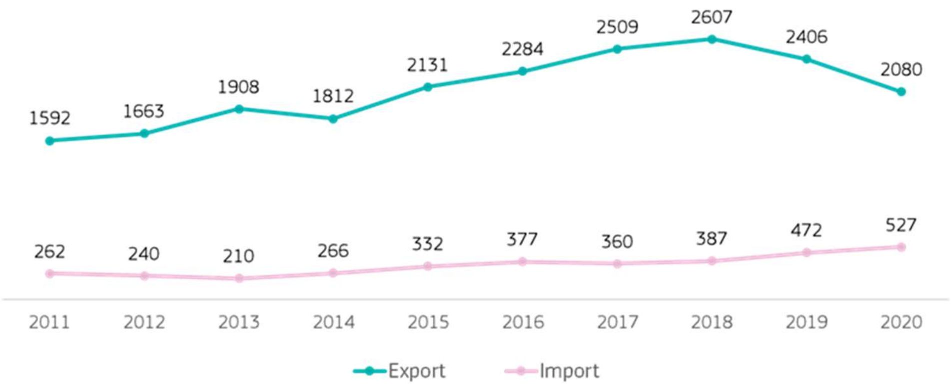
Figure 26: EU production value and top producers disclosing data among the Member States [EUR Million]



Source: JRC based on PRODCOM data

The pandemic further increased the decline in extra-EU exports that began already before 2020 (**Figure 27**). The extra-EU exports account for 35% of the global export share for 2018-2020. For the same period, Germany is the leading global importer. China is the top global exporter, exporting more than twice as much as the second-ranked Netherlands. The UK is an important trade partner, both for EU imports and exports.

Figure 27: Extra-EU import and export [EUR Million]



Source: JRC based on COMEXT data

7.4 Future outlook

Construction projects across the world were abruptly disrupted due to the Covid-19 pandemic. However, prefabricated construction emerged as the emergency architecture solution. Modular units supported those serving on the first lines, while prefabricated techniques were used to build hospitals in record times

(Alderton, 2021). Nevertheless, market growth was affected by disruptions of supply chains, termination of cost management contracts, and shortages of subcontractors and materials.

Prefabricated solutions can accelerate the pace of deep energy renovation in the construction industry. Considerable cost savings can be achieved through shorter construction times, fewer mistakes on-site, and standardisation (BPIE, 2019). Moreover, construction work put on hold during the pandemic is resuming, and growing urbanisation continues to drive demand for new housing. Digitalisation is critical in achieving efficiency goals. 3D printing systems are a core element for maintaining competitiveness and creating possibilities for reduction, substitution, recycling, and mitigation in the use of raw materials and traditionally manufactured components (European Commission, 2020b).

A 2020 survey noted that the standardisation of design and delivery methods and the local availability of facilities and skilled labour are among the top globally common obstacles inhibiting more use of prefabrication (DODGE, 2020). Other factors determining whether a market is likely to embrace modular construction include demand for property, the possibility of achieving scale and repeatability, and the choice of manufacturing materials (Bertram et al., 2019).

7.5 Scoreboard and key insights

EU competitiveness in prefabricated buildings is worrying, particularly in innovating companies and early and later stage investment. Public R&D investment is increasing, yet slower than EU GDP and with large fluctuations over the years. EU patenting activity is behind the booming activity in China and the US. Trade-related indicators show that the EU still has a strong presence globally, with a 35% share of global exports. However, the trade balance is decreasing. EU production is increasing at a plodding pace, and this poses the threat that non-EU producers may capture the growing EU markets.

Figure 28: Scoreboard for prefabricated buildings

Scoreboard	Prefabricated Buildings	EU performance in the reference period		
Public R&D		2%	2015-2019	EU CAGR
Early Stage		2%	2015-2020	EU share of global total value
Later Stage		2%	2015-2020	EU share of global total value
Patents		21%	2016-2018	EU share of global total HVI
Companies		21%	2015-2020	EU share of innovating companies
Employment			2015-2020	EU CAGR
Production		1%	2015-2020	EU CAGR
Turnover			2015-2020	EU CAGR
Imports & Exports		35%	2018-2020	EU share of global exports
Trade Balance		Medium	2015-2020	EU trade balance trend

Source: JRC

8 Superinsulation materials

The increased climate ambition for building sector through Fit for 55 climate package ([71]), the Energy Performance of Buildings Directive (EPBD) ([72]) and the Energy Efficiency Directive (EED) ([73]), mentioned above, set the overarching framework for energy efficiency policy in the EU. Moreover, the European Commission's Renovation Wave strategy (COM(2020) 662 final) aims to boost renovation rate and increase energy performance and integration of renewable heating and cooling in buildings. Insulation is a key element in improving energy efficiency of buildings, enabling also electrification of heating through heat pumps (see **Box 2** for more information).

8.1 Overview of the solution and current status

The scope here covers materials and technologies that improve the thermal insulation of buildings. It includes materials such as slag wool and recycled materials, and techniques such as vacuum insulation. However, prefabricated buildings, elements of smart energy management solutions or building envelopes, are excluded as they are assessed separately (see Chapters 7, 12 and 17).

The thermal properties of traditional building insulation materials have significantly improved over the years. Materials with the best performance per unit cost dominate the markets. Yet, no single insulation material can address the building performance issue. New, innovative materials with superior insulation properties can provide promising solutions. Wool minerals (glass and stone wool) and plastic foams (EPS, XPS, PUR) are the most common options in Europe and globally (Pavel and Blagoeva, 2018). Although there is no official definition of superinsulation in terms of thermal conductivity values, IEA-EBC Annex 65 characterises it as such materials that make use of the Knudsen Effect when used in vacuum insulation panels or advance porous materials systems (IEA-EBC, 2020).

The global market of building insulation materials was estimated at EUR 23 billion ([74]) in 2020, and it is expected to reach EUR 27 billion ([75]) by 2026 (Mordor Intelligence, 2020). US insulation materials manufacturing had a gross output in 2020 of EUR 16 billion, and directly employed more than 39 000 people across 45 states (American Chemistry Council, 2021). In 2019, the European market for thermal insulation products was approximately EUR 15 billion and is expected to have a compound annual growth rate of 2.4% until 2023.

According to the prior work, 31% of companies active in the superinsulation material area had their headquarters in the EU (European Commission, 2020a). In addition, non-European companies also set up offices in Europe to facilitate the import of vacuum insulation panels into Europe. For instance, Fujian Super Tech Advanced Material established an office in Ireland under the 'Metra Group' and Siltherm (also a Chinese manufacturer) set up Siltherm Europe (European Commission, 2020a). Moreover, six out of the 10 major manufacturers were European, specialised in one or two applications. For example, Rockwool group produced only mineral wool, but was the world leader in stone wool insulation products (Pavel and Blagoeva, 2018).

According to a BPIE report, super-insulating materials are high cost because they were originally developed for aerospace, Formula1, or industrial applications. Therefore, their transfer to the construction sector requires adaptation. Single materials or products need to evolve to system solutions that are cost-effective for both labour and material cost, customised to the current and future needs of the construction market. Manufacturers of insulation materials are investing in R&D in the move towards advanced insulation materials. However, their focus remains on conventional insulation due to its growing market. Manufacturers of highly technological insulation materials (e.g. Panasonic, BASF, and Promat) are interested in entering the construction market, but have had little success so far. Compared to conventional players, they have the disadvantage of not having a wide network in place, both with building services and on-site workforces (i24c and BPIE, 2016).

([71]) COM(2021) 550 final, 14th July 2021.
([72]) COM(2021) 802 final, 15th December 2021. 2021/0426 (COD).
([73]) Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC (OJ L 315 14.11.2012, p. 1)
([74]) Foreign currencies are converted to EUR based on the annual averages published by the European Central Bank
([75]) Forecasted values are converted to EUR based on Bloomberg forecasted rates. For values later that 2026, a fixed rate is assumed at EUR 1.21 per USD.

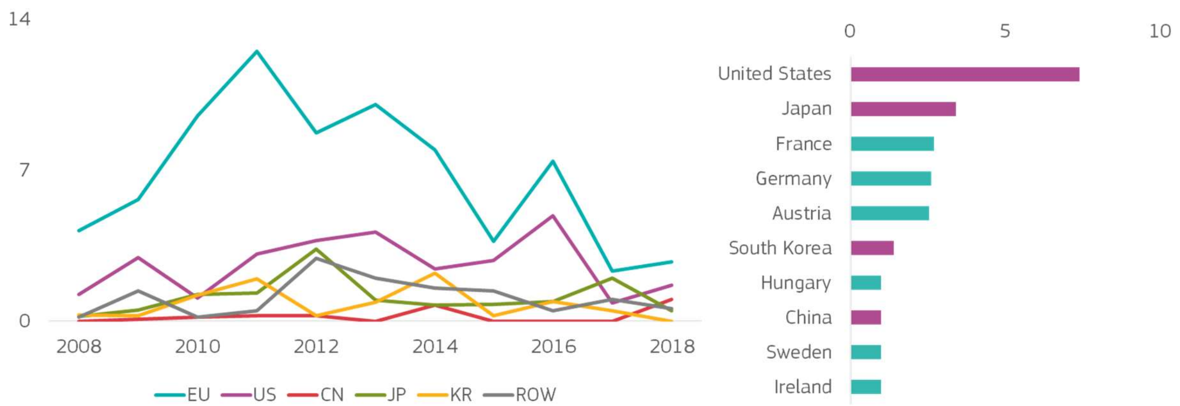
8.2 EU positioning in innovation

The data on public investment is available for a limited group of countries covered by the IEA, with some major economies, such as Germany, Italy, the US and South Korea not reporting. The total reported investment for 2017-2019 is nearly EUR 105 million, with Japan and Switzerland being the top investors among the reporting countries. In 2015, Japan put in action the Top Runner Program, a mandatory standard programme based on the Energy Conservation Act, which included specifications for insulation materials (Japan Agency for Natural Resources and Energy, 2015). The EU holds around 25% of the total reported investment during 2017-2019 (nearly EUR 27 million), with an increasing trend.

Limited information is available for venture capital investment. The leading countries are the UK, US, and Sweden, in both early and later stage investment. The EU holds 25% of the disclosed early stage investment value and 18% of the disclosed later stage investment value.

In the EU, patenting activity spiked in 2011 (**Figure 29**), one year after the adoption of the Energy Performance of Buildings Directive (EPBD)([76]). This activity went into a general decline until 2016, when the package "Clean Energy For All Europeans" (COM(2016) 860)([77]) was launched. US patenting activity also spiked in 2016, one year after signing the Energy Efficiency Improvement Act. Six out of 10 countries and companies that hold high-value investments are European. The EU holds 45% of high-value inventions, while the US holds 27%. The US is the biggest applicant of high-value patents, while most of the submissions are to patent offices located outside Europe, the US, China, and South Korea.

Figure 29: Trend in high-value inventions for the major economies (left) and top 10 countries in 2016-2018 (right)



Source: JRC based on PATSTAT

The innovation landscape is dominated by corporates as VC companies constitute less than a third of innovators. Only the US and France have a mixture of corporates and VCs (**Figure 30**). The US, Japan, and Germany are the frontrunners. At a 45% share, the EU has the biggest pool of innovators.

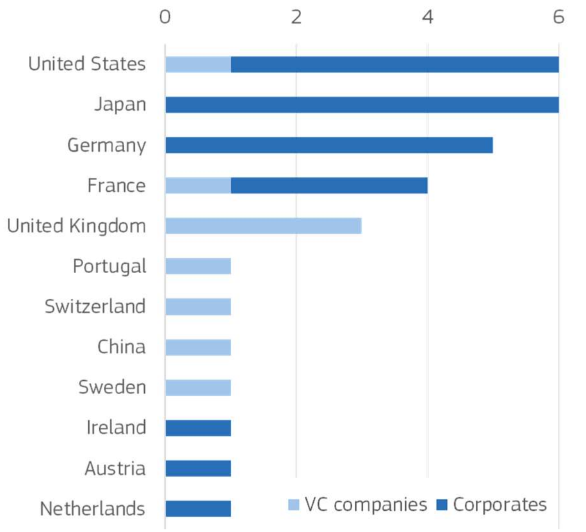
Current research on superinsulation focuses on introducing new materials with better insulating, environmental, and financial performance, improving their durability and aging, developing new measurement methods, and exploring their application field (Berardi and Sprengard, 2020).

IEA-EBC is an international energy research and innovation programme that enables collaborative R&D projects among its members. Its 26 member countries propose new national programmes, leverage R&D resources, and exchange technology, training, and capacity-building (IEA-EBC, 2021). Innovation hubs, such as the European Construction Technology Platform (ECTP), also foster innovation. Some industry groups target specific technologies or applications, including the Vacuum Insulation Panel Association (VIPA) and various passive house groups. The engagement of building designers could also support greater commercial deployment, e.g., via the Architects Council of Europe (ACE) (European Commission, 2020a).

([76]) Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (OJ L 153 18.6.2010, p. 13)

([77]) COM(2016) 860 final, 30th November 2016.

Figure 30: Number of innovating companies in 2015-2020



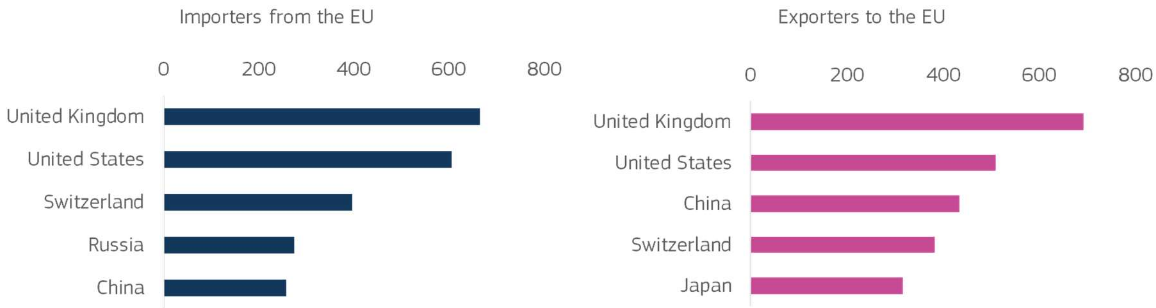
Source: JRC compilation of sources

8.3 EU positioning in current market

EU production remained relatively steady from 2011 to 2020. Germany and France hold approximately one-third of the total EU production in superinsulation materials, but significant amounts are not disclosed by the Member States.

Extra-EU imports and exports both increased in 2011-2020, and were slightly affected by the pandemic. The UK, the US, Switzerland, and China, are part of the global value chains in this solution, as there is major re-exporting with the EU (**Figure 31**). US, the world's largest global importer, covers 21% of its imports from the EU, while the UK, the biggest importer from the EU, imports 71% of its imports from the EU. However, UK exports to the EU are slightly higher than imports from the EU. The EU account for 23% of non-EU exports in 2018-2020 and is capturing most of the growing non-EU markets.

Figure 31: Top 5 importers from the EU (left) and top 5 exporters to the EU (right) in 2018-2020 [EUR Million]



Source: JRC based on COMEXT data

In 2020, the EU trade surplus was steady at about EUR 363 million. EU internal trade account for 76% of all EU imports. France covers 81% of its importing needs from other EU Member States (**Figure 32**). Germany and Poland send 60% and 72% of their exports internally. Germany is the biggest global exporter and the second-biggest global importer.

There is no statistical data available for employment generated for superinsulation materials. However, Pavel and Blagoeva (2018) estimated that roughly 17-19 jobs are created per EUR 1 million invested in improving energy efficiency in buildings.

Figure 32: Top 10 trading partners of Germany, Poland and France in 2018-2020 [EUR Million]

Source: JRC based on COMEXT data

8.4 Future outlook

The future demand for superinsulation is a function of climate adaptation, cost of energy and cost of living area. Application of phase change materials in insulation panels and other technologies may compete with superinsulation for achieving low energy usage in commercial buildings (European Commission, 2020a). Current and future energy performance standards and regulations demand high insulation levels, and traditional insulation materials cannot always do the job. Therefore, super-insulating materials provide promising solutions. Approximately 75% of the current European building stock will still be standing in 2050, and the largest part of their energy consumption is due to space heating. The growth in central and eastern Europe combined is expected to exceed that of western Europe, where the thermal insulation market is more mature. There is also a high market potential in niche areas of the renovation market, such as refurbishments with weight or space limitations or to avoid thermal bridges (IEA-EBC, 2019-2022).

Improvements in building shells and thermal insulation are largely driven by building codes which regulate the design and construction of new buildings. For new buildings, the IEA envisages that building codes in cold climates will reach standards that reduce energy demand to between 15 and 30 kWh/m2/year of useful energy for heating and cooling by 2030. Achieving these standards for new buildings is expected to increase construction costs by 2-7%. However, these costs are expected to decline over time as high-performance building shell materials achieve mass-market penetration. Retrofitting the existing stock is important since many of today's buildings will probably still be in use in 2050 (IEA and ETSAP, 2012).

Building energy codes are a mature regulatory policy lever. On the other hand, building energy performance standards are a newer policy tool (EBC, 2021). Integrating energy efficiency into building codes encourages the improvement of insulation as a strategy to increase energy efficiency. Building renovation passports are complementary to energy performance certificates that have the potential to trigger additional investment and reduce the danger of the wrong implementation of measures (European Commission, 2020e).

According to a recent IEA report (IEA, 2021b), 'the 2020 drop in buildings sector CO_2 emissions resulted primarily from lower activity in the services sector.' Despite the introduction of minimum standards, 'all new buildings and 20% of the existing building stock would need to be zero-carbon-ready as soon as 2030' in order to achieve the 2050 targets.

Demand for insulation dropped when the world went into lockdown, and construction projects were put on hold. As a result, the prices of insulation installation and the insulation itself rose. When the global lockdown began to ease, consumer behaviour became unpredictable, and manufacturers have had to adjust their business plans accordingly (Comfort1stInsulation, 2021).

Despite its cost-effectiveness, there are many barriers to energy efficiency in buildings, including access to finance, insufficient information, split incentives, users' lifestyle choices, and multiple decision-makers (IEA and ETSAP, 2012).

8.5 Scoreboard and key insights

The EU has strong performance in all innovation related indicators, which indicates that EU has a strong innovation landscape and EU companies are well positioned to capture future markets Only, in public R&D investments, the performance is average, as investment fall behind the EU GDP. EU production is following a slightly increasing trend, with a small decrease after the pandemic. Nevertheless, the EU has a strong manufacturing base in this area, as majority (76%) of EU imports are met internally. The EU captured a 23% share of global non-EU exports, which is only slightly below the threshold of strong performance, and the EU has a positive, yet slightly declining, trade balance.

Figure 33: Scoreboard for superinsulation materials

Scoreboard	**Superinsulation Materials**	EU performance in the reference period		
Public R&D	●	2%	2015-2019	EU CAGR
Early Stage	●	25%	2015-2020	EU share of global total value
Later Stage	●	18%	2015-2020	EU share of global total value
Patents	●	45%	2016-2018	EU share of global total HVI
Companies	●	45%	2015-2020	EU share of innovating companies
Employment			2015-2020	EU CAGR
Production	●	2%	2015-2020	EU CAGR
Turnover			2015-2020	EU CAGR
Imports & Exports	●	23%	2018-2020	EU share of global exports
Trade Balance	●	Medium	2015-2020	EU trade balance trend

Source: JRC

9 Heat pumps

At the moment of writing, the REPowerEU communication has proposed to frontload the roll-out of heat pumps by doubling deployment rate to reach cumulative 10 million units installed over the next 5 years ([78]). Eventually the target is 30 million installed heat pumps by 2030, as envisioned by the 'Fit for 55' package in 2021 ([79]). The heat pump sector was strengthened by the adoption of legislation such as the revised Energy Performance of Buildings Directive ([80]), the Renewable Energy Directive ([81]), the Energy Efficiency Directive ([82]), and the upcoming revision of F-Gas Regulation (Regulation (EU) No 517/2014) and the introduction of Ecodesign labelling for heating products. Moreover, the European Commission's Renovation Wave strategy (COM(2020) 662 final) aims to boost renovation rate and increase integration of renewable heating and cooling in buildings.

Box 2: How to reduce fossil fuel use in buildings?

EU climate target of reducing greenhouse gas emissions by 55% by 2030 and the building envelope renovation ambition in Renovation Wave strategy ([83]) imply a drastic transformation of buildings sector. A recent study shows that envelope renovation rate currently standing at 1.3% needs to increase to 2.5% of stock every year and include a switch to low-carbon heating systems such as heat pumps (Nijs, et al., 2021). This means that by 2030, more than 15 million dwellings (about half) using oil or coal and around 25 million dwellings (one fourth) using gas should replace their fossil fuel boilers with low-carbon heating alternatives. Particularly dwellings using fossil fuel heating would benefit from renovations that combine energy efficiency improvements with a fuel switch ([84]). The study estimates that the required investments for building renovation amounts to around EUR 159 billion per year in the period 2022-2030, out of which about EUR 100 billion goes to envelope renovations and the remaining part to heating system switch. Thus, the market for building envelope renovations can double (driven by the increasing renovation rate and depth)(see also Chapters 8, 12 and 17), and the market for heating system replacement could triple (driven by higher equipment costs and the extra effort needed to retrofit existing systems) (Nijs, et al., 2021).

9.1 Overview of the solution and current status

The scope of the heat pumps solution covers air-, ground- and water-source heat pumps ([85]),([86]). The heat pumps considered here cover building space (residential and commercial) and water heating applications, focusing therefore mainly on heating, although it is not always possible to make the distinction in the datasets. Heat pumps can also be used for cooling, in the case of reversible or multifunctional heat pumps, and these are considered primarily under the cooling and air-conditioning technologies in Chapter 19. Heat pumps can also be used for industrial applications but temperatures above 100 °C are still at development stage (EHPA, 2020a)([87]). This application therefore constitutes a smaller fraction ([88]) and is impossible to separate from the data at this stage.

In total, the EU had 42 million installed heat pumps in operation, of which 38 million were air-source heat pumps and nearly 2 million were ground-source heat pumps (EurObserv'ER, 2021)([89]). The biggest number of air-source heat pumps was in Italy (~18 million), followed by France (~9 million) and Spain (~5 million), where heat pumps are mainly used for cooling. The biggest number of ground-source heat pumps was in Sweden (~560 000) and Germany (~410 000). Cooling-only heat pumps represent approximately two thirds of the heat pump market (SWD(2021)307).

([78]) COM(2022) 108 final, Strasbourg 8th March 2022. REPowerEU: Joint European Action for more affordable, secure and sustainable energy.
([79]) COM(2021) 550 final, 14th July 2021.
([80]) COM(2021) 802 final, 15th December 2021. 2021/0426 (COD)
([81]) COM(2021) 557 final, 14th July 2021. 2021/0218 (COD)
([82]) COM(2021) 558 final, 14th July 2021. 2021/0203 (COD)
([83]) COM(2020) 662 final, Brussels 14.10.2020
([84]) More details in the report from Nijs, et al. (2021).
([85]) Including piping, valves, heat exchangers, oil separators, compressors, evaporators, condensers, accumulators, electronic expansion valves, pumps, refrigerant, controllers and fan motors.
([86]) Air-source heat pumps are also known as aerothermal heat pumps; ground-source heat pumps are also known as geothermal heat pumps.
([87]) See for more examples at EHPA (2020).
([88]) Fewer than one 1000 industrial and heating network heat pumps are sold annually in the EU (EU SWD(2021) 307).
([89]) Only heat pumps that meet the efficiency criteria (seasonal performance factor) defined by Directive 2009/28/EC are taken into account.

Over 3.6 million air-to-air heat pumps, nearly 580 000 air-to-water heat pumps and 100 000 ground-source heat pumps were sold in the EU in 2020, a growth of 1%, 15% and 9% respectively from 2019 (EurObserv'ER, 2021). Air-to-air heat pumps are mainly used for cooling, and the biggest markets are Italy, Spain and France. Air-to-water is mainly used for heating, and the market for these grew particularly fast in Poland (with 108% growth from 2019), Denmark (51%), Germany (44%), Belgium (36%), and Sweden (34%), driven by strong incentives. In Hungary, the air-to-water heat pump market exploded from non-existent to over 5 000 sold units in 2020. The Netherlands saw the biggest increase of ground source heat pump sales, at 65% growth from 2019. The market for heat pumps used mainly for heating has been growing by an average of 12% annually (SWD(2021)307)([90]), and despite the impact of the pandemic, grew by over 14% in 2020 compared to 2019 .

Globally, the market grew at an average rate of 10% per year between 2014 and 2020. While the Americas are still the biggest market, both for new buildings and boiler replacement, growth in Europe and the Middle East has outpaced Americas in the last three years (BNEF, 2021h).

The European heat pump sector is well established, with a few large companies and some innovative SMEs. It is a world leader in highly efficient heat pumps (European Commission, 2021d). The sector is represented through several industry associations – most notably the European Heat Pump Association (EHPA). The main challenge is to increase market share in the renovation market by replacing boilers, which still account for the majority of heating system sales. Heat pumps are best utilised in situations with limited heating and cooling requirements, i.e. in buildings with high energy performance. Older houses are likely to be less suitable.

Heat pumps are not yet sufficiently cost-effective in all situations, mainly due to high upfront investment costs (in particular for ground-source heat pumps). However, previously an unfavourable price ratio between electricity and gas (EHPA, 2020b)([91]) is changing in favour of heat pumps with the current developments in the energy market. In addition, control systems are required in order to achieve peak efficiency from ground-source heat pumps. Further development is also needed for end-of-life solutions to ensure safe disposal of refrigerants and to meet EU Fluorinated Greenhouse Gas (F-Gas) Regulation (European Commission, 2020a), (see Chapter 19). According to EHPA, any new measures envisioned under F-Gas Regulation revision, may slow down the deployment of heat pumps (Euractiv, 2022).

9.2 EU positioning in innovation

Overall EU public R&D investment grew by 18% on average from 2015, with Austria, Germany, Denmark, France, Belgium and Czechia among the global top 10 investors. This finding should, however, be treated with caution, as data is fragmented and limited to IEA Members.

Venture capital investments grew significantly during the 2015-2020 period compared to 2009-2014. Early stage investments grew from less than EUR 6 million to EUR 51 million and later stage investments grew from less than EUR 15 million to over EUR 71 million. EU start-ups captured 13% of all early stage investments and over 50% of later stage investments. In both stages, the US is in the lead, followed by Ireland, which attracted increasing investments, especially at later stage. The Netherlands, Austria, Denmark and Latvia are also among the top 10 countries attracting early stage investments. Sweden, Czechia, Belgium, the Netherlands and France are among the top 10 countries attracting later stage investments.

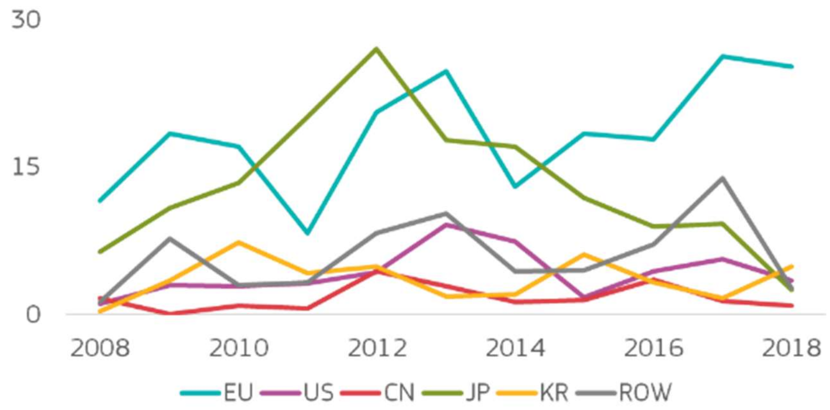
The EU share of high-value patents, 48% of the world total (2016-2018), remains strong and is growing; see **Figure 34**. In other major economies the patenting trend is either decreasing, as in Japan, or stagnating, as in South Korea, the United States and China. In the rest of the world, patenting activity has surged in recent years, driven by Turkey and Canada, but it is too early to say how permanent the trend is. Germany, France, Italy and Sweden are among the top 10 patenting countries globally. Arcelik (Turkey) leads among the companies, but Europe is well represented in the global top 10, with companies from Germany, Spain and Sweden.

The EU hosts 44% of all innovating companies, which is an indication of a strong innovation landscape. The EU ecosystem is comprised of about 40% VC-backed companies and 60% patenting corporates. The US hosts the biggest number of VC companies, while Japan has the biggest number of innovating corporates. Among EU countries, the Netherlands hosts the biggest pool of VC companies.

([90]) Data is from the European Heat Pump Association (EHPA), which considers 21 European countries (including UK, NO, CH and 18 EU MSs). BG, CY, EL, HR, LV, LU, MT, RO and SI are not included.

([91]) This ratio varies by country and is in part a result of tax policies.

Figure 34: Trend in high-value inventions for the major economies



Source: JRC based on EPO Patstat

Areas of innovation include hybrid technology, refrigerant-free technology, electrochemical compressors, 3D-extruded components, price- or weather-based performance management software, and new business models such as 'plug and play' solutions and heating and cooling as a service. The circularity of heat pumps should still be improved with better reparability and modular design, and the operating range needs to be extended to capture the renovation market segment (SWD(2021)307). Investment went into digital technologies (software, analytics) for optimising the running of heat pumps, and into hardware solutions to improve the efficiency of existing systems and better integration of heat pumps into larger energy systems. European start-ups are also active in exploring Internet of Things solutions for components and for system performance (Ziehl-Abegg SE offers cloud-based fan monitoring and predictive maintenance, for example) (European Commission, 2020a).

9.3 EU positioning in current market

The heat pump sector employed nearly 320 000 people ([92]) in the EU in 2020. Most jobs were in France, Italy, Portugal and Spain, which have the highest number of installed heat pumps. These countries are mostly active in reversible air-to-air heat pumps that are primarily used for cooling, but it is impossible to differentiate the data by end-use ([93]). Assuming that cooling accounts for approximately two thirds of the EU market, heating-only jobs account for over 100 000. The sector has experienced a significant increase in jobs since 2017.

The turnover of the EU heat pump sector stood at EUR 41 billion in 2020, with France, Italy and Germany generating the most. Again, approximately two thirds of this should be attributed to 'cooling' (Chapter 19). As with employment, turnover grew by an average 7% per year during the 2015-2020 period. Many of the heat pumps sold and installed in Europe are also still manufactured in the EU, with only compressors largely imported from China (EurObserv'ER, 2019). Thus, a large part of the value creation in the heat pump value chain stays within the EU.

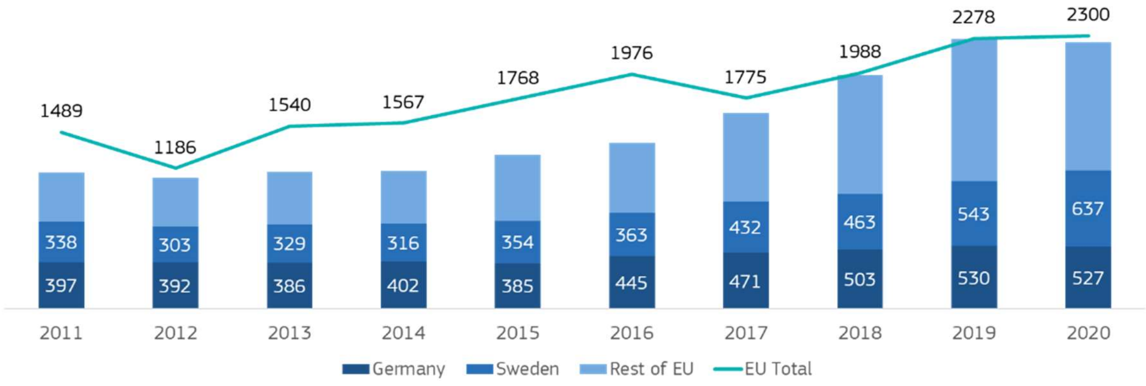
The EU production value of heat pumps has continued to grow (**Figure 35**), despite the impact of the pandemic in 2020, except in Spain and Italy ([94]). Sweden took the top spot as the biggest producer, ahead of France and Germany. EU production stood at just over EUR 2 billion and has been growing by an average of 5% annually since 2015. Production has increased the most since 2015 in Czechia, Spain, Denmark and France. This indicates that EU has a strong manufacturing base.

([92]) This includes both direct and indirect employment. Direct employment refers to equipment manufacturing, installation and operation and maintenance. Indirect employment refers to secondary activities such as transport and other services.

([93]) Reversible air-to-air heat pumps are included in the numbers reported by EurObserv'ER, but it is impossible to differentiate the data by end-use. Therefore, part of this market falls into the scope of Cooling. Especially countries such as France, the Netherlands, Italy, Spain and Portugal include a sizeable proportion of reversible air-to-air heat pumps in their statistics as they meet performance criteria set by the Renewable Energy Directive. In contrast, Germany and Austria, do not include reversible air-to-air heat pumps in their statistics.

([94]) In Italy production dropped by as much as 60% in 2020 compared to the previous year.

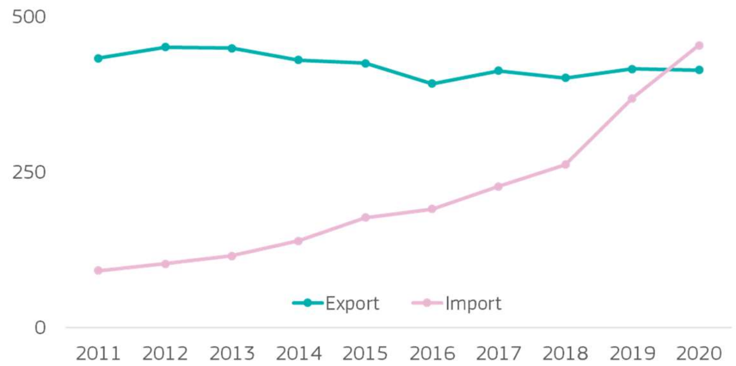
Figure 35: EU production value and top producers disclosing data among the Member States [EUR Million]



Source: JRC based on PRODCOM data

Extra-EU exports of heat pumps remained relatively constant between 2011 and 2020, standing at nearly EUR 415 million in 2020 (**Figure 36**). During the same period, however, extra-EU imports grew, reaching EUR 455 million, indicating the increased competitiveness of non-EU producers in the EU market. The EU share of global exports was 43%, or 75% if intra-EU exports are included (2018-2020). A significant share is, however, from re-exporting. France is the biggest exporter globally, followed by Germany and China. Sweden, Italy, Czechia, Austria and Slovakia are also among the top 10 global exporters. The EU captures existing heat pump markets fairly well. There are not many export opportunities that EU countries are not capturing, except for the US and Mexico, where imports from non-EU countries are outpacing those from EU countries. Moreover, as the biggest importers are all from Europe, and eight of them EU Member States, the EU constitutes the biggest import market.

Figure 36: Extra-EU import & export [EUR Million]



Source: JRC based on COMEXT data

The EU trade balance turned negative for the first time in 2020, due to growing imports from China and stagnating exports. France, Sweden and Germany have the biggest trade surplus, doing better in 2018-2020 than in the 2015-2017 period. The trade balances of Slovakia, Italy and Czechia also improved over the same period, while in all other EU countries, the trade balance deteriorated. The Netherlands, Poland and Finland have the biggest trade deficits and these continue to deepen.

9.4 Future outlook

In their Recovery and Resilience Plans, Czechia will boost renewable energy production with EUR 500 million, including support for acquisition of heat pumps for households; Austria will support private households with EUR 159 million to replace oil and gas heating with more sustainable heating; and with EUR 5.8 billion, France will finance a large-scale renovation programme to increase the energy efficiency of buildings. Other countries have also expressed support for renovation programmes and the improvement of energy efficiency in buildings.

Compared to the rest of the world, European market penetration has lagged behind China, Japan and the United States. US demand is driven by installation incentives and the Asia-Pacific market is driven by construction sector growth (European Commission, 2020a). However, the European market has recently shown strong growth and there is further potential in Europe. The installed stock of heat pumps is expected to double in Europe within about five years. There is underdeveloped market potential, especially in large markets such as France, Italy and Germany. There is an opportunity for cogeneration providers to enter the heat pump manufacturing space (European Commission, 2020a). Schemes for building renovation, energy efficiency and tax reductions in Sweden, Germany and France helped to increase heat pump market penetration, and similar schemes are planned as part of the Resilience and Recovery Plans of EU Member States.

Europe is a recognised market leader in heat pumps, especially in larger heat pumps for the 'light commercial' and 'heat networks' segments. European manufacturers are technology leaders in air-water, ground-water and brine/water-water heat pumps (SWD(2021)307). The EU holds 48% of high-value patents globally and captured over 50% of later stage venture capital investments, indicating its strong capacity for innovation in the area.

The European market has grown steadily but is still far below its potential, as decarbonisation of the heating sector requires a much faster uptake of heat pumps in order to achieve the 2030 and 2050 climate goals of the European Union. The policies put in place to phase out oil and gas are a key driver of the demand for heat pumps in Europe. Other factors include building energy management systems and digitalisation in general, as well as system integration, which provides new business opportunities in grid balancing, optimisation and efficient energy use (SWD(2021)307). Technology improvements and hybrid solutions combining heat pumps with a peak demand source (usually gas) will also allow integration into a larger share of buildings, including existing buildings. This offers massive opportunities through the Renovation Wave.

The European heat pump industry has not yet fully exploited economies of scale in manufacturing and installation that would improve the cost-effectiveness of the solution. In recent years, some major consolidation ([95]) has taken place among the main heat pump players, but further integration may be needed to compete with non-EU manufacturers (SWD(2021)307). Because the European ecosystem is made up of many SMEs and only a few big players, R&D capacities are limited to adapting to new regulations and improving the performance or cost of products (SWD(2021)307).

The deteriorating trade balance indicates that non-EU producers are becoming more competitive in the European market, capturing the market growth. This is partly caused by fragmented and nationally focused markets that increase transaction and distribution costs, and reduce competition in both the manufacturing and the installation segments of the value chain (SWD(2021)307). There is also a risk that big air conditioning manufacturers who can produce equipment at low cost, especially in Asia-Pacific and the US and Mexico, will turn their attention to conquering the heat pump market. Negative trade balance in 2020 could also be explained by the pandemic, as production dropped especially in the countries with the strictest lockdown measures, such as France, Spain and Italy. In Italy, production dropped by as much as 60% in 2020 compared to 2019.

Deployment is hampered by the lack of building experts and qualified heating & cooling installers to provide customer information and integrated solutions and ensure optimal operations (SWD(2021)307). The issue can be addressed with regular and high-quality retraining. The creation of standards and labels at European level could also help companies to operate across the EU.

Apart from common materials such as steel, copper, aluminium and zinc, heat pumps do not have specific vulnerabilities (European Commission, 2021d). However, the circularity of heat pumps could be improved.

9.5 Scoreboard and key insights

Figure 37 shows that the EU scores highly on several innovation related indicators – slightly increasing public R&D investment, a strong global position in high-value patenting, a high share of later stage investments and a high share of innovators headquartered in the EU. As the EU captured only 13%, the score for early stage investments is average. With the booming market, turnover and employment have increased in the EU. The lack of qualified installers is not expected to be insurmountable since existing heat installers can be retrained. However, this retraining should be made a priority to ensure a smooth transition. While EU production is

([95]) In 2016 Midea (CHN) acquired a majority holding in the Italian Clivet group. In 2018 Stiebel Eltron (DE) took over Danfoss Varmepumpar AB (SE). In 2019 Hisense acquired Slovenian Gorenje. In 2020 NIBE Industrier AB (SE) acquired Waterkotte (DE).

increasing, there are some worrying trends. Growth in the European market is increasingly being captured by non-EU producers, as evidenced by the transformation of the trade surplus into a deficit in 2020. While imports are growing, EU exports have stagnated, revealing the increasing competitiveness of non-EU producers. Future market opportunities lie in digitalisation and system integration with smart grids and building management systems. The European market still has growth potential, stimulated by positive policy developments. Strong EU performance in innovation suggests that European industry has the potential to capture future markets, but must better deploy economies of scale if it is to overcome cost-cutting competition from outside the EU.

Figure 37: Scoreboard for heat pumps

Scoreboard	**Heat Pumps**	EU performance in the reference period		
Public R&D	green	18%	2015-2019	EU CAGR
Early Stage	amber	13%	2015-2020	EU share of global total value
Later Stage	green	51%	2015-2020	EU share of global total value
Patents	green	48%	2016-2018	EU share of global total HVI
Companies	green	44%	2015-2020	EU share of innovating companies
Employment	green	6%	2015-2020	EU CAGR
Production	green	5%	2015-2020	EU CAGR
Turnover	green	7%	2015-2020	EU CAGR
Imports & Exports	green	43%	2018-2020	EU share of global exports
Trade Balance	red	Low	2015-2020	EU trade balance trend

Source: JRC

10 Wind rotors – wind energy

Wind energy is a crucial part of the EU energy system and is expected to become a main pillar of the EU targets towards deep decarbonisation. Moreover, the offshore renewable energy strategy (ORES) adopted in 2020 sets the ambition to deploy at least 60 GW of offshore wind energy and 1 GW of ocean energy by 2030 with a view to reaching, by 2050, 300 GW of offshore wind and 40 GW of ocean energy capacity.

The 2030 Climate Plan scenario (CTP-MIX) projects a production of 847 TWh of onshore wind in 2030 (share of total electricity generation: 27%), and 2 259 TWh in 2050 (share: 33%). The same scenario foresees offshore wind to generate 229 TWh in 2030 (share: 7%) and 1 154 TWh in 2050 (share: 17%) ([96]). In terms of capacity deployed this equals 366 GW in 2030 and 963 GW in 2050 of onshore wind and 73 GW in 2030, 290 GW in 2050 of offshore wind.

Both onshore wind and bottom-fixed offshore wind are established technologies and have realised a remarkable cost reduction in the last decades. Moreover, through consistent public and private R&I investments floating offshore wind technology is on the brink to become a commercial solution, thus allowing to unleash the offshore resource potential of so far untapped EU sea basins.

Cumulative installed onshore wind capacity in the EU increased by 109% from 78 GW in 2010 to 164 GW in 2020. The increase in deployment was even more pronounced for the offshore wind sector, surging form 1.6 GW in 2010 to 14.6 GW in 2020.

The following chapter on wind rotors pursues and expands earlier analyses on the competitiveness of the sector (e.g. compare with the assessment in (European Commission, 2020a)). This entails the analysis of the development of main competitiveness indicators complemented with a detailed analysis of the EU supply chain for wind rotors, both in the onshore and offshore wind sector.

10.1 EU positioning in innovation

10.1.1 Investment trend

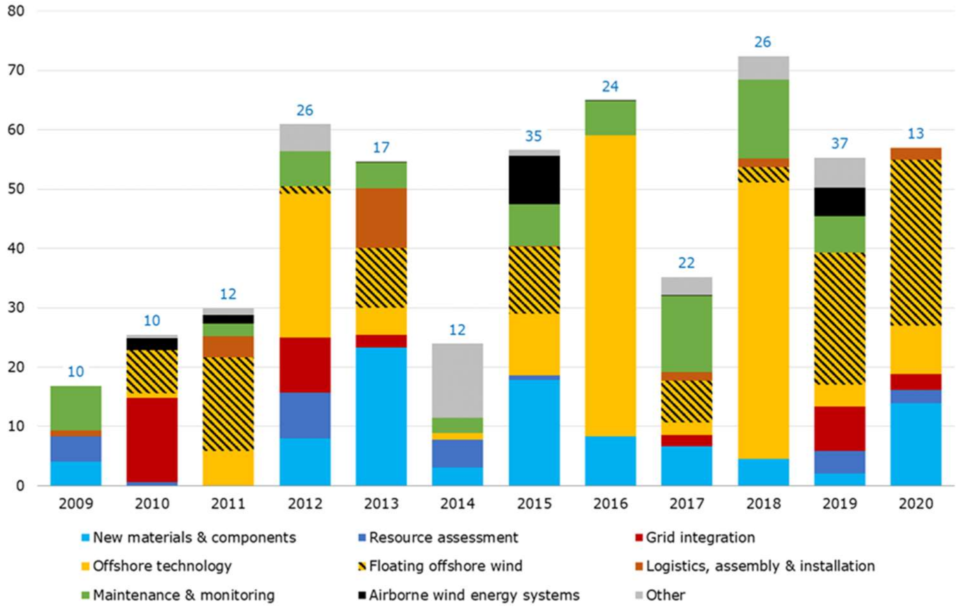
In the period 2017-2019, Japan led at country level on public R&D investment in wind energy, with about EUR 415 million spent, followed by Germany, the United States, Norway and South Korea. The Netherlands, Denmark, Spain and France were also amongst the top ten countries investing in wind energy. However, taking the EU Member States together, their combined public R&D investment spend on wind energy was EUR 496 million, surpassing that of Japan in the same period.

EU public R&D investment remained roughly constant between 2012 and 2016, at around EUR 120 to EUR 145 million. The trend subsequently increased, reaching EUR 179 million by 2019. This equates to a 32% increase in public R&D investment since 2010. Preliminary numbers for selected EU Member States in 2020 indicate that this increase in public investment is continuing.

Additionally to Member State funding above**, Figure 38** shows the development of R&I funding in the period 2009-2020 under the Horizon 2020 funding programme (2014-2020) and under its predecessor, the Seventh Framework Programme (FP7) (2007-2013). EUR 28 million was granted to wind energy projects starting in 2020, of which 49% was focused on floating offshore technology wind research, 24% on new materials & components and 14% on offshore wind technology. Since 2009, FP7 and Horizon 2020 have allocated substantial funding across all wind research R&I priorities, with projects on offshore wind technology (EUR 158 million), floating offshore wind (EUR 106 million) and research on new materials & components (EUR 91 million) accumulating most of the funds (Telsnig, 2020).

([96]) EC CTP-MIX

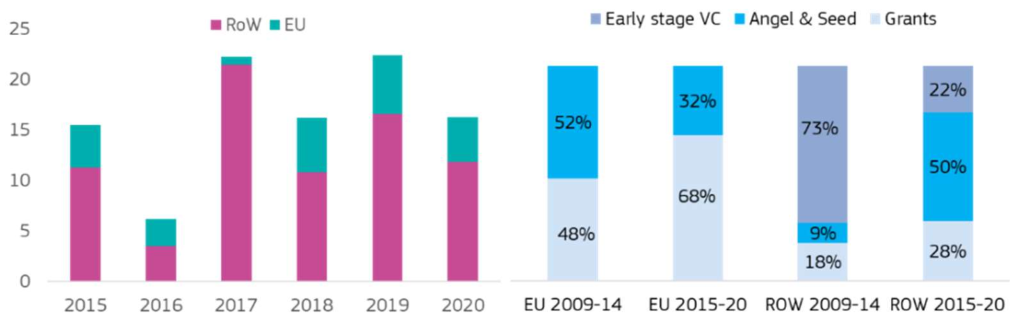
Figure 38 Evolution of EU funding categorised by R&I priorities for wind energy under FP7 (2009-2013) and Horizon 2020 (2014-2020) programmes and the number of projects funded in the period 2009-2020 [EUR Million]



Source: JRC 2021

Since 2017, global early stage investment has ranged between EUR 16 million and EUR 22 million. EU investment increased from EUR 1 million in 2017 to over EUR 4 million in 2020. The share of EU investment remains moderate, with about 24% of all early stage investment in the period 2015 to 2020, with 55% going to the United States (see **Figure 39**, left). While EU countries show a strong share of early stage investment through grants in the last decade, their global competitors invest at a higher rate through early stage venture capital (see **Figure 39**, right).

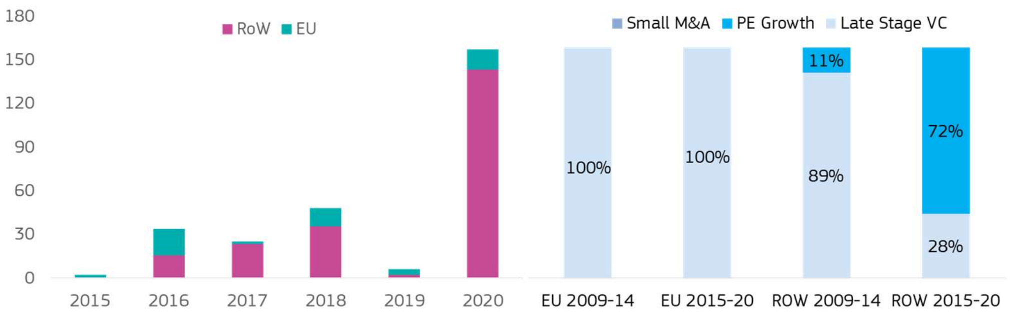
Figure 39 Early stage investment by region [EUR Million] (left) and share by investment type and region (right)



Source: JRC based on Pitchbook

Later stage investment show no clear trend, with extremes of EUR 2 million and EUR 157 million in the period 2015-2020. About 80% of these investment originate in China, the United States, Canada, the United Kingdom, South Korea and Japan, with EU countries just accounting for about 20%. Since 2009, the EU has relied exclusively on later stage venture capital whereas since 2015, the rest of the world has seen a shift towards private equity growth. This is also the case where later stage investment peak in 2020, when Chinese blade manufacturer Aeolon received around EUR 100 million in development capital from a consortium of six Chinese investment firms (see **Figure 40**).

Figure 40 Later stage investment by region [EUR Million] (left) and share by investment type and region (right)



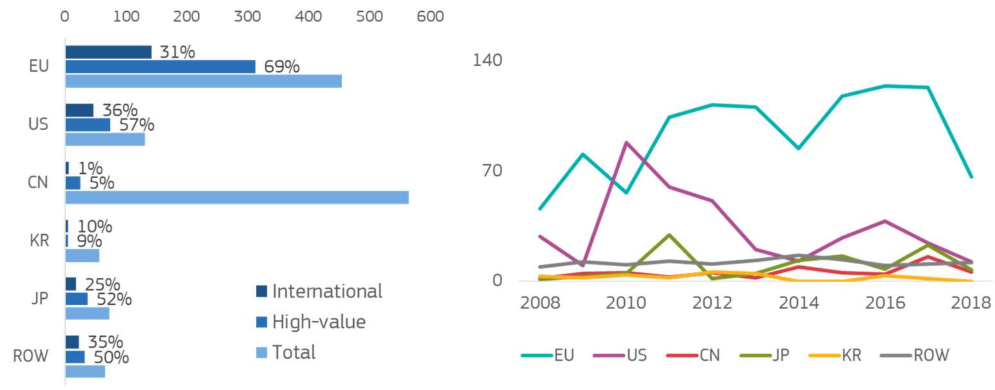
Source: JRC based on Pitchbook

Overall, China and the United States lead in terms of venture capital investments, although between the periods 2009-2014 and 2015-2020, the US experienced a significant drop in VC investments from EUR 428 million to EUR 62 million.

10.1.2 Innovation trend

China ranks first in wind energy inventions after overtaking the EU in 2009, which had been world leader since 2006. However, Chinese patenting activity focusses on its internal market. In the period 2016-2018, only about 5% of the Chinese patenting inventions filed on wind energy technologies were high value, while high-value inventions account for about 69% of all European wind energy inventions filed. The share of high-value inventions in the United States and Japan is 57% and 52% respectively, but both have significantly lower numbers in absolute terms (see **Figure 41**).

Figure 41 Number of inventions and share of high-value and international activity (2016-2018) (left) and trend in high-value inventions for the major economies (right)



Source: JRC based on EPO Patstat

Globally, in the period 2016-2018, the EU's share of high-value inventions was 64%, followed by the US (15%), Japan (8%), China (5%) and Korea (1%). This means an increase of 7 percentage points when compared to the EU share of high-value patents in the period 2015-2017.

EU companies keep the lead in terms of high-value inventions filed in the period 2016-2018. Germany and Denmark are the leading countries, followed by the United States, Japan and China. EU-based original equipment manufacturers (OEMs) (e.g. Enercon (Wobben Properties GmbH), Senvion, Vestas and SiemensGamesa) hold a leading position in high-value patents, followed by General Electric (US), the Danish subsidiary of LM Wind Power (US), Mitsubishi Heavy Industries (JP), Goldwind (CN) and NTN Corp (JP).

EU applicants show the highest share of inventions protected in United States (34%) and China (31%) in the period 2016-2018, whereas the United States protect a substantial share of their inventions in Europe (37%) and China (43%). China, Japan and South Korea protect a significantly lower number high-value patents, yet Europe and the United States are again the main destinations of IP protection.

The EU hosts about 38% of all innovators, of which about 59% are venture capital companies and 41% are corporates, in similar proportions to the rest of the world (66% and 34% respectively). However, the number of EU venture capital companies is moderate when compared to the ROW with only 36% stemming from EU

Box 3: Intellectual property rights (IPR) in the wind energy sector

A patent is a legal title granting its holder the right, in a specific country and for a limited time, to prevent others from exploiting an invention for commercial purposes without authorisation (Pasimeni & Georgakaki, 2020). In order to acquire the relevant knowledge and overcome the technological gap, companies build on technology cooperation, licensing or even strategic purchases of selected foreign wind firms (Watson, et al., 2015).

Comparing high-value inventions of the leading wind OEMs since 2010 shows that EU, US and JP companies are ahead in the major patent offices (EPO, USPTO, SINO). Only Envision Energy ApS, the Danish subsidiary of Envision, can be found within the Top 10 companies filing high-value inventions, with the remaining Chinese OEMs trailing behind.

In recent years, targeted wind technology areas crucial for Chinese OEMs catching up to European manufacturers in the offshore and grid integration sector have included the drive train (**permanent magnet direct drive technology** (e.g. 2008: Goldwind (CN) acquiring Vensys (DE); 2009: XEMC (CN) acquiring Darwin (NL)), **super compact drive (SCD) technology** for offshore wind (e.g. 2015: MingYang (CN) acquiring Aerodyn (DE)) and electronic control components (**low-voltage ride-through (LVRT) technology** (e.g. Sinovel using AMSC Windtec (US) LVRT components; 2012: Sinovel acquiring IPR from Mita-Teknik (DK)). Knowledge transfer also takes place directly in Europe, as many Chinese OEMs established their R&D centres in European countries (Envision Energy ApS, Goldwind or Ming Yang in DK, XEMC Darwin in NL) in order to generate international patents through their European subsidiaries filed by European inventors (Lam, et al., 2017).

Protection of IPR is an important issue among competitors and markets. IP infringement remains the leading reason in 2020 for the reluctance of EU companies to take their innovative technologies to China (EU Chamber of Commerce in China, 2020). Moreover, IP litigations between major OEMs are used to secure a competitive advantage in certain markets but hold the risk of higher project development costs on the consumer side, project delays and less innovation. **It is estimated that the wind energy industry lost up to EUR 4.6 billion ([97]) to avoidable IP infringements and trade secrets theft** (in legal losses, blocking of product sales, denial of market access and loss of revenue) (Renewables Now, 2019). Recent patent infringement cases around the low-voltage ride-through (LVRT) or zero-voltage ride-through (ZVRT)([98]) exemplify an OEM's strategy to either close the technological gap or protect its home market.

In China, Sinovel's long-term, market-leading position was based on a production license (for 1.5 MW turbines) acquired from Fuhrländer (DE) in 2004. Upgraded products in the following years also relied heavily on electronic control components from Windtec (AT-based subsidiary of AMSC (US)) providing low-voltage ride-through (LVRT) capabilities enabling optimised grid integration. In 2013, AMSC accused Sinovel of stealing intellectual property from AMSC in 2011 in order to produce its own turbines. In 2018, Sinovel was fined by a US court followed by a settlement agreement between the two companies ([99]). In 2012, Sinovel went into a strategic partnership with Mita-Teknik (DK), purchasing the intellectual property rights on software and source code for electrical control systems (Sinovel, 2016) (Department of Justice, Office of Public Affairs, 2019).

In the US, General Electric (GE) has enforced its IP rights since 2003 after acquiring Enron Wind (and their patents on wind control systems; '705 patent' on zero-voltage ride-through (ZVRT)). By 2005, most European OEMs (Nordex, Acciona and Senvion) signed license agreements in order to prevent IP litigations in the US market. An exception was the refusal to license of Mitsubishi Heavy Industries (MHI), followed by an IP litigation with GE in 2008, which was settled with a cross-licensing agreement in 2013. However, within this five-year period, the case added substantial IP infringement cost risk to potential MHI asset owners, which resulted in MHI being driven out of the US onshore wind market.

([97]) Converted from USD 5.3 billion using average exchange rate of the respective year.

([98]) Low-voltage ride-through (LVRT) or zero-voltage ride-through (ZVRT) technology enable wind turbines to maximise power capture in fluctuating wind speeds and to cope with fluctuating grid voltage.

([99]) It is estimated that AMSC lost $1 billion in shareholder equity and almost 700 jobs because of this IPR infringement.

Similarly, GE and Vestas made claims against each other in 2017 over the breach of multiple patents (including the ZVRT patent), a litigation that was finally settled with the cross-licensing of patents in 2019 ([100])(Vestas, 2019). In 2020, GE sued SiemensGamesa RE (SGRE) of infringing the LVRT and ZVRT patents with the US International Trade Commission (ITC), confirming the complaint in 2021 for the LVRT, followed by a final ITO decision confirming the LVRT infringement in January 2022 (S&P Global, 2022; WPM, 2021c). The complaint with regards to the ZVRT patent was rejected. In response, SGRE filed a litigation in 2020 against GE, claiming that GE's Haliade X turbines infringe the IPR of SGRE's offshore direct drive technology. The ongoing patent dispute also expanded to other markets in 2021 when GE sued SGRE in the UK of infringing its ZVRT patent, a case that holds the potential to delay the delivery of major offshore wind projects in the UK for which SGRE will supply wind turbines (1.4 GW East Anglia 3 and 1.4 GW Hornsea Project 2) (Mitsubishi Heavy Industries, 2013; Recharge, 2020; WPM, 2021a; WPM, 2021b).

10.2 EU positioning in current market

10.2.1 Manufacturing facilities and supply chain

The wind energy sector has evolved into a global industry. WindEurope/WoodMackenzie (2020) identifies about 800 manufacturing facilities, with the majority operating in China (45%) and Europe (31%), followed by India (7%), Brazil (5%) and North America (4.5%). In Europe, the leading markets, Germany, Spain, Italy, Denmark and France host a substantial number of manufacturers (Wind Europe/Wood Mackenzie, 2020) ([101]). Looking more broadly at wind-related activities (e.g. R&D centres, operations, construction, services and ports), about 550 companies/entities are located in European countries.

The section below identifies the structure and main players in the EU supply chain for wind rotors, for both onshore and offshore wind sectors, according to the following supply chain categories:

1. **Project developers and owners** – Companies developing wind farms or holding stakes through M&A in projects, thus owning the components (WTG (rotors)) of the wind farm
2. **Tier 1 component manufacturers** – Companies involved in the manufacturing and assembly of the main components. This includes the following components: blade, shaft, foundation, gearbox, generator, nacelle (and nacelle assembly), substation (offshore), power converter, tower, transformer
3. **Tier 2 component manufacturers** – Companies producing smaller sub-components that merge, integrate or enable the proper operation of main components: blade bearing, control system, HV export cables, inter-array cables, main bearing, pitch system, switchgear, turbine controller, yaw system components.([102])

Tier 3 component manufacturers providing specialised solutions and innovations for the wind sector are not covered in the supply chain analysis.

Moreover, the different players in the EU supply chain are analysed by manufacturing location and country of origin. The sourcing strategy of the various original equipment manufacturers (OEMs) is identified through current market shares of their latest wind turbine models deployed in the EU, and information on the wind turbine model component suppliers as reported in the latest component certificates of international certification bodies.

10.2.2 Project developers and ownership

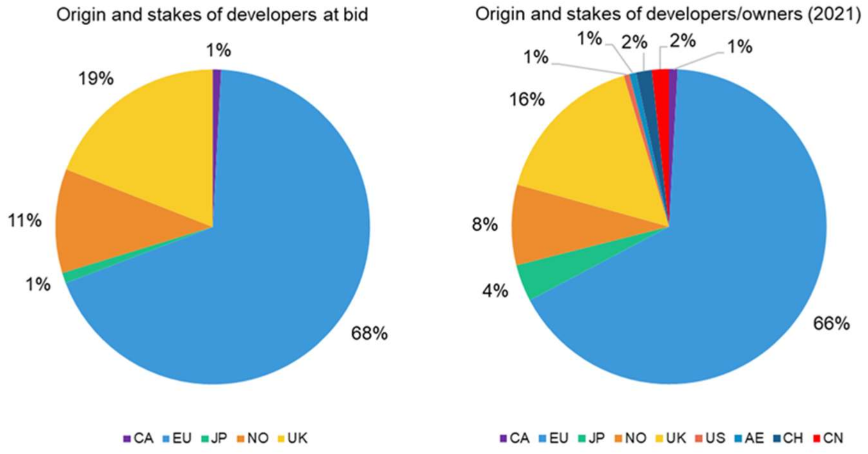
Across all EU countries, a cumulative offshore wind capacity of about 21 GW has been allocated through competitive tendering procedures, which are expected to be commissioned until 2025. With about 13 GW of offshore capacity, the top five developers (Ørsted, Vattenfall, RWE Renewables (innogy SE), SSE Renewables and Equinor) account for more than 60% of the ownership of the allocated capacity. Since the announcement of their successful bid, EU developers have kept their ownership almost stable at about 66% (losing only 2%) of the total competitive tendered offshore capacity (see **Figure 42**).

Notably, the latest competitive tender schemes in the Netherlands and the United Kingdom (Hollandse Kust Noord and UK CfD Allocation Round 3) saw a strong presence of the European O&G majors (Equinor, Shell,

([100]) U.S. Patents No. 7,629,705, No. 6,921,985, No. 7,102,247 and No. 7,859,125
([101]) The WindEurope/WoodMackenzie (2020) data set covers Tier1 and Tier2 component manufacturers of the following components: Nacelle, Bearings, Blades, Converters, Gearboxes, Generators, Castings, Forgings, Towers.
([102]) Tier 1 and Tier 2 categorisation and reported component suppliers based on the JRC Wind Manufacturers Database

Eni, Total) stepping into the field of offshore wind development. A small share of projects is hold by non-European companies stemming from Japan (Diamond Generating E.L., Kansai Electric Power, J-Power/Electric Power Development, Mitsubishi UFJ), China (Red Rock Power, China Resources Company, CTG Corp.), Switzerland (Partners Group), Canada (Enbridge Inc.), VAE (Masdar) and the United States (Global Infrastructure Partners).

Figure 42: Developers and ownership of allocated capacity in competitive offshore tenders in Europe until 2020



Source: JRC analysis

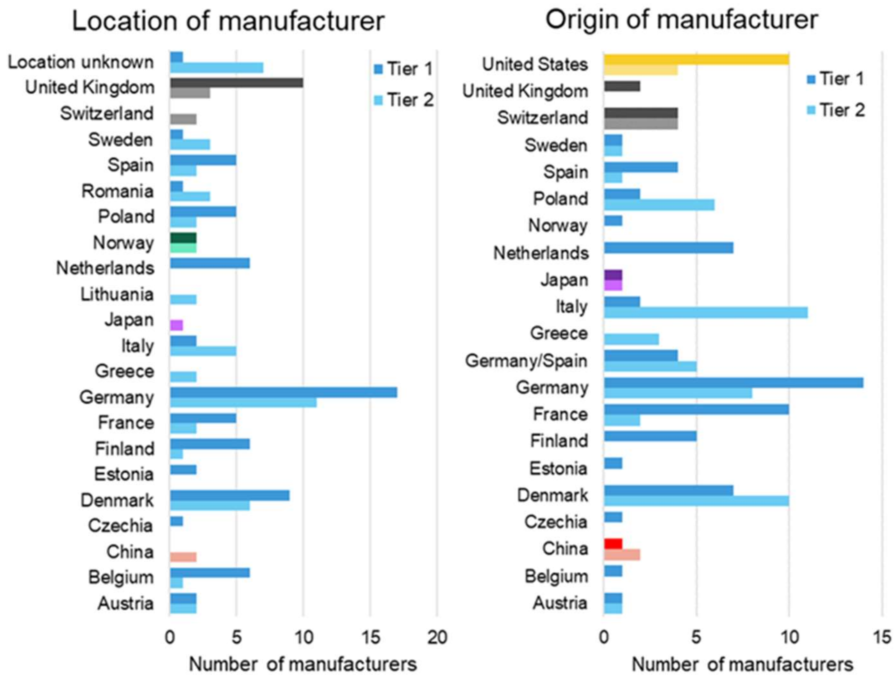
In the onshore wind developer market, the ownership structure is much more fragmented. About 1900 project developers and 3000 project owners developed onshore wind projects that came into operation in the last decade. Energy utilities (Enel, EDP, EDF, Engie, RWE) lead in holding most of the deployed capacity in this period, with foreign players also among them, such as CGN (China).

10.2.3 Offshore manufacturing supply chain

The European manufacturing supply chain for offshore wind at Tier 1 and Tier 2 level (see Table 1 in Annex 2) builds mainly on companies from EU Member States. Tier 1 and Tier 2 suppliers have 138 facilities located in the EU, of which about 84% are of EU origin. Tier 1 suppliers are located in the leading EU offshore wind markets around the North Sea and Baltic Sea, such as Germany, Denmark, the United Kingdom, the Netherlands and Belgium, as well as in countries that can leverage a strong onshore wind supply chain (Spain) or that host a specific Tier 1 component (Finland: transformer manufacturers). Moreover, suppliers of offshore wind components can be found all over Europe, even in landlocked countries. There is only some indication of Tier 2 components coming from non-European companies in China and Japan (see **Figure 43**). 78% of the identified offshore wind facilities are owned by manufacturers from the EU, followed by companies from the US (10%), Switzerland (6%), China (2%), Japan (1.5%) and the United Kingdom (1.5%).

The EU offshore market has further consolidated in recent years, following Senvion's insolvency at the end of 2019 and Vestas's buying out of Mitsubishi Heavy Industries (MHI) from their offshore wind joint venture in 2020 (WPM, 2020a; WPM, 2020b). With SiemensGamesa RE, Vestas and General Electric RE, there are currently three offshore original equipment manufacturers (OEMs) with manufacturing capabilities in EU waters.

Figure 43 Manufacturers of the European offshore manufacturing supply chain: location (left) and origin (right) of Tier 1 and Tier 2 component suppliers



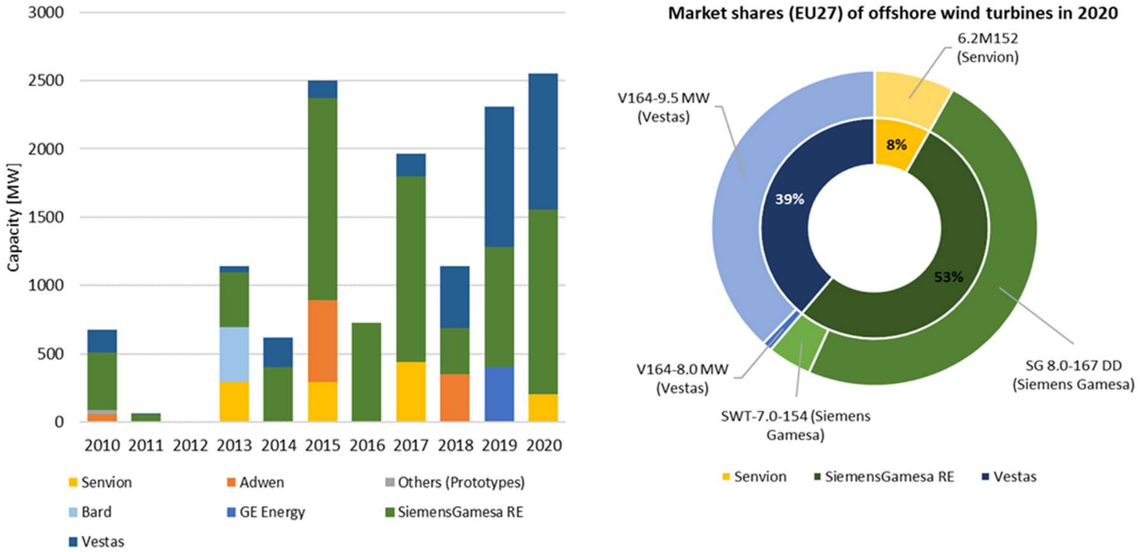
Source: JRC Wind Manufacturers Database, 2021. Note: Includes facilities with joint onshore and offshore component production

Today, the three main offshore OEMs have an estimated 6.5-8 GW of nacelle assembly capacity at European ports (Wind Europe/Wood Mackenzie, 2020). In 2020, SiemensGamesa RE and Vestas held together a market share of 92% in EU countries (see **Figure 44**). Moreover, GE Renewable Energy currently tests its 12 MW GE Haliade-X in Maasvlaakte (Port of Rotterdam), which first produced power in November 2019 and will have its first commercial installation at the Dogger Bank C offshore wind farm (UK). However, wind turbine certificates published by the IEC (International Electrotechnical Commission) reveal that all offshore OEMs have established their own supply chain and sourcing strategy for the subcomponents of their offshore wind rotors (see Table 1 in Annex 2) (IECRE, 2021).

Wind turbine rotors by Siemens RE and Vestas deployed in 2020 build on a strong European supply chain, with most of the components being sourced from EU companies. Yet both OEMs source some components from non-EU countries, highlighting the importance of trade relations (UK) and of maintaining the EU's competitive advantage in offshore wind (China). Vestas manufactures blades, shaft and yaw components in the United Kingdom and some of its switchgears in Norway, Japan and China. Similarly, SiemensGamesa RE has a strong UK-based production of blades, shaft and yaw components, yet the company seems to diversify its production more markedly among different countries. The company has, for example, certified TMB (Zhejiang Tianma Bearing Group Limited), a company based and producing in China, as a component supplier. Based on current component certificates, components of the upcoming Haliade X model by GE Renewables are expected to be located in EU Member States.

In 2021, Chinese OEM MingYang entered the EU offshore wind market by securing a deal to supply 10 offshore wind turbines to the 30 MW Port of Taranto (Beleolico) offshore wind project (replacing the previously planned Senvion turbines), which will be the first commercial EU offshore wind farm in the Mediterranean Sea (end of 2021). MingYang will execute the project from its EU HQ in Germany while turbines seem to be shipped from China. Moreover, monopiles will be provided by a Spanish manufacturer (Haizea Wind Group) (Offshore energy, 2021a; WPM, 2021b).

Figure 44: Market shares (EU) of offshore wind OEMs in 2010-2020 (left) and market share in 2020 and the respective offshore wind turbine models deployed (right)

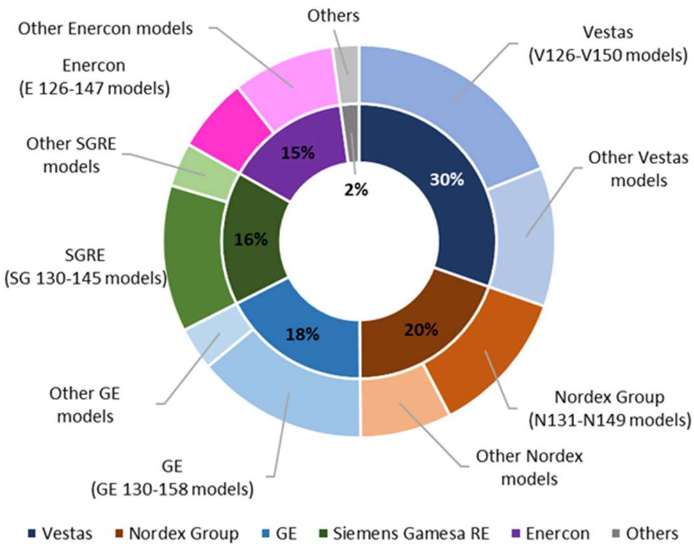


Source: JRC Wind Manufacturers Database, 2021. Note: Market shares (EU) include capacity deployed at Borselle III and IV (NL) which were fully commissioned on 06/01/2021

10.2.4 Onshore manufacturing supply chain

In 2020, EU companies held about 80% of the EU onshore wind rotor market. The rated capacity of onshore wind turbines continues to increase towards models above 3 MW, increasing their annual market share within the EU from 2% in 2010 to about 81% in 2020 (Telsnig, 2020). This means an increase in the wind blade size of current onshore wind rotor models, with OEMs installing more than 60% of their models in the 120 m to 150 m rotor diameter range (**Figure 45**).

Figure 45 Market shares (EU) of onshore wind OEMs in 2020 and the respective offshore wind turbine models deployed



Source: JRC Wind Manufacturing Database, 2021.

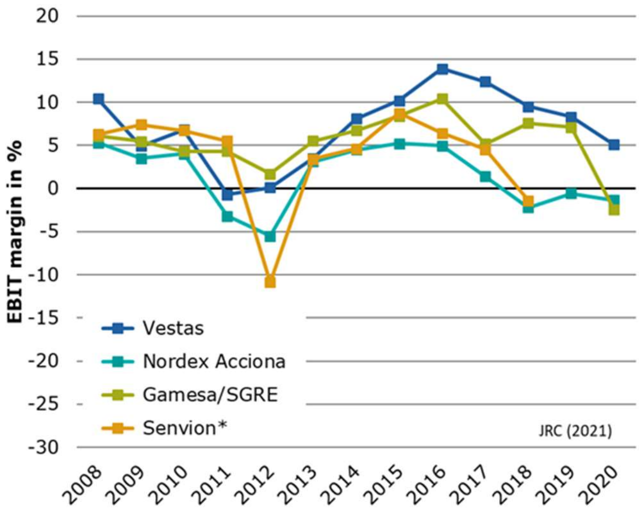
As in the offshore sector, European OEMs mainly source their onshore wind rotor components from companies based in EU Member States. Component certificates of some recent onshore models confirm the competitiveness of Chinese manufacturers in some components, such as blade bearings and shafts. Given the global scale of the onshore wind industry, European OEMs seem to source their components from multiple suppliers (in contrast to the offshore case) and cooperate with component suppliers with a global manufacturing footprint (e.g. pitch system, bearing of the Vestas V150) (see Table 2 in Annex 2).

10.2.5 Employment

Wind is a strategic industry for Europe. It is estimated that the sectors offers between 280 000 and 300 000 quality jobs (WindEurope, 2022)([103]), 77 000 of which relate to offshore wind. In 2020, Germany ranked first in terms of direct and indirect jobs, followed by Spain and the Netherlands.

The trend in employment figures shows no growth in the period 2015-2020, a period also characterised by declining EBIT margins of listed EU OEMs. This can be explained by high competition in turbine orders, particularly in the period 2017-2018, and increased material costs for the main turbine components. In 2020, these factors were further intensified through the impact of Covid-19, which created logistical challenges for all manufacturers. As a result, only Vestas could present a positive EBIT margin (+5.1%), whereas NordexAcciona (-1.3%) and SiemensGamesa RE (-2.5%) reported negative figures (Telsnig & Vazquez Hernandez, 2019)([104])(**Figure 46**). Moreover, turnover in the wind power sector ranged between EUR 34 billion and EUR 44 billion in the period 2015-2020, showing a compound annual growth rate of 4%.

Figure 46: EBIT margin (operating profit/revenues) of the leading listed EU OEMs



Source: Telsnig (2022).

Figures on labour productivity in the offshore wind sector, measured in direct full term equivalents (FTE) per MW installed, have been declining in recent years as the learning effect improves, with more capacity installed in the sector. Yet the scope and boundary conditions of these studies differ significantly, ranging from case studies at project level to econometric models and scenario-based projections estimating the employment factor at country or sector level (SEE). Direct job estimates for single projects are in the range of 16.3-15.8 FTE/MW for projects in the period 2013-2016 (QBIS, 2020; IRENA, 2018). Due to productivity improvements, some studies estimate a further decrease in specific direct labour requirements to 9.5 FTE/MW per project by 2022 (QBIS, 2020). Although these numbers show the expected learning effect, they cannot be used to estimate the total number of jobs in the industry as the extrapolation from project-level capacity to installed capacity in the market would lead to double counting and thus an overestimation.

Current econometric models estimating the number of jobs using employment factors, trade data and/or contribution to GDP of the sectors involved shows direct employment figures declining from about 4 $FTE/MW_{Installed}$ in 2010 to a range of 1.8-2.9 $FTE/MW_{Installed}$ in 2020. When including indirect employment effects, 2.2 to 5.1 $FTE/MW_{Installed}$ seems plausible (Deloitte/WindEurope , 2017; WindEurope, 2020b; Ortega, et

([103]) These are estimates using different methods. WindEurope estimates the figure to be 300 000 while EurObserv'ER estimates the figure to be 280 000 jobs.
([104]) Data update April 2021.

al., 2020; JRC, 2020a; GWO, 2020)([105]). Scenario-based analyses estimate a further decline in direct labour productivity to about 1.2 $FTE/MW_{Installed}$ by 2050.

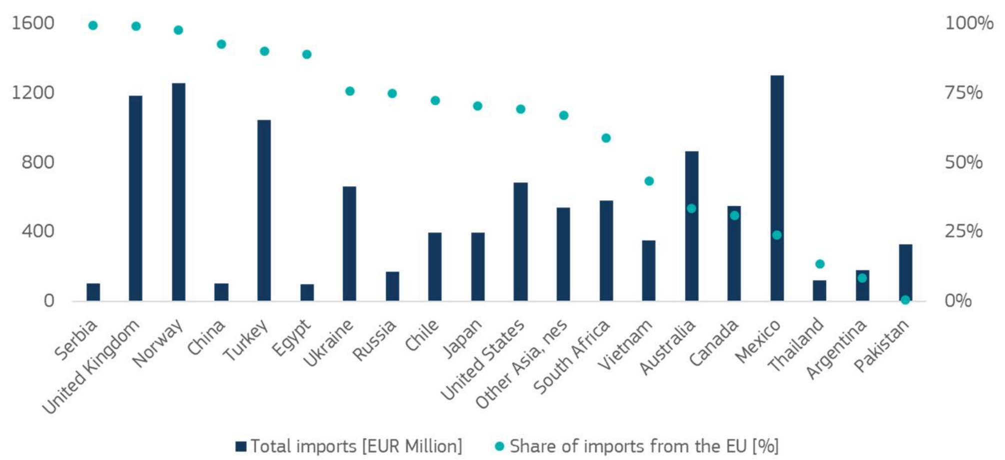
The onshore wind sector shows a lower specific labour productivity than offshore, based on the latest case studies and econometric models. Direct job estimates for single onshore wind projects are in the range 1.7-3.0 FTE/MW for projects in the period 2015-2019. Differences in this spread seem to originate in project size and geographical scope (Ejdemo & Söderholm, 2015; Okkonena & Lehtonen, 2016). Econometric models at regional and national levels estimate the number of direct jobs at 0.5-2.3 $FTE/MW_{Installed}$ with European estimates declining to about 0.7 $FTE/MW_{Installed}$ in 2019 (Llera Sastresa, et al., 2010; Brown, et al., 2012; Dvořák, et al., 2017; WindEurope, 2017)([106]). Long term scenario models estimate future labour productivity for onshore wind at a similar scale, with values ranging from 0.35 to 0.9 $FTE/MW_{Installed}$ (Ortega, et al., 2020).

10.2.6 Trade

In the last decade, the EU had a positive trade balance for electric generating sets. EU exports to the rest of the world ranged between EUR 2 billion and EUR 3 billion, while imports from outside were substantially lower at between EUR 26 million and EUR 313 million. However, a decrease in exports and an increase in imports (mainly from China and India) resulted in a decrease of the EU trade balance in the period 2018-2020 by about 20%.

The leading countries in wind capacity deployment and manufacturing capabilities are among the top global exporters of wind-related trade goods. In the period 2018-2020, Denmark (EUR 6 billion) and Germany (EUR 5.8 billion) rank in the top spots, followed by China (EUR 6 billion), Spain (EUR 6 billion) and the Netherlands (EUR 6 billion). Top importers during this period are Mexico, Norway, the United Kingdom, Turkey and the Netherlands, importing wind generating sets for between EUR 0.9 billion and EUR 1.3 billion. Moreover, major foreign markets show high shares of imports from the EU during this period. The share of imports from the EU to the United Kingdom, China, Japan and the United States accounted for 99%, 93%, 71% and 69%, respectively (**Figure 47**).

Figure 47: Top 20 non-EU importers and share of imports from the EU in 2018-2020



Source: JRC based on UN Comtrade data.

([105]) Updated figures on employment using the Deloitte/WindEurope model.
([106]) 2020 data update.

10.3 Future outlook

EU MSs host a substantial part of the global wind energy supply chain and are the leading suppliers of the EU onshore and offshore wind rotor market. Wind turbine rotors by EU OEMs build on a strong European supply chain, with most of the components being sourced from EU companies. Yet some components are sourced from non-EU MSs countries, highlighting the importance of trade relations (UK) and of maintaining the EU's competitive advantage in offshore wind (China).

Following the capacity deployment path outlined in the ORES and CTP a substantial offshore wind capacity can be expected in so far untapped EU sea basins. This holds the opportunity for an uptake of floating offshore wind projects, strengthening technology leadership in this emerging sector. Moreover, the shift to new sea basins will trigger the need for investments in infrastructure and manufacturing facilities at ports and stimulate regional economic growth and cooperation ([107]).

In the mid-term, repowering of onshore wind plays a crucial role in reaching the MSs NECP targets. This also offers the possibility to optimise the resource potential of onshore wind sites with the best wind resource while using more powerful but fewer turbines.

Permitting delays pose a challenge to achieve the mid- and long term targets towards climate neutrality. This can particularly be observed by reduced onshore wind capacity additions since 2018 resulting from complex permitting rules and potential exposure to legal challenges. Lack of social acceptance for new onshore wind farms might be an additional challenge as current scenarios assume deployments to be 5-6 times higher in 2050 as compared to current levels.

The ORES highlights that there might be a bottleneck when it comes to skilled workers in the offshore wind sector. MSs will need to design and shape more education and training schemes targeting the offshore renewable energy sector to prevent skill shortages (particularly with respect to engineers, scientists and engineering technicians)

The EU has had a positive trade balance in wind energy related equipment in the last 20 years. Yet there is some stagnation in the growth of this indicator as third countries catching up on the EU's first mover advantage, but also by third country policies aimed at protecting their domestic market or forcing EU companies to localise production capacity (e.g. through local content requirements).

A further risk for wind energy is the supply of critical raw materials (e.g. rare earth materials for permanent magnets (neodymium-iron-boron (NdFeB))) which are mainly imported from China (European Commission, 2020b). Moreover the EU's Circular Economy Action Plan stresses the need to scale up the circular economy and decouple economic growth from resource use by doubling the circular material use rate in the coming decade. Given the ageing wind fleet and the substantial share of wind turbines reaching their end of life, recycling and the transition to a circular economy will become key, particularly in the area of composite waste from wind turbine blades. Circularity in the wind sector requires R&I and deployment, but the industry is already very committed for circularity. However, at this stage most circular economy initiatives address a single component/material rather than operating at system level (Telnsig, 2022).

([107]) SWD(2021) 307 final.

10.4 Scoreboard and key insights

The EU competitiveness scoreboard in wind rotors shows that EU performs well in the public R&D, early stage and later stage investments, patenting, companies, turnover and imports & exports (**Figure 48**). The EU score on the trade balance is at medium. Although positive on a high level, the trade balance has been decreasing gradually in the last years. Low scores can be observed for the indicators on employment and production. EU employment in the wind sector has seen no growth in the period 2015-2020, analogously production volumes dropped since 2016. This can be explained by fierce competition in the sector. Since 2016 margins of EU OEMs are declining due to high competition in turbine orders and increased material costs for main turbine components. In 2020 these factors were further intensified through the impact of Covid-19 which created logistic challenges for all manufacturers.

Figure 48: Scoreboard for wind energy rotors

Scoreboard	**Wind Rotors - Wind Energy**	EU performance in the reference period		
Public R&D	●	6%	2015-2019	EU CAGR
Early Stage	●	24%	2015-2020	EU share of global total value
Later Stage	●	19%	2015-2020	EU share of global total value
Patents	●	64%	2016-2018	EU share of global total HVI
Companies	●	38%	2015-2020	EU share of innovating companies
Employment	●	0%	2015-2020	EU CAGR
Production	●	-7%	2015-2020	EU CAGR
Turnover	●	4%	2015-2020	EU CAGR
Imports & Exports	●	70%	2018-2020	EU share of global exports
Trade Balance	●	Medium	2015-2020	EU trade balance trend

Source: JRC

11 Photovoltaic solar panels

Solar PV is another workhorse of decarbonising energy system. It is a mature energy technology – the world's fastest-growing – thanks to a significant decrease in the cost of installation and rapidly growing demand as a result of the global shift to low-carbon electricity production. The main legislative driver has been a series of EU renewable energy directives, starting with EU Directive 2009/28/EC (RED-I), which set obligatory renewable energy targets for EU Member States by 2020. In 2019 it was amended (RED-II) as part of the 'Clean Energy for All Europeans' package (COM(2016) 860), which set common rules for the internal market for electricity and promoted the use of renewable energy with new 2030 targets. The new Climate Law ([108]), requiring a 55% emissions reduction by 2030, is creating an extra push to accelerate deployment. The amended RED-III directive will revise the renewable energy target upwards to 40% and is expected to be adopted in 2022. Additionally, over recent years, a number of national initiatives have boosted the uptake of solar PV.

11.1 Overview of the solution and current status

The scope of the photovoltaic solar panels or modules (hereafter, solar PV) solution covers photovoltaic panels for converting solar energy into direct current electricity, polysilicon production and precursors, thin film production and silicon repurposing and recycling. However, balance of system components (trackers, mounting systems, cabling, inverters etc.), solar farm development and concentrated solar power are excluded.

Global power generation from solar PV is projected to grow from 821 TWh in 2020 to 23 460 TWh in 2050 (IEA, 2020a). In the EU, solar PV capacity is expected to grow about five- to six-fold ([109]), from 160 GW_{DC} in 2021, to reach the EU's long-term decarbonisation objectives (SWD(2021)307 final). Solar PV demand is also expanding into a growing number of markets and applications. At present, nearly all solar PV panels produced use crystalline silicon, with only 5% using thin-film technology. However, other options, including multi-layer tandem devices, may predominate by 2050, influenced also by materials availability and sustainability (Carrara, et al., 2020).

Globally, China is the single biggest solar PV market. After years of slowdown, EU installations are growing again at 12% annually, reaching nearly 16 GW installed in 2021. This is still slower than the 30% compound annual growth rate recorded globally (SWD(2021)307 final). Germany is the biggest market in Europe, followed by Italy, Spain and France, together accounting for 69% of cumulated EU installations in 2021. The EU market was estimated at EUR 17 billion in 2020, which is about 13% of the global total, and is expected to grow to EUR 27 billion by 2030 (European Commission, 2021a). In 2019, approximately EUR 13 billion was invested in new solar PV capacity deployment in the EU (European Commission, 2021a). Utility-scale projects have seen the largest growth, taking an increased share of the market. In the future, according to BloombergNEF, utility-scale projects will absorb over 60% of the required investment, at EUR 3.6 trillion globally by 2050 (Bloomberg NEF, 2020).

Solar PV manufacturing has shifted to Asia-Pacific, with China in particular dominating some parts of the value chain. There are significant gaps in EU manufacturing capacity, namely for the silicon wafers and cells at the core of the technology, which are currently imported. With Chinese dominance in manufacturing extending throughout the value chain, downstream industries in Europe risk supply chain vulnerabilities and a steady reduction in negotiating power (SWD(2021)307 final).

11.2 EU positioning in innovation

According to IEA data, EU Member States annual public funding for R&I on solar photovoltaics has stabilised at about EUR 145 million ([110]), which is lower than the peak seen in 2013 at nearly EUR 170 million. The stagnation of public investment may be explained by a reluctance to invest in a sector without a local manufacturing base and a shifting of research funds to other sectors such as batteries (SWD(2021)307 final). Globally, Germany and France are the biggest public investors, followed by Japan, Switzerland and Canada. However, data is fragmented and limited to IEA members, and not all countries break down their investment

([108]) Regulation (EU) 2021/1119: European Climate Law

([109]) Expected capacity in 2050 is 770-1 030 GW in order to reach decarbonisation goals in the Commission's 2018 Long Term Scenarios.

([110]) This is a lower value than reported in the SWD(2021)307, which looked at a broader IEA category of 'solar energy technologies' for which more IEA member countries report, but it also includes areas other than solar PV.

to identify solar PV specifically. Additionally to Member State funding, nearly EUR 260 million was invested under Horizon 2020 into activities related to solar PV over the period 2014-2020 (SWD(2021)307 final).

Globally, early stage investment increased from under EUR 40 million in 2015 to over EUR 100 million in 2020. Over the same period, EU investments grew from EUR 7 million to EUR 45 million. As depicted in **Figure 49**, the EU share of all early stage investment reached about 23% in 2015-2020. In 2020, the EU saw a record year and captured over a third of all early stage investment that year. While the US remains the leading destination, early stage investment there dropped significantly in 2015-2020 compared to the 2009-2014 period. At the same time investment increased elsewhere, including Germany, Poland, the Netherlands and France.

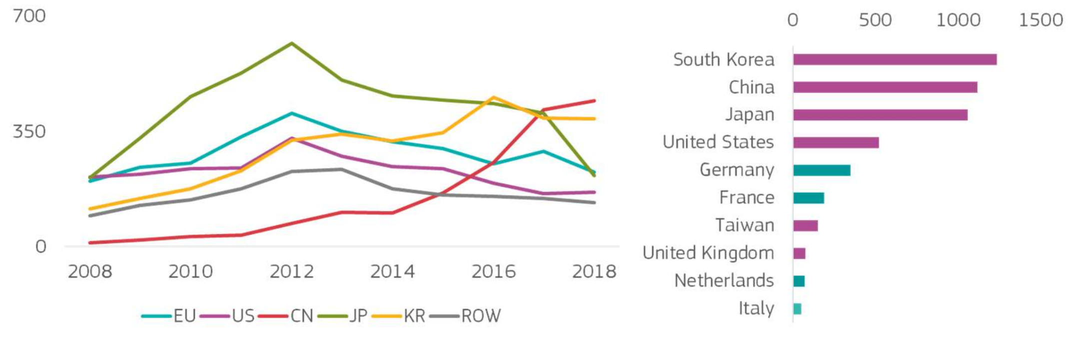
In contrast, later stage investment stagnated globally, dropping to just above EUR 200 million in 2020. At 17%, the EU captured a slightly lower share of later stage investment than at early stage. The US is, by far, the leading destination of later stage investment, despite a decrease from nearly EUR 3 billion in 2009-2014 to less than EUR 1 billion in the most recent years of 2015-20. The US is followed by Germany, China and the UK. Sweden, the Netherlands, France and Poland are also in the top 10. While in recent years, investment decreased in the rest of the world, they increased in European companies. This indicates more confidence among private investors in the innovations being developed by European solar PV companies.

Figure 49: Early stage (left) and later stage investment (right) by region in [EUR Million]

Source: JRC based on Pitchbook

Patenting activity in the field of high-value inventions has seen a very dynamic evolution over the past decade (2008-2018). **Figure 50** shows how Japan, the US and the EU are losing ground to the increasing patenting activity of South Korea and China. China in particular has seen remarkable growth since 2014 and overtook South Korea and Japan in the latest available data. The EU now holds only 15% of cumulative high-value patents approved globally in the 2016-2018 period. Germany, France, the Netherlands and Italy are among the top 10 patenting countries (**Figure 50**).

Figure 50: Trend in high-value inventions for the major economies (left) and top 10 countries in 2016-2018 (right)



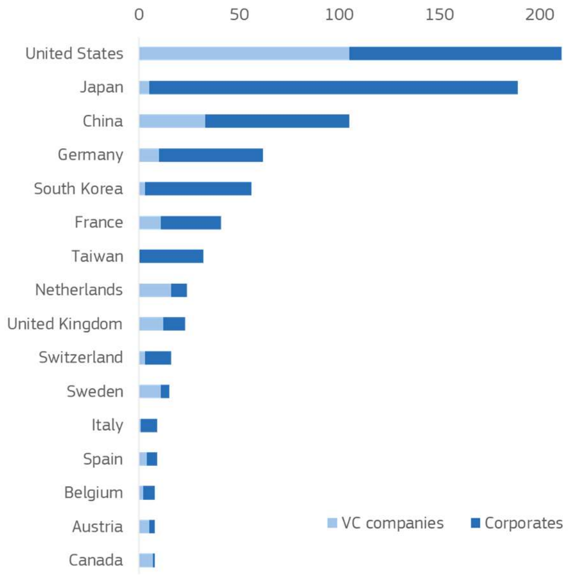
Source: JRC based on EPO Patstat

South Korean and Japanese corporates dominate patenting activity, with two Chinese and only one German company – Merck, among the top 10 patenting corporates. Globally, Samsung holds the most patents by far.

In the European context, German companies dominate, with French, Italian and Dutch corporates also in the top 10. Merck and Cynora hold the biggest EU patent portfolio.

In Japan and South Korea in particular, innovations are centred on corporates, with start-ups playing a very limited role (**Figure 51**). In contrast, the US is home to over 40% of all VC companies identified in this area, thus hosting a large ecosystem of start-ups and scale-ups. The EU hosts about 23% of all innovators, out of which roughly half are VC companies and the rest are corporates.

Figure 51: Number of innovating companies in 2015-2020



Source: JRC compilation from different sources

EU organisations have been at the forefront of developing advanced cells, such as heterojunction silicon cells, where the crystalline silicon wafer is given a thin layer of amorphous silicon. Meyer Bergen has set up production in Germany and, in Italy, ENEL Green Power recently received an Innovation Fund grant to scale up its production of innovative bifacial heterojunction (B-HJT) photovoltaic cells and modules to GW level (European Commission, 2021e).

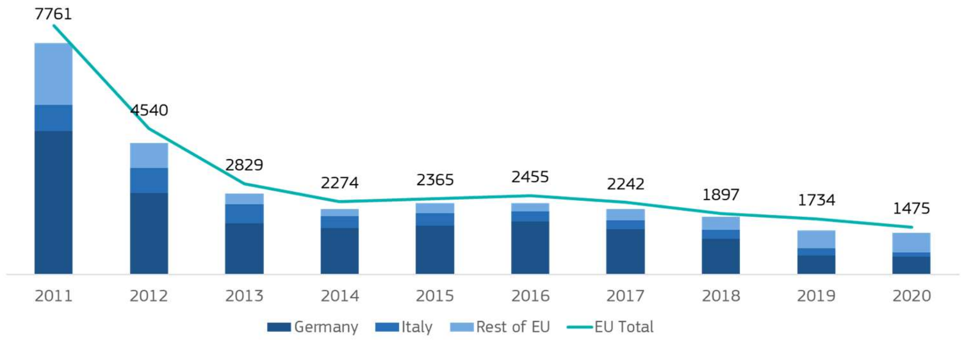
The film technology has higher efficiency but is also more expensive and uses critical raw materials. One promising cost-effective option is a silicon tandem, where an economic thin film perovskite solar cell is deposited on silicon wafers in a double-junction configuration. Oxford PV is now planning to establish a production line of 100 MW for this technology in 2022.

Another area of innovation is deployment, with application of solar PV close to the point of electricity use and/or in combination with other activities or infrastructure, such as agri-photovoltaics, PV facades and windows for buildings, vehicle-integrated PV, floating PV, and carparks, to name a few. PV module recycling and repurposing technology is accelerating as well, an area where, for example, ROSI Solar (FR) and LuxChemtech (DE) are active.

11.3 EU positioning in current market

The EU production volume of solar PV cells has not fully recovered from its drop from the peak levels seen in 2011. The production value dropped from nearly EUR 8 billion in 2011 to less than EUR 2 billion in 2020 (also reflecting the substantial decrease in module prices), see **Figure 52**. In result, the EU relies increasingly on imports as manifested by the growing trade deficit. China controls the manufacturing of most segments, including wafers, cells and modules (SWD(2021)307 final). Germany is still the largest manufacturer of polysilicon, which requires higher technical specifications and expensive factories with longer lead-times to build (SWD(2021)307 final).

Figure 52: EU production value and top producers disclosing data among the Member States [EUR Million]



Source: JRC based on PRODCOM data

After the decline in 2011, both employment and turnover in the solar PV value chain have reversed the trend and seen a significant growth in recent years with compound annual growth rate of 17% and 18% respectively over 2015-2020. In 2020, the value chain employed nearly 166 000 people and generated a turnover of about EUR 21 billion. The photovoltaic sector employs a highly educated and skilled work force for the areas of R&D, polysilicon and wafer production, and cells and module manufacturing. Also demanding in terms of skills are system design, installation, operation and maintenance, decommissioning and recycling (SWD(2021)307 final).

Extra-EU exports, at almost EUR 2 billion, have remained largely the same since 2011, corresponding to 4% of global export value. If EU internal trade is included, the share grows to 10%. At the same time, imports from the rest of the world are growing again, reaching EUR 8 billion in 2020. China is the biggest exporter to the EU and also globally.

The EU trade deficit with RoW has a causal link with the rate of annual installations (SWD(2021)307 final), which started to grow again in 2017. The biggest importers are the Netherlands and Germany, which both also re-export within the EU. The UK is the second biggest destination of EU exports (EUR 600 million over 2018-2020), and the EU accounts for nearly 50% of total UK imports.

11.4 Future outlook

The EU is still a leader in cutting-edge solutions in parts of the value chain (European Commission, 2020a). Attracting an increasing share of private early- and late-stage investments shows that EU companies have the potential for future growth. Another positive sign is the emergence of new EU players such as Poland as top destinations for private investment.

The global PV manufacturing industry is undergoing a technological change which requires investment in new production technology. There have been several announcements recently about plans to launch or scale up production capacity in the EU, including Meyer Burger (CH/DE) and ENEL Greenpower (IT) producing heterojunction solar cells and modules, IconiQ (NL) using novel cell technology, and NexWafe (DE) that will manufacture high-quality mono-crystalline wafers with an innovative low-energy process (SWD(2021)307 final).

In comparison with the US and China, EU solar PV production had the best performance in terms of the energy return on energy invested, and in terms of energy return on carbon invested (including lifecycle carbon emissions) (Liu & van den Bergh, 2020). This can give a competitive advantage to European producers, especially if and when the energy efficiency and carbon performance of products become decisive purchasing decisions. High standards related to end-of-life and circular economy initiatives can create a PV recycling industry in Europe.

The launch of the European Raw Materials Alliance is expected to strengthen the EU by reducing external dependencies on critical raw materials. With regard to end-of-life, PV modules have had to comply with the WEEE Directive since 2012, fostering the development of recycling processes. In addition, a proposal to introduce Ecodesign and Energy Labelling requirements for PV is currently under assessment, and can further support the transition to a circular economy and provide new business opportunities for European players.

Public investment has stagnated over recent years and the repercussions may already be evident in the EU's loss of share of high-value inventions. In order to maintain its leading role in technology in the future, the EU should increase public funding (SWD(2021)307 final). The UK is a big importer from the EU and it also stands out in terms of private investments. The post-Brexit future may include trade disruption and uncertainty in cooperation in this area (European Commission, 2020a).

Recently there seems to be increased interest from investors and industry in ramping up EU production. EU start-ups and scale-ups attracted record high investments in 2020, and based on early signs, this seems to have continued into 2021. The updated EU New Industrial Strategy welcomes the efforts of the industry-led European Solar Initiative to scale up the manufacture of solar photovoltaics (COM(2021)350 final) ([111]). Several projects, mentioned earlier, are already taking off in the EU. Although EU module production is starting to grow again, it remains a minor player in the global market.

There are several vulnerabilities identified in the solar PV supply chain: (1) the EU is highly dependent on imports of raw materials ([112]); (2) there is market concentration for some raw materials and main components (such as cells, modules and inverters), and (3) low substitutability for some critical raw materials (Carrara, et al., 2020; European Commission, 2021d).

11.5 Scoreboard and key insights

EU competitiveness score in public R&D remains medium, as there has been no growth in investment. The EU is losing ground to South Korea and China, coming only fourth with a 15% share of total high-value inventions. EU production is decreasing still, while dependence on imports is increasing. Therefore, after years of improvement, the trade balance deficit is growing again.

The EU captures 25% of all early stage investment and 17% of all later stage investment, showing that European companies have been gaining more traction in recent years (2015-2020). Together with some positive news from the industry, EU companies have an opportunity to regain a manufacturing base and capture market growth with better-performing next generation solar PV panels. Employment and turnover figures are growing, showing positive market development in Europe.

Figure 53: Scoreboard for solar PV

Scoreboard	**Photovoltaic solar panels**	EU performance in the reference period		
Public R&D	●	0%	2015-2019	EU CAGR
Early Stage	●	25%	2015-2020	EU share of global total value
Later Stage	●	17%	2015-2020	EU share of global total value
Patents	●	15%	2016-2018	EU share of global total HVI
Companies	●	23%	2015-2020	EU share of innovating companies
Employment	●	17%	2015-2020	EU CAGR
Production	●	-9%	2015-2020	EU CAGR
Turnover	●	18%	2015-2020	EU CAGR
Imports & Exports	●	4%	2018-2020	EU share of global exports
Trade Balance	●	Low	2015-2020	EU trade balance trend

Source: JRC

([111]) COM(2021) 350 final, 5th May 2021. Updating the 2020 New Industrial Strategy: Building a stronger Single Market for Europe's recovery.
([112]) Boron, Germanium, Silicon, Gallium and Indium are deemed especially critical (European Commission, 2020b).

12 Building energy management systems

The 2018 and 2021 revisions of the Energy Performance of Buildings Directive (EPBD)([113]) emphasise the potential of smart technologies in the building sector, introducing the smart readiness indicator (SRI)([114]) to raise awareness of the value behind building automation and electronic monitoring of technical building systems. The 2021 revision of the EPBD focuses on the energy savings potential of buildings and on ways to accelerate their decarbonisation. The Renewable Energy Directive (RED II)([115]) covers the overall policy for the production and promotion of energy from renewable sources in the EU to achieve its 2030 renewable energy target. The Energy Efficiency Directive (EED)([116]),([117]) sets the overarching legal framework for energy efficiency policy in the EU and includes an important provision targeting government buildings. The Energy Labelling Directive ([118]) establishes the information required regarding energy and other environmental resources consumption reported by household appliances.

12.1 Overview of the solution and current status

The scope of the smart buildings energy management systems (SBEMS) covers digital-integrated systems (including hardware and software) built to manage energy in public, commercial, and residential buildings. It also covers systems designed to manage the interaction between these buildings and the energy grid. This includes components that enable demand flexibility (building automation and control technologies, heating ventilation and air conditioning (HVAC) management systems, occupant-centric control (OCC) systems and elements that allow a closer building/grid integration and participation in market services (smart meters and energy resource management systems). The scope does not include grid management technologies, or hardware or software designed to facilitate energy management outside the building system. These technologies are covered in the grid energy management systems in Chapter 13.

In 2010, the Energy Performance of Buildings Directive (EPBD)([119]) introduced the concept of smart buildings to promote the integration of renewable sources, user interactivity, energy efficiency and adaptability and required Member States to implement intelligent metering systems and roll out at least 80% by 2020 for the case of electricity. According to the benchmarking report, in January 2018, 34% of all electricity metering points in the EU-28 were equipped with a smart meter (European Commission, 2020f). This number was expected to have reached 72% by 2020, based on the originally announced rollout. However, given the speed of deployment observed in 2017 (pre-pandemic), the estimations show a 43% penetration rate. The smart built environment indicator (SBEI), weighing 16 different indicators, including smart meter deployment and connectivity, shows that Nordic Member States and the Netherlands, were on the right track, while especially some Southern and Eastern Member States still had a long way to go (De Groote et al., 2017).

In the markets outside the EU, Canada had the highest reported smart meter penetration at over 82% by the end of 2018 (Wadhera et al., 2018). The US follow with 75% by the end of 2020 (Cooper and Shuster, 2021), and China with 69% by the end of 2019 (Nhede, 2021a), while the penetration rate in Australia had not exceeded 35% by September 2021 (AEMC, 2021).

In 2020, the global smart building market was worth EUR 50 billion ([120]) according to Fortune Business Insights, while the European market size was nearly EUR 3 billion (FBI, 2021). Focusing on home energy management systems, the global market is projected to grow from nearly EUR 4 billion in 2019 to more than EUR 10 billion in 2028 ([121]), while the smart meter market is estimated at EUR 19 billion in 2019 and projected to grow to EUR 32 billion in 2027 ([122]).

([113]) COM(2021) 802 final, 15th December 2021. 2021/0426 (COD).
([114]) Commission Implementing Regulation (EU) 2020/2156 of 14 October 2020 detailing the technical modalities for the effective implementation of an optional common Union scheme for rating the smart readiness of buildings OJ L 431, 21.12.2020, p. 25–29
([115]) Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (OJ L 328 21.12.2018, p. 82)
([116]) Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC (OJ L 315 14.11.2012, p. 1)
([117]) COM(2021) 558 final Brussels, 14.7.2021 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0558
([118]) Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (recast) (OJ L 285 31.10.2009, p. 10)
([119]) Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast) (OJ L 153 18.6.2010, p. 13)
([120]) Foreign currencies are converted to EUR based on the annual averages published by the European Central Bank
([121]) Forecasted values are converted to EUR based on Bloomberg forecasted rates. For values later that 2026, a fixed rate is assumed at EUR 1.21 per USD.
([122]) COM(2021) 950 final, Brussels 26.10.2021 https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021DC0950

The European Commission has launched a number of financing initiatives such as Smart Finance for Smart Buildings (SFSB) (European Commission, 2018), to support energy performance achievements. The need to leverage smart meter data to improve energy management is expected to increase revenue generation in global markets to EUR 6 billion by 2030 (Nhede, 2021b).

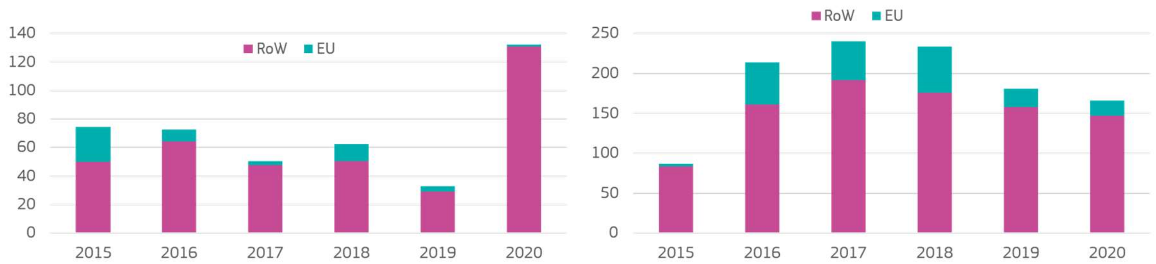
For a successful smart building assessment programme, it is important to adjust the assessment models by collecting and analysing data from numerous sources and types of organisations, so criteria remain valuable and relevant as technology evolves (Soncodi, 2021). According to recent studies (Capgemini Invent, 2020; Mir et al., 2021), today's state-of-the-art buildings are passively optimised. Therefore, it is essential to implement new, dynamic, active paradigms that effectively manage the variability and uncertainty of power consumption and renewable generation, for example, through the effective integration of storage systems and other low-carbon energy technologies. At the same time, it is crucial to increase the positive decarbonised energy balance of the building and layout efficient investments for grid connection. Moreover, significant efforts will have to be made to ensure the security and privacy of the smart building solutions, focusing on the cybersecurity of the IoT components. Within a broader scope, interoperability, scalability, and cost-effectiveness of the smart building solutions will need to be improved in order to facilitate their quick deployment on a large scale.

12.2 EU positioning in innovation

The total public R&D investment for 2017-2019 is EUR 67 million, with Canada and Austria being the top investors among the reporting countries, while some major economies, such as Germany, Italy, the US and South Korea not reporting. Around 46% of total investment during 2017-2019 was in the EU (EUR 31 million), with an increasing trend, while five Member States are among the top investors.

In terms of early and later stage investment globally (**Figure 54**), early stage investment dropped in 2017 and 2019. Nevertheless, the comeback was fast in 2020, with early stage investment quadrupling compared to the previous year. However, the EU did not follow this rebound trend and reached a new low in 2020. Later stage investment peaked in 2017 and 2018 and decreased in 2019 and 2020. The EU share is around 12% of early stage and just over 18% of later stage investment.

Figure 54: Early (left) and later (right) stage investment by region [EUR Million]



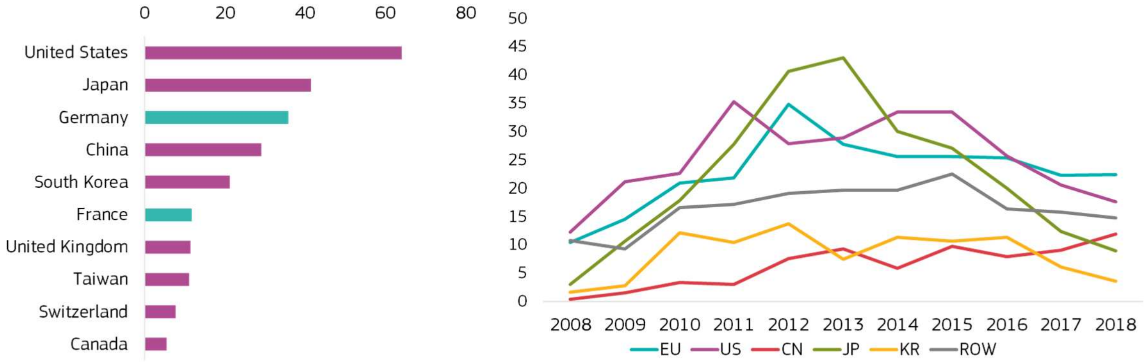
Source: JRC based on Pitchbook

The US is the top country in both early and later stage investment. Germany and France are the only EU Member States which feature in the early stage ranking – fourth and fifth place respectively – while four Member States feature in the later stage ranking, starting with Germany in fourth place. The EU has a higher share of the number of deals for early and later stage investments (24% and 25% respectively), which indicates that EU deals are lower in value than compared to the rest of the world.

The US and Japan hold most of the high-value inventions for 2016-2018, followed by Germany (**Figure 55**). Japan actively sought solutions for an efficient, resilient and sustainable energy system, after the Fukushima nuclear accident in 2011, and this effort is visible in its patenting activity. EU patenting activity does not show large fluctuations, while only two Member States, Germany and France, are among the top high-value patent holders. While patenting activity slows down in some major economies, the EU obtains the top position for 2018. Also, China's patenting activity has been steadily rising since 2008, which is when the Chinese Act on the Energy Efficiency of Civil Buildings ([123]) was first implemented. In 2016-2018, the EU held 26% of the

([123]) CHINA: Regulation No. 530 of 2008 on Energy Conservation in Civil Buildings https://policy.asiapacificenergy.org/node/54 global share in high-value inventions, slightly higher than the US, whose market attracted most of the high-value filings for the same period.

Figure 55: Top 10 countries in high-value inventions in 2016-2018 (left) and trend of high-value inventions for major economies (right)



Source: JRC based on PATSTAT

Japanese companies dominate patenting, with only two German companies in the top 10. It features mainly electronic orientation, such as the three leading companies: LG, Mitsubishi, and Siemens.

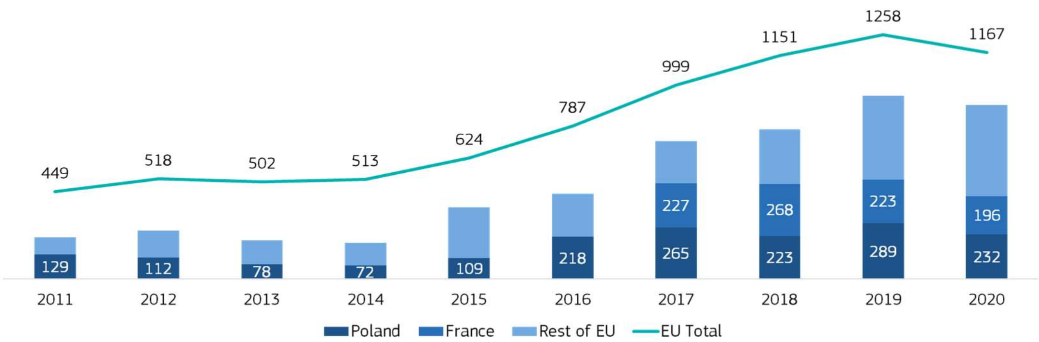
Buildings energy management systems (BEMS) is an emerging market, with more VC companies than corporates, except for Japan, China, Switzerland, Taiwan, and South Korea, where corporates dominate the market. The US hosts most of the innovating companies in the area, with approximately 3.5 times more than Japan. Only 26% of the world's innovators are headquartered in the EU, and more than half are VC companies.

There is considerable focus on advanced building automation, analytics, and integrated building management (both hardware and software). In Europe, some of the emerging themes concerning innovation include artificial intelligence heat management, energy efficiency as a service, and grid integration services.

12.3 EU positioning in current market

EU production has been steadily growing for the past ten years but dropped slightly in 2020, due to the pandemic. **Figure 56** shows that Poland and France together hold approximately 40% of EU production as the biggest producers. Nevertheless, significant amounts of EU production are not disclosed. Italy is the third biggest producer, holding around 12% of EU production during 2018-2020.

Figure 56: EU production value and top producers disclosing data among the Member States [EUR Million]



Source: JRC based on PRODCOM data

Extra-EU exports follow the same rising trend as EU production until 2020, when they drop by 23% compared to 2019. Extra-EU exports during 2018-2020 account for 9% of the global share. The UK is the top partner for the EU, importing more than twice as much as the United Arab Emirates from the EU. Meanwhile, extra-EU imports have an increasing trend. China and Tunisia are the top exporters to the EU. EU internal trade accounts for more than 70% of all EU imports. Italy is the biggest importer, with Romania and Poland as its biggest partners. The EU trade balance deficit was EUR 80 million in 2020.

12.4 Future outlook

The Digital Single Market Strategy intends to remove virtual borders, boost digital connectivity, and make it easier for consumers to access cross-border online content. ICT is expected to have an impact on buildings and households in the form of management systems, sensors, and appliances. The roll-out of smart metering systems ([124]) outlines the common minimum functional requirements that smart meters should present and includes recommendations on data protection and security considerations, along with the proposal for a methodology for the cost-benefit analysis that the Member States should perform for the roll-out of smart meters. The Strategy on Connectivity for a European Gigabit Society ([125]) sets out a vision of Europe where the availability and take-up of very high capacity networks enable the widespread use of products, services and applications in the Digital Single Market.

Distribution grid automation, home energy management systems (HEMS), smart meters, and smart charging are essential for the EU's ambitions in relation to buildings and mobility. These technologies are each expected to contribute around 8% of the estimated EU and UK investment in power distribution grids until 2050, and it is anticipated that markets for associated digital services will also continue to grow ([126]).

Moreover, smart building technologies set up new business opportunities for several sectors in the IT space, with some of the potential benefits for end users including the automation of mundane actions, the customisation of living spaces, a decrease in energy consumption and cost, and an increase in the security and safety of the home environment (Serrenho and Bertoldi, 2019).

Challenges identified by ICF include delays in transposing the rules, a lack of tools to incentivise the market without negatively affecting competitiveness, the presence of different market actors, and the need for interoperability (European Commission, 2020a). In addition, digital technologies depend strongly on multiple elements like copper, gallium, germanium, gold, indium, PGMs, rare earths, and tantalum (European Commission, 2020b). Europe's reliance on foreign digital components and assemblies is increasing as it falls behind on the production of key digital technologies (European Commission, 2020b).

12.5 Scoreboard and key insights

The current assessment shows that EU competitiveness is worrying in public R&D and imports & exports. The trade balance is negative but, before the pandemic, the trend was improving and had the potential to become positive. This may be linked to EU production, which is increasing; yet, it was negatively affected by the pandemic. The EU has an average share in early stage and a higher share in later stage investment. EU patenting activity is strong, indicating an existing potential for innovation.

Figure 57: Scoreboard for building energy management systems

Scoreboard	**Building Energy Management Systems**	EU performance in the reference period		
Public R&D		-2%	2015-2019	EU CAGR
Early Stage		12%	2015-2020	EU share of global total value
Later Stage		18%	2015-2020	EU share of global total value
Patents		26%	2016-2018	EU share of global total HVI
Companies		26%	2015-2020	EU share of innovating companies
Employment			2015-2020	EU CAGR
Production		13%	2015-2020	EU CAGR
Turnover			2015-2020	EU CAGR
Imports & Exports		9%	2018-2020	EU share of global exports
Trade Balance		Medium	2015-2020	EU trade balance trend

Source: JRC

([124]) Commission Recommendation of 9 March 2012 on preparations for the roll-out of smart metering systems OJ L 73, 13.3.2012, p. 9–22
([125]) COM(2016) 587 final Brussels, 14.9.2016 https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52016DC0587
([126]) COM(2021) 952 final https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2021:952:FIN

13 Grid energy management systems

The European Green Deal (COM(2019) 640) and the Recovery plan for Europe (COM(2020) 456) along with the Clean Energy for All Europeans package (COM(2016) 860) emphasise the importance of digitalisation in the next generation of grid systems. To reach zero-carbon emissions, more utility-scale and distributed renewable energy resources will have to interconnect with the grid. The intermittent generation will boost the use case for digital grid management technologies in European balancing markets. The deployment of smart grids is one of the three priority thematic areas under the Trans-European Networks for Energy regulation (TEN-E) (European Investment Bank, 2021), aiming to help integrate renewable energy, complete the European energy market and allow consumers to better regulate their energy consumption. The EU has implemented a priority list ([127]) for the development of harmonised network codes in order to achieve a fully integrated internal energy market.

13.1 Overview of the solution and current status

The scope of the grid energy management system (GEMS) solution covers techniques, processes, and equipment to manage power networks digitally. The focus is on the transmission, distribution, metering, communication and control of networks, and not on the power generation or type of energy source. Energy storage is also omitted here, since for example, the battery storage is assessed separately in Chapter 3. Key components include sensors, communication and power-conditioning equipment, automated switches and smart meters adapted for remote reading. However, this solution does not include smart appliances or smart meters for home users, inverters, demand response or grid edge technologies, or other on-building energy systems (e.g., plug loads) since many of those are already included in the building energy management system (BEMS), see Chapter 12.

The synchronous grid of Continental Europe, with the exception of Nordic and Baltic countries, is the largest synchronous electrical grid (by connected power) in the world. Electricity grids are commonly divided into transmission (high voltage) and distribution (medium and low voltage) networks. These networks, in turn, are managed and operated by transmission system operators (TSO) and distribution network operators (DSOs), respectively. European Distribution System Operators (E.DSO)([128]) gathers 42 members in 24 countries and promotes the development and large-scale testing of smart grid technologies in real-life situations, new market designs and regulation. The European Network of Transmission System Operators for Electricity (ENTSO-E)([129]) gathers 42 members and one observer member across 35 countries. ENTSO-E members facilitate one of the world's largest power markets, which maintains and develops 300 000 km of lines and serves half a billion customers. A 2018 report noted that 'to maintain the safety and reliability of future power systems with a high penetration rate of variable renewable energy', the technological scarcities for system operators fall into six categories: frequency control, voltage control, congestion management, system adequacy, rotor angle stability, and system restoration. The same report also suggested that scoping for 'real-time balancing markets' would require a fundamentally new market design (EU-SysFlex, 2018).

The distribution automation global market had an estimated value of EUR 11 billion ([130]) in 2020 and is expected to reach EUR 15 billion ([131]) by 2025 ([132]). A DNV study (2019) of almost 2 000 energy industry professionals revealed that only 52% of DSOs had digitalisation as a core part of their publicly stated strategy, while this fell to 39% for TSOs. The status of digitalisation is an important indicator of the overall status in smart systems, and, according to the International Digital Economy and Society Index (I-DESI), Denmark was the leading country, with an average score, across the four years of the study, of nearly 65 out of 100 (European Commission, 2020g). Iceland was the top non-EU country with an average of almost 64, while the US and Japan had around 60 and 51 respectively. However, the corresponding average for the EU was just above 47, placed only above China (nearly 38), which had the largest increase and is likely to outperform the EU in the next evaluation (European Commission, 2020g).

At company level, a BNEF report ranked Enel, EDF, and Iberdrola in the top tier of the largest publicly listed power utilities on their digital innovation capability. The same report noted that the power utility companies

([127]) Commission Implementing Decision (EU) 2020/1479 of 14 October 2020 establishing priority lists for the development of network codes and guidelines for electricity for the period from 2020 to 2023 and for gas in 2020 OJ L 338, 15.10.2020, p. 10–11

([128]) Link to the website: https://www.edsoforsmartgrids.eu/

([129]) Link to website: www.entsoe.eu

([130]) Foreign currencies are converted to EUR based on the annual averages published by the European Central Bank

([131]) Forecasted values are converted to EUR based on Bloomberg forecasted rates. For values later that 2026, a fixed rate is assumed at EUR 1.21 per USD.

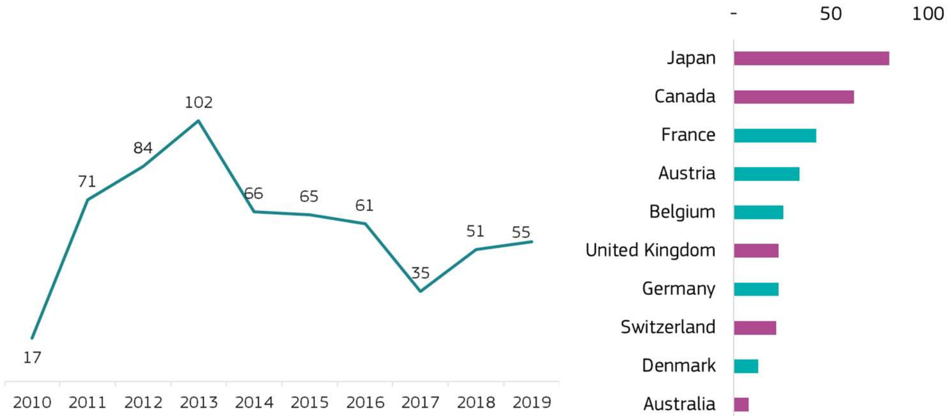
([132]) COM(2021) 952 final https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2021:952:FIN face the dual challenges of deregulation and decarbonisation. Both challenges would require utilities to invest in modernisation of the grid to support the integration of renewable and decentralised resources, while ensuring reliable power supply to end-consumers (BNEF, 2021i).

Grid operators and distributors employ electronics and electrical equipment. The overall pool of vendors is made up of traditional large original equipment manufacturers and some smaller companies that provide targeted services. Schneider Electric and Siemens are the primary EU-based vendors, while the global list includes GE, OSI, ABB, and ACS Power (European Commission, 2021a).

13.2 EU positioning in innovation

The EU holds around 40% of the total reported public R&D investment during 2017-2019 (EUR 141 million), with a decreasing trend (**Figure 58**). The total investment for 2017-2019 is EUR 341 million, with Japan and Canada being the top investors among the reporting countries. Historically, Japan was one of the first countries to invest in smart grid research and development, in the aftermath of the Great East Japan Earthquake in 2011 (NEDO, 2020). On the other side, Canada launched the Smart Grid Program in 2018, spanning 10 years (Natural Resources Canada, 2018). The US was the top investor until 2015, the year when the Smart Grid Investment Grant (SGIG) (SmartGrid.gov, 2009) under the American Recovery and Reinvestment Act came to an end (Recovery Act)([133]). The European Technology & Innovation Platform Smart Networks for Energy Transition (ETIP SNET)([134]) plays an important role in guiding R&D to support Europe's energy transition. Moreover, BRIDGE ([135]) is a European Commission initiative which unites Horizon 2020 Smart Grid, Energy Storage, Islands, and Digitalisation Projects to create a structured view of crosscutting issues encountered in the demonstration projects which may constitute an obstacle to innovation.

Figure 58: EU Member States public R&D investment (left) and top 10 IEA Members in 2017-2019 (right) [EUR Million]



Source: JRC based on IEA data

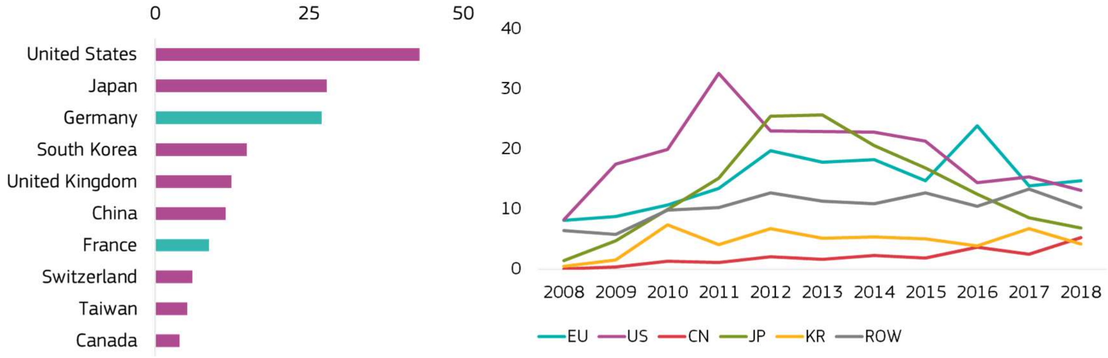
The EU share of both early and later stage investment is negligible, representing around 4% for both. The US and China are the leading countries in both early and later investment in 2015-2020. Only Germany and the Netherlands are amongst the top countries for early stage investment (seventh and tenth position, respectively), and only France, Portugal, and Sweden (fifth, ninth, and tenth position, respectively) are amongst the top countries for later stage investment.

In the US, the patenting activity related to climate mitigation through smart grids spiked in 2011 (**Figure 59Error! Reference source not found.**), two years after the launch of the SGIG programme. Yet, EU patenting activity spiked in 2016, a year after the framework strategy for a resilient Energy Union ([136]) was

([133]) H.R.1 - 111th Congress (2009-2010) American Recovery and Reinvestment Act of 2009 (2009, February 17) https://www.congress.gov/bill/111th-congress/house-bill/1/text
([134]) Link to the website: https://www.etip-snet.eu/
([135]) Link to the website: https://www.h2020-bridge.eu/
([136]) Opinion of the European Economic and Social Committee on the 'Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank on A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy' (COM(2015) 80 final) and the 'Communication from the Commission to the European Parliament and the Council on Achieving the 10 % electricity interconnection target — Making Europe's electricity grid fit for 2020' (COM(2015) 82 final) OJ C 383, 17.11.2015, p. 84–90

adopted. The top EU investors, Germany and France, are also the top EU holders of high-value inventions but are behind the US and Japan. The EU holds the biggest global share (26%) in high-value inventions together with the US. The US and the EU exchange the highest portion of their patenting flows, yet the US remains the most targeted market for high-value patent submissions.

Figure 59: Top 10 countries in high-value inventions in 2016-2018 (left) and trend of high-value inventions for major economies (right)



Source: JRC based on PATSTAT

During 2015-2020, corporates dominate the Grid EMS innovation landscape, except for in the UK, Sweden, and Australia, where VC companies have the biggest share. The US hosts most of the innovating companies, having about 2.5 times more than that of Japan or Germany. Nearly a third of all innovating companies are headquartered in the EU, and almost three quarters of them are corporates.

Distribution automation devices and smart metering have been employed for over a decade now; yet, there are still many promising research projects running, focusing on standardisation, interoperability, and cyber security ([137]). Mission Innovation members have identified the top R&D priorities in the field of smart grids and have agreed in six joint tasks: storage integration, demand response, regional electricity highways, flexibility options, new grid control architectures, and power electronics (Mission Innovation, 2019).

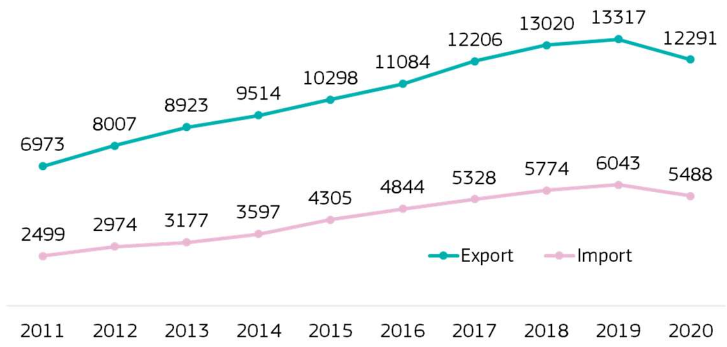
13.3 EU positioning in current market

The EU production of apparatuses for the smart control of electricity distribution, as part of the overall grid energy management system, has been slightly affected by the Covid-19 pandemic and the ongoing shortage in semiconductors. Over 2011-2020, EU production rose slowly but steadily. Germany holds roughly half of the total EU production in these smart apparatuses, approximately eight times more than France or Spain, the second and third largest producers in the EU. Czechia was among the top three producers in 2014-2018, yet, in 2019-2020, its production dropped almost by half.

Extra-EU imports and exports roughly doubled between 2011 and 2019, prior to the pandemic, which caused a drop of approximately 8% in extra-EU exports and 9% in extra-EU imports in 2020 (**Figure 60**). During 2018-2020, the EU exported to and imported from the same top-five partners: China, the US, the UK, and Switzerland, except for Russia, which is only among the top importers from the EU, and South Korea among the top exporters to the EU. The rate of change is approximately the same for both imports and exports.

([137]) COM(2021) 950 final, Brussels 26.10.2021 https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021DC0950

Figure 60: Extra-EU import and export trend [EUR Million]



Source: JRC based on COMEXT data

Extra-EU exports accounted for 28% of global exports for 2018-2020, while 68% of the imports were covered internally. Thus, the EU has a strong position globally. The US and China are the largest growing import markets, where the EU held 14% and 48% share of the total imports respectively. The EU exporters seem to be capturing Chinese growth but losing ground in the US market.

The EU trade balance surplus was about EUR 7 billion in 2020 and has a slightly rising trend. Spain in particular imports more than half (59%) from the other EU Member States. Romania is sending 84% of its exports internally. However, Germany, the biggest global exporter, mainly exports to non-EU partners (64%). Germany plays a central role in trading smart devices, as it is also the second biggest global importer and the top EU producer.

13.4 Future outlook

The take-up of smart grid technologies is expected to continue its robust rise in close correlation with electrification, decentralisation, grid reliability, and operating efficiency while increasing investments are required to upgrade ageing grid infrastructure ([138]). Growing renewable energy penetration may also help to drive the emergence of global service markets to resource optimisation via grid management systems (European Commission, 2021c). A 2021 study estimates that investments of EUR 375 to 425 billion will be needed until 2030 to make European distribution grids fit for purpose (Eurelectric, 2021). These investments will sustain 440-620 thousand quality and local jobs per year in the EU27 and UK (Eurelectric, 2021).

Some of the threats identified by prior assessment include the shift from a rate-of-return regulation, based on assets and revenues, to new value sources, such as high-tech and renewables, which disrupts the traditional business models (European Commission, 2020a). Another point is that the need for flexibility has already increased the costs for congestion management. Currently, policies do not fully support utility-side innovation since many regulatory regimes reward cost savings, whereas smartening the grid often produces other qualitative or softer benefits that cannot be easily rate-based. Moreover, cyber security and data ownership are critical for the functionality of the grid (European Commission, 2020a). In addition, digital technologies depend strongly on multiple elements like copper, gallium, germanium, gold, indium, PGMs, rare earths, and tantalum (European Commission, 2020b). Europe's reliance on foreign digital components and assemblies is increasing as it falls behind on the production of key digital technologies (European Commission, 2020b).

([138]) COM(2021) 950 final, Brussels 26.10.2021 https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021DC0950

13.5 Scoreboard and key insights

EU positioning in innovation raises concern, particularly in regards to public R&D and venture capital investment. In terms of patenting activity, with 29% of high-value filings, EU performance is strong. The EU is a host to a higher share of patenting corporates, at 31%, than VC companies, at 25%, therefore having average performance in innovating companies. Nevertheless, the EU hosts the biggest pool of patenting corporates, which suggests that EU has a strong potential for innovation. Trade-related indicators show that the EU still has a strong presence globally, with nearly a third of non-EU exports. While production grows slower than EU GDP, the EU seem to have a strong manufacturing base in this area, manifested by very strong and growing trade surplus.

Figure 61: Scoreboard for grid energy management systems

Scoreboard	**Grid Energy Management Systems**	EU performance in the reference period		
Public R&D	●	-4%	2015-2019	EU CAGR
Early Stage	●	4%	2015-2020	EU share of global total value
Later Stage	●	4%	2015-2020	EU share of global total value
Patents	●	29%	2016-2018	EU share of global total HVI
Companies	●	29%	2015-2020	EU share of innovating companies
Employment			2015-2020	EU CAGR
Production	●	2%	2015-2020	EU CAGR
Turnover			2015-2020	EU CAGR
Imports & Exports	●	28%	2018-2020	EU share of global exports
Trade Balance	●	High	2015-2020	EU trade balance trend

Source: JRC

14 Hydrogen production – electrolysers

Hydrogen has a key role to play in decarbonising the energy system, as is evident in the scenario analysis supporting the European Commission's long-term strategic vision. While it has a role in all scenarios, in the most prominent cases, it could cover 10%, or even 17% of final energy consumption in 2050 ([139]). The importance of hydrogen in achieving the decarbonisation agenda set out in the European Green Deal (COM(2019) 640)([140]) is reflected in the legislation and initiatives adopted and proposed since:

- The NextGenerationEU (COM(2020) 456)([141]) recovery package has built its priorities around the Green Deal. It includes clean hydrogen as one of the key technologies for the clean energy transition to receive investment through the Strategic Investment Facility.
- The EU strategy on Energy System Integration (COM(2020) 299)([142]) includes hydrogen as one of its four pillars, creating a link between electricity and gas grids and providing long-term energy storage.
- The European Hydrogen Strategy (COM(2020) 301)([143]), highlights the importance of hydrogen for sectors which are difficult to decarbonise through electrification, such as heavy transport and parts of the energy-intensive industries. It has set targets both for electrolysis (6 GW by 2024 and 40 GW by 2030) and renewable hydrogen produced (1 million tonnes and 10 million tonnes by 2024 and 2030, respectively). It also introduced a new Clean Hydrogen Partnership to help bring hydrogen technologies to market through research, demonstration and development.
- The European Clean Hydrogen Alliance, announced as part of the New Industrial Strategy for Europe (COM(2020) 102)([144]) Communication and launched in the context of the European Hydrogen Strategy (COM(2020) 301), has as a main objective to facilitate large-scale deployment of hydrogen technologies. It has prepared a pipeline proposed by industry to create a European hydrogen economy, to which 446 projects on hydrogen production were submitted.
- The Clean Hydrogen Partnership has been launched as the successor of the Fuel Cell and Hydrogen Joint Undertaking 2 (FCH 2 JU) under Horizon Europe ([145]), increasing the focus on hard to decarbonise sectors: industrial and energy system uses, maritime transport and aviation.
- The Strategic Forum for Important Projects of Common European Interest (IPCEI) has included hydrogen technologies and systems as one of the six key strategic value chains, prioritised on the basis of their potential for Europe's industrial competitiveness (European Commission, 2019a), which can receive support from Member States. 22 Member States and Norway have committed to launch such projects in the hydrogen sector ([146]) with the first wave of proposals submitted to the Commission in late 2021.
- The Fit-for-55 Communication (COM(2021) 550)([147]) includes proposals for the amendment of the Renewable Energy Directive to include targets of 2.6% for the consumption of renewable transport fuels of non-biological origin and a 50% share of renewable hydrogen consumption for industry. The revision of the EU Emissions Trading System (ETS) will include hydrogen production with electrolysers, making free allowances available to renewable and low-carbon operators. To ensure that the industries which need to adopt green hydrogen to decarbonise (e.g. steel, fertilisers and electricity) are not at a disadvantage by competition from countries that do not share the EU ambition towards decarbonisation,

([139]) European Commission, In-depth analysis in support of the Commission communications COM(2018) 773: A Clean Planet for all – A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy 10% of final energy consumption in 2050 in the 1.5-degree scenarios 1.5TECH and 1.5LIFE; 17% in the 2- degree H2 scenario

([140]) COM(2019) 640 The European Green Deal https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

([141]) COM(2020) 456 Europe's moment: Repair and Prepare for the Next Generation https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0456&from=EN

([142]) COM(2020) 299 Powering a climate-neutral economy: An EU Strategy for Energy System Integration https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2020:299:FIN

([143]) COM(2020) 301 A hydrogen strategy for a climate-neutral Europe https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

([144]) COM(2020) 102 A new industrial strategy for Europe https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0102&from=EN

([145]) COUNCIL REGULATION (EU) 2021/2085 establishing the Joint Undertakings under Horizon Europe and repealing Regulations (EC) No 219/2007, (EU) No 557/2014, (EU) No 558/2014, (EU) No 559/2014, (EU) No 560/2014, (EU) No 561/2014 and (EU) No 642/2014 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R2085&from=EN

([146]) Manifesto for the development of a European "Hydrogen Technologies and Systems" value chain, https://www.bmwi.de/Redaktion/DE/Downloads/M-O/manifesto-for-development-of-european-hydrogen-technologies-systems-value-chain.pdf?__blob=publicationFile&v=10

([147]) COM(2021) 550 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality https://ec.europa.eu/info/sites/default/files/chapeau_communication.pdf a Carbon Border Adjustment Mechanism (CBAM) will aim to level the price of carbon between EU production and imports.

The annual hydrogen demand in Europe is around 7.8 million tonnes (Fuel Cells and Hydrogen Observatory, 2021c)([148]). The global demand is estimated by the IEA (IEA, 2019a) to be over 70 million tonnes per year, used in pure form, and an additional 20 million tonnes used in industrial processes when mixed without separation from other gases. According to the same source, less than 1% is produced from renewable resources or from fossil fuel plants equipped with CCUS. Worldwide, 80% of hydrogen production comes from natural gas reforming and coal gasification, and just 0.03% from electrolysis (IEA, 2021c). The remainder is a by-product in industrial facilities. By 2020, there was nearly 300 MW of electrolyser capacity installed worldwide, 40% of which is located in Europe (IEA, 2021c). While capacity in Europe has been increasing rapidly, in 2019 electrolytic hydrogen only accounted for 0.14% of total production capacity. This indicates the scale of the challenge, while the policy initiatives listed above highlight areas of priority for action (demonstration, scaling up and integration in the energy system), the sectors that would benefit most (energy-intensive industry and heavy-duty transport), and where there could be an impact on competitiveness.

The focus of this chapter is on the production of green hydrogen through electrolysis, and the electrolysers used in the process. In short, the state of the art in the main electrolysis technologies is as follows (Davies, et al., 2021):

- Alkaline electrolysis is an established technology for low-temperature applications. Cost-effective projects of considerable (MW) size are available. The technology is stable over a long lifetime and does not use noble metal catalysts. It does, however, operate at lower current densities than other electrolysers and has limited load flexibility.
- Polymer exchange membrane electrolysers have the advantage of high current density and voltage efficiency that makes them more suited to dynamic operation and coupling with renewable electricity generation sources. Their drawback lies in the durability of the catalyst and membrane and in higher costs, associated with the use of platinum group metals.
- Solid oxide electrolysers still have challenges to overcome before deployment at large scale. These are related to the ability of materials to withstand the high temperatures at which the technology operates, as well as their criticality (rare-earth metals). The need to bring materials to temperature slowly also limits the flexibility of the technology.
- Anion exchange membrane electrolysers and protonic ceramic electrolysers could have technical advantages, but are at lower levels of technology development and cannot currently achieve the level of performance of the other technologies.

14.1 EU positioning in innovation

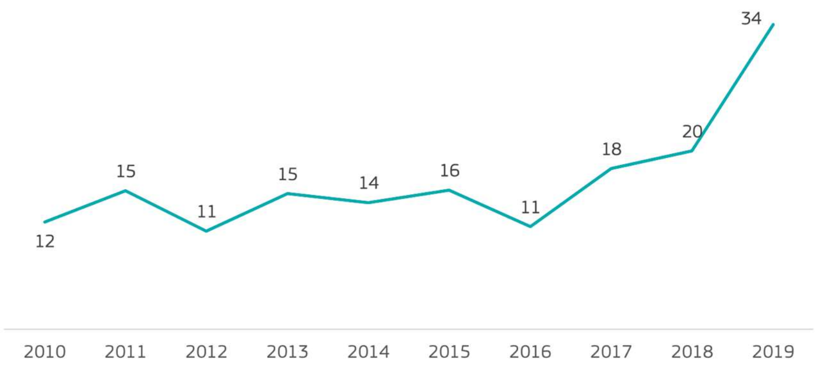
Public R&D investment in hydrogen production has been increasing in EU Member States (**Figure 62**). The data is not granular enough to draw insights on how much funding addresses electrolysis or green hydrogen production, so it is very likely that support for conventional technologies is included in this figure. Among the Member States that are IEA members, France accounts for nearly half of the EU investment. Czechia, Germany, Denmark, Austria and Belgium have also invested over EUR 2.5 million in hydrogen production R&D in the period 2017-2019 and are in the top 10 IEA members reporting R&D expenditure in this area. Combined with the 22% increase in the reported R&D investments from EU Member States between 2015 and 2019, this indicates a strong position for the EU, in terms of future technology development. In addition to the funding provided by national programmes, in the period 2008-2020 the EU, through the Fuel Cell Joint Undertaking, has dedicated over EUR 150 million to electrolyser technologies ([149]). Furthermore, the Horizon2020 Green Deal call has made EUR 92.4 million available to three projects that will develop and demonstrate large-scale electrolysers linking renewables and industrial applications (European Commission, 2020c).

However, the actual expenditure in hydrogen production technologies in general, and electrolysers in particular, both in the EU and in other major economies, is difficult to judge. Data tends to be reported under the ‘hydrogen’ heading, also including other hydrogen technologies or under the combined ‘hydrogen and fuel

([148]) 8.4 Mt MtH2/y including EU, UK, Norway, Switzerland and Iceland

([149]) Fuel Cell and Hydrogen JU, 2021, in SWD(2021) 307 final PART 4/5 Progress on competitiveness of clean energy technologies 6 & 7 - Batteries and Hydrogen Electrolysers cell' category. For example, since 2016, the US reports all related expenditure, an average of EUR 85 million per year, as 'unallocated' under the latter category. Similarly, for the same period, Japan has reported public investment averaging EUR 100 million per year in hydrogen R&D, but provided no further breakdown. For comparison, for the same period, the expenditure shown in **Figure 62** represents a third of the combined EU Member States' budgets for 'hydrogen' research as reported to the IEA. In addition, EU Horizon2020 funds have contributed another EUR 65 million per year. This confirms that, historically, the EU has had a strong position, and has kept pace in R&D investment with other global technology leaders in hydrogen technologies. The Clean Hydrogen Partnership (EUR 1 billion of EU funds for 2021-2027)([150]), combined with effort from the EU national programmes, will help maintain the EU's position. For reference, selected active hydrogen programmes from Japan and the US are of the order of EUR 0.6 billion and EUR 0.3 billion per year, while, in 2019 alone, China reported R&D investment of over EUR 0.5 billion (IEA, 2021d).

Figure 62: EU Member States public R&D investment in hydrogen production [EUR million]



Source: JRC based on IEA data

Going forward, on the hydrogen production side, and electrolysis in particular, the Hydrogen Strategy (COM(2020) 301)([151]) emphasises the need for research and innovation to develop larger, more efficient and cost-effective electrolysers, and new materials, while scaling up manufacturing capabilities. Additional R&I efforts are also needed in: distribution, storage and dispensing infrastructure; large-scale industrial and transport end-use applications; improved and harmonised (safety) standards; critical raw materials; and environmental impacts. The EU Hydrogen Public Funding Compass ([152]) is an online guide of public funding sources for renewable and low-carbon hydrogen projects. It provides information on funding opportunities by type of stakeholder, type of funding, and project life-cycle stage, on both EU and national programmes, to support the development of a European hydrogen value chain.

The sustained support to R&I from public funds, along with the historical importance of hydrogen production for the EU chemical industry, has created an active community of innovators in the area of electrolysers. EU patenting output in electrolysers, as part of climate change mitigation technologies ([153]), is high, putting the EU in a leading position, along with Japan, among the major economies (**Figure 63**). At country level, Germany is the best performing MS, mainly through the activity of Siemens, which was also at the top of the world ranking for high-value inventions in the period 2016-2018. Haldor Topsoe and Hymeth, both headquartered in Denmark, and Bosch (Germany) also featured in the top 10 for the same period. EU activity is spread across a number of inventors and less concentrated than that of Japan, which has a number of multinationals with a high performance in the top 10 (Toshiba, Honda Motor Co, Asahi, Panasonic, Fujitsu). Japanese companies protect their inventions worldwide, accounting for more than half of the inventions protected in the EU and US in the period 2016-2018. Given this very strong performance from domestic companies, very few international inventions from other countries seek protection in Japan. EU high-value inventions are predominantly protected in China (23%), the US (29%) and other jurisdictions outside the major economies (38%). In China, patent filings in electrolysers have been increasing exponentially. However, as with

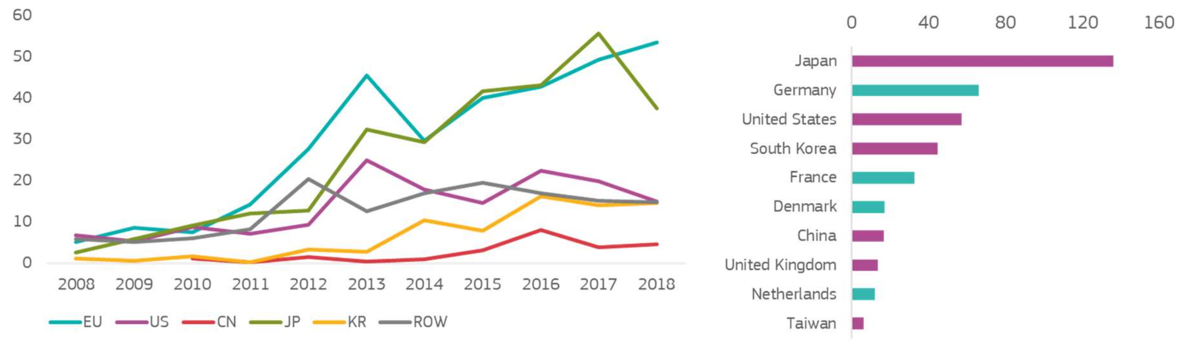
([150]) COUNCIL REGULATION (EU) 2021/2085 establishing the Joint Undertakings under Horizon Europe and repealing Regulations (EC) No 219/2007, (EU) No 557/2014, (EU) No 558/2014, (EU) No 559/2014, (EU) No 560/2014, (EU)

([151]) COM(2020) 301 A hydrogen strategy for a climate-neutral Europe https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

([152]) Website available at: https://ec.europa.eu/growth/industry/strategy/hydrogen/funding-guide_en

([153]) Compared to the previous study, fewer codes are included, focusing on inventions on electrolysis as a climate change mitigation technology increased patenting activity in China in other technological areas, these filings are restricted to the domestic market and do not seek international protection.

Figure 63: Trend in high-value inventions for the major economies (left) and top 10 countries in high-value inventions in 2016-2018 (right)



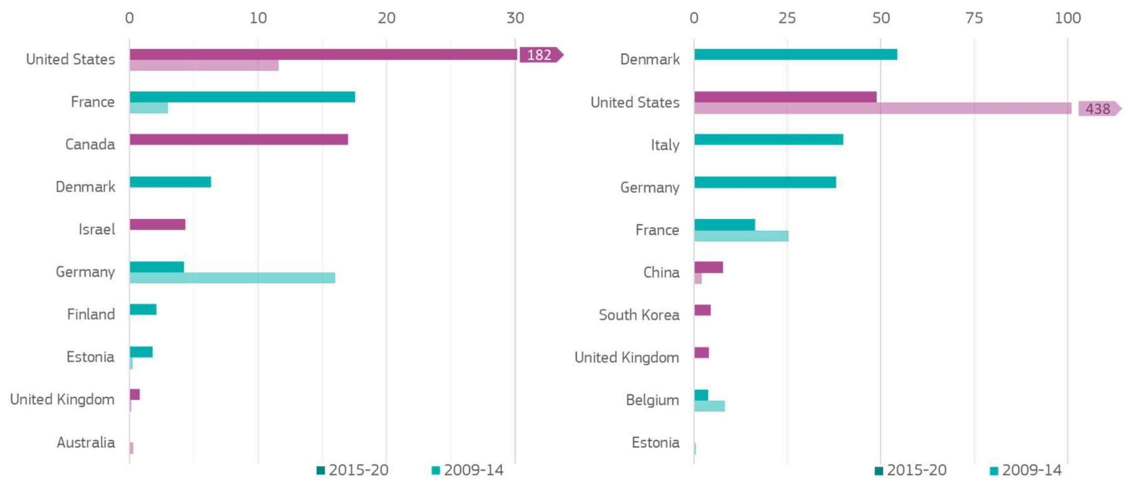
Source: JRC based on EPO Patstat

Beyond the top companies mentioned previously, Japan has a very strong base of corporate innovators in general, and a market that does not seem approachable to foreign technology or investment. In contrast, in the US and increasingly in the EU, a significant amount of investment for innovators and start-ups is in the form of venture capital.

The EU accounted for a quarter of the number and 14% of the disclosed value of early stage transactions in the period 2015-2020, amounting to over EUR 32 million, two thirds of which were invested in the last two years. Even more impressively, the EU accounted for nearly half of the transactions and 70% of global disclosed later stage investment in the same period. This amounted to EUR 152 million, over a third of which was invested in 2020. Companies located in France, Denmark and Germany attracted the majority of early stage investment in the EU. Denmark, Italy, Germany and France hosted the recipients of most later stage investments. In the same period, Denmark attracted more later stage investment than the United States, with Italy and Germany not far behind – a notable performance, considering the strength of venture capital investment in the United States (**Figure 64**).

Japan leads in terms of hosting innovating companies, due to a high number of innovating corporates. The United States follow closely, with start-ups accounting for more than half of the companies identified. Germany and France follow, the first with a very strong corporate innovator base, the second with an almost equal split between corporates and start-ups. Overall, the EU hosts around 30% of the innovating companies identified globally, both in terms of corporates and in terms of start-ups. This is above the EU average in Climate Tech but below the top performers.

Figure 64: Top countries in early (left) and later (right) stage investment in 2015-2020 [EUR Million]

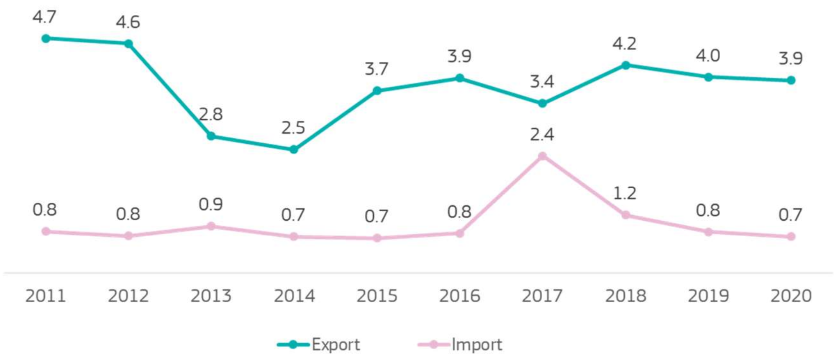


Source: JRC based on Pitchbook

14.2 EU positioning in current market

The available trade data does not differentiate between green hydrogen and hydrogen produced by conventional methods based on fossil fuels. It provides an overview of EU positioning in the current hydrogen market as an indication of the starting point and scale of opportunity in transitioning to green hydrogen. Although production has declined by an average 3% per year since 2015, the EU trade balance for hydrogen remains positive. EU production covers the majority of EU market needs. Only 2% of member state hydrogen imports originate outside the EU. In addition, the EU accounts for 6% of global hydrogen exports. Canada is a major exporter of hydrogen, while the US is the largest importer. This is a growing market, with a number of international trade projects announced in the course of 2020 and 2021, but still estimated to fall short of what is needed to fulfil net zero emission scenarios (IEA, 2021c).

Figure 65: Extra-EU import and export of hydrogen [EUR million]



Source: JRC based on COMEXT data

Though we cannot track trade in electrolysers, half of the manufacturers of large-scale electrolysers are located in the EU (Buttler & Spliethoff, 2018)([154]), predominantly in Germany and France, but also Denmark, Italy and Spain. This provides the EU with a good industrial basis to take advantage of future market opportunities.

Similarly, while current production of green hydrogen is very low, and there is no data available on current employment and turnover, there are a number of studies on the potential future job creation from investments in the green hydrogen value chain. These are summarised in the outlook section below.

14.3 Future outlook

BloombergNEF (BNEF, 2021j; BNEF, 2022) estimated electrolyser shipments of at least 1.8 GW in 2022, with China accounting for over 60% of global installations. The major actors in China would be state owned enterprises (Sinopec, Petro China). Plug Power Inc is the main installer in the US, while the EU market includes many suppliers (Nel ASA, ITM Power Plc). However, BloombergNEF also estimate that the electrolyser manufacturing capacity scheduled to come online is much greater than that needed to cover hydrogen demand, which may affect prices. As clean hydrogen projects for industry are set to increase significantly in 2022, there is less concern in recent outlooks about the gap between planned electrolyser capacity and clean hydrogen demand.

Member States have also formulated national and regional hydrogen strategies, in parallel to the European Hydrogen Strategy. A study analysing the role of hydrogen in National Energy and Climate Plans (NECPs) (FCH 2 JU, 2020) developed two (high and low) scenarios of hydrogen demand in 2030 (42 and 183 TWh/a respectively([155])), based on the level of ambition in each Member State. To cover the hydrogen demand estimated in the two scenarios, 13 and 56 GW of electrolyser capacity will have to be installed, respectively ([156]). The scenarios examined could also create between 104 000 and 357 000 jobs in the construction and operation of hydrogen technologies, spread out across a number of sectors. The majority of job creation was

([154]) In: SWD(2021) 307 final PART 4/5 Progress on competitiveness of clean energy technologies 6 & 7 - Batteries and Hydrogen Electrolysers

([155]) for EU28.

([156]) assuming an average annual utilisation rate of 4 800 full load hours.

associated with the increased need for renewable electricity; around 5% (5 000 – 18 000 jobs) was linked to the electrolyser segment of the value chain.

Another estimate of employment impacts from investments in the EU green hydrogen value chain estimates that 3 000 to 3 800 jobs could be created per EUR 1 billion invested per year between 2030 and 2050 in hydrogen production. Two thirds would be direct jobs, while half of the estimated jobs would be in the machinery and equipment sector (European Commission, 2020d). The market potential for electrolysers (including balance of plant) in particular is estimated at EUR 45-55 billion by 2050 (IRENA, 2022)([157]). While the EU, along with China and Japan, is at the forefront of electrolyser production, China in particular seems to be moving much faster in reducing costs and increasing shipments, but also in realising bigger project installations. The lower production costs and more established supply chain have also enticed foreign brands to build factories and set up joint ventures in China for the production of electrolysers (BNEF, 2022). China has great potential for both renewable electricity generation and the largest hydrogen demand globally. While it may manage, eventually, to cover its own demand for renewable hydrogen, it is unlikely to become an exporter in this commodity (Nakano, 2022). Nonetheless, in a parallel to the solar PV industry, the drive to produce and install electrolysers to cover the needs for its vast internal market may just provide enough momentum to dominate exports in the technology too, and thus threaten EU prospects.

There are also material and supply constraints to consider. Out of 30 core raw materials needed for the production of fuel cells, electrolysers and hydrogen storage technologies, 13 are on the 2020 Critical Raw Materials (CRM) list (European Commission, 2020b). PEM electrolysers, for instance, require the use of noble metal catalysts like iridium and platinum for the cathode, both of which are mainly sourced from South Africa (84% of EU supply). The markets for these materials are rather inelastic to short-term disruptions, which can lead to price spikes and affect costs throughout the value chain (IRENA, 2022)([158]). Beyond the production of electrolysers, scaling up production of renewable hydrogen from electrolysis will require the availability of renewable electricity at scale (and competitive cost). Any material or value chain constraints affecting technologies such as wind and solar PV (Magagna, et al., 2017) will also have an indirect effect on renewable hydrogen production.

14.4 Scoreboard and key insights

As one of the main pathways for decarbonisation, the renewable hydrogen production and electrolysers sector has a high potential for growth and is attracting increasing amounts of venture capital investment. The EU appears strong on innovation aspects, performing well in terms of public R&D investment, patenting output and later stage investment. It is also not far from transitioning from a medium performance to a good one, in terms of capturing early stage investment and hosting innovating companies. In addition to a strong research and innovation base and performance, the EU has a number of policy initiatives in place, and a well-established community of stakeholders and instruments to facilitate exchange, collaboration and access to dedicated funding.

The EU production of fossil-fuel-based hydrogen covers its own market needs, and sustains a positive trade balance. Nonetheless, production has been declining slightly, and the EU is only capturing a small share of the global market, compared to the size of its economy.

There is no information on EU performance in the emerging green hydrogen market. The EU is host to a considerable share of global electrolyser capacity and currently well placed in terms of electrolyser production. However, it could face competition from other major economies, and particularly, from the deployment drive and cost reductions in China. Other issues to address include ensuring demand for green hydrogen, dependence on (critical) raw material imports, and thus supply disruption and price volatility.

Figure 66 shows a summary scoreboard for the solution.

([157]) USD 50-60 billion.
([158]) USD 50-60 billion.

Figure 66: Scoreboard for hydrogen production – electrolysis

Scoreboard	**Hydrogen Production - Electrolysis**	EU performance in the reference period		
Public R&D		22%	2015-2019	EU CAGR
Early Stage		14%	2015-2020	EU share of global total value
Later Stage		70%	2015-2020	EU share of global total value
Patents		33%	2016-2018	EU share of global total HVI
Companies		30%	2015-2020	EU share of innovating companies
Employment			2015-2020	EU CAGR
Production		-3%	2015-2020	EU CAGR
Turnover			2015-2020	EU CAGR
Imports & Exports		6%	2018-2020	EU share of global exports
Trade Balance		High	2015-2020	EU trade balance trend

Source: JRC

15 Hydropower and pumped storage

Traditional hydropower is a renewable energy source that converts water power into mechanical power by means of a rotating turbine, and finally into electricity through an electric generator. Water power can be in the form of potential power (pressure and weight) and kinetic power (the water flow velocity), and flows from higher altitudes to lower altitudes. Pumped storage hydropower (PSH ([159])) plants work the other way round. The power is transferred from the turbine, fed by an electric generator, to the water (by increasing its pressure and/or velocity) for storing it at a higher altitude. This energy-consuming process is used to compensate the surplus of energy available in the electric grid during the low-energy demand periods (e.g. during the night), while during peak demand periods (or over the more remunerative daily timeframes) PSH plants work as traditional hydropower plants (HPs) to satisfy the energy demand. Therefore, PSH plays an important role in providing flexibility to the energy grid.

The hydropower sector is complex and includes complete electromechanical equipment (e.g., turbine, generator, gearbox, distributor, draft tube and casing), the civil structures (e.g., dam, penstocks and canals), plus the Operation and Maintenance (O&M) equipment to monitor the status of the components, the hydrological and environmental conditions (e.g., water levels, flow rates, electric load and seepage from the dam). The hydroturbine is a component of the electromechanical equipment (EME). When considering a big hydropower plant or a plant built from scratch, EME cost is generally 30% of the total costs (Singal, et al., 2010; Van Vuuren, et al., 2011). As a consequence, a significant proportion of investment in the hydropower sector refers to the civil works and associated consultancy services that are very difficult to track. Therefore, it is expected that the indicators where only the hydroturbine is considered, e.g., production, imports and export, are underestimated.

15.1 Overview of the solution and current status

With a view to achieving climate neutrality by 2050, renewable energy – including hydropower – plays a central role in the decarbonisation sector. In 2020, hydropower supplied one sixth of global electricity generation, the third largest source after coal and natural gas. Installed hydropower capacity reached 1 330 GW in 2020 (International Hydropower Association (IHA), 2021), including 158 GW of pumped hydropower storage (PSH), and 16 GW of large hydropower (>10 MW per plant) which was added in 2019 (International Hydropower Association (IHA), 2021). Hydropower also provides 509 MW off-grid hydro electrification services, representing 8% of the currently installed distributed electrification capacity, mainly in Africa (32%), South America (30%) and Asia (25%) (Kougias, 2019). Hydropower capacity is led by East Asia, where the global leader is China, with an installed hydropower capacity of 341 GW, 29 GW of which is PSH. However, a relative comparison shows that the installed GW per inhabitant is 0.35 kW/people in the EU, 0.35 kW/people in North America and 0.24 kW/people in China, demonstrating that the EU is a strategic developer of hydropower.

However, several challenges hamper large hydropower deployment, and it is not easy to secure the investments necessary to ensure the proper operation of ageing assets that are crucial for electricity security. Hydropower projects have longer pre-development, construction and operational timelines than other renewable energy technologies, hence investment risks are higher, requiring specific policy instruments and incentives as well as a longer-term policy perspective and vision (IEA, 2021e).

In order to respond to the increasing need for flexibility of operation, hydropower electromechanical equipment needs to reach higher levels of digitalisation, which is not a trivial exercise as wireless communication possibilities are limited within dam constructions. This is also required to optimise operation, facilitate O&M, reduce costs, and increase resilience against physical and cyber threats. Existing hydro facilities were, in many cases, built decades ago. It will be a challenge to incorporate up-to-date IT advancements in existing and operating stations that currently use obsolete systems. Operational decision-making, integrating lifetime and maintenance planning in liberalised power markets, is also an important challenge for existing plants in particular (Quaranta, et al., 2021; European Commission, 2020). Another important barrier to large-scale deployment is the difficulty of simultaneously pursuing renewable energy, climate, and environmental goals.

([159]) Mixed PSH are connected to a natural inflow when generating power (thus they are connected to rivers), while closed loop hydropower are closed system, not connected to a natural water inflow.

Box 4: Sustainability conundrum of hydropower

The hydropower sector is the focus of major debate, especially in the EU: on the one hand, hydropower contributes to renewable energy targets (e.g. EU National Energy and Climate Plans ([160])), to integrate variable renewable energy (wind and solar) into the electricity grid and to mitigate climate change; on the other hand, it seems to contradict the Water Framework Directive, which is designed to preserve the good ecological status of water bodies.

As a low-carbon energy technology with no direct emissions, hydropower contributes to energy targets and climate change mitigation. Its advantages include the reliability of supply, very high conversion factors (efficiency) and flexibility. Therefore, it can adjust its generation to balance short-term variations in the intra-day market, and support security of supply for seasonal variations. It also supports frequency regulation. Because of this, although its share of total generation remained stable over the last decade in the EU due to the growth of wind, solar PV, coal and natural gas, hydropower flexibility is critical for integrating rising levels of wind and solar PV into electricity systems (IEA, 2021e). Multipurpose reservoir plants can have important additional functions for society, often more important than hydropower generation per se: irrigation and drinking water provision, flood risk management, river navigation and recreation. However, hydropower can be responsible (or in the case of multipurpose installations, co-responsible) for ecosystem deterioration, especially when barriers obstruct the natural river flow with ecological, hydrological and morphological consequences. Hydroelectric reservoirs can be responsible for methane and carbon emissions due to the decomposition of vegetation (Lu, et al., 2020). Strict standards and associated legislation were therefore put in place in the EU to protect ecosystems and the environment, meaning that new hydropower development has, since 2000, had to fulfil higher sustainability requirements.

It is clear that hydropower needs to achieve a good balance between the different policies, i.e. the need for flexible and renewable energy, multi-services, and not harming the environment. Without major policy change, global hydropower expansion is expected to slow down this decade, due to several barriers that are hampering the faster deployment of hydropower (IEA, 2021e). Indeed, after a total capacity increase of 70% over the last 20 years, hydropower capacity is expected to rise by only another 17% before 2030. Therefore efforts have been made to stimulate significant R&D investment and novel technologies to solve the debate (Kougias, et al., 2019; Quaranta, et al., 2021; Quaranta, et al., 2020; Quaranta & Davies, 2021; IEA, 2021e), with a focus on the following main topics:

1) Flexibility to compensate for the highly variable generation of wind and solar plants and to provide ancillary services, at both daily and at seasonal scale, working efficiently under off-design conditions. PSH plants are essential to provide and consume energy on demand.

2) Electrification of rural areas, stimulating small-scale hydropower by the powering of existing hydraulic structures and small barriers, already in place for other purposes.

3) Minimisation of impacts generated by HPs and the need to be environmentally friendly.

4) Novel construction techniques and materials, to reduce costs and increase lifespan.

5) Modernisation of the existing and aged hydropower fleet with novel technologies.

In the last decade, the annual energy generation from hydropower in the EU has oscillated between 335 and 400 TWh/y depending on the hydrological conditions. The average value was 360 TWh/year (Kougias, 2019), with an installed power of 155 GW in EU27+UK (151 GW in EU27), subdivided among Run-of-River HP (RoR), PHS and hydropower plants with a storage capacity (SPP). PSHs produced 32 TWh (therefore, on average, 328 TWh/y are from traditional hydropower, i.e. generating electricity from natural inflows) with a global efficiency of the global closed cycle of 71% (energy generated/adsorbed electricity for pumping). When considering the 2019 data, 40 TWh/y are generated by PHS, out of which 56% (23 TWh/y) are mixed PHS (of which 43%, 10 TWh/y, are used for pumping) and 44% are from closed loop PHS (Quaranta, et al., 2021). This is – on average – 13% of the EU's total net electricity production and represents one third of the annual renewable electricity generation. In recent years the highest EU generation was recorded in 2014 at 387 TWh (SWD(2020) 953 final). In 2015-2019, capacity additions in the EU were mainly concentrated in Portugal, Austria, Italy, and France. This includes some large-scale PHS stations such as the Frades-II (780 MW) and the Foz Tua (270 MW) in Portugal and the Obervermuntwerk-II (360 MW) in Austria. Additions also refer to

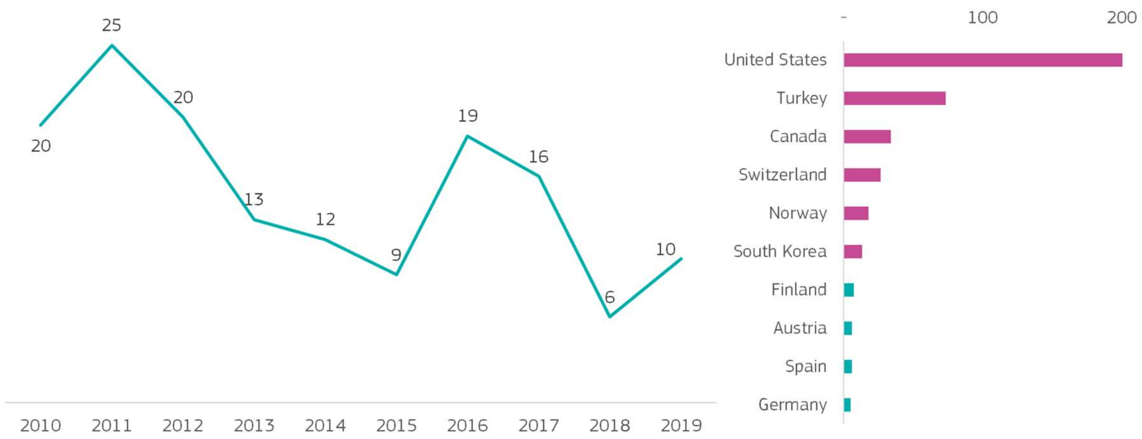
([160]) EU countries established 10-year integrated national energy and climate plans (NECPs) in 2019 for the period from 2021 to 2030, under the Regulation on the governance of the energy union and climate action (EU/2018/1999).

rehabilitation and upgrades of existing stations such as La Bâthie, La Coche, and Romanche-Gavet in France. The European energy sector is a market leader of small hydropower technology (Wagner, et al., 2019) and several leading hydropower companies are based in the EU (see the following sections below).

15.2 EU positioning in innovation

Despite hydropower's technological maturity, research efforts are still ongoing and new concepts are emerging, as discussed in section 1.1, to address environmental requirements and the energy targets related to renewable energy and climate change. In the last decade (2010-2020), public spending for R&D in the EU ranged between EUR 5 million and EUR 25 million per year (**Figure 67**), with a decreasing trend. The global reducing trend may be down to the progressive depletion of optimal sites for HPs. The main hubs of public spending from 2017 are Austria, Germany, Finland and Spain. Funding is somewhat stable in Germany, France and Sweden, but in most Member States the annual public spending on hydropower R&D is irregular and dominated by targeted actions, short-term national policies and specific EU calls. Comparing with variable renewable energy sources, public spending on hydropower is significantly lower. This is because renewable energy policy in the past two decades has focused primarily on driving the costs down of less mature wind and solar PV. At EUR 10 million per year, the average EU public spending in 2017-2019 is slightly lower than in Canada (EUR 18 million). Corporate R&D is generally the main driver of technological advances in hydropower in the EU (EUR 138 million in 2015) (EurObserv'ER, 2019).

Figure 67: EU Member States public R&D investment (left) and top 10 IEA Members in 2017-2019 (right) [EUR Million]

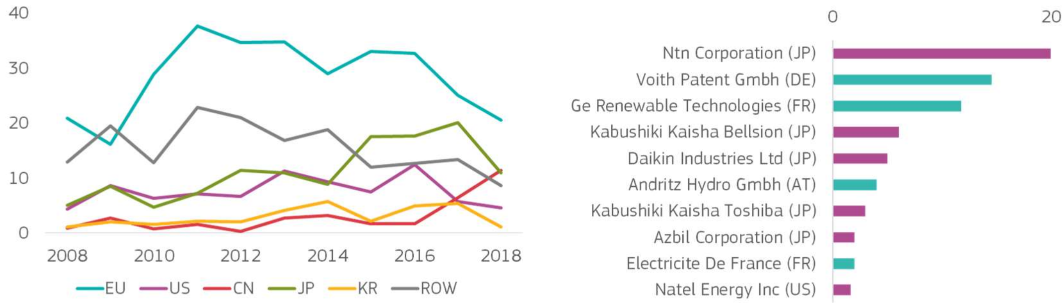


Source: JRC based on IEA data

The EU attracts 24% of global early stage venture capital investment, and 7% of later stage investment. The US and China capture most of the venture capital investment.

The EU is the leading economy in terms of the number of patents (**Figure 68**, left), and the trend has been reasonably stable over the years. The EU holds 36% of all high-value inventions globally (2016-2018). Germany, France, Austria and Italy are the biggest contributors, all of them in the Alpine environment, where the main innovative hydropower companies are located (**Figure 68**, right). These companies are often involved in EU-funded hydropower research projects, e.g. Fithydro (aiming to make hydropower more sustainable and fish-friendly) and X-Flex Hydro (to make hydropower more flexible).

Figure 68: Trend of high-value inventions for major economies (left) and top 10 companies in 2016-2018 (right)



Source: JRC based on EPO Patstat

15.3 EU positioning in current market

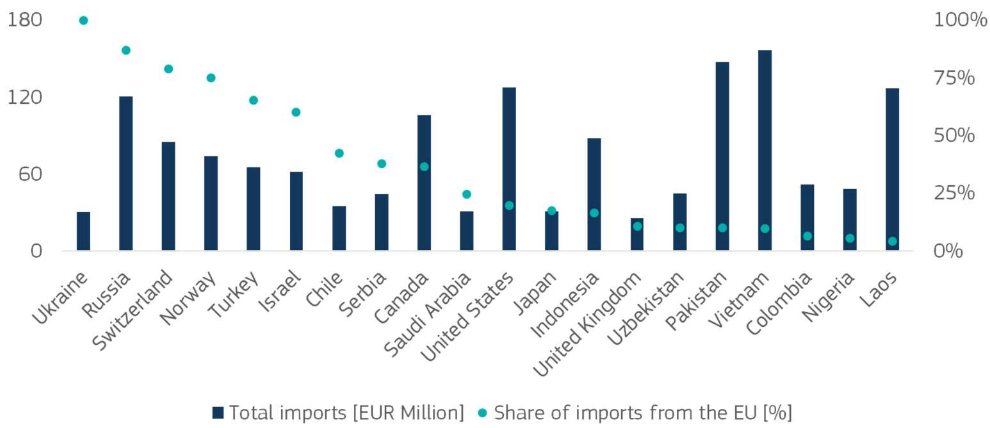
Globally, hydropower provides direct employment to 2 million people, representing almost 20% of total direct jobs in the renewable energy sector. In the EU, the number of direct and indirect jobs in hydropower is estimated to have totalled 36 000 ([161]) in 2020, with Italy and France, located at the heart of the Alps, topping the list. EU hydropower employment decreased in 2020 with respect to 2015, probably due to the reduction of feed-in tariff in some countries. The installed power under construction also reduced in 2020 with respect to 2015, in agreement with the employment figures.

The annual turnover of hydropower electricity generation in the EU was nearly EUR 5 billion in 2020, with a decreasing trend. Leading Member State in terms of turnover was Italy with nearly EUR 2 billion.

Despite its relatively low share in the global employment market (4%), the EU industry holds an important share in global exports ([162]). Global exports accounted for over EUR 1 billion over the period 2018-2020. The EU held 47% of all global exports and 40% if intra-EU trade is excluded. The major share of global exports by the EU is due to the big EU hydro companies (see previous Section 15.2). The biggest exporter is China, with a 23% share, followed by Austria (14%), Italy (8%) and Germany (6%). The remaining exports are mainly generated by India and Brazil. EU imports accounted for EUR 420 million from 2018 to 2020. However, 75% of that was intra-EU trade.

The EU has a significant presence in Russia, Switzerland, Norway, Canada and Chile, supplying 87%, 79%, 75%, 37% and 43% of all imports, respectively, making the EU the world leader in hydropower technology (included pumped hydro) (Gérard et al., 2021). Vietnam and Pakistan are the biggest import markets globally; however, the EU has only a 10% market share there in the hydropower sector (**Figure 69**).

Figure 69: Top 20 non-EU importers in 2018-2020



Source: JRC based on UN Comtrade data

([161]) EurObserv'ER allocates employment and turnover figures to the year of project commissioning. Therefore, as hydropower projects are typically big and lengthy, the figures can fluctuate significantly between the years.

([162]) The main categories of goods associated with hydropower technology are: "hydraulic turbines and water wheels" (28112200) and "parts for hydraulic turbines and water wheels" (28113200).

The EU's trade balance has been positive over the period 2011-2020. However, trade surplus has decreased since its peak at EUR 466 million in 2015 to EUR 233 million in 2020. Austria, Italy and Czechia have the biggest trade surpluses.

15.4 Future outlook

Global cumulative hydropower capacity is expected to expand from about 1330 GW in 2020 to just over 1555 GW by 2030. The EU28 long-term strategy modelling exercise provides future projections of hydropower development grouped together with wave, tidal, and biomass power. Projections indicate small additions and average hydroelectricity generation of 375 TWh/year. The dedicated projections for PSH show higher deployment rates and 4 GW of new PSH until 2030 (total 51 GW). The anticipated 2030-2050 PSH growth varies between scenarios from 8 GW (Baseline) to 19 GW (SWD(2020)953 final ([163])).

In Quaranta et al. (2021) it is estimated that the annual generation from existing HPs can be increased by approximately 8%, implementing hydropower digitalisation, modern electromechanical equipment and new waterways at existing hydropower plants. Additional strategies to increase generation from the modernisation of aged plants include floating PV (the potential is as high as 730 GW by covering 14% of the European hydropower reservoirs) ([164]), dam heightening (useful especially to increase storage capacity), reservoir interconnection and additional waterways for improved satisfaction of peak energy demand. Hydropower potential can be increased by installing micro-HPs in existing infrastructures (Punys, et al., 2019; Quaranta, et al., 2022), e.g. in water distribution networks (aqueducts), in existing low head barriers (e.g. water wheels in water mills) and in wastewater treatment plants, and installing hydrokinetic turbines in high flow velocity contexts (e.g. at the tailrace of HPs). Although the technical potential from these technologies is limited to approximately 10 TW/h at EU scale, these plants can increase market trade, enable electrification of rural areas, support industrial development, allow for self-consumption (e.g. during the treatment process in wastewater plants, (Llácer-Iglesias, et al., 2021)) and facilitate smart grid generation.

The European energy sector is a market leader in small hydropower technology (Wagner, et al., 2019). European players are well placed to capture growing markets in the EU and abroad. The main hubs of hydropower activity are in France, Germany and Italy, but also certain other countries such as Austria, Spain, Sweden and Czechia host a significant number of companies (Hydropower & Dams, 2020). The majority of EU-based companies are commercial companies (85%). These companies are active in the design, manufacture and supply of hydropower equipment, including automation and control systems. They are also active in consultancy, R&D, and the construction of civil works. A smaller number of companies are national (≈10%) and international (≈5%) organisations active in hydropower (SWD(2020) 953 final).

In recent years, China has been the leading hydropower turbine market, followed by India, Brazil and Ethiopia. Between 2013 and 2017, Dongfang Electric and Harbin Electric (both from China) sold approximately 40 GW of capacity in China. The penetration of EU-based companies in the Chinese market over the same period was significant, with Voith Hydro providing 12 GW, GE 11 GW, and Andritz nearly 1 GW of capacity. EU-based companies secured 35% of the total capacity orders in China over the analysed period. Outside China, the three EU-based companies delivered 74% of the total orders in terms of capacity (2013-2017). Voith delivered 11 GW, Andritz 9 GW, and GE 7 GW. All Chinese manufacturers combined delivered 16% of total capacity. This shows that EU manufacturers are global leaders. The remaining share was almost equally divided between Japanese, Indian, and Norwegian companies (SWD(2020) 953 final).

The hydraulic and mechanical equipment typically uses materials that are available in most parts of the world, such as steel, concrete, and – to a lesser extent – copper, so that hydropower expansion may not be limited by material availability. Concrete is used for dam construction and the required civil works, including the power station. In large-scale stations, concrete may also be used in the construction of tunnels and caverns. The manufacture of mechanical components for hydropower typically uses steel. Furthermore, over the last decade, several novel materials have been introduced in the hydropower sector, e.g. fibre-reinforced composites for small-scale hydropower and hydrokinetic turbines (Quaranta and Davies, 2021).

Hydropower equipment does not contain critical materials such as lithium and cobalt (used in electric vehicles), or neodymium, praseodymium, and dysprosium (used in electric vehicles and wind power). Indigenous materials are typically used, and this explains the high added value of hydropower to local economies. Copper is used at relatively low quantities in the generator sets.

([163]) SWD(2020)953 final, 14th October 2020. Accompanying the document on progress of clean energy competitiveness.

([164]) Hydropower can integrate other renewable energy sources such as solar PV. Solar PV can be installed on hydropower reservoirs with several benefits: evaporation reduction, improvement of PV efficiency, and reducing algae growth.

However, hydropower development may involve substantial excavation and tunnelling, requiring significant amounts of energy to run the appropriate machinery, and explosives are often used. Furthermore, the emerging variable speed technology generally uses permanent magnets, and some micro hydropower turbines with low rotational speed (water wheels, Archimedes screws) would be more efficient with permanent magnets, which would, though not essential, avoid the use of gearboxes. However, the material components of permanent magnets may suffer from shortages in the near future, worsened by the Chinese monopoly (the EU plays a major role only in the assembly stage, where its share is above 50%), (European Commission, 2020b; Stegen, 2015). This should stimulate the development of novel electromechanical equipment (e.g., Kougias et al, 2019) and the improvement of the lifecycle of such materials (e.g., recycling) (Stegen, 2015). Nevertheless, hydropower and pumped storage (along with biomass gasifiers, gas turbines and heat pumps) are not considered critical, despite their strategic importance to the EU energy system and their potential contribution to EU resilience (European Commission, 2021d). Hydropower is also the best renewable energy for reducing pressure on mineral resources. The Extraction of Mineral Resources indicator is measured in kilograms of antimony equivalent (kgeq.Sb) per kilogram extracted to take into account existing reserves, the rate of extraction and the "depletion" of each mineral substance: the value for hydropower is 0.017, while it is 0.04 for coal, 0.3 for wind and 14 for solar PV.

15.5 Scoreboard and key insights

The EU shows strong performance in nearly all innovation related indicators. Only in later stage investment the score is low. EU investment in later stage dropped in 2015-2020 compared to the earlier period of 2009-2014, and therefore, the EU captured only 7% of all investment. In terms of companies, the EU hosts 32% of all innovators, which is a strong ecosystem. Production is overall at lower level than seen in 2015-2016, however, it is rising again in 2020. As hydropower projects are big and span over long periods, production of hydropower turbines is thus volatile. This is also reflected in declining employment and turnover figures. However, the EU still has a strong global presence with a 40% share of all non-EU exports. The EU is a market leader in the area of small hydropower technology with many small manufacturers. Their production is difficult to track as it is relatively low with respect to the bigger producers. The trade balance is decreasing, but it is still positive.

Figure 70: Scoreboard for hydropower and pumped storage

Scoreboard	**Hydropower and pumped storage**	EU performance in the reference period		
Public R&D	●	3%	2015-2019	EU CAGR
Early Stage	●	24%	2015-2020	EU share of global total value
Later Stage	●	7%	2015-2020	EU share of global total value
Patents	●	36%	2016-2018	EU share of global total HVI
Companies	●	32%	2015-2020	EU share of innovating companies
Employment	●	-17%	2015-2020	EU CAGR
Production	●	-7%	2015-2020	EU CAGR
Turnover	●	-13%	2015-2020	EU CAGR
Imports & Exports	●	40%	2018-2020	EU share of global exports
Trade Balance	●	Medium	2015-2020	EU trade balance trend

Source: JRC

16 Offshore operations for RE installation

The European Offshore Renewable Energy Strategy aims to increase the currently installed offshore wind capacity of 15 GW to at least 60 GW by 2030, and to install at least 1 GW of ocean energy. By 2050 the targets are 300 GW for wind and 40 GW for ocean energy (COM(2020)741 final ([165])). This requires an estimated EUR 800 billion of investment by 2050, two thirds of which will fund the development of infrastructure. The strategy underlines the need to improve manufacturing capacity and port infrastructure and to address skill gaps and shortages to ensure higher installation rates. The Commission has established a dedicated platform on offshore renewables within the Clean Energy Industrial Forum, bringing together all the actors relevant to supply chain development.

Europe's ambitious plans to install renewable offshore energy bring with them a need for offshore operations. Offshore operations cover various services such as installation, storage of components, shipping, preassembly, and operations and management (O&M). The scope here is constrained to the installation and service vessels, offshore structures and port operations needed for renewable energy.

16.1 Overview of the solution and current status

Offshore renewable energy sources consist of several clean energy technologies that are at different levels of maturity. Bottom-fixed offshore wind turbines already satisfy 2% of the EU's power demand (WindEurope, 2021a). Floating offshore wind farms are being developed in the North and Baltic Sea, and also in the Mediterranean Sea and Atlantic Ocean. Ocean energy, mainly wave and tidal, is increasing in maturity and will also play an important part in decarbonising Europe's energy system. Floating photovoltaic power plants are being installed in landlocked waters, but their application is now also being explored in European seas (Offshore Energy, 2021b; Oceans of Energy, 2021).

The impact of offshore operations varies across renewable energy technologies. In offshore wind, installation costs range from 8% to 19% of total costs, while foundation costs range from 14% to 22% (IRENA, 2021). For floating offshore wind farms, substructure costs are 30%, installation costs 14%, and port services 4% of the total CapEx (ETIPWind Executive Committee, 2020). For wave energy, almost half of the cost is associated with installation, connection, decommissioning, and O&M, while for tidal energy, it is even higher – reaching 75% of the total cost (SI Ocean, 2013).

Installation

Today, most offshore operations needs are related to offshore wind. Up to 18 different types of vessel are involved during the full offshore wind project life-cycle: including site survey, installation of foundations and turbines, export and inter-array cables, transportation of personnel and equipment, and decommissioning (ECSA, 2020). The most important vessels in this context include jack-up vessels for wind turbine installation, heavy-lift vessels for foundations and substations, service operations vessels (SOV), crew transfer vessels (CTV), floatels (floating hotels), tugboats and anchor handling tugs.

Out of 100 jack-up vessels globally, Europe has almost half, with 48 jack-up vessels in operation and nine more under construction. China follows closely, with 42 jack-up vessels and nine more under construction (GWEC, 2020). Depending on weather conditions, jack-up vessels are capable of installing one turbine per day, while heavy-lift vessels can install 1.5 to 2 foundations per day. These two vessel types are usually in the water 70% of the time (due to weather conditions) and will install around 100 turbines in a year if contracted.

Some floating offshore concepts can be assembled onshore, and thus benefit from the use of heavy-lift vessels and smaller vessels instead of expensive jack-up vessels, especially for projects in water depths greater than 80 m. Due to the possibility of assembling at the port area with fewer vessel-related costs, floating offshore projects could see reduced installation costs (GL Garrad Hassan; Erik ter Horst, 2013). However, large floating wind turbines rely more heavily on onshore cranes and space at ports, which are already in high demand.

Just as the offshore wind market is very competitive and cost-driven in Europe, so is the offshore operations market. In most cases, developers request proposals either for a full engineering, procurement, construction, and installation (EPCI) contract, or for parts of it, and they do the same for O&M. Developers tend to select the cheapest offer, which they use as a cost estimate when entering renewable energy auctions or tenders. Developers all over Europe have been bidding at low prices (Telsnig & Vazquez Hernandez, 2019), which in

([165]) COM(2020)741 final, 19th November 2020. An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future.

some cases has led to situations where winners are chosen by lottery (S&P Global, 2021). This is putting pressure on original equipment manufacturers (OEMs) and offshore operations companies to reduce their costs.

Offshore installation operations in Europe are almost exclusively driven by European companies. In the Asia-Pacific region (excluding China), European companies (mostly UK and Norwegian) have a significant market share, at least in the short term, because they have not experienced any bottlenecks in Europe. The strong growth and the large pipeline of offshore wind projects in Europe have created a robust supply chain that is present also globally.

Box 5: Installation vessels' race against bigger turbines - from bottlenecks to overcapacity

Europe is facing an oversupply of inadequate jack-up vessels, as only seven of them have the crane capacity and hook height sufficient to install wind turbines of 12 MW and above. As offshore wind turbines are dramatically increasing in size, more than 10 jack-up vessels are used for construction support and geotechnical investigation, while another five are used for O&M. Heavy-lift vessels in Europe are mostly used for installation and transportation of monopiles, jackets, and substations. However, only 15 of them have a lifting capacity above 2500 t, which is generally needed for wind turbines of 10 MW and above (GWEC, 2020).

With plans to significantly increase offshore wind capacity, paired with heavier wind turbines (as they grow in size and power rating), which are also becoming taller, companies in the offshore installations supply chain have to order newer vessels and upgrade existing ones. Even though installation vessels are expected to have a lifetime of at least 20 years (Bloomberg, 2019), some companies are upgrading them after 7-9 years. DEME Group is performing main crane and hook height upgrades on its Sea Installer (which was built in 2012) and Sea Challenger (built in 2014) (DEME Group, 2021), and Cadeler on Wind Osprey (built in 2012) and Wind Orca (built in 2012) (OffshoreWind.biz, 2021).

European companies have ordered (mostly in China) nine jack-up vessels, with a delivery date of 2022-2025, which would be large enough to install next-generation offshore wind turbines of up to 20 MW. Furthermore, five heavy-lift vessels have been ordered to install ultra-large foundations and turbine installations. If the jack-up vessels and heavy-lift vessels are delivered on time, European offshore installations should not face bottlenecks until 2026 (GWEC, 2020). Other offshore renewable energy sources are unlikely to experience the same bottlenecks, as there is a strong capacity of smaller vessels due to the strong growth of offshore wind capacity (BVGassociates, 2015).

The Chinese supply chain is facing similar problems, as the rush by developers to complete projects before the expiration of feed-in tariffs is likely to cause an over-capacity of installation vessels from 2022 ([166]) (GWEC, 2020). If the European supply chain continues to be pressured by cost decreases, the Chinese supply chain could exploit the domestic over-capacity and enter the European market. At the same time, although Chinese companies increased their capabilities (the vessel fleet has increased by 600% since 2015 (WPM, 2019)), a lack of experience in installing offshore wind projects provides the potential for foreign subcontractors to enter the market (Energy Iceberg, 2020). A recent example includes the suction installation services performed by SPT Offshore (NL) for the first suction pile jacket in the South China Sea (SPT Offshore, 2020).

While some supply chain contractors are ordering new vessels, others are developing next generation dynamic positioning heavy-lift cranes ([167]) (e.g. Boskalis' Bokalift and GeoSea's Orion). Floating offshore projects face challenges in the relative motion between the lift vessel and floating turbine, which will result in increasing demand for dynamic positioning systems and other motion-compensation systems (Carbon Trust, 2021). Recently, the wind turbine manufacturer Vestas, in collaboration with the developer Parkwind and the vessel operator Heerema, introduced a dual-crane vessel that enables floating installation involving dynamic lifting (Ocean Energy Resources, 2021). Alternative lifting solutions, such as climbing crane technology, could also play a role, lowering installation costs (by not using expensive jack-up vessels), but requiring advance knowledge of future turbine specifications and possible adaptions to turbine designs (Carbon Trust, 2020).

Operations and Maintenance

New technologies, such as drones, and remote surveillance and diagnostics, are being considered to reduce the need for on-site human intervention. Some vessels remain necessary for O&M services. Floating offshore

([166]) 10 new offshore vessels were added in the past 12 months.
([167]) During offshore heavy-lifting operations, the vessel needs to maintain its desired position in the face of external environmental forces such as wind and waves.

renewable energy sources can have both portside and offshore maintenance strategies, depending on the complexity of the repair procedures. Both strategies have their pros and cons, with port-side strategies relying less on offshore vessels, but more on heavyweight onshore cranes, which are limited in number. Offshore maintenance is affected by weather downtime and the availability of vessels, but in some cases, it is the cheapest maintenance strategy (Carbon Trust, 2018). The O&M jack-up vessels currently used in the offshore wind sector will not be suitable for servicing floating offshore wind farms, as they must operate in deeper waters and in some cases need a higher hook height (Wood Mackenzie, 2021).

As the offshore wind turbine fleet is ageing, the market for major component replacement, decommissioning, and repowering is also growing and becoming increasingly attractive. It is crucial to develop innovative solutions that minimise the environmental impact, but also enable automated and remote operations.

Synergies with the Oil & Gas sector

Offshore renewable energy operations have many synergies with the offshore oil and gas (O&G) sector, sharing many technologies and elements of their supply chain. Foundations and subsea structures provide a potential crossover business, as does the use of vessels for O&M during installation and operation. The IEA estimates that about 40% of the full lifetime costs of an offshore wind project have significant synergies with the offshore oil and gas sector, which could mean a EUR 320 billion market opportunity in Europe (IEA, 2019b). The experience from the O&G, bridge and naval production sectors helped many companies to pivot easily to offshore operations for renewable energy, e.g. Boskalis (NL) and Jan de Nul (BE). There is also significant overlap in terms of heavy-lift vessels from the O&G sector, but these vessels are mostly focused on lifting capacity rather than lift height, which is crucial for offshore wind (Carbon Trust, 2021).

Port operations

In recent years, Europe has seen its ports being more involved in delivering offshore renewable capacity and performing O&M services. European ports currently support the deployment of 3 GW of new offshore wind farms every year, which will need to increase to 11 GW by 2030 (WindEurope, 2021b). Most active ports dealing with offshore wind are in the North Sea, such as Eemshaven, Port of Amsterdam, Port of Den Helder, but also in the Baltic Sea, e.g. Port of Ronne A/S, the Atlantic Ocean, e.g. Port of Bilbao, and in the Mediterranean Sea, e.g. Port-La-Neuvelle. Ports play an important role in continued cost reductions and increased build-out times of offshore renewables. They will also have a central role in delivering renewable hydrogen from offshore renewables and decommissioning ageing offshore infrastructure. Port operations can include onshore transportation and storage, load-out, pre-assembly, fabrication, O&M, decommissioning, and other services.

While gaining experience from working with offshore wind, ports will require a plan for space allocation and accommodation of the various renewable energy sources (Anchor Qea, 2021), as other technologies mature. Floating structures and substructures will require significant assembly and storage area compared to bottom-fixed technologies. Future turbines of 18 MW and above could require monopiles of 12 m diameter, while floating substructures could have as much as a 36 m diameter, which is a tenfold increase in the surface area (Arup, 2020). The expected yard size that is required to fabricate the structures is on average about 10 ha, while some manufacturers require up to 40 ha (Carbon Trust, 2015).

At some ports, e.g. Siemens Gamesa Renewable Energy port in Hull (UK), turbine blades are manufactured at a facility adjacent to the quayside, after which they are loaded onto the installation vessels. Turbine towers are assembled at the Hull site from smaller pieces shipped in from different locations. This means that the seabed next to the quayside must be deep enough to accommodate jack-up vessels (Anchor Qea, 2021). The length of the blades will dictate the open lay-down area needed.

All these extra requirements mean that ports need to plan their investments ahead of market development in order to avoid causing bottlenecks. Delays in the port of Gdynia are already causing potential delays for the first round of offshore wind projects in Poland (SEO, 2021). WindEurope estimates that Europe's ports need to invest EUR 6.5 billion between now and 2030 to support the expansion of offshore wind alone (WindEurope, 2021b).

16.2 EU positioning in innovation

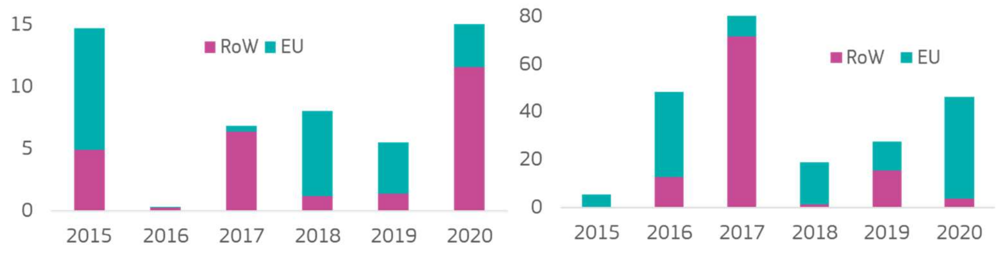
Using offshore wind as a proxy ([168]) for public R&D investments, an increasing investment trend can be seen, reaching EUR 34 million in 2019. The biggest public investors among countries that report to the IEA in this

([168]) The offshore wind category includes new materials for sea salt exposure; foundation and platform technologies.

area are Norway and Japan, followed by Denmark, France and Germany. Norway and Japan are both looking to expand their offshore capacity, in particular in floating offshore wind. Denmark and Germany are home to Europe's largest OEMs in offshore wind, while France, which also hosts some substantial manufacturing capacity in GE RE (US), is establishing itself as a new emerging market, particularly in floating offshore wind.

Venture capital investment has increased significantly in the period from 2015 to 2020 compared to the previous period (2009-2014). Early stage investment reached EUR 51 million and later stage investment reached EUR 227 million over this period. The EU captured 50% of all early stage investment and 54% of all later stage investment. The UK attracted most venture capital, followed by the Netherlands, France, Denmark and the US.

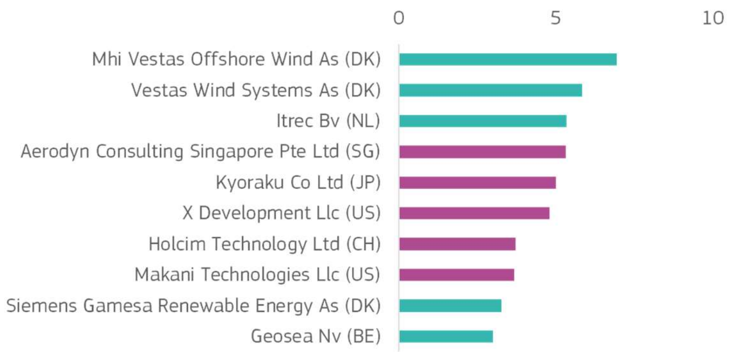
Figure 71: Early (left) and later (right) stage investment by region [EUR Million]



Source: JRC based on Pitchbook

The EU is a global leader among major economies with a 52% share of all high-value inventions in the period 2016 to 2018. At country level, the US leads, followed closely by a number of EU Member States: Denmark, the Netherlands, France, Spain and Germany. EU companies are also well represented, with five EU companies among the top 10 by patenting activity. Many wind OEMs, such as Vestas and Siemens Gamesa, are among the companies patenting inventions in offshore installations. Vestas is patenting methods for transporting wind blades, support structures for wind turbines, repair methods and blade handling aboard vessels. Itrec Bv is developing a hoisting crane for offshore vessels and an adjustable pile-holding system. Geosea Nv has high-value patents in a method for transporting buoyant structures with a vessel and self-supporting structures, while Deme Offshore is also active in self-support structures for wind turbines, and devices and methods for lifting objects from a vessel.

Figure 72: Top 10 companies in high-value inventions in 2016-2018



Source: JRC based on EPO Patstat

Roughly half of the innovators in the innovation landscape of offshore operations are big corporates and the other half are VC companies. The EU hosts 43% of all innovating companies, while the Netherlands hosts the biggest number of VC-funded companies. Overall, the EU seems to be an attractive destination for VC funding as it plays host to nearly half of all VC companies.

Some of the innovating companies in the Netherlands include Tetrahedron, which is developing technological services for installing offshore wind turbines, Oceans of Energy, which is developing floating solar systems, and GBM Works, which is developing low-noise installation of foundations for offshore wind turbines. In

France, Spinergie is exploring the digitalisation of offshore operations, Open Ocean is developing oceanography software and BW Ideol is developing floating offshore wind farms.

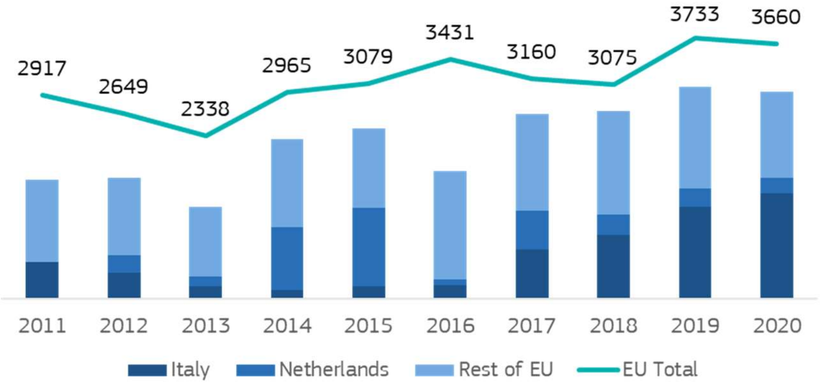
Vestas and Maersk Supply Service are developing a vertical installer crane solution for more efficient installation of offshore wind turbines (offshoreWIND.biz, 2018). A Horizon2020 project, ELICAN, demonstrated a cost-effective, self-installing substructure for offshore wind turbines that is crane-free and reduces the dependency on heavy-lift vessels for installation (CORDIS, 2019a). Another project, TELWIND, developed a floating substructure and a self-erecting telescopic tower, which enables a full onshore preassembly of the wind turbine (CORDIS, 2019b). And project, NEXUS, is developing a specialised vessel and logistics for safe and sustainable servicing of offshore wind farms (CORDIS, 2021a).

16.3 EU positioning in current market

Offshore renewables are expected to generate new local jobs and business opportunities in offshore operations and ports, as discussed above. However, a reliable and comparable source for offshore operations in various renewable sources was not found. WindEurope estimates that each GW of offshore wind capacity results in an additional 3 439 direct jobs in offshore operations, which would more than double by 2030 (WindEurope, 2020b)([169]).

The EU has a strong production base of offshore vessels and infrastructures, with production growing steadily and reaching EUR 3.7 billion in 2020. Italy, Germany and the Netherlands are the top producers, although some countries keep their data confidential, e.g. Belgium, which has many offshore operating companies such as Jan de Nul and Smulders. Although Italy has a very small offshore renewables capacity, the Italian supply chain is active in offshore operations all around Europe (Saipem has, for example, been contracted to transport and install foundations for two French offshore wind projects). The Dutch offshore services sector is also very active abroad; DEME Group, for example, received contracts for the Kaskasi and Code Wind III offshore wind farms in Germany. Naturally, not all production and trade is exclusive to renewable energy deployment. As discussed above, the oil and gas sector shares some of the technological capacity and there is therefore spill-over.

Figure 73: EU production value and top producers disclosing data among the Member States [EUR Million]



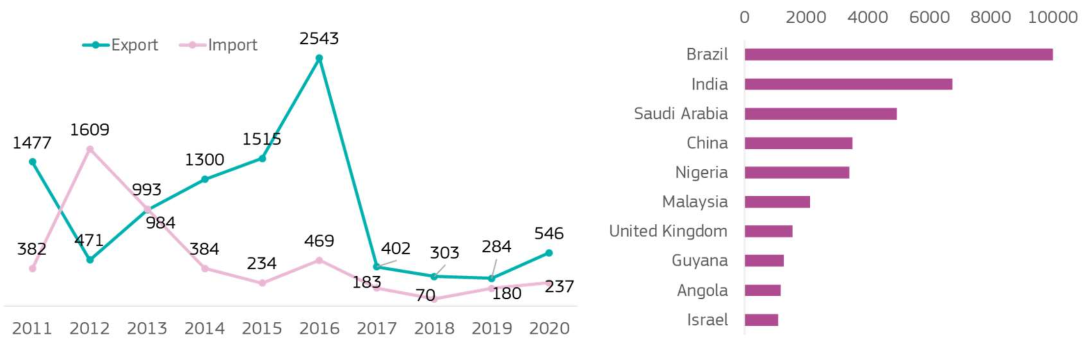
Source: JRC based on Prodcom data

EU exports have been volatile, dropping from EUR 2.5 billion in 2016 to EUR 0.5 billion in 2020. The EU has therefore only a 3% share of extra-EU exports, with the Netherlands being the main exporter. Nevertheless, the majority of global trade in offshore vessels and infrastructures is not related to renewables, but to the oil and gas sector and others such as dual-use technologies. This can be seen in major global import markets. Still, the EU exports more than it imports, resulting in a positive trade balance. The peak in exports in 2016 can be traced to significant exports of offshore vessels to Brazil during the period 2014 to 2016 (roughly 50% of EUR 1.6 billion in 2016), most likely in relation to oil exploration and deployment (Bloomberg, 2021), and exports of floating or drilling platforms to Norway (70% of EUR 0.8 billion), part of which may be related to offshore wind. Some products under the tracked trade headings can also be considered dual-use technologies, which can face trade restrictions (SIPRI and Ecorys for DG Trade, 2015). In recent years, the UK,

([169]) Not including indirect jobs.

as the biggest offshore wind market, has been the main importer from the EU (with the EU responsible for 40% of total UK imports) but with a decreasing trend, perhaps due to anticipation of Brexit.

Figure 74: Extra-EU import & export (left) and top 10 global importers in 2018-2020 (right) [EUR Million]



Source: JRC based on Comext and Comtrade

16.4 Future outlook

As different parts of the offshore wind and ocean energy value chains are present throughout Europe, and not just in coastal areas, there are great opportunities for local industry and jobs. Offshore operations, from vessels to ports, will need an upgrade and more skilled workers. As the EU already has a strong production base of offshore vessels and infrastructure, its industry is also well placed to capture emerging business opportunities outside the EU. Europe is expected to be the leading offshore wind market, which means market growth for offshore operators. With an ageing offshore wind fleet, the EU can gain first-mover advantage and help European companies to increase their market share globally, as is the case with offshore installations today.

Offshore operations offer employment opportunities for various skilled workers, which can help to mitigate job losses in the fossil fuel industry. The offshore oil and gas sector can be particularly pivotal in providing spill-over effects in terms of skills and technological capacity. However, the sector will require new skills and re-skilling. The offshore renewable energy sector in Europe is already facing difficulties in recruiting; 17-32% of companies are experiencing skills gaps, while 9-30% are experiencing skills shortages in technical occupations (COM(2020)741 final). The Global Wind Workforce Outlook forecasts that to install 34 GW of offshore wind capacity, over 44 000 people will require new training in Europe in 2021-2025 (GWEC and GWO, 2020). In the UK, shortages are already being experienced and a Green Jobs Taskforce has been created (UK Department for Business, Energy & Industrial Strategy, 2020). It is estimated that in the UK, employment demand in offshore wind will require an additional 10 200 technicians and engineers to install 30 GW by 2032 (Energy & Utility Skills, 2018). Employment is expected to increase in all phases of the project lifecycle, but particularly in construction and installation, and operations and maintenance. Decommissioning/repowering may experience significant jobs growth, but only after 2032. Many companies in the sector that do not have the 'employer brand' of operators or OEMs are struggling to attract talent from both within and from outside the sector.

Due to Brexit, the UK no longer participates in the North Seas Energy Cooperation forum, which could negatively impact future offshore grid developments, including the uptake of hybrid offshore renewable energy projects (e.g. wind farms that have a grid connection in two countries). EU exports of offshore vessels and infrastructure to the UK have also experienced a decrease in recent years.

Ports will require massive upgrades to be able to deliver an increased installation rate. However, lack of clarity on future volumes of offshore renewables is slowing down the development of ports and the rest of the supply chain. In addition, rapid technological advances, namely the growing size of turbines, puts offshore operators in a constant race to keep their fleets of vessels and cranes up to date. The competitive European market, especially in offshore wind, also applies constant pressure on European offshore operators and other parts of the supply chain to reduce their costs. This may lead to a window of opportunity for the Chinese supply chain to enter and capture European market growth.

16.5 Scoreboard and key insights

The EU shows very strong performance in all indicators related to innovation. Public R&D investments show a growing trend, while in patents and venture capital investments, the EU captures over half of the global total, punching well above its economic weight. The EU plays host to nearly half of all innovating companies, which provides good opportunity to maintain leadership and capture future markets.

The EU has a strong production base in offshore vessels and infrastructures. Nevertheless, in order to deliver on higher offshore renewable installation rates, industry needs to invest in the EU supply chain, from port upgrades and new vessels, to re-skilling and attracting skilled workers. Globally, the EU captures only 3% of extra-EU exports, as much of the trade is related to offshore oil and gas. EU industry can gain from first-mover advantage in offshore installations, and repowering and decommissioning, to enter non-EU markets.

Figure 75: Scoreboard for offshore operations for RE installations

Scoreboard	**Offshore operations for RE installation**	EU performance in the reference period		
Public R&D		31%	2015-2019	EU CAGR
Early Stage		50%	2015-2020	EU share of global total value
Later Stage		54%	2015-2020	EU share of global total value
Patents		52%	2016-2018	EU share of global total HVI
Companies		43%	2015-2020	EU share of innovating companies
Employment			2015-2020	EU CAGR
Production		4%	2015-2020	EU CAGR
Turnover			2015-2020	EU CAGR
Imports & Exports		3%	2018-2020	EU share of global exports
Trade Balance		Medium	2015-2020	EU trade balance trend

Source: JRC

17 Building envelope technologies

According to IEA's tracking buildings 2021 report, 18% of global energy- and process-related emissions in 2019 came from the electricity and heat used in buildings. The same report noted progress in decoupling energy consumption from floor area growth. Energy use in buildings increase by an average 1% per year during 2010-2019, while floor area expanded by an average 2% (IEA, 2021f). However, the report concluded that 'buildings remain off-track to achieve carbon neutrality by 2050' unless 'all new buildings and 20% of the existing building stock (are) zero-carbon-ready ([170]) as soon as 2030'.

The energy performance of building envelopes has a critical impact on the energy consumption of space heating and cooling. Integrated façade systems can result in energy savings of up to 60% for lighting, 20% for cooling, and 26% for peak electricity, while proper air sealing can reduce heating needs by 20-30% (IEA, 2013).

The cornerstone of European legislation for transforming the building sector is the Energy Performance of Buildings Directive (EPBD)([171]) and its amendments in 2021, which includes minimum requirements for building envelope elements and adopts a definition for nearly zero-energy buildings. The amendment of the Renewable Energy Directive (RED-II)([172]) covers the production and promotion of energy from renewable sources to achieve the EU's 2030 renewable energy target. The Energy Efficiency Directive (EED)([173]) sets the overarching legal framework for energy efficiency policy in the EU and includes an important provision targeting government buildings. According to a 2021 JRC report, all EU Member States implemented the EPBD requirements by the end of 2018, with new or updated legislation, however, the share of existing EU buildings which have an energy performance certificate is limited to around 10% (Zangheri et al., 2021).

17.1 Overview of the solution and current status

The scope of the building envelope technologies covers technologies and integrated solutions for the outer shell of buildings that improve their thermal performance (in both new construction and retrofit) and facilitate integration of renewable energy sources. These include, for instance, solar windows, reflective facades, integrated renewable energy systems and dynamic insulation. However, the scope does not include superinsulation materials, prefabricated buildings or smart energy management solutions, as these are examined separately. While the several solutions addressing decarbonisation of buildings in this report are closely connected and intertwined, they all focus on different areas: prefabricated buildings focus on efficiency and innovation in the construction, superinsulation focus mainly on materials, and building envelope technologies focus on building integrated solutions.

A report released by newswire in 2019 estimated that the global building envelope market was worth EUR 120 billion ([174]) in 2018 and was expected to reach around EUR 150 billion by the end of 2025 (Newswire, 2019). The European Construction Sector Observatory (ECSO, 2021) identified insulation and substitution of single-glazed windows as two of the main renovation trends. The same report noted that 'the global market for green roofs is expected to grow by more than 17% by 2027 compared to 2020 levels'. Bioarchitecture techniques improve the efficiency of building envelopes with ecological-friendly solutions. For example, green roofs provide natural insulation, increase the efficiency of solar panels thanks to its cooling effect, and reduces the CO_2 emissions thanks to photosynthesis.

Building envelopes must comply with energy efficiency and safety requirements, while satisfying comfort and aesthetics at the same time. They need to have higher thermal efficiency, while being thinner or flexible. Moreover, the manufacturers need to satisfy a diverse range of national legal requirements and architectural styles. Consequently, production standardisation is hindered and costs remain high.

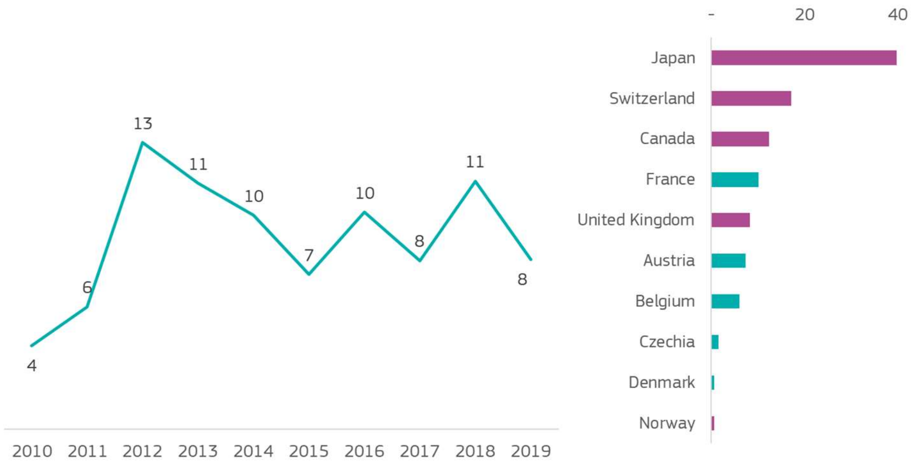
17.2 EU positioning in innovation

The total public R&D investment for this solution was EUR 105 million in 2017-2019, with Japan and Switzerland investing the most among the reporting countries. With EUR 27 million and an increasing trend,

([170]) There is no international standard for zero-carbon buildings. In 2021, the EPBD recast (OJ L 153 18.6.2010, p. 13) included a definition for zero-energy buildings (NZEB).
([171]) Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast) (OJ L 153 18.6.2010, p. 13)
([172]) Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (OJ L 328 21.12.2018, p. 82)
([173]) COM(2021) 558 final Brussels, 14.7.2021 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0558
([174]) Foreign currencies are converted to EUR based on the annual averages published by the European Central Bank

the EU accounted for around 25% of total investment during 2017-2019, while five Member States were among the top investors (**Figure 76**).

Figure 76: EU Member States public R&D investment (left) and top 10 IEA Members in 2017-2019 (right) [EUR Million]

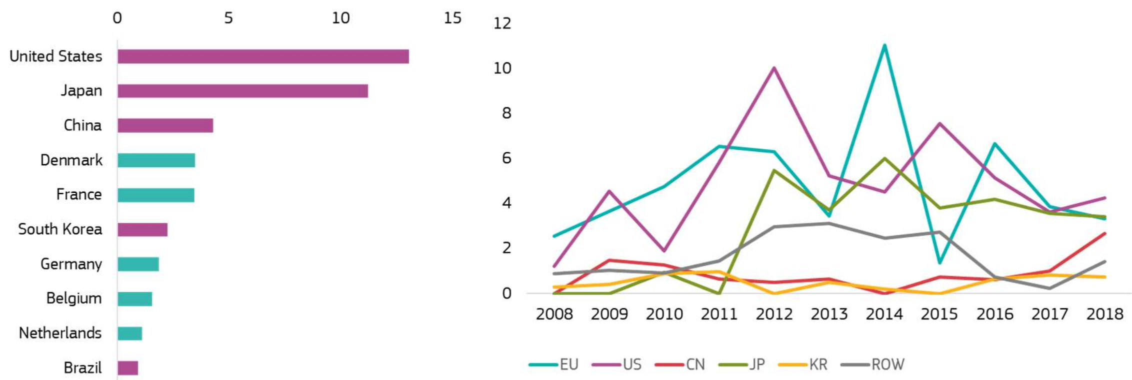


Source: JRC based on IEA data

Early and later stage investment peaked in 2018, while both investment activities were supressed in 2019. In 2020, early stage investment recovered, with a more active presence for the EU. Nevertheless, the EU share still represented only 4% of early and 8% of later stage investment during 2015-2020.

In the EU, patenting activity related to building envelopes spiked in 2014 and plummeted the following year, only to recover again in 2016 with a declining trend (**Figure 77**). In the US and Japan, patenting activity spiked in 2012, which in the case of Japan, may have been stimulated by efforts to improve building envelopes after the earthquake in 2011. China seems to become more active after 2016 with the launch of its 13th five-year plan. The top EU investors in R&D, France, Belgium, and Denmark, are also among the top holders of high-value inventions but are behind the US, Japan, and China. The EU is the leading economy on high-value inventions, with 29% of the global share – 1% more than the US. The US and EU markets attract most of the patent applications.

Figure 77: Top 10 countries in high-value inventions in 2016-2018 (left) and trend of high-value inventions for major economies (right)



Source: JRC based on PATSTAT

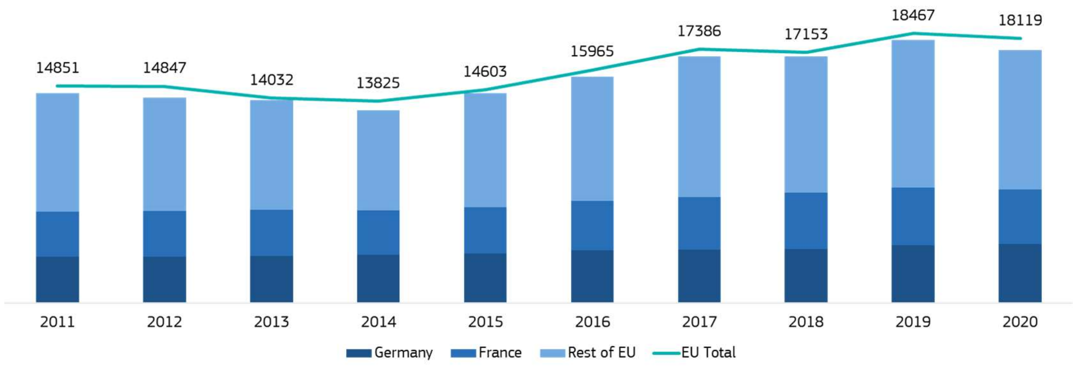
VC companies dominated the building envelope innovation landscape in 2015-2020, except for in Japan and Brazil, where corporates dominated. The US hosts most of the innovating companies, having more than four times that of Japan or Germany. About a third of all innovating companies are headquartered in the EU, and less than one third of them are corporates.

Research efforts focus on better constructability, retrofit suitability, durability, thermal conductivity, moisture management, dynamic flexibility, less labour-intensive air sealing, and lower construction and installation costs (NREL and ORISE, 2020; NREL and DOE, 2020). Innovative research in the field focuses on adaptive or responsive envelopes, looking for new materials discovery, novel technological approaches and applied engineering, i.e. developing materials and installation methods to yield air sealing without significant teardown (NREL and ORISE, 2020). The cost of window systems can be further reduced with improvements in the thermal performance and dynamic facades and glazing systems (NREL and DOE, 2020).

17.3 EU positioning in current market

Over 2011-2020, EU production rose slowly but steadily, and the Covid-19 pandemic didn't make a significant impact (**Figure 78**). Germany and France combined hold around 40% of the EU total, and Italy comes third with about 15%.

Figure 78: EU production value and top producers disclosing data among the Member States [EUR Million]



Source: JRC based on PRODCOM data

Extra-EU imports and exports roughly doubled between 2011 and 2019. EU imports increased by 5% during the pandemic in 2020, while exports dropped by 4%. Extra-EU exports accounted for 22% of global exports for 2018-2020, while 84% of EU imports were met internally. The EU captured most of the growing non-EU markets. However, the largest global importer, the US, imported only 9% of its total imports from the EU, despite being the third largest EU importing partner. The EU trade balance surplus was about EUR 0.7 billion in 2020 and has a slightly rising trend. Germany, the second biggest global exporter, mainly exports to EU partners (59%).

There is no statistical data available for employment. A study from the BPIE estimated that an average of 18 jobs is created per EUR 1 million invested in the energy renovation of buildings; however, this average 'varies across the EU depending on national circumstances and employment cost' (BPIE, 2020).

17.4 Future outlook

To unlock investments, the European Commission launched its Renovation Wave ([175]) strategy in 2020. In January 2022, the European Commission adopted the new Guidelines on State aid for climate, environmental protection and energy (CEEAG)([176]) to create incentives for both the owner, who bears the renovation cost, and the tenant. The new rules replaced the old Energy and Environmental Aid Guidelines (EEAG)([177]), in force since 2014, and are intended 'to facilitate the development of economic activities in a manner that improves environmental protection' to help the Member States to reach the European Green Deal ([178]) objectives in a targeted and cost-effective manner.

Nevertheless, the European Builders Confederation estimated a decline of 20% to 25% in construction activity and a loss of almost 3 million jobs in the EU for both 2020 and 2021, as compared with 2019 (EBC, 2020).

([175]) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives COM/2020/662 final.

([176]) Communication from the Commission – Guidelines on State aid for climate, environmental protection and energy 2022 C/2022/481 OJ C 80, 18.2.2022, p. 1–89.

([177]) Communication from the Commission — Guidelines on State aid for environmental protection and energy 2014-2020 OJ C 200, 28.6.2014, p. 1–55.

([178]) COM(2019) 640 final Brussels, 11.12.2019.

The IEA estimated that investment in energy efficient buildings fell by nearly 15% in 2020, putting more than 25 million jobs at risk (IEA, 2020b).

The European Construction Sector Observatory identified four main types of barrier hampering building envelope renovations (ECSO, 2021):

1) Technical barriers, including lack of skilled workers, accessibility of users' energy data, and the need to develop promising technologies that are at low TRL levels today
2) Financial barriers, including high upfront investment cost, long payback timeframe, and lack of funding opportunities
3) Social barriers, including decision-making processes and users' limited awareness and understanding of benefits
4) Regulatory barriers, including building permit procedures and architectural constraints.

In addition, a 'pay-for-performance' instead of 'pay-for-measures' incentives would create the needed market for energy efficiency and lead to greater large-scale energy savings (KnaufEnergy Solutions, 2022).

17.5 Scoreboard and key insights

EU score in early and later stage investment, with below the EU average shares of 4% and 8% respectively, is worrying. Public R&D investment has an increasing trend, yet the rate is below EU GDP. The EU still hosts nearly a third of all innovating companies and holds 29% of all high-value patents in 2016-2018. The EU captured 22% of global exports, while less than 20% of all EU imports came from outside of the EU. The trade balance is increasing, as well as EU production, indicating a strong manufacturing capacity.

Figure 79: Scoreboard for building envelope technologies

Scoreboard	**Building Envelope Technologies**	EU performance in the reference period		
Public R&D	●	2%	2015-2019	EU CAGR
Early Stage	●	4%	2015-2020	EU share of global total value
Later Stage	●	8%	2015-2020	EU share of global total value
Patents	●	29%	2016-2018	EU share of global total HVI
Companies	●	31%	2015-2020	EU share of innovating companies
Employment			2015-2020	EU CAGR
Production	●	4%	2015-2020	EU CAGR
Turnover			2015-2020	EU CAGR
Imports & Exports	●	22%	2018-2020	EU share of global exports
Trade Balance	●	High	2015-2020	EU trade balance trend

Source: JRC

18 Heating and cooling networks

18.1 Overview of the solution and current status

District heating and cooling networks are important solutions for decarbonisation as they offer a centralised and energy-efficient way to supply heating and cooling energy in densely populated urban areas and also industrial sites. They allow for the integration of different clean energy sources and systems, and offer grid flexibility services through demand response. The scope of this solution includes technologies and elements that contribute to the efficiency and decarbonisation of heating and cooling networks, e.g., heat exchange units and thermal storage. However, this solution does not include power generation or smart management systems.

Simultaneous district heating and cooling networks are still at an early stage of development (Buffa et al., 2019). In 2017, the EU had around 6 000 district heating and 115 district cooling systems in operation (Euroheat & Power, 2017). Moreover, several simultaneous district heating and cooling networks are in operation as pilot projects in the EU (D2Grids, 2021). Cooling demand is growing more than heating demand. In 2020, the number of days in the EU with weather conditions that required heating was around one quarter of those in 1979, while the days with cooling requirements almost tripled for the same period (Eurostat, 2021).

In 2021, the global district heating market was estimated at around EUR 155 billion ([179]) and is projected to reach nearly EUR 327 billion ([180]) in 2028 (FBI, 2022). According to the IEA's report on district heating (IEA, 2021j), 40% of the district heat generated globally in 2020 was used for industrial heating and only 8.5% for heating buildings. Globally, district heating and cooling networks still rely on fossil energy: coal was the main energy source (45%), mainly due to China, which had a national average of 70%, followed by natural gas (40%), and then renewables (8%) and oil (3.5%). However, some European countries exceeded the average. For example, Denmark produced around 20% of its district heat from solar energy and provided more than 45% of the total district heat produced to buildings (residential, commercial, and government). In 2020, 23% of the total energy used for heating and cooling in the EU came from renewable sources (Eurostat, 2022).

A 2021 JRC analysis identified ten key factors for the success of district heating and cooling networks (Galindo Fernánde et al., 2021). These factors included 1) adequate incentives for efficient DHC through national policies, 2) supporting new investments through direct and indirect funding, 3) commitment of local authorities and stakeholders, 4) integration of DHC planning in urban planning, 5) tuning of buildings regulation and urban planning to enable DHC connection, 6) mapping of the potential energy sources and ensuring technical compatibility, 7) employment of power-to-heat solutions, 8) valorisation of synergies with other networks (e.g., electricity) and urban infrastructures (e.g., water), 9) valorisation of synergies and seasonality for district cooling, and 10) adoption of optimisation and flexible strategies (Galindo Fernánde et al., 2021).

Distributed heating and cooling networks (DHCN) provide scale-intensive, infrastructure-based services, which require a high market share. Financial challenges mainly relate to the high capital investments required to retrofit for renewable energy sources. Sources of fossil fuels that are subsidised or do not account for negative externalities create an artificially uncompetitive field for renewable sources (IRENA and IEA, 2020). Technical challenges include ageing networks and their switch to low-temperature operating conditions, and inefficiencies due to oversizing, hidden by poorly performing buildings, or under-sizing, hidden by weather-compensated control systems (Reguis et al., 2021; IRENA and IEA, 2020).

18.2 EU positioning in innovation

Reporting of public R&D expenditure under the IEA framework does not allow for the tracking of data specific to heating and cooling networks. Therefore, it is not possible to determine an EU public investment trend. However, from 2014 to 2020, the EU funded 58 relevant projects through Horizon 2020 with nearly EUR 387 million (Saletti et al., 2020).

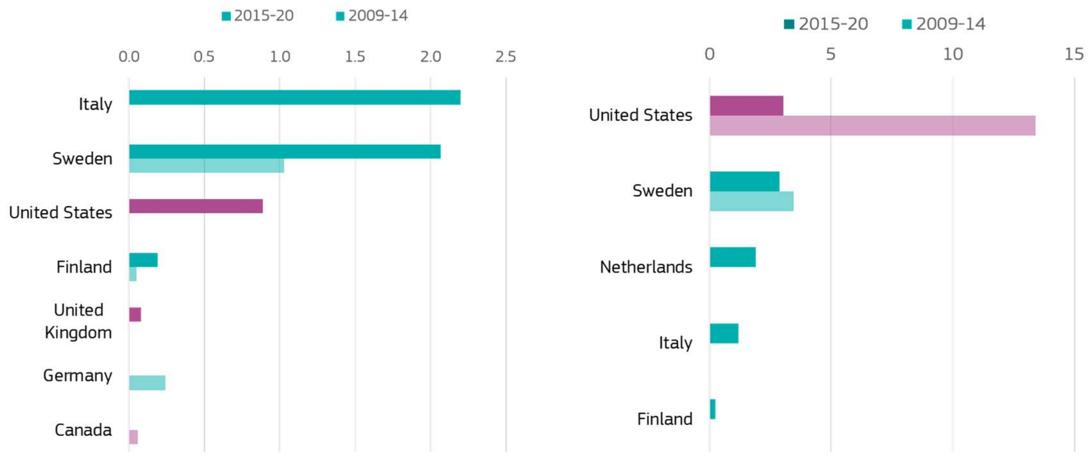
During 2015-2020, the EU captured 82% of all early stage investment. Italy attracted over EUR 2 million (49% of the EU total) in the same period (**Figure 80**). Early stage investment enjoyed a record year in 2019, reaching nearly EUR 3 million, mainly thanks to a EUR 2 million grant acquired by Aqua Robur (Sweden). Later

([179]) Foreign currencies are converted to EUR based on the annual averages published by the European Central Bank

([180]) Forecasted values are converted to EUR based on Bloomberg forecasted rates. For values later that 2026, a fixed rate is assumed at EUR 1.21 per USD.

stage investment peaked in 2015 and 2020, reaching over EUR 9 million globally from 2015 to 2020. The EU captured 67% of all later stage investment in 2015-2020. The US was in the lead during 2015-2020, attracting over EUR 10 million, with Honolulu Seawater AC (US) alone attracting more than EUR 2 million in 2015. Sweden is again second, capturing 46% of EU later stage investment. Investment in the Netherlands and Italy was to Gradyent (Netherlands), which attracted nearly EUR 2 million in 2020, and Microchannel devices (Italy), which attracted over EUR 1 million in the same year.

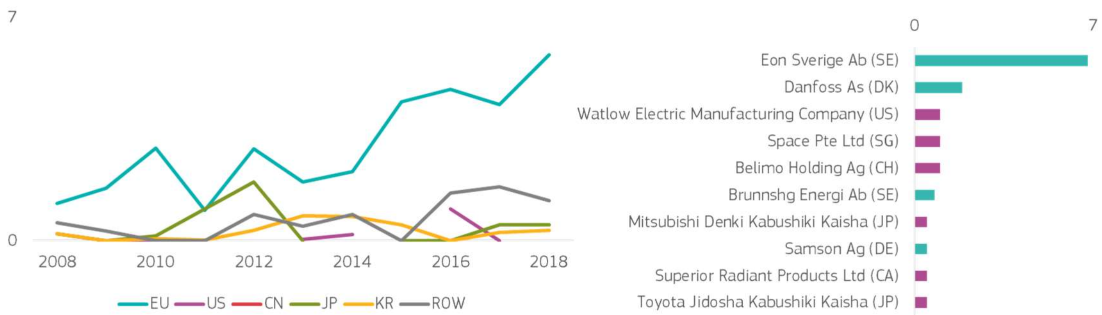
Figure 80: Top countries in early (left) and later (right) stage investment [EUR Million]



Source: JRC based on Pitchbook

EU patenting activity is increasing steadily. The EU holds 68% of all high-value inventions. Sweden and Denmark, with a traditionally high penetration of district heating systems, are the leading patenting countries globally, followed by Germany and Italy in the fourth and sixth position respectively. Swedish Eon Sverige Ab (SE) is the leading patenting company (**Figure 81**).

Figure 81: Trend in high-value inventions for major economies (left) and top 10 companies in 2016-2018 (right)



Source: JRC based on EPO Patstat

Sweden and the US host the biggest number of innovating companies, followed by Switzerland and China. Sweden has the biggest ecosystem of VC companies, while Switzerland and Japan have the biggest number of innovating corporates. The EU has the second biggest pool of VC companies. Overall, the global number of VC companies and corporates indicates that this is a growing innovation ecosystem.

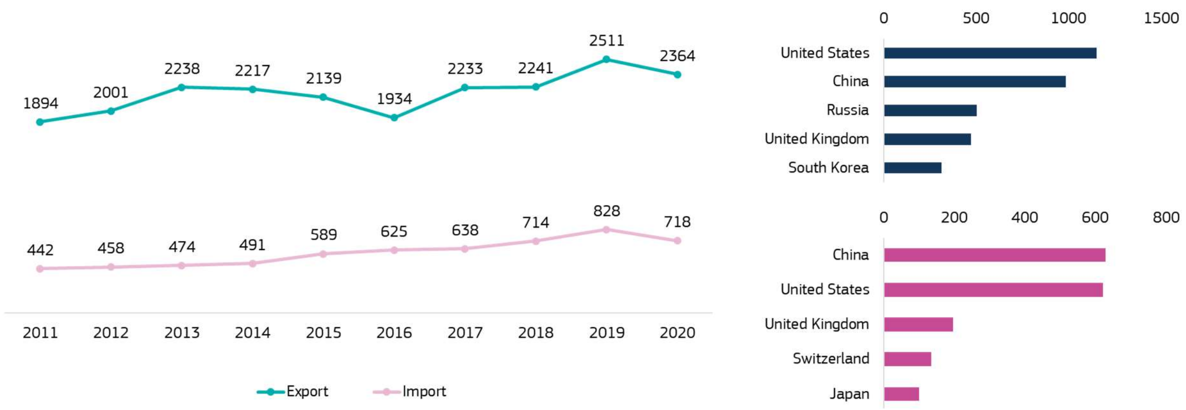
New technologies under development to improve the efficiency of the piping systems include sustainable insulation materials, coatings to reduce pressure losses, and quick-fit joints for easy installation (Moustakidis et al., 2019). Research efforts are focused on the design and retrofit of low-temperature distribution networks, including simultaneous cooling distribution, while increasing the share of renewable and waste energy sources. The digitalisation of the sector focuses on optimisation, automation, and prediction and prevention techniques. However, the drive for innovation in the sector seems to rely on political intervention (Knutsson et al., 2021).

18.3 EU positioning in current market

The EU production of heat exchange units, an important component of heating and cooling networks ([181]), has decreased by an average 1% annually since 2015, reaching EUR 4.5 billion in 2020. Italy and Germany are the biggest producers, responsible for approximately half of the total EU production.

Extra-EU exports and imports have grown slowly but steadily since 2011, reaching over EUR 2 billion and nearly EUR 1 million respectively in 2020 (**Figure 82**). China and the US are the biggest exporters to and importers from the EU. Extra-EU trade accounts for 34% of the global share, and there is potential for the EU to capture a bigger share in the growing markets of India, Thailand, and Indonesia. Internal imports account for more than 70% of all EU imports. Germany is the biggest EU importer and exporter. The EU trade surplus was nearly EUR 2 billion in 2020.

Figure 82: Extra-EU import and export (left); Top 5 importers from the EU (top right) and top 5 exporters to the EU (bottom right) in 2018-2020 [EUR Million]



Source: JRC based on Comext data

A 2019 EC study estimates that the heating and cooling industry as a whole employs around 650 800 FTEs, when also considering integration with the renewable energy sector (biomass, biogas, heat pumps, and solar-thermal segments) (European Commission, 2019b).

18.4 Future outlook

The Energy Performance of Buildings Directive (EPBD)([182]) states that EU Member States should consider the "use of district heating and cooling when planning, designing, building and renovating industrial or residential areas". The Renewable Energy Directive (RED) was revised in 2019 (RED II)([183]), setting common rules for the internal market for electricity and promoting the use of renewable energy. The amended RED III directive will revise the renewable energy target upwards to 40% and is expected to be adopted in 2022. The priority list ([184]) for the development of harmonised network codes adopted harmonised rules for their management including capacity allocation, congestion management, data exchange and balancing interoperability rules. The EU Emissions Trading System Directive (EU ETS)([185]) was amended in 2021, enabling sector integration. Distribution network operators (DSO) and transmission system operators (TSO) can coordinate, unlocking the potential of waste heat recovery and use (Corscadden et al., 2021).

A 2021 JRC report highlights that only six EU Member States address cooling in their National Climate and Energy Plans (NECPs) and that most of the plans do not meet the objectives of the Renewable Energy

([181]) Heat exchangers are also used in other applications, not exclusively in heating and cooling networks. Therefore, production and trade data should be interpreted with caution.

([182]) Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (OJ L 153 18.6.2010, p. 13)

([183]) Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (OJ L 328 21.12.2018, p. 82)

([184]) Commission Implementing Decision (EU) 2020/1479 of 14 October 2020 establishing priority lists for the development of network codes and guidelines for electricity for the period from 2020 to 2023 and for gas in 2020 OJ L 338, 15.10.2020, p. 10–11

([185]) Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC OJ L 275 25.10.2003, p. 32

Directive (Articles 23 and 24 of RED II), regarding the increased share of renewables in the heating and cooling sector (Toleikyte and Carlsson, 2021). Therefore, there seems to be room for improvement, which should also translate into more targeted action in relation to heating and cooling networks.

In January 2022, the European Commission adopted the new Guidelines on State aid for climate, environmental protection and energy (CEEAG)([186]). The new rules ([187]) are designed 'to facilitate the development of economic activities in a manner that improves environmental protection' to help the Member States to reach the European Green Deal ([188]) objectives in a targeted and cost-effective manner. In the case of district heating and cooling, highly-efficient cogeneration is included.

Increasing urbanisation is expected to drive the market growth of district heating and cooling globally (FBI, 2022). Heating and cooling networks can also support flexibility in the power sector by providing reserve capacities for balancing services (Boldrini et al., 2022). It can provide a cost-efficient flexibility to the electricity grid via power-to-heat solutions with electric boilers or large-scale heat pumps, especially when coupled with thermal storage (Galindo Fernández et al., 2021).

Heating and cooling networks integrate several technologies (e.g., insulation, solar, digitalisation) and, thus, integrate their dependencies. Investment in new projects can be undermined by inconsistencies and uncertainty in policies which can result in a fragmented and unstable market (IRENA and IEA, 2020). The supply chain bottlenecks caused by the pandemic, and redirection of investments to the healthcare system, impeded progress in the district heating and cooling market (Market Data Forecast, 2022; FBI, 2022).

18.5 Scoreboard and key insights

The EU scores highly in innovation-related indicators, showing leadership in the development of decarbonised heating and cooling networks. There is a slightly decreasing trend only in the production of heat exchangers. Still, the EU has a strong manufacturing capacity, manifested by a positive and growing trade surplus. During 2018-2020, extra-EU exports accounted for 34% of global exports, but in 2020 there were still some growing markets in which the EU can capture a bigger share.

Figure 83: Scoreboard for heating and cooling networks

Scoreboard	**Heating and Cooling Networks**	EU performance in the reference period		
Public R&D			2015-2019	EU CAGR
Early Stage	●	82%	2015-2020	EU share of global total value
Later Stage	●	67%	2015-2020	EU share of global total value
Patents	●	68%	2016-2018	EU share of global total HVI
Companies	●	53%	2015-2020	EU share of innovating companies
Employment			2015-2020	EU CAGR
Production	●	-1%	2015-2020	EU CAGR
Turnover			2015-2020	EU CAGR
Imports & Exports	●	34%	2018-2020	EU share of global exports
Trade Balance	●	High	2015-2020	EU trade balance trend

Source: JRC

([186]) Communication from the Commission – Guidelines on State aid for climate, environmental protection and energy 2022 C/2022/481 OJ C 80, 18.2.2022, p. 1–89.
([187]) Communication from the Commission – Guidelines on State aid for climate, environmental protection and energy 2022 C/2022/481 OJ C 80, 18.2.2022, p. 1–89.
([188]) COM(2019) 640 final Brussels, 11.12.2019.

19 Cooling and air-conditioning technologies

Energy demand for cooling is the fastest growing end-use in the buildings sector. Although it has started from a low level compared to heating, it has more than tripled since 1990 (IEA, 2021g). In 2020, space cooling accounted for nearly 16% (1885 TWh) of buildings sector final electricity demand, and by 2050, that number could more than triple (IEA, 2021g). In addition, cooling systems contribute to large peaks in electricity demand, which can overwhelm power grids during extreme heat waves. There are roughly 2 billion AC units in operation in the world, 70% of which are in residential units (IEA, 2021g).

19.1 Overview of the solution and current status

The scope of the solution focuses on space cooling, including air conditioning. The decarbonisation challenge relates to the refrigerants in use and the consumption of energy, as cooling demand is expected to increase, e.g. comfort cooling and the cooling of data centres. It is important to note that some air conditioners are reversible heat pumps that can also be used for heating. Air conditioners themselves are also in effect 'heat pumps', but for clarity, 'heat pumps' in this report refers to those used primarily for heating. This chapter covers reversible heat pumps and air conditioners, as they are used primarily for cooling.

In the EU, cooling demand in the residential sector is projected to grow from 35 TWh in 2015 to 137 TWh in 2050 in a business-as-usual case, and 78 TWh in an energy efficiency scenario (SWD(2016) 24 final)([189]). However, yearly cooling demand potential in the residential sector will reach an estimated 292 TWh, up to a maximum of 404 TWh by 2050 (Jakubcionis & Carlsson, 2017). Most EU cooling demand feeds electricity-driven, vapour-compression air conditioners, which use refrigerants. There are also some low-carbon solutions based on natural heat sinks, e.g. the district cooling system in Helsinki (FI), the snow storage cooling in Sundsvall (SE), various aquifer cooling systems in the Netherlands and a groundwater cooling system in Freiburg (DE) (RVO, 2018).

On the industrial side, increasing digitalisation means more data centres with cooling needs. The electricity consumption of data centres globally was 286 TWh in 2016, projected to grow to 1287 TWh by 2030 ([190]) (Koot & Wijnhoven, 2021). Assuming a share of approximately 40% related to cooling (Aspen Global Change Institute and Lawrence Berkeley National Lab, 2014), the demand for cooling could increase from 114 TWh to 515 TWh by 2030. However, data centres can also play a pivotal role in sector coupling, by integrating efficiency, renewables and demand side management (Ratka & Boshell, 2020). Waste heat generated for cooling can be used in district heating systems (Chapter 18), and this is already happening in several places today, for instance Stockholm (DCD, 2021).

Highly efficient air conditioner (AC) units are available on the market, yet consumers tend to purchase ones which are two to three times less efficient (IEA, 2021g). The challenge of increasing the average efficiency of cooling systems has been due to both technological and policy issues. The recently announced Global Cooling Prize ([191]) noted that ultra-efficient air conditioners, with 80% lower climate impacts than baseline units, are technically feasible. Policies need to be framed to catalyse the commercialisation and adoption of these more efficient units by, for example, setting performance standards according to the best-performing products instead of a minimum acceptable level (Matson, 2021). Overall, energy efficiency standards and requirements for cooling have been less strict than for heating.

Another challenge is to find effective replacements for refrigerants with high global warming potential. The Montreal Protocol (1987) succeeded in replacing the fluorinated gases (CFCs) most harmful to the ozone layer. In the EU, the F-Gas Regulation (Regulation (EU) No 517/2014)) further limited F-gases (HFCs) sold from 2015 onwards, phasing them down to one-fifth of 2014 sales by 2030. However, the Commission is currently reviewing options to improve the regulation in view of increased climate ambitions and recent international obligations on hydrofluorocarbons (HFCs) under the Montreal Protocol. With a long lifetime, HFCs have 2 000 times greater global warming potential than that of CO_2, and since 1990, HFC emissions caused by refrigerants have increased by 10-15% annually across the world (Capgemini Invent, 2020). New ultra low-GHG refrigerants (GWP <5), such as ammonia, CO_2 (R744), water (R718), R-455A, R-32 and natural alternatives, are available, but not deployed at scale.

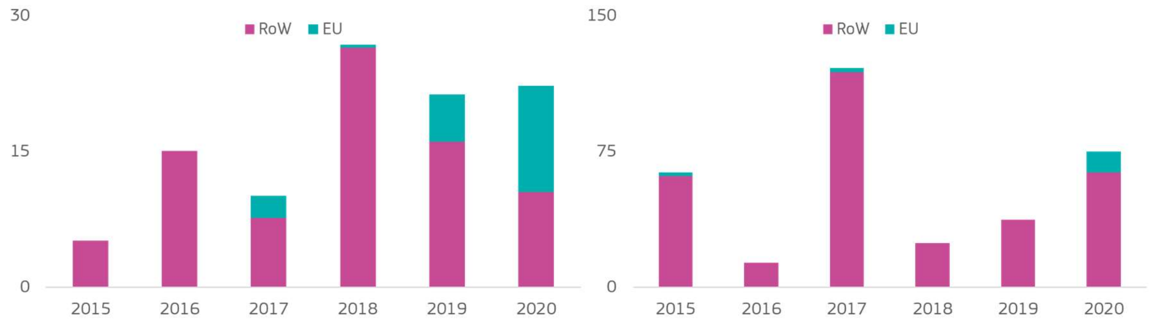
([189]) SWD(2016) 24 final. 16th February 2016, Brussels.
([190]) Projections consider increase of use, end of Moore's law and IoT, but include high uncertainty.
([191]) The Global Cooling Prize was launched by RMI with Mission Innovation and the Department of Science and Technology of the Government of India in 2018.

19.2 EU positioning in innovation

EU public R&I investment in heat pumps and chillers (heat pumps in Chapter 9)([192]) grew at an average 18% annually from 2015 to 2019. Austria is the biggest public investor globally, and other EU countries are also well represented in the top 10. Total EU public investment reached EUR 14 million in 2019.

Early and later stage venture capital investment was higher in 2015-2020 than in 2009-2014, at EUR 101 million and EUR 334 million respectively in the later period, compared to EUR 67 million and EUR 129 million before. In the EU, early stage investment grew to nearly 20 times the size, capturing 20% of all early stage investment now (**Figure 84**). In 2020, the EU, and especially Spain, saw a record year, attracting well over half (EUR 12 million) of all early stage investment that year. However, in the later stage, EU investment dropped significantly, from EUR 58 million (2009-2014) to EUR 16 million (2015-2020), dropping from a 45% share to only 5%. The US is the leading destination of VC investment, followed by the UK and Canada. Spain, Germany, Sweden, France and Italy are the EU countries that made it to the global top 10.

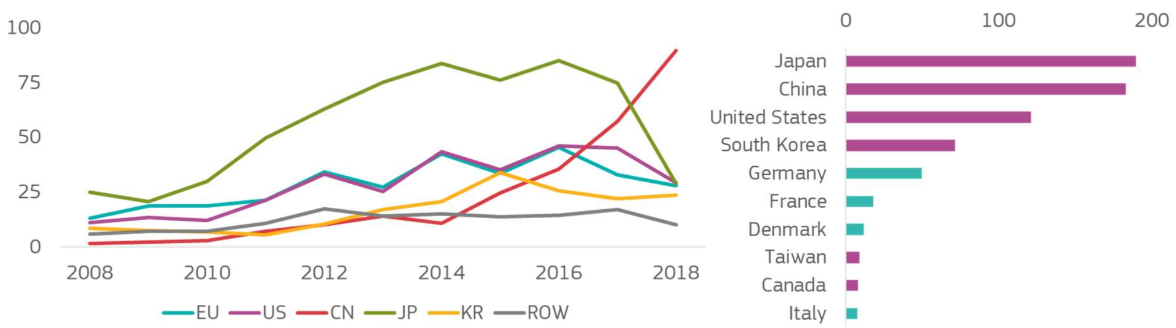
Figure 84: Early (left) and later (right) stage investment by region [EUR Million]



Source: JRC based on Pitchbook

Overall patenting activity seems to be increasing. Japan experienced strong growth from 2010 to 2014, but more recently its activity has dropped. Japan is followed by China, where patenting activity surged in 2014, overtaking Japan in 2018. The EU held 15% of all high-value inventions during 2016-2018 period, with Germany, France, Denmark and Italy in the global top-10 countries with high-value patents.

Figure 85: Trend in high-value inventions for major economies (left) and top 10 countries in 2016-2018 (right)

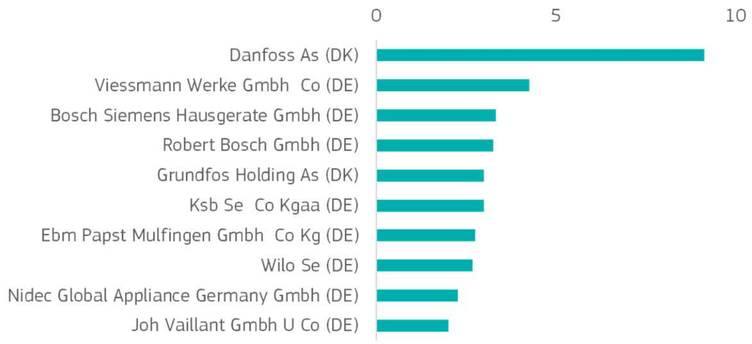


Source: JRC based on EPO Patstat

Japanese, Chinese, Korean and US corporates dominate patenting in the cooling area. Mitsubishi (JP) and Qingdao (CN) hold the largest patent portfolio. According to EIT report, the portfolios of Mitsubishi (JP) and LG (KR) have the highest IP strength (EIT, 2018). The most active European corporate is Danfoss As (DK), followed mainly by German corporates and one other Danish company, Grundfos Holding As (DK).

([192]) IEA code 144 includes 'Heat pumps and chillers'.

Figure 86: Top 10 EU companies in high-value inventions in 2016-2018



Source: JRC based on EPO Patstat

The US has the biggest number of innovating companies in the area of cooling technologies, with just over half being VC companies and the other half patenting corporates. The EU plays host to nearly a third of all VC companies and 21% of all patenting corporates, and enjoys a growing ecosystem of VC companies.

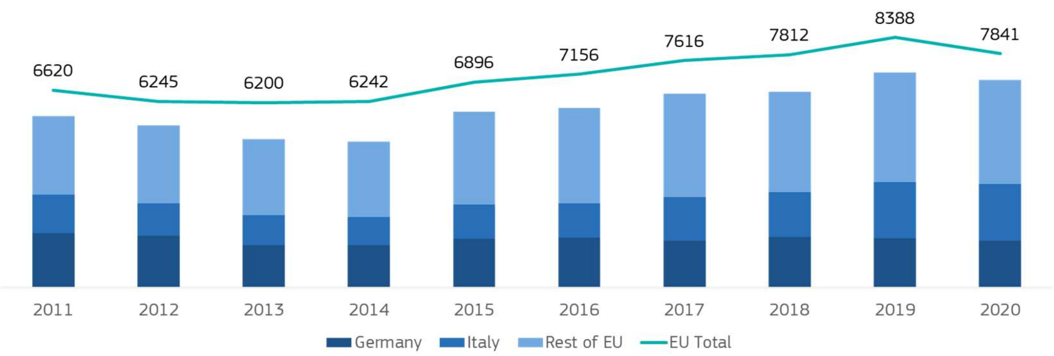
Finalists and winners of the Global Cooling prize showcased a variety of technological possibilities, including solar photovoltaics, evaporative cooling, enhanced dehumidification, smart hybrid designs of vapour-compression and solid-state cooling approaches (Matson, 2021; Global Cooling Prize, 2021). New solid-state-based cooling technologies use refrigerants that are non-explosive, non-toxic and easier to recycle, and also provide other benefits, such as customisation to different temperatures and reversibility, that can significantly improve energy efficiency (CORDIS, 2021b).

19.3 EU positioning in current market

There is no data on employment and turnover specific to cooling. However, two thirds of the EU heat pump market is related to cooling (see Chapter 9).

EU production of air-conditioning equipment (excluding that used in motor vehicles) and parts for air conditioning, such as condensers, absorbers, evaporators and generators, has increased steadily since 2014, reaching over EUR 8 billion in 2019. Production seems to have been affected by the pandemic, dropping in value in 2020. Nearly all Member States have some production, but Germany and Italy are the biggest producers. Italy's production has increased over the 10-year period, while Germany's production has been decreasing. Some countries do not disclose the data, which explains the higher overall EU total in **Figure 87**.

Figure 87: EU production value and top producers disclosing data among the Member States [Million EUR]



Source: JRC based on PRODCOM

EU exports were increasing steadily before the pandemic, from EUR 2.3 billion in 2011 to over EUR 3 billion in 2019. This figure dropped to EUR 2.5 billion in 2020. Over the same period, imports decreased at first, only to start increasing sharply in 2015. Imports climbed to nearly EUR 5 billion in 2020 and did not seem to be affected by the pandemic. China and Thailand are the main exporters to the EU, and also globally. The EU generates only 8% of extra-EU global exports, which grows to 23% if intra-EU exports are included. The majority of imports, at 58%, are intra-EU. The biggest EU exporters are Italy, Germany, Czechia and Netherlands, while the biggest EU importers are Germany, France, Italy and Spain.

The EU trade deficit has been growing since 2013, reaching EUR 2.4 billion in 2020. Czechia, Italy and Belgium have the biggest trade surpluses, while Germany, Spain and France have the biggest trade deficits.

19.4 Future outlook

Cooling technologies are addressed in the EU by the Ecodesign Directive ([193]), Energy Performance of Buildings Directive ([194]) and F-gas Regulation (Regulation (EU) No 517/2014). The Renewable Energy Directive (RES-Directive) sets mandatory national targets ([195]) for the overall share of energy from renewable sources. In 2021, the Commission adopted new rules to account for renewable cooling ([196]). The methodology introduces thresholds for cooling systems which can be recognised as renewable, allowing them to be counted towards meeting renewable energy targets. The methodology creates incentives to use the best available technologies and to further develop innovative cooling technologies. Globally, the G7 has agreed to double the efficiency of cooling systems sold worldwide by 2030 as part of the Super-Efficient Equipment and Appliance Deployment (SAED) (The White House, 2021).

By 2050, two-thirds of all households worldwide are expected to be equipped with air-conditioning systems (CORDIS, 2021b). In addition, growing digitalisation will increase the cooling demand from computing and data centres. While the conventional air-conditioner market is dominated by Asian countries, EU industry can play a role in developing more efficient and sustainable cooling systems and applications. A positive indication of this is that EU companies have attracted 20% of all early-stage investments. The EU also has a growing manufacturing base in this area.

Data centre operators and some trade associations have agreed to make data centres climate-neutral in Europe by 2030 (Climate Neutral Data Centre, 2020). This self-regulatory initiative consists of several commitments, energy efficiency being one of them. In the EU, a voluntary programme, The European Code of Conduct for Data Centres, was created in 2008 to improve energy efficiency in a cost-effective way (European Commission, 2016). As part of it, the JRC regularly updates the list of identified best practices for data centre operators, the latest of which was published in 2021 (Acton, et al., 2021).

The market is dominated, especially in the residential segment of air-conditioning, by Asian countries (China, Thailand, Malaysia, Japan and South Korea) followed by Mexico and the US. European manufacturers in this segment are smaller. Thailand and China also dominate reversible heat pumps but are followed by European countries, such as Spain and Italy, which mainly supply the European market ([197]). With growing cooling demand in Europe too, these big air conditioner manufacturers can saturate the market with lower-efficiency solutions that undermine the EU's energy efficiency ambitions. In addition, they pose a threat to European technology leaders in other closely linked segments such as air-to-water, ground-water and brine/water-to-water heat pumps, with their enormous manufacturing capacities (see Chapter 9).

([193]) Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (recast) (OJ L 285 31.10.2009, p. 10)

([194]) COM(2021) 802 final, 15th December 2021. 2021/0426 (COD)

([195]) The European Commission proposed to revise targets of the RES-Directive as part of the package "Delivering on the European Green Deal". The current EU-level target of 'at least 32%' of renewable energy sources in the overall energy mix is increased to at least 40% by 2030. The Commission also proposes to increase energy efficiency targets from 32.5% to an overall reduction of 36-39% for final and primary energy consumption by 2030.

([196]) Commission Delegated Regulation (EU) amending Annex VII to Directive (EU) 2018/2001 as regards a methodology for calculating the amount of renewable energy used for cooling and district cooling C/2021/9392 final.

([197]) EU SWD(2021)307 Parts 1-5. Brussels 26.10.2021

19.5 Scoreboard and key insights

Asian countries, together with Mexico and the US, dominate the cooling and air-conditioning market. The EU is seeing an increasing trend in public investment in heat pumps and chillers, which are closely related to cooling and air conditioning. In 2020, the EU captured over half of all early-stage investments globally, which may mark the emergence of an EU-based ecosystem of innovative, next-generation cooling solutions. In other innovation-related indicators, the EU lags behind its competitors. In terms of manufacturing capacity, EU production is steadily increasing. However, imports are also increasing and so the EU trade deficit is growing.

Figure 88: Scoreboard for cooling and air-conditioning technologies

Scoreboard	**Cooling and AC technologies**	EU performance in the reference period		
Public R&D	●	18%	2015-2019	EU CAGR
Early Stage	●	20%	2015-2020	EU share of global total value
Later Stage	●	5%	2015-2020	EU share of global total value
Patents	●	15%	2016-2018	EU share of global total HVI
Companies	●	24%	2015-2020	EU share of innovating companies
Employment			2015-2020	EU CAGR
Production	●	3%	2015-2020	EU CAGR
Turnover			2015-2020	EU CAGR
Imports & Exports	●	8%	2018-2020	EU share of global exports
Trade Balance	●	Low	2015-2020	EU trade balance trend

Source: JRC

20 Decarbonisation of steel through H-DRI and electrification

The steel industry is one of the biggest industrial emitters, responsible for about 5% of EU emissions and 7% of global greenhouse gas emissions (Somers, 2021). The majority of emissions are inherent to the prevailing steelmaking process of using coke and coal in blast furnaces to reduce iron ore to iron. Globally, over 70% of steel is produced via the primary route, using blast furnaces and basic oxygen furnaces, and the remaining nearly 30% is produced using electric arc furnaces in the secondary route (World Steel Association, 2020).

With the new European Climate Law, the EU has set a clear and more ambitious emissions reduction target of 55% by 2030. A key policy mechanism to reduce industry's emissions is the EU Emission Trading System (ETS), which, in consequence, is set to reduce emissions by 61% by 2030 against 2005 levels ([198]). However, EU industry faces global competition, with production in many third countries currently facing lesser CO_2 emission costs on their production. For this reason, the Commission has also proposed the introduction of a Carbon Border Adjustment Mechanism (CBAM), to ensure exporters to the EU face the same carbon prices as EU industry is subject to under the ETS.

The ratio between the two main production routes has remained largely unchanged in the EU, with nearly 60% of production via the primary route (blast furnace/basic oxygen furnace) and the remaining 40% using the secondary route (electric arc furnace) (Eurofer, 2021). Integrated plants (combining blast furnaces and basic oxygen furnaces) have optimised their material and energy flows, and are among the most energy and CO_2-efficient in world. Potential emission reductions through additional incremental efficiency improvements have been nearly fully exploited. Achieving deep decarbonisation will require major changes to the industry.

The focus in this chapter is on low-CO_2 steel-making based on electrification via the secondary route, and renewable hydrogen-based direct reduction of iron (DRI)([199]). The main technologies enabling these processes are the electric arc furnace (including graphite electrodes, a key component) and DRI shaft furnace, and the essential input materials are recycled steel scrap and DR-grade pellets. Electric arc furnaces are a mature technology and already used in the so-called secondary route, in which steel scrap is directly melted into steel in an electric arc furnace. DRI furnaces are also a mature technology and used as part of another method of primary steel production, whereby iron ore is directly reduced in its solid state to produce direct reduced iron (DRI, also called sponge iron), bypassing the need for a blast furnace and coke oven. The DRI is then melted and refined to steel in electric arc furnaces. Replacing natural gas or coal currently used for DRI with green hydrogen would cut nearly all ([200]) carbon emissions in steelmaking. Thus, the novelty of this solution is a 'new' combination of already mature and existent technologies with the addition of green hydrogen.

20.1 Overview of the solution and current status

The EU is the second largest steelmaker in the world, accounting for 8% of total global crude steel production, higher than the US share (4%) and Japan (5%), but lower than China, which produces over half of all global crude steel (58%) (Eurofer, 2021). The sector has, however, struggled over the last decade, suffering from a permanent drop in demand after the 2008 financial crisis, and increasing international competition from both neighbouring countries and overseas. The EU went from being a net exporter historically to a net importer in 2016, and faces downward pressure on the utilisation of production capacity from structural overcapacity in the sector (McKinsey, 2021b). In this already challenging business environment, the industry is expected to make major strategic investments, with impact until 2050 and beyond, in the next 5-10 years to address both economic viability and environmental sustainability (Somers, 2021).

Decarbonising the recycling route is a straightforward case of only using clean energy. However, this route is constrained by the finite supply and low quality of steel scrap. Steel scrap prices are currently very high due to strong demand and could become volatile in the future (BNEF, 2021m). The quality of steel scrap, namely the level of contamination, also presents certain limitations to its use.

The EAF market seems competitive, with over 80 different EAF manufacturers. EU manufacturers are well represented in building European plants but also globally. The top manufacturers (by number of plants installed) in the EU and worldwide are shown in **Table 4** below.

([198]) COM(2021) 551 final 14th July 2021.

([199]) There are also other technological solutions being considered to decarbonise steelmaking, such as through CCUS and iron ore electrolysis. In the context of CIndECS, these are not considered as part of this solution, as they have different value chains, and thus should be considered separately. In fact, albeit not entirely the same value chain, CCUS is considered a solution in CIndECS in the scope of decarbonising the cement industry. Iron ore electrolysis is still at an early TRL level. Currently, the H-DRI route seems to be the main solution considered by European steelmakers (Somers, 2021), hence it is chosen for assessment in 2021.

([200]) The H-DRI process could reduce 95% of CO_2 emissions compared to the primary route.

Table 4: Top manufacturers of EAF plants in the EU and globally

Manufacturer name	Plants in the EU	Non-EU plants	Total plants
SMS GROUP, DE	27	71	98
ABB, DE-SE-CH	21	33	54
TENOVA, IT	17	33	50
DANIELI, IT	13	101	114
FUCHS SYSTEM, DE	10	28	38
PRIMETALS TECHNOLOGIES, DE	6	32	38
CZECH MANUFACTURER, CZ	4	-	4
LECTROMELT, US	4	36	40
SMS CONCAST, CH	4	25	29
KRUPP, DE	3	17	20
MAN GHH, DE	3	23	26
VAI, AT	3	20	23
NKK, JP	-	20	20

Source: JRC based on Plantfacts database (2019)([201])

The direct reduction process is already a well-established technology using mainly natural gas, with 111 million tons of DRI (approximately 5% of global steel production) produced globally in 2019, of which India and Iran accounted for 60% (World Steel Association, 2020). There is currently only one commercial DRI plant ([202]) in the EU that has been in operation since the 1970s (World Steel Association, 2020). Although DRI production represents a small share, it has increased by 46% between 2015 and 2019 (World Steel Association, 2020).

The existing market for shaft furnace DRI is split along two main technology providers: Midrex and HYL-Energiron (Midrex Technologies Inc., 2020). HYL-Energiron is a technology developed by Techint and Danieli under the partnership of Tenova HYL and Danieli & C (Tenova, 2021). Midrex has a dominating market share: it accounts for 80% of world DRI production via the shaft furnace (Midrex Technologies Inc., 2020). These two companies are also providing the DRI technology for most of the H-DRI pilot projects in the EU (Somers, 2021). Midrex and HYL-Energiron are both further developing the technology to be compatible with 100% hydrogen use. The other furnace type uses fluidised bed processes. Notably, the South Korean steelmaker Posco (#6 in the world), is developing the FINEX technology with PRIMETALS (Austrian technology company) to use hydrogen in the future.

Green steel made with hydrogen in a DRI furnace is currently not deployed anywhere at market scale. There are, however, a few pilot and demonstration projects operational or planned in the near future, mostly in the EU and China (see full list in (Somers, 2021)). SSAB (SE) delivered its first green steel from the HYBRIT pilot plant to its customer, Volvo Group, in July 2021.

The main challenges of green steel are economic: they relate to price, and the sufficient supply and infrastructure of green hydrogen. The cost of steelmaking by 2050 (i.e. for nth-of-a-kind commercial plants([203])) using H-DRI is estimated to be up to 10-60% ([204]) higher than the cost of the primary route today (without considering the cost of CO_2 emissions) according to two studies focussing on Europe (see more in Somers (2021)). At the lowest end, Bloomberg NEF estimates the future costs to be below current costs (BNEF, 2021m). The main variable explaining the differences is the assumed cost of green hydrogen, which varies from 1 EUR/kg to over 5 EUR/kg, depending on the study. The Hybrit project, the first to produce green steel from its H-DRI demonstration plant, estimated the costs to be 20-30% higher than the cost of producing crude steel (Hybrit, 2018), but it is expected to become a more attractive investment in the future due to lower electricity costs and higher CO_2 prices (Pei, et al., 2020).

Besides renewable hydrogen from renewable electricity, other low-CO_2 hydrogen sources are being considered to decarbonise steel production. The priority for the EU, as stated in the Commission's Hydrogen Strategy, is to develop and enable renewable hydrogen, while the use of other forms of low-carbon hydrogen can be

([201]) This can be used as an indicative list of top manufacturers (note: the database contains many plants that were built by companies that have merged with others or have folded. Because of these many consolidations, the list above is indicative only).
([202]) The plant is operated by ArcelorMittal in Hamburg.
([203]) Once more established, the technology can benefit from economies of scale, existing infrastructure and do not face the challenges and costs a first-of-a-kind may have.
([204]) Based on Agora Energiewende and Material Economics

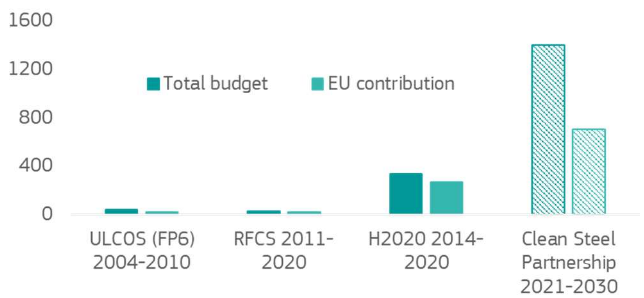
considered in a transition phase. The use of fossil-based hydrogen with carbon capture requires the development of extensive infrastructure to transport and store the CO_2 emitted during production, and the full lifecycle greenhouse gas emissions (including upstream methane leakage) need to be considered. At the time of writing, one project in the EU linked to low-CO_2 steelmaking is exploring the use of fossil-based hydrogen with carbon capture.

A large number of H-DRI projects announced in the EU are planning to use natural gas as a transition fuel and gradually increase the share of green hydrogen as it becomes economically available. This would require DRI plants that can operate with varying input gas types. Some technological aspects would still need to be addressed in this regard, for instance the thermodynamics of the process ([205]). Plant operation with varying mixtures of hydrogen and natural gas would, in addition, provide demand-side flexibility to the grid by allowing flexible operation of electrolysers (Muller, et al., 2021).

20.2 EU positioning in innovation

There is no data available that would be specific enough to determine the contribution of R&D specifically to steel decarbonisation. However, at European level, the European Commission has in the past been instrumental in supporting early-stage (low TRL) R&D&I projects in the steel sector. Several of the key decarbonisation technologies being considered by the steel industry were developed via the EU's ultra-low CO_2 steelmaking (ULCOS) programme, which was funded via the Commission's 6th Framework Programme. The EU's Horizon Europe funding programme and the Research Fund for Coal and Steel (RFCS) co-finance research and innovation projects in the areas of coal and steel. The RFCS has, however, in the past, financed a smaller number of projects that can be considered to be developing emission reduction technologies. Research in steel decarbonisation financed under EU framework programmes totalled EUR 390 million during the period from 2004 to 2020, with major steel industry actors participating. An unprecedented level of funding, with a total budget of EUR 1.7 billion and EU contribution of EUR 700 million, has been announced under the Clean Steel Partnership, formally launched in June 2021. The Clean Steel Partnership estimates R&D&I needs between 2021 and 2030 at around EUR 2.6 billion (ESTEP, 2021).

Figure 89: EU R&D funding programmes [EUR Million]

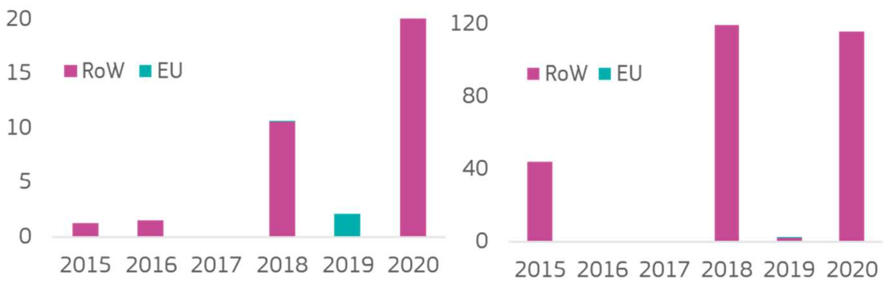


Source: Adapted from Somers (2021)

Private investment into start-ups and scale-ups working in steel decarbonisation is still limited, as most innovation tends to be financed with companies' own resources. In addition, the deployment of H-DRI is heavily dependent on the development of auxiliary technologies, such as renewable hydrogen and clean power, investments for which are covered in other sections of the report. Steel production requires vast capital investment, hence the entry of new companies is difficult. One of the VC-funded companies, Boston Metal (US), is developing a technology whereby iron ore is reduced solely through electricity at high temperature (molten oxide electrolysis) that could potentially be an important new technology. However it is not expected to be deployed at scale before 2040 (Somers, 2021). The electrolytic process is also being developed in the EU by ArcelorMittal, but the focus is on the low-temperature electrolysis referred to as electrowinning (Somers, 2021). H2Green, a recent EU start-up that aims to produce H-DRI steel in Sweden and Spain, raised venture capital investments in 2021 (S&P Global Market Intelligence, 2021; H2GreenSteel, 2021), which are not yet captured in the data of **Figure 90** below.

([205]) Reaction with carbon monoxide is exothermic, while the reduction with hydrogen is endothermic.

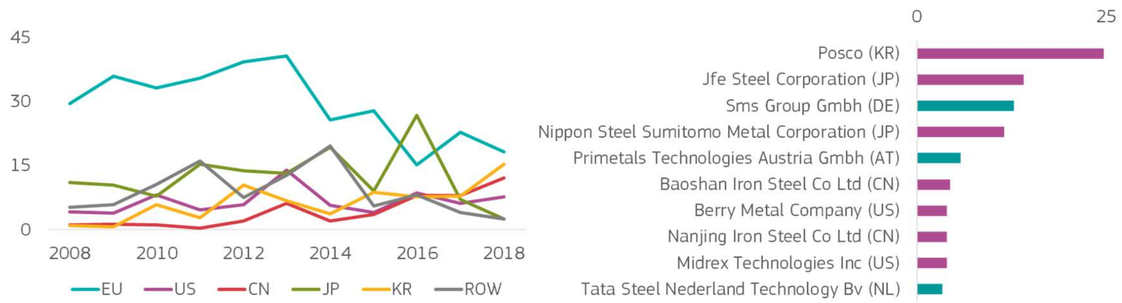
Figure 90: Early (left) and later (right) stage investment by region [EUR Million]



Source: JRC based on Pitchbook

The EU is a clear global leader in developing and patenting climate change mitigation technologies in the steel sector. However, the majority of patenting activity relates to recycling and process efficiency activities, with, so far, less activity related to steelmaking with breakthrough technologies, such as hydrogen-DRI (Somers, 2021), upon which this report focuses. Looking more specifically at technologies essential for H-DRI ([206]) (see **Figure 91**), the EU still has the largest number of high-value inventions, albeit with a decreasing trend since 2013. EU-based entities filed 30% of internationally protected inventions, followed by Japan (19%) and Korea (16%). Korean Posco holds the most high-value inventions among companies. Its activity is driven by patenting related to electric arc furnaces. SMS Group (DE), Primetals (AT) and Tata Steel (NL) are among the global top 10, but other EU EAF manufacturers are also well represented. DRI furnaces for H-DRI are currently only produced by Midrex Tech (US) and HYL/Energiron (Tenova (IT) HYL and Danieli (IT) partnership), which are also represented among patenting companies.

Figure 91: Trend of high-value inventions for major economies (left) and top 10 companies in 2016-2018



Source: JRC based on EPO Patstat

Steelmaking, including low-CO_2 steel, is dominated by big corporates due to the characteristics of the sector as mentioned above. The EU is home to over 40% of all innovating companies (corporates and VC-funded companies combined). The US and Sweden host the most VC-funded companies, four and three respectively.

20.3 EU positioning in current market

While there are no figures for employment and turnover specific to low-CO_2 steelmaking or the relevant equipment manufacture, looking at the whole sector gives an idea of the size of the sector being affected. The EU steel sector directly employs 314 000 people. Steel jobs are spread across all of the EU, however, in proportion to total population of the country, steel jobs are most pronounced ([207]) in Luxembourg, Slovenia, Slovakia, Austria, and Czechia (Eurofer, 2021). According to Eurostat data, in 2018 the sector generated some EUR 162 billion in turnover ([208]), with an increase of 25% over the period from 2015 to 2018. In the same year, the sector generated EUR 29 billion of direct gross value added ([209]).

([206]) CPC codes: Y02P 10/134 ('avoiding CO_2, e.g. using hydrogen') and (C21B or C21C or C21D) OR Y02P 10/20 ('recycling') and C21C 5/52 OR Y02P10 ('technologies related to metal processing') and C25C and (C21B or C21C or C21D).

([207]) The highest number of jobs per 100 000 people.

([208]) Eurostat SBS for NACE 24.10: Iron and steel manufacturing.

([209]) Eurostat SBS for NACE 24.10: Iron and steel manufacturing.

Steel production in the EU is dominated by a handful of countries: Germany produced 26% of all EU steel in 2020, followed by Italy (15%), France (8%) and Spain (8%) (Eurofer, 2021). Primary steel plants are huge industrial sites, which often have more than one blast furnace on top of the other up- and downstream processing plants. There are 25 such integrated sites in the EU (Somers, 2021). Electric arc furnace production sites are, on the other hand, much smaller installations, with around 120 EAF production sites in the EU. The highest concentration of steelmaking capacity is located between the Rhine-Ruhr and Benelux regions, a highly industrialised zone in Europe (Somers, 2021).

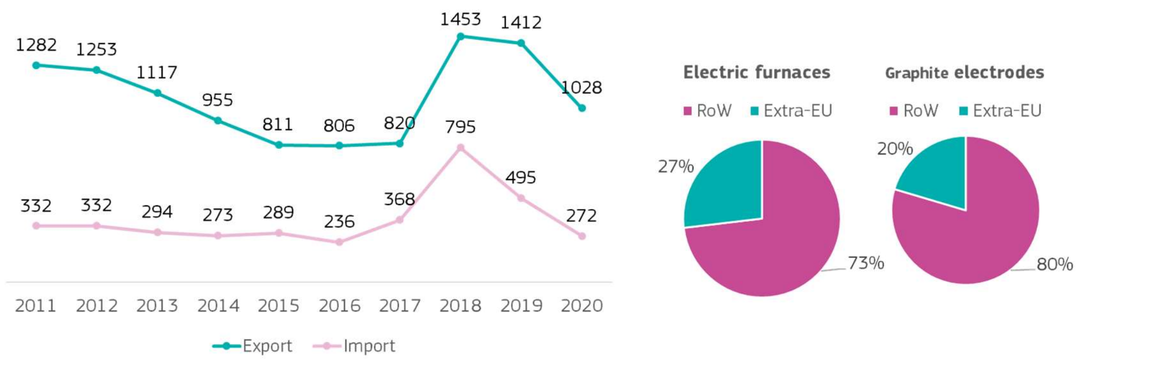
For the purpose of this report, an effort was made to identify production codes specific to manufacturing equipment for the H-DRI and EAF route. Unfortunately, tracking of technology and essential materials is very challenging with the existing production and trade code classifications, which do not offer sufficient granularity to filter out production and trade related to hydrogen steelmaking equipment and technologies, DRI production or EAF equipment and technology. Furthermore, steel plants have long operating lives and are built to order from tailor-made components. In the end, production and trade data for all types of industrial and laboratory electric furnaces and ovens, and graphite electrodes (210) were chosen as a proxy for tracking electric arc furnaces, and the data should therefore be treated with caution.

Production data shows that Germany and Italy are the main producers of electric furnaces. This is consistent with the data for manufacturers of EAF plants in **Table 4**. The EU total has been consistently over EUR 600 million in past years, but dropping to less than EUR 500 million in 2020. The production data of graphite electrodes is kept confidential by Member States. Nevertheless, total EU production peaked in 2018 at EUR 1.5 billion, possibly due to the restart of production in Italy (Steel Orbis, 2018). In 2020, production seemed to be affected by the pandemic and dropped to EUR 0.6 billion.

In 2020, the EU imported 21.2 million tonnes of finished steel products and exported 17.7 million tonnes. After peaking in 2018, imports to the EU have been decreasing. Exports have had a decreasing trend since 2012. The trade balance of the EU turned from positive to negative in 2016, but has improved since 2018 (Eurofer, 2021).

Extra-EU trade of electric furnaces and graphite electrodes shows that the EU exports more than it imports. In electric furnaces, Germany is the biggest EU exporter and third biggest exporter globally behind China and the US. However, there is lots of re-exporting, as many countries, e.g. Germany, Italy and the US are both biggest exporters and importers. The EU captures a 27% extra-EU share of global exports. The peak in 2018 is associated with graphite electrodes, of which Spain is the leading EU exporter and Italy the leading EU importer. The EU exports graphite electrodes mostly to Turkey, Russia, Iceland, Korea and the US. China is by far the biggest exporter to the EU and the biggest exporter globally of graphite electrodes. The EU holds a 20% extra-EU share of global exports of graphite electrodes. According to BloombergNEF, demand for graphite electrodes is expected to grow by 126% between 2021 and 2030, driven by demand for EAF and batteries (BNEF, 2021l).

Figure 92: Extra-EU import & export of electric furnaces and graphite electrodes combined [EUR Million] (left) and extra-EU share in global export of electric furnaces and graphite electrodes in 2018-2020 (right)



Source: JRC based on Comext and Comtrade data

(210) PRODCOM codes: 28211354 ('industrial or laboratory electric furnaces and ovens, excluding induction- and resistance-heated; equipment for the heat treatment of materials by induction, other than ovens and furnaces'), 28211470 ('parts for industrial or laboratory electric, induction or dielectric furnaces and ovens or heating equipment'), 27901330 ('carbon electrodes for furnaces').

A shift towards direct reduction will increase demand for high-grade ores. Therefore, DR-grade pellets will be an important traded commodity in the future, but no detailed trade data is available. Currently, the view appears to be that supply is already quite tight and might get more problematic in the future. The quality of iron ore supply could determine where DRI-plants are sited and spur new technologies to improve utilisation of lower quality ore and sinter (BNEF, 2021k).

20.4 Future outlook

Adoption of new technologies relies on increasing carbon prices in the future. In 2020, the average ETS price was 25 EUR/tCO_2, climbing to nearly 100 EUR/tCO_2 in February 2022. According to external studies, the CO_2-abatement cost for H-DRI steel in the EU is estimated to be between 0 and 144 EUR/tCO_2 breakeven costs (depending on the future cost of electricity and hydrogen). Currently, the free allocation of allowances means that steelmakers are effectively facing much lower carbon rates, weakening the price signal that would incentivise investments (Somers, 2021). However, the Commission's proposal combines the introduction of a CBAM with a gradual phase-out of free allocations to the industry, the current carbon leakage prevention mechanism.

The majority of steel in Europe and globally is produced using blast furnaces that in many decarbonisation pathways will need to be replaced with direct reduction and electric arc furnaces. This could create new business opportunities for many European electric arc furnace manufacturers and engineering companies. The H-DRI pathway will also require the build-up of DRI shaft furnaces, which at the moment are dominated by only a few companies. Also here, European companies are developing new DRI technologies based on hydrogen, and seem to be well placed to capture the growing market. The EU Innovation Fund recently selected for funding, as part of the large scale demonstration projects call, the Hybrit project in Sweden ([211]) (European Commission, 2021e).

European steelmakers, in particular SSAB and ArcelorMittal, have an opportunity to take the lead in green steel, as they have the best-developed strategies to hit net-zero goals and commercial-scale carbon-neutral steel production plans on the way (Bloomberg Intelligence, 2021). However, many other steel producers have announced similar commitments, most recently at COP26 in Glasgow through the Steel Breakthrough Agenda endorsed by 25 countries, following other initiatives, such as the Leadership Group for Industry Transition, led by Sweden and India, and the Clean Energy Ministerial's Industrial Deep Decarbonisation Initiative (IDDI), led by India and the UK. So there is also an emergent momentum building globally.

An important aspect in the commercialisation of low-CO_2 technologies is the creation of markets that can foster demand and an ability to pass on the higher costs of zero-carbon steel today. This has been stressed in the High-Level Group on Energy-Intensive Industry's Master Plan (HLG EII, 2019) as well as in the EU's Industrial Strategy (COM(2020) 102 final) . In the update of its Industrial Strategy, the European Commission stressed the importance of the creation of markets for climate-neutral and circular products (COM(2021) 350 final) . For many downstream sectors, such as automotive, construction and wind, the use of zero-carbon steel can be a competitive advantage and the price premium on final products is relatively small: only about a 1% increase on the price of a car made with green steel (Energy Transitions Commission , 2018; Rootzen & Johnsson, 2016) .

Demand-pull from downstream sectors can be instrumental in accelerating steel decarbonisation, with first signs already emerging. European automakers, e.g. Daimler Mercedes-Benz, partnering with Swedish start-up H2GreenSteel and SSAB, and Volvo Group's collaboration with Hybrit and SSAB, are very proactive in buying green steel (BloombergNEF, 2021c), creating market pull in Europe. There is also an initiative, SteelZero, in which organisations commit to procuring 100% net-zero steel by 2050, with interim objectives by 2030 (The Climate Group, 2020).

([211]) Aiming to produce 1.2 Mt of H-DRI steel annually (including 500 MW electrolysis and replacing two blast furnaces by EAFs.

While green steel would have a price premium today, by 2050, net-zero steel could become cheaper than coal- or gas-based production, according to BNEF (BNEF, 2021m). As steelmaking assets have long investment cycles, it is important to strike the right balance and timing in transforming to new technologies. According to different estimates, the total investments needed to decarbonise the sector in the EU by 2050 are in the range of EUR 66-100 billion ([212]) (IEA, 2020c; Material Economics, 2019; McKinsey, 2021a; Roland Berger, 2020; Bloomberg Intelligence, 2021).

The decarbonisation of steel is dependent on abundant and cheap renewable energy and availability and reduced costs for green hydrogen. According to recent studies, the H-DRI+EAF route using green hydrogen requires around 4 MWh of electricity per tonne of steel ([213]), depending on the electrolyser efficiency and heat integration options (Somers, 2021). In an extreme case, if all current primary steel production in the EU is replaced with the H-DRI route, and taking into account the electricity demand for the secondary route, the power demand of the steel sector alone would represent 35% of the EU's total renewable electricity production in 2019 (Somers, 2021). This could give a competitive advantage to new geographical areas that have access to abundant clean energy. North Africa or Australia could, for example, produce DRI to be exported to EAFs in Europe and elsewhere.

The use of electric smelting processes open up the opportunity to significantly increase the use of scrap compared to the traditional blast furnace route. The big issue with scrap for high quality steel recycling is the contamination of scrap with elements such as copper and tin. Recycling companies that are developing technologies to improve scrap separation and quality are key enablers to increase the circular economy within the EU. A shift to the direct reduction route requires a supply of high quality ores, which are in short supply in existing production sites such as Australia (BNEF, 2021k).

A transition to renewable hydrogen-based steelmaking will require huge amounts of renewable energy. According to one estimate, it would require 30 TWh of new renewable energy per year to produce enough hydrogen to fully convert the production of Voestalpine (Austria's largest steelmaker) – almost half of Austrian electricity demand (2019) (Wyman, 2020; Knitterscheidt, 2019). Just to supply enough green hydrogen for the production of steel at the Tata Steel site in the Netherlands, it is estimated that 4 GW of electrolyser capacity (consuming 35 TWh per year) would be required (Roland Berger, 2021). At European level, if all current primary route production was made via H-DRI, this would require an additional annual energy demand of 400-500 TWh, which corresponds to 18% of total EU consumption currently (Rechberger, et al., 2020).

The European steel industry experienced a slump in 2020, seeing a drop in production of 11%, but bounced back with a demand recovery and a surge in steel prices in 2021, allowing European producers to improve their margins. The pandemic brought about a reshuffling amongst the top steel producing companies globally (Somers, 2021). Chinese firm Baowu Group overtook ArcelorMittal (LU), the top producer over the last two decades, by a considerable margin in 2020. Seven of the top ten global producers are now Chinese, and only one other EU company, Thyssenkrupp, is within the world's top 50.

([212]) Bloomberg Intelligence have used a capital intensity of EUR 220-260 per tonne of CO_2 abated as a benchmark to estimate capital investment costs. Thus, to achieve 30% emission reduction by 2030 would incur EUR 23 billion of capital investments and to achieve net-zero, it would be as high as EUR 66 billion, which excludes the build-out of hydrogen infrastructure and renewable energy capacity.

([213]) Hydrogen electrolyser represents 75% of this electricity demand, which indicates strong interlinkage with development of the hydrogen production value chain.

20.5 Scoreboard and key insights

The EU is already a leader of energy- and CO_2-efficient steel production, based on average CO_2-intensities (Somers, 2021), thanks to years of incremental improvement and a strong EU framework for applying best available technologies (BATs). The EU is also leading in patenting activity in breakthrough technologies, such as H-DRI, with a 30% share of high-value inventions globally. Also, two thirds of global decarbonisation projects, as identified by the Green Steel Tracker dataset (Vogl, et al., 2021), are based in Europe. This indicates that the EU has the capacity to capture the emerging market opportunities. European downstream industries, such as automotive, seem to be the lead markets, creating demand pull to green steel.

Deep decarbonisation of steel will, nevertheless, depend on the accelerated development and adoption of other technologies, such as electrolysers and hydrogen infrastructure, and the availability of abundant renewable energy. This will require vast infrastructure investments and coordinated cross-border planning between Member States and industry.

Figure 93: Scoreboard for decarbonisation of steel through H-DRI and electrification

Scoreboard	**Steel (H-DRI and electrification)**	EU performance in the reference period		
Public R&D			2015-2019	EU CAGR
Early Stage		6%	2015-2020	EU share of global total value
Later Stage		0.04%	2015-2020	EU share of global total value
Patents		30%	2016-2018	EU share of global total HVI
Companies		43%	2015-2020	EU share of innovating companies
Employment		0.1%	2015-2019	EU CAGR
Production		-3%	2015-2020	EU CAGR
Turnover		8%	2015-2018	EU CAGR
Imports & Exports		22%	2018-2020	EU share of global exports
Trade Balance		High	2015-2020	EU trade balance trend

Source: JRC

21 Decarbonisation of cement through CCUS

The European Green Deal recognises that 'energy-intensive industries, such as steel, chemicals and cement, are indispensable to Europe's economy, as they supply several key value chains.' Cement, which together with a mixture of aggregates (sand, gravel and crushed stone) and water make up concrete, accounts for 95% of its CO_2 footprint. Concrete has a colossal carbon footprint — at least 8% of global emissions caused by humans come from the cement industry alone (Ellis, et al., 2019). Thus, the decarbonisation of this sector is essential if we are to achieve climate neutrality by 2050.

21.1 Overview of the solution and current status

Cement has two main sources of CO_2 emissions: the burning of fossil fuels in the clinker/lime furnace and the process-related emissions from the decarbonisation of the limestone. Together these two sources make up about 85% of total CO_2 emissions of the entire Portland cement (the most common type of cement) production value chain. For this sector, where the CO_2 mitigation potential is limited, breakthrough technologies are essential for achieving the necessary reductions. Carbon Capture and Storage (CCS) or Carbon Capture and Utilisation (CCU) can reduce emissions by up to 75% compared to 2010 (CEMBUREAU, 2013).

In Europe, there are currently three CCUS projects under construction in the cement sector, expected to be operational in the mid-2020s. These projects are the HyNet North West - Hanson Cement CCS (UK), LEILAC (BE) and Norcem Brevik (NO). In September 2021, two more initiatives were announced, one in France and one in Poland. More recently, a project in France, awarded under the Innovation Fund, will capture unavoidable emissions in a cement plant. The captured CO_2 will be partly stored geologically in the North Sea and partly integrated into concrete.

While there is clear momentum building in the sector, there are also associated challenges. The first is economic: in this industry, profit margins tend to be low and cyclical, varying according to the cost of raw materials and the rate of economic growth. Thus, investment in new technology may not be a priority in company budgets (Gross, 2021). While decarbonisation is a one-way path, the price of cement is expected to escalate massively when the industry invests in technology to lower its emissions. The costs of producing the construction material could double for the production of clinker with CCS technology (Gardarsdottir, et al., 2019). The second challenge is technological: while direct CO_2 capture and oxycalcination are promising technologies with great potential for new cement plants, the prospect of their use in the retrofitting of existing plants is less likely. Given the current overcapacity, and the age and life ahead of existing facilities, the construction of new cement plants integrated with CCUS at a relevant scale for climate mitigation seems unlikely. Post-combustion CO_2 capture technologies are the preferred option for retrofitting existing facilities (Plaza, et al., 2020). Thirdly, trade raises additional challenges. Materials that produce large emissions are often traded internationally. This means that regulating emissions in one area may push production and emissions into another market, rather than eliminating them, an effect known as carbon leakage.

To address this issue, the European Commission adopted a proposal for a new Carbon Border Adjustment Mechanism (CBAM) on July 2021. As the EU Emissions Trading System (EU ETS) becomes stricter and a border tax on carbon is introduced for products entering the EU, carbon capture technology will become necessary for cement manufacturers to reduce emissions. The increasing price of the EU ETS allowance and the proposal for the new CBAM are expected to ease the effect of investing in CCS for the industry and eventually make them competitive.

Norway's Norcem Brevik will make use of amine-based Aker solutions' ACCTM technology to capture 0.4 Mt CO_2/y by 2023. LafargeHolcim cement carbon capture will use Svante's adsorption-based VeloxothermTM process to capture up to 2 Mt CO_2/y. LEILAC 2 will also demonstrate CO_2 capture with its 'direct separation' technology at the significant scale of 0.1 Mt CO_2/y by 2024. While HyNet North West - Hanson Cement CCS is conducting a feasibility study as of October 2021, the plan is to develop a 800 000 t/yr carbon capture installation at Hanson UK's Padeswood cement plant in Flintshire.

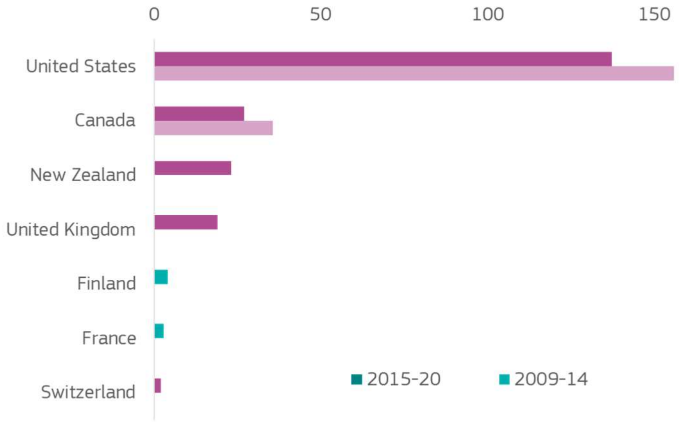
Companies that dominate the European scene include Heidelberg Cement (Germany), Holcim (Switzerland), Italcementi (Italy) and Lafarge (France). Heidelberg Cement, Calix, IKN Gmbf, Italcimenti and LafargeHolcim are the ones with the most involvement in CCS projects. Eqiom Bétons is also participating in the project recently awarded by the Innovation Fund.

21.2 EU positioning in innovation

Public R&D data tracked by the IEA includes only the broad category of CCUS. In the EU, R&D investment has primarily been dispersed through Horizon 2020, with nearly EUR 80 million in funding for the sector.

In terms of venture capital investment, no early stage investment have been identified in the EU. However, Horizon 2020 has funded two small & medium enterprise (SME) projects, coordinated in the UK and in Norway. Nevertheless, this contribution is fairly small, confirming the observation that it is mostly large corporates who are leading activity in the sector in the EU. Between 2015 and 2020, Finland (EUR 4 million) and France (EUR 3 million) were the only EU countries with some later stage investment activity, albeit minimal when compared with the US which is the country with the highest later stage investment (~EUR 122 million), see **Figure 94**.

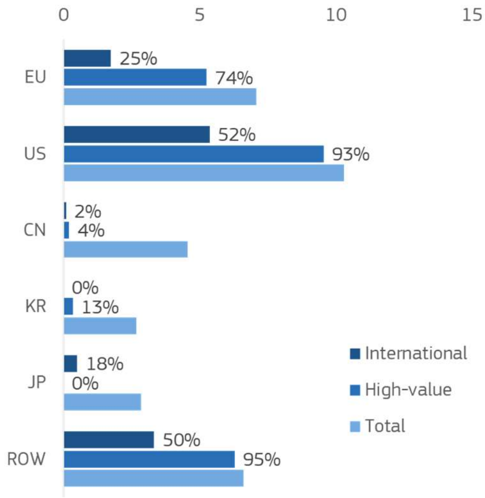
Figure 94: Top countries in early and later stage investment [EUR Million]



Source: JRC based on Pitchbook

Concerning patenting activity, the EU registered seven inventions in the cement sector, coming second to the US with 10 inventions. **Figure 95** shows that 25% of these inventions represent international activity and 74% are high-value inventions, i.e. those containing applications to more than one office, effectively seeking protection in more than one country or market.

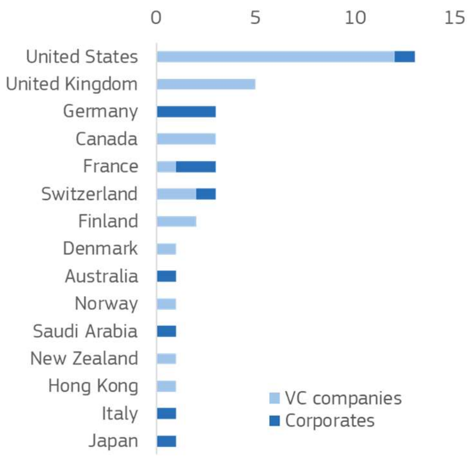
Figure 95: Number of inventions and share of high-value and international activity for major economies in 2016-2018



Source: JRC based on EPO Patstat

The US and UK host the most innovating companies and a large majority of all start-ups and scale-ups in this sector (**Figure 96**). The EU hosts only 13% of all VC companies. However, the EU has some important patenting corporates. Half of the top ten companies with high-value CCUS inventions in the cement sector are European. These are the German Thyssenkrupp AG, Thyssenkrupp Industrial Solution AG, Heidelbergcement AG and Hconnect 2 GMBH, the Italian Italcement SPA and the French Soletanche Freyssinet. Thyssenkrupp and Heidelbergcement also participate in consortia undertaking Horizon 2020 projects (ANICA, AC2OCEM, and LEILAC 2).

Figure 96: Number of innovating companies in 2015-2020



Source: JRC compilation of sources

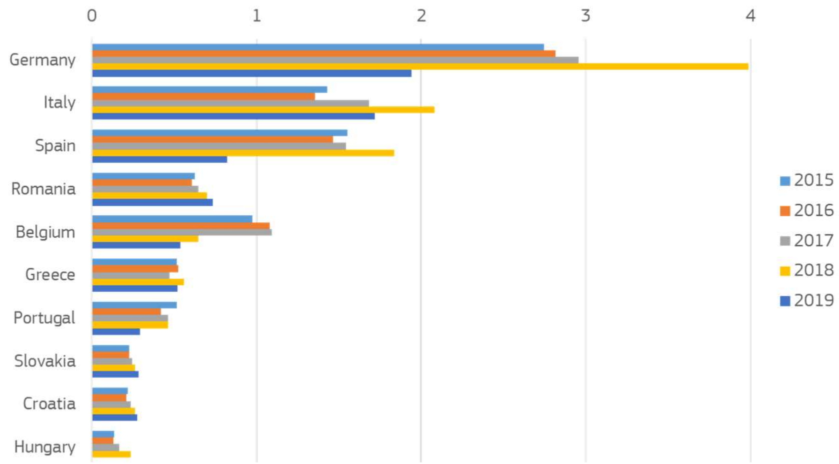
There are a number of different CCS technologies that are applicable to cement production, for example variants of post-combustion CO_2 capture such as solvent scrubbing or the use of solid sorbents, calcium looping, oxy-fuel and 'direct capture'. Direct capture uses the indirect radiative heating of the limestone-containing raw meal feed to the system to 'directly' produce a pure stream of CO_2 (Bui, et al., 2018). Moreover, there are breakthrough technologies which are enabling inherent CO_2 capture, without requiring additional work or energy for CO_2 separation. While these could lead to considerable reduction in capture costs, they cannot be retrofitted to existing plants as they incorporate CO_2 capture into their fundamental process design. Typical examples are the Allam-Fetvedt power generation cycle and the Calix Advanced Calciner for lime and cement manufacturing. Svante's VeloxoThermTM is another breakthrough technology that has been selected for a front-end-engineering-design (FEED) study to capture CO_2 from the flue gas of the cement kiln and natural gas-fired boiler in a Lafarge Holcim cement production facility in the US (Global CCS Institute, 2021). The mineralisation of CO_2, also known as mineral carbonation or CO_2 mineral sequestration, for the long-term storage of CO_2, is another CCS option (Metz, et al., 2005). In the cement sector, the technology works by injecting CO_2 into the concrete mix, where it reacts with calcium ions found in cement and converts into calcium carbonate.

21.3 EU positioning in current market

In 2018, there were 56 000 cement sector ([214]) direct jobs in the EU. Germany is the country with the most direct jobs in the sector (~14 000), followed by Italy (6 450 direct jobs) and Spain (5 405 jobs). Except for Germany, for which employment spiked in 2018 (~14 000 direct jobs) compared to the previous years (~8 000 on average for 2015-2017) or most of the leading countries in the sector, employment in the sector has been steady. Similarly, in 2018, Germany had the highest turnover (~EUR 4 billion) followed by Italy (~EUR 2 billion) and Spain (~EUR 1.8 billion). Germany recorded the highest turnover, with an upward trend from 2015, which is also the case for Italy and Spain (except for 2016). With the exception of Belgium, which recorded a decrease in turnover from 2018, and Hungary, which showed an increase in turnover from 2018, the rest of the top 10 EU countries document relatively steady turnover values. At EU level, turnover grew between the years 2016 and 2018 from nearly EUR 15 billion to EUR 18 billion. The cement sector also supports other sectors, such as construction. There is no data on how big a share of this is related to the decarbonisation of cement, but it gives an indication of the significance of the industry to the EU.

([214]) Manufacture of cement.

Figure 97: Top 10 EU countries by turnover in 2015-2019 [EUR Million]



Source: JRC based on Eurostat SBS data

For production and trade, we have used amines as a proxy because they are essential to post-combustion carbon capture. The EU production value of amines has been relatively steady since 2013. After a spike in 2018 with a production value of EUR 201 million, it has been decreasing ever since with production values of EUR 169 million and EUR 174 million in 2019 and 2020, respectively. The figures have not been made publicly available at national level.

With regard to trade, Belgium, Spain, Germany, Italy and France were the leading importers of amines in the EU between 2018 and 2020. Belgium was also the top exporter, with a positive trade balance of EUR 55 million, followed by Sweden, Germany, the Netherlands and Spain. In 2020, Sweden enjoyed a positive trade balance of EUR 22 million while Spain, Italy and France were neutral or negative (EUR 28 million, EUR 15 million and EUR 0 million, respectively). Within Europe, Belgium's top export partners were Germany, France, Italy, the Netherlands, Spain and Austria. Beyond the EU, Belgium exported amines to the United States, the United Kingdom and China. Sweden's destinations were Italy, Belgium, Germany and Poland. Outside the EU, Sweden exported amines to Norway, China, Turkey, Argentina, Brazil and the United Kingdom. Spain imported amines from Germany, Belgium and France, and to a lesser extent from Sweden, the Netherlands and Italy. Outside the EU, Spain's import partners were Saudi Arabia, Mexico and the United Arab Emirates.

Globally, Saudi Arabia is the biggest exporter, while China is the biggest importer of amines. Belgium, Sweden and Germany are the biggest EU exporters. The EU has a 24% share of all global exports and 15% share if intra-EU trade is excluded. A full 65% of EU imports are in fact EU internal trade. The EU captures over 75% of all UK and US imports, although EU exports to the US are decreasing in the most recent years. The EU only captures 10% of imports in the biggest non-EU import markets, China and India.

21.4 Future outlook

The European Green Deal aims to make Europe climate-neutral by 2050. The Climate Law converted this political commitment for climate neutrality into a legal obligation. Raising the EU's 2030 climate target to 55% is further incentive to act urgently. These targets make the role of CCUS even more critical, and large-scale deployment within the 2020s will be crucial for the climate ambitions of the European Union.

Norway has committed almost EUR 1.6 billion (NOK 16.8 billion) to the Longship project, which aims to be operational by 2024. In 2020, the first call for projects under the EU's EUR 10 billion Innovation Fund was launched and four CCUS projects were selected. One of these, the K6 project, will reduce CO_2 emissions at the Lumbres cement plant in France.

Fostering innovation, Horizon 2020 has funded projects in Belgium, Germany and Italy and more calls for CCUS are expected in the successor funding scheme, Horizon Europe.

The European Commission's Joint Research Centre (JRC) compared the decarbonisation options in eight scenarios across four publications, which explore different pathways to achieve deep decarbonisation of the cement sector by 2050. All scenarios achieving deep decarbonisation of the sector include carbon capture technologies, seen as the most important technology to reduce process emissions (JRC, 2020b). Furthermore, a recent study suggests that the global market for CCUS could be in the region of EUR 300 billion (GBP 260 billion) turnover per annum by 2050 (UK for Business, Energy & Industrial Strategy, 2021).

In reality, 2021 has seen unprecedented advances for CCUS technologies. So far, more than 100 new CCUS facilities (in all sectors) have been announced worldwide, and the global project pipeline for CO_2 capture capacity is on track to quadruple. In Europe, it is the first time that two CCS projects, one in Norway (Norcem) and one in France (Dunkirk), will be under construction simultaneously in the cement sector.

Of the European cement leaders, LafargeHolcim is expanding its CCUS portfolio, with more than 20 projects across the US, Canada and Europe.

There is no agreed definition or model for identifying a complete CCUS supply chain. While the main elements of the supply chain are distinct and well known (capture, transportation, utilisation and/or storage), the services that could accommodate this chain directly and indirectly are not mapped. These need to be identified, mapped and understood in terms of capability development, skills and innovation, and finance and trade. Only then can any issues or potential material dependencies be identified for deploying CCUS at scale in the cement sector.

Nevertheless, the essence of a global CCUS supply chain is the facilitation of transport and the best use of storage capacity, where certain regions can receive CO_2 from other regions with limited storage capacity or restrictions in CO_2 storage (Zhang, 2021)([215]).

Industrial facilities are long-lived assets and thus bear the risk of "locking in" emissions for decades. Furthermore, exposure to highly competitive, low-margin international commodity markets highlights the challenges they have to face. Such exposure allows for limited space for companies to invest in innovation or low-carbon production routes where this increases costs. For companies operating globally, an increase in production costs by adopting low-carbon processes and technologies will put them at an economic disadvantage. This is especially the case where there is no carbon price or CO_2 emissions are not regulated.

On 14 July 2021, the European Commission adopted a proposal for a new Carbon Border Adjustment Mechanism. This will put a carbon price on imports of a targeted list of products so that European climate targets do not lead to 'carbon leakage'. This may be an opportunity for European industry, discouraging carbon-intensive production from being forced outside Europe.

The IEA suggests that 'establishing a market for premium lower-carbon materials can minimise competitiveness impacts. Public and private procurement for lower-carbon cement, steel and chemicals can accelerate the adoption of CCUS and other lower-carbon processes. The large size of contracts for these materials could help establish significant and sustainable markets worldwide' (IEA, 2019c).[216]

Experience has shown that there is no one-size-fits-all policy approach to support investment in CCUS industrial applications. Policies will need to consider the specific characteristics of each sector and the challenges the industries are facing in different regions, including potential impacts on their competitiveness.

([215]) In this regard, the multilateral cooperative mechanism enabled by the London Protocol offers the most feasible approach to achieve this objective. The London Protocol provides a framework for preventing sea pollution from dumping or waste and other matter incineration at sea, and by activities including carbon capture and storage in sub-seabed geological formations and marine geoengineering activities, such as ocean fertilisation.

21.5 Scoreboard and key insights

With regard to innovation, the EU seems to trail behind the US and the rest of the world in CCUS technological development, but not by far. The EU did not capture any early stage investment deals in 2015-2020 and only attracted 5% of later stage investments. The EU is also behind the US in patenting activity, however, capturing 24% of all high-value inventions, which is nearly at the threshold of strong performance German, French and Italian companies are among the global leaders in high-value filings. While big EU corporates are well represented in this area, the EU hosts only 13% of the world's VC companies. 2021 has seen an unprecedented level of announcements, so technological advances are picking up, and the EU should be careful not to get left behind.

EU cement manufacturing is an important sector, providing direct jobs to about 56 000 people and generating EUR 18 billion in turnover in 2018, with an increasing trend since 2016. The EU's chemical cluster is an important player in the global trade of amines, essential components for post-combustion carbon capture. Belgium stands out in particular as the biggest EU importer and re-exporter. EU exports and imports are both growing, and in 2020, the trade balance moved from deficit to surplus for the first time since 2018. Globally, Saudi Arabia is the biggest exporter while China is the biggest importer.

Figure 98: Scoreboard for decarbonisation of cement through CCUS

Scoreboard	**CCUS for cement industry**	EU performance in the reference period		
Public R&D			2015-2019	EU CAGR
Early Stage		0%	2015-2020	EU share of global total value
Later Stage		5%	2015-2020	EU share of global total value
Patents		24%	2016-2018	EU share of global total HVI
Companies		24%	2015-2020	EU share of innovating companies
Employment			2015-2020	EU CAGR
Production		-1%	2015-2020	EU CAGR
Turnover		10%	2016-2018	EU CAGR
Imports & Exports		15%	2018-2020	EU share of global exports
Trade Balance		High	2015-2020	EU trade balance trend

Source: JRC

22 Ammonia use as fuel

For the world to decarbonise, shipping must decarbonise (World Economic Forum, 2021), and achieving carbon neutrality in the shipping sector by 2050 requires that zero-emission ships become the dominant choice by 2030. However, while technologies to produce zero-emission fuels and vessels are to a large extent available, they are in most instances not market ready. Similarly, the higher costs and limited availability of sustainable alternative fuels creates a wide competitiveness gap with respect to traditional fuels.

Ammonia is likely to play a notable role while transitioning on a path to zero in 2050 and represents a credible long-term zero-emission fuel for deep sea routes (Fahnestock, et al., 2021). The use of green ammonia in dual-fuel engines is one of the main fuel pathways foreseen for the deep decarbonisation of shipping from the outset. Ammonia can be used in gas turbines and as a primary fuel in fuel cells, thus constituting an appealing and competitive alternative to other maritime fuels. It is a more cost-effective solution than hydrogen and it is envisioned that ammonia powered-systems will become the most favourable in economic terms (fuel cost and total cost of vessel ownership) (Cheliotis, et al., 2021; Maersk Mc-Kinney Moller Center for Zero Carbon Shippin, 2021). In addition, its future competitiveness will not be affected by scaling constraints as in the case of biofuels, by the limited availability of biogenic carbon sources as in the case of e-methanol, or by the costs for natural gas as a feed stock and carbon capture as in the case of blue fuels (Maersk Mc-Kinney Moller Center for Zero Carbon Shippin, 2021).

22.1 The scope of the solution and current status

The scope of this solution covers the production of ammonia synthesised from green hydrogen, its supply, storage, distribution and use as a maritime transport fuel (by direct combustion in an engine or a turbine or by direct chemical reaction in a fuel cell) and as a green energy carrier. It excludes the currently predominant production processes based on natural gas and carbon capture (blue ammonia) or methane pyrolysis (turquoise ammonia), the existing uses of ammonia (fertilisers, refrigeration, explosives, textiles and pharmaceuticals) and its use as energy storage for electricity generation or heat transfer.

Ammonia is one of the primary chemicals with the largest production volume and is to a very large extent produced from natural gas-based steam reforming (IEA, 2021h) and used as fertiliser. It benefits from well-established infrastructures and as opposed to hydrogen, there is already significant industry expertise in port handling and on board storage of ammonia as a commodity (but not as fuel)(The Royal Society, 2020). The current production of ammonia could, however, only cover a moderate fraction of the demand for marine fuels (Brinks & Hektor, 2020) and, moreover, the current production of green ammonia via electrolysis only represents a fraction of a percentage point of the current market (IEA, 2021h).

Ammonia can be viewed as a fuel that can be ready across the value chain within a timeframe of 3-4 years (Frelle-Petersen, et al., 2021) and is expected to play a pivotal role beyond 2030. Its deployment phase is, however, likely to rely on the transitional use of blue or turquoise ammonia, as green ammonia production facilities have not yet reached technological and commercial readiness. Indeed, green ammonia production is not yet cost-competitive as compared to conventional fossil-fuel based ammonia, and the new pilot projects scheduled in the coming years only aim to bring the total production of green ammonia for conventional uses to 3 Mt by 2030 (IEA, 2021h).

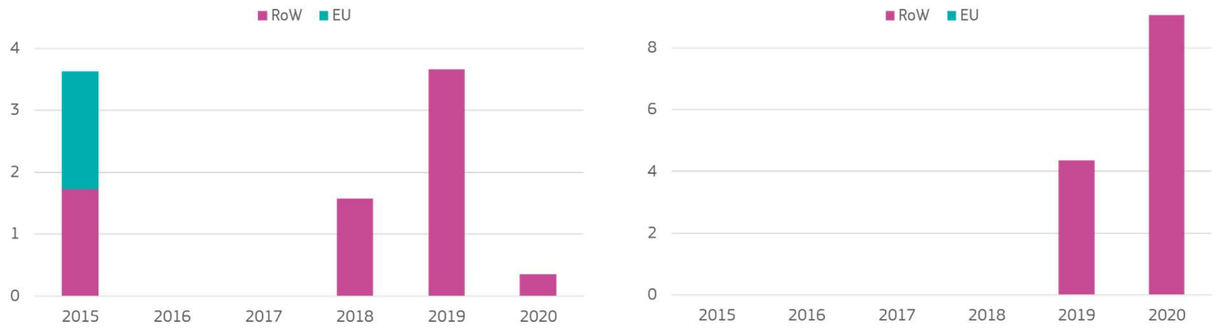
Similarly, technological and commercial gaps are still to be filled and there is a general need for demonstration projects at every segment of the value chain. In particular, the safe bunkering and on board management of ammonia as a fuel has not been proven on a commercially sustained basis and there is a need to further develop technological safety mechanisms and legal frameworks. Furthermore, ammonia-based propulsion systems still require further development, both for engine and fuel cell systems.

22.2 EU positioning in innovation

Public funding trends are not available, as IEA classification does not allow for sufficiently specific tracking of investment flows. However, among 21 pilot and demonstration projects identified worldwide (Fahnestock & Bingham, 2021) for the production and use of green ammonia as a maritime fuel, seven have received public funding (four in the EU and three in Norway). It is also worth noting that the EU has funded several R&D projects with a consolidated investment of EUR 30 million since 2020, targeting the novel production processes of green ammonia (Telegram, ORACLE) and its use as an alternative fuel in vessel engines (ENGIMMONIA), fuel cells (ShipFC) and direct conversion (HiPowAR) applications.

The number of venture capital companies which have been identified remains very limited, confirming that the innovation effort is mainly led by public research institutions and corporate industrials. Recent early stage investments (**Figure 99**) were made in venture capital companies that are not located in the EU and mostly consist of grant funding. They benefited a few companies that address clean ammonia synthesis technologies (Starfire energy, US), after exhaust treatment (Daphne Technology, US) and ammonia fuel cells (GenCell, Israel). While investment in the EU accounts for 21% of early stage investment overall in 2015-2020, it was limited to grant funding in 2015. Similarly, no later stage investment has been made in the EU since 2015.

Figure 99: Early (left) and later (right) stage investment by region [EUR Million]



Source: JRC based on Pitchbook

Due to the lack of specific identification codes, patents cannot be used to identify corporate innovators, monitor areas of innovation or produce statistics. There are, however, clearly identified needs for technology improvement and the testing and demonstration of prototypes for a better knowledge of the operational behaviour of ammonia across the value chain.

A review of pilot and demonstration projects identified across different sources (Frelle-Petersen, et al., 2021; Fahnestock & Bingham, 2021; IEA, 2021i) indicates that the EU is showing strong leadership, with key EU industry players driving the innovation effort. EU- and industry-led initiatives such as the Maersk Mc-Kinney Møller Center for Zero Carbon Shipping (Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, 2022) and Ammonfuel (Ammonia Energy Association, 2022) are also developing industry-wide perspectives for the use of ammonia as a marine fuel.

MAN Energy Solution (Germany) has announced that it will conduct the first R&D engine tests on ammonia at full scale in 2022 (MAN Energy Solutions, 2020) and the demonstration of a full engine test, including emission after treatment, to the market in 2023-24. Wärtsilä (Finland) has announced that it will proceed to field-test ammonia in dual-fuel and spark-ignited gas engines in collaboration with ship owners in 2022 and is also planning to test an ammonia four-stroke engine together with partners (Ammonia Energy Association, 2020). There are also planned retrofit engine (Motorship, 2020) and ammonia fuel cell (Fraunhofer, 2021) solutions for existing ships. Among the 21 pilot and demonstration projects identified worldwide by the Getting to Zero Coalition (Fahnestock & Bingham, 2021) for the production and use of green ammonia as a maritime fuel, six are located in Europe and 10 rely on collaborations, including a leading EU innovator.

We also currently identify nine more advanced pilot plants projects dedicated to the production of green ammonia. Four are located in the EU (two in Denmark, one in Spain and one in the Netherlands), one in Norway and four in Australia, Chile, the United States and the United Arab Emirates. In particular, Haldor Topsøe (Denmark) is developing a facility based on Solid Oxide Electrolyser Cells (SOEC) electrolysis, to be ready by 2024 (Topsoe, 2021). Yara (Norway) together with industrial partners, announced in 2021 the development and demonstration of the world's first green ammonia bunkering terminal (Yara, 2021).

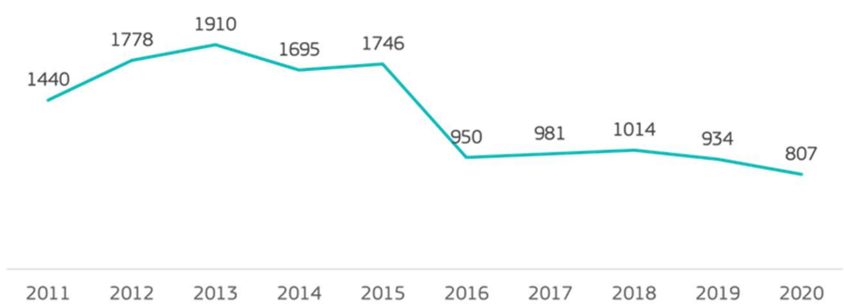
While ammonia synthesis is a technology-ready process, further innovation related to the development of electrolysers for green hydrogen could further reduce the capital and operational costs of ammonia. New approaches to displace the energy-intensive Haber-Bosch process are being developed (e.g. thermal-, electro-, plasma-, and photocatalytic ammonia synthesis using new catalysts, electrodes, and sorbents)). Ammonia is not currently handled as a fuel and there is a need for further demonstration of concepts for bunkering vessels (with ship-to-ship fuelling while loading cargo), of safe piping and of control systems. The prevention of ammonia slip to ensure safe on-board storage and novel ship design to adapt to higher volumes of fuels constitute key innovation areas for vessels operations. For propulsion, improvements in injection and combustion technologies are needed for the development of ammonia engines, in combination with NOx emission reduction systems. As an alternative, the use of ammonia requires direct ammonia fuel cells.

22.3 EU positioning in current market

There are currently no available identification codes for trade and production that specifically relate to production or energy conversion technologies for green ammonia. There is no market yet for the use of green ammonia as a maritime fuel, and production facilities are still being planned or at an early stage of scale-up. The following analysis is therefore based on global trade and production codes related to the production of ammonia as a commodity and does not differentiate between production pathways or applications, and thus provides an overview of EU positioning in the current ammonia market as an indication of the starting point and the scale of the opportunity in transitioning towards green ammonia.

Global ammonia production volume amounted to 185 Mt in 2020, of which the EU only represents 8%, far behind China (29%), Russia (10%), the United States and the Middle East (9% each) (IEA, 2021i). EU ammonia production has halved since 2013, to EU 807 million in 2020 (**Figure 100**). It is difficult to determine where EU production has declined as not all EU countries disclose their production data.

Figure 100: EU production value [EUR Million]



Source: JRC based on PRODCOM data

The EU is a mature market for the international trading of ammonia as a commodity and hosts around 20% of the bunkering infrastructures in ports currently identified worldwide (Ammonia Energy Association, 2022; IEA, 2021i; DNV, 2022). Over the past 3 years, 66% of EU imports came from outside the EU while the EU only accounted for 2% of global extra-EU export. This is also reflected in trade deficit, which has slowly reduced, reaching EUR 478 million in 2020 (**Figure 101**). The relative trade balance remains largely negative in almost all EU Member States, with the exception of Croatia, Hungary, Poland, the Netherlands and Slovakia. Top exporters to the EU are large natural gas-producing countries, in particular Russia (EUR 680 million), Algeria (EUR 658 million) and Trinidad (EUR 308 million).

Figure 101: Extra-EU trade balance [EUR Million]

Source: JRC based on COMEXT data

22.4 Future outlook

Following a global agreement at COP 26 to speed up action to reduce emissions, the International Maritime Organization (IMO) has agreed to revise its initial greenhouse gas (GHG) Strategy by 2023 (IMO, 2021) but has failed to commit to the full decarbonisation of international shipping by 2050.

As part of the Fit-for-55 communication (COM(2021) 550)([217]), the European Commission has put forward key measures to support such a target, including the FuelEU Maritime Regulation proposal (COM(2021) 562)([218]), the inclusion of shipping in the EU Emissions Trading System, the revision of the Renewable Energy Directive (RED II) and the revision of the Alternative Fuels Infrastructure Directive (AFID). While remaining technology neutral, this regulatory basket proposes a consistent framework to support the uptake of green ammonia as a maritime transport fuel by incentivising decarbonising behaviours, pushing the use of low-carbon fuels and supporting their production and supply.

The EU hydrogen strategy and the momentum behind electrolytic hydrogen projects on the supply side (see Chapter 14) places the EU in a good position to decarbonise a major share of its ammonia production via electrolysis (up to 70% by 2050 in IEA SDS scenarios (IEA, 2021i)). The EU would then account for 25% of global electrolysis-based ammonia production, on an equal footing with China (considering the rapid build-up of its capacity) and India (as one of the largest projected markets for renewables deployment in the coming years).

Beyond 2030, the share of ammonia in the maritime fuel mix is expected to increase steadily, to between 25% to more than half by 2050 (Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, 2022; Ammonia Energy Association, 2022; DNV-GL, 2019; IEA, 2020d), depending on the transitional role that LNG will play towards deep decarbonisation. As it becomes the destination fuel for ocean-going vessels, ammonia could represent roughly 130 Mt of annual fuel consumption, almost twice as much as that used worldwide for fertiliser production in 2019 (IEA, 2020d).

A transition towards the use of green ammonia as an alternative maritime fuel requires industry and policymakers to act in concert, from global to local. The early years of the transition are indeed made more complicated by the several alternative fuel options and their much higher price than the fossil fuels used today.

Ensuring proper incentive schemes is essential to avoid any delays in investment in favour of short-term solutions such as LNG (Englert, et al., 2021) which would not achieve deep decarbonisation in the long term, and could result in technology lock-ins and stranded assets.

Other gaps related to the safe bunkering, on-board management and conversion of green ammonia as a maritime fuel, together with its limited availability, limit its relevance to the medium and long term. Green ammonia is expected to play a pivotal role beyond 2030, but decarbonising the industry still requires the parallel deployment of other net-zero fuel alternatives such as biofuels and blue fuels.

The main challenges for the uptake of this solution are therefore the adoption of global transition strategies and industry-wide measures, and the identification of first movers that can push the industry to reach a tipping point (Smith, et al., 2021). Like other net-zero maritime fuel solutions, green ammonia is not yet seen as a prospective commercial opportunity across the value chain. The necessary investments will not be realised unless actors across the value chain commit and collaborate, from ship-owners and maritime fuel producers to port infrastructures, and without an enabling regulatory framework to support innovation, new business models and new financing solutions.

Overcoming the first mover challenges requires collective action and the sharing of risks to support the scaling up of pilots and demonstrators into industry-wide solutions via initiatives such as:

- Mission Innovation's Zero-emission shipping partnership to foster innovation and international collaborations between states, international organisations, research institutions and corporations.
- The establishment of industrial alliances such as the new industrial alliance proposed by the European Commission to boost the supply and affordability of renewable and low-carbon fuels.
- The development of green corridors, supported by enabling policy measures and investments along trade routes between major port hubs where zero-emission solutions are supported.

([217]) COM(2021) 550 final, 14th July 2021 Brussels

([218]) COM(2021) 562 final Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC

Industry leadership cannot, however, drive the transition alone, and the activation of other critical levers is essential to ensure a global level playing field, unlock project finance and bridge the competitiveness gap with:

— Safety and environmental standards to provide a clearer framework for new technologies and solutions.

— Common metrics for carbon accounting, clarifying emissions from the various links in the cycle of extraction, production and use of fuels.

— Global carbon pricing designed to support both developing countries and early adopters where revenue can be reinvested in the industry through subsidising R&D or infrastructure projects.

— The development of green financing mechanisms to help the industry support the required capital expenditures.

22.5 Scoreboard and key insights

Green ammonia as an alternative fuel for maritime transport represents an opportunity for the EU to decarbonise its own production, supply an emerging market and reduce its dependency.

The EU is showing strong leadership, with key industry players driving the innovation effort towards commercial demonstration and developing a global and industry-wide perspective. This first mover dynamic is supported by EU public funding for R&D projects – albeit upstream – dedicated to the production of green ammonia and its use in vessel applications.

EU production of fossil-fuel based ammonia has been halved since 2013, and meeting current EU demand relies to a large extent on imports from non-EU and large natural gas-producing countries. While the trade balance has been improving, it remains largely negative in most EU Member States.

The EU is a mature market for the trading of ammonia as a commodity, and benefits from well-established infrastructures in ports. The market for green ammonia remains very limited, and as production pilot projects are still at an early stage, there is no information yet on EU performance.

There is, however, a clear lack of private venture capital investment in the EU and worldwide, despite its importance in this early phase. This emphasizes the need for supporting policy measures and a dedicated community of stakeholders to facilitate collaboration and foster investment across the whole value chain and along trade routes.

Figure 102: Scoreboard for ammonia use as fuel

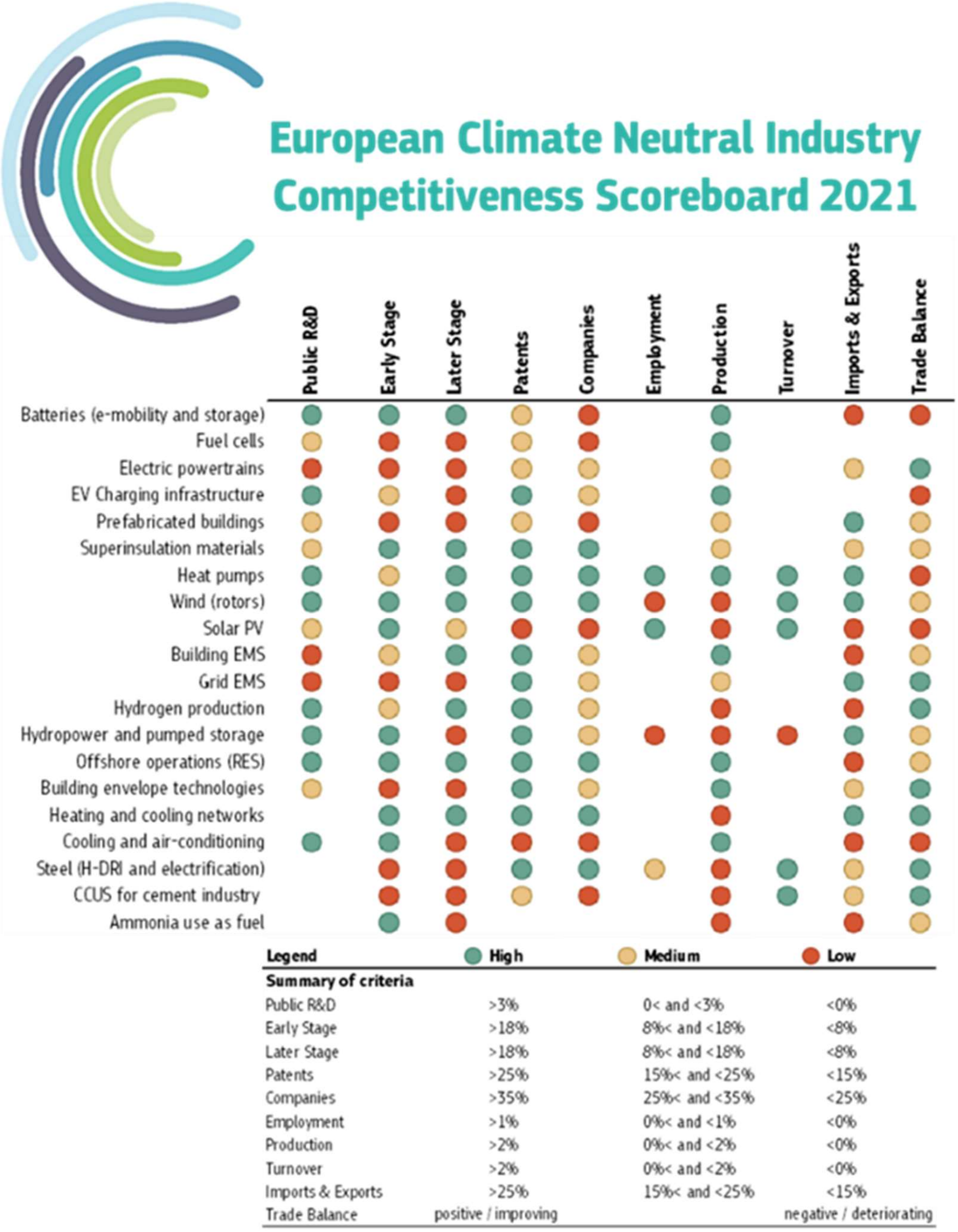
Scoreboard	**Ammonia use as fuel**	EU performance in the reference period		
Public R&D			2015-2019	EU CAGR
Early Stage	● (green)	21%	2015-2020	EU share of global total value
Later Stage	● (red)	0%	2015-2020	EU share of global total value
Patents			2016-2018	EU share of global total HVI
Companies			2015-2020	EU share of innovating companies
Employment			2015-2020	EU CAGR
Production	● (red)	-14%	2015-2020	EU CAGR
Turnover			2015-2020	EU CAGR
Imports & Exports	● (red)	2%	2018-2020	EU share of global exports
Trade Balance	● (yellow)	Medium	2015-2020	EU trade balance trend

Source: JRC

23 Conclusions

European industry plays a central role in delivering the transformational change needed to achieve climate neutrality, reduce energy dependency and address rising energy prices. In order to succeed, EU industry needs to remain competitive and continue to innovate. This new scoreboard measures EU progress on climate neutral solutions key to achieving these goals (**Figure 103**). The summary scoreboard for 2021 provides a snapshot of the EU's competitive position and performance across 20 key climate-neutral solutions, 12 of which are carried over from a previous assessment and eight of which have been added in 2021. The scoring criteria benchmark the value or trend in the indicator for each solution against the performance of the EU economy and its relative share in the global economy. In addition to the ten key competitiveness indicators, which provide the basis for the annual scoreboard, an extensive number of sub-indicators support and underpin the competitiveness analysis of each solution.

Figure 103: European Climate Neutral Industry Competitiveness Scoreboard 2021



Source: JRC

Overall findings

The EU performs well on innovation related indicators, especially high-value patents, public R&D investment and early-stage venture capital investment. The EU performs at medium or high level in patenting activity across nearly all climate neutral solutions assessed. In 12 solutions, the EU holds a significant share, over 25%, of all high-value filings. EU public R&D investment in climate-neutral solutions is growing in all but three solutions in 2015-2019. Also, venture capital investment in climate and energy solutions is increasing overall in recent years. The EU performs better at early stage investment, financing start-ups, than at later stages, financing scale-ups. Nevertheless, there are exceptions, such as batteries, in which the investment at both stages increased and the EU captured significant shares in both. The EU hosts over 35% - the threshold of strong performance – of identified innovating companies in 6 solutions.

EU production, as an indication of EU manufacturing capacity, grew in 12 solutions in 2015-2020. In regards to EU external trade, the EU performs strongly, accounting for over 25% of extra-EU exports, in 6 solutions. At the same time, a big share of EU imports are EU internal trade, illustrating the importance and strength of the European single market. The EU has a positive trade balance in 11 solutions and trade deficit in 7 solutions. In all solutions, where the EU has negative trade balance, China is the main exporter to the EU, with the exception of ammonia, which is primarily imported from Russia.

The pandemic had a mixed impact. Venture capital investment was practically unaffected by the pandemic, with investments continuing to rise in 2020. By contrast, the production of most solutions experienced some contraction in 2020, amounting to a 4% overall decline on 2019 values. Nevertheless, there were exceptions. The production of batteries and fuel cells continued to grow by 52% and 64% respectively in 2020 compared to 2019. Extra-EU exports declined by 3% in 2020 compared to 2019, whereas EU imports from outside the EU increased by 3%. For example, in heat pumps, 2020 was the first year in which the EU trade surplus turned into a deficit, due to increasing imports from China.

In the 2015-2020 period, employment and turnover in solar PV and heat pumps increased faster than EU employment and GDP overall. By contrast, wind experienced no employment growth, but still generated a 4% increase in turnover. There are significant difficulties in consolidating employment and turnover figures, and data is therefore unavailable for majority of solutions.

Future work will focus on addressing data gaps where possible, expanding the scoreboard to cover more solutions and monitoring the evolution of the indicators to provide insights on the change in EU competitiveness across the relevant ecosystems.

The EU areas of strength

The report confirms EU areas of strength: wind (rotors), heat pumps, hydropower, offshore operations (for installation of renewables) and heating and cooling networks, where EU performs well on most indicators. The EU continues to lead in all innovation related indicators for wind rotors, and maintains its strong position globally, with a 70% share of all extra-EU exports and hosting a substantial proportion of the global wind energy supply chain. EU heat pump industry is innovative and well positioned to benefit from increasing deployment. Imports from China have, however, increased during the last years. In hydropower and pumped storage, EU public investment is growing and the EU captured a high share of early stage investment and patents globally. While EU exports have been decreasing, the EU still captures 40% of all extra-EU exports, indicating a strong global presence for EU manufacturers of hydroturbines. The EU plays host to over 40% of all innovating companies in offshore operations, thanks to being a first mover. The EU has a strong production base of offshore vessels and infrastructures, and European offshore operators are well represented globally, e.g. in the Asia-Pacific region. However, rapid developments in turbine sizes are causing bottlenecks for operators in terms of up-to-date vessels and overcapacity. Ports will require major upgrades to meet the offshore renewable energy targets. The EU is a global leader in heating and cooling networks innovation. However, retrofits of existing networks will also require a retrofit of the buildings involved.

The EU areas of improvement

There are signs of improvement in some key technologies, such as batteries, solar PV and hydrogen production. EU public R&D investment in batteries grew by nearly 30% annually in 2015-2019. Early stage investment grew from EUR 1 million in the 2009-2014 period to nearly EUR 600 million in the 2015-2020 period, while later stage investment increased from EUR 45 million to EUR 1.1 billion over the same period. In solar PV, EU companies are attracting more venture capital investment than before, indicating that EU start-ups and scale-ups are becoming relatively more attractive than companies in other regions. As one of the main pathways for decarbonisation, the renewable hydrogen production and electrolysers sector has a high potential for growth and is attracting increasing amounts of venture capital investment. As host to 40% of global electrolyser capacity, and half of the manufacturers of large-scale electrolysers, the EU has a good industrial basis to take advantage of future market opportunities.

Green ammonia as a sustainable alternative fuel for maritime transport, while still at a very nascent stage, represents a first mover opportunity for the EU, provided the required investment is made across the whole value chain and along trade routes. 75% of pilots and demonstration projects currently identified are either located in Europe or rely on solutions provided by leading EU corporate innovators.

The EU areas in need of attention

The report reveals also areas of weaknesses and potential threats. There are some trends of concern in transport-related solutions, such as fuel cells, electric powertrains and EV charging infrastructure, particularly in innovation-related indicators. Investment in the EU, in both public R&D and attracted venture capital, seems to fall behind that of competitors, and the EU hosts a smaller share of innovating companies in these areas compared to the other solutions assessed. The exception is EV charging infrastructure, where EU public R&D investment is increasing and EU applicants account for a significant share of high-value inventions.

EU public R&D investment is growing at a lower rate than EU GDP for construction-related solutions (prefabricated buildings, superinsulation materials, and building envelope technologies) and is decreasing for building EMS. The level of venture capital investment in prefabricated buildings and building envelope technologies is also lower than the EU average and might indicate that the sector could do more to support the delivery and reap the benefits of building sector decarbonisation and the Renovation Wave. In cooling & air-conditioning, the EU is falling behind on innovation, but capturing a significant share of early stage investment in 2015-2020. It is increasingly dependent on imports, the effects of which spill over to the closely-related heat pumps market.

In grid EMS, the EU performs well in patenting activity, production, exports and trade balance, but investments in innovation need to increase in order to facilitate the development of future grid systems. The increasing integration of renewable energy systems pose a challenge to existing software and analytic solutions, while cybersecurity is also a concern. The EU relies on foreign digital components and assemblies for its digital technologies.

Emerging solutions for the decarbonisation of energy-intensive industries

The EU has the potential to take the lead in green hydrogen-based steelmaking. The EU is already a leader in energy- and CO2-efficient steel production, and with a 30% share of high-value inventions globally, the EU leads in patenting activity in breakthrough technologies. About two thirds of global steel decarbonisation projects via the H-DRI route are based in Europe. Deep decarbonisation of steel production will, nevertheless, depend on the accelerated development and adoption of other technologies, such as electrolysers and hydrogen infrastructure, and the availability of abundant renewable energy.

In Europe, there are three CCUS projects in the cement industry expected to be operational in the mid-2020s, with a couple more announced recently. While there is clear momentum, some challenges, both economic and technological, remain. Moreover, the EU seems to be falling behind the US on innovation indicators.

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List of abbreviations and definitions

AFC	Alkaline Fuel Cell
CCUS	Carbon, capture, use and storage
CRM	Critical Raw Materials
DMFC	Direct Methanol Fuel Cell
DRI	Direct reduction of iron
EAF	Electric arc furnace
MCFC	Molten Carbonate Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
PCFC	Proton Ceramic Fuel Cell
PEM	Polymer Electrolyte Membrane Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
R&D	Research and development
SOFC	Solid Oxide Fuel Cell
SPFC	Solid Polymer Fuel Cell
TRL	Technology readiness level
VC	Venture capital

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Annexes

Annex 1. Climate neutral solutions assessed

	Public R&D	Early and later stage investments	Patents	Companies	Employment	Production	Turnover	Imports & Exports and Trade balance
Source	IEA	Pitchbook	EPO Patstat	Pitchbook and other sources	EurObserv'ER or alternative sources	Prodcom	EurObserv'ER or alternative sources	Comext and Comtrade
1 Batteries (e-mobility, storage)	1311, 6311	Based on consolidated and validated list of VC companies.	Y02E 60/10, Y02T 10/70, Y02W 30/84, Y04S 10/14	Keywords and expert validation for VC companies and corporates through patenting activity.	N/A	27202300 (discontinued in 2019); From 2019 split to: 27202310, 27202320, 27202330, 27202340, 27202350 (Li-ion), 27202395	N/A	850760
2 Fuel cells	52		Y02B 90/10, Y02E 60/50, Y02P 90/40		N/A	27904200	N/A	N/A
3 Electronic powertrains	1312		Y02T 10/64, Y02T 10/72		N/A	27111050, 27111070, 27111090, 27112250, 27112403, 27112405, 27112407, 27112530	N/A	850132, 850133, 850134, 850140, 850152, 850153

4 EV charging infrastructure	1314		Y02T 10/92; Y02T 90/10; Y02T 90/12; Y02T 90/14; Y02T 90/16; Y02T 90/167; Y04S 30/10; Y04S 30/12; Y04S 30/14 ; Y04S 10/126		N/A	27115033 (available until 2015); 27904133 (available between 2016-2018); 27115050 (available after 2019)	N/A	85044055 (Comext only)
5 Prefabricated buildings	1211		B28B 7/22			16232000; 25111030; 23612000; 25111050; 22232000; 23611200	681091 (all years); 940600 (discontinued in 2017); 940610 (from 2017); 940690 (from 2017)	
6 Superinsulation materials	1211	Based on consolidated and validated list of VC companies.	Y02A 30/24; Y02A 30/242; Y02A 30/244; Y02B 80/00; Y02B 80/10	Keywords and expert validation for VC companies and corporates through patenting activity.		23911230, 23911250, 23911290, 23991910, 23991920, 23991930, 23141250	680510, 680520, 680530, 680610, 680620, 680690, 701939	
7 Heat pumps	144		Y02B 10/40, Y02B 30/12, Y02B 30/13, Y02B 30/52		EurObserv'ER (direct and indirect jobs)	28251380	EurObserv'ER (direct and indirect turnover)	841861
8 Wind rotors – Wind energy	32		Y02B 10/30, Y02E 10/70, Y02E 10/72, Y02E 10/727, Y02E 10/728,		EurObserv'ER (direct and indirect jobs)	28112400	EurObserv'ER (direct and indirect turnover)	850231

			Y02E 10/74, Y02E 10/76 where coinciding with (F03D 1/06 OR F03D 3/06)					
9 Solar PV	312		Y02B 10/10, Y02E 10/50, Y02E 10/52, Y02E 10/541, Y02E 10/542, Y02E 10/543, Y02E 10/544, Y02E 10/545, Y02E 10/546, Y02E 10/547, Y02E 10/548, Y02E 10/549		EurObserv'ER (direct and indirect jobs)	26112240, 26114070	EurObserv'ER (direct and indirect turnover)	854140, 854190
10 EMS for Buildings	1221		Y02B 70/30, Y02B 70/3225, Y02B 70/34, Y02B 90/20			26516370		902830
11 EMS for Grids	622	Based on consolidated and validated list of VC companies.	Y02E 40/70; Y04S 20/222; Y04S 10/50; Y04S 20/00; Y04S 20/30	Keywords and expert validation for VC companies and corporates through patenting activity.		27123170, 27123203, 27123205		853710, 853720
12 Hydrogen production – Electrolysis	511		Y02E 60/36, Y02P 90/45 where coinciding with C25B			20111150		280410
13 Hydropower and pumped	36		Y02E 10/20, Y02B 10/50		EurObserv'ER (direct and	28112200; 28113200	EurObserv'ER (direct and indirect	841011, 841012, 841013,

storage					indirect jobs)		turnover)	841090
14 Offshore operations for RE installation	322		Y02E10 where coinciding with (F03D13/25 OR E02B17 OR E02D27 OR B63B21 OR B63B35 OR B63B73 OR B63B75)			30114030; 30114050; 30115000; 30119100; 30119200		890520; 890590; 890790
15 Building envelope technologies	1211		Y02B 80/00, Y02B 80/22, Y02B 30/90			23121330; 22231470; 25121050		700800; 392530; 761010
16 Heating and Cooling networks			Y02B 30/17			28251130		841950
17 Cooling and air-conditioning	144	Based on consolidated and validated list of VC companies.	Y02B 30/54, Y02B 30/70	Keywords and expert validation for VC companies and corporates through patenting activity.		28251220; 28251250; 28251270; 28253010		841510, 841581, 841582, 841583, 841590, 847960
18 Steel decarbonisation (H-DRI and electrification)	N/A		Y02P 10/134 and (C21B or C21C or C21D) OR Y02P 10/20 and C21C 5/52 OR Y02P10 and C25C and (C21B or C21C or C21D)		Eurofer (direct jobs)	28211354, 28211470, 27901330	NACE 24.1	851430, 851490, 854511

19 CCUS for cement industry	N/A		Y02P 40/18		NACE 23.51	20144233, 20144235	NACE 23.51	292211, 292212, 292215
20 Ammonia use as fuel	N/A		N/A			20151075, 20151077		281410, 281420

Annex 2. Wind component sourcing

Table 1: Component sourcing strategy of OEMs for selected offshore wind rotors

Turbine model	Haliade X-12MW	SG 8.0-167 DD	V164-9.5 MW
OEM	GE Renewable Energy	SiemensGamesa RE	Vestas
Country (HQ) of OEM	US	DE-ES	DK
	Main components (country of origin/country of manufacturing location)		
Blade	LM Wind Power (US/FR)	SiemensGamesa RE (DE-ES/DE-UK)	Vestas (DK/UK)
Blade bearing	Rollix (FR/FR)	Rollix (FR/FR)	Rollix (FR/FR)
		Thyssenkrupp Rothe Erde GmbH (DE/DE)	Liebherr (CH/DE)
		TMB (Zhejiang Tianma Bearing Group Limited) (CN/CN)	
Pitch System	Liebherr Components Biberach GmbH (CH/DE)	SiemensGamesa RE (DE-ES)	LJM (DK/DK)
			GLUAL (ES/ES)
Shaft	GE Renewable Energy (US/FR)	SiemensGamesa RE (DE-ES/DE-DK-UK)	Vestas (DK/DK-UK)
Main bearing	Timken (US/RO)	Thyssenkrupp Rothe Erde GmbH (DE/DE)	Timken (US/RO)
		SKF (SE/AT-DE-FR-SE)	
Gearbox	n.a.	n.a	ZF (DE/DE)
Yaw System - Drive & Brake	Liebherr Components Biberach GmbH (CH/DE)	SiemensGamesa RE (DE-ES/DE-DK-UK)	Lafert Group (Sumitomo) (JP/IT)
			Vestas (DK/UK)
Yaw System - Bearing	GE Renewable Energy (US/FR)	SiemensGamesa RE (DE-ES/DE-DK-UK)	Vestas (DK/UK)
Yaw System - Gear type	Liebherr Components Biberach GmbH (CH/DE)	Comer Industries (IT/IT)	Comer Industries (IT/IT)
Generator	GE Renewable Energy (US/FR)	Siemens (DE/DE)	The Switch (Yakasawa) (JP/FI)
Converter	ABB (CH/PL)	Siemens (DE/DE)	Vestas (DK/DK)
Transformer	ABB (CH/FI)	Siemens (DE/DE-AT)	Siemens (DE/DE-AT)
			ABB Oy Transformers (CH/FI)
Switchgear	GE Renewable Energy (US/FR)	Siemens (DE/DE)	ABB Distribution Solutions Distribution Automation (CH/NO)
			Siemens (DE/DE)
			Mitsubishi Electric (JP/JP-CN)

Note: Components manufactured in EU countries (highlighted in blue), in both EU and European countries (light blue) in European countries (grey) and non-European countries (red).

Source: JRC, IEC, 2021.

Table 2: Component sourcing strategy of OEMs for selected onshore wind rotors

Turbine model	V150-4.0 MW / V150-4.2 MW	E-126 EP3	SWT-DD-130 4.3MW
OEM	Vestas	Enercon	SiemensGamesa RE
Country (HQ) of OEM	DK	DE	DE-ES
	Main components (country of origin/country of manufacturing location)		
Blade	Vestas Wind Systems A/S (DE-ES/DE-DK-ES-IT)	TPI Kompozit Kanat 2 (US/TR)	SiemensGamesa RE (DE-ES/DK)
Blade bearing	Vestas Wind Systems A/S (DK/DK)	Liebherr Components Biberach GmbH (CH/DE) Thyssenkrupp Rothe Erde GmbH (DE/DE) IMO GmbH & Co.KG (DE/DE)	Thyssenkrupp Rothe Erde GmbH (DE/DE) TMB (Zhejiang Tianma Bearing Group Limited) (CN/CN) ZWZ (CN/CN)
Pitch System	LJM (DK/DK) Liebherr (CH/DE) HINE Hydraulics (US/ES-BR-US-IN-CN) Hengli (US/US-DE-JP-CN)	Emod (DE/DE) Ruckh (DE/DE)	Fjero A/S (DK/DK) Hydratec Industries N.V. (NL/NL)
Shaft	Vestas (DK/DK)	Heger Group (DE/DE)	Siemens (DE/DE) Jiangsu Hongde Special Parts Co LTD (CN/CN)
Main bearing	FAG (Schaeffler Group) (DE/DE) SKF (SE/AT-DE-FR-SE) JTKET / KOYO (JP/JP-UK-DE-CZ-RO-CN-IN-PH)	PSL, a.s. (DE/SK) FAG (Schaeffler Group) (DE/DE) SKF (SE/AT-DE-FR-SE)	Thyssenkrupp Rothe Erde GmbH (DE/DE) AB SKF (SE/SE)
Gearbox	ZF (DE/DE) Winergy (DE/DE)	n.a	n.a
Yaw System - Drive & Brake	Lafert Group (Sumitomo) (JP/IT) ABB (CH/EU) Bonfiglioli (IT/IT)	Emod (DE/DE) Ruckh (DE/DE)	Siemens (DE/DE)
Yaw System - Bearing	Vestas Wind Systems A/S (DK/DK)	Liebherr Components Biberach GmbH (CH/DE) Thyssenkrupp Rothe Erde GmbH (DE/DE)	SiemensGamesa RE (DE-ES/DK)
Yaw System - Gear type	Comer Industries (IT/IT) Bonfiglioli (IT/IT)	Liebherr Components Biberach GmbH (CH/DE) Bonfiglioli (IT/IT)	Comer Industries (IT/IT) Bonfiglioli (IT/IT) Siemens (DE/DE) ABB (CH/EU)
Generator	Vestas Nacelles Deutschland (DK/DE)	Windgeneratorenfertigung Magdeburg GmbH (DE/DE)	SiemensGamesa RE (DE-ES/DK)
Converter	Vestas Wind Systems A/S (DK/DK)	Elektric Schaltanlagenfertigung GmbH (Enercon) (DE/DE)	SiemensGamesa RE (DE-ES/DK)
Transformer	Siemens (DE/DE-AT) SGB (DE/DE)	J. Schneider Elektrotechnik GmbH (DE/DE)	SGB (DE/DE)
Switchgear			Siemens (DE/DE)

Note: Components manufactured in EU27 countries (highlighted in blue), in both EU and European countries (light blue) in European countries (grey) and non-European countries (red).

Source: JRC, IEC, 2021.

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