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EUROPEAN CLIMATE NEUTRAL INDUSTRY COMPETITIVENESS SCOREBOARD (CINDECS)

Annual Report 2022

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Contents

Abstract

This report is the second annual report of European Climate Neutral Industry Scoreboard, which 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 (European Commission, 2020a). The objective of the scoreboard is to assess the EU's competitive position in climate-neutral solutions across important industrial ecosystems related to the energy transition. The previous assessment, the 2021 annual report, analysed 20 climate-neutral solutions, in the ecosystems of renewable energy, energy-intensive industry, mobility-transport-automotive, construction and electronics. This report provides an update of these 20 solutions and adds eight new climate-neutral solutions. 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, which are included in the accompanying datasets and annotated in the individual technology chapters. 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 2022.

It also contains as Annex to the report:

- Final $D2_{2022}$ Datasets of the 28 climate neutral solutions;
- Final $D3_{2022}$ Scoreboard of the 28 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.
- More focus has been placed on three of the solutions – small modular (nuclear) reactors, permanent magnets and bio-based circular fertilisers – with input from external experts in the latter two. The first two were also the subject of dedicated expert workshops.

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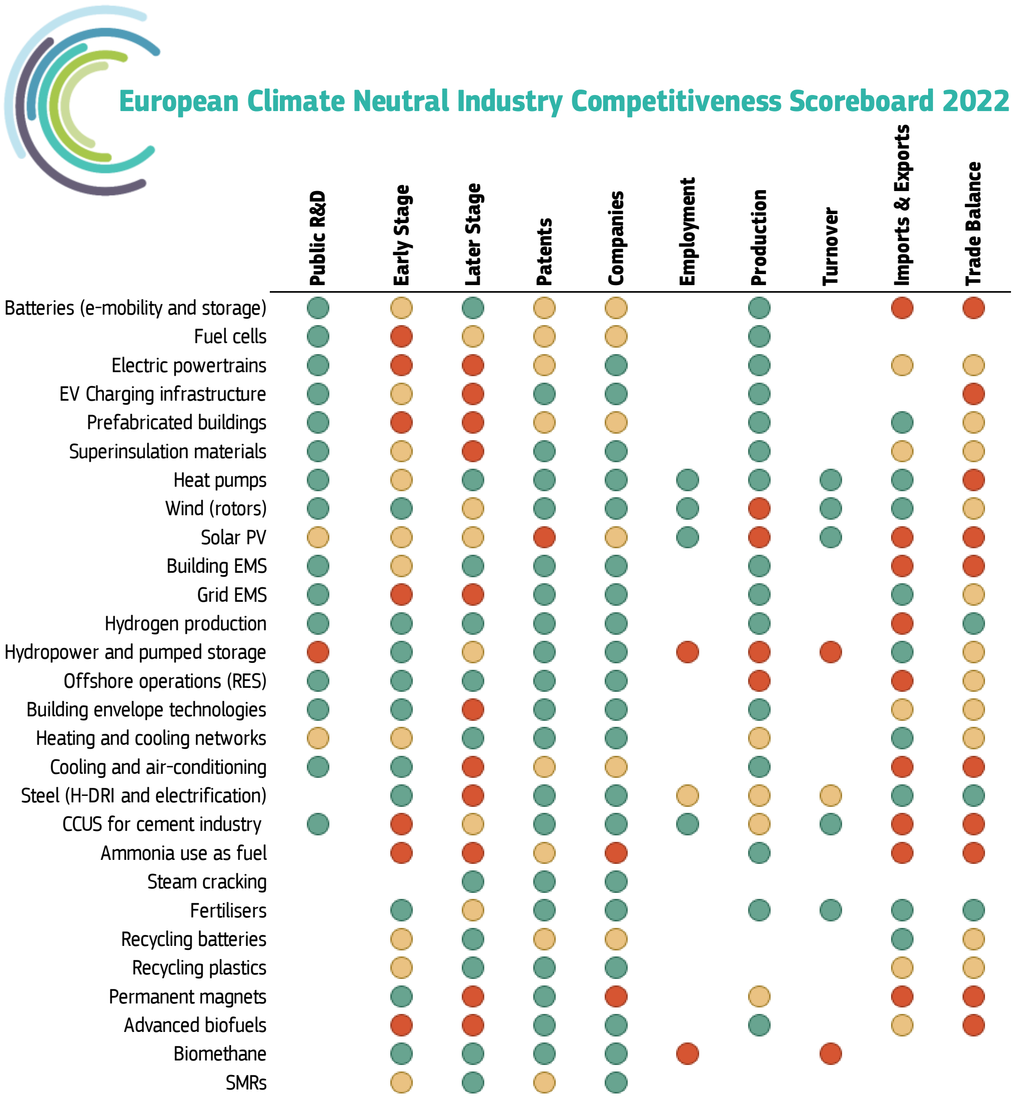
Executive summary

The 2022 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, its Industrial Plan, and the objective of climate neutrality by 2050.

The summary scoreboard for 2022 provides a snapshot of the EU's competitive position and performance across 28 key climate-neutral solutions, 20 of which are carried over from the previous assessment and eight of which were added for 2022. The scoring criteria benchmark the values or trends for each indicator in each solution against the performance of the EU economy as a whole, or in terms of 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 the analysis of individual solutions and are made available in comprehensive datasets.



Legend	High	Medium	Low	Reference
Summary of criteria				
Public R&D	>2%	0< and <2%	<0%	2% EU GDP CAGR (2016 to 2020)
Early Stage	>18%	8%< and <18%	<8%	18% and 8% EU's economic size and EU average performance
Later Stage	>18%	8%< and <18%	<8%	18% and 8% EU's economic size and EU average performance
Patents	>25%	15%< and <25%	<15%	~27% EU's economic size x 1.5
Companies	>25%	15%< and <25%	<15%	25% and 15% EU average in climate technologies
Employment	>1%	0%< and <1%	<0%	1% EU employment CAGR (2016-2020)
Production	>3%	0%< and <3%	<0%	3% EU GDP CAGR (2016-2021)
Turnover	>2%	0%< and <2%	<0%	2% EU GDP CAGR (2016-2020)
Imports & Exports	>25%	15%< and <25%	<15%	~23% EU's economic size x 1.3
Trade Balance	positive / improving		negative / deteriorating	

Reversed for circular solutions (plastics and batteries recycling)

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 the European economy, society and industry to achieve climate neutrality. Faced with the challenge of energy dependence and rising energy prices, REPowerEU ([4]) has accelerated the urgency of this change. Adopted in 2023, the Green Deal Industrial Plan ([5]) aims to secure Europe's lead in industrial innovation and to scale up EU manufacturing of clean technologies by introducing the Net Zero Industry Act ([6]) and the Critical Raw Materials Act ([7]). EU industry needs to remain competitive to reap the benefits of the green transition. This scoreboard measures EU progress on the 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 States' National Climate and Energy Plans and Recovery and Resilience Plans, and are aligned with their long-term decarbonisation needs. The technologies assessed here are also aligned with REPowerEU ([8]) and Net Zero Industry Act ([6]), which define the strategic net-zero technologies.

Key conclusions

In 2016-2020, EU Member State public R&D investment increased in all 17 climate-neutral solutions for which data was available, with the exception of hydropower and pumped storage. In 15 of these solutions, public R&D investment grew faster than EU GDP, indicating a strong performance. Public investment increased most in batteries and offshore operations, in which investment grew by an average of 30% annually (2016-2020). For hydrogen production, grid EMS and CCUS ([9]) for the cement industry, the average growth rate was also double-digit (2016-2020).

Venture capital investment in climate-neutral solutions is increasing overall. In 2016-21 (as compared to the 2015-20 period), the EU captured a higher share of later stage investment and a lower share of early stage investment (the latter dropped in 2021). This trend is directly related to the scaling up of the Swedish manufacturer Northvolt, which was the sole recipient of 89% of EU venture capital investment in batteries and almost half of EU venture capital investment overall in 2016-21. Beyond batteries and battery recycling, early stage investment in the EU is, however increasing, and the EU still performs better at financing early ventures than later scale-ups. The overall grant intensity (share of grant funding in early stage investment) is similar in the EU (22%) to the rest of the world (21%). It is, however, much lower in the EU than in the rest of the world for three solutions (fuel cells, hydrogen production and small modular reactors (SMRs)).

The EU hosts over 25% - the threshold for strong performance – of identified venture capital and corporate companies for 20 of the 28 monitored solutions. The share of venture capital companies in EU-based innovators is comparable to that of the rest of the world. However, the EU achieves a lower performance in key solutions including batteries & battery recycling, fuel cells and solar PV.

The EU is strong overall in patenting activity – in 19 of the 28 climate-neutral solutions assessed, the EU captured over 25% of high-value patents in 2016-2019. The weakest performance is in solar PV, where Chinese and South Korean patenting activity has surged ahead of the EU, which has a declining patenting trend. While the EU captures less than 15% globally, its patent portfolio in solar PV is one of the biggest among the solutions assessed, preceded by batteries and followed by fuel cells and EV charging infrastructure. In four solutions, namely heating and cooling networks, biomethane, permanent magnets and wind rotors, the EU captures over half of all high-value inventions globally.

EU production, as an indication of EU manufacturing capacity, grew faster than EU GDP in 19 solutions in 2016-2021. The most notable compound annual growth rate, at 72%, was in batteries. Production has generally improved compared to 2015-2020, reflecting the economic rebound from the pandemic, with the exception of three solutions: offshore operations, where performance dropped slightly; fuel cells, which

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([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.
([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(2023) 62 final, 1st February 2023
([6]) COM(2023) 161 final, 16th March 2023 and SWD(2023) 68.
([7]) COM(2023) 160 final, SWD(2023) 160, SWD(2023) 161, SWD(2023) 162, SEC(2023) 360.
([8]) COM(2022) 108 final, 8th March, REPowerEU: Joint European Action for more affordable, secure and sustainable energy.
([9]) Carbon capture, utilisation and storage.

maintained a strong performance; and hydropower and pumped storage, whose performance remained weak. Increased production costs from 2021 onwards affect this indicator to varying degrees across the solutions.

Regarding EU external trade, the EU performed strongly in 2019-2021, accounting for over 25% of extra-EU exports in eight solutions. The EU largely maintained its position compared to 2018-2020, apart from the steel solution, whose performance improved and CCUS, which marginally declined. The majority of EU imports were covered by internal trade except for five solutions: 73% of permanent magnet imports came from China; 70% of ammonia imports came from Algeria, Russia and Trinidad and Tobago; 65% of solar PV imports came from China; 65% of offshore platform and vessel imports came from China, India and South Korea; and 59% of nuclear machinery and 50% of nuclear fuel, both relevant to the small modular reactors (SMRs) value chain, came from Russia.

In 2021, the EU had a positive trade balance in 14 solutions and a trade deficit in 11 solutions. China was the main exporter to the EU in seven solutions with a negative trade balance (solar PV; batteries; cooling and air-conditioning; permanent magnets; EV charging; heat pumps; and buildings EMS). Compared to 2020, the EU trade balance deteriorated except for four technologies (wind rotors; hydrogen; offshore operations; and steel). In 2020, the trade balance in heat pumps turned negative for the first time (EUR 40 million), and in 2021, the deficit increased almost tenfold (EUR 390 million). In this context it should also be noted that many technologies depend on imported materials, giving impetus to the Critical Raw Materials Act adopted in 2023. Here, circular solutions chosen for the 2022 assessment come into play. Hence, in the case of waste trade, a trade surplus indicates a loss of opportunity for circularity. The EU had a declining trade surplus in plastic scrap, implying improvements in circularity, while in spent batteries, the volumes of which are still small, exports are on the rise, implying the need to improve recycling within the EU.

There are significant difficulties in consolidating employment and turnover figures, and data is therefore unavailable for the majority of solutions. Nevertheless, renewable energies, for which data is available, show that employment and turnover increased by 12% and 14% respectively in 2021 on 2020 figures. Growth was fuelled particularly by increasing demand for heat pumps and solar PV. At the same time, wind contracted in terms of jobs and turnover due to a faltering installation rate. A strong bounce-back from the pandemic has been accompanied by employment shortages spilling over from the overall economy, in combination with inertia in the clean energy sector in terms of building the skills capacities required for the green and digital transitions. Therefore, it is of utmost importance to bridge the skills gap and address the supply chain risks identified for (critical) materials to ensure the competitiveness of the EU's climate-neutral industry.

Main findings

The report confirms that the EU is strong when it comes to innovation in climate-neutral (technology) solutions. The EU is a powerhouse in green patenting and plays host to a large share of innovators. Public R&D investment is increasing, as is early stage venture capital investment. Nevertheless, the EU still trails behind its competitors in financing scale-ups and commercialising its green innovations. The report finds that EU production bounced back strongly after the pandemic, but growing demand was increasingly met with imports and the EU trade balance in many strategic net-zero technologies therefore deteriorated. Employment and turnover are growing in solar PV and heat pumps in particular, thanks to strong deployment. Globally, the EU largely maintained its position in extra-EU exports, especially in wind, where the EU holds the biggest trade surplus. The report identifies areas of strength in wind (rotors), heat pumps, offshore operations (for the installation of renewables) and heating and cooling networks, where the EU performs well on most indicators. There are signs of improvement in some key net-zero technologies, such as batteries, solar PV and hydrogen production. Moreover, the EU is active in many emerging solutions for the energy-intensive industry, such as steel decarbonisation through H-DRI and electrification, and some circular solutions, such as bio-based circular fertilisers and plastics recycling. The report also reveals areas of weakness and potential threats. EU performance is more often weak in transport-related solutions such as electric powertrains and EV charging infrastructure, and in building-related solutions such as prefabricated buildings, superinsulation and building EMS.

Related and future JRC work

Future work will focus on addressing data gaps where possible, improving the analytical framework and indicators, and continuing to monitor 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 report, on the protocol of the assessment methodology. For more details on the first 20 climate-neutral solutions, readers should consult the first edition of the CIndECS report.

1 Introduction

The European Green Deal (European Commission 2019) is Europe's new growth strategy ([10]). At its heart 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 ([11]), which also included the target of reducing greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. In 2022, the REPowerEU Plan ([12]) was adopted to address energy dependency and rising energy prices in the fast evolving geopolitical situation. The Plan seeks to accelerate the adoption of several of the assessed solutions by, for instance, frontloading deployment targets for heat pumps, wind power and solar energy, and boosting green hydrogen production and uptake in the energy-intensive industries.

The new Industrial Strategy for Europe, published in 2020 ([13]), and its recent update in 2021 ([14]), gives industry a leading role in carrying out this transformation. The Green Deal Industrial Plan ([15]), adopted in 2023 together with supporting acts on Net Zero Industry ([16]) and Critical Raw Materials ([17]), aims to secure Europe's lead in industrial innovation and to scale up the manufacturing of clean technologies, both of which are assessed in this report. A central tenet of these policies 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, NextGenerationEU, 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 above-mentioned EU priorities. Member States have allocated 40% of the spending in their plans to climate measures and about 26% on the digital transition, both of which exceed the initial targets (European Commission, 2023).

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, and 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 2020 study, for which the JRC provided data and guidance on indicators. This 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 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

([10]) COM(2019) 640 final, 11th December 2019: The European Green Deal.
([11]) Regulation (EU) 2021/1119: European Climate Law
([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
([13]) COM(2020) 102 final, Brussels 10.3.2020
([14]) COM(2021) 350 final, Brussels 5.5.2021
([15]) COM(2023) 62 final, 1st February 2023
([16]) COM(2023) 161 final, 16th March 2023 and SWD(2023) 68.
([17]) COM(2023) 160 final, SWD(2023) 160, SWD(2023) 161, SWD(2023) 162, SEC(2023) 360.

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 the 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 in the Recovery and Resilience Plans (RRPs); and (3) market relevance in terms of existing or expected European market growth. The final decision to include eight new solutions in 2021, and a further eight in 2022, was taken in consultation with experts.

Figure 1 depicts the climate-neutral solutions assessed in this report. The first 12 solutions, shown on the left, were included in the previous study (European Commission, 2020a) and updated in the 2021 assessment and this report. The next eight solutions were first included in the 2021 assessment and the scoreboard. In this 2022 assessment, a further eight solutions have been added. 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 Annex 1.

Figure 1: Climate-neutral solutions assessed ([18]) (right)

1. Batteries
2. Fuel cells
3. Electric powertrains
4. EV charging infrastructure
5. Prefabricated buildings
6. Super-insulation materials
7. Heat pumps
8. Wind rotors
9. Solar PV
10. EMS for Buildings
11. EMS for Grids
12. Hydrogen production

Added in 2021 assessment

13. Hydropower and pumped storage
14. Offshore operations (RES)
15. Building envelope technologies
16. Heating and cooling network
17. Cooling and air-conditioning
18. Decarbonisation of steel (H-DRI and electrification)
19. CCUS for cement
20. Ammonia as fuel

Added in 2022 assessment

21. Electrification of steam cracking
22. Bio-based circular fertilisers
23. Batteries recycling
24. Plastics recycling
25. Permanent magnets (RES)
26. Advanced biofuels
27. Biomethane
28. Small modular (nuclear) reactors

Source: JRC, 2023

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

2 The assessment approach and methodology

The assessment framework, upon 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 ([19]) 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 ten 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 ten countries with high value inventions
			Flow of high value inventions
			Top patenting entities – top ten in the World and top ten in the EU
5	Innovating companies	Pitchbook, CTG and other sources (e.g. BloombergNEF) for VC companies ([20]) 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

([19]) Research, development and demonstration.
([20]) 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 ten 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 ten 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 ten 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 ten 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, 2023

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 investment	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 investment	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.
Patents (high-value)	EU global share	1.5 x EU's economic size ([21])	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

([21]) 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, 2023

Figure 2: Scoring criteria thresholds in 2022

Legend	High	Medium	Low	Reference
Summary of criteria				
Public R&D	>2%	0< and <2%	<0%	2% EU GDP CAGR (2016 to 2020)
Early Stage	>18%	8%< and <18%	<8%	18% and 8% EU's economic size and EU average performance
Later Stage	>18%	8%< and <18%	<8%	18% and 8% EU's economic size and EU average performance
Patents	>25%	15%< and <25%	<15%	~27% EU's economic size x 1.5
Companies	>25%	15%< and <25%	<15%	25% and 15% EU average in climate technologies
Employment	>1%	0%< and <1%	<0%	1% EU employment CAGR (2016-2020)
Production	>3%	0%< and <3%	<0%	3% EU GDP CAGR (2016-2021)
Turnover	>2%	0%< and <2%	<0%	2% EU GDP CAGR (2016-2020)
Imports & Exports	>25%	15%< and <25%	<15%	~23% EU's economic size x 1.3
Trade Balance	positive / improving		negative / deteriorating	

Reversed for circular solutions (plastics and batteries recycling)

Source: JRC, 2023

The economic data used in the study are in current prices, as well as scoring benchmarks. Thus, the price increase that started in 2022 shall not affect the scoring of performance. Still, some of the technologies have been affected by the increase of prices and when possible this has been considered in the qualitative analysis.

2.1 Data collection and validation

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 authorities, its quality and reliability is subject to the quality, coherence and completeness of the reporting from the initial data providers, 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 the monitoring of individual solutions and technologies in all cases. The key points of uncertainty regarding each database are listed below.

— Public R&D investment 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 investment flows with varying degrees of granularity, affecting the capacity to monitor individual solutions.

— Companies in the present study are identified through keywords (detailed in the protocol of the assessment methodology), and validated by expert screening. This ensures that the company lists are more robust and the selection criteria more transparent and reproducible. More detail on the changes made can be found in the protocol of the assessment methodology ([22]).

— 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 has reduced the level of detail available.

([22]) 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 a 'follow-the-money' approach based on the capital investment made and the associated employment and 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 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 total production. The Member States may choose to keep production values confidential, limiting the analysis. There may be also underreporting from 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 to six digits, which is not always specific enough to track individual solutions and technologies.

— Early and later stage investment is based on Pitchbook database, which is behind a paywall but provides a better coverage of investment flows globally than the data source previously used. Still, it is impossible to determine the completeness of the data. Reliability and reproducibility have 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 ([23]). In addition to the more general issues mentioned above, there are also 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 the datasets used in the previous study. The technical report on the assessment methodology includes a detailed description of all the codes and sources used for all 28 climate-neutral solutions.

Data availability in regards to the most recent year differs for the assessed indicators. In order to provide the most recent data but align the timeframe among the different indicators, the study aligns the starting year but applies different end-year for each indicator as presented in **Figure 2** and all individual scoreboards. In the previous assessment (Scoreboard 2021) the starting year was 2015 for each indicator. In this study, the starting year is 2016 for each indicator, while the end-year depends on the most recent available data.

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

3 Batteries

Batteries are a key enabling technology which makes it possible to reap the benefits of electrification, by enabling higher penetration of renewables, and opening up the possibilities for far more energy-efficient transport modes ([24]) (SWD(2021)307 final ([25])). As electrified transport is the primary market for batteries, the focus here is on Li-ion batteries ([26]) and next-generation batteries ([27]). 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 An updated status and recent developments

By 2050, the entire fleet of 270 million vehicles should be zero-emission in the EU and over 50 million are expected on roads already by 2030 (today there are around 1.7 million), in addition to 80 GW of stationary batteries (4.6 GW in 2021) (Bielewski, et al., 2022). Lithium-based chemistries[28] dominate the e-mobility market today and will continue to do so, but the role of other chemistries will increase in the future. For Li-ion batteries, there remains room for improvement in their energy density, essential especially for heavier transport and aviation.

Historically, Europe has a large chemical industry cluster and a large ecosystem around batteries, such as lead-acid batteries. In Li-ion batteries, dominated by China, South Korea and Japan, 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). In total the European Battery Alliance ([29]) has generated investment exceeding EUR 100 billion for the EU to stay on track to meet 69% of Li-ion batteries demand by 2025 and 89% by 2030 (Bielewski, et al., 2022). 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 – a situation that is not likely to change fast. Efforts are focused on improving the recyclability of batteries, but recycling will ease EU's raw material resilience only towards 2030 (Bielewski, et al., 2022) (see Chapter 25 for battery recycling). This makes it hard for EU-headquartered companies to be able to mass-produce battery cells at competitive prices. The EU is also dependent on importing manufacturing equipment mainly from Asia (Bielewski, et al., 2022).

The global market of Li-ion batteries was estimated at EUR 41 billion ([30]) 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. China is the leader of the battery value chain, especially upstream: it controls over 80% of the world's Li-ion battery raw material refining capacity, 77% of cell production capacity and 60% of battery component manufacturing capacity (Bielewski, et al., 2022). The EU is stronger downstream in the final products as it produces a fifth of EVs globally. Nevertheless, the lack of domestic raw materials and advanced materials supply is a persistent problem despite the initiatives under way. The new proposal for a Battery Regulation, which addresses circularity, will also facilitate sustainable mining, which is one of the issues to be addressed.

3.2 EU positioning in innovation and major changes

The EU-wide strategic research agenda has stimulated public R&D investment in recent years. In 2020, EU public R&D investment rose to EUR 185 million. France nearly tripled its funding in 2020, thus becoming the biggest public investor ahead of Canada. Other big EU spenders, Germany and Austria, maintain their level of public R&D funding. Based on the early non-complete data for 2021, Belgium also increases its funding, and Sweden and Hungary report significant public spending for the first time at this level. In addition to this, under

([24]) 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.

([25]) European Commission SWD(2021) 307 final, Brussels 26.10.2021

([26]) Li-ion batteries are leading in electrification of transport thanks to their superior energy density.

([27]) 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.

([28]) For a full list of Li-ion based batteries, see Bielewski et al. (2022).

([29]) The European Commission launched the European Battery Alliance to address the gap in industrial capacity in 2017, followed by a Strategic Action Plan covering the whole value chain in 2018.

([30]) For comparison, lead-acid batteries stood at EUR 33 billion in 2020. Converted from USD to EUR using 2020 exchange rate.

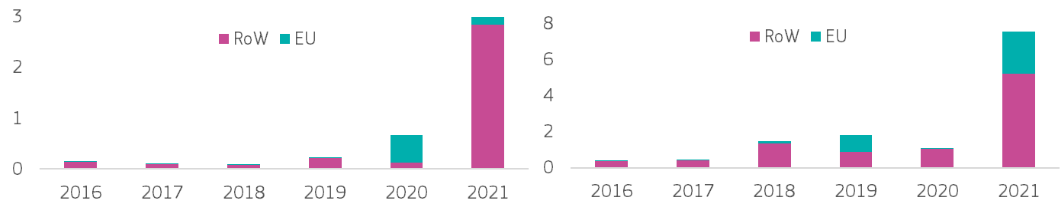
the Horizon Europe programme, over EUR 900 million has been earmarked for research on batteries for the period 2021-2027 – an amount almost twice of that under Horizon 2020 (Bielewski, et al., 2022). Country-level data is subject to the IEA data and countries reporting to the IEA. The US, previously the biggest investor, and South Korea, with strong patenting activity in batteries, have not reported at this level in recent years. China, with the third biggest patent portfolio in the area and one of the top spenders globally in energy R&D (IEA, 2022a), does not report at a sufficient level of granularity.

In terms of private investment, global venture capital for battery developers skyrocketed in 2021, amounting to EUR 11 billion, i.e. more than the cumulative investment realised since 2010. As shown in **Figure 3**, both early and later stage investment reached all time-highs in 2021, supported by a few megadeals with battery manufacturers from Sweden (Northvolt, EUR 2.6 billion, later stage VC) and China (Svolt, EUR 2.6 billion, early stage VC and China aviation Lithium Battery, EUR 1.5 billion, PE growth).

Global early stage investment quadrupled in 2021, essentially due to large deals in the Chinese company SVOLT. The EU accounts for 17% of the disclosed value of early stage transactions in the period 2016-21, amounting to over EUR 736 million (69% of which results from an investment in the Swedish company Northvolt in 2020). China, which attracted most of early stage investment over the current period (66%), takes over the lead from Sweden (13%) and the US (10%), where investment has decreased since the previous period.

The main driver of VC investment growth since 2018 is the larger number and value of later stage deals, reflecting a clear trend towards the scale-up and expansion of production capacities. The EU accounts for 27% (i.e. EUR 3.5 billion) of disclosed values of later stage investment over the 2016-21 period. Supported by a much larger base of VC companies, the US preserves its leadership, attracting 33% of later stage investment over the period. It is, however, closely challenged by the megadeals seen in China (29%) and Sweden (25%).

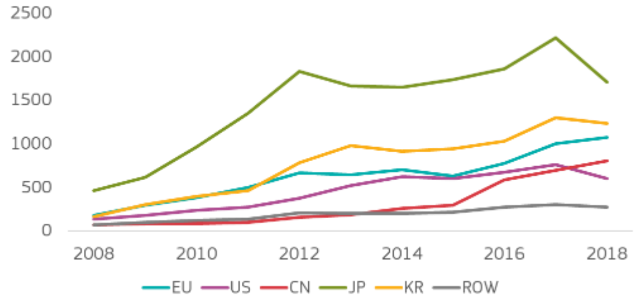
Figure 3: Early (left) and later (right) stage investment by region [EUR Billion]



Source: JRC based on Pitchbook, 2023

EU patenting activity is increasing steadily and catching up with the leaders (**Figure 4**), Japan and Korea, who hold 32% and 21% of all high-value inventions respectively (2017-2019). The EU holds 16% of all high-value inventions. Germany, France and Sweden are the leading patenting countries in the EU but behind Japan, South Korea, China and the US. Globally, it is mainly Korean and Japanese companies who stand out in terms of patenting activity, with one German company (Bosch Gmbh) in the top ten. Lg Chem Ltd (KR), followed by Toyota (JP) and Samsung (KR) are the leading patenting companies. In **Figure 4**, the decline of Japan and the EU in 2019 is most probably due to increased application processing times during the pandemic.

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



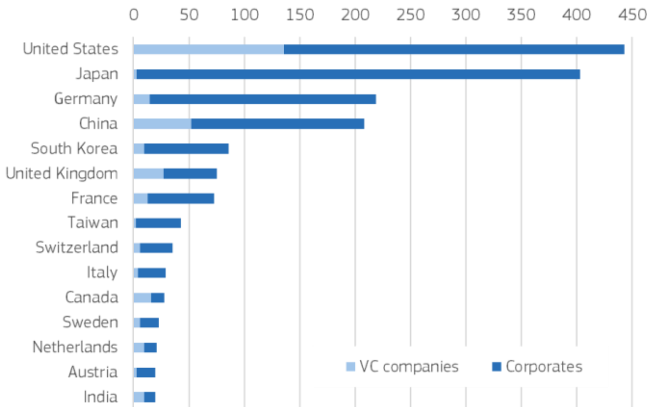
Source: JRC based on EPO Patstat, 2023

Battery technology offers further opportunities for cost reduction, efficiency gains, lifespan improvements and safety gains, and a potential to reduce dependence on third countries regarding the critical raw materials (lithium, cobalt and nickel). The Batteries Europe technology platform published a strategic research agenda and detailed technology roadmaps for all segments of the battery value chain. In Li-ion, innovation is focused on advanced materials, 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 at the same time containing more energy per unit weight than Li-ion and being safer (SWD(2021)307 final).

The EU has moved too slowly on stationary battery technologies (in general, stationary applications are lagging behind mobile applications) and on those battery technologies based on abundant raw materials, such as flow batteries and sodium-ion (independent of application, stationary or mobile). There are some companies and projects in both and the recent establishment of Flow Batteries Europe can improve EU's overall competitiveness in the former (Bielewski, et al., 2022).

As shown in **Figure 5**, corporates represent the majority (80%) of innovators in battery technologies identified around world and the top five countries host 73% of identified innovators. Corporates largely prevail in Japan (second), Germany (fourth) and South Korea (fifth). Only the US (1st), and to some extent China (third), report a significant base of venture capital companies. In the EU, which accounts for 24% of companies active over the current period, Germany, France and, to some extent, the Netherlands, hosts the major share of active companies.

Figure 5: Number of innovating companies by type (2016-21)



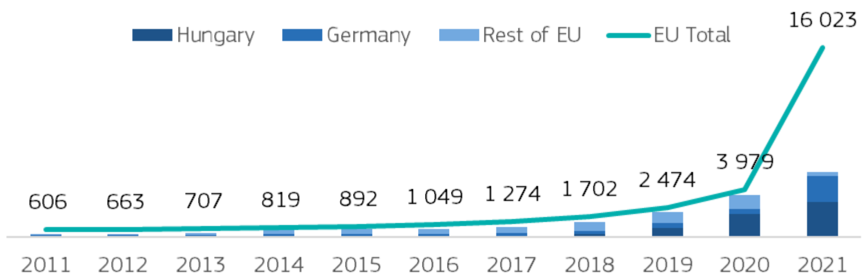
Source: JRC compilation from different sources, 2023

3.3 EU positioning in the current market and major changes

The EU production of batteries measured in value ([31]) has increased by an average 72% annually in period 2016-21, reaching EUR 16 billion in 2021 (see **Figure 6**). The biggest producers are Hungary and Germany, where many non-European companies have already established their manufacturing plants. Many Member States, notably Poland which has manufacturing plants and a growing positive trade balance, kept their data for 2021 confidential – hence the gap in the chart. Unfortunately, data does not distinguish between battery cell, module or system (e.g. EV battery) and therefore it is impossible to determine the manufacturing capacity of the EU and its countries with precision. Nevertheless, it is clear that annual production volumes of Li-ion batteries are increasing in the EU and if all planned projects are operational on time, the EU will become self-sufficient by the 2030. Still, it takes time for manufacturing plants to reach full operational capacity. For example, the first Tesla giga-factory took five years (Bielewski, et al., 2022).

([31]) 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 94% 2021, constituting the majority of reported production value.

Figure 6: EU production value and top producers disclosing data among the Member States [EUR Million]



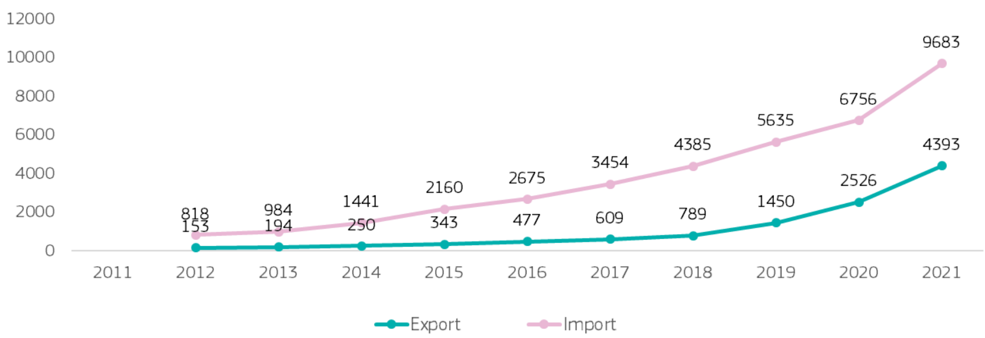
Source: *JRC based on PRODCOM, 2023*

For employment and turnover, this year's report uses Eurostat Structural Business Statistics which monitors the indicators at an aggregated level ([32]), thus including the manufacture of all types of battery, big or small, and all types of chemistry. In total, battery manufacturing employed 37 000 people in 2019. For 2020, the EU total is not disclosed. The biggest employers were Germany and Poland, which have many manufacturing plants. From 2019 to 2020, Hungary more than doubled its employment, while German jobs grew 20% and Sweden experienced significant growth. Of the top five EU employers, Poland and France did not disclose their values for 2020. Highly automated battery manufacturing plants may have a lower labour intensity yet are still expected to create a significant amount of new jobs: approximately 3 300 people for a factory of 30 GWh and in total up to 1-4 million in the EU (Bielewski, et al., 2022; European Institute of Innovation and Technology, 2022). It is estimated that there will already be a supply gap of up to 800 000 skilled workers by 2025 (European Institute of Innovation and Technology, 2022). To address this, EBA250 Academy (established in 2021) will train 160 000 workers every year with the right competences and skills (Bielewski, et al., 2022).

In terms of turnover, EU battery manufacturing generated EUR 14 billion in 2019. The value for 2020 is not disclosed. Germany, Poland and Spain generated the most turnover, yet Hungary and France experienced the biggest growth from 2019 to 2020, surpassing Spain. Poland did not disclose its turnover for 2020.

Extra-EU imports have grown steadily since 2012, reaching nearly EUR 10 billion in 2021. Extra-EU exports only really started growing after 2018, when EU production increased, and reached EUR 4 billion in 2021. Exports continued to increase faster than imports, yet they are still far from the imported volumes. Poland, where LG Chem plant came online in 2018, is still the biggest EU exporter, but with the majority of trade staying inside the EU. Germany is the biggest EU exporter to outside the EU, but also the biggest importer in the EU and globally due to its big automotive sector. Globally, China is by far the biggest exporter and the biggest exporter to the EU. The EU share of exports grew from 6% to 9%, and the share of EU imports covered internally improved from 45% to 52% in 2021. This reflects the increased manufacturing in the EU, but may also include some level of re-exporting.

Figure 7: Extra-EU import & export (left) and top 5 EU exporters in 2018-2020 (right) [EUR Million]



Source: *JRC based on Comext data, 2023*

([32]) Eurostat Structural Business Statistics monitors indicators at NACE activity level, meaning 4-digit level. We have used C.27.20 for manufacturing of batteries.

The EU has a negative trade balance, which is still degrading, reaching over EUR 5 billion in 2021. In 2021, the trade deficit grew again, faster than in 2020. Poland and Hungary, supplying the EU market almost exclusively ([33]), had the biggest trade surpluses. In Poland in particular, where many factories have come online, the trade surplus seem to grow exponentially from 2018 onwards. In contrast, Germany, France and Belgium have the biggest trade deficits, and growing. Whereas in France and Belgium, the trade deficit seems to plateau, the German deficit seems to increase exponentially, reflecting the booming demand coming from the German automotive sector that is trying keep pace in the EV race. Whereas previously nearly 60% of German imports came from outside the EU, mainly from China and South Korea, now the biggest supplier is Poland, and less than 50% comes from outside the EU. This is a sign that EU self-sufficiency, while still far away, is improving.

3.4 Scoreboard - key insights and change in EU performance

Thanks to a concerted effort together with the industry, the overall EU positioning in the battery value chain is taking great strides forward. On the innovation side, EU public R&D spending keeps increasing while already corresponding to over half of the global total investment. Due to megadeals with Northvolt (SE), EU scale-ups are capturing a larger share of later stage investment than before in a record-breaking venture capital market. Another positive sign is that the last two years have seen an emergence of many new start-ups and scale-ups, therefore expanding the battery ecosystem headquartered in the EU. The EU position has deteriorated only in early stage investment, where the EU captured only 17%. As Northvolt has moved to scale-up stage, new players are needed to attract growing early stage investment. With regard to patents, the EU is on an upward trajectory, indicating the strengthened position of the EU innovation landscape, although competitors South Korea and China are also increasing their patenting activity. To avoid falling behind, investment is needed in the development of non-CRM-dependent battery chemistries, which are already being developed by China and others, but are receiving less attention in the EU.

EU manufacturing is on an upward trend, tripling in 2021 compared to 2020. While growing, it is still far from meeting demand, reflected by a growing trade deficit of EUR 5 billion. New production plants and investment are already on the way, but operating all the planned plants at full capacity will require time and a sufficient supply of skilled workers. Moreover, at present, European cell manufacturing relies largely on South Korean and Chinese subsidiaries. The battery value chain promises significant job creation and business opportunities for the EU, but global competition is fierce as the US, with its recent Inflation Reduction Act, also wants to tap into the opportunity, and attracting a share from China – which currently controls the market – will not come easy. Building manufacturing capacity in the EU means high upfront costs and is more expensive than in China, which already has supply chains and integrated production ecosystems in place (BNEF, 2022a). In addition, even with domestic manufacturing capacity, the EU would still continue to rely on China for critical materials, unless full value chain activities, upstream in particular (materials and components), are developed in parallel, and for battery manufacturing technology (Carrara, et al., 2023). In terms of global trade, the EU captures only 9% of exports at the moment. Nevertheless, the advantage of EU-produced batteries in the future may be that they are more sustainable and circular, which can be factored alongside costs, as many downstream buyers, such as the automotive industry, are already paying attention to lifecycle emissions and the ESG-ratings ([34]) of producers.

Figure 8: Scoreboard for batteries

Scoreboard	**Batteries**	EU performance in the reference period			Change from 2021
Public R&D	●	38%	2016-2020	EU CAGR	↑
Early Stage	●	17%	2016-2021	EU share of global total value	↓
Later Stage	●	27%	2016-2021	EU share of global total value	↑
Patents	●	16%	2016-2019	EU share of global total HVI	→
Companies	●	24%	2016-2021	EU share of innovating companies	↑
Employment			2016-2020	EU CAGR	
Production	●	72%	2016-2021	EU CAGR	↑
Turnover			2016-2020	EU CAGR	
Imports & Exports	●	9%	2019-2021	EU share of global exports	↑
Trade Balance	●	Low	2016-2021	EU trade balance trend	→

Source: JRC, 2023

([33]) Poland and Hungary export 95% and 90% respectively of their exports within the EU.
([34]) Rating of environmental, social and governance risks.

4 Fuel cells

4.1 An updated status and recent developments

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), with the rationale and main changes documented in the previous edition of this report (Kuokkanen, et al., 2022). The same document also contains an overview of the main fuel cell technologies, applications and characteristics, as well as an outline of the broad range of legislation affecting the technology.

Polymer electrolyte membrane or proton exchange membrane fuel cells (PEMFC) are the type predominantly used for mobility, which currently dominates fuel cell applications. High temperature PEMFCs are not as developed as low temperature PEMFCs, while direct methanol fuel cells (DMFCs) are mainly used for portable, smaller size, applications. Solid oxide fuel cells (SOFC) are at a somewhat lower technology readiness level (TRL) and mostly used for stationary applications, as are phosphoric acid fuel cells (PAFC) and molten carbonate fuel cells (MCFC). Alkaline fuel cells (AFC) have military, space, back-up power and off-grid power uses. All are commercialised in some way apart from proton ceramic fuel cells (PCFC), which are at a lower TRL.

Given the wide range of applications, the fuel cell sector is affected by a broad range of legislation, referenced in the previous edition of this report (Kuokkanen, et al., 2022) along with legislation and initiatives relating to hydrogen production (see Chapter 14). The Fuel Cell and Hydrogen Observatory (FCHO) policy module presents an overview of EU and national policies (FCHO, 2022b).

The green economic recovery plans pursued globally should offer an opportunity for the sector to expand. 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 combined heat and power (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 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, 2021a)). 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 investment 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, 2020b).

In terms of vulnerabilities, the fuel cell supply chain runs its highest risk at the stage of raw materials (the EU share of production is 3%). However, the supply chain for components and assemblies is not diversified and predominantly relies on imports from the US and China. PEMFC and SOFC require24 different raw materials, 18 of which are considered critical (Carrara, et al., 2023). Even though the supply of raw materials required is diversified among many suppliers, the supply risk is significant due to political instability in the countries that host the resources. The risk is somewhat lower for assemblies and processed materials (the EU share of production is 12% and 15% respectively) and in components (EU has a 25% share of production). The high cost of platinum is one of the major challenges in PEM fuel cell production. The platinum loading on the electrocatalyst is closely related to durability and, as previously mentioned, its reduction is a main point of

([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 research and innovation, along with recycling and circularity options by design, as alternatives (palladium, ruthenium, iridium) are also considered as strategic raw materials (Carrara, et al., 2023).

4.2 EU positioning in innovation and major changes

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.

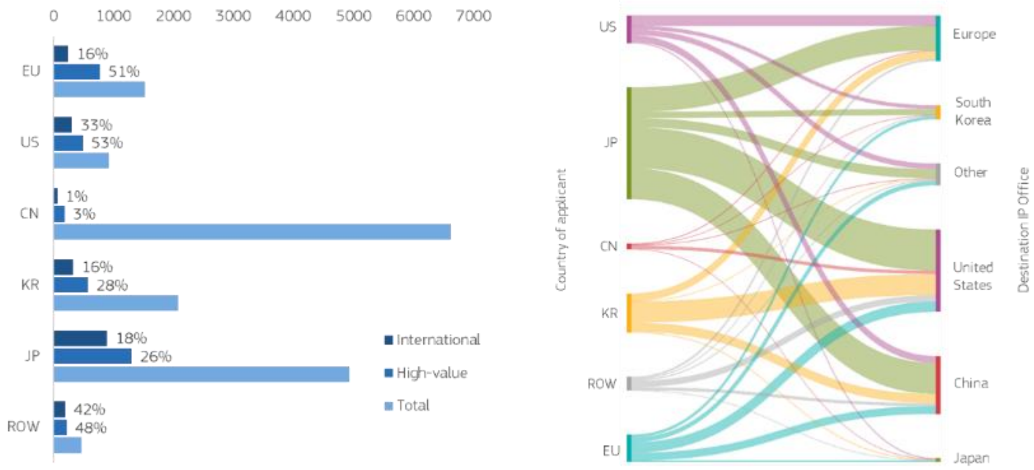
Figure 9: EU Member States public R&D investment in fuel cells [EUR million]

Source: JRC based on IEA data, 2023

Though relatively stable, since 2016 public investment has cumulatively been approximately half of what it was over the previous five-year period (**Figure 9**). However, expenditure seems to be picking up again with the increase in Member States' R&D budgets above that of EU GDP. In addition, in the period 2014-2020, EU Framework Programmes have contributed in excess of EUR 300 million to fuel cell R&D. The two combined outperform R&D investment 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.. 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). Going forward, the Clean Hydrogen JU will disburse another EUR 1 billion in the period 2021- 2027 (FCH 2 JU, 2022).

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 10**). South Korea, while second in terms of overall activity, has lower shares of high-value patents, ending on par with the EU in terms of international IP protection. The patenting trends presented here monitor filings in fuel cell technology as part of climate change mitigation technologies. Though different in scope, overall they are in good agreement with recent studies published by the EPO (EPO and OECD/IEA, 2023) and WIPO (WIPO, 2022). While collectively ahead of other major economies, the EU share in high-value filings, at 22%, 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. Among EU Member States, Germany performs the strongest, catching up with the US in third place, while France and Austria also represent the EU in the top ten. Companies from Japan and South Korea also dominate the top ten of innovators, with the exception of Bosch (Germany), a subsidiary of General Motors (United States) and AVL (Austria). The automotive industry has a very strong presence in both the global and EU top ten of fuel cell innovators. Audi, Volkswagen and BMW are in the EU top ten, which consists of companies headquartered in Germany, with the exception of AVL (Austria) and Widex As (France).

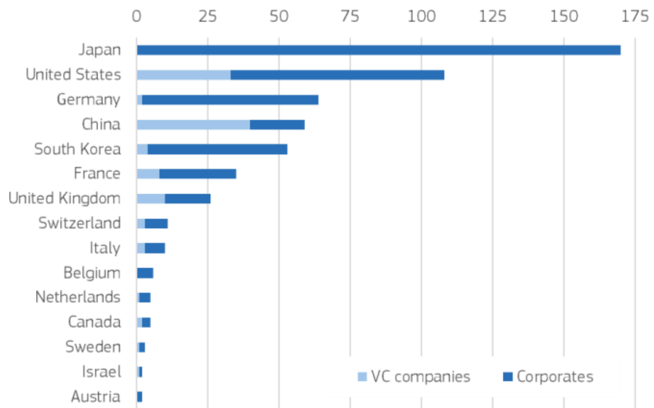
Figure 10: Number of inventions and high-value for major economies in the period 2016-2019 (left) and international protection of high value inventions (right)



Source: JRC based on EPO Patstat (right chart by Sankey/MATIC), 2023

Japan hosts the majority of innovators, nearly 30% of the all identified entities, and all from the corporate sector (**Figure 11**). 80% of all identified innovators are corporate companies, the US Germany and South Korea also displaying a strong corporate innovative base. The US and China also host a significant share of active VC companies. The EU achieves an average competitive position, supported by a corporate base concentrated in Germany and France, but limited by the low number of VC companies.

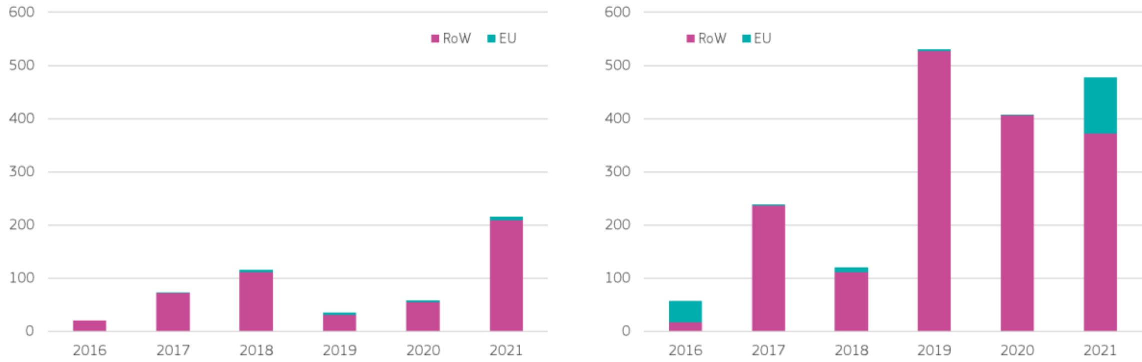
Figure 11: Number of innovating companies by type (2016-21)



Source: JRC based on Pitchbook, 2023

It follows that the EU attracts a small share of global VC investment (**Figure 12**). Over the 2016-21 period, EU-based companies only attracted 3% (EUR 17 million) of global early stage investment and 9% (EUR 162 million) of global later stage investment. France and Italy are hosts to recipient companies. The US maintains leadership over the 2016-21 period, both with respect to early stage investment (high levels of grants) and later stage investment (manufacturers of fuel cell vehicles). 14% of US early stage investment are grants and they represent 80% of identified subsidies worldwide over the same period (Giner Labs being a big beneficiary). In China, both early and late stage investment increased sharply in 2021, to the benefit of hydrogen fuel cell product and component manufacturers. Despite low previous levels of investment, in 2021, China accounted for 67% of disclosed early stage (major backing for FTXT Energy Technology) and 47% of disclosed later stage investment (including SHPT, Sinosynergy, Zhizhen New Energy Equipment, Fenergy, Thinkre New Material, Cemt, Shanghai Kunhua New Energy Technology Co. or Nowogen).

Figure 12: Early (left) and later (right) stage investment by region [EUR Million]



Source: JRC based on Pitchbook, 2023

The overview of the main fuel cell technologies provided in the previous version of this report (Kuokkanen, et al., 2022), also listed the challenges, which constitute areas for improvement and further development, for each. 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 to make 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 proposed for 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.

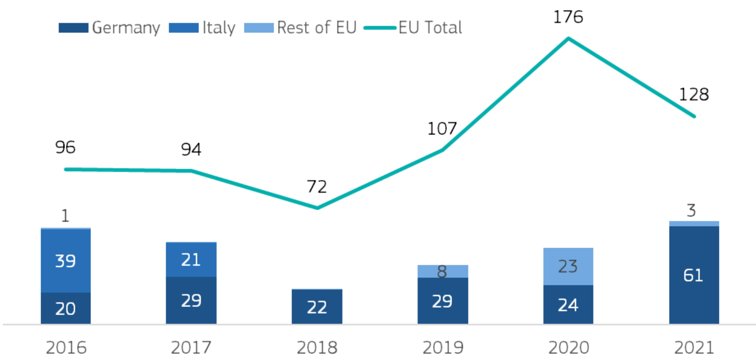
Scaling up PEM fuel cell stacks to the required power, while maintaining low weight and dimensions at a low cost, as well as addressing lifetime, performance and reliability issues, are also challenges for the deployment of heavy duty vehicles. The durability currently achieved for passenger vehicles 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 the current market and major changes

Eurostat PRODCOM contains data under a dedicated code from 2016 onwards. Statistics show a significant increase in production up to 2020. Statistics are not disclosed for all Member States; even though the reported EU total production value is markedly lower in 2021 compared to 2020, the trend over the last five years is still one of increase, and 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 13: EU production value and top producers disclosing data among the Member States [EUR Million]



Source: JRC based on PRODCOM, 2023

Internationally, 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.

Fuel cell shipments are dominated by PEMFC and SOFC. The fuel cell industry rebounded strongly after the pandemic. Statistics on shipments by region of deployment or system integration (FCHO, 2022a) (**Figure 14**) show that, while gaining ground, production (and deployment) in Europe is low compared with other regions, and Asia in particular. Compared to last year's figures and, in agreement with the trend observed for EU production, EU figures have stagnated and Europe's share in global figures has dropped.

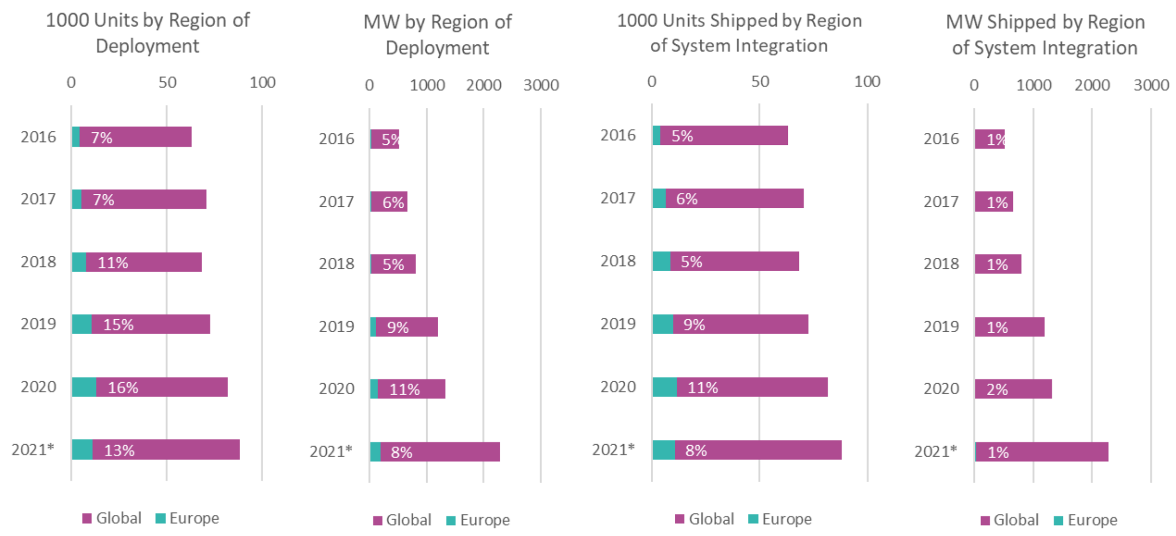
South Korea (Hyundai) and Japan (Toyota) are the clear leaders in fuel cell cars, with vibrant markets in road transport in general. China's support policies also drive a very large and expanding market, especially for buses and trucks. Despite the restrictions and changes in public transport brought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

Figure 14: Europe's share in fuel cell shipments by area of deployment and system integration (final manufacturer)



*2021 figures include projections for the 4th quarter

Source: JRC adapted from FCHO (FCHO, 2022a)

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 Scoreboard – key insights and change in EU performance

The previous edition of this report noted that 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. Levels of public R&I funding have increased, as has later stage investment, both improving performance in the scoreboard to good and average respectively. Nonetheless, production has been 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. An update on the associated raw material bottlenecks has been recently published (Carrara, et al., 2023), along with proposed policy actions to address them through the European Critical Raw Materials Act.

Figure 15: Scoreboard for fuel cells

Scoreboard	**Fuel Cells**	EU performance in the reference period			Change from 2021
Public R&D		6%	2016-2020	EU CAGR	
Early Stage		3%	2016-2021	EU share of global total value	
Later Stage		9%	2016-2021	EU share of global total value	
Patents		22%	2016-2019	EU share of global total HVI	
Companies		23%	2016-2021	EU share of innovating companies	
Employment			2016-2020	EU CAGR	
Production		6%	2016-2021	EU CAGR	
Turnover			2016-2020	EU CAGR	
Imports & Exports			2019-2021	EU share of global exports	
Trade Balance			2016-2021	EU trade balance trend	

Source: JRC, 2023

5 Electric powertrains

The decarbonisation of transport, especially in the light vehicle segments, relies largely on electrification. The electric powertrain, in addition to the battery, is an essential component of fully electrical and hybrid electrical vehicles.

The scope of the solution focuses on the electric components responsible for the 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 An updated status and recent developments

The electric car market is one of the most dynamic clean energy markets. EV sales doubled in 2021, reaching a new record of 6.6 million and a 10% share in all new car sales (IEA, 2022b). In the EU, electric vehicles represented an 18% share of all new car registrations in 2021 (EEA, 2022). Strong growth has continued in 2022 in all main markets, with China in the lead, followed by the EU and the US. EV adoption has been driven by sustained policy support, including subsidies and incentives. In the EU, the EV market has been stimulated by EU policies that have gradually tightened the emissions performance standards of vehicles. In 2022, a provisional deal was reached by the European Parliament and the European Council to ban sales of combustion engine cars and vans in the EU from 2035 (European Parliament, 2022a). An improving product offering and the rollout of charging infrastructure are also increasing consumer confidence. Nevertheless, the total number of EVs on the road is still low, representing fewer 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 ([36]). China – at 86 000 vehicles sold in 2021, and Europe – at about 60 000, lead in electric light-commercial vehicle (LCV) registrations, but their cumulative stock is still small (IEA, 2022b). Electric buses and heavy-duty vehicles also saw an increase in registrations in 2021, with sales of 14 000 globally, and a cumulative stock of 670 000 buses and 66 000 heavy-duty trucks (IEA, 2022b). The electrification of heavy-duty vehicles still faces some technical and development challenges, e.g. megacharging needs (see Chapter 6). While the 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 ([37]). 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, 2021a).

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 (Bobba, et al., 2020). 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 Chinese EV industry is consolidating to be more competitive and looking at Europe for potential export growth opportunities, which have so far been very low. 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 (Bobba, et al., 2020).

The EV supply chain has suffered from severe shortages of semiconductors that control most of the EV functions, and while the situation has been improving, shortage is expected to continue in 2023, according to Financial Times (Financial Times, 2022).

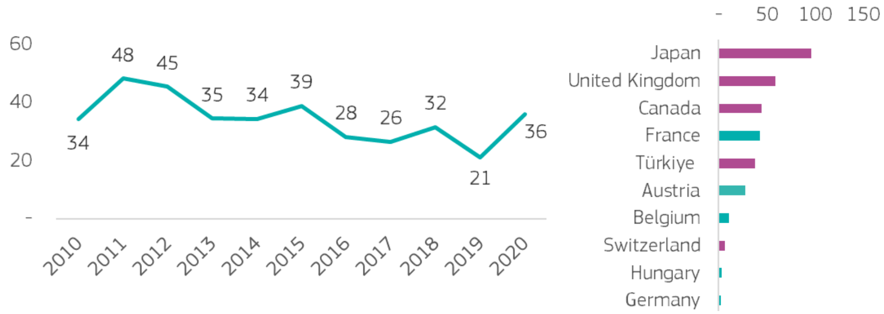
([36]) See more information on new registrations by segments in EU SWD(2021)307.

([37]) According to central MIX scenario for the Fit for 55 proposals (COM(2021) 550 final).

5.2 EU positioning in innovation and major changes

The EU public investment trend has slowly decreased since 2011, yet in 2020, investment increased (**Figure 16**). The departure of the UK, the second 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.

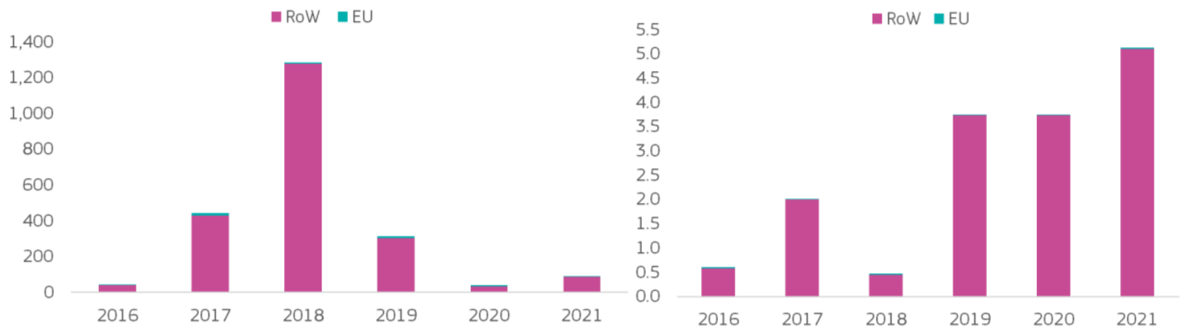
Figure 16: EU Member States public R&D investment (left) and top ten IEA Members in 2017-2019 (right) [EUR million]



Source: JRC based on IEA data, 2023

In terms of venture capital investment globally, electric powertrain companies attracted significant amounts of early (EUR 2 billion) and especially later stage (nearly EUR 16 billion) investment during the 2016-2021 period. Early stage investment has slowed down since its record level in 2018, while later stage investment continued to grow in 2021. However, the EU share of this is negligible, representing less than 2% of early stage investment and less than 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 Canada. Germany, the Netherlands, Finland and Italy are the best performing EU countries. The US and China are far ahead of others in later stage investment, where they attracted nearly EUR 10 billion and EUR 5 billion respectively in 2016-2021. Germany, Finland, Belgium and the Netherlands are the best performing EU countries. In both early and later stage investment, the EU attracts a higher share of deals, which implies that based on disclosed data, deal values in the EU are significantly smaller than those in China and the US.

Figure 17: Early (left) and later (right) stage investment by region [EUR million]

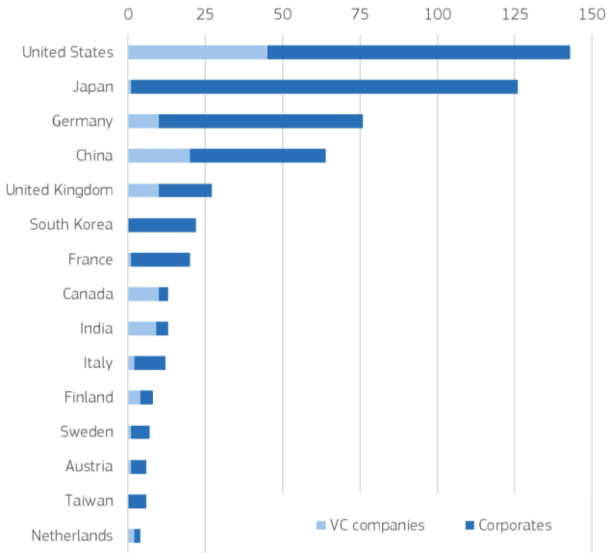


Source: JRC based on Pitchbook, 2023

Patenting activity increased until 2012 but has largely plateaued since. Japan is by far the leader in patents with a 45% 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 ten patenting countries. Japanese, US and South Korean companies dominate patenting, with only one European company, Bosch, in the top ten. The leading three companies are in the automotive sector: Toyota, Honda and Ford. 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 entry into the EV race.

For this solution, innovating companies are predominantly corporates (**Figure 18**). The US has overtaken Japan as the host of the largest pool of innovators, thanks to a high share of VC companies. Japan on the other hand has the largest pool of innovating corporates and only one VC company. The EU hosts about a quarter of all innovating companies, with more corporates than VC companies.

Figure 18: Number of innovating companies in 2016-2021



Source: *JRC compilation of sources, 2023*

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, such as Renault and Valeo, 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).

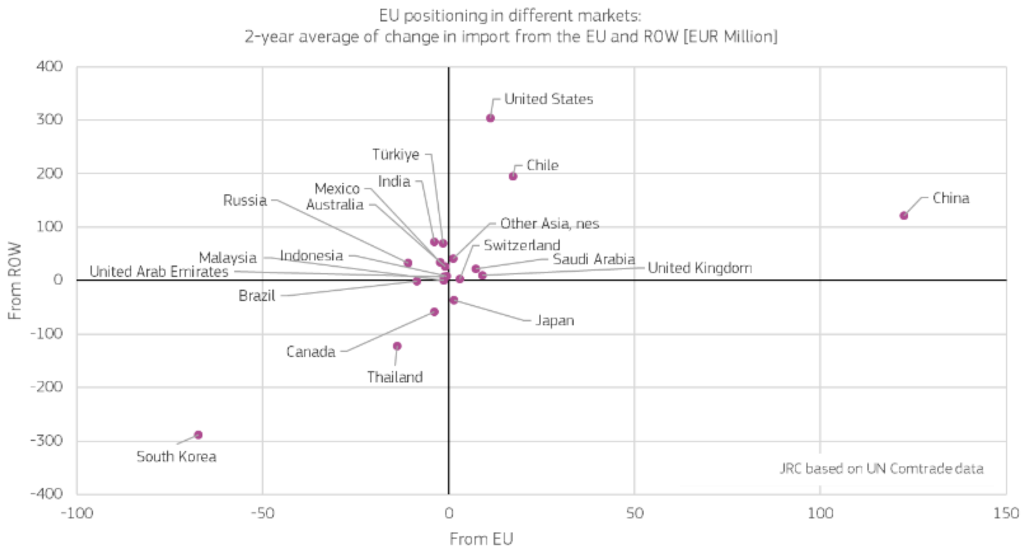
5.3 EU positioning in the current market and major changes

The EU's production value ([38]), staying stable at about EUR 4 billion per year for over a decade, jumped to over EUR 5 billion in 2021. Germany is the biggest producer, followed by Italy and France. 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 over EUR 2 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 Hungary are the top EU exporters, all featuring in the top ten 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 China, the US, and Chile, but losing ground in Mexico, Russia and Türkiye (**Figure 19**).

([38]) 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 19: EU positioning in different markets: change in import from the EU and RoW in 2019-2020 [EUR million]



Source: JRC based on Comtrade data, 2023

The EU trade surplus peaked in 2013 at EUR 1.6 billion, after which it gradually decreased to less than EUR 1 billion in 2021. As the world's second biggest exporter, Germany has the strongest positive trade balance, and growing, reaching EUR 1.4 billion in 2021, followed by Finland and Czechia. Belgium has the biggest trade deficit, and it is growing.

5.4 Scoreboard – key insights and change in EU performance

EU performance has remained largely the same as in the previous assessment. EU public R&D investment has followed a decreasing trend since 2011, but in 2020, investment increased. The EU score remains a cause for concern, particularly in venture capital investment. The number of patents and innovating companies gives more hope, although the activity is concentrated to Germany, with its 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 their late entry to the EV race. Current market-related indicators show that the EU still has a strong manufacturing base of electric motors, and production value increased in 2021. While EU exports are largely stagnating, imports from outside the EU grew by 30% in 2021 from 2020 values. As a result, the still positive trade balance deteriorated in 2021. This indicates that the EU needs to catch up to stay competitive and capture the growing EU market and a bigger share of the EV value chain.

Figure 20: Scoreboard for electric powertrains

Scoreboard	**Electric powertrains**	EU performance in the reference period			Change from 2021 assessment
Public R&D	🟢	6%	2016-2020	EU CAGR	↑
Early Stage	🔴	2%	2016-2021	EU share of global total value	→
Later Stage	🔴	1%	2016-2021	EU share of global total value	→
Patents	🟡	19%	2016-2019	EU share of global total HVI	→
Companies	🟢	25%	2016-2021	EU share of innovating companies	→
Employment			2016-2020	EU CAGR	
Production	🟢	7%	2016-2021	EU CAGR	↑
Turnover			2016-2020	EU CAGR	
Imports & Exports	🟡	23%	2019-2021	EU share of global exports	→
Trade Balance	🟡	Medium	2016-2021	EU trade balance trend	↓

Source: JRC, 2023

6 Electrical vehicle charging infrastructure

The scope of electric vehicle charging infrastructure includes the design, installation, operation, and maintenance of charging stations ([39]) and associated equipment that is used to charge electric vehicles. The scope also includes the development and management of communication networks, payment systems, and software platforms to support the charging infrastructure. It may also involve policy and regulatory frameworks to facilitate the deployment of charging infrastructure and ensure its interoperability and accessibility. 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). The 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, 2021a).

6.1 An updated status and recent developments

By 2025, the European Green Deal (COM(2019) 640 final)([40]), 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 (up from 350 000 today (IEA, 2022b)) serving at least 30 million zero-emission vehicles, according to Sustainable and Smart Mobility Strategy (2020)([41]). In its comprehensive package, the Commission proposed the revision of the Alternative Fuels Infrastructure Regulation ([42]),([43]) to require charging points at regular intervals on major highways, namely every 60 kilometres for electric charging on TEN-T core network. In October 2022, the European Parliament reached an agreement on this target (European Parliament, 2022b). Several Member States have included investment in charging infrastructure in their Recovery and Resilience Plans under NextGenerationEU; these include Italy (EUR 32 billion ([44])), Austria (EUR 256 million ([45])), Belgium (EUR 920 million ([46])) and Lithuania (EUR 341 million ([47])). Germany plans to incentivise the uptake of electric cars with EUR 2.5 billion, creating a stimulus for private investment in infrastructure.

Publicly accessible chargers ([48]) grew by 40% from 2020 and reached 1.8 million units in 2021, of which ~30% were fast chargers (IEA, 2022b). China leads in terms of the number of EV chargers installed, with over 4 700 000 fast chargers and 680 000 ([49]) slow chargers in 2021. Europe is in second place with 50 000 fast public chargers and 300 000 slow chargers in 2021 (IEA, 2022b). Fast chargers continue to be rolled out at a higher pace in Europe than slow chargers. Still, a recent report estimates that installations need to pick up the pace and quadruple in Europe by 2025 to meet the targets and avoid slowing down EV adoption (ACEA, 2022). The US is trailing China and Europe in public charging points.

([39]) While the focus is on public charging points, separating public charging infrastructure from private in the various datasets, is, impossible.

([40]) COM(2019) 640 final, 11th December 2019.

([41]) COM(2020) 789 final, 9th December 2020.

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

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

([44]) 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.

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

([46]) 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.

([47]) 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.

([48]) 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).

([49]) This is more than half of the world's stock of slow chargers.

The European charging market is very diverse (50) and competitive, especially in comparison with the US, which has limited public charging infrastructure in general, with Tesla dominating the market (51). This is in part thanks to EU regulation, which requires Member States to establish a minimum number of charging points and to ensure the interoperability and accessibility of the charging infrastructure. In comparison, the US does not have federal regulations in place for EV charging infrastructure, but some states have established their own regulations and targets. The Chinese market is more consolidated. Only three operators in China (52) and the US (53) account for a 70% market share, whereas in Europe (54), 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 (55) (16%) in fast and ultra-fast public charging, with the exception of the German market (BNEF, 2021b).

According to Bloomberg NEF, due to lower utilisation and higher costs, European and US operators have further to go before they are profitable in comparison with China. The average public charger in Chinese networks delivered more than double the daily amount of energy than in US and European networks (56) 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, 2021b).

Europe has a strong, competitive industry in both charging hardware and charging platforms, which have grown annually by 26% and 28% respectively (European Commission, 2021a). 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, 2021a).

One of the challenges facing the development of EV charging infrastructure is the cost, financing required, grid capacity and reliability, and interoperability. 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 (57)(European Commission, 2020a). Investment needs are estimated to be up to EUR 280 billion by 2030: with 30% for private and 30% for public charging infrastructure, 15% towards grid upgrades and 25% in renewable power capacity (ACEA, 2022). 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. Different charging strategies and technologies are being developed, from depot charging to megachargers along highways, battery swapping and electric road systems (IEA, 2022b).

6.2 EU positioning in innovation and major changes

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 2018-2020, EU

(50) The European market has a operators from various industries: oil and gas, utilities, automotive, pure-play and others.

(51) 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

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

(53) The three biggest operators in the US: ChargePoint, Tesla, Semacharge.

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

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

(56) 46 kWh per charger per day in China against 19 kWh per charger in the US and Europe.

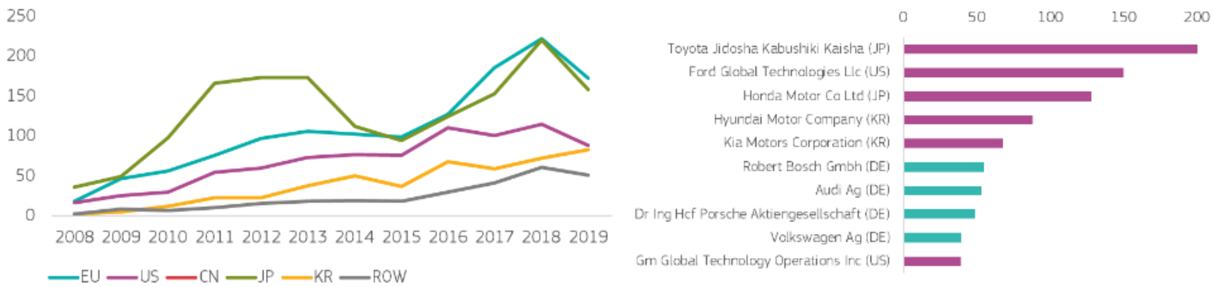
(57) With evolving technologies and standards, there is a risk that EV infrastructure will become rapidly outdated, creating investor uncertainty.

investment totalled EUR 50 million and the trend seems to be increasing slightly. France was the biggest investor among the reporting countries.

Venture capital investment has increased globally, particularly later stage investment, which saw yet another record year in 2021. The EU is attracting relatively more early stage investment and captured 16% of the global total during 2016-21. EU companies attracted only 8% of later-stage investment during the same period. Overall, Spain, Germany, France, the Netherlands, Sweden and Finland attracted the most venture capital from EU countries. Globally, China has overtaken the US, both being far ahead of the rest with over EUR 1 billion of investment.

Globally, patenting activity has been on the rise, and especially since 2015 in the EU, which overtook Japan as the leading patenting economy (see **Figure 21**). The EU holds 28% of high-value inventions, followed by Japan with 26% and the US with 17%. Germany, France and Sweden rank among the top ten countries globally.

Figure 21: Trend in high-value inventions for major economies (left) and top ten companies in 2019-2020 (right)



Source: JRC based on PATSTAT, 2023

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 ten (see **Figure 21**). Among the EU-based corporates, German companies are the most active in patenting.

EV charging is an emerging, yet dynamic market, with more innovating corporates than VC companies. The majority of VC companies received investment in the past five years. The EU hosts 28% of all VC companies and 32% 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 innovators at country level.

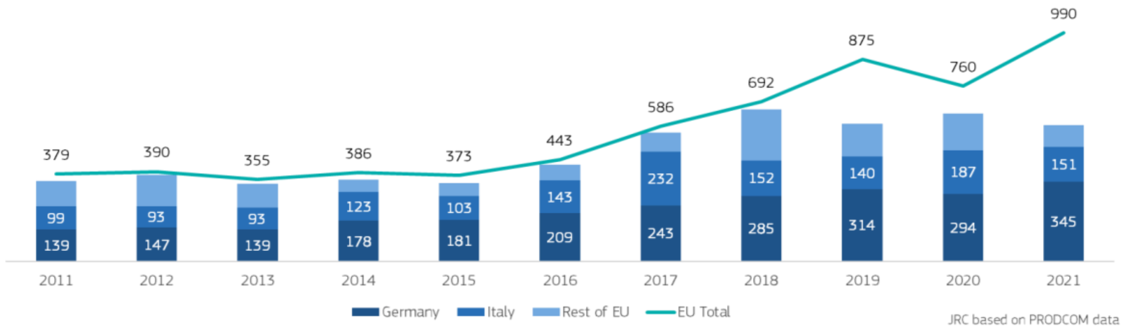
Areas of innovation include predictive maintenance, smart charging, vehicle-to-grid solutions, peer-to-peer energy trading and autonomous payments using blockchain. For instance, innovative charging stations such as robotic chargers (Mob-Energy), battery swapping stations (Zeway) and wireless charging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

6.3 EU positioning in the current market and major changes

Since 2015, the production value ([58]) has increased annually, and after a drop during the pandemic in 2020, it recovered and reached a new record level of nearly EUR 1 billion. **Figure 22** shows that Germany and Italy are the biggest producers, but significant amounts of EU production have not been disclosed in recent years.

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

Figure 22: EU production value and top producers disclosing data among the Member States [EUR Million]

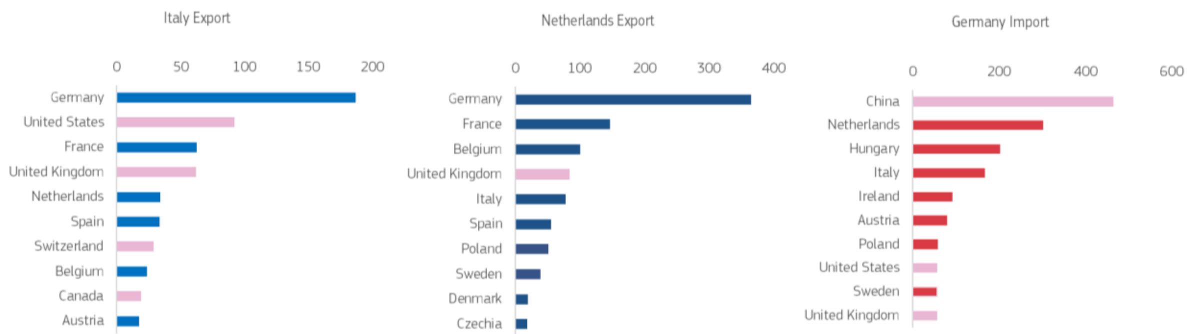


Source: JRC based on PRODCOM data, 2023

Both exports from and imports to the EU continued to grow in 2021 ([59]). Imports increased by 40% and reached over EUR 1 billion. The biggest exporter to the EU by far was China, with nearly EUR 1.7 billion in 2018-20. The main destinations of EU exports are the US, at EUR 380 million, and the UK at EUR 320 million. EU internal trade accounts for well over half (58%) 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 deficit grew to a new record of EUR 430 million in 2021. Italy and the Netherlands are among the EU countries with the biggest positive trade balance, with Italy exporting nearly 60% and Netherlands 84% internally (**Figure 23**). Germany, France and Spain have the biggest trade deficits. Germany imports nearly 60% internally.

Figure 23: Top ten partners of Italy, Slovakia and Germany in 2019-2021 [EUR Million]



Source: JRC based on COMEXT data, 2023

6.4 Scoreboard – key insights and change in EU performance

Figure 24 depicts a two-fold picture of EU positioning in EV charging infrastructure. The EU score remains high in public R&D funding, patenting trends and innovating companies. EU patenting activity has surged and overtaken Japan in recent years. The EU hosts nearly a third of all innovators, with the biggest pool of corporates and the second biggest pool of VC companies, behind the US. At the same time, lower scores in venture capital investment, especially at the later stage, may pose a challenge for growth of EU scale-ups as the market matures. Nevertheless, in the last two years, EU companies have attracted more later stage investment deals. EU production continues to grow, along with imports from China to the EU, resulting in a growing trade deficit. This exposes the threat that non-EU producers may capture growing EU markets.

The EU charging market is very competitive, with many large companies setting high-level charging targets and announcements, including BP, Shell, Enel, EDF, Iberdrola and Volkswagen. As 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. The level of private financing available

([59]) 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.

varies among Member States, depending on regulatory certainty and incentives, and maturity and saturation of the market. 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. In terms of supply chain risks, EV charging shares similar risks to other digital technologies and is a net-importer of electronic boards, semiconductors and microprocessors.

Figure 24: Scoreboard for EV charging infrastructure

Scoreboard	**EV charging infrastructure**	EU performance in the reference period			Change from 2021
Public R&D	●	8%	2016-2020	EU CAGR	↓
Early Stage	●	16%	2016-2021	EU share of global total value	→
Later Stage	●	8%	2016-2021	EU share of global total value	↑
Patents	●	28%	2016-2019	EU share of global total HVI	→
Companies	●	30%	2016-2021	EU share of innovating companies	→
Employment			2016-2020	EU CAGR	
Production	●	17%	2016-2021	EU CAGR	→
Turnover			2016-2020	EU CAGR	
Imports & Exports			2019-2021	EU share of global exports	
Trade Balance	●	Low	2016-2021	EU trade balance trend	→

Source: JRC, 2023

7 Prefabricated buildings

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 (see Chapter 17 on building envelopes), while services related to transportation, installation, and assembly are excluded.

7.1 An updated status and recent developments

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. Moreover, assembling failures fuel the misconception that modular buildings are cheap temporary structures of limited use. Nevertheless, standardised modules present a lower damage risk and transport limitations than specialised ones. Technological enhancements include modular systems of steel framed, concrete full volumetric, and some new cross-laminated timber (CLT), while advanced manufacturing techniques embrace full digital design within building information modelling (BIM) and high precision environments, using advanced laser technologies in the production process (Kivlehan, 2022). The European Federation of Premanufactured Buildings (EFV) promotes the competitiveness of prefabricated construction in Europe ([60]). The European PropTech Association – PropTech House (PROTECH)([61]) 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.

Prefabricated solutions span a range of market segments relating to construction materials (i.e. wood, steel), type (i.e. permanent, relocatable), and application (i.e. commercial, hospitality). MarketResearchFuture estimated the global prefabricated building market to be worth nearly EUR 139 billion in 2022 and projected to reach EUR 281 billion ([62]) by 2030 (MarketResearchFuture, 2022). According to the same report, government initiatives to promote energy efficient buildings and cut down on construction waste drive the industry. Asia-Pacific dominated the market, especially China with its 13th Five-Year Plan. Europe's prefabricated buildings market was the second largest.

Box 1: Zero-emission buildings ([63])

In February 2023, the European Parliament Committee on Industry, Research and Energy voted to update the EU Energy Performance of Buildings Directive (EPBD) ([64]). The adopted text introduces mandatory Minimum Energy Performance Standards (MEPS) that must be first reached by 2027 for public and by 2030 for residential buildings. The target is for all European buildings to achieve an energy efficiency grade of D by 2033, and by 2050, all buildings should be climate neutral. Member States should adjust their national renovation plans.

([60]) Link to the website: http://e-f-v.eu/eng/index.html
([61]) Link to the website: https://www.proptechhouse.eu/
([62]) Forecasted values are converted to EUR based on a fixed rate at EUR 1.21 per USD.
([63]) "A zero emission building is defined as a building with a very high energy performance, with the very low amount of energy still required fully covered by energy from renewable sources and without on-site carbon emissions from fossil fuels." (https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/nearly-zero-energy-buildings_en)
([64]) European Parliament, Press Release 09-02-2023, Ref.: 20230206IPR72112

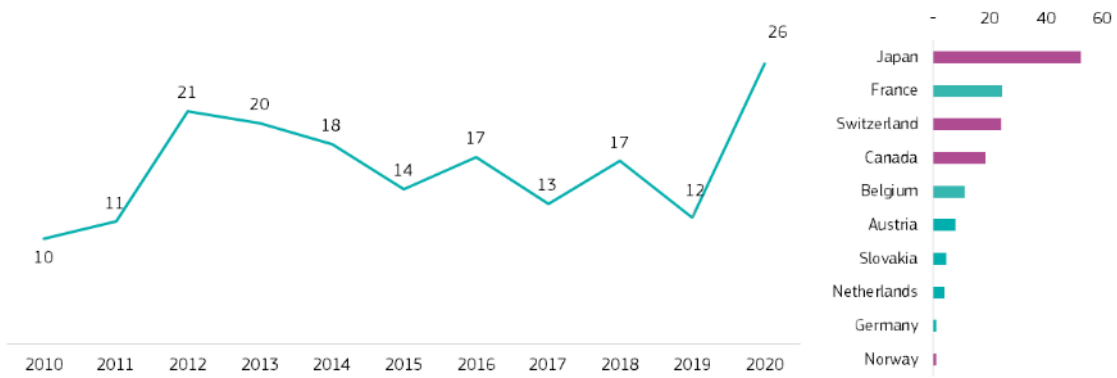
In force since 2010, the Energy Performance of Buildings Directive (EPBD) ([65]) seeks to achieve a highly energy-efficient and decarbonised building stock by 2050, to provide investment stability, and to empower both consumers and businesses to understand how to cut energy consumption and save money. The Energy Efficiency Directive (EED) ([66]) seeks to increase the national annual energy savings obligations. The amendment of the Renewable Energy Directive (RED-II) ([67]) covers the production and promotion of energy from renewable sources to achieve the EU's 2030 renewable energy target. Moreover, in December 2022, the Council and the European Parliament agreed to extend the EU Emissions Trading Scheme (ETS-II) to the buildings and transport sector ([68]).

MarketResearchFuture estimated the global zero-energy building market at nearly EUR 121 billion in 2021 and projected to reach EUR 284 billion by 2030 (MarketResearchFuture, 2019). According to the same report, the market growth depends on government initiatives, homeowner awareness and the availability of a skilled workforce. North America dominated the market share, followed by Asia Pacific and Europe. Some of the key players were Siemens (DE), Schneider electric (FR), Johnson controls international (IE) and Kingspan group (IE).

7.2 EU positioning in innovation and major changes

In 2020, public R&D investment more than doubled. The total amount for 2018-2020 was EUR 151 million, with the EU having a 36% share (EUR 54 million). Japan remained the top investor among the reporting countries, while France climbed to second place from fourth previously. Five more Member States were among the top investors (**Figure 25**). The scope of the selected IEA code (1211) includes technologies which relate to the structure, assembly, protection, or thermal efficiency of the building envelope, including windows. However, IEA (69) clarifies that some projects might include multiple technologies and the funding might not be possible to be split. Moreover, the categories at the four-digit level are optional in reporting and some investments might be "hidden" by being aggregated at a reporting higher level. Prefabricated buildings, superinsulation materials and building envelope technologies are considered to fall under the same IEA code, and, therefore, the public R&I figures are not exclusive to each solution. Instead the same public R&I value concern all three solutions, as discussed in the methodology (70).

Figure 25: EU Member States public R&D investment (left) and top ten IEA Members in 2017-2019 (right) [EUR Million]



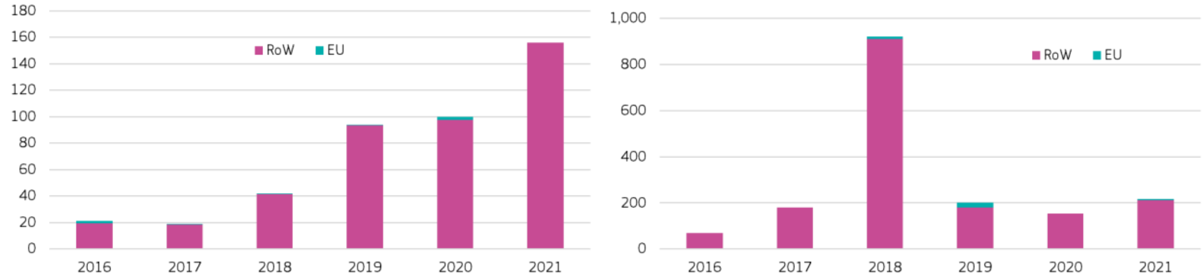
Source: *JRC based on IEA data, 2023*

Early stage investment increased by 56% in 2021, reaching EUR 156 million. Nevertheless, the EU had no investment registered for that year, and the EU share in early stage investment value in 2016-2021 was barely over 1%. After a 24% drop in 2020, global later stage investment increased by 42% in 2021, but it

([65]) 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)
([66]) Directive 2012/27/EU of the European Parliament and 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)
([67]) 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)
([68]) European Parliament, Press Release 18-12-2022, Ref.: 20221212IPR64527
([69]) IEA (2011), IEA Guide to Reporting Energy RD&D Budget/ Expenditure Statistics, available at https://iea.blob.core.windows.net/assets/751c1fce-72ca-4e01-9528-ab48e561c7c4/RDDManual.pdf
([70]) European Climate Neutral Industry Competitiveness Scoreboard (CINDECS) – Protocol of the assessment methodology, JRC129397 (not yet published).

was still less than one quarter of the investment value in 2018 (**Figure 26**). The EU registered investment only in 2018, 2019 and 2021, remaining at 2% of the total later investment share during 2016-2021. 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 26: Early (left) and later (right) stage investment by region [EUR Million]



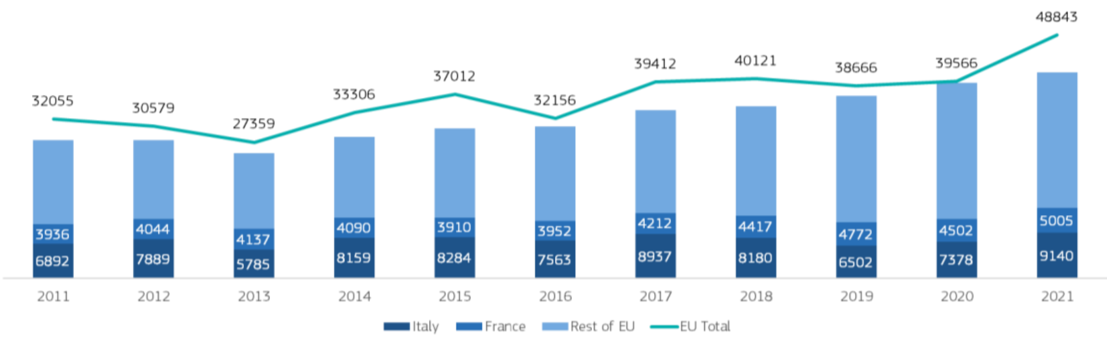
Source: *JRC based on Pitchbook, 2023*

Patenting activity in prefabricated buildings is low. China and Russia were the top high-value invention holders, followed by Germany. Europe had some patenting activity but no rising trends. Prefabricated and modular construction is an emerging market, mainly consisting of innovative VC companies. During 2016-2021, the US hosted most of the innovating companies; more than double that of the UK. Only 21% of all innovating companies had their headquarters in the EU.

7.3 EU positioning in the current market and major changes

While the pandemic in 2020 did not seem to make a significant impact, EU production grew by 23% in 2021. The increase in 2021 was mainly due to an increase in production in Italy (+24%), the top EU producer, and in Spain (+40%), in fifth place. Germany, the second top European producer, declared a 32% reduction in its production for 2021.

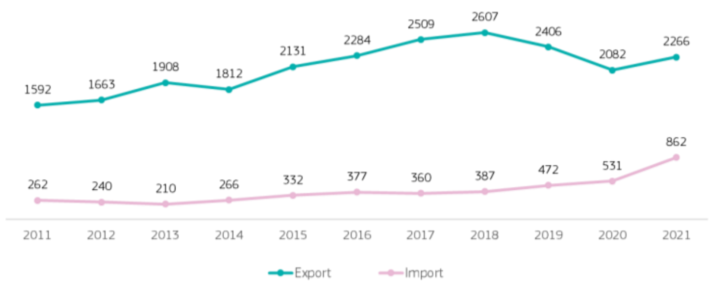
Figure 27: EU production value and top producers disclosing data among the Member States [EUR Million]



Source: *JRC based on PRODCOM data, 2023*

After a 13% drop during the 2020 pandemic, extra-EU exports increased by 9% and extra-EU imports by 62% in 2021 (**Figure 28**). Extra-EU exports accounted for 33% of the global export share for 2019-2021. During the same period, China was the top exporter globally and to the EU, exporting almost twice as much as the second-ranked Netherlands. Germany was the top global importer, importing almost twice as much as the second-ranked Netherlands. The UK was an important trade partner, for EU imports and exports. Since 2019, EU imports have grown much faster than exports, shrinking the trade balance to EUR 1.4 billion in 2021.

Figure 28: Extra-EU import and export [EUR Million]



Source: *JRC based on COMEXT data, 2023*

7.4 Scoreboard – key insights and change in EU performance

EU competitiveness in innovation for prefabricated buildings has slightly improved but remains worrying. EU public R&D investment surged in 2020, increasing the compound annual growth rate to 11%, indicating a strong performance. The EU maintained its share of innovative companies and high-value inventions, yet venture capital investment in EU-based start-ups and scale-ups remains very limited. This may indicate that the construction industry in the EU is more conservative and new emerging companies face barriers to entering the market. The EU production value has gradually increased since 2016 and is spread across nearly all EU Member States, demonstrating that the EU has a strong industrial base. Trade-related indicators also show that the EU maintains a strong presence globally, with a 33% share of global exports. However, due to growing imports from outside the EU in recent years, the EU trade balance, which is still positive, is decreasing.

Figure 29: Scoreboard for prefabricated buildings

Scoreboard	**Prefabricated Buildings**	EU performance in the reference period			Change from 2021
Public R&D		11%	2016-2020	EU CAGR	↑
Early Stage		1%	2016-2021	EU share of global total value	→
Later Stage		2%	2016-2021	EU share of global total value	→
Patents		21%	2016-2019	EU share of global total HVI	→
Companies		21%	2016-2021	EU share of innovating companies	→
Employment			2016-2020	EU CAGR	
Production		9%	2016-2021	EU CAGR	↑
Turnover			2016-2020	EU CAGR	
Imports & Exports		33%	2019-2021	EU share of global exports	→
Trade Balance		Medium	2016-2021	EU trade balance trend	→

Source: JRC, 2023

8 Superinsulation materials

The scope of this chapter 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, 17).

8.1 An updated status and recent developments

Insulation is a key element in improving the energy efficiency of buildings, also enabling the electrification of heating through heat pumps (see Chapter 9 for more information). 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 buildings 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 materials that make use of the Knudsen Effect when used in vacuum insulation panels or advanced porous materials systems (IEA-EBC, 2020).

MarketsandMarkets (MarketsandMarkets, 2023) estimated the global thermal building insulation market at EUR 27 billion ([71]) in 2022 and expected it to reach EUR 43 billion ([72]) by 2027. Plastic foam was identified as the largest material segment of the building thermal insulation market in 2021, followed by glass wool. Yet, stone wool had the second largest segment in the European market for the same year. The same report estimated that the EU accounted for the largest share in terms of value in 2021. EU-based companies identified amongst the key players include Knauf (DE), Rockwool (DK), Saint-Gobain (FR), BASF (DE) and Altana (DE).

8.2 EU positioning in innovation and major changes

The data on public investment is available for a limited group of countries covered by the IEA, with some major economies, such as Italy, the US and South Korea, not reporting. The scope of the selected IEA code (1211) includes technologies which relate to the structure, assembly, protection, or thermal efficiency of the building envelope, including windows. However, IEA ([73]) clarifies that some projects might include multiple technologies and the funding might not be possible to be split. Moreover, the categories at the four-digit level are optional in reporting and some investments might be hidden by being aggregated at a reporting higher level. Prefabricated buildings, superinsulation materials and building envelope technologies are considered to fall under the same scope, and, therefore, the public R&I figures are not exclusive to each solution. Instead the same public R&I value concern all three solutions, as discussed in the methodology ([74]). The total reported investment for 2018-2020 was nearly EUR 151 million, with Japan, France 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 enjoyed around 36% of the total reported investment during 2018-2020 (more than EUR 54 million), with an increasing trend.

Limited information is available for venture capital investment. In early stage investment, the leading countries remain the UK and the US, who more than doubled their investment in 2016-2021 compared to 2015-2020. In Switzerland, early stage investment surged and overtook Sweden in third place. In later stage investment, China took the lead. The EU's share in the disclosed early stage investment value dropped to 8% and 0% in the disclosed later stage investment value because the EU registered no later stage investment deals in 2016-2021.

The EU maintained the lead in high-value patenting activity despite the declining trend (**Figure 30**). However, US and Japanese patenting activities reached the European level in 2019, due to a drop in EU patenting activity. The EU had 43% of high-value inventions in 2016-2019, while the US had 20% and Japan had 15%.

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

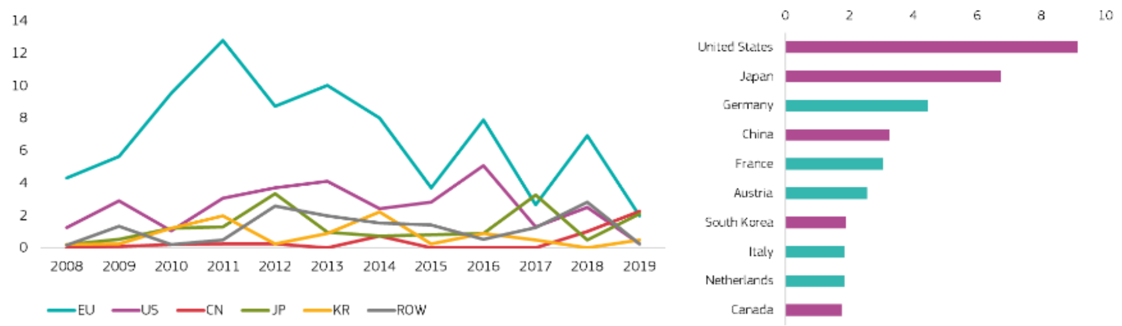
([72]) Forecasted values are converted to EUR based on a fixed rate at EUR 1.21 per USD.

([73]) IEA (2011), IEA Guide to Reporting Energy RD&D Budget/ Expenditure Statistics, available at https://iea.blob.core.windows.net/assets/751c1fce-72ca-4e01-9528-ab48e561c7c4/RDDManual.pdf

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

The EU and US were the biggest applicants for high-value patents, while most submissions were to patent offices outside Europe, the US, China, and South Korea.

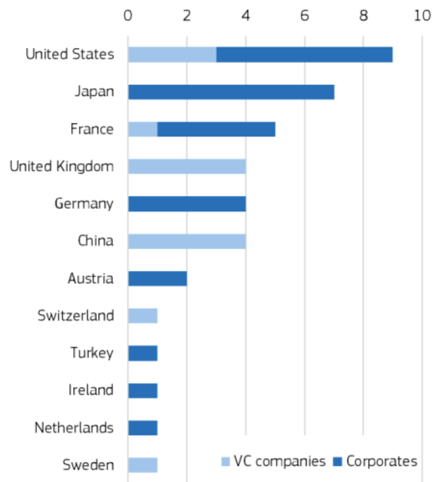
Figure 30: Trend in high-value inventions for the major economies (left) and top ten countries in 2016-2019 (right)



Source: *JRC based on PATSTAT, 2023*

The innovation landscape is dominated by corporates as VC companies constitute around a third of innovators. Only the US and France have a mixture of corporates and VCs (**Figure 31**). The US, Japan, and France are the frontrunners, while Germany dropped to fifth place, after the UK. The EU share dropped to 35%, but it remains the biggest pool of innovators.

Figure 31: Number of innovating companies in 2016-2021



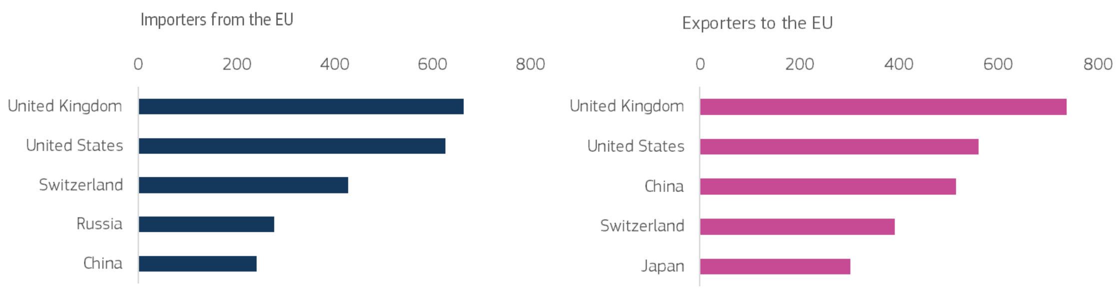
Source: *JRC compilation of sources, 2023*

8.3 EU positioning in the current market and major changes

After a 5% drop in 2020, EU production increased by 15% in 2021, reaching a ten-year high production value of EUR 6.6 billion. Germany and France held approximately one-third of total EU production in superinsulation materials during 2019-2021.

In 2020, extra-EU imports and exports shrunk by almost one tenth. The UK, the US, Switzerland, and China were significant EU trade partners in this solution, as there was major re-exporting in the EU (**Figure 32**). The US, the world's largest global importer, acquired 22% of its imports from the EU, while the UK, the biggest importer from the EU, imported 70% of its imports from the EU. However, UK exports to the EU were slightly higher than imports from the EU. The EU accounted for 23% of non-EU exports in 2019-2021 and captured most of the growing non-EU markets.

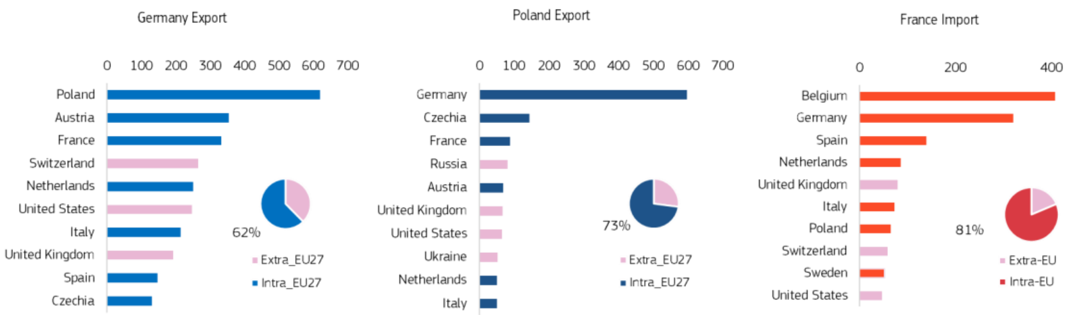
Figure 32: Top 5 importers from the EU (left) and top 5 exporters to the EU (right) in 2019-2021 [EUR Million]



Source: JRC based on COMEXT data, 2023

After a negligible drop in 2020 (-3%), the EU trade surplus slumped by 25% in 2021, dropping to nearly EUR 267 million. EU internal trade accounted for 75% of all EU imports. France, the Member State with the biggest trade deficit, covered 81% of its importing needs from other EU Member States (**Figure 33**). Germany and Poland, the Member States with the biggest trade surplus, sent 62% and 73% of their exports internally. Germany remained the biggest global exporter and the second-biggest global importer.

Figure 33: Top ten trading partners of Germany, Poland and France in 2018-2020 [EUR Million]



Source: JRC based on COMEXT data, 2023

There is no statistical data available for employment generated in 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.

8.4 Scoreboard – key insights and change in EU performance

EU performance declined in all innovation-related indicators, except public R&D investment, which doubled compared to the previous three-year period. 2017 was the last year the EU registered an early stage investment deal, while non-EU countries more than tripled their early stage investment in 2021 alone. As a result, the EU share dropped from 25% to 8%, and the related indicator dropped to medium. In later stage investment, the EU registered its last deal in 2015 and had no deals in 2016-2021. The EU maintained its strong competitiveness with innovative companies, yet it started losing ground, and non-EU countries doubled the number of their VC companies. In the market-related indicators, the EU maintained a medium presence. EU production continued its increasing trend, indicating a strong manufacturing base in this area, as the majority (75%) of importing needs were met internally. The EU maintained a 23% share of global non-EU exports, slightly below the threshold of strong performance. However, extra-EU imports increased by more than exports, and the EU trade surplus shrank even more.

Figure 34: Scoreboard for superinsulation materials

Scoreboard	**Superinsulation Materials**	EU performance in the reference period			Change from 2021
Public R&D		11%	2016-2020	EU CAGR	
Early Stage		8%	2016-2021	EU share of global total value	
Later Stage		0%	2016-2021	EU share of global total value	
Patents		43%	2016-2019	EU share of global total HVI	
Companies		35%	2016-2021	EU share of innovating companies	
Employment			2016-2020	EU CAGR	
Production		4%	2016-2021	EU CAGR	
Turnover			2016-2020	EU CAGR	
Imports & Exports		23%	2019-2021	EU share of global exports	
Trade Balance		Medium	2016-2021	EU trade balance trend	

Source: JRC, 2023

9 Heat pumps

Heat pumps play an important role in decarbonising heating and cooling in the buildings sector by enabling higher energy efficiency; greater use of renewable energy sources, ambient energy and waste heat; and increased flexibility of the energy system (Lyons, et al., 2022).

The scope of the heat pumps solution covers air-, ground- and water-source heat pumps ([75]). The heat pumps considered here cover building space (residential and commercial) and water heating applications, focusing therefore mainly on heating. Heat pumps can also be used for cooling, in the case of reversible or multifunctional heat pumps, although it is not always possible to make the distinction in the datasets. Cooling and air-conditioning technologies are considered primarily in Chapter 19. Heat pumps can also be used for industrial applications and temperatures up to 160 °C are being demonstrated, while temperatures higher than that are still in research and development stage (Lyons, et al., 2022). This application therefore constitutes a smaller fraction ([76]) and is impossible to separate from the data at this stage.

9.1 An updated status and recent developments

The European heat pump market has been booming in recent years thanks to concerted policy action at EU level ([77]) and different support schemes at Member State level. The REPowerEU Plan, which was put forward to tackle the energy crisis and energy dependency, proposed to frontload the rollout of heat pumps by doubling the deployment rate to reach a cumulative 10 million additional units installed over the next five years ([78]). Eventually the target is 30 million additional installed heat pumps by 2030, in line with the 'Fit for 55' package in 2021 ([79]).

There were 17 million heat pumps, mainly used for heating and hot water, in Europe ([80]) by 2021 (European Heat Pump Association, 2022). This is still less than a third of the number of gas boilers in the EU (Lyons, et al., 2022). Including all reversible air-to-air heat pumps (also those used primarily for cooling) raises the figure to over 42 million (EurObserv'ER, 2023)([81]). The heat pump market is growing fast in the EU. According to the EHPA, every fourth heating device sold in Europe in 2021 was a heat pump, reaching nearly 2.2 million heat pumps sold, which was about 34% more than the previous year (European Heat Pump Association, 2022). Early data suggests an even faster market growth in some countries in 2022. For example, in August alone, 150 000 Germans applied for a heat pump subsidy announced that month, which is equivalent to the sales of the whole year in 2021 (Bundesverband Warmepumpe (BWP), 2022); sales in the first half of 2022 were double the same period in 2021 in Poland, the Netherlands, Italy and Austria (IEA, 2022c); Finland records growth of 80% in H1 2022 ([82]). This makes the EU the fastest growing market worldwide in recent years.

Globally, heat pump sales increased by 13% in 2021 over 2020 levels (IEA, 2022c) continuing a steady double-digit growth. Still, they provide only 10% of global heating needs in buildings, with the highest penetration in northern Europe: 60% in Norway and 40% in Sweden and Finland (IEA, 2022c). Europe still has the most market potential due to the many gas heating boilers to be replaced.

The European heat pump industry is well established, innovative and leading in most heat pump segments (air-water, ground-water and brine/water-water). The EU industry consists of many SMEs and a few large manufacturers, and none of the companies dominate the entire EU market. Some consolidation has taken place recently; for example, Midea (China) acquired a majority stake in the Italian Clivet group, Stiebel Eltron (DE) took over Danfoss Varmepumpar (SE), Hisense (China) acquired Gorenje (SI) and Nibe (SE) acquired Waterkotte (DE). Consolidation may be essential to exploit economies of scale and ensure competitiveness against Asian-Pacific air conditioner giants that could potentially compete with lower costs. China and the US are implementing policies to support manufacturers, including for exports (Lyons, et al., 2022), potentially

([75]) Including piping, valves, heat exchangers, oil separators, compressors, evaporators, condensers, accumulators, electronic expansion valves, pumps, refrigerant, controllers and fan motors.
([76]) Fewer than one 1000 industrial and heating network heat pumps are sold annually in the EU (EU SWD(2021)307).
([77]) For list of policy actions, please see the previous report, Kuokkanen et al. (2022), and Lyons et al. (2022).
([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]) EHPA data includes 18 EU Member States and Norway, Switzerland and the UK.
([81]) Only heat pumps that meet the efficiency criteria (seasonal performance factor) defined by Directive 2009/28/EC are taken into account.
([82]) https://www.sulpu.fi/record-high-sales-growth-of-80-recorded-for-heat-pumps-in-the-first-six-months-of-the-year-in-finland/

eyeing the EU market. In this regard, the creation of standards and labels at European level, via Ecodesign for example, can help companies to operate across the EU.

There are around 170 heat pump factories in Europe, with the majority being assemblers only, rather than also component manufacturers (Lyons, et al., 2022). The production of compressors, which account for about 25% of the total value of a heat pump, has become a specialised activity dominated by a small number of global suppliers, including Mitsubishi Electric (Japan), but also European players such as Danfoss (DK), Bitzer and GA (DE), Tecumseh (FR) and Emerson Copeland (BE)(Lyons, et al., 2022). Controllers, another key part (25% of the value), include Italian CAREL as a leading manufacturer, while semiconductors have very complex supply chains of their own (Lyons, et al., 2022). Other key components are heat exchangers, housing, valves, fan, pipework and refrigerant. Scaling up production to meet demand will also require the scaling up of these components and materials.

Heat pumps are improving their cost-competitiveness and efficiency ([83]), which along with technological developments such as hybrid systems, digitalisation and integration with other energy technologies, is enabling a rollout of heat pumps to a larger share of existing buildings (Lyons, et al., 2022). Hybrid systems ([84]) are popular especially in Italy and the Netherlands. The current energy crisis is changing a previously unfavourable price ratio between electricity and gas in favour of heat pumps. In addition, many countries have different support schemes to incentivise households for deployment. Still, the high up-front investment cost remains the main factor in deterring households. A number of non-cost barriers, such as a lack of information, split incentives for building owners and tenants, and building regulations, also hold back consumer adoption (IEA, 2022c).

On the supply side, a general shortage of workforce is already creating bottlenecks at the installation stage in several Member States, and the limited availability of some materials and components, such as semiconductors, causes risks of delay in the short term (Lyons, et al., 2022). Heat pumps do not have specific vulnerabilities in terms of material dependencies. However, heat pumps are susceptible to price increases of materials such as metals. For instance, the price of copper has made some manufacturers look at aluminium as a replacement (IEA, 2022c). There are also untapped opportunities to improve the circularity of heat pumps.

Meanwhile, some previously identified bottlenecks may have been resolved. For instance, the energy performance of the building stock is set to improve thanks to the Renovation Wave, and heat pumps are increasingly able to operate efficiently even in less well insulated houses. Also, the Commission proposal on amendment of the F-Gas Regulation ([85]) has been designed to ensure that the timing of the switch from F-gases to natural refrigerants does not prohibit the rapid growth needed under REPowerEU.

9.2 EU positioning in innovation and major changes

EU public R&D investment continued to grow in 2020, with Austria, Netherlands, Denmark, Germany, France, Belgium and Spain among the global top ten investors. In 2020, the Netherlands recorded investment for the first time and immediately ranked second in the EU, with a 22% share of the EU total. Despite funding for heat pumps being small compared to some other clean energy technologies, the EU spends a significant amount on public R&D relative to several major economies worldwide. Globally at the country level, Japan is the biggest public investor ([86]). However, in addition to Member State funding, the EU supports innovation through Horizon Europe, Innovation Fund, Interreg and LIFE. Under the Horizon 2020 and 2014-2022 programme periods, the biggest recipients of EU funding have been Spain, Germany and Italy (Lyons, et al., 2022).

On the private side, venture capital investment going to start-ups and scale-ups increased significantly in 2016-2021 compared to 2010-2015. Early stage investment grew seven-fold, and stands at the same level as later stage investment (which increased only fourfold). This is mainly due to limited activity in the past, but also the emergence of start-ups, which are only on the verge of reaching scale-up stage. As shown in **Figure 35**, global venture capital investment steadily increased to an all-time high in 2021, reaching EUR 57 million

([83]) For more information on costs, see Lyons et al. (2022).

([84]) Hybrid systems have an advantage that they can be deployed in buildings that are less well insulated. At the same time, they may result in higher emission by extending the use of gas boilers (used as a back-up) for longer, delaying also deeper renovations. For more, see Lyons et al. (2022).

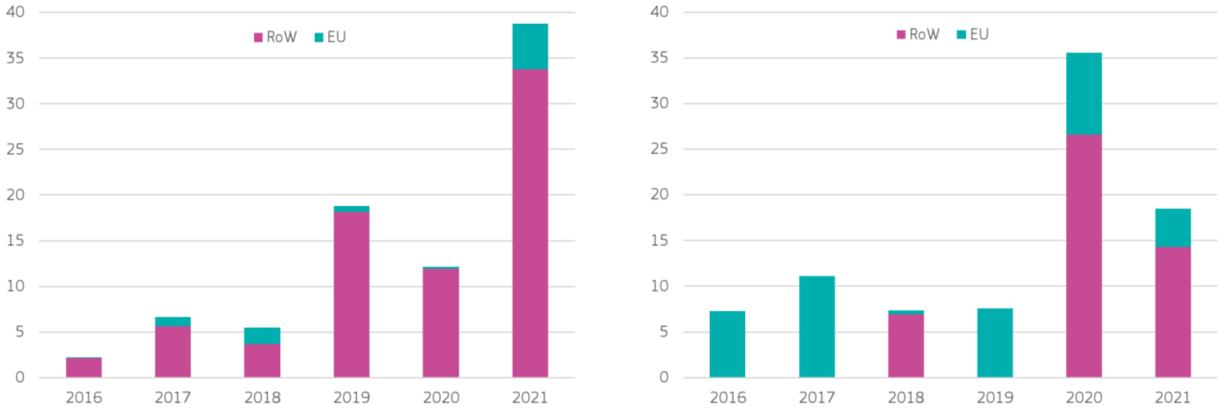
([85]) For more details, see Lyons et al. (2022).

([86]) This data, however, is, limited to IEA Members and their disclosures, therefore, should be interpreted with caution.

(up 28% on 2020). Nevertheless, 60% of early and later stage investment over 2016-2021 benefited only three companies in the United States (Dandelion Energy, Stone Mountain Technologies and Thermolift)([87]).

Despite a significant increase in 2021, the EU has not kept pace with the rest of the world and only accounts for 10% of early stage investment over the 2016-21 period, amounting to EUR 9 million. The US and Norway are in the lead, followed by Ireland and the Netherlands in the early stages. In contrast, the EU is doing better at later stages, accounting for 45% of investment. However, EU later stage investment displays a sharp drop-off after 2017, as seen in **Figure 35**. The US is again in the lead, followed by Ireland and Sweden. Examples of EU companies receiving venture capital investment include Exergyn (IE), Heat transformers (NL), Easyserv (SE) and TECCONTROL (FR)([88]).

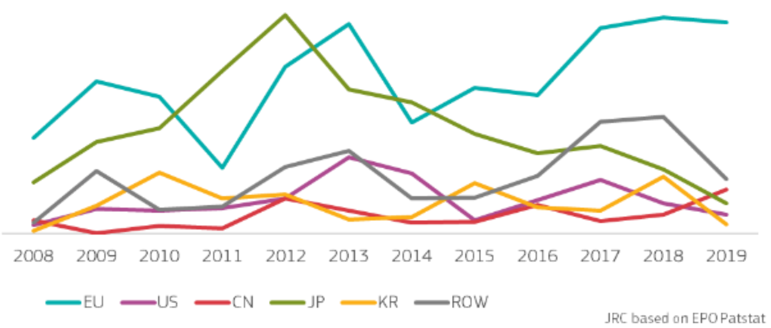
Figure 35: Early (left) and later (right) stage investment by region [EUR Million]



Source: JRC based on Pitchbook, 2023

EU patenting activity, with 45% of the world's high-value inventions (2016-2019), remains strong and growing; see **Figure 36**. In all other major economies the patenting trend is decreasing, with the exception of China, where activity is picking up. At country level, Germany has the biggest portfolio of high-value patents, followed by Japan and Turkïye. France, Italy and Sweden also feature in the top 10. Arcelik (Turkïye) leads among the companies, followed by Mitsubishi (Japan) and Bosch Siemens (Germany). With five companies among the top 10, the EU is well represented among the patenting corporates.

Figure 36: Trend in high-value inventions for the major economies



Source: JRC based on EPO Patstat, 2023

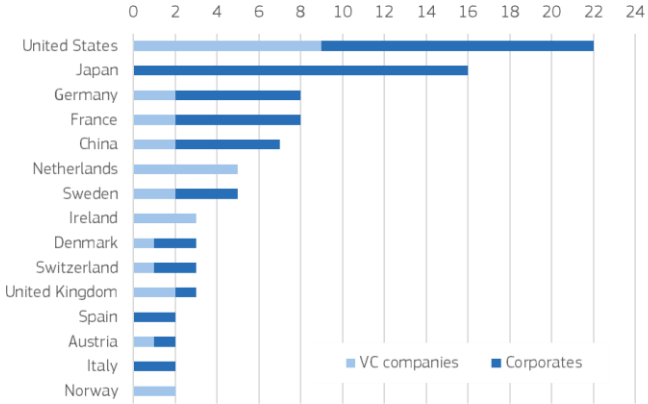
As shown in **Figure 37**, identified innovators are distributed across many countries. Together, the US (first) and Japan (second) host 38% of active companies. The US relies on a strong base of venture capital companies, while all innovators in Japan are corporates. The EU hosts 42% of identified innovators, has a

([87]) See https://dandelionenergy.com/ (ground-source heat pumps), https://stonemountaintechnologies.com/ (gas-fired heat pumps) and https://thermoliftsolutions.com/ (heat pumps using helium as refrigerant.

([88]) See www.exergyn.com/ (shape memory alloys), www.easyserv.se/ (digitalisation) and www.teccontrol.fr/ (hot water, and solutions provider).

strong position with a good balance between VC companies (45%) and corporate innovators (55%), and prevails among followers (Germany, France, the Netherlands, Sweden and Ireland). The Netherlands host the biggest number of start-ups in the EU.

Figure 37: Number of innovating companies by type (2016-2021)



Source: JRC compilation from different sources, 2023

Innovation efforts are currently focused on smart and flexible features, better efficiency, wider ambient temperature range, higher temperature output, lower noise, reduced size, improved ease of installation, enhancing recyclability, and substitutes for certain materials, such as refrigerants to lower the environmental footprint (Lyons, et al., 2022). Efforts are also going towards large-scale heat pumps for industry and district heating solutions. Next-generation heat pumps need to operate efficiently in very cold temperatures, over a larger temperature range, and in buildings with lower insulation, which means a need for research and development in components, such as compression technologies, and system designs (IEA, 2022c).

9.3 EU positioning in the current market and major changes

The heat pump sector, in a broad sense, employed nearly 320 000 people ([89]) 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, yet it is impossible to differentiate the data by end-use ([90]). Assuming that cooling accounts for approximately two thirds of the EU market, heating-only jobs account for over 100 000.

Using a more targeted definition of the sector, the European Heat Pump Association (EHPA) estimates the total to stand at nearly 120 000 employees, with 37% of them in manufacturing (European Heat Pump Association, 2022). More importantly, the sector has experienced a significant increase in jobs since 2017, and according to the EHPA, the jobs are mostly in small and medium-sized companies in rural areas outside the urban centres.

The new manufacturing factories coming online, especially those in Europe where labour costs are higher than in Asia-Pacific, can benefit from improvements in labour productivity due to digitalisation and automation. For example, innovative sensor controls and programming can streamline manufacturing processes and increase the efficiency of assembly lines, while modular designs and standardised components compatible with different types of heat pumps and 3D printing can reduce manufacturing times (RHC and EHPA, 2021). Essentially this also means slower growth of jobs in manufacturing in Europe than the growth rate of sales. On the other hand, installing takes twice as long as installing a boiler, and although there is innovation in technology and business models to try and reduce that, it will remain a labour-intensive step in deployment. Therefore, there is still significant job creation potential in sight.

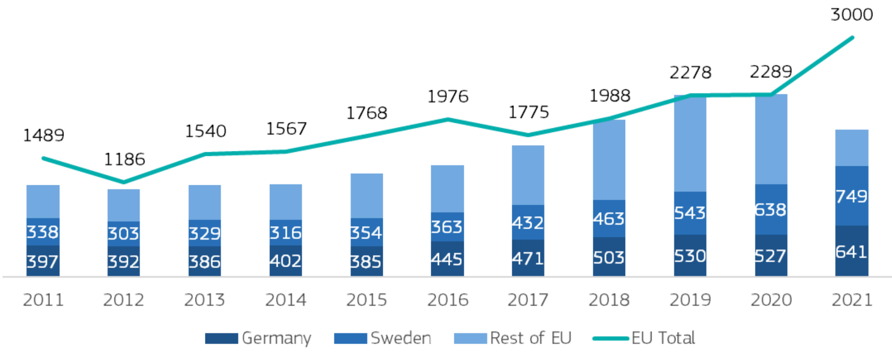
([89]) This includes both direct and indirect employment. Direct employment refers to equipment manufacturing, installation and operation and maintenance. Indirect employment refers to secondary activities such as transport and other services.

([90]) 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.

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 and air-conditioning technologies’ (Chapter 19). According to the EHPA, the total market value in 2021([91]) was almost EUR 15 billion ([92]) (European Heat Pump Association, 2022). As with employment, turnover grew by an average 7% per year during the 2015-2020 period, and the growth is expected to continue even more strongly in 2021-2022 according to early data. Many of the heat pumps sold and installed in Europe are also still manufactured in the EU, with only compressors largely imported from China. Thus, a large part of the value creation in the heat pump value chain stays within the EU.

Demand growth has spurred EU manufacturing, which recorded the highest ever year-to-year increase of 30% in 2021 and reached EUR 3 billion in production value, based on Eurostat Prodcom data. Sweden has rectified its position as the biggest producer, ahead of France and Germany, although France has not disclosed its value for 2021. Production also increased in Spain, Italy and Finland, while many countries did not disclose their figures in 2021. This indicates that the EU has a strong manufacturing base. However, it is yet to be seen whether European industry is able to scale up fast enough to meet the exploding demand in the short term. Several companies have announced the expansion of production lines, for example: StiebelEltron is investing EUR 600 million to triple production by 2025; Viessman is investing EUR 1 billion in development and a new production site in Poland; Vaillant is investing EUR 130 million in Slovakia; Panasonic is looking at increasing production in Czechia (EUR 145 million); Bosch is investing EUR 355 million; NIBE is investing EUR 460 million in Sweden; and Daikin Europe is planning to invest EUR 1.2 billion at four different production sites by 2025, including opening a new site in Poland (IEA, 2022c). In total, the announced investments in the pipeline to 2025 already amounted to more than EUR 4 billion by the end of 2022.

Figure 38: EU production value and top producers disclosing data among the Member States [EUR Million]

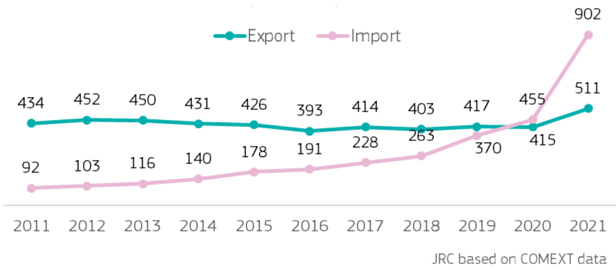


Source: *JRC based on PRODCOM data, 2023*

Extra-EU exports of heat pumps remained relatively constant between 2011 and 2021, standing at EUR 500 million in 2021 (**Figure 39**). During the same period, however, extra-EU imports grew, reaching over EUR 900 million, indicating a penetration of non-EU producers, mainly from China, in the growing EU market. The EU share of global exports dropped slightly from 43% to 37% in 2016-2021 compared to 2015-2020. France is the biggest exporter globally, followed by Germany and China. EU internal trade plays a significant role in EU countries’ exports, so it may include re-exporting. The EU captures the existing export market fairly well, as there are not many export opportunities which EU countries are not capturing, except for the US, Australia, Chile and United Arab Emirates, where imports from non-EU countries are outpacing those from EU countries. Nevertheless, non-EU export opportunities are small compared to the EU Single Market, which is the biggest export market.

([91]) EHPA focuses on heat pumps, covering 19 EU countries and the UK and Switzerland.
([92]) This includes the installation and taxes.

Figure 39: Extra-EU import & export [EUR Million]



Source: JRC based on COMEXT data, 2023

The EU trade deficit further increased in 2021, due to growing imports from China and stagnating exports. The Netherlands, Poland and Finland have the fastest growing trade deficit, as these are also the fast-growing markets. France, which has a strong trade surplus historically, has seen a fast deteriorating trade balance in recent years. Meanwhile, Sweden and Czechia are seeing growing trade surpluses, which indicates that their production, especially that of Sweden, is increasingly channelled towards exports. Swedish producers are serving mainly neighbouring markets such as Germany, Finland, the Netherlands and Denmark.

9.4 Scoreboard – key insights and change in EU performance

Figure 40 shows that the EU scores highly on most innovation-related indicators. However, compared to the previous assessment (Kuokkanen, et al., 2022), EU performance in these indicators is slightly dropping. EU public R&D investment is growing but less than in the previous assessment. The EU still holds a strong global position in high-value patenting and later stage investment, even with a slight drop of its share. Also, the EU continues to host a high share of innovators headquartered in the EU, with five corporates among the top 10 patenting entities. At the same time, EU-based start-ups have not attracted early stage investment to the same extent as start-ups from elsewhere, which is a worrying sign amidst growing venture capital investment globally. The EU has a strong foothold in innovation, but efforts are needed to maintain this leadership. As future market opportunities lie in digitalisation and system integration with smart grids and building management systems, the success of EU industry lies in capitalising on spill-over and networking effects between the industrial ecosystems.

With the booming market, turnover and employment are increasing 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 and the availability of skilled labour. EU production continued its strong growth, which signals industry's capacity to meet the growing demand. Demand is expected to grow even more strongly in 2022 and the years to come, which suggests intensified competition with non-EU producers who enter the market. Chinese producers in particular are already taking up a slice of the EU market, as evidenced by the transformation of the trade surplus into a growing deficit since 2020. US manufacturers supported by the Inflation Reduction Act may also be eyeing the European market. A strong EU performance in innovation should help the industry to tap this potential, but it must better deploy economies of scale if it is to overcome cost-cutting competition from outside the EU. In addition, the industry needs long-term supportive regulations, including the removal of any potential barriers in the Single Market, to promote investment in EU manufacturing lines. This is necessary in order to avoid suffering the same fate as solar PV and losing the industrial base from Europe.

Figure 40: Scoreboard for heat pumps

Scoreboard	**Heat Pumps**	EU performance in the reference period			Change from 2021 assessment
Public R&D		8%	2016-2020	EU CAGR	↓
Early Stage		10%	2016-2021	EU share of global total value	↓
Later Stage		45%	2016-2021	EU share of global total value	↓
Patents		45%	2016-2019	EU share of global total HVI	↓
Companies		42%	2016-2021	EU share of innovating companies	↓
Employment		7%	2016-2020	EU CAGR	→
Production		9%	2016-2021	EU CAGR	↑
Turnover		8%	2016-2020	EU CAGR	→
Imports & Exports		37%	2019-2021	EU share of global exports	↓
Trade Balance		Low	2016-2021	EU trade balance trend	→

Source: JRC, 2023

10 Wind rotors – wind energy

10.1 An updated status and recent developments

Wind energy is a crucial element of the EU energy system and a main pillar of EU targets towards deep decarbonisation. Moreover, the REPowerEU Plan (COM(2022) 230) introduces an accelerated rollout of renewables, increasing the target from 40% to 45% by 2030. With respect to wind energy, the REPowerEU Plan proposes an installed capacity of 510 GW by 2030. 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 investment, floating offshore wind technology is on the brink of becoming a commercial solution, thus unleashing the offshore resource potential of EU sea basins untapped thus far.

The cumulative installed onshore wind capacity increased by 122% in the EU, from 78 GW in 2010 to 173 GW in 2021. The increase in deployment was even more pronounced for the offshore wind sector, surging from 1.6 GW in 2010 to 15.6 GW in 2021.

A substantial increase in both onshore and offshore capacity is necessary in order to achieve national and EU goals. Offshore wind capacity can be expected in EU sea basins which have not yet been exploited. This offers 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 investment in infrastructure and manufacturing facilities at ports and stimulate regional economic growth and cooperation ([93]).

Potential bottlenecks and supply risks in the wind sector might arise from the need for critical raw materials: particularly the rare earth elements used in the permanent neodymium-iron-boron (NdFeB) magnets of the turbine generators, which are mainly imported from China (Telsnig, et al., 2022a).

Given the ageing wind fleet and the substantial share of wind turbines reaching their end of life, repowering or recycling will become key. In the mid-term, repowering of onshore wind will play a crucial role in reaching Member States' 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.

The appropriate recycling of wind turbine components will play a crucial role in retrieving critical raw materials and reusing them. Circularity in the wind sector requires R&I and deployment, but the industry is already very committed to circularity. However, at this stage, most circular economy initiatives address a single component/material rather than operating at system level (Telsnig, 2022b).

Permitting delays pose a challenge to achieving the mid- and long term targets towards climate neutrality. This can particularly be observed in the reduced onshore wind capacity additions since 2018 resulting from complex permitting rules and potential exposure to legal challenges. A lack of social acceptance for new onshore wind farms might be an additional challenge, as scenarios project deployments to be 5-6 times higher in 2050 than currently. The Commission has made legal proposals and guidance to accelerate permitting as part of the REPowerEU package.

The Offshore Renewable Energy Strategy (ORES) highlights that there might be a bottleneck when it comes to skilled workers in the offshore wind sector. Member States 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).

10.2 EU positioning in innovation and major changes

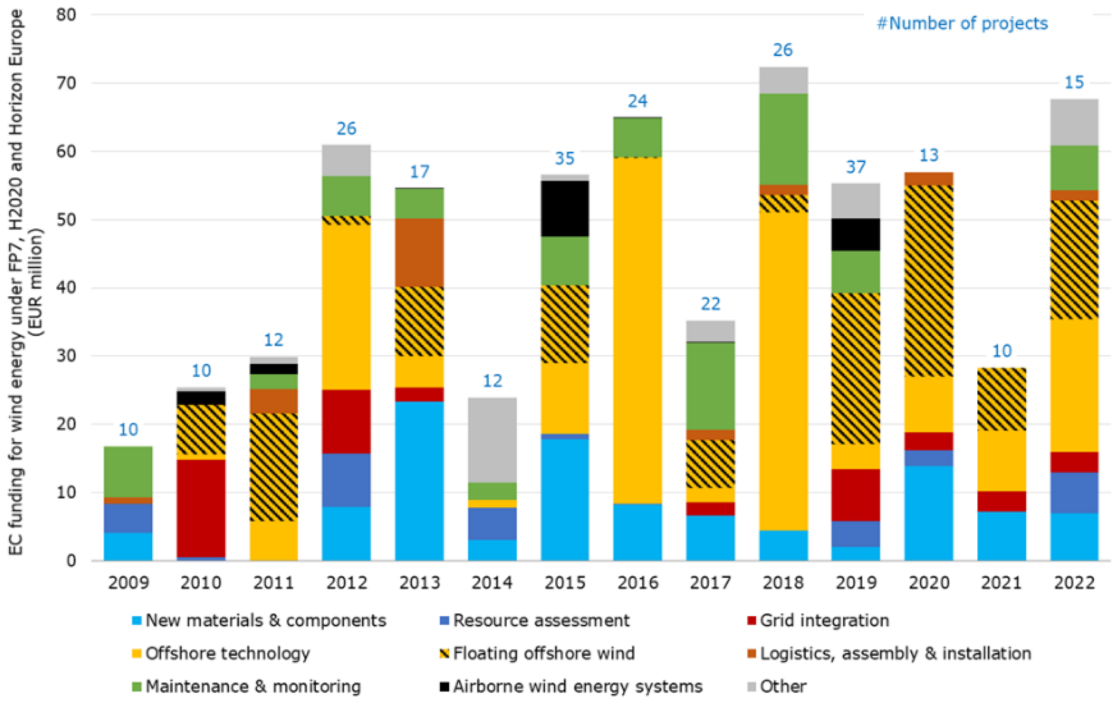
In the period 2018-2020, Japan kept its lead at country level on public R&D investment in wind energy, with about EUR 507 million spent, followed by Norway, the United States, Germany and South Korea. The Netherlands, Denmark, Spain and France were also amongst the top ten countries investing in wind energy. However, taking the EU Member States together, their combined public R&D investment spend on wind energy was EUR 575 million, surpassing that of Japan in the same period.

EU public R&D investment remained roughly constant between 2012 and 2016, and reached its peak in 2019 (EUR 208 million). In 2020 there was a substantial decrease in public spending (EUR 163 million), mainly due to a decrease in the spending of the Netherlands, Spain, France and Belgium.

([93]) SWD(2021) 307 final

In addition to the Member State funding above**, Figure 41** shows the development of R&I funding in the period 2009-2022 under Horizon Europe funding programme (2022), Horizon 2020 (2014-2021) and under its predecessor, the Seventh Framework Programme (FP7) (2007-2013). EUR 30 million was granted to wind energy projects starting in 2021, of which 46% was focused on offshore technology wind research, 24% on new materials & components and 14% on offshore wind technology. There is a considerable reduction in the EU funding for wind energy in 2021, due to the closure of the H2020 programme. However, in 2022 after the start of the Horizon Europe funding framework, the funding bounced back to the same levels as 2018-2020. Since 2009, FP7, Horizon 2020 and Horizon Europe have allocated substantial funding across all wind research R&I priorities, with projects on offshore wind technology (EUR 186 million), floating offshore wind (EUR 132 million) and research on new materials & components (EUR 106 million) accumulating most of the funds (Telsnig, et al., 2022a).

Figure 41: Evolution of EU funding categorised by R&I priorities for wind energy under FP7 (2009-2013), Horizon 2020 (2014-2021), and Horizon Europe (2022) programmes and the number of projects funded in the period 2009-2022 [EUR Million]



Source: JRC, 2023

In 2021, a single deal resulted in the investment of EUR 860 million ([94]) in the private Chinese company ENVISION. This investment alone outweighs global early and later stage VC investment in Onshore Wind technology developers realised since 2016. This outlier is not included in the following analysis for readability. However, it confirms the success of Chinese high-growth companies in attracting investment to finance the scale-up and expansion of their activities.

Early and later stage investment in EU VC companies is shown in **Figure 42** and compared to the rest of the world. Overall, China and the US lead in terms of venture capital investment, although between the periods 2010-15 and 2016-21, the US experienced a significant drop in VC investment from EUR 534 million to EUR 225 million.

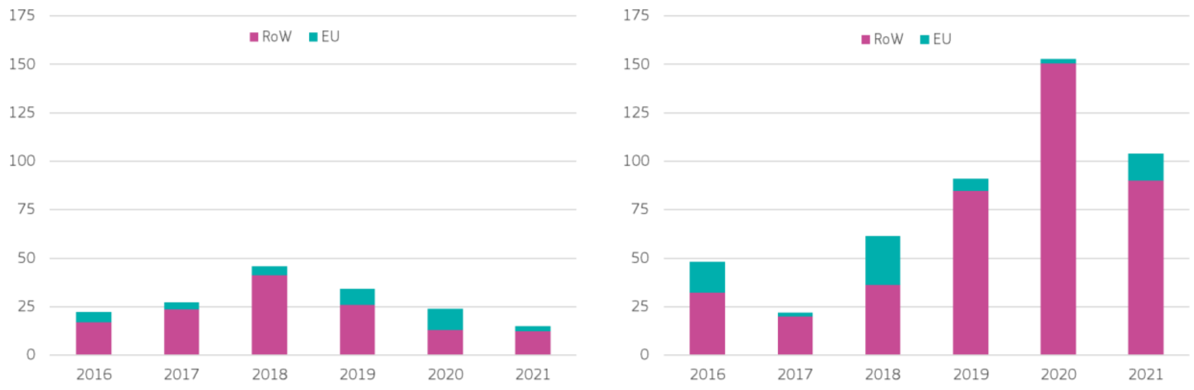
After a peak in 2018, global investment in early onshore wind-related ventures sharply declined and in 2021, reached its lowest levels since 2014. It amounts to EUR 168 million over the 2016-21 period (12% down on the previous period). The EU accounts for 21% of early stage investment, amounting to EUR 35 million over the period. Despite a sharp drop-off in 2021, investment in early EU ventures has grown since 2017 and is more than double that of 2010-2015 (138%). However, this essentially takes the form of grants rather than

([94]) PE growth capital.

private equity investment. The US received by far the most investment in early ventures (52%) over the current period, followed by China (8%) and the UK (7%). Investment in the EU is distributed over several countries: Latvia, Spain, Sweden, the Netherlands and France.

Excluding the outlying deal in the Chinese ENVISION group, global later stage investment peaked in 2020, putting an end to the growth initiated in 2017 and sustained by investment in China and the US. Chinese firms attracted most of the investment (41%) over the current period, overtaking the US (30%) where investment decreased as compared to the previous period. It should be noted that the later stage investment realised in China effectively benefited only two firms (CLOBOTICS, provider of cloud-based data analytics services and AEOLON, manufacturer of wind turbine blades). Despite a rebound in 2021, investment in EU firms has decreased over the period (27% down on the previous period), amounting to EUR 66 million and accounting for 14% of global investment.

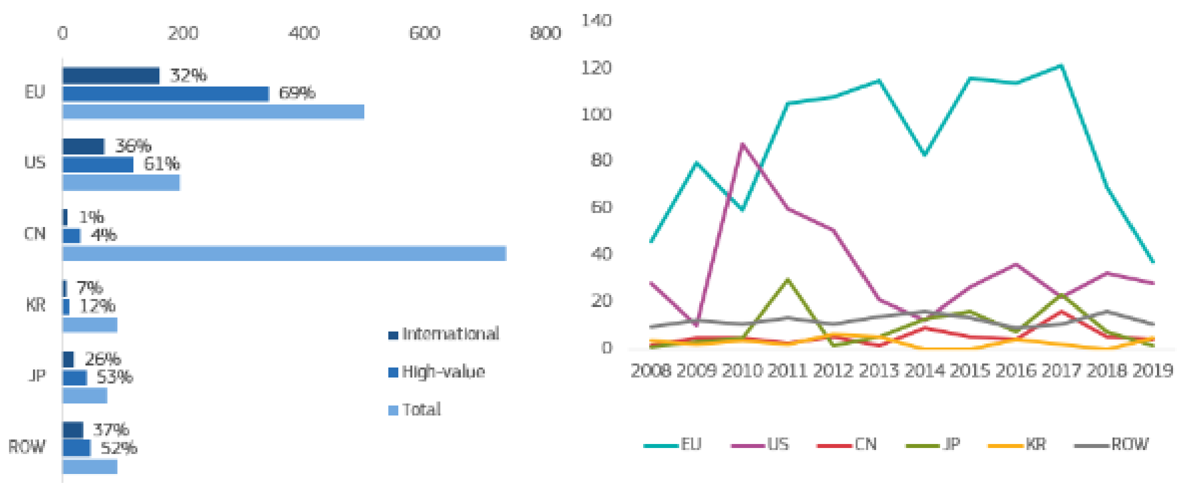
Figure 42: Early (left) and later (right) stage investment by region [EUR Million]



Source: JRC based on Pitchbook, 2023

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 2016-2019, only about 4% 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 61% and 53% respectively, but both have significantly lower numbers in absolute terms (see **Figure 43**).

Figure 43: Number of inventions and share of high-value and international activity (2017-2019) (left) and trend in high-value inventions for the major economies (right)



Source: JRC based on EPO Patstat, 2023

EU companies keep the lead in terms of high-value inventions filed in the period 2016-2019. Germany and is the leading country, followed by the United States, Denmark, 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, while General Electric (US), the Danish subsidiary of LM Wind Power (US), Mitsubishi Heavy Industries (JP), Goldwind (CN) and NTN Corp (JP) complete the list of leading 10 companies.

EU applicants show the highest share of inventions protected in United States (35%) and China (26%) in the period 2016-2019, 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 40% of all innovators, of which about 39% are venture capital companies and 61% are corporates, in similar proportions to the rest of the world (43% and 57% respectively). The top five countries host almost 60% of identified innovators. The US (1st) and the UK (fifth) have a very strong base of venture capital companies while most of innovators in Japan (second), Germany (third) and China (fourth) are corporate innovators. Within Europe, several countries also report a strong share of venture capital companies (France, Spain, The Netherlands).

10.3 EU positioning in the current market and major changes

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)([95]). In 2020, EU companies held about 80% of the EU onshore wind rotor market, while 78% of the identified offshore wind facilities are owned by manufacturers from the EU. A detailed analysis of the manufacturing facilities and supply chains for onshore and offshore wind rotors can be found in (Kuokkanen, et al., 2022).

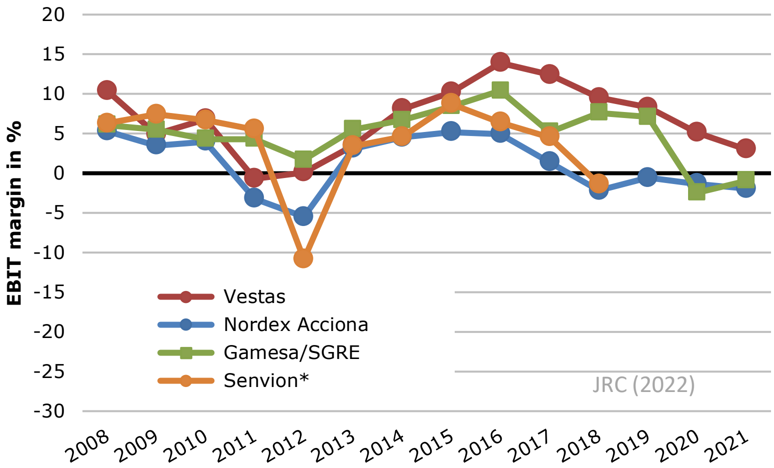
Wind is a strategic industry for Europe. It is estimated that the sectors offers between 280 000 and 300 000 quality jobs (WindEurope, 2022)([96]), 77 000 of which relate to offshore wind. In 2021, Germany ranked first in terms of direct and indirect jobs, followed by Spain and the Netherlands.

The trend in employment figures shows no growth in the period 2015-2021, 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, COVID-19 introduced logistical challenges for all manufacturers. These challenges continued into 2021, reducing further the EBIT margin for most OEMs. As a result, only Vestas could present a positive EBIT margin (+3%) in 2021. NordexAcciona reported a negative EBIT (-2%) and SiemensGamesa RE reduced their negative EBIT from -2.5% in 2020 to -0.9%in 2021 (**Figure 44**).

([95]) 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.

([96]) 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.

Figure 44: EBIT margin (operating profit/revenues) of the leading listed EU OEMs



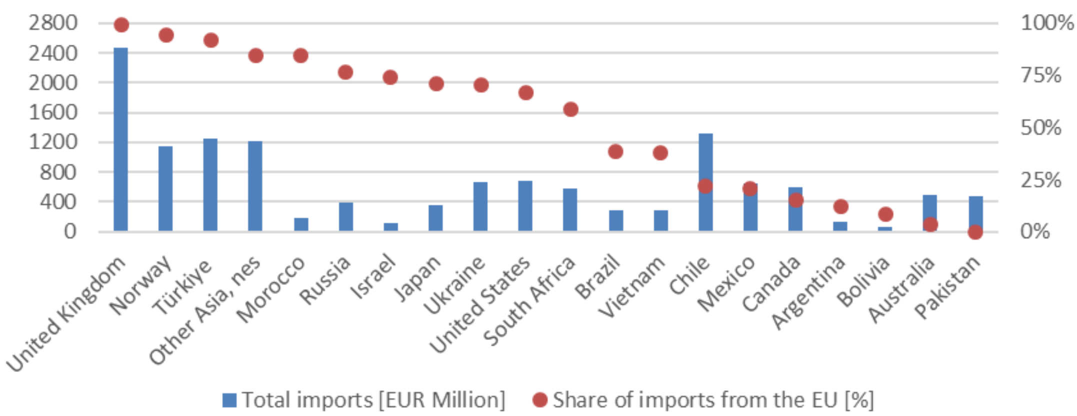
Source: Clean Energy Technology Observatory (Telsnig, et al., 2022a)

Future scenarios estimate global wind energy jobs to grow almost fivefold by 2050, reaching about 5.5 million jobs. In order to mobilise this workforce, recruiting, training and retaining skilled workers will be needed. This might include the transfer of skills from the oil and gas industry to the wind sector as it is estimated that about 70% of jobs (FTE) in the oil and gas sector overlap well or partially with the offshore renewable segment.

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 3.5 billion, while imports from outside were substantially lower at between EUR 26 million and EUR 642 million. In the period 2019-2021, extra-EU imports and exports increased.

The leading countries in wind capacity deployment and manufacturing capabilities are among the top global exporters of wind-related trade goods. In the period 2019-2021, Germany (EUR 6 billion) and Denmark (EUR 6 billion) rank in the top spots, followed by China (EUR 3 billion), Spain (~EUR 2 billion) and the Netherlands (~EUR 2 billion). The top importers during this period are the United Kingdom, Chile, Türkiye and Norway, importing wind generating sets at a cost of between EUR 3 billion and EUR 1 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, Norway and Türkiye accounted for 99%, 95%, and 92% respectively (**Figure 45**).

Figure 45: Top 20 non-EU importers and share of imports from the EU in 2019-2021



Source: JRC based on UN Comtrade data, 2023

10.4 Scoreboard – key insights and change in EU performance

The EU competitiveness scoreboard in wind rotors shows that the EU performs well in public R&D and early stage investment, patenting, companies, turnover and imports & exports (**Figure 46**). All types of investment (public R&D, early stage and later stage) are positive, but EU performance has decreased since the previous assessment (in 2016-2021 compared to 2015-2020) (Kuokkanen, et al., 2022). Employment has seen a slight growth in the period 2016-2020 but was improved compared to 2015-2020 figures. Low scores can be observed for production. This can be explained by fierce competition in the sector. Since 2016, the margins of EU OEMs are declining due to high competition in turbine orders and increased material costs for the main turbine components, however the decrease was smaller in 2016-2021 compared to 2015-2020, thanks to a rebound of production value in 2021. The EU continues to host a significant share of the global wind energy supply chain, as can be seen by the dominant position of the EU in global exports (65% of non-EU exports). The EU score for trade balance is medium. Although the surplus is large, due to the above-mentioned factors, it has been decreasing gradually in recent years.

Figure 46: Scoreboard for wind energy rotors

Scoreboard	**Wind Rotors - Wind Energy**	EU performance in the reference period			Change from 2021
Public R&D		2%	2016-2020	EU CAGR	↓
Early Stage		21%	2016-2021	EU share of global total value	↓
Later Stage		14%	2016-2021	EU share of global total value	↓
Patents		58%	2016-2019	EU share of global total HVI	↓
Companies		40%	2016-2021	EU share of innovating companies	→
Employment		1%	2016-2020	EU CAGR	→
Production		-1%	2016-2021	EU CAGR	↑
Turnover		6%	2016-2020	EU CAGR	→
Imports & Exports		65%	2019-2021	EU share of global exports	↓
Trade Balance		Medium	2016-2021	EU trade balance trend	→

Source: JRC, 2023

11 Photovoltaic solar panels

Solar PV is another workhorse for decarbonising the energy system. It is a mature energy technology and the world's fastest-growing, thanks to a significant decrease in the costs and rapidly growing demand as a result of the global shift to low-carbon electricity production. This chapter focusses on the photovoltaic solar panels or modules (hereafter, solar PV) that convert solar energy into direct current electricity, and the associated supply chain. However, balance of system components (inverters, mounting systems, cabling, trackers, inverters etc.) and solar PV plant development are excluded.

11.1 An updated status and recent developments

Global cumulative installed capacity exceeded 1TW in 2022, of which, 170 GW was in the EU (Chatzipanagi, et al., 2022). The EU capacity is expected to double by 2025 and grow three- to six-fold by 2030 (SolarPower Europe, 2021; EurObserv'ER, 2022). 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, multi-junction and perovskites – a promising thin-film technology – may become more prevalent by 2050, influenced also by materials availability and sustainability. At the same time, photovoltaics are growing beyond the traditional ground-mounted and rooftop applications to a number of innovative solutions such as agricultural-PV, PV on landfill sites, PV integrated in building envelopes, PV on hydro dams, irrigation channels and floating PV on water surfaces, PV in car parks, on sound barriers and integrated in vehicles (Chatzipanagi, et al., 2022).

Globally, China is the single biggest solar PV market. After years of slowdown, EU installations are growing again at 13% annually (2011-2021), reaching nearly 170 GW of installed capacity in 2021 (Chatzipanagi, et al., 2022). This is still slower than the 28% compound annual growth rate recorded globally in the same period (Chatzipanagi, et al., 2022), but SolarPower Europe's estimate suggests that in 2022, annual growth was 25%, reaching nearly 210 GW in 2022 (SolarPower Europe, 2022). Germany is the biggest market in Europe, followed by Italy, Spain and France (EurObserv'ER, 2022), together accounting for 67% of cumulated EU installations in 2021. The EU market was estimated at EUR 21 billion in 2020, which is about 16% of the global total (EUR 136 billion) (Fortune business insights).

Solar PV manufacturing is concentrated in the Asia-Pacific region, with China in particular dominating the value chain. China accounted for approximately 79% of global 190 GW PV cell production in 2021 (Jager-Waldau, 2022). This is because China continues to be the most cost-competitive location for manufacturing, mainly due to lower energy, labour and investment costs (IEA, 2022d) as well as a large and dynamic domestic market. There are significant gaps in EU manufacturing capacity, namely for the silicon wafers and cells at the core of the technology, the vast majority of which are currently imported. Nevertheless, 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 processes and circular economy initiatives can create a PV recycling industry in Europe (WEEE Directive, Ecodesign, etc.).

With Chinese dominance in manufacturing extending throughout the supply chain, downstream industries in Europe risk vulnerabilities and a steady reduction in negotiating power (SWD(2021)307 final). The EU also faces vulnerabilities related to imports containing certain critical raw materials ([97])(Bobba, et al., 2020). For the EU, the use of silver may become a particular concern with increasing manufacturing activity. This also holds for silicon and for solar glass, which is imported largely from China (Chatzipanagi, et al., 2022). 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.

Solar PV technology has become cheaper (system costs have fallen by over 80% since 2010) and more efficient (average PV module efficiency increased from 9% in 1980 to 21% in 2021), yet further R&D efforts

([97]) The materials with a high supply risk and defined as critical raw materials for the EU are silicon metal, indium, gallium, germanium and borates (Bobba, et al., 2020). However, the EU imports final products rather than the primary raw materials and therefore is not directly influenced by these, see more information in (Chatzipanagi, et al., 2022).

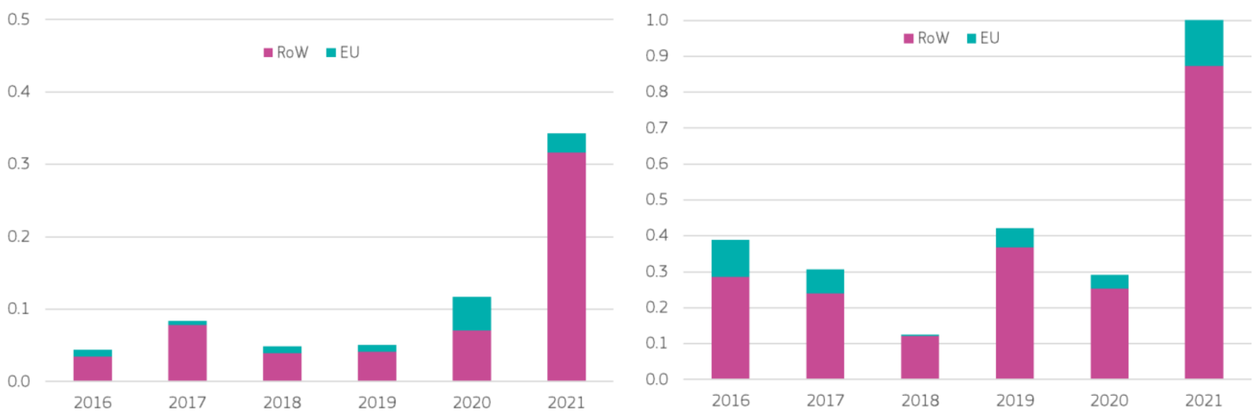
towards improving performance, integration and sustainability are essential (Chatzipanagi, et al., 2022). Silicon-based technology is likely to continue to dominate.

11.2 EU positioning in innovation and major changes

According to IEA data, EU Member States' annual public funding for R&I on solar photovoltaics has remained stable and below the level seen a decade ago (peaking in 2013 at EUR 220 million), thus going against a global decreasing trend. The stagnation of EU 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 remain the biggest public investors, followed by Japan, Switzerland and Canada. Of the EU countries, Sweden and Hungary increased their funding based on the early data for 2021. It should be stressed, however, that the data is fragmented and limited to IEA members, and not all countries break down their investment to identify solar PV specifically, for example the US. Additionally to EU Member State funding, the Horizon 2020 programme (2014-2020) contributed EUR 330 million to solar PV research, mainly on new technologies and materials (EUR 108 million). Funding for PV continues under Horizon Europe. The new Innovation Fund (launched 2020) has already awarded EUR 126 million to solar projects, targeting EU's manufacturing capabilities (Chatzipanagi, et al., 2022).

With regard to private investment, solar PV – a mature technology – saw a new peak in venture capital investment in 2021, surpassing the highest levels seen in the early 2010s to amount to over EUR 1 billion. This represents a threefold increase as compared to 2020 and puts an end to a period of lower investment starting in 2014 (due to lower levels of investment in the US). As shown in **Figure 47**, the main drivers of this trend are later stage investment realised outside of the EU: the number of deals doubled in 2021 and average deal sizes grew back to the highs of the early 2010s.

Figure 47: Early (left) and later (right) stage investment by region [EUR Million]



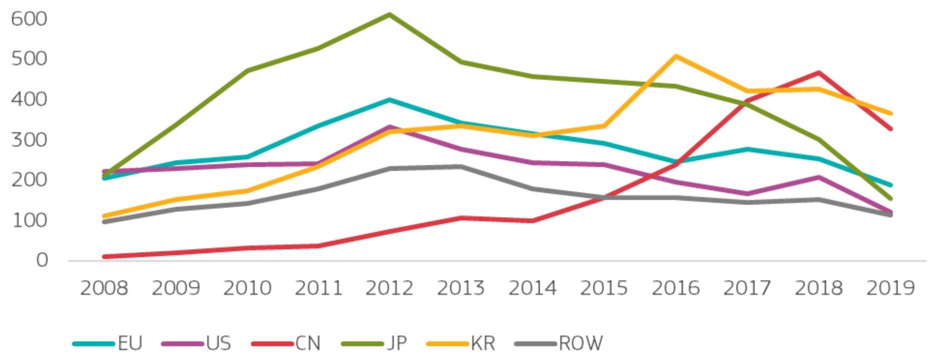
Source: *JRC based on Pitchbook, 2023*

Global early stage investment doubled in 2020, almost tripled in 2021 and amounted to EUR 700 million over the 2016-21 period (up 25% on 2010-15). Early stage investment in the EU peaked after a record year in 2020 and the EU only accounts for 16% of early stage investment over the period 2016-21 (as compared to 23% over 2015-20). Investment in the EU is supported by fewer deals and lower levels of grant funding than in the rest of the world. The Member State that attracted the most investment over the current period is Germany (6.5%), with similar levels as Canada and the UK. However, it remains far behind China (30%), which overtook the US (29%), where early stage investment dropped significantly as compared to the 2010-2015 period.

Despite investment values reaching an all-time high in 2021, later stage investment decreased over the 2016-21 period as compared to previous period (2010-15), amounting to EUR 2.5 billion. The EU accounts for 16% of that investment and strengthens its position with higher investment levels since 2016 (EUR 400 million, up 115% on 2010-15). The US remains by far the first destination of later stage investment over the current period (40%) but is slowly being challenged by China (27%), which attracted more investment in 2020 and 2021. The UK (7%) is next in line, together with Germany (7%) and Sweden (5%), which attracted most EU later stage investment.

Based on data from Patstat 2022 spring edition, patenting activity in the field of high-value inventions has seen a very dynamic evolution over the past decade (2008-2019). **Figure 48** shows how Japan, the US and the EU are losing ground to the growing patenting activity of South Korea and China. China, in particular, has seen remarkable growth since 2014 and now competes with South Korea for the leading position. The EU holds only 14% of cumulative high-value patents approved globally in the 2017-2019 period. Germany, France, the Netherlands and Italy are among the top ten patenting countries (**Figure 48**).

Figure 48: Trend in high-value inventions for the major economies (left) and top ten countries in 2016-2018 (right)

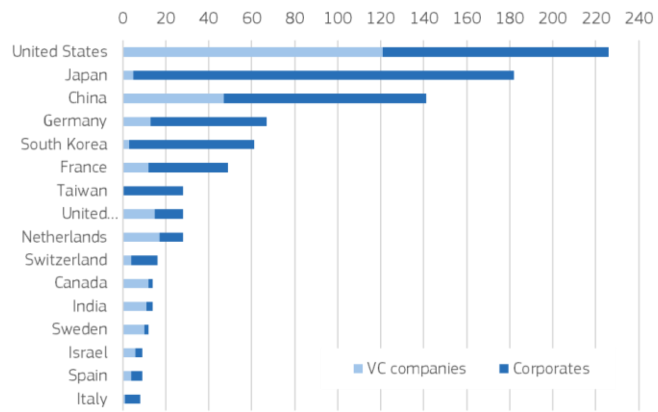


Source: JRC based on EPO Patstat, 2023

South Korean and Japanese corporates dominate patenting activity, with two Chinese and only one German company – Merck, among the top ten 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 ten. Merck and Cynora hold the biggest EU patent portfolio.

Figure 49 shows the countries ordered by the number of innovating companies, which consist of corporates that have relevant patenting activity and venture capital companies active in solar PV. Five countries host 70% of identified innovators, led by the US (24%). The US, and to some extent China (third), have a strong base of venture capital companies, while most of innovators in Japan (second), Germany (fourth) and South Korea (fifth) are corporate innovators. Europe hosts 22% of identified companies and competes with the US. In the EU, venture capital companies represent 39% of active innovators and play a bigger role among innovators in the Netherlands and Sweden than in other Member States.

Figure 49: Number of innovating companies by type (2016-21)



Source: JRC compilation from different sources, 2023

11.3 EU positioning in the current market and major changes

EU production volume has seen a decreasing trend in the past five years. Nevertheless, in 2021, the production value nearly doubled, growing for the first time since 2016. This reflects new manufacturing capacity additions, e.g. ENEL Green Power in Italy and Meyer Bergen's expansion in Germany (see more manufacturing plants in the Clean Energy Technology Observatory Report (Chatzipanagi, et al., 2022)). Nonetheless, this largely reflects the assembly of modules and China still controls the manufacturing of wafers and cells (SWD(2021)307 final). Germany is still among the largest manufacturers of polysilicon globally (Bernreuter Research , 2020 (updated 2022)), while Iceland and Norway produce metallurgical silicon. Norway and France have some, limited, ingot and wafer manufacturing, while Hungary and Lithuania have some solar cell manufacturing capacity. Several European countries produce modules (Chatzipanagi, et al., 2022).

Both employment and turnover in the solar PV value chain have seen a significant growth in recent years with a compound annual growth rate of 25% and 27% respectively over 2016-2020. In 2020, the value chain employed nearly 166 000 people and generated a turnover of about EUR 21 billion (EurObserv'ER, 2022), although other sources provide much higher estimates of jobs in the EU – from 195 000 to 357 000 in 2020 and from 235 000 to 466 000 in 2021 (SolarPower Europe, 2021; IRENA, 2022a). The photovoltaic sector employs a highly educated and skilled workforce 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).

Concerning trade, 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 12%. At the same time, imports from the rest of the world are growing again, reaching EUR 11 billion in 2021. China is by far the biggest exporter to the EU and also globally. The biggest importers are the Netherlands and Germany, which both also re-export within the EU. The Netherlands, Spain and Poland have the largest trade deficit, and growing, reflecting expansion of deployment, and in the case of the Netherlands, the 'Rotterdam effect' ([98]). Overall, the EU trade deficit reached EUR 9 billion in 2021.

11.4 Scoreboard – key insights and change in EU performance

The EU competitiveness score in public R&D remains medium, as there has been no growth in investment. However, against a global decreasing trend, it is in fact positive that the EU countries have maintained stable funding. In venture capital investment, EU performance is medium in both early and later stages as the EU share in early stages dropped from 25% to 16% in 2016-2021. Nevertheless, the EU hosts 22% of innovators, hosting a fourth of all VC companies. In patenting activity, the EU is losing ground to South Korea and China, coming only fourth with a 14% share of total high-value inventions. The EU still leads in some advanced segments and technologies, but without further effort it may be hard to maintain this lead.

In terms of the current markets, employment and turnover are growing strongly, thanks to booming deployment in the EU. Without significant upstream manufacturing, the EU is heavily dependent on imports and the increases in deployment therefore benefit Chinese module producers the most (bearing in mind that modules represent approximately 40% of value for utility systems and less for rooftop systems). So while the EU trade deficit for PV reached EUR 9 billion in 2021, EU production grew and in fact, nearly doubled, for the first time in a decade. Together with some positive news from the industry, the EU Solar Initiative ([99]), and the recently announced Net-Zero Industry Act ([100]), EU companies have an opportunity to regain a manufacturing base and capture market growth with better-performing, next-generation solar PV panels. In addition, the EU is leading in the manufacturing of equipment and inverters, though in the latter, China is increasing its market share (Chatzipanagi, et al., 2022). Since the global PV industry is undergoing a technological change, the EU has potential to improve its position in upstream activities and capture a bigger share of the value chain.

([98]) Trade values for the Netherlands often include the 'Rotterdam effect', meaning that the Dutch port is an entry point for many overseas products that are subsequently shipped to other EU countries.

([99]) The European Solar Initiative, an industrial alliance, aims to establish 20 GW of manufacturing capacity in Europe by 2025.

([100]) President of the European Commission, Ursula Von der Leyen, announced at the World Economic Forum in Davos 17th January 2023.

Figure 50: Scoreboard for solar PV

Scoreboard	Photovoltaic solar panels	EU performance in the reference period			Change from 2021
Public R&D		1%	2016-2020	EU CAGR	→
Early Stage		16%	2016-2021	EU share of global total value	↓
Later Stage		16%	2016-2021	EU share of global total value	→
Patents		14%	2016-2019	EU share of global total HVI	→
Companies		22%	2016-2021	EU share of innovating companies	→
Employment		25%	2016-2020	EU CAGR	↑
Production		-6%	2016-2021	EU CAGR	↑
Turnover		27%	2016-2020	EU CAGR	↑
Imports & Exports		4%	2019-2021	EU share of global exports	→
Trade Balance		Low	2016-2021	EU trade balance trend	→

Source: *JRC, 2023*

12 Smart building energy management systems

The revisions of the Energy Performance of Buildings Directive (EPBD)([101]) emphasises the potential of smart technologies in the building sector, introducing the smart readiness indicator (SRI)([102]) to raise awareness of the value behind building automation and electronic monitoring of technical building systems. The Energy Efficiency Directive (EED)([103]),([104]) sets the overarching legal framework for energy efficiency policy in the EU and includes an important provision targeting government buildings. The Energy Labelling Directive ([105]) establishes the information required regarding energy and other environmental resources consumption reported by household appliances.

The scope of smart building 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.

12.1 An updated status and recent developments

The adoption of the Digitalisation of Energy Action Plan ([106]) highlights the importance of digital tools in a smart and interactive energy system, and smart meters are essential for the digitalisation of the energy sector. The Energy Performance of Buildings Directive (EPBD)([107]) required Member States to implement intelligent metering systems and to roll out at least 80% by 2020 in the case of electricity. With 100% penetration, Sweden is in the lead, followed by Finland (99%), Estonia (98%) and Spain (91%). However, other Member States, including Germany, Croatia, Cyprus, Czechia, Greece and Ireland, decided against a national smart meter rollout plan (Simon, 2019).

According to Fortune Business Insights, the global smart building market was worth EUR 57 billion in 2021([108]) and is forecast to reach EUR 328 billion by 2029([109])(FBI, 2022). According to the same analysis, the energy management segment held less than a quarter of the market share, while North America is expected to hold the biggest market share. The top players identified include Cisco Systems Inc., Siemens AG, ABB Ltd., Schneider Electric SE, Endeavor Business Media, IBM Corporation and Huawei Technologies Co. Ltd.

As the technologies in SBEMS are becoming mature, the research trend moves towards detailed system integration to cost-effectively improve users' experience and the sustainability of the built environment. Future SBEMS would require advanced control and management systems to facilitate the real-time operation and integration of relevant energy subsystems into the network at a regional or higher level with various processes, i.e. grid demand-response, carbon tax or credit (Kim, et al., 2022). Yet, most of the current research is conducted on non-commercial buildings, such as campuses, residential or government buildings (Saputra & Ramadhan, 2023).

12.2 EU positioning in innovation and major changes

The total public R&D investment for 2018-2020 has increased to nearly EUR 86 million, with Canada and France being the top investors among the reporting countries, and some major economies, such as Germany, Italy, the US and South Korea, not reporting. More than half (54%) of total investment during 2018-2020 was

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

([102]) 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

([103]) 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)

([104]) COM(2021) 558 final Brussels, 14.7.2021 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0558

([105]) 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)

([106]) COM(2022)552 final, 18th October 2022.

([107]) 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)

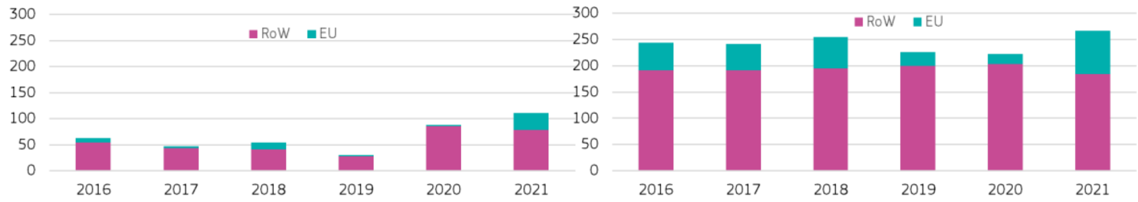
([108]) Foreign currencies are converted to EUR based on the annual averages published by the European Central Bank

([109]) Forecasted values are converted to EUR based on a fixed rate, assumed at EUR 1.21 per USD.

in the EU (EUR 47 million), while six Member States were among the top investors, with Denmark and Hungary being the new additions.

Figure 51 shows the state of early and later stage investment globally. The EU's early stage investment increased tenfold in 2021, mainly due to a EUR 25 million deal in the German company Comgy (operator of digital sub-metering services), while the rest of the world dropped by 8%. In 2021, later stage investment exceeded the previous 2018 peak by 4%. EU investment increased by 35% compared to 2018 and more than quadrupled compared to 2020. The EU share in 2016-2021 increased to 16% for early stage investment and nearly 20% for later stage investment.

Figure 51: Early (left) and later (right) stage investment by region [EUR Million]

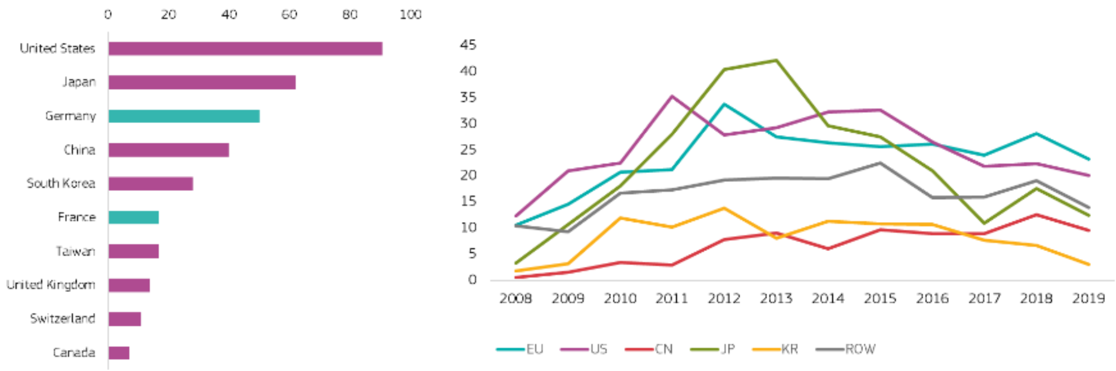


Source: JRC based on Pitchbook, 2023

The US was the top country in both early and later stage investment. Germany and France climbed to third and fourth place in the early stage after Norway dropped to sixth place. The previous four Member States remained in the later stage ranking, with Germany climbing to third place. The EU had a higher share of the number of deals in both early and later stage investment (26% and 28%, respectively), which indicates that EU deals are lower in value than the rest of the world.

The US and Japan accounted for most of the high-value inventions in 2016-2019, followed by Germany (**Figure 52**). While patenting activity has slowed down in some major economies, the EU has maintained the lead since 2017. China's patenting activity has been steadily rising since 2008, when the Chinese Act on the Energy Efficiency of Civil Buildings ([110]) was first implemented. While the US leads the board in terms of countries, the EU as a region held 26% of the global share in high-value inventions, slightly higher than the US (23%), whose market attracted most of the high-value filings for the same period.

Figure 52: Top ten countries in high-value inventions in 2016-2019 (left) and trend of high-value inventions for major economies (right)



Source: JRC based on PATSTAT, 2023

Japanese companies dominate patenting, with only two German companies in the top ten. The patenting is mainly in electronics, with Siemens, Panasonic and Mitsubishi in the lead.

SBEMS is an emerging market, with more VC companies than corporates, except for Japan, China, Germany, Taiwan, South Korea and Switzerland, where corporates dominate the market. The US hosts most of the

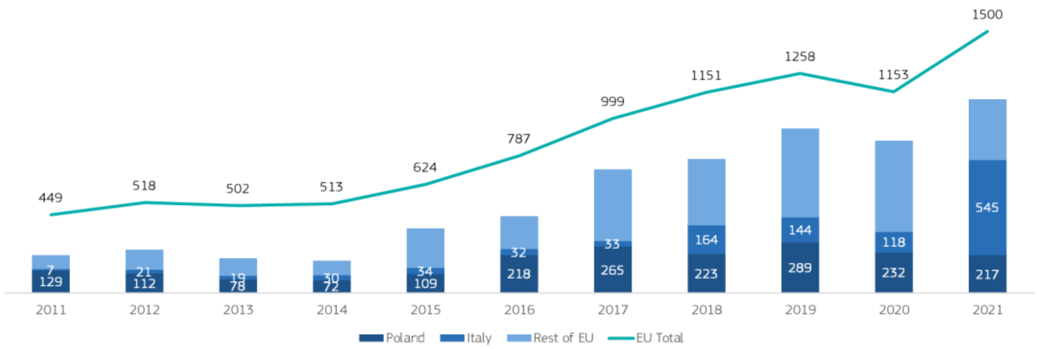
([110]) CHINA: Regulation No. 530 of 2008 on Energy Conservation in Civil Buildings https://policy.asiapacificenergy.org/node/54 innovating companies in the area, with approximately three times more than Japan. Only 27% of the world's innovators are headquartered in the EU, and more than half are VC 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 the current market and major changes

In 2021, EU production recovered and increased by 19% compared to 2019. **Figure 53** shows that Poland and Italy together held approximately 40% of EU production as the biggest producers. Nevertheless, significant amounts of EU production were not disclosed. France was the third biggest producer, holding around 16% of EU production during 2019-2021.

Figure 53: EU production value and top producers disclosing data among the Member States [EUR Million]



Source: JRC based on PRODCOM data, 2023

In 2021, extra-EU exports increased by 6% after a 23% drop the previous year. During 2019-2021, extra-EU exports accounted for 9% of the global share. The UK remained the top partner for the EU, importing almost three times as much as the United Arab Emirates from the EU. Meanwhile, extra-EU imports increased by 28% after practically no change in the year of the pandemic. China and Tunisia remained the top exporters to the EU. EU internal trade accounts for more than 70% of all EU imports. Italy was the biggest importer, with Romania and Poland as its biggest partners. The EU trade balance deficit almost doubled to EUR 152 million in 2021.

12.4 Scoreboard – key insights and change in EU performance

The EU's position in the SBEMS value chain has improved overall. However, the trade deficit has more than doubled, and the trend is not improving. EU production is increasing, yet it cannot cover internal demand. The EU has improved its share in early and later stage investment, but at the early stage it still scores medium. EU patenting activity remained strong, and public R&D investment improved from weak to strong, indicating potential for innovation.

Figure 54: Scoreboard for building energy management systems

Scoreboard	Building Energy Management Systems	EU performance in the reference period			Change from 2021
Public R&D		7%	2016-2020	EU CAGR	
Early Stage		16%	2016-2021	EU share of global total value	
Later Stage		20%	2016-2021	EU share of global total value	
Patents		26%	2016-2019	EU share of global total HVI	
Companies		27%	2016-2021	EU share of innovating companies	
Employment			2016-2020	EU CAGR	
Production		14%	2016-2021	EU CAGR	
Turnover			2016-2020	EU CAGR	
Imports & Exports		9%	2019-2021	EU share of global exports	
Trade Balance		Low	2016-2021	EU trade balance trend	

Source: JRC, 2023

13 Grid energy management systems

The digitalisation of the power grid system is of great importance to make it fit for increased use and production of green electricity. The REPowerEU Plan (COM(2022) 230) requires a profound transformation of the energy system and proposes large-scale investment in the power grid by 2030. 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). The revised TEN-E Regulation ([111]) sets new EU rules for cross-border energy infrastructures. The EU action plan to digitalise the energy sector highlights the importance of more interactive and smarter power grids to embrace the benefits of the green transition. Moreover, smart grids are expected to support energy security in the future ([112]), as revealed by the emergency synchronisation of the electricity grids of Ukraine and Moldova with Europe's grid ([113]).

The scope of the grid energy management system (GEMS) solution covers techniques, processes, and equipment to manage power networks digitally, enabling distributed and intelligent operation and management, with efficient integration of new and existing services and technologies. 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, 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.

13.1 An updated status and recent developments

Digitalisation is critical for ensuring grid flexibility and increasing efficiency. The Digitalising the energy system EU action plan (COM(2022) 552) expects about EUR 584 billion of investment in the EU electricity grid between 2020 and 2030, out of which a sizeable EUR 170 billion is needed for digitalisation. In 2022, the European Network of Transmission System Operators for Electricity (ENTSO-E) expanded by synchronising with the networks of Ukraine and Moldova after the Russian invasion of Ukraine ([215]). The geopolitical situation increased electricity demand, sped up the deployment of clean energy alternatives, and put the EU grid under pressure (Kurmayer, 2023).

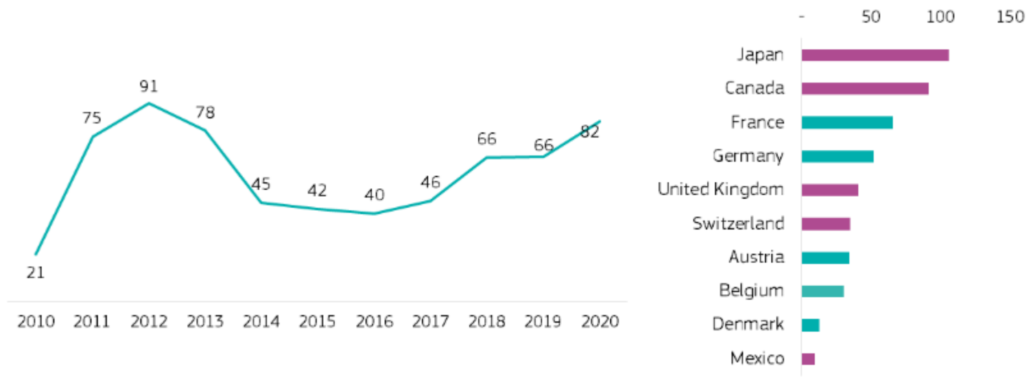
Precedence Research (Precedence Research, 2023) estimated the size of the global distribution automation market value at EUR 18 billion ([114]) in 2021 and forecast it to reach EUR 51 billion ([115]) by 2030. The market share of the software segment was estimated at 44%. The same analysis points to Asia Pacific as the biggest market share holder in 2021, with almost EUR 7 billion, while the EU market was valued at EUR 5 billion.

13.2 EU positioning in innovation and major changes

The EU holds around 40% of the total reported public R&D investment during 2018-2020 (EUR 214 million), with an increasing trend (**Figure 55**). The total investment for 2018-2020 increased to EUR 498 million, with Japan and Canada remaining the top investors among the reporting countries. France and Germany increased their spending and were the top EU public investors. Austria, Belgium and Denmark had the same spending level as in 2017-2019.

([111]) OJ L 152, 3.6.2022, p. 45–102 http://data.europa.eu/eli/reg/2022/869/oj
([112]) European project Sysflex https://eu-sysflex.com/documents/
([113]) European Commission, STATEMENT/22/1789, 16 March 2022 https://ec.europa.eu/commission/presscorner/detail/en/statement_22_1789
([114]) Foreign currencies are converted to EUR based on the annual averages published by the European Central Bank
([115]) Forecasted values are converted to EUR at a fixed rate of EUR 1.21 per USD.

Figure 55: EU Member States public R&D investment (left) and top ten IEA Members in 2018-2020 (right) [EUR Million]

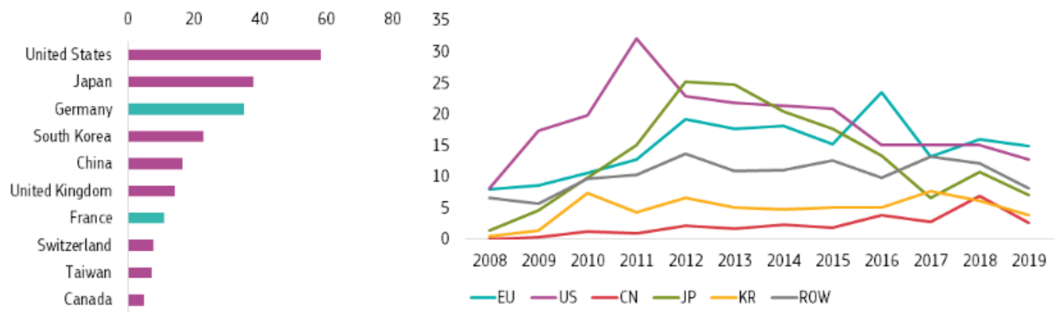


Source: JRC based on IEA data, 2023

In 2016-2021, the EU share of both early and later stage investment remained negligible, representing around 5% for both. The US and China remained the leading countries in both early and later investment for the same period. Only Germany and the Netherlands were amongst the top countries for early stage investment (seventh and tenth position, respectively), and only France remained amongst the top countries for later stage investment (dropped to seventh position from fifth in 2015-2020).

EU patenting activity continued its increasing trend and remained on top in 2019 (**Figure 56**). Germany and France were the top EU holders of high-value inventions but remained behind the US and Japan. The EU had the biggest global share (27%) in high-value inventions, ahead of the US (24%). The US and the EU exchanged the highest portion of their patenting flows, yet the US remained the most targeted market for high-value patent submissions.

Figure 56: Top ten countries in high-value inventions in 2017-2019 (left) and trend of high-value inventions for major economies (right)



Source: JRC based on PATSTAT, 2023

During 2015-2020, corporates dominated the GEMS innovation landscape, except for in the UK, Sweden, and Australia, where VC companies had the biggest share. The US had most of the innovating companies. Nearly a third of all innovating companies were headquartered in the EU, and almost three quarters of them were corporates. The relatively small pool of VC companies in the EU is reflected in the small share of early and later stage investment captured by the EU.

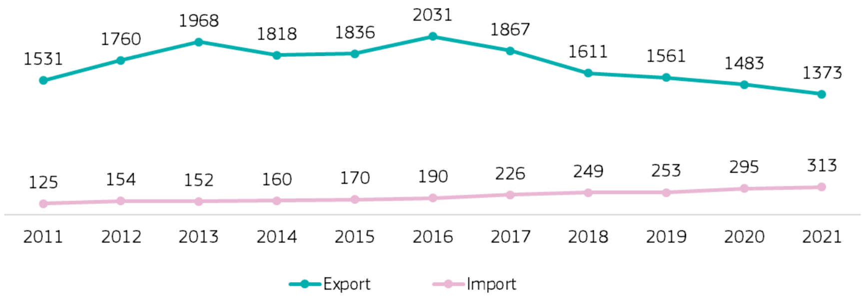
13.3 EU positioning in the current market and major changes

In this report, low-voltage apparatus is excluded from the trade and production codes (see report on Methodology ([116])) as it is less relevant for grid-level solutions. The change of codes has resulted in smaller production and trade values. In 2020, the production value of low-voltage apparatus was nearly four times higher than high-voltage, the export value was eight times higher, and the import value 20 times. The changes resulted in an improved production indicator, while the indicator for the trade balance has deteriorated from strong to average.

([116]) European Climate Neutral Industry Competitiveness Scoreboard (CINDECS) – Methodology Report, JRC134501 (in publication).

Over 2011-2021, EU production rose slowly, reaching nearly EUR 2.8 billion. Germany held roughly half of the total EU production value in these smart apparatuses, more than four times higher than Spain, the second producer in the EU. France, Greece, Belgium, Romania and Slovakia did not disclose their production data for 2021. Extra-EU exports saw a decreasing trend between 2016 and 2021, while extra-EU imports increased for the same period (**Figure 57**), shrinking the EU trade balance to EUR 1 billion in 2021. During 2019-2021, EU exports were balanced between the US, the United Arab Emirates and Switzerland with an exporting value of nearly EUR 280 million each. The EU imports came mainly from Norway (EUR 280 million) and then from Türkiye (EUR 176 million) and China (EUR 126 million). China was the biggest global exporter (EUR 3.3 billion), followed by Germany (EUR 2.8 billion).

Figure 57: Extra-EU import and export trend [EUR Million]



Source: *JRC based on COMEXT data, 2023*

Extra-EU exports accounted for 32% of global exports for 2019-2021; thus, the EU has a strong position globally. 70% of imports were covered internally. The US market was the largest growing import market, with the EU holding a 27% share of its total imports. EU exporters seem to be losing ground in the US and the Asian growing markets, with the exception of Singapore.

Finland was the Member State with the biggest trade deficit during 2019-2021, importing mostly internally from other EU countries (89%), with Estonia providing nearly half of it. Germany and France, the EU countries with the biggest trade surplus and also the second and third biggest global exporters, mainly exported to non-EU partners. Germany plays a central role in trading smart devices, as it was also the sixth global importer and the top EU producer.

13.4 Scoreboard – key insights and change in EU performance

The EU has maintained its positioning in the GEMS value chain. The EU's positioning in innovation has improved, particularly with regard to public R&D, increasing from EUR 66 million in 2019 to EUR 82 million in 2020. Yet, the EU position in early and later investment remains alarming. In terms of patenting activity, with 27% of high-value filings, EU performance remains strong. The EU is a host to a higher share of patenting corporates, at 30%, than VC companies, at 22%, and hosts the biggest pool of patenting corporates, which suggests that the 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. As production is growing slightly faster than EU GDP, the EU seems to have a strong manufacturing base in this area. However, its import needs are growing, and the trade balance, while remaining positive, is on a decreasing trend.

Figure 58: Scoreboard for grid energy management systems

Scoreboard	**Grid Energy Management Systems**	EU performance in the reference period			Change from 2021
Public R&D		20%	2016-2020	EU CAGR	↑
Early Stage		5%	2016-2021	EU share of global total value	→
Later Stage		5%	2016-2021	EU share of global total value	→
Patents		27%	2016-2019	EU share of global total HVI	↓
Companies		27%	2016-2021	EU share of innovating companies	→
Employment			2016-2020	EU CAGR	
Production		4%	2016-2021	EU CAGR	→
Turnover			2016-2020	EU CAGR	
Imports & Exports		32%	2019-2021	EU share of global exports	↑
Trade Balance		Medium	2016-2021	EU trade balance trend	↓

Source: JRC, 2023

14 Hydrogen production – electrolysers

14.1 An updated status and recent developments

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 ([117]). The importance of hydrogen in achieving the decarbonisation agenda set out in the European Green Deal (COM(2019) 640)([118]) is reflected in the legislation and initiatives adopted and proposed since and detailed in the previous version of this report (Kuokkanen, et al., 2022). In addition, the Fit-for-55 Communication (COM(2021) 550)([119]) in general (e.g. REFuelEU) and the following in particular, will have an impact on the hydrogen sector:

- the revisions of the Renewable Energy Directive (REDII) and the EU Emissions Trading Scheme (ETS) – political agreement in REDII for 42% of renewable hydrogen in total hydrogen consumption in industry by 2030 and rules to define what constitutes renewable hydrogen[120]
- the adoption of the Alternative Fuel Infrastructure Regulation (AFIR) and Hydrogen and Decarbonised Gas Market package
- REPowerEU (COM/2022/230 final) - increasing Europe's ambition of 10 Mt of locally produced renewable hydrogen, already given in the Hydrogen strategy of 2020, with 10 Mt of imports by 2030 ([121])
- the Electrolyser Partnership, which has set a target to achieve 25 GW/year of manufacturing capacity by 2025 (European Commission, 2022a)
- Two waves of Important Projects of Common European Interest' (IPCEIs) in the hydrogen sector have been approved, with more expected in 2023 ([122]). These will provide EUR 10.6 billion in public funding, and are expected to draw in an additional EUR 15.8 billion of private investment to allow Member States to finance relevant hydrogen projects, including R&D.
- the EU Green Deal Industrial Plan (COM(2023) 62 final)([123]), the European Critical Raw Materials Act (COM(2023) 160)([124]) and Net Zero Industry Act (COM(2023) 161)([125]).

The Fuel Cells and Hydrogen Observatory (FCHO, 2023) maintains a comprehensive list of relevant EU and national policies, including details of their relevance to the hydrogen value chain.

The annual hydrogen demand in Europe remained stable, at around 7.8 million tonnes (Fuel Cells and Hydrogen Observatory, 2021b)([126]). Globally, less than 1% is produced from renewable resources or from fossil fuel plants equipped with CCUS and just 0.04% from electrolysis (IEA, 2022e). By 2020, there was nearly 300 MW of electrolyser capacity installed worldwide, 40% of which was located in Europe (IEA, 2021a).

While production capacity in Europe has been increasing, and recent dramatic increases in gas prices made renewable hydrogen more cost competitive, by the end of 2020, water electrolysis only accounted for 0.1% of the total 11.5 Mt production capacity, another 3.7% coming from by-product electrolysis (i.e., capacity from chlorine and sodium chlorate production). Power to hydrogen facilities had increased to 0.25% of production capacity by 2022, still remaining marginal overall (Hydrogen Europe, 2022).

([117]) 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

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

([119]) 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

([120]) European Commision (2023) European Green Deal: EU agrees stronger legislation to accelerate the rollout of renewable energy, Press release, Breussels, 30 March 2023

([121]) COM (2022) 230 final REPowerEU Plan https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

([122]) IPCEIs on hydrogen https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/ipceis-hydrogen_en

([123]) COM(2023) 62 final A Green Deal Industrial Plan for the Net-Zero Age https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan_en

([124]) Critical Raw Materials Act (COM(2023) 160) Proposal for a regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/102

([125]) COM(2023) 161Proposal for a regulation of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act) https://single-market-economy.ec.europa.eu/publications/net-zero-industry-act_en

([126]) 8.7 Mt MtH2/y including EU, UK, Norway, Switzerland and Iceland (Hydrogen Europe, Clean Hydrogen Monitor 2022)

The focus of this chapter is on the production of renewable hydrogen through water 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. Cost-effective projects of considerable (tens of 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 and has a higher footprint 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 and thermal cycling 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. Fed with an industrial source of heat (waste heat from industrial processes for example), this electrolysers can produce hydrogen with a significantly lower energy consumption compared to other technologies.
- 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 and the scale of deployment achieved by the other technologies. These technologies significantly reduce the dependency on critical raw materials and platinum group metals while providing the same flexibility as proton exchange membrane electrolysers.

The capacity installed currently in Europe consists of 59% (84 MW) polymer exchange membrane electrolysers, 40% (57 MW) alkaline and less than 1 MW each for each solid oxide and anion exchange membrane electrolysers. The 3.3GW/year electrolyser manufacturing capacity in Europe is similarly split between PEM and alkaline with very little on solid oxide. Based on the latest announcements from electrolyser manufacturers, the electrolyser manufacturing capacity in Europe could reach 53 GW/year, with 25% (13.25 MW) polymer exchange membrane electrolysers, 31% (16.43 MW) alkaline, and 21% (11.13 MW) solid oxide (the remaining 23% are still unknown) (Hydrogen Europe, 2022).

14.2 EU positioning in innovation and major changes

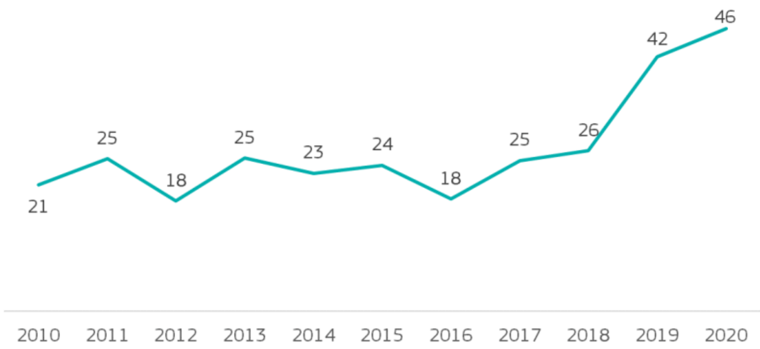
Public R&D investment in hydrogen production has been increasing in EU Member States (**Figure 59**). The data is not granular enough to draw insights on how much funding addresses electrolysis or renewable hydrogen production, so it is very likely that support for conventional technologies is included in this figure. Among the Member States that are IEA members, France accounts for nearly half of the EU investment. The Netherlands, Czechia, Germany, Belgium and Denmark have also invested over EUR 6 million in hydrogen production R&D in the period 2018-2020 and are in the top ten IEA members reporting R&D expenditure in this area. Combined with the 26% increase in the reported R&D investment from EU Member States between 2016 and 2020, this indicates a strong position for the EU, in terms of future technology development. In addition to the funding provided by national programmes, since 2008 the EU, through the Fuel Cell Joint Undertaking, has dedicated over EUR 150.5 million to electrolyser technologies ([127]). Furthermore, Horizon2020 has made EUR 130 million available to develop water electrolysis, while the Innovation Fund has provided over EUR 240 million to such projects (Dolci, et al., 2022).

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 cell’ category. Expenditure shown in **Figure 59** 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

([127]) 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

Hydrogen Partnership (EUR 1 billion of EU funds for 2021-2027([128]), complemented by at least an equivalent amount of private investment), 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 in 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, 2021b).

Figure 59: EU Member States public R&D investment in hydrogen production [EUR million]



Source: *JRC based on IEA data, 2023*

Going forward, on the hydrogen production side, and electrolysis in particular, the Hydrogen Strategy (COM(2020) 301)([129]) 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 ([130]) 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 ([131]), is high, putting the EU (31% of global high value inventions) in a leading position, along with Japan, among the major economies (**Figure 60**). At country level, Germany is the best performing MS, mainly through the activity of Siemens, which was also second (behind Toshiba of Japan) in the world ranking for high-value inventions in the period 2016-2019. Haldor Topsoe, headquartered in Denmark, also features in the top ten for the same period, while Hymeth (Denmark) and Bosch (Germany) have dropped positions compared to the previous reporting. 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 ten (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 2016-2019. 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 (22%), the US (31%) and other jurisdictions outside the major economies (39%). In China, patent filings in electrolysers have been increasing exponentially. However, as with increased patenting activity in China in other technological areas, these filings are restricted to the domestic market and do not seek international protection. Though different in scope, overall these trends are in good agreement with recent studies published by the EPO (EPO and OECD/IEA, 2023) and WIPO (WIPO, 2022).

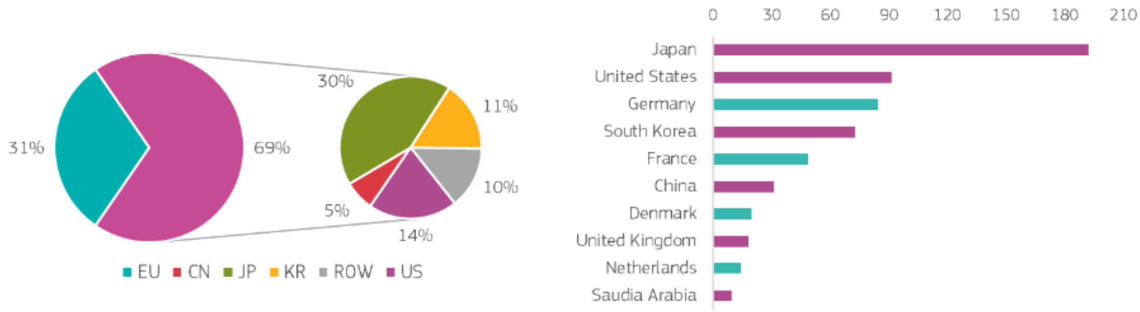
([128]) COUNCIL REGULATION (EU) 2021/2085 establishing the Joint Undertakings under Horizon Europe and repealing Regulations (EC) No 219/2007, (EU) No 557/2014, (EU) No 558/2014, (EU) No 559/2014, (EU) No 560/2014, (EU)

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

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

([131]) Compared to the previous study, fewer codes are included, focusing on inventions on electrolysis as a climate change mitigation technology

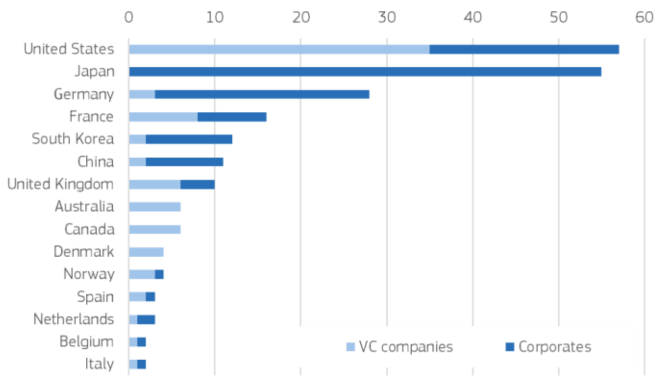
Figure 60: Share in high-value inventions for the major economies (left) and top ten countries in high-value inventions (right) for the period 2016-2019



Source: JRC based on EPO Patstat, 2023

In terms of innovating companies (**Figure 61**), The United States (24%) leads, with start-ups accounting for more than half of the companies identified. Japan follows, reflecting the large amount of innovating corporates identified in the patenting trends above. Germany and South Korea also have a strong corporate innovator base while France has an almost equal split between corporates and start-ups. Overall, the EU as a whole has a strong position, as it hosts 28% of the innovating companies identified globally, 60% of which are corporates.

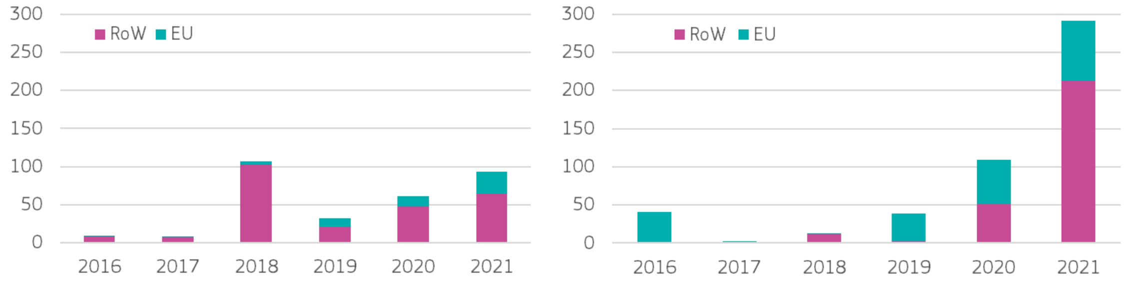
Figure 61: Number of innovating companies by type (2016-21)



Source: JRC compilation from different sources, 2023

As shown in **Figure 62**, in 2021, disclosed global VC investment amounted to EUR 385 million, more than double that of 2020, and at its highest since 2010. This confirms a clear acceleration of investment in renewable and low carbon hydrogen production companies over the 2016-21 period, which has almost doubled as compared to the period 2015-20, and a strong performance for the EU compared to its economic size. Early ventures remain heavily subsidised, both in and outside of the EU, as grants represent 68% of disclosed global early stage investment in identified companies. The EU accounts for 19% of the disclosed value of early stage transactions in the period 2016-2021, amounting to over EUR 58 million. Investment in the EU has steadily increased since 2017, with over 70% concentrated over the past two years in Finland and France (and to a lesser extent in Denmark). The US, hosting 64% of investment, accounts for the bulk of investment growth over the current period. Over the 2016-21 period, global later stage investment amounted to EUR 495 million (a 30% increase compared to 2015-20). Later stage investment outside the EU quadrupled in 2021 and, in this year alone, equalled all EU later stage investment since 2016. With large deals in 2021 (e.g. in the company PowerTap Hydrogen), the US captured 34% of later stage investment. Increasingly attracting investment, the EU as a whole accounted for 43% of later stage investment over 2016-21 (particularly in France, Denmark and Italy).

Figure 62: Early (left) and later (right) stage investment by region [EUR Million]

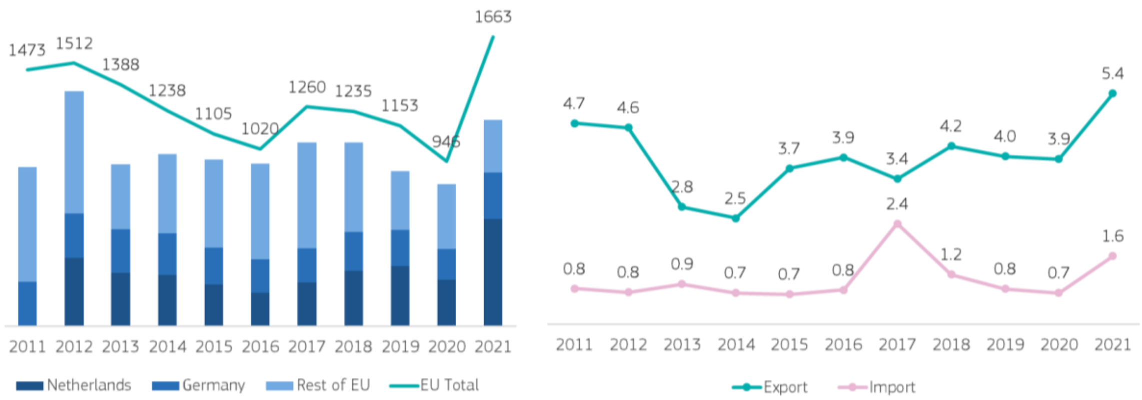


Source: *JRC based on Pitchbook, 2023*

14.3 EU positioning in the current market and major changes

The available trade data does not differentiate between renewable or low-carbon 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 renewable or low carbon hydrogen. Although production had declined by an average 3% per year since 2015, it showed a significant increase in 2021 (mainly from the Netherlands) and the EU trade balance for hydrogen remains positive (**Figure 63**). 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, 2021a).

Figure 63: Production (left) and extra-EU import and export of hydrogen [EUR million]



Source: *JRC based on COMEXT data, 2023*

The choice of electrolyser technology is only known for less than a third of planned projects. Proton exchange membrane electrolysis is prevalent to 2025, while alkaline technology is preferred for use in larger projects and thus overtakes in terms of capacity in the longer term (Hydrogen Europe, 2022). Though we cannot track trade in electrolysers, half of the manufacturers of large-scale electrolysers are located in the EU (Buttler & Spliethoff, 2018)([132]), predominantly in Germany and France, but also in Denmark, Italy and Spain. This provides the EU with a good industrial basis to take advantage of future market opportunities.

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

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

14.4 Scoreboard – key insights and change in EU performance

BloombergNEF (BNEF, 2021c; BNEF, 2022b) estimated that electrolyser shipments reached 0.79 GW in 2022 (BloombergNEF, 2023), with China accounting for over 78% 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). BloombergNEF forecasts that electrolyser shipments could reach at least 2 GW in 2023, with China accounting for 58% of the total. However, BloombergNEF also estimates 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.

The implementation of national hydrogen strategies 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 (FCH 2 JU, 2020). The majority of job creation was 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. The lower end of this estimate is in line with the additional jobs in electrolyser manufacturing estimated in the needs assessment to strengthen the EU's Net-Zero technology manufacturing capacity (SWD(2023) 68)([133]). Another scenario of employment impacts from investment in the EU renewable 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. (European Commission, 2020b). According to the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 Joint Undertaking, 2019), industries like machinery and equipment, automotive, electricity, and gas supply, are estimated to create ten jobs (direct and indirect) for every EUR 1 million in earnings. Manufacturing equipment and end-use applications generate an average of 13 jobs per EUR 1 million in revenue, while aftermarket services and new business models create 15 jobs per EUR 1 million in revenue.

The market potential for electrolysers (including balance of plant) in particular is estimated at EUR 45-55 billion by 2050 (IRENA, 2022b)([134]). While the EU, along with China and Japan, is at the forefront of electrolyser production, China 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, 2022b). 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 of 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 (Bobba, et al., 2020). PEM electrolysers, for instance, require the use of noble metal catalysts like iridium for the anode 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, 2022b). 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.

As one of the main pathways for decarbonisation, the renewable hydrogen production and electrolysers sector has high potential for growth and is attracting increasing amounts of venture capital investment. The EU also appears strong on innovation aspects, performing well in terms of public R&D investment, patenting output and hosting innovating companies. In addition, 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 while production had been declining slightly over previous years, it recovered in 2021. The EU sustains a positive trade balance,

([133]) SWD(2023) 68 final Investment needs assessment and funding availabilities to strengthen EU's Net-Zero technology manufacturing capacity

([134]) USD 50-60 billion.

nonetheless only capturing a small share of the global market, compared to the size of its economy. Planned industrial projects using clean hydrogen could require 6.1 Mt of hydrogen per year by 2030, the vast majority of which will use water electrolysis for its production (Hydrogen Europe, 2022). The EU is host to a considerable share of global electrolyser capacity and currently well placed in terms of electrolyser production. While projects in the pipeline could increase manufacturing capacity for electrolysers to 53GW/y by 2030 and enable the production in excess of 11 Mt of hydrogen annually, investment in the majority of them is yet to be fully confirmed (Hydrogen Europe, 2022).

However, the EU could face competition from other major economies, in the form, for example, of the US Inflation Reduction Act (to which the EU is responding with the EU Green Deal Industrial Plan and Net-Zero Industry Act) and particularly, from the deployment drive and cost reductions in China. Other issues to address include ensuring demand for renewable or low-carbon hydrogen, dependence on (critical) raw material imports, and thus supply disruption and price volatility. An update on the associated raw material bottlenecks has recently been published (Carrara, et al., 2023), along with proposed policy actions to address them through the European Critical Raw Materials Act.

Figure 64 shows a summary scoreboard for the solution.

Figure 64: Scoreboard for hydrogen production – electrolysis

Scoreboard	**Hydrogen Production - Electrolysis**	EU performance in the reference period			Change from 2021
Public R&D	●	26%	2016-2020	EU CAGR	↑
Early Stage	●	19%	2016-2021	EU share of global total value	↑
Later Stage	●	43%	2016-2021	EU share of global total value	↓
Patents	●	31%	2016-2019	EU share of global total HVI	→
Companies	●	28%	2016-2021	EU share of innovating companies	→
Employment			2016-2020	EU CAGR	
Production	●	10%	2016-2021	EU CAGR	↑
Turnover			2016-2020	EU CAGR	
Imports & Exports	●	6%	2019-2021	EU share of global exports	→
Trade Balance	●	High	2016-2021	EU trade balance trend	→

Source: JRC, 2023

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 hydropower-storage (PHS ([135])) plants also work the other way round, both 'turbining' and pumping water. In pumping mode, 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), PHS plants work as traditional hydropower plants (HPs) to satisfy the energy demand. Therefore, PHS plays an important role in providing flexibility to the energy grid.

The hydropower sector is complex and the large projects include complete electromechanical equipment (e.g., turbine, generator, gearbox, distributor, draft tube and casing), the civil structures (e.g., dam, reservoir for reservoir-type hydropower plants, tunnels, penstocks and canals), plus the operation and maintenance (O&M) equipment to monitor the status of the components and 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). For a big hydropower plant or a plant built from scratch, the EME generally constitutes 30% of the total cost. As a consequence, a significant proportion of investment in the hydropower sector refers to civil works and associated consultancy services that are very difficult to track. Where the hydroturbine is considered in isolation, e.g., production, imports and export, it is therefore likely that the indicators are underestimated.

15.1 Updated status and recent developments

With a view to achieving climate neutrality by 2050, renewable energy – including hydropower – plays a central role in decarbonisation. In 2021, hydropower supplied one sixth of global electricity generation, the third largest source after coal and natural gas. Installed hydropower capacity reached 1 360 GW in 2021 (International Hydropower Association (IHA), 2022), including 165 GW of PHS (the EU hosts more than a quarter of the global PHS turbine capacity), and 30 GW of new hydropower capacity which was added in 2021, globally (International Hydropower Association (IHA), 2022). Hydropower also provides more than 1500 MW off-grid hydro electrification services mainly in Africa, South America and Asia , according to 2023 data (IRENA, 2023). Hydropower capacity is led by East Asia, where the global leader is China, with an installed hydropower capacity of 391 GW, 36 GW of which is PHS. However, a relative comparison shows that the installed GW per inhabitant is 0.35 kW/person in the EU, 0.35 kW/person in North America and 0.24 kW/person in China, demonstrating that the EU is a strategic developer of hydropower.

Hydropower presents several benefits and strengths with respect to other renewable energy sources, e.g., flexible operation, very high overall efficiency (capable of reaching 90%), long lifespan and no use of critical materials (unlike wind, solar and batteries). Multi-purpose hydropower reservoirs can provide several additional benefits (e.g., flood control, water supply, fire-fighting, and tourism) that will be of high relevance in the future, especially in light of climate changes.

However, several challenges hamper large hydropower deployment, and it is not easy to secure the investment necessary to ensure the proper operation of ageing assets crucial for electricity security. Large hydropower projects have longer pre-development, construction and operational timelines than other renewable energy technologies, increasing the investment risks and requiring specific policy instruments and incentives as well as a longer-term policy perspective and vision (IEA, 2021c). An important barrier to large-scale deployment is the difficulty of simultaneously pursuing renewable energy, climate, and environmental goals. Operational decision-making, integrating lifetime and maintenance planning in liberalised power markets, is also a major challenge for existing plants in particular (Quaranta, et al., 2021; European Commission, 2020c).

Therefore, global cumulative hydropower capacity is expected to expand from about 1 360 GW in 2021 to just over 1 555 GW by 2030. The EU27 long-term strategy modelling exercise provides future projections of hydropower development grouped together with wave, tidal, and biomass power. Projections indicate small additions and an average hydroelectricity generation of 375 TWh/year. The dedicated projections for PHS

([135]) Mixed PHS is connected to a natural inflow (a river) when generating power, while closed loop hydropower is a closed system, not connected to a natural water inflow.

show higher deployment rates and 4 GW of new PHS until 2030 (total 51 GW). The anticipated 2030-2050 PHS growth varies between scenarios from 8 GW (baseline) to 19 GW (SWD(2020)953 final ([136])). The mentioned projections can be fulfilled as described in Quaranta et al. (2022), who summarised the different possibilities of new capacity addition without installing new barriers and dams. For example by modernising the existing hydropower fleet (Quaranta, et al., 2021), by integrating it with other energy strategies (e.g., heat extraction from the generator) (Quaranta & Muntean, 2023) and by new micro-schemes in existing water infrastructures (Quanranta, et al., 2022), it is possible to increase hydropower generation by more than 12% (+40 TWh), in the same market and hydrological conditions as 2021. Water-energy storage can increase by 30 TWh by interconnecting existing reservoirs to form new PHS plants in the whole Europe, and by 140 TWh by virtual interconnection and coordination of hydropower reservoirs.

The hydropower sector is the focus of major debate, especially in the EU: on the one hand, hydropower contributes to renewable energy targets, to grid flexibility and stability by integrating variable renewable energy into the electricity grid, and to mitigating climate change effects on water resources by the multiple use of reservoirs; on the other hand, it seems to contradict the Water Framework Directive, which is designed to preserve the good ecological status of water bodies, although only a small percentage of barriers in rivers are for hydropower. For a comprehensive discussion and a SWOT analysis, see (Quaranta, et al., 2022).

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 (Quaranta, et al., 2022) with an installed power of 151 GW in EU27, subdivided into run-of-river hydropower (RoR), PHS and hydropower plants with a storage capacity (SPP). PHS produced 32 TWh (therefore, on average, 328 TWh/y is from traditional hydropower) with an overall cycle efficiency of 71% (energy generated/adsorbed electricity for pumping). Between 2020 and 2021, the European countries with the highest added hydropower capacity were Türkiye (+513 MW), Norway (+396 MW), Austria (+150 MW), Greece (+21 MW), Spain (+16 MW) and Switzerland (+12 MW) (considering data of IHA 2021 and IHA 2022). In the last five years (2015-2019), capacity additions in the EU were mainly developed 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. Major rehabilitation and upgrades of existing stations have taken place, for example in the La Bâthie, La Coche, and Romanche-Gavet projects in France. Significant PHS development took place in Switzerland with Linthtal (1200 MW) and Nant de Dranse (900 MW). The European energy sector is a market leader in small hydropower technology (Wagner, et al., 2019) and several leading hydropower companies are based in the EU (see below).

15.2 EU positioning in innovation and major changes

The European energy sector is a market leader in hydropower technology, especially in small hydropower and sustainable and environmental solutions.

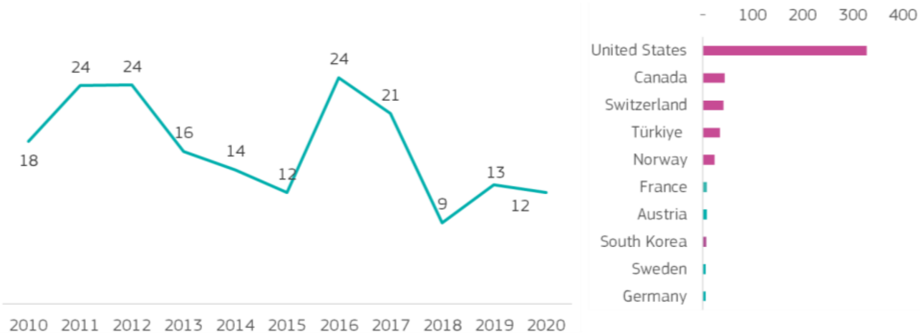
Despite hydropower's technological maturity, research efforts are still ongoing and new concepts are emerging, as discussed in section 1.1, to address environmental requirements and the energy targets related to renewable energy and climate change. Efforts have been made to stimulate significant R&D investment and novel technologies to solve the debate (Kougias, et al., 2019; Quaranta, et al., 2021; Quaranta, et al., 2020; Quaranta & Davies, 2021; IEA, 2021c; Fry & Schleiss, 2022) with a focus on the following main topics:

- 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. PHS plants are essential to provide and consume energy on demand.
- Small-scale hydropower by the powering of existing hydraulic structures and small barriers, already in place for other purposes, and micro-schemes (<100 kW) in water and wastewater distribution networks.
- Minimisation of impacts generated by hydropower and the need to be environmentally friendly.
- Novel construction techniques and materials, to reduce costs and increase lifespan.
- Modernisation of the existing and aged hydropower fleet with novel technologies.
- Digitalisation of the hydropower sector.

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

In the last decade (2010-2021), public spending for R&D in the EU ranged between EUR 6 million and EUR 24 million per year (**Figure 65**), with a decreasing trend. The global reducing trend may be down to the progressive depletion of optimal sites for hydropower. 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. Compared 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 down the costs 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 65: EU Member States public R&D investment (left) and top ten IEA Members in 2018-2020 (right) [EUR million]



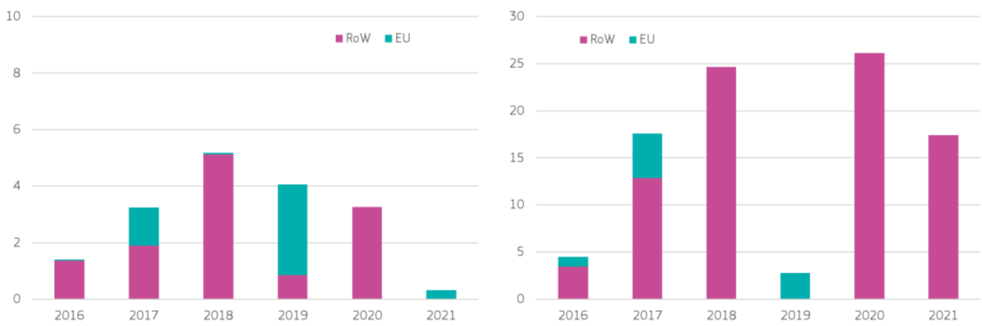
Source: JRC based on IEA data, 2023

As shown in **Figure 66**, the global level of VC investment in hydropower-related ventures increased over the 2016-2021 period, amounting to EUR 110.5 million (a 40% increase on the previous period). While annual investment has fluctuated since 2016, that of 2021 is significantly lower (a reduction of 40% from 2020) and below the period average.

Global investment in early ventures represents only 15% of all VC investment in the 2016-2021 period and decreased to the lowest levels in over a decade, both in the EU and the rest of the world, after a peak in 2018. Since 2016, early stage investment has amounted to EUR 18 million, with the EU accounting for 28%. It is worth noting that there are no reported grants for the EU-based companies identified, while grants make up the majority of early stage investment in the rest of the world (almost 75%).

The level of later stage investment in the EU over the period is very low at 9%, and zero in three of the six years. Later stage investment in the rest of the world therefore constitutes the majority (85%) of all VC investment in hydropower-related ventures, amounting to EUR 93 million over the period. They are mostly concentrated into the last four years and in the United States (75% of all investment). The sole US company, Natel Energy, has attracted EUR 56.2 million since 2016 (EUR 64.79 million since its inception), developing a novel turbine for low-head applications and with a fish-friendly conceptual design. China attracted the second largest share of investment over the period (12%, amounting to EUR 13.5 million), followed by France (9%).

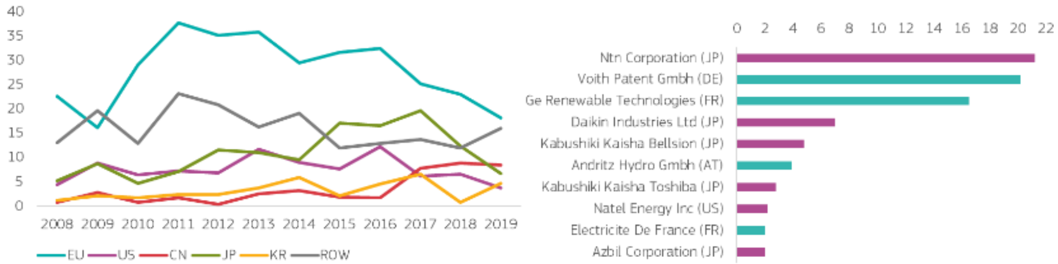
Figure 66: Early (left) and later (right) stage investment by region [EUR million]



Source: JRC based on Pitchbook, 2023

The EU is the leading economy in terms of the number of patents (**Figure 67**, left), and the trend has been reasonably stable over the years. The EU holds 36% of all high-value inventions globally (2016-2019). 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 67**, 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 (to make hydropower more flexible).

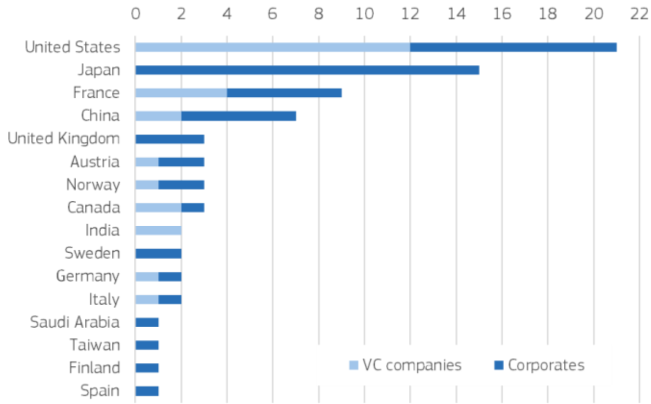
Figure 67: Trend of high-value inventions for major economies (left) and top ten companies in 2016-2019 (right)



Source: JRC based on EPO Patstat, 2023

As shown in **Figure 68**, the number of identified innovators is rather limited for this technology in most countries. Four countries host 64% of active companies. The US (in first place in terms of individual countries) has the most identified companies (26%). The EU as a whole hosts 27% of active companies in this context, mostly in countries connected to the Alps such as France, Germany, Italy and Austria. The US in particular relies on a relatively strong base of venture capital companies while all innovators in Japan (in second place) are corporates.

Figure 68: Number of innovating companies by type (2016-21)



Source: JRC compilation from different sources, 2023

15.3 EU positioning in the current market and major changes

Globally, hydropower provides direct employment to 2.36 million people in 2021, representing almost 20% of total direct jobs in the renewable energy sector. In the EU, the number of direct and indirect jobs in hydropower was estimated to be 99 000 ([137]) in 2018, with Italy and France, located at the heart of the Alps, topping the list. EU hydropower employment decreased in 2020 to 36 000, probably due to the fact that the installed power under construction reduced in 2020 with respect to 2015. A 10% increase of hydropower in the year 2030 would create 27 000 jobs in the EU, mainly outside the hydropower sector itself (Quaranta, et al., 2022).

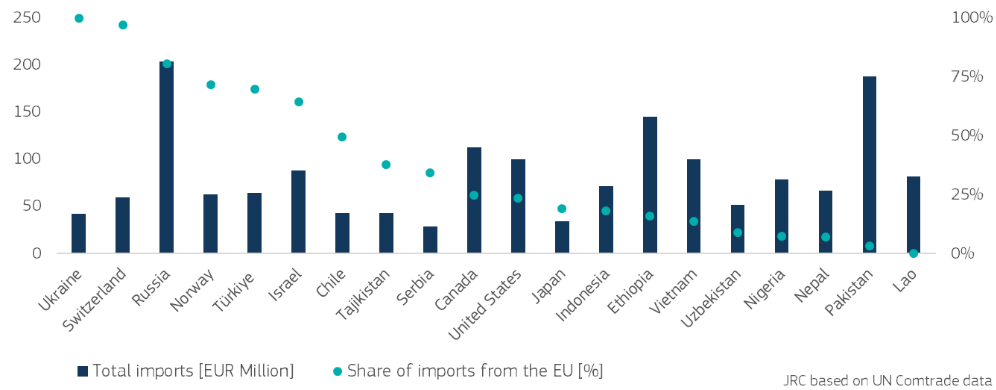
The annual turnover of hydropower electricity generation in the EU was approximately EUR 12 billion in 2018. Leading Member States in terms of turnover are Austria (EUR 2.85 billion in 2018), Italy (EUR 2.25 billion),

([137]) 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.

France (EUR 1.55 billion), Spain (EUR 1.18 billion) and Germany (EUR 1.06 billion). In 2020 it decreased to EUR 4.65 billion, led by Italy with EUR 1.63 billion. Global exports accounted for over EUR 2 billion over the period 2019-2021. The EU held 47% of all global exports and 39% if intra-EU trade is excluded. The major share of global exports by the EU is due to the big EU hydro companies (see Section 15.2 above). The biggest exporter is China, with a 22% share, followed by Austria (13%), Italy (7%) and Germany (7%). The remaining exports are mainly generated by Brazil and India. EU imports accounted for EUR 394 million from 2019 to 2021, and 73% of this was intra-EU trade.

The EU has a significant presence in Ukraine, Switzerland, Russia, Norway, Türkiye and Israel, supplying 100%, 97%, 80%, 72%, 70% and 64% of all their imports (based on the percentage share, rather than on the absolute value of imports), respectively, making the EU the world leader in hydropower technology (including pumped hydro) (Gérard et al., 2021). Russia and Pakistan are the biggest import markets globally in the hydropower sector; 80% of Russian hydropower imports come from the EU (**Figure 69**). As the Russian hydropower sector is growing (Savchina, et al., 2022), the Russian hydropower expansion may represent an export opportunity for EU hydropower companies, but that may be undermined by the current geopolitical situation. 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) (Quaranta et al., 2022).

Figure 69: Top 20 non-EU importers in 2019-2021



Source: JRC based on UN Comtrade data, 2023

The EU's trade balance was positive over the period 2011-2021. However, trade surplus decreased from its peak at EUR 466 million in 2015 to EUR 211 million in 2021. Austria, Italy and Germany have the biggest trade surpluses.

15.4 Scoreboard - key insights and change in EU performance

EU performance in innovation-related indicators is two-sided. On the one hand, public R&D funding decreased at an average annual rate of 16% in 2016-2020. On the other hand, the EU captures a larger share of (albeit limited) venture capital investment, both at early and later stages, which indicates private interest in EU-based start-ups and scale-ups. The EU hosts nearly a third of active innovators in the area, with a balanced ecosystem of venture capital companies and corporates. Even if it rises again in 2020-2021, EU production is at a much lower level than it was previously (2011-2017). As hydropower projects are big and span long periods, production value (manufacturing) of hydropower turbines can vary year by year. 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 and a positive trade balance. 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.

Figure 70: Scoreboard for hydropower and pumped storage

Scoreboard	**Hydropower and pumped storage**	EU performance in the reference period			Change from 2021
Public R&D		-16%	2016-2020	EU CAGR	↓
Early Stage		28%	2016-2021	EU share of global total value	↑
Later Stage		9%	2016-2021	EU share of global total value	→
Patents		35%	2016-2019	EU share of global total HVI	→
Companies		27%	2016-2021	EU share of innovating companies	↓
Employment		-17%	2016-2020	EU CAGR	→
Production		-9%	2016-2021	EU CAGR	→
Turnover		-14%	2016-2020	EU CAGR	→
Imports & Exports		39%	2019-2021	EU share of global exports	→
Trade Balance		Medium	2016-2021	EU trade balance trend	→

Source: JRC, 2023

16 Offshore operations for RE installation

The European Offshore Renewable Energy Strategy (ORES) 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 ([138])). REPowerEU calls for the faster installation of both onshore and offshore wind energy. This requires an estimated EUR 800 billion investment by 2050, two thirds of which will fund infrastructure development. 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 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 focuses on installation and service vessels, offshore structures and port operations needed for renewable energy.

16.1 An updated status and recent developments

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, 2021; 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).

A detailed overview of the current status of the installation, operations and maintenance, port operations can be found in the previous version of this report (Kuokkanen, et al., 2022).

16.2 EU positioning in innovation and major changes

Public R&D investment in offshore wind ([139]) has been steadily increasing in the EU since 2016 and amounts to EUR 129 million over the 2018-20 period (**Figure 71**). As a whole, the funds mobilised by EU Member States that are IEA members remain behind those of Norway, which leads the investment race with a reported EUR 250 million over the same period.

With comparable shares, France, Denmark and Germany account together for more than 77% of EU public R&D investment over the period. France is establishing itself as a leading emerging market (in floating offshore wind in particular) and has substantial manufacturing capacity in GE Renewable Energy (US). It mobilised higher level of investment over the period than Denmark and Germany, which are home to Europe's largest OEMs in offshore wind.

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

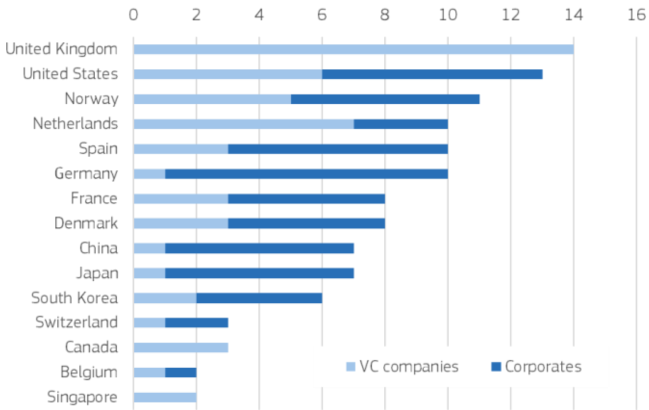
([139]) The IEA Offshore wind technologies category is used as a proxy for offshore operations for RE installation. R&D activities focus on the performance and the reliability of offshore wind technologies and also include new materials for sea salt exposure and foundation and platform technologies.

Figure 71: EU Member States public R&D investment in offshore wind [EUR million]

Source: JRC based on IEA data, 2023

Innovators in offshore operations for RE installation are rather distributed worldwide (11 countries host 80% of the identified companies). The three countries that host the most innovators are the United Kingdom, the United States and Norway (respectively accounting for 11%, 10% and 9% of identified companies). As shown in **Figure 72**, they are, however, closely followed by several EU Member States and the EU as a whole accounts for 42% of active innovators over the 2016-21 period. Globally, corporates account for only slightly more than half (53%) of identified innovators. Leading countries, and in particular the United Kingdom (first) and the Netherlands (fourth), benefit from a stronger base of venture capital companies.

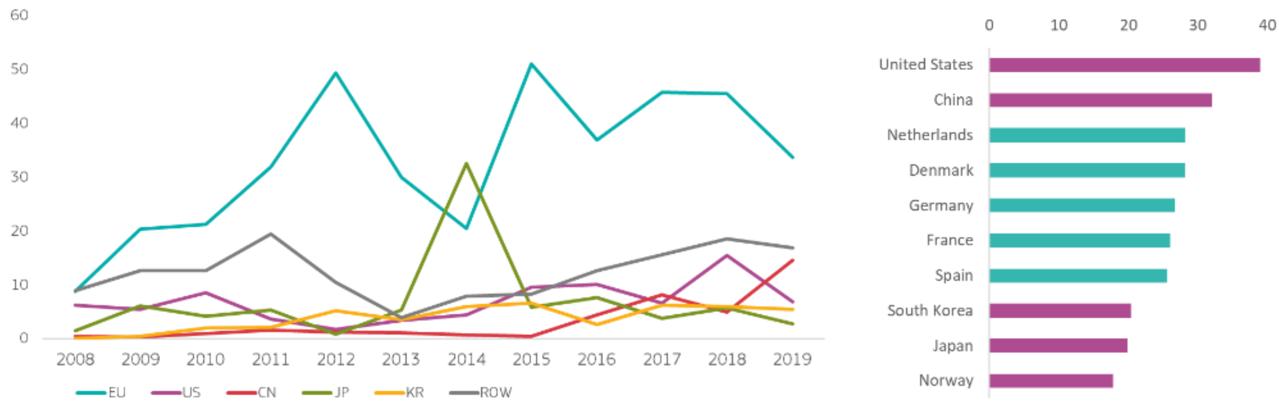
Figure 72: Number of innovating companies by type (2016-21)



Source: JRC based on Pitchbook, 2023

With a higher share of corporates among its innovators (60% of identified EU companies), the EU patenting output along selected codes is high. It puts the EU in a leading position (48% of global high-value inventions over the 2016-19 period), far ahead the United States and China (**Figure 73**). At country level, the Netherlands (third) is the best performing Member State, in particular through the activity of Huisman-Itrec BV, which tops the world ranking for high-value inventions over the period 2016-19. EU companies are well represented, with six EU companies among the global top ten of high value inventions. EU patenting output is spread across a number of inventors and mostly located in the Netherlands, Denmark, Germany, France and Spain (which are grouped together in the world ranking).

Figure 73: Trend in high-value inventions for the major economies (left) and top ten countries in high-value inventions in 2016-2019 (right)



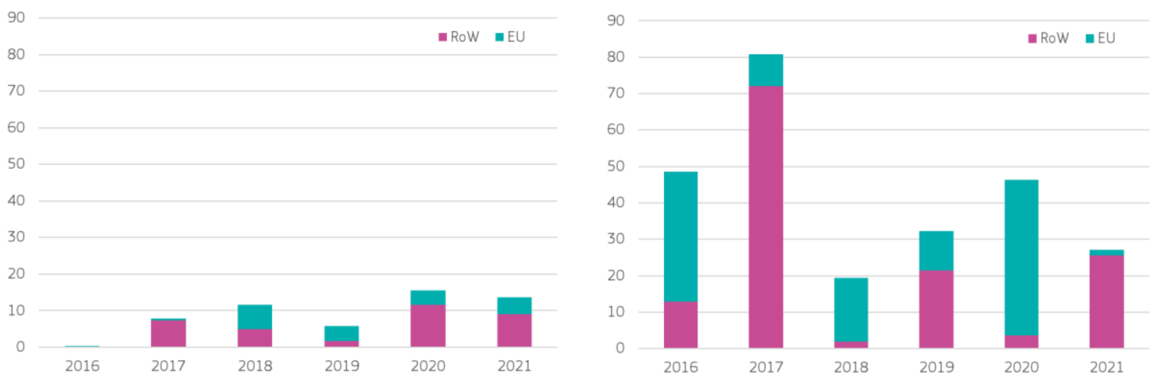
Source: JRC based on EPO Patstat, 2023

Worldwide, levels of Venture Capital (VC) investment amount to EUR 309.5 million over the 2016-21 period and are significantly higher (2.3 times) than that of the previous 2010-15 period. Most of the top line growth is due to an outstanding increase of later stage investment in the EU over the 2016-21 period (8.7 times that of 2010-15).

The EU displays a strong competitive position despite decreasing levels of early stage investment in France. Over the 2016-21 period, the EU has captured 36% of early stage investment (amounting to EUR 19.8 million) and 46% of later stage investment (amounting to EUR 117.2 million). It has increased its share of investment as compared to 2010-15 in line with its weight, as it hosts 36% of identified venture capital companies.

With the strongest base of VC companies and large expansion deals in a company developing remotely operated underwater vehicles (Rovop), the UK remains the main destination of both early and late stage investment. Among the countries that have captured the most early stage investment over the 2016-21 period, the US (second) and Japan (third) outrank a group of EU Member States (including Spain, the Netherlands and Denmark). In the group of countries that have captured the most later stage investment over the 2016-21 period, Denmark (second) and the Netherlands (third) outrank the US as a result of large deals in companies like Blue Ocean Robotics (offshore robotics, DK) and Strohm (thermoplastic composite pipes, NL).

Figure 74: Early (left) and later (right) stage investment by region [EUR Million]



Source: JRC based on Pitchbook, 2023

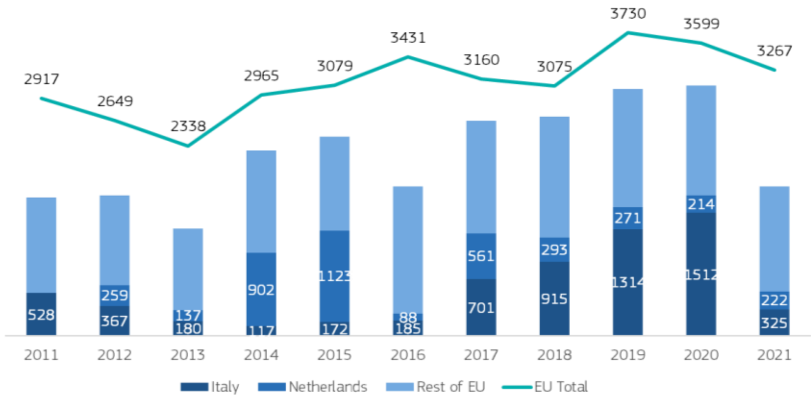
16.3 EU positioning in the current market and major changes

Offshore renewables are expected to generate new local jobs and business opportunities in offshore operations and ports, as discussed above. However, we have not identified a reliable and comparable source for employment in offshore operations for RE. 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)([140]).

The EU has a strong production base of offshore vessels and infrastructures. However, while EU production levels have grown steadily over recent years, they dropped from EUR 3.6 billion in 2020 back to their 2017 level in 2021, with a production value of EUR 3.3 billion. This may, however, be due to a reporting artefact and remains to be confirmed as it is mainly caused by a drastic drop of Italy's reported production value. 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) and Italy has historically been the top EU producing country.

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. Some countries also keep their data confidential, e.g. Belgium, which has many offshore operating companies such as Jan de Nul and Smulders. Naturally, not all production and trade is exclusive to renewable energy deployment.

Figure 75: EU production value and top producers disclosing data among the Member States [EUR Million]



Source: *JRC based on Prodcom data, 2023*

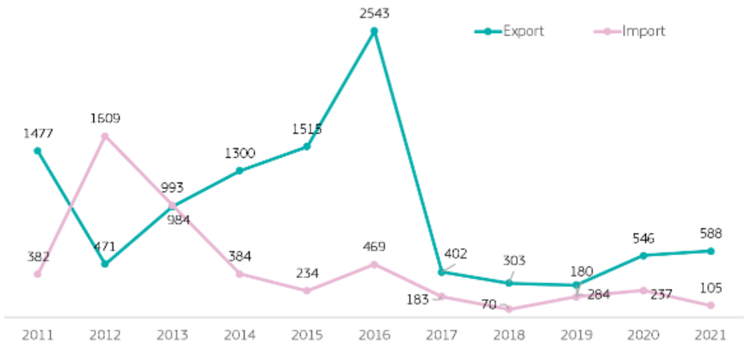
Accounting for a 3% share of extra-EU exports, the EU has a limited role in the global trade of solutions for offshore operations. Still, the EU exports more than it imports, resulting in a positive trade balance that has steadily increased over recent years as shown in **Figure 76**.

Looking at the top global importers, however, indicates that the majority of global trade in offshore vessels and infrastructures is historically not related to renewables, but to the oil and gas sector and others such as dual-use technologies. In particular, the peak in extra EU 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), only some of which may be related to offshore wind.

In recent years, the UK, as the biggest offshore wind market, has been the main importer from the EU. While the EU maintains a positive trade balance with the UK, the share of the EU in UK imports has been decreasing and reached 22% over 2019-21, possibly due to Brexit. On the other hand, the EU has a negative trade balance with China, which is the main exporter to the EU (and therefore probably also to the top extra-EU importers, Croatia, Poland and the Netherlands).

([140]) Not including indirect jobs.

Figure 76: Extra-EU import & export [EUR Million]



Source: *JRC based on Comext and Comtrade, 2023*

16.4 Scoreboard – key insights and change in EU performance

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 2022-26 report (GWO, 2022) reveals a 33% growth in the number of wind technicians needing standard industry training: up from 426 700 in 2021 to 568 800 by 2026. 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. In order to deliver on the offshore wind targets in European waters until 2030, (WindEurope, 2021) estimates the investment needs for new port infrastructure and upgrading of existing ports to be about EUR 6.5 billion (WindEurope, 2021). This includes investment in existing facilities, the building of new port terminals, decommissioning facilities, adaptions of ports to host floating offshore wind, hydrogen infrastructure and the infrastructure related to energy islands operations and products. 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.

The EU shows very strong performance across all indicators related to innovation. Public R&D investment shows a growing trend. The EU captures almost half of the global total patent output and hosts nearly half of all innovating companies, providing a good opportunity to maintain leadership and capture future markets.

While the EU is punching above its economic weight regarding venture capital investment, its share in global early and later stage investment however decreased as compared to last year's scoreboard.

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 77: Scoreboard for offshore operations for RE installations

Scoreboard	**Offshore operations for RE installation**	EU performance in the reference period			Change from 2021
Public R&D		35%	2016-2020	EU CAGR	
Early Stage		36%	2016-2021	EU share of global total value	
Later Stage		46%	2016-2021	EU share of global total value	
Patents		48%	2016-2019	EU share of global total HVI	
Companies		42%	2016-2021	EU share of innovating companies	
Employment			2016-2020	EU CAGR	
Production		-1%	2016-2021	EU CAGR	
Turnover			2016-2020	EU CAGR	
Imports & Exports		3%	2019-2021	EU share of global exports	
Trade Balance		Medium	2016-2021	EU trade balance trend	

Source: JRC, 2023

17 Building envelope technologies

The scope of this chapter comprises technologies and integrated solutions for the building envelope, intending to improve their thermal performance (in both new construction and retrofit) and facilitate the integration of onsite renewable energy production. Some technologies included are 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. Thus, the focus of this chapter is solely on building integrated technologies and solutions.

17.1 An updated status and recent developments

The global building envelope market was estimated at EUR 149 billion ([141]) in 2022 and is expected to reach around EUR 274 billion by 2028 (Precision Reports, 2023). Henkel, Rockwool International, Saint-Gobain and Knauf Insulation are among the largest manufacturers of related components. According to the European Construction Sector Observatory([142]), "building envelope renovations focusing on the insulation and the substitution of single-glazed windows with double-glazed ones are expected to lead to a 50% and 90% reduction in heating demand and CO2 emissions, respectively" (ECSO, 2021). The same report identified technical, financial, social and regulatory barriers to building envelope renovation, such as a lack of skilled workers, long payback timeframes, user's limited awareness and understanding of the benefits and complex building permit procedures. Another report by a think-tank concluded that better insulation of residential buildings in the EU could reduce final energy consumption by 777 TWh, or 44% of the final energy used for residential space heating in 2020 (BPIE, 2023).

Building envelopes must comply with energy efficiency, safety and environmental requirements, while providing the required comfort and aesthetics. Preferably, they have a high thermal efficiency, while being flexible without requiring too much space. Moreover, the manufacturers need to satisfy a diverse range of national legal requirements and fit with various architectural styles. Consequently, production standardisation remains a barrier.

The policymakers and construction industry increasingly acknowledge that in order to reduce emissions in the building sector, it is necessary to address the entire lifecycle of buildings, from the production of components to the construction, operation, maintenance, and ultimately, the end-of-life of the building. Denmark and France have already introduced whole-life carbon limits for new constructions, aiming to minimise all emissions related to the building (BPIE, 2021). Applying whole-life carbon considerations in policymaking and the construction sector will also influence the building envelope technologies, where most of the insulation materials are carbon-intensive. This growing focus on materials and technologies with a small carbon footprint could make space for new innovations and possibly also export opportunities in the future.

The EU's Renovation Wave Strategy ([143]) sets out to double the number of renovations and will thus dramatically increase the demand for building envelope technologies. Furthermore, the high energy prices and the urgent need to make the EU independent of foreign fossil fuels adds to the demand for building envelope technologies. While the increase in demand is currently hampered by high material and energy prices, and the lack of skilled installers, it is likely that the demand for building envelope technologies will increase dramatically until 2030. The EU trade balance for this technology will probably become negative, unless measures are taken to increase EU manufacturing capacities.

17.2 EU positioning in innovation and major changes

The global public R&D investment for this solution increased to EUR 151 million in 2018-2020, with Japan and Switzerland remaining the top investors among the reporting countries. With EUR 54 million and an increasing trend, the EU accounted for around 36% of total investment during the same period, while six Member States were among the top investors. The scope of the selected IEA code (1211) includes technologies which relate to the structure, assembly, protection, or thermal efficiency of the building

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

([142]) The European Construction Sector Observatory is an initiative under the European Commission. It regularly analyses and carries out comparative assessments on the construction sector in all 27 EU countries and the UK, aiming to keep European policymakers and stakeholders up to date on market conditions and policy developments. Available: https://single-market-economy.ec.europa.eu/sectors/construction/observatory_en

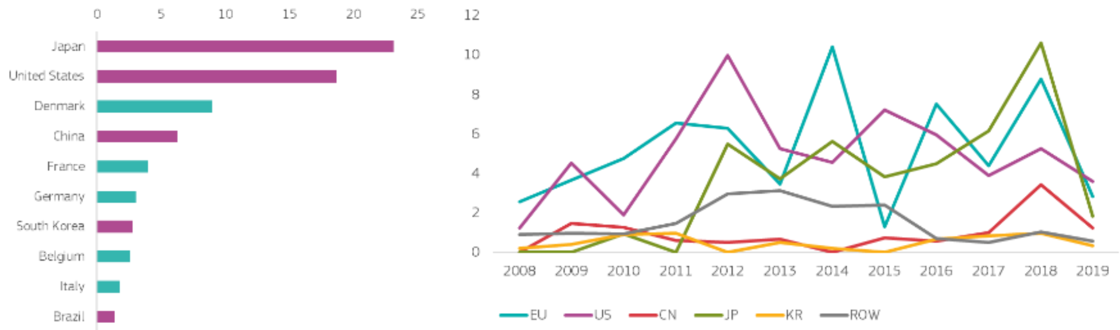
([143]) European Commission's (2020) "A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives" COM(2020) 662 final, Brussels. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662

envelope, including windows. However, IEA ([144]) clarifies that some projects might include multiple technologies and the funding might not be possible to be split. Moreover, the categories at the four-digit level are optional in reporting and some investments might be hidden by being aggregated at a reporting higher level. Prefabricated buildings, superinsulation materials and building envelope technologies are considered to fall under the same scope, and, therefore, the public R&I figures are not exclusive to each solution. Instead the same public R&I value concern all three solutions, as discussed in the methodology ([145]).

Early stage investment declined in 2021 after the recovery in 2020. The EU's share of disclosed early stage investment increased to 18% during 2016-2021. Later stage investment increased almost sixfold in 2021, with the EU share remaining at 8% for the same period.

According to the data, the EU's patenting activity fluctuated with spikes in 2014, 2016 and 2018. However, the overall trend is negative (**Figure 78**). In 2018, the patenting activity of Japan and China also spiked. China seems to become more active after 2016 with the launch of its 13th five-year plan. Five Member States featured among the top holders of high-value inventions in 2016-2019, with Denmark in third place behind Japan and the US. The EU and US were the leading economies for high-value inventions, with 30% of the global share each. The US and EU markets attracted most of the patent applications.

Figure 78: Top ten countries in high-value inventions in 2016-2019 (left) and trend of high-value inventions for major economies (right)



Source: JRC based on PATSTAT, 2023

VC companies dominated the building envelope innovation landscape in 2016-2021, except for in Japan and Brazil, where corporates dominated. The US hosts most of the innovating companies, having more than four times that of second-placed Japan. More than a third of all innovating companies are headquartered in the EU, and less than one third of them are corporates.

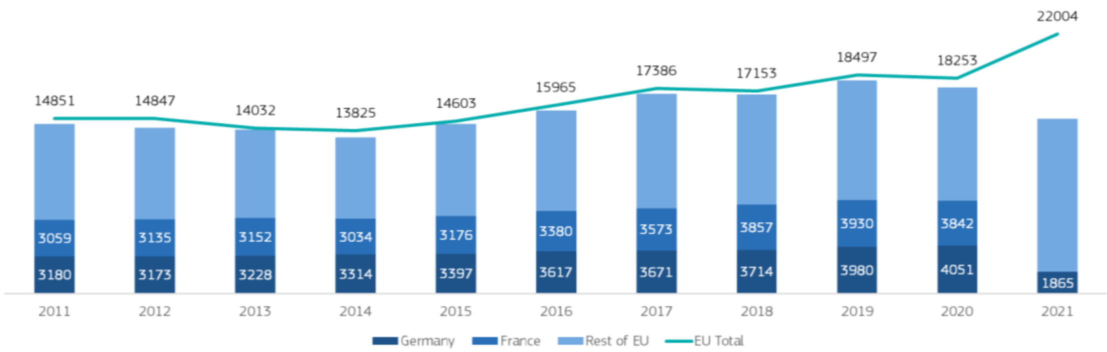
17.3 EU positioning in the current market and major changes

EU production has seen an increasing trend since 2014 and increased by more than 20% in 2021, following a dip in 2020 (**Figure 79**). Germany and France held together around 30% of the EU total in 2019-2021, yet France hasn't disclosed its production for 2021. Italy is the third largest producer with more than 17% of the EU share.

([144]) IEA (2011), IEA Guide to Reporting Energy RD&D Budget/ Expenditure Statistics, available at https://iea.blob.core.windows.net/assets/751c1fce-72ca-4e01-9528-ab48e561c7c4/RDDManual.pdf

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

Figure 79: EU production value and top producers disclosing data among the Member States [EUR Million]



Source: JRC based on PRODCOM data, 2023

In 2021, extra-EU exports returned to their pre-pandemic level, while EU imports increased by 31%. Extra-EU exports as a share of global exports dropped slightly to 20% in 2019-2021, while 83% of EU imports were met internally within the union. The EU trade surplus decreased by 7% to EUR 0.65 billion in 2021. The EU captured most of the growing non-EU markets for the same period. However, the largest global importer, the US, acquired only 9% of its total imports from the EU, despite being the third largest EU importing partner. Germany, the second biggest global exporter, mainly exports to other EU Member States (61%).

There is no statistical data available for employment. The sector is still quite labour-intensive but new technologies are being developed to minimise labour dependences (e.g. robotics, AI and 3D-printing), as described in Chapter 7 on prefabricated buildings. However, the EU's Renovation Wave Strategy[146] sets out to double the number of renovations and it is estimated that this will create an additional 160 000 green jobs in the EU construction sector. A report by BPIE, in which 35 research reports were reviewed, concluded 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 Scoreboard - key insights and change in EU performance

The EU's performance in innovation has improved, except for the later stage investment indicator, which remained the same. Public R&D investment reached a ten-year high. The EU share in early stage investment increased from 4% for 2015-2020 to 18% for 2016-2021, while the number of deals has not changed much (from 22 to 24), implying that the value of the deals has also increased. The EU now hosts more than a third of all innovating companies and held 30% of all high-value patents in 2016-2019. The EU had a slightly lower share of global exports in 2019-2021 (20%) compared to 2018-2020 (22%). In 2021, extra-EU imports increased by 31%, and the trade surplus decreased for a second consecutive year, altering the indicator from strong to medium. In 2021, EU production increased by 20%, indicating a strong manufacturing capacity.

Figure 80: Scoreboard for building envelope technologies

Scoreboard	**Building Envelope Technologies**	EU performance in the reference period			Change from 2021
Public R&D	●	11%	2016-2020	EU CAGR	↑
Early Stage	●	18%	2016-2021	EU share of global total value	↑
Later Stage	●	8%	2016-2021	EU share of global total value	→
Patents	●	30%	2016-2019	EU share of global total HVI	→
Companies	●	34%	2016-2021	EU share of innovating companies	↑
Employment			2016-2020	EU CAGR	
Production	●	7%	2016-2021	EU CAGR	↑
Turnover			2016-2020	EU CAGR	
Imports & Exports	●	20%	2019-2021	EU share of global exports	→
Trade Balance	●	Medium	2016-2021	EU trade balance trend	↓

Source: JRC, 2023

([146]) European Commission's (2020) "A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives" COM(2020) 662 final, Brussels. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662

18 Heating and cooling networks

18.1 An updated status and recent developments

District heating and cooling networks play a vital role in decarbonisation by offering an efficient and central source of heating and cooling in urban areas and industrial sites. The networks allow for the integration of different energy sources and systems, with the ability to integrate variable renewable energy sources and offer flexibility to the power grid. The scope of this solution comprises technologies contributing to higher efficiencies and decarbonisation of heating and cooling networks, such as heat exchange units and thermal energy storages. The scope does not include power generation or smart energy management systems.

Around 50% of the energy consumption in the EU is utilised for heating and cooling in buildings and industries, with 75% of this energy sourced from fossil fuels. In 2018, district heating consumed 445 TWh of energy, with the EU operating around 6 000 district heating networks in 2017. District cooling consumed 3.1 TWh of energy with 115 district cooling networks (Euroheat & Power, 2017) (European Commission, 2022b).

While district heating only constitutes 12% of the total heating and cooling supply, the countries that have largely implemented this technology, such as the Nordics, have demonstrated notable success in decarbonising the heating and cooling sector. In some EU Member States, the district heating and cooling networks are extensively developed and are integral to their vision of a flexible, efficient, and decarbonised energy system. Conversely, in other Member States, the use of district heating and cooling is minimal. According to data from the European Commission (European Commission, 2022b), Germany, Poland, and the Nordic countries comprise 68% of the EU's total district heating usage (2018 data), while the use of district heating in the Benelux and most southern European countries is scarce. However, ongoing urbanisation is expected to drive a market growth of district heating and cooling globally (FBI, 2022).

District cooling networks are much less common, where Sweden represents 75% of the installed capacity (Pezzutto, et al., 2022). District cooling systems not only allow more efficiency compared to individual solutions and access to sources such as waste heat, but they also help manage peak demands and therefore support electrification in other sectors, such as transport. Cooling demand is, however, growing faster 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). District cooling networks could play a much larger role in the future.

Traditionally, district heating and cooling networks have operated without any advanced control technologies. Conventional control is focusing on ensuring a sufficient supply and optimising the economic and environmental performance of the system (Schmidt, 2021). The ongoing transition towards a more complex system with a higher share of renewables and waste heat is requiring more sophisticated control strategies, to facilitate the more complex system efficiently. At the same time, digitalisation and technological innovations have made more advanced control possible, improving the reliability, sustainability and performance of the system (Schmidt, 2021). District heating systems are gradually utilising smarter technologies and operate on lower temperature (Volt, et al., 2022).

District heating and cooling networks can support flexibility in the power sector by providing reserve capacities for balancing services (Boldrini et al., 2022). Frontrunner cases show the networks can play a central role in future energy systems by offering flexibility to the power sector and by enabling a high integration of renewable energy sources. It can provide 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 energy storage systems (European Commission, 2022b). It is clear that heating and cooling networks can also play an important role in smart and decarbonised cities.

In 2021, the global district heating market was estimated at around EUR 155 billion ([147]) and is projected to reach nearly EUR 327 billion ([148]) by 2028 (FBI, 2022). According to the IEA's report on district heating, 40% of the district heat generated globally in 2020 was used for industrial heating and only 8.5% for heating buildings (IEA, 2021d). Globally, district heating and cooling systems primarily rely on fossil fuels, with coal being the largest energy source at 45%, largely due to China's national average usage of 70%, followed by natural gas (40%), renewable energy sources (8%) and oil (3.5%).

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

([148]) 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.

Box 2: Success factors and barriers

A JRC analysis identified ten key factors for the success of district heating and cooling networks (European Commission, 2022b). These factors include 1) adequate incentives for efficient DHC through national policies, 2) supporting new investment 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) exploration of synergies with other networks (e.g., power grids) and urban infrastructures (e.g., water), 9) valorisation of synergies and seasonality for district cooling, and 10) adoption of optimisation and flexible strategies (European Commission, 2022b).

District heating and cooling networks provide an infrastructure-based service which require a relatively high market share of connected buildings and industries within a limited geographical area. However, there are several challenges hampering a wider and faster implementation of these networks, including 1) financial challenges mainly related to the high capital investment required to implement or retrofit a district heating and cooling network, 2) fossil fuel sources that receive subsidies or fail to consider negative impacts, creating an unfair playing field for renewable energy sources (IRENA and IEA, 2020), 3) technical challenges including ageing networks and their switch to low-temperature operating conditions, 4) 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), and 5) inconsistent and uncertain policies which can cause instability and fragmentation in the market, undermining investment in new projects (IRENA and IEA, 2020).

The EU aims to achieve a climate-neutral economy by 2050, with an intermediate target to reduce greenhouse gases by 55% by 2030. To speed up the reduction of gas consumption, the REPowerEU Plan ([149]) recently proposed to increase the EU renewable energy target to 45%. A crucial element to achieve this is decarbonising the heating and cooling sector, where district heating and cooling networks play a key role. The EU has established several strategies to facilitate the spread and improvement of these systems, including the EU strategy on energy system integration ([150]), the EU strategy on heating and cooling ([151]), and the Action plan on the digitalisation of the energy sector ([152]) (Volt, et al., 2022).

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 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)([153]). The new rules ([154]) 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 ([155]) objectives in a targeted and cost-effective manner. In the case of district heating and cooling, highly efficient cogeneration is included.

18.2 EU positioning in innovation and major changes

The EU has also developed a broad policy framework to facilitate the uptake of district heating and cooling networks and increase the share of renewables in the thermal networks. The Energy Efficiency Directive (EED) ([156]) defines *efficient district heating and coolin*g (Art. 2) and requires Member States to conduct economic and

([149]) European Commission "REPowerEU" [Website] Available: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

([150]) EU Energy System Integration Strategy, COM(2020) 299 final. Available: https://energy.ec.europa.eu/topics/energy-systems-integration/eu-strategy-energy-system-integration_en

([151]) EU Heating and Cooling Strategy, COM(2016) 51. Available: https://energy.ec.europa.eu/topics/energy-efficiency/heating-and-cooling_en

([152]) EU Action plan on the digitalisation of the energy sector. Available: https://ec.europa.eu/info/news/action-plan-digitalisation-energy-sector-roadmap-launched-2021-jul-27_en

([153]) 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.

([154]) 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.

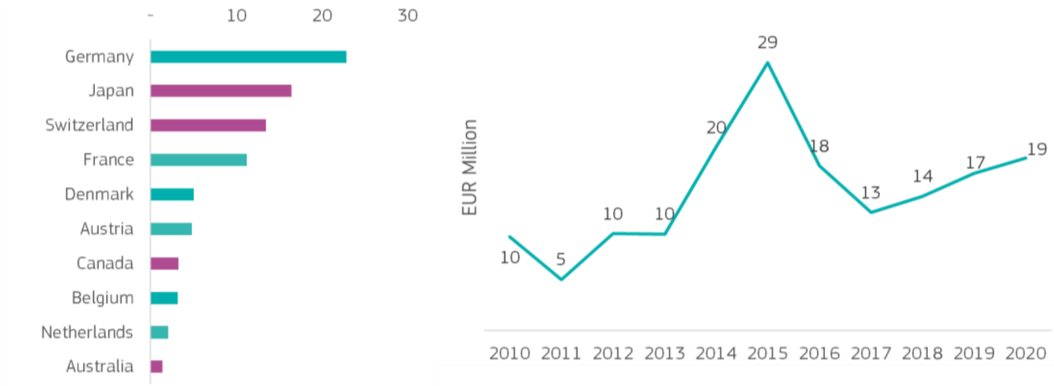
([155]) COM(2019) 640 final Brussels, 11.12.2019.

([156]) Energy Efficiency Directive [2018/2002, 2012/27/EU] Available: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en geographic analyses to identify district heating and cooling potentials (Art. 14) ([157]). The Renewable Energy Directive (RED) sets out a target of an annual increase in the percentage of renewable heating and cooling (Art. 23) and sets an annual target for increasing the share of renewables in district heating and cooling (Art. 24). RED also asks Member States to enable producers of energy from renewable energy sources and from waste heat and cold to access district heating and cooling networks (also Art. 24)([158]). In addition, the European Performance of Buildings Directive (EPBD) ([159]) sets out several provisions to improve the efficiency of new and existing buildings, which is a prerequisite for lower-temperature district heating and cooling networks ([160]) (Volt, et al., 2022).

The EU has also enacted a number of strategic plans and platforms in which DHC is explored and supported. The European Strategic Energy Technology Plan ([161]) is advancing the deployment of low-carbon technologies, with innovation platforms on renewable heating and cooling and smart networks for the energy transition, among others. Positive energy districts are one of many explored topics. The related European Partnership for Clean Energy Transition ([162]), co-supported by industry, public organisations, research and citizens' organisations, aims to accelerate the energy transition by enabling energy research and innovation on different levels. Focus areas of the multilateral partnership include renewables, DHC, energy storage and system integrations. Furthermore, the EU has launched a mission to have *100 climate-neutral and smart cities* by 2030. The Smart Cities Marketplace ([163]) supports this mission by offering knowledge, capacity-building support and facilitation of finance solutions for cities. The Covenant of Mayors for Climate and Energy ([164]) brings together local and regional authorities, which commit to the EU's climate and energy objectives. Implementers in European cities can use the platform to exchange experiences and views (Volt, et al., 2022).

Figure 81 shows the public research and development investment in thermal energy storage, which is used as a proxy for the wider sector. The data reveals that Germany allocates the largest amount of public funds towards research and development, while Denmark, in proportion to its population size, has the highest spending among all European Union Member States. The data also shows that public investment has slowly increased over the last 11 years, with a peak in 2015. Moreover, from 2014 to 2020, the EU funded 58 relevant projects through Horizon 2020 with nearly EUR 387 million (Saletti et al., 2020).

Figure 81: Top ten IEA Members in 2018-2020 (left) and EU Member States public R&D investment (right) [EUR Million]



Source: JRC based on IEA data ([165]), 2023

([157]) Efficient DHC is defined as systems using at least 50% RES, 50% waste heat, 75% cogenerated heat or 50% of a combination of such energy and heat

([158]) Renewable Energy Directive 2018/2001/EU, 2009/28/EC. Available: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en

([159]) European Performance of Buildings Directive 2018/844/EU, 2010/31/EU. Available: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

([160]) A new report carried out for the European Commission provides a good overview of the policy framework for DHC, with a special focus on the RED recast (European Commission, 2022b).

([161]) European Commission "Strategic Energy Technology Plan" [Website] Available: https://energy.ec.europa.eu/topics/research-and-technology/strategic-energy-technology-plan_en

([162]) CETPartnership [Website] Available: https://cetpartnership.eu/

([163]) European Commission "Smart Cities Marketplace" [Website] Available: https://smart-cities-marketplace.ec.europa.eu/

([164]) Covenant of Mayors [Website] Available: https://www.eumayors.eu/en/

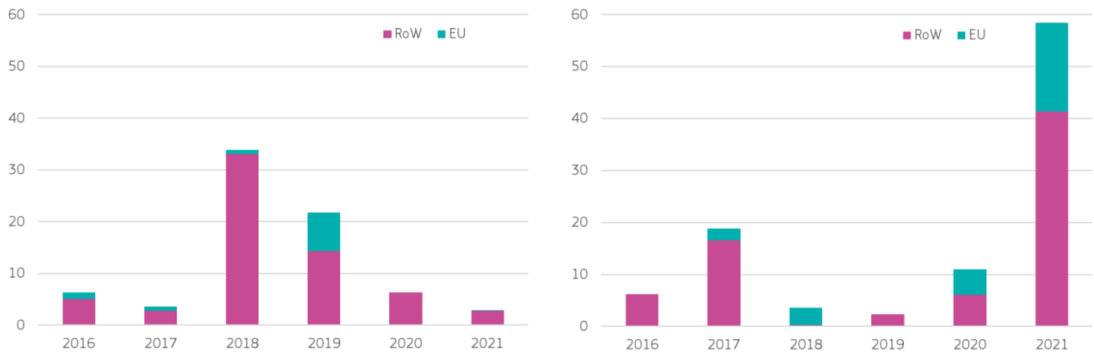
([165]) IEA codes: 632. Thermal energy storage is used as a proxy for heating & cooling networks.

Venture capital investment amounted to EUR 175 million over the 2016-21 period and is significantly higher than during the previous 2010-15 period, globally (almost double at 1.8 times the size) and in the EU in particular (at 2.6 times the size). As shown in **Figure 82**, this is due to a peak in early stage investment in 2018 followed by a remarkable increase in later stage investment. In 2021, later stage investment reached an all-time high of EUR 58.5 million (5.3 times that of 2020), driven by more numerous and larger deals realised outside of the EU.

During the 2016-21 period, the EU attracted 14% of all early stage investment, amounting to EUR 10.2 million, and 28% of the later stage investment, amounting to EUR 27.6 million. Despite its good performance compared to 2010-15, investment levels remain below the EU average.

Most of the companies that raised over EUR 10 million of capital in the 2016-21 period are focusing on thermal energy storage solutions and are located in the US (Echogen Power Systems, Phase Change Energy Solutions), the UK (Sunamp), China (Ray Power Technology) and Denmark (Hyme Energy, founded in 2021).

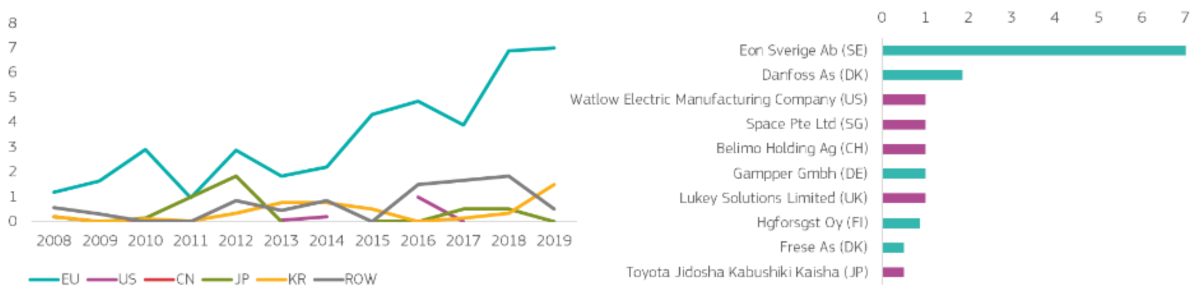
Figure 82: Early (left) and later (right) stage investment by region [EUR Million]



Source: JRC based on Pitchbook, 2023

The EU is steadily increasing its patenting activity and holds 69% of all high-value inventions. Sweden and Germany, countries with a relatively high penetration of district heat and cold networks, are the leading patenting countries globally, followed by Denmark and Finland in the fourth and fifth position. Swedish E.ON Sverige AB is the leading patenting company, followed by the Danish company Danfoss (**Figure 83**).

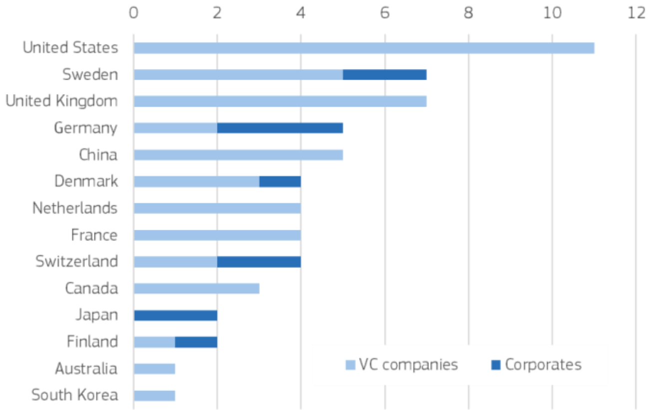
Figure 83: Trend in high-value inventions for major economies (left) and top ten companies in 2016-2019 (right)



Source: JRC based on EPO Patstat, 2023

The US has the largest number of companies investing in innovation, followed by Sweden and the United Kingdom. The US has the most venture capital companies (11), while Sweden (5) has the most in the EU. The EU hosts 42% of all venture capital companies. Overall, the global number of venture capital companies and corporates indicates that this is a growing innovation ecosystem within this field. As shown in **Figure 84**, venture capital companies constitute most of the identified innovators and are distributed across many countries. Led by the US, the top five countries host together 55% of active companies. The EU has a strong competitive position and hosts 45% of innovators. Five EU member states rank in the top ten countries, including Sweden (second) and Germany (fourth), behind the UK (third) but ahead of China (fifth).

Figure 84: Number of innovating companies by type (2016-21)



Source: *JRC compilation from different sources, 2023*

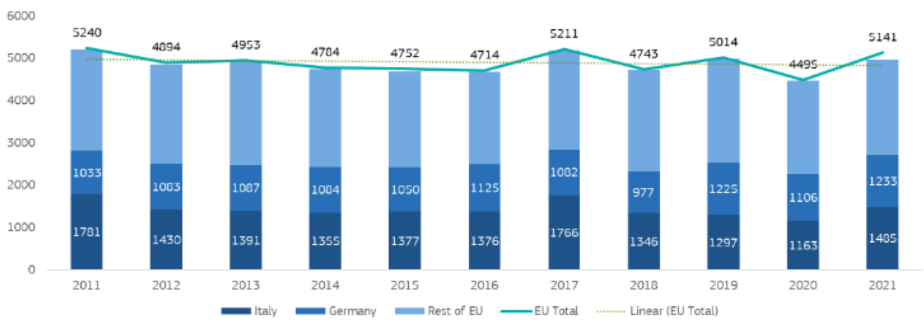
New technologies under development to improve the efficiency of the piping systems include sustainable insulation materials, coatings to reduce pressure losses, and quick-fit joints for easy installation (Moustakidis et al., 2019). Research efforts are focused on the design and retrofit of low-temperature 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).

District heating and cooling networks are not equally represented in all Member States and account for around 12% of the EU's total final heating and cooling demand. One of the key actions for a more integrated energy system, in the European Commission's Strategy for Energy System Integration, was therefore to "accelerate investment in smart, highly-efficient, renewables-based district heating and cooling networks"([166]). The uptake of new networks remains limited, but the climate mitigation needs and energy dependency concerns are triggering a growing interest among policymakers and companies.

18.3 EU positioning in the current market and major changes

The EU production of heating and cooling network components ([167]) has been rather constant over the last 10 years. EU production decreased by 2% between 2011 and 2021, reaching EUR 5 billion in 2021. Italy and Germany are the largest producers, responsible for more than half of the total EU production in 2021.

Figure 85: EU production value and the biggest producers [EUR Million]



Source: JRC based on PRODCOM data, 2023

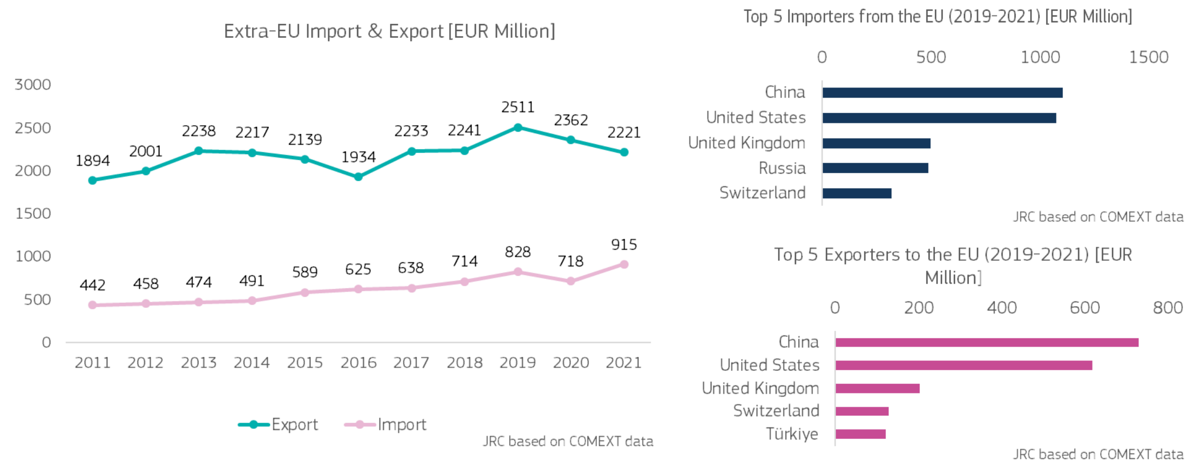
Extra-EU imports and exports have grown slowly since 2011, reaching over EUR 2 billion of exports and nearly EUR 1 million in imported goods (**Figure 86**). China and the US are the largest exporters to the EU and they

(166) European Commission "EU strategy on energy system integration" [Website] Available: https://energy.ec.europa.eu/topics/energy-systems-integration/eu-strategy-energy-system-integration_en

(167) 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.

import the most from the EU. Extra-EU trade accounts for 33% of the global share, and there is potential for the EU to increase exports to the growing markets of India, Thailand, and Indonesia. Internal imports (i.e. imports from another EU Member State) account for more than 70% of all EU imports. Germany is the largest exporter in the world and the largest importer in the EU. The EU trade surplus was more than EUR 2 billion in 2021.

Figure 86: 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, 2023

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

18.4 Scoreboard – key insights and change in EU performance

The EU scores highly in innovation-related indicators, showing leadership in the development of decarbonised heating and cooling networks. The EU captured slightly smaller shares of venture capital investment due to expanding the scope to include thermal storage, but at later stages, the EU captures nearly a third of all investment. The EU also hosts nearly half all identified innovating companies in the area. In the production of heat exchangers, the EU performance is medium as, although production is growing, it is growing less than the EU GDP overall. Still, the EU has a strong manufacturing capacity, manifested by a positive trade surplus, which however, dropped in 2021 due to the simultaneous increase of imports and decrease of exports. During 2018-2021, extra-EU exports accounted for 33% of global exports, but in 2021 there were still some growing markets of which the EU can capture a larger share.

Figure 87: Scoreboard for heating and cooling networks

Scoreboard	**Heating and Cooling Networks**	EU performance in the reference period			Change from 2021
Public R&D		1%	2016-2020	EU CAGR	
Early Stage		14%	2016-2021	EU share of global total value	↓
Later Stage		28%	2016-2021	EU share of global total value	↓
Patents		69%	2016-2019	EU share of global total HVI	→
Companies		45%	2016-2021	EU share of innovating companies	↓
Employment			2016-2020	EU CAGR	
Production		2%	2016-2021	EU CAGR	↑
Turnover			2016-2020	EU CAGR	
Imports & Exports		33%	2019-2021	EU share of global exports	→
Trade Balance		Medium	2016-2021	EU trade balance trend	↓

Source: JRC, 2023

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, 2022f). In 2021, space cooling accounted for nearly 16% (about 2000 TWh) of buildings sector final electricity demand, and this could increase by 40% by 2030 (IEA, 2022f). In addition, cooling systems contribute to large peaks in electricity demand, which can overwhelm power grids during extreme heat waves. There are over 2 billion AC units in operation in the world (IEA, 2022f), 70% of which are in residential units (IEA, 2021e).

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.

19.1 An updated status and recent developments

Cooling technologies are addressed in the EU by the Ecodesign Directive ([168]), Energy Performance of Buildings Directive ([169]) and F-gas Regulation (Regulation (EU) No 517/2014). The Renewable Energy Directive (RES-Directive) sets mandatory national targets ([170]) for the overall share of energy from renewable sources. In 2021, the Commission adopted new rules to account for renewable cooling ([171]). 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).

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, 2021e). 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 ([172]) 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 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. 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.

In the EU, cooling demand in the residential sector is projected to grow fourfold in a business-as-usual case by 2050, and only twofold in an energy efficiency scenario (SWD(2016) 24 final)([173]). 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).

([168]) 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)

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

([170]) 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.

([171]) 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.

([172]) 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.

([173]) SWD(2016) 24 final. 16th February 2016, Brussels.

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 1 287 TWh by 2030 ([174]) (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).

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).

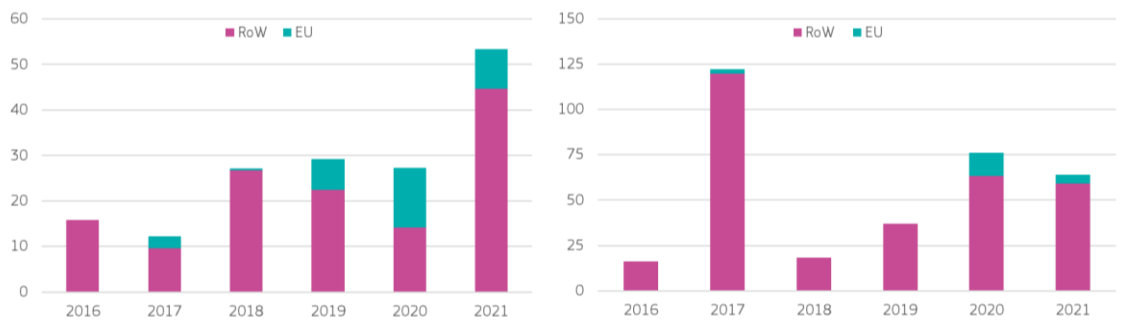
The market is dominated, especially in the residential segment of air-conditioning, by Asian countries (China, Thailand, Malaysia, Japan and South Korea) followed by Mexico and the US. European manufacturers in this segment are smaller. Thailand and China also dominate reversible heat pumps but are followed by European countries, such as Spain and Italy, which mainly supply the European market ([175]). 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).

19.2 EU positioning in innovation

EU public R&I investment in heat pumps and chillers (heat pumps in Chapter 9)([176]) grew at an average 8% annually from 2016 to 2020. Austria is the second biggest public investor globally after Japan, and other EU countries are also well represented in the top ten. Total EU public investment reached EUR 19 million in 2020.

Venture capital investment has increased significantly in 2016-2021 compared to 2010-2021. Early stage investment is growing in particular, and the EU has captured larger shares of it in the last three years (**Figure 88**). The US is the global leader with Spain in second position. At the same time, the EU is attracting much less later stage investment (only 6% of the global total) in 2016-2021 compared to 2010-15. The US is the leading destination of VC investment, followed by the UK.

Figure 88: Early (left) and later (right) stage investment by region [EUR Million]

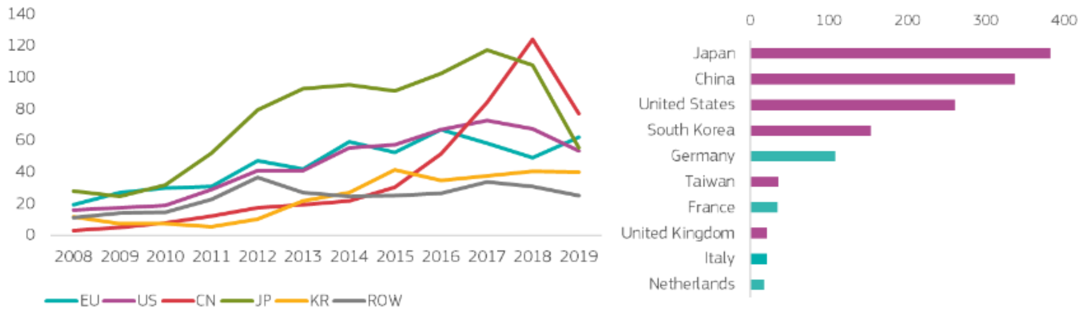


Source: JRC based on Pitchbook, 2023

Overall patenting activity seems to be increasing. Japan (26% share) is the leading country in the number of high-value inventions, followed by China (23%), which experienced strong growth after 2015. The EU holds 16% of all high-value inventions in 2017-2019, with Germany, France, Italy and the Netherlands in the global top ten.

([174]) Projections consider increase of use, end of Moore's law and IoT, but include high uncertainty.
([175]) EU SWD(2021)307 Parts 1-5. Brussels 26.10.2021
([176]) IEA code 144 includes 'Heat pumps and chillers'.

Figure 89: Trend in high-value inventions for major economies (left) and top ten countries in 2017-2019 (right)



Source: JRC based on EPO Patstat, 2023

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 Philips (NL), followed mainly by German and Danish companies.

The EU hosts 24% of all innovators in the area of cooling technologies, having the biggest pool of corporates and second biggest pool of VC companies, after the US. At country level, the US has the biggest pool of innovating companies, followed by Japan and China.

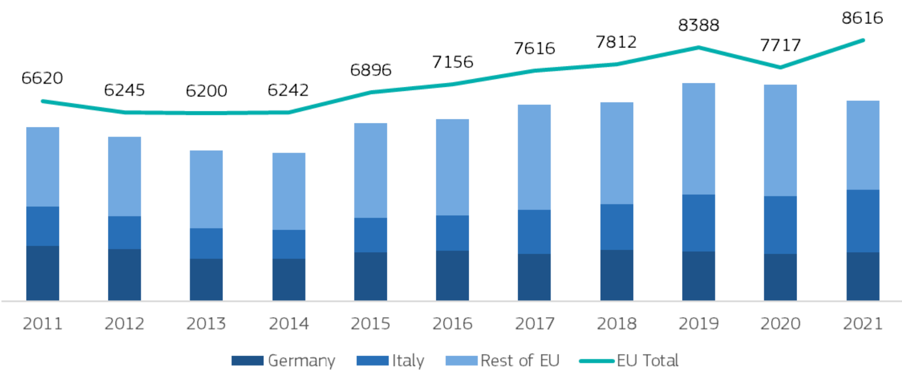
Finalists and winners of the Global Cooling prize showcased a variety of technological possibilities, including solar photovoltaics, evaporative cooling, enhanced dehumidification, smart hybrid designs of vapour-compression and solid-state cooling approaches (Matson, 2021; Global Cooling Prize, 2021). 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). Passive cooling is another research area. For example, MIT scientists have combined evaporative cooling, radiative cooling and insulation in a slim layer that can provide up to 9 ^{0} Celsius of cooling from the ambient temperature and with no need of power (Chandler, 2022).

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 nearly EUR 9 billion in 2020. Production was slightly affected by the pandemic but has recovered and bounced back in 2021 from 2020 figures. Nearly all Member States have some production, but Italy and Germany are the biggest producers. Italy's production has increased over the 10-year period, while Germany's production has slightly decreased. Some countries do not disclose the data, which explains the higher overall EU total in **Figure 90**.

Figure 90: EU production value and top producers disclosing data among the Member States [Million EUR]



Source: JRC based on PRODCOM, 2023

EU exports have remained largely stable since 2011. Over the same period, imports decreased at first, only to start increasing sharply in 2015. Imports climbed to nearly EUR 6 billion in 2021. 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 57%, are intra-EU. The biggest EU exporters are Italy, Germany, Czechia, Netherlands and Belgium, while the biggest EU importers are France, Germany, Italy, Spain and the Netherlands.

The EU trade deficit has been growing since 2013, reaching EUR 3 billion in 2021. Czechia, Belgium and Slovakia have the biggest trade surpluses, while France, Spain and Germany have the biggest trade deficits.

19.4 Scoreboard – key insights and change in EU performance

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 2021, the EU continued to attract early-stage investment, which may mark the emergence of an EU-based ecosystem of innovative, next-generation cooling solutions. The EU hosts the largest pool of innovating corporates and second largest pool of VC companies after the US. In other innovation-related indicators, the EU remains 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, reaching over EUR 3 billion in 2021.

Figure 91: Scoreboard for cooling and air-conditioning technologies

Scoreboard	**Cooling and AC technologies**	EU performance in the reference period			Change from 2021
Public R&D	●	8%	2016-2020	EU CAGR	↓
Early Stage	●	19%	2016-2021	EU share of global total value	→
Later Stage	●	6%	2016-2021	EU share of global total value	→
Patents	●	16%	2016-2019	EU share of global total HVI	→
Companies	●	24%	2016-2021	EU share of innovating companies	→
Employment			2016-2020	EU CAGR	
Production	●	4%	2016-2021	EU CAGR	→
Turnover			2016-2020	EU CAGR	
Imports & Exports	●	8%	2019-2021	EU share of global exports	→
Trade Balance	●	Low	2016-2021	EU trade balance trend	→

Source: JRC, 2023

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).

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 steelmaking based on electrification via the secondary route, and renewable hydrogen-based direct reduction of iron (DRI)([177]). 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 ([178]) carbon emissions in steelmaking. Thus, the novelty of this solution is a 'new' combination of already mature and existing technologies with the addition of green hydrogen.

20.1 An updated status and recent developments

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 ([179]). However, EU industry faces global competition, with production in many third countries currently facing lesser CO_2 emission costs in 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. 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 the CBAM with a gradual phase-out of free allocations to the industry, the current carbon leakage prevention mechanism.

Decarbonisation of the steel industry creates new business opportunities for many European electric arc furnace manufacturers and engineering companies (see the full list of EAF suppliers in the previous assessment in Kuokkanen et al. (2022)). The H-DRI pathway will also require the build-up of DRI shaft furnaces, which at the moment are dominated by only two companies, Midrex and HYL-Energiron. Also here, European companies are developing new DRI technologies based on hydrogen, and seem to be well placed to capture the growing market. 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. 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).

([177]) 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.

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

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

Many steel producers have announced net-zero commitments as part of the global Steel Breakthrough Agenda, including SSAB and ArcelorMittal, who have commercial-scale carbon-neutral production plans on the way (Bloomberg Intelligence, 2021). 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. 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 (BNEF, 2021d), 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).

The decarbonisation of steel is dependent on abundant and cheap renewable energy and availability and reduced costs for green hydrogen. 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 price of green hydrogen is the main variable in future steel cost estimates. 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).

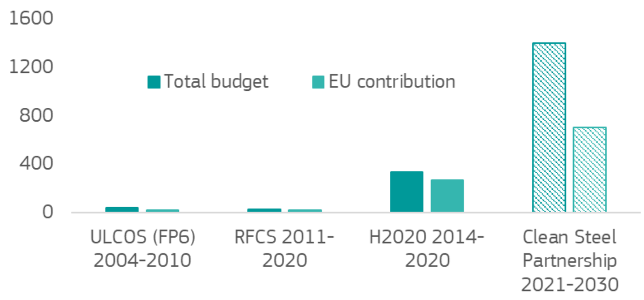
The use of electric smelting processes opens up the opportunity to significantly increase the use of scrap compared to the traditional blast furnace route. Steel scrap prices are currently very high due to strong demand and could become volatile in the future (BNEF, 2021f). The big issue with scrap for 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, 2021d).

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, and plans to have commercial-scale production in 2026. H2 Green Steel, a start-up from Northvolt's founders, is planning to open the first commercial plant already in 2025. Although Sweden seems to lead the way, there are similar plans in other European countries, both from steel incumbents such as ArcerlorMittal and Thyssenkrupp, but also increasingly from start-ups such as GravitHy, which plans to produce green steel in France in 2027 and Blastr Green Steel (NO) which is planning green steel investment in Finland.

20.2 EU positioning in innovation and major changes

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. 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. 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). Fourteen projects are already funded under the Clean Steel Partnership, with several of them active in green hydrogen-based steel manufacturing.

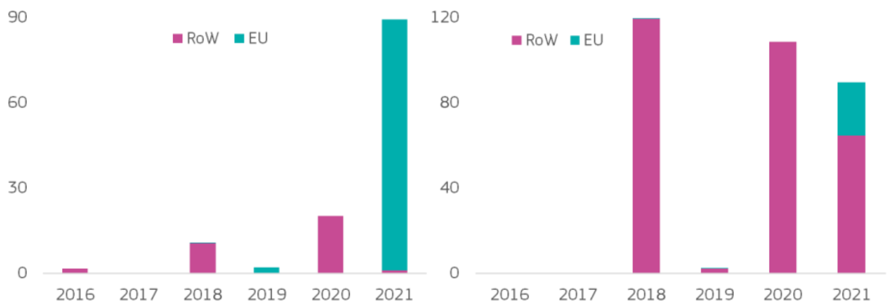
Figure 92: EU R&D funding programmes [EUR Million]



Source: Adapted from Somers (2021)

Private investment in start-ups and scale-ups working in steel decarbonisation is still limited, as most innovation tends to be financed with companies' own resources. Nevertheless, early stage investment surged in 2021, thanks to a megadeal (EUR 90 million) in H2 Green Steel (SE). With that, Sweden and the EU captured 73% of all early stage investment in 2016-2021. At later stage, 2021 did not see a similar increase. Overall, the EU captured only 8% of later stage investment in 2016-2021. The US is a leader and followed by Finland and Sweden. 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 this report. Steel production requires vast capital investment, making the entry of new companies difficult. One of the VC-funded companies, Boston Metal (US), is developing a potentially important new technology whereby iron ore is reduced solely through electricity at high temperature (molten oxide electrolysis). 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).

Figure 93: Early (left) and later (right) stage investment by region [EUR Million]

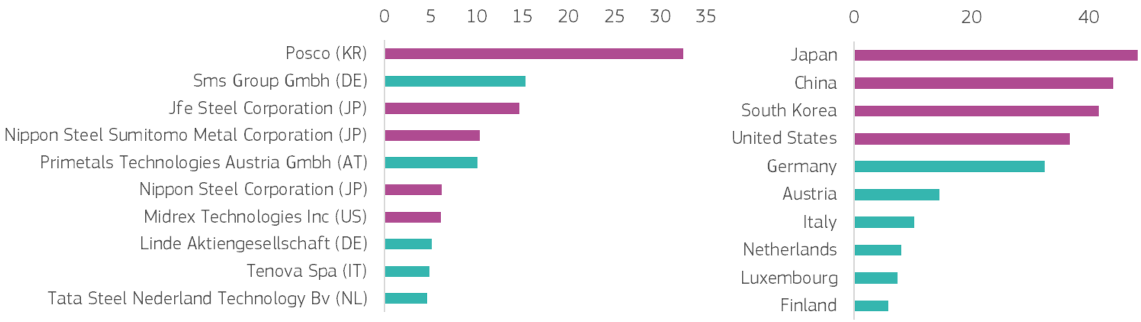


Source: JRC based on Pitchbook, 2023

The EU is a 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 ([180]), the EU still has the largest number of high-value inventions, albeit with a decreasing trend since 2013. EU-based entities filed 31% of high-value inventions, followed by Japan (18%) and China (16%), which activity has been gradually increasing in the past years. 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), Linde (DE), Tenova (IT) and Tata Steel (NL) are among the global top ten (see **Figure 94**). 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.

([180]) 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).

Figure 94: Top ten companies (left) and top ten countries (right) by high-value patents in 2017-2019



Source: *JRC based on EPO Patstat, 2023*

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 34% of all innovating companies (corporates and VC-funded companies combined). The EU is doing relatively better in the share of VC companies, where the EU hosts 40% of all start-ups and scale-ups. The US and Sweden host the most VC-funded companies, six and three respectively.

20.3 EU positioning in the current market and major changes

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 (2019), with the jobs being spread across all of the EU (Eurofer, 2021). According to Eurostat data, in 2020 the sector generated some EUR 126 billion in turnover ([181]), with an increase of 5% over the period from 2016 to 2020.

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, the 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 ([182]) 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 in Kuokkanen et al. (2022). EU production has remained constant in recent years. The production data of graphite electrodes is kept confidential by Member States. Nevertheless, as Spain is the main exporter of graphite electrode, we can assume that Spain is also one of the major producers.

Extra-EU trade of electric furnaces and graphite electrodes shows that the EU exports more than it imports, generating 26% of global exports. 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 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 Türkiye, Russia, Iceland, Korea and the US. China is by far the biggest exporter to the EU and the biggest exporter globally of graphite electrodes. In fact in 2022, EC imposed anti-

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

([182]) 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').

dumping duties on imports of graphite electrodes from China as there was evidence of Chinese imports being sold in the EU at significantly dumped prices (European Commission, 2022c). 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, 2021e).

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 the utilisation of lower quality ore and sinter (BNEF, 2021d).

20.4 Scoreboard – key insights and change in EU performance

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 31% 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. Some of the most ambitious ones plan to start commercial production of green steel in the EU already in the mid-2020s. This indicates that the EU is at the forefront of decarbonising steel industry and 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 investment and coordinated cross-border planning between Member States and industry.

Figure 95: Scoreboard ([183]) for decarbonisation of steel through H-DRI and electrification

Scoreboard	**Steel (H-DRI and electrification)**	EU performance in the reference period			Change from 2021
Public R&D			2016-2020	EU CAGR	
Early Stage		73%	2016-2021	EU share of global total value	↑
Later Stage		8%	2016-2021	EU share of global total value	↑
Patents		31%	2016-2019	EU share of global total HVI	→
Companies		34%	2016-2021	EU share of innovating companies	↓
Employment		1%	2016-2019	EU CAGR	→
Production		2%	2016-2021	EU CAGR	↑
Turnover		1%	2016-2020	EU CAGR	↓
Imports & Exports		26%	2019-2021	EU share of global exports	↑
Trade Balance		High	2016-2021	EU trade balance trend	→

Source: JRC, 2023

([183]) Employment reference period is in red because due to the data unavailability it differs from the reference period in other solutions. Instead of 2016-2020, the data is available only for 2016-2019.

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. However, the sector was responsible for around 7% of the 35 Gt of global CO_2 emissions in 2020. In 2021, cement production in the EU led to 110 $MtCO_2$ emissions, or 4% of all EU27 CO_2 emissions. Thus, the decarbonisation of this sector is essential if we are to achieve climate neutrality by 2050. While various technologies enable emission reductions within the cement industry, carbon capture, utilisation and storage (CCUS) has received the highest share of EU financial support in recent years (Marmier, 2023).

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, 2020). Furthermore, 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).

21.1 An updated status and recent developments

Cement has two main sources of CO_2 emissions: the burning of fossil fuels in the kiln and process-related emissions from the calcination of the limestone. Together these two sources make up about 85% of total CO_2 emissions of the entire production value chain of Portland cement (the most common type of cement). For this sector, where the CO_2 mitigation potential is limited, breakthrough technologies such as carbon capture, utilisation and storage (CCUS) are essential for achieving the necessary reductions.

2022 has seen unprecedented advances for CCUS technologies. As of September 2022, the total capacity of projects in development was 244 million tonnes per annum (Mtpa) of CO_2 – an increase of 44% over the past 12 months (Global CCS Institute, 2022). In Europe, there are currently two projects under construction in the cement sector employing carbon capture and storage. These projects are LEILAC-2 (DE) and Norcem Brevik (NO). Under the Innovation Fund, four projects, ANRAV-CCUS (BU), C2B: Carbon2Business (DE), GO4ECOPLANET: KUJAWY GO4ECOPLANET (PL) and K6 Program (FR) are explicitly planning to investigate the technology in the cement sector. The C2B project also entails a CO_2 use path where the oxyfuel cement plant will be integrated into a pre-selected IPCEI hydrogen project in Germany, which will erect a 500 MW (first stage) and 2 GW (scale-up) electrolyser and a large-scale methanol synthesis plant as well as a methanol to olefin route in the region. In addition, Norway has committed almost EUR 1.6 billion (NOK 16.8 billion) to the Longship project, which aims to be operational by 2024.

Other CCUS projects connected to facilities are progressing in the assessment of their feasibility, though without EU funding for the time being: Catch4climate (DE); C^2inCO2: Calcium Carbonation for industrial use of CO_2 (DE); C2PAT: Carbon2ProductAustria (AT); Concrete Chemicals (DE); Fastcarb: Carbonatation accélérée de granulats de béton recyclé (FR); GreenCem (DK); Greensand (DK); and Westkueste100: Complete sector coupling: Green hydrogen and decarbonisation on an industrial scale (DE).

While there is clear momentum building in the sector, there are also associated challenges such as rising global capacity, decreasing internal demand and most recently, a global pandemic and surging fuel prices. In the cement 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 technologies may not be a priority in company budgets (Gross, 2021). While decarbonisation is a one-way path, the price of cement is expected to increase massively when the industry invests in technologies 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). There is also a technological challenge: 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 rising global capacity landscape, the construction of new cement plants integrated with CCUS at a relevant scale for climate mitigation may be unlikely. Post-combustion CO_2 capture technologies are the preferred option for retrofitting existing facilities (Plaza, et al., 2020). Moreover, trade raises additional challenges. Materials whose production imply large GHG 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, Parliament and Council adopted a proposal for a new Carbon Border Adjustment Mechanism (CBAM) on July 2021. The increasing price of the EU ETS allowance and the proposal for the new CBAM are expected to ease the effect of investing in decarbonisation technologies, including CCS, for the industry, and eventually make them competitive.

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, 2019). 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.

The CINDECS report of 2021 presented the different CO_2 capture options that are applicable in the cement sector. 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. Marmier (2022) provides an updated overview of ongoing projects investigating the capture of CO_2 in cement facilities.

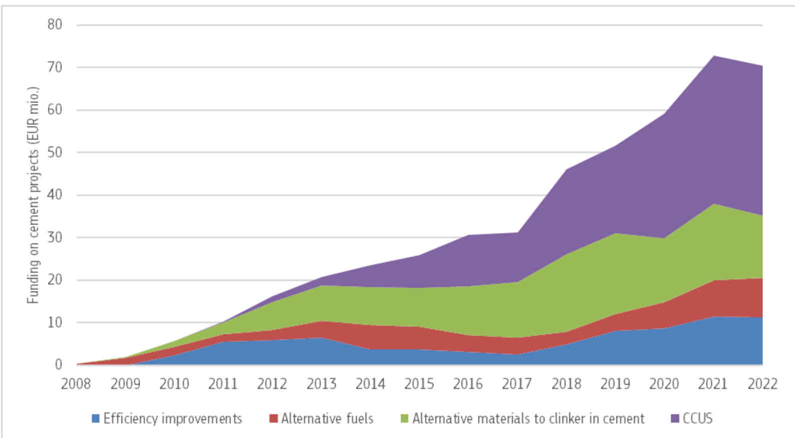
Companies that are involved in projects incorporating CCUS for the cement sector include Calix (Europe), Cementir (Italy), CEMEX (Germany), Dyckerhoff (Germany), Eqiom (France), Heidelberg Cement (recently renamed Heidelberg Materials) (Germany), Holcim (Switzerland), Italcementi (Italy), Lafarge (France), Schwenk (Germany), Titan (Greece) and Vicat (France).

As identified by Kapetaki et al. (2022), 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. On the way forward, the set needs to be identified, mapped and understood in terms of capability development, skills and innovation, and finance and trade (Kapetaki, et al., 2022). Any issues or potential material dependencies could then be identified for deploying CCUS at scale in the cement sector.

21.2 EU positioning in innovation and major changes

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, though other sources of funding do also contribute to innovation and the overall objective of decarbonisation. European funding on cement decarbonisation options (**Figure 96**) sees increased expenditures, from EUR 19.2 million in 2012 to EUR 75.6 million in 2022. Cement decarbonisation options include energy efficiency, alternative fuels and alternative materials to clinker in cement and CCUS, the latter taking the lion's share (48%) in 2022 (Marmier, 2023).

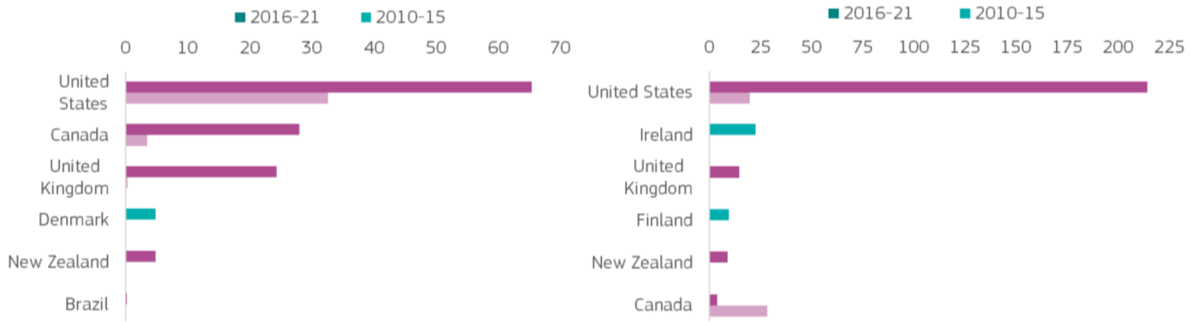
Figure 96 Funding on decarbonisation projects in Europe since FP7 programme



Source: *(Marmier, 2023)*

In terms of venture capital investment, early stage investment has been identified in the EU in 2019 and 2020. Between 2015 and 2021, Denmark was the only EU country with early stage investment activity (EUR 4.8 million), albeit minimal when compared with the US which is the country with the highest early stage investment (~EUR 65 million)(**Figure 97**). The US also leads in terms of later stage investment, with around EUR 214 million. Ireland, Finland and France are the EU countries with some later stage investment activity (EUR 22.5 million, EUR 9.3 million and EUR 3 million, respectively).

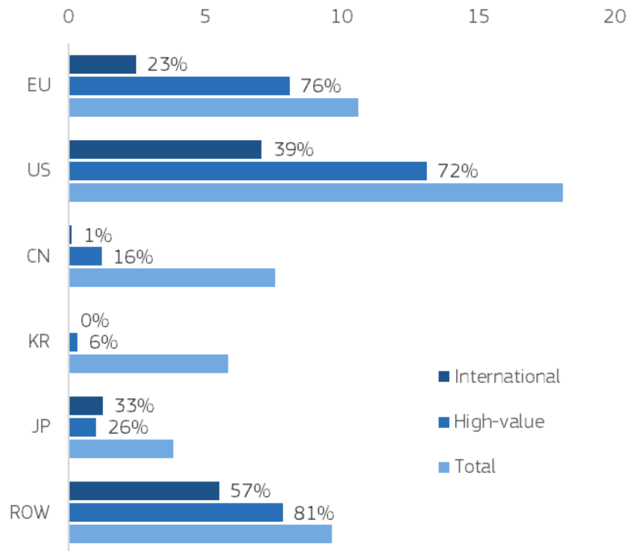
Figure 97: Top countries in early (left) and later (right) stage investment [EUR million]



Source: JRC based on Pitchbook, 2023

Concerning patenting activity, the EU registered 11 inventions in the cement sector, coming second to the US with 18 inventions. **Figure 98** shows that 23% of these inventions represent international activity and 76% are high-value inventions, i.e. those containing applications to more than one office, effectively seeking protection in more than one country or market.

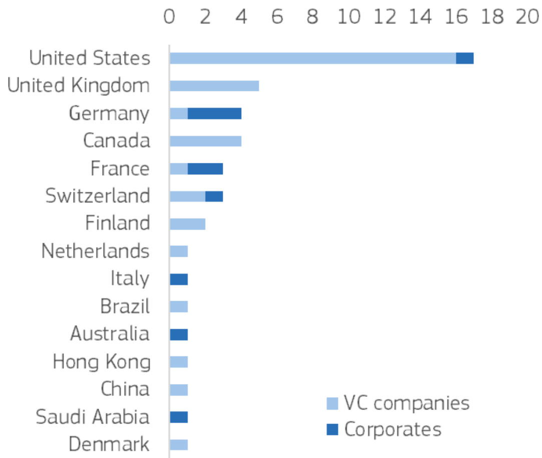
Figure 98: Number of inventions and share of high-value and international activity for major economies in 2016-2019



Source: JRC based on EPO Patstat, 2023

The US and UK host the most innovating companies and a large majority of all start-ups and scale-ups in this sector (**Figure 99**). The EU hosts 15% of all VC companies. However, the EU has some important patenting corporates. 25% of the top companies with CCUS activity in the cement sector are European. These are the German Thyssenkrupp AG, Thyssenkrupp Industrial Solution AG, Heidelbergcement AG, the Italian Italcement SPA and the French Air Liquide and Soletanche Freyssinet.

Figure 99: Number of innovating companies in 2016-2021

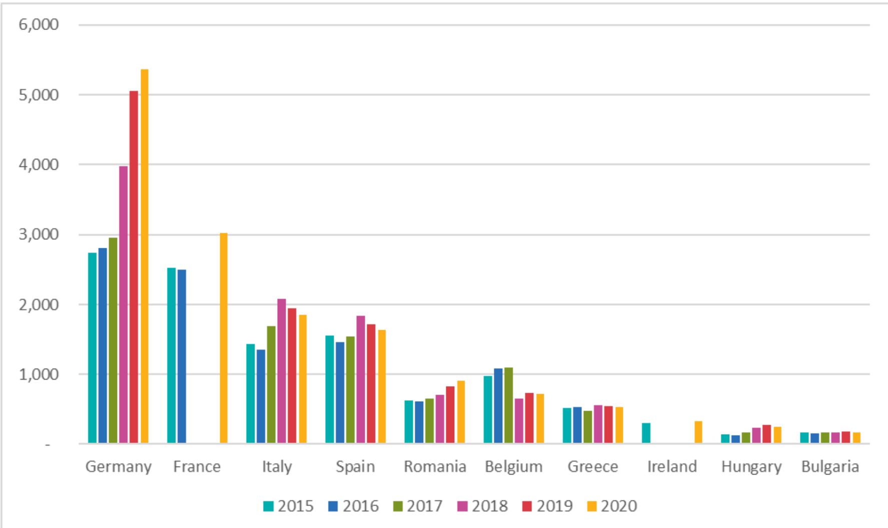


Source: *JRC compilation of sources, 2023*

21.3 EU positioning in the current market and major changes

In 2020, there were nearly 57 000 cement sector ([184]) direct jobs in the EU. Germany is the country with the most direct jobs in the sector (~14 000), followed by France (7 241) and Italy (5 343). Employment in the sector has been steady for most of the leading countries in the sector, 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). In 2020, Germany had the highest turnover (~EUR 5.36 billion) followed by France (~EUR 3 billion), Italy (EUR 1.85 billion) and Spain (~EUR 1.64 billion). Germany's turnover recorded an upward trend from 2015. Greece, Italy and Spain recorded a decrease in turnover from 2018, and in Belgium's case from 2017. At EU level, turnover grew between the years 2016 and 2020 from nearly EUR 15 billion to more than EUR 20 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.

Figure 100: Top ten EU countries by turnover in 2015-2019 [EUR million]



Source: *JRC based on Eurostat SBS data, 2023*

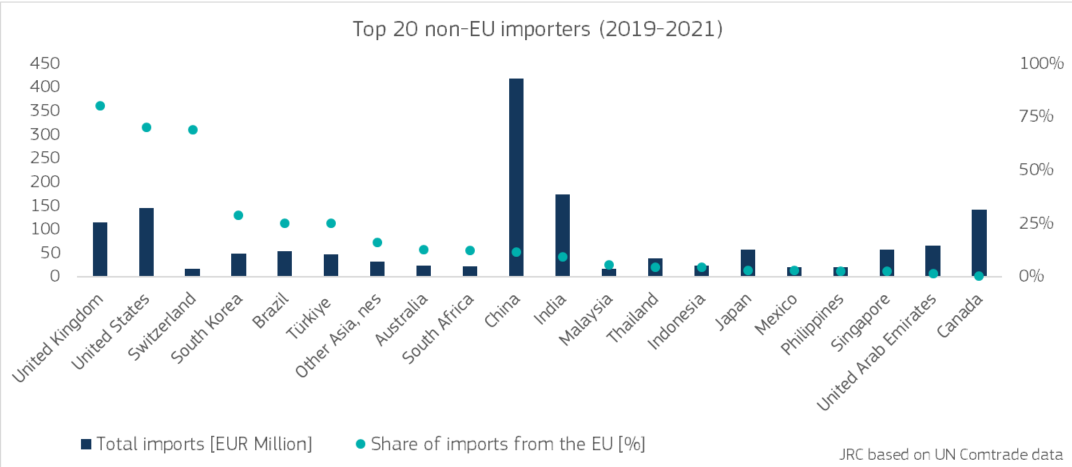
For production and trade, we have used amines as a proxy because they are essential to post-combustion carbon capture. The EU production value of amines was relatively steady between 2013 and 2018. After a spike in 2018 with a production value of EUR 201 million, it decreased to EUR 169 million and EUR 163 million in 2019 and 2020, respectively. The figure increased again in 2021, reaching EUR 196 million.

([184]) Manufacture of cement.

With regard to trade, Belgium, Spain, Germany, Italy and France were the leading importers of amines in the EU between 2019 and 2021. Belgium was also the top exporter, with a positive trade balance of EUR 82 million. In 2021, Sweden also enjoyed a positive trade balance of EUR 16 million while Malta was neutral and Spain, Italy and France recorded a negative balance (EUR 43 million, EUR 33 million and EUR 8 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, Poland, Germany, Belgium, Spain and Greece. Outside the EU, Sweden exported amines to Norway, China, Türkiye and Brazil. 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, the United States, 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 countries in the Top ten global exporters make up nearly 20% share of the global total. The EU captures 80% of UK and 70% of US imports, although EU exports to the US have been decreasing in recent years. The EU only captures 10% of imports in the biggest non-EU import markets, China and India.

Figure 101: Top-20 non-EU importers and the EU share in these markets (2019-2021)



Source: JRC based on UN Comtrade, 2023

21.4 Scoreboard – key insights and change in EU performance

Overall, while the EU trails behind the US and the rest of the world in CCUS technological development on some indicators, the situation is improving. Carbon capture, utilisation and storage (CCUS) has received the highest share of EU R&D funding in recent years (Marmier, 2023). Approximately 13% of later stage investment was captured in the EU, which was an improvement from only 5% previously. While the US leads in patenting activity, EU activity is improving and the EU as a block captured 26% of all high-value inventions. German and French companies are among the global leaders in high-value filings. While big EU corporates are well represented in this area, the EU hosts only 18% of the world's VC companies. A low number of start-ups is also reflected in levels of early stage investment, with Denmark the only EU country to capture early stage deals in 2016-2021.

In terms of current markets, EU cement manufacturing is an important sector, providing direct jobs to about 57 000 people and generating nearly EUR 20 billion in turnover in 2020, 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 trade balance has been both positive and negative in the past five years. Globally, Saudi Arabia is the biggest exporter while China is the biggest importer.

Figure 102: Scoreboard ([185]) for decarbonisation of cement through CCUS

([185]) EU employment reference period is in red because due to the data unavailability the reference period is different than for other solutions. Instead of 2016-2020, it covers only 2018-2020.

Scoreboard	**CCUS for cement industry**	EU performance in the reference period			Change from 2021
Public R&D		18%	2016-2020	EU CAGR	
Early Stage		4%	2016-2021	EU share of global total value	↑
Later Stage		13%	2016-2021	EU share of global total value	↑
Patents		26%	2016-2019	EU share of global total HVI	→
Companies		27%	2016-2021	EU share of innovating companies	↑
Employment		1%	2018-2020	EU CAGR	
Production		1%	2016-2021	EU CAGR	→
Turnover		8%	2016-2020	EU CAGR	→
Imports & Exports		14%	2019-2021	EU share of global exports	→
Trade Balance		Low	2016-2021	EU trade balance trend	↓

Source: JRC, 2023

22 Electrification of steam cracking

Steam cracking is a leading petrochemical process for the production of the key building blocks of the chemical industry – ethylene and propylene. This is expected to remain so in the foreseeable future (Amghizar, et al., 2017; Gao, et al., 2019). The initial process is cracking, which means that the feedstock is heated to the point that the heat transfer is sufficient to “crack” the molecules into several smaller molecules, in particular to the desired light olefins, ethylene and propylene (Amghizar, et al., 2017). Today, steam cracking is the most energy-intensive process in the chemical industry, accounting for approximately 8% of the sector’s total primary energy demand (Mynko, et al., 2022; Ren, et al., 2008), as it relies on fossil-based energy.

The petrochemical industry is an important sector for the EU economy as it is the second-largest chemical producer in the world (with a 15% share) after China, at EUR 594 billion in sales in 2021 (Cefic, 2023). Nevertheless, the sector faces challenges emerging from both the need to decarbonise and the pressure to be cost-competitive. Energy accounts for 70% of the production cost in a typical ethane- or naphtha-based olefin plant (Ren, et al., 2006). Still, the cost of the feedstock is substantially more important for the product margin. In Europe, it is primarily naphtha which is cracked (70%). Naphtha is substantially more expensive than cheap, shale-derived ethane. As the bulk of the emissions (more than 80%) can be attributed to fuel combustion in the steam cracking furnaces, the electrification of steam cracking would significantly reduce the carbon footprint.

Steam crackers are long-term assets, as building and operating them requires significant investment. The European steam cracking fleet is rather old – the youngest ethylene installation (ethane cracker) is 25 years old. In recent years, most new chemical plants have been built in America, China and other parts of Asia, taking advantage of cheaper raw materials and growing demand from local economies. Europe was still the largest investor in 2001, but since then has lost its market share from 27% to less than 12% in 2021 (Cefic, 2023). In 2015, a new furnace was installed in a Belgian cracker by TotalEnergies, whilst other crackers, e.g. in Carling (FR), have been closed down due to a lack of competitiveness, poor market growth and outdated infrastructure. Although steam cracking technology is considered to be mature, the complexity of the process and the harsh operating conditions leave plenty of room for technological improvement (Symoens, et al., 2018).

22.1 State of the art of technological development

Several advances in steam cracking technology have been implemented to increase its energy efficiency and production yield, including high-emissivity coatings, oxy-fuel combustion methods, new burner technology, heat recovery schemes and 3D reactor geometries (Amghizar, et al., 2020). These changes have, however, only produced marginal gains, as is typical for mature technologies. In terms of emission reductions, several innovative ideas, such as the low-emission furnace of Technip Energies (Mynko, et al., 2022), are currently on the table and are the subject of some limited research. However, the electrification of cracking could drastically enhance energy efficiency and product yield and is receiving significant attention from industry and academia (Bonheure, et al., 2021; Eryazici, et al., 2021). Most innovations focus on electrifying the furnace or developing an alternative electrified process such as one based on plasma (Delikonstantis, et al., 2019).

Coolbrook’s patented **rotodynamic reactor** (RDR) is one of the most advanced technologies. Coolbrook is developing its technology with ABB and conducted the first live pilot in December 2022. The next step will be to deploy the technology in commercial demonstration projects at its customers’ sites. The RDR technology is based on **turbomachinery**. The advantage of the RDR is the short residence time that is beneficial for light olefin yields (Gholami, et al., 2021), making it potentially the most selective cracking technology. Unlike the ‘low-emission’ furnace, in the RDR-based cracking complex, the energy source for both furnace and separation area is electrical. The turbomachine-like reactor utilises high-speed rotation to transform mechanical energy into thermal energy. All designs in the patented literature connect the reactor inlet and outlet with a vaneless spaced duct in which multiple stages are positioned. The reactor operation relies on the fact that the stator accelerates and distributes the flow across the rotor. The latter accelerates the fluid, providing the required kinetic energy reaching supersonic levels, which is then reduced in the subsequent diffuser cascade. The subsonic fluid enters a vaneless space where residence time, turbulence and temperature are sufficiently large for chemical reactions to take place. After this vaneless space, another stage is implemented and the process repeats itself until the desired conversion is reached and the fluid is discharged from the reactor outlet (within a continuous process).

The reactor resembles a multi-stage compressor, but is, however, neither comparable to a compressor nor to a turbine since it presents contrasting features in the sense that it aims to keep pressure low while increasing temperature. From an energy perspective, the advantage is clear: kinetic energy can be directly transformed into heat without intermediate heating elements. Among the other advantages is the reduced size of the plant, as heating by combustion is absent. The coking is also reduced thanks to the short residence time: as low as 10 ms in contrast to the 100-1 000 ms of a standard coil. Still, coke can present a problem since a metal alloy is intended for the construction. In general, the main difference between the patented designs is related to the shape of the vaneless space, whereas the general hydrodynamic principles remain the same.

Technip Energies and Siemens Energy announced an exclusive agreement to jointly develop, commercialise and license the **Rotating Olefins Cracker (ROC) technology** to decarbonise the olefin production process. They entered into a memorandum of understanding with the Cracker of the Future Consortium (COF) in October 2021 to express the intention of installing a hydrocarbon demonstration unit utilising the ROC technology in a plant operated by one of the COF members. The COF comprises major industry players such as Borealis (part of OMV), BP, Repsol, TotalEnergies, Versalis and coordinator Brightlands Chemelot Campus. The COF selected the ROC technology after assessing more than a dozen electricity-based heating technologies for olefin crackers.

Other options of process intensification and electrification include reactors using induction, resistance, microwave and shockwave heating. Both **resistive and inductive heating** offer the advantage that implementation in existing furnaces is relatively easy and cheap. This is because in most cases, during a turnaround, all the furnace tubes of a traditional steam cracking furnace are replaced. Hence, the conventional tubes can be replaced with resistive or induction supporting tubes (and side equipment), electrifying the cracking unit without drastically changing the furnace design. Nevertheless, the furnace electrified via resistive or inductive heating suffers disadvantages inherent to its design. Firstly, it is expected that with both the resistance and inductive heating, the heat transfer route will create coking at the tube surface. The presence of coke indicates the occurrence of secondary reactions that greatly reduce the (light) olefin yield. Secondly, coke forms an insulating layer affecting the conductive resistance against the heat transfer from the tube surface to the process fluid (Symoens, et al., 2018). To overcome this growing resistance and maintain the same cracking severity, additional power must be supplied, leading to higher electricity consumption and thus OpEx. Providing additional power to the tube will, in turn, lead to a higher tube metal temperature, which is limited by the metallurgy of the tube itself. Decoking reactors every few weeks will lead to considerable adverse effects on the process economics (Amghizar, et al., 2020). Besides coking, the way heat is transferred from the furnace side to the process side limits the obtainable yield and ethylene selectivity.

Microwave heating exploits molecular interactions of the mixture to heat the fluid from the inside, hence circumventing the need for an intermediate hot material when used for fluids other than gases. Experimental results from a pilot-scale application are promising (Ng, et al., 2013), yet scalability remains a challenge for this technology.

Nozzle-type **shockwave heating** is a type of pyrolytic reactor, which utilises hot carrier gases and a nozzle to generate supersonic hot carrier gas flows. The feedstock is mixed with the hot carrier gas and the reaction zone is placed adjacent to the mixing zone. A shockwave results in an instantaneous increase in static pressure and temperature, which is high enough to satisfy the high energy needs of the occurring endothermic reactions. Hydrogen combustion is deemed to be the most suitable for the production as this results in the formation of water vapour which improves the light olefin yields. Different configurations exist and are patented, but not all dedicated to steam cracking.

Table 3 summarises the advantages and disadvantages of different innovative reactor materials and structures, and heating technologies for steam cracking.

Table 3: Summary of innovative reactor materials and structures, and heating technologies for steam cracking

	Advantages/Features	Disadvantages/Issues
Material		
Ceramic	High temperature resistance High thermal conductivity	Brittleness, thermal shock fragility Complex joining of elements, and

	Suitable electrical properties for resistive heating application Coke inhibition	limited length of manufacture Specific range of suited resistive heating temperatures
Metal	Good thermal and electrical properties (Resistivity higher than for ceramic materials) Optimal mechanical properties	Catalytic coking due to Nickel Limited conventional alloy temperature resistance to 1 100-1 200 °C
Structure		
Honeycomb	High surface/volume ratio Low pressure drops Modular manufacturing Possible reactor size reduction Ceramic material	Possibly inhomogeneous heat distribution Currently patented electrical heating applications do not reach high temperatures Single channel electrical contact is challenging
Multistructured	High surface to volume ratio Simple manufacturing Possible reactor size reduction	Complex and delicate electrical contacting Coking due to metal material
Rotor Stator	High ethylene yield Low residence time Low coking High energy efficiency Expected plant size reduction	Delicate component, relatively unexplored technology Metal material: coking and possibly more complicated decoking due to geometry Rotating equipment slightly less energy efficient than direct electrical heating
Heating		
Resistive	Easiest implementation among electrical heating technologies Fast heating	Skin effect Suitable resistivity required Direct current requirement
Induction	High heating efficiency and velocity Great control of the temperature dynamics and localisation	High capital investment High magnetic permeability material required Better suited for liquid or gas phase catalyst packed reactors
Impedance	Hybrid compromise between resistive and induction heating, easily implemented Alternated current easily provided	Applied for low to medium temperature range industrially, lacking high temperature application Only metal tubing applications known Skin effect
Microwave	Direct heating of the bulk of the fluid without intermediate resistances Projected overall energy savings	Not possible to directly heat gas phase reactants, requiring suspectors

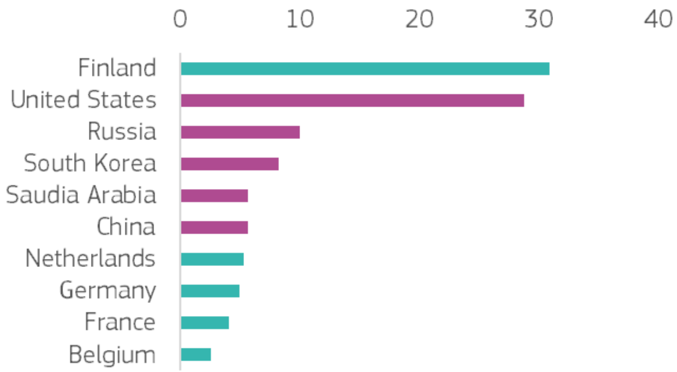
Source: JRC based on expert input, 2023

22.2 EU positioning in innovation

As technologies to electrify steam cracking are still at a very early stage, the data related to innovation indicators is very scarce. There is no public R&D investment data, while thus far only one venture capital deal has been recorded. This was in 2017 to a Finnish start-up, Coolbrook, which raised EUR 3.6 million of later stage capital. Coolbrook has developed a rotodynamic reactor to replace traditional cracking furnaces and also a rotodynamic heater, which is able to reach 1 700 °C without burning fossil fuels, thus serving many industrial processes that require high temperatures. They aim to commence full commercial deployment by 2025 (Coolbrook, 2022). Coolbrook has entered into partnerships with Shell, Braskem, CEMEX, Ultratech and ArcerlorMittal. In 2023, Coolbook also signed agreements with big chemical industry companies, Linde Engineering and SABIC, to collaborate on electrifying ethylene production (Coolbrook, 2022).

There seems to be increased activity in terms of patenting, especially in the EU. Neste (FI) is the leading patenting corporate in the electrification and decarbonisation of the chemical industry. The EU leads with a 43% share of total high-value inventions, followed by the US at 25%. The EU chemical industry is the second largest R&I investor in the world after China (Cefic, 2023), which is partially reflected in its high performance in patenting. However, the share of private R&I spending for the EU, US and Japan, decreased in 2011-2021, compared to China, whose share significantly increased in the same period (Cefic, 2023).

Figure 103: High-value inventions - top ten countries (2016-2019)



Source: JRC based on EPO Patstat, 2023

22.3 EU positioning in the current markets

As this solution is at a very early stage of development and no unique codes exist in the relevant classifications, there is no data for the market indicators.

The EU chemical industry is concentrated in a few Member States; Germany, France, Italy, the Netherlands and Belgium were responsible for about 70% of chemical industry sales in the EU in 2018 (Cefic, 2020). However, the industry's emissions are much less concentrated than those of the steel sector, for example, as more than 400 crackers are responsible for half of the sector's total emissions (European Commission, 2022). This means that there is significant market potential in the decarbonisation of crackers.

22.4 Future outlook

The European Commission published an industry roadmap for energy-intensive industries to accelerate the development and uptake of low-carbon technologies (European Commission, 2022). The chemical industry was one of the three focus areas. In 2022, the Commission proposed to revise the Industrial Emissions Directive (Directive 2010/75/EU) to reach the EU's 2050 zero-pollution ambition as announced under the European Green Deal. Moreover, the Commission has strengthened the EU ETS, which directly targets the emissions of the energy-intensive industries in the EU in order to align it with the ambition of a 55% net reduction by 2030 (European Commission, 2021). In order to avoid carbon leakage in sectors such as the chemical industry, the Commission has adopted the Carbon Border Adjustment Mechanism, which will eventually make the free allocation of carbon allowances redundant. This, together with the EU ETS average price moving closer to 100 EUR/tCO_2, will incentivise the chemical industry to develop decarbonisation paths. There are, however, many challenges to the deployment of low-carbon technologies.

The electrification of steam cracking requires large quantities of green and non-interrupted electricity. The penetration of intermittent renewable energy makes electricity prices volatile, leading to periods of very low or even negative prices for industrial consumers, but also periods of very high prices. The other hurdle relates to the first-mover disadvantage. Companies running industrial-scale furnaces want to have “the latest proven technology”, which is a paradox, since ‘proven’ implies 20 years of running. As a result, the penetration of new technologies is very slow as nobody wants to have the prototype. Steam cracking plants develop very few significantly novel technologies because these require a lot of effort and capital, while the gains are typically very small in comparison. Most development is therefore incremental in nature. At the same time, technology providers experience valley of death curves as they need significant capital to demonstrate the operation of expensive technology over long periods of time. The declining share of the EU chemical industry makes the situation even more difficult as industry faces intense global competition.

The reason gains are small is because about 80% of the cost of the process relates to feedstock. A cheaper feedstock, or one which can generate more valuable light olefins, makes immediate impact, while installing new equipment takes longer (around five years). This is why new steam crackers are built in locations with access to cheap feedstock, such as China, Brazil, Saudi Arabia and Russia. Another cost component is energy. Energy costs in the EU are much higher compared to other parts of the world, especially countries with abundant access to fossil-based energy.

The carbon footprint of olefin production is not currently accounted for in the price, creating no incentive to companies to develop more sustainable and efficient solutions. The lack of global carbon pricing creates an unfair playing field, with little or no carbon pricing in many regions compared to that which EU companies face.

Finally, finding skilled labour is becoming more difficult as regions compete for the same pool of talent.

22.5 Scoreboard and key insights

Data is limited, as can be seen from the scoreboard in **Figure 104**, below. The EU leads in patenting activity related to the decarbonisation of the chemical industry. This activity seems to be picking up in recent years, with Neste (FI) being the leading corporate for high-value inventions in the area. Thus far, the only venture capital deal is to an EU-based start-up, Coolbrook (FI), which is developing an entirely different way to achieve the electrification of steam cracking and high-temperature heat. If successful, this can become a break-through technology for the chemical and other energy-intensive industries. At the same time, big industrial companies are exploring other decarbonisation paths. Sufficient access to ‘patient’ capital is essential to enable the demonstration and prototyping of these new capital-intensive technologies.

Figure 104: Scoreboard for electrification of steam cracking

Scoreboard	Electrification of Steam Cracking	EU performance in the reference period		
Public R&D			2016-2020	EU CAGR
Early Stage			2016-2021	EU share of global total value
Later Stage	●	100%	2016-2021	EU share of global total value
Patents	●	43%	2016-2019	EU share of global total HVI
Companies	●	50%	2016-2021	EU share of innovating companies
Employment			2016-2020	EU CAGR
Production			2016-2021	EU CAGR
Turnover			2016-2020	EU CAGR
Imports & Exports			2019-2021	EU share of global exports
Trade Balance			2016-2021	EU trade balance trend

Source: JRC, 2023

23 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 fossil 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 also 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 Shipping, 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 feedstock and carbon capture as in the case of blue fuels (Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, 2021).

23.1 The scope of the solution and current status

The scope of this solution covers the production of ammonia synthesised from renewable 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, 2021f) 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, 2021f).

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 production pilot projects are still at an early stage.

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.

23.2 EU positioning in innovation and major changes

The use of ammonia as a transport fuel remains an emerging application and to that extent, indicators supporting the monitoring of this area of innovation are limited.

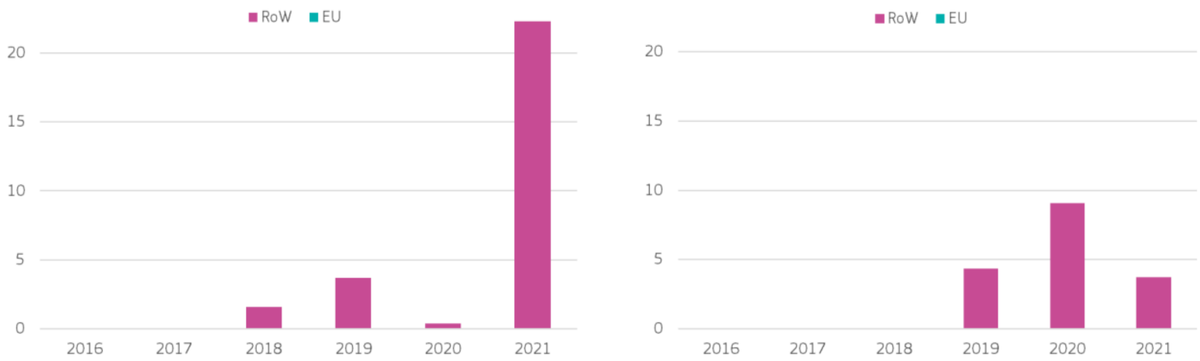
The reporting of the IEA does not allow the production of specific public R&D investment figures. The EU has, however, funded several R&D projects since 2020 with a total investment of EUR 32.5 million, targeting the novel production processes of green ammonia (Dare2X, Telegram, ORACLE) and its use as an alternative fuel in vessel engines (ENGIMMONIA), fuel cells (ShipFC) and direct conversion (HiPowAR) applications.

While not specific to ammonia, a selection of patent codes related to the supply and use of non-hydrocarbon fuels to controlling engines enables the identification of a set of corporate innovators and to produce output statistics.

The number of identified innovators remains limited, among both corporates and venture capital (VC) companies. Most of the VC companies identified were founded in the last four years. This includes five new ventures developing solutions for the production and use of green ammonia as a fuel that were founded in 2021. Those companies are located in the US (Amogy, Faraday fuels and HGen), Australia (Jupiter Ionics) and New Zealand (Liquium).

As it does not host any active ventures, the EU has not any attracted early or later stage investment over the 2016-21 period. Driven by a larger deal in the US company Amogy, early stage investment (**Figure 105**) surged in 2021, prefiguring increased investor interest in most of the newly founded ventures. In 2021, the US company Starfire Energy raised the first later stage investment targeting carbon-free ammonia production. Levels of later stage investment, however, remain lower, and otherwise benefited companies addressing after-exhaust treatment to limit ammonia slip (Daphne Technology, US) and ammonia fuel cells (GenCell, Israel).

Figure 105: Early (left) and later (right) stage investment by region [EUR Million]

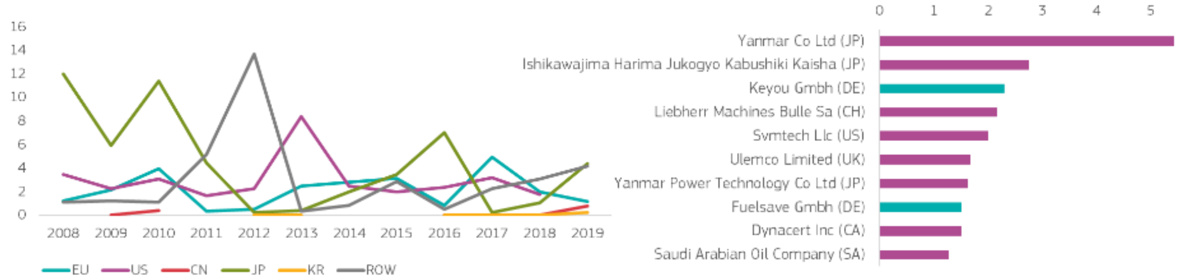


Source: JRC based on Pitchbook, 2023

As displayed in **Figure 106**, the patenting output in this domain is rather low. Japan is in a leading position in the period 2016-19, mainly through the activity of engine manufacturer Yanmar which is also at the top of the world ranking for high-value inventions. Germany is the only EU Member State in the top five of high-value inventions over the 2016-19, and ranks third behind the US, mainly via the activity of developers of hydrogen-based solutions.

However, the patenting output does not reflect the actual innovation effort in the domain, of key EU industrial corporates such as MAN Energy Solution (Germany) or Wärtsilä (Finland). 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.

Figure 106: Trend in high-value inventions for the major economies (left) and top ten companies in high-value inventions in 2016-19 (right)



Source: *JRC based on EPO Patstat, 2023*

A majority of the 203 zero emission pilots and demonstration projects that the Getting to Zero Coalition has identified in 2022 (GMF, 2022a) are connected to Europe (56%) and Europe is, in particular, showing strong leadership in ship technology projects.

While those projects are not all related to ammonia, this mapping of zero emission pilots and demonstration projects confirms an increased focus on hydrogen-derived fuel production, with a clear trend towards green hydrogen electrolysis and green ammonia synthesis. Ammonia now represents 58% of ship technology projects and became the preferred solution for large vessel ship technology projects. It also represents 26% of fuel production projects and 16% of bunkering and infrastructures projects.

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. Using fuel cells for power generation, as an alternative to the direct combustion of ammonia, either requires direct ammonia fuel cells or its preliminary conversion to hydrogen.

23.3 EU positioning in the current market and major changes

There are currently no available identification codes for trade and production that specifically relate to production or energy conversion technologies for green ammonia. 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. It therefore 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 volumes amounted to 185 Mt in 2020, of which the EU only represents 9%, far behind China (25%), North America (12%), Russia (10%), India and the Middle East (resp. 9% and 8%) (Mission Possible Partnership, 2022).

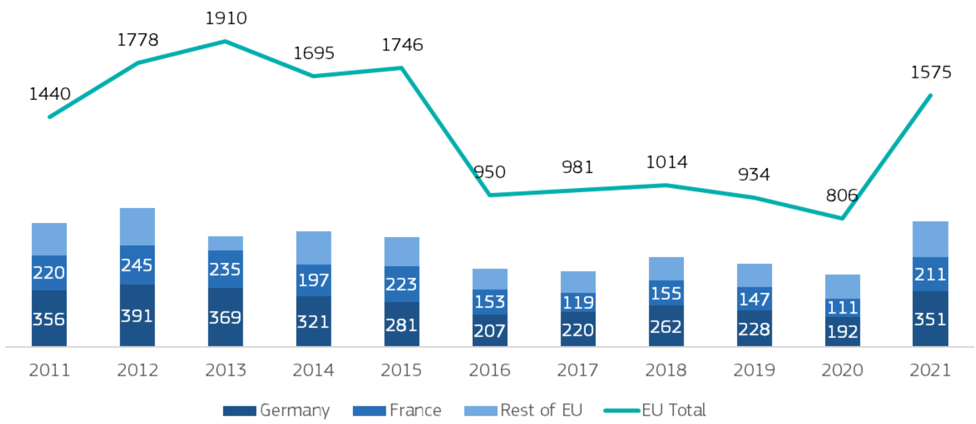
Putting an end to a long downward trend (**Figure 107**), the ammonia production value in the EU displays an enormous rebound in 2021 to EUR 1 575 million (double that of 2020) and takes up again with the higher values seen during the 2010-15 period. As shown in **Figure 108**, the value of extra-EU imports has similarly increased by a factor of 2.45.

These trends are, however, driven by the sustained price increase of natural gas and ammonia that started in the course of 2021 and continued in 2022 after the military aggression of Russia against Ukraine. Soaring prices actually led many European ammonia plants to curtail their production (and eventually shut down production facilities) in 2021 as it became much cheaper to import ammonia into Europe.

In 2021, Haldor Topsøe (Denmark) announced the development of 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).

Numerous green ammonia plant projects have been announced since and renewable ammonia capacity is expected to increase further. They include new-builds but also the transformation of existing fossil-fuel based ammonia plants from fertiliser companies. Different sources estimate a total announced green ammonia production capacity ranging between 71 Mt per year (IRENA, 2022c) and 133 Mt per year (EMSA, 2022), likely to be fully operational before 2040. The EU, however, only accounts for 4% of this expected total production capacity (essentially in Spain, Germany and Denmark).

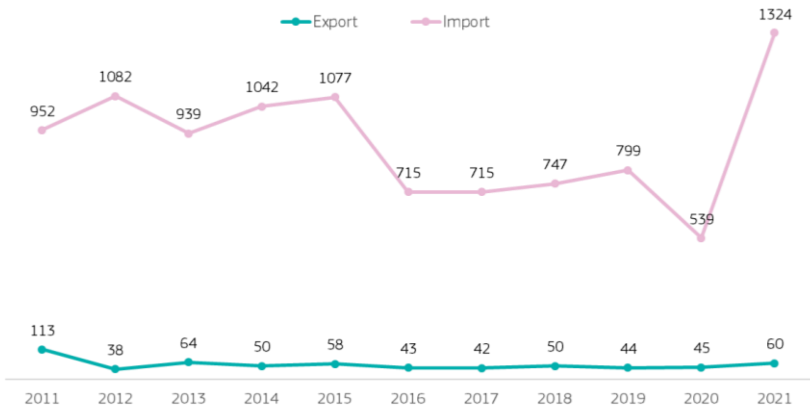
Figure 107: EU production value [EUR Million]



Source: *JRC based on PRODCOM data, 2023*

The EU dependency on imports keeps growing: extra-EU imports reached an all-time high of EUR 1 324 million in 2021 and amplified the downward trend of the extra-EU trade balance initiated in 2016. Over 2019-21, the share of EU imports coming from outside the EU has increased to 70% and the extra-EU share in global exports has dropped below 1%. The relative trade balance remains largely negative in almost all EU Member States, with the exception of Croatia, Hungary and Slovakia. Top exporters to the EU are large natural gas-producing countries, in particular Algeria (EUR 877 million) and Russia (EUR 836 million).

Figure 108: Extra-EU import & Export [EUR Million]



Source: *JRC based on COMEXT data, 2023*

23.4 Scoreboard – key insights and change in EU performance

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)([186]), the European Commission has put forward key measures to support such a target, including the FuelEU Maritime Regulation proposal (COM(2021) 562)([187]), 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 on hydrogen production) 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, 2021h)). 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, 2020), depending on the transitional role that LNG will play towards deep decarbonisation. In its Net-Zero Emissions scenario, (IEA, 2022g) states that, by 2050, ammonia meets around 45% of demand for shipping fuel. 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, 2020).

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 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 investment 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. Immediate collaboration amongst all sector stakeholders plays an important role to ramp up demand in a sector that has the potential to make or break the demand for green ammonia.

This includes initiatives such as:

- Mission Innovation's Zero-emission shipping partnership (Mission Innovation, 2022) to address innovation gaps and foster international collaborations between states, international organisations, research institutions and corporates.

([186]) COM(2021) 550 final, 14th July 2021 Brussels

([187]) 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

— 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 ([188]).

— The development of green corridors (GMF, 2022b), supported by enabling policy measures and investment along trade routes between major port hubs where zero-emission solutions are supported.

By 2030, as the green ammonia supply and the ammonia powered vessel fleet begin to scale, market based measures will be essential to close the price difference cause by the gap in production costs between green ammonia and fossil fuel alternatives.

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 with 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). This first-mover dynamic is also supported by EU public funding for R&D projects 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. Due to the sustained price increase of natural gas and ammonia initiated 2021, EU's ammonia production is even likely to have shrunk in 2022 and the declining trade balance is largely negative in most EU Member States.

The market for green ammonia remains very limited and production pilot projects are still at an early stage. While numerous green ammonia production plants have been announced, the share of the EU in the total expected production capacity remains very low to date.

There is also a clear lack of private venture capital companies and investment in the EU, despite the role they could play in this early phase of an emerging market. This emphasizes the role of incumbents and 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 109: Scoreboard for ammonia use as fuel

Scoreboard	**Ammonia use as fuel**	EU performance in the reference period			Change from 2021
Public R&D			2016-2020	EU CAGR	
Early Stage		0%	2016-2021	EU share of global total value	↓
Later Stage		0%	2016-2021	EU share of global total value	→
Patents		22%	2016-2019	EU share of global total HVI	
Companies		5%	2016-2021	EU share of innovating companies	
Employment			2016-2020	EU CAGR	
Production		11%	2016-2021	EU CAGR	↑
Turnover			2016-2020	EU CAGR	
Imports & Exports		1%	2019-2021	EU share of global exports	→
Trade Balance		Low	2016-2021	EU trade balance trend	↓

Source: JRC, 2023

([188]) https://transport.ec.europa.eu/transport-themes/clean-transport-urban-transport/alternative-fuels-sustainable-mobility-europe/renewable-and-low-carbon-fuels-value-chain-industrial-alliance_en

24 Bio-based circular fertilisers

24.1 Overview of the solution and current status

In order to feed a growing population, increasing amounts of synthetic fertilisers are being used throughout the world. Fertiliser production has increased from about 40 million tonnes in 1961 to over 200 million tonnes in 2019 (Ritchie, et al., 2022a). Potassium (K) and Phosphate (P) are mined from finite natural resources, whereas Nitrogen (N) is extracted from the atmosphere (where it is present in abundance), but requires large amounts of natural gas to produce. Approximately 1% of the world's total energy consumption is associated with the production of synthetic Nitrogen fertilisers via the Haber-Bosch process (Capdevila-Cortada, 2019), equivalent to 1 750 TWh of total energy use or more than 4% of global natural gas consumption (~40 000 TWh) (Ritchie, et al., 2022b). The consumption of fertilisers has been stable in the EU27 over the last decade (at 11 million tonnes in 2020) (Eurostat, 2022), but the movement towards sustainable agriculture and resource independence from fossil fuels are major drivers for the substitution of fossil resource-based fertilisers with circular, recovered nutrients (see Figures below).

The Russian invasion of Ukraine in early 2022 dramatically affected both natural gas availability and its price, reshaping the entire fertiliser market. In November 2022, the European Commission published a communication on how to address fertiliser availability and affordability in light of this market turbulence ([189]). This directly affects food security, meriting further action to reduce our dependence on fossil resource-based mineral fertilisers and stimulate the production and use of circular, bio-based alternatives. In addition to food security, our nutrient intensity, as measured by our overall external input of nutrients into the agro-food system as well as subsequent losses to the environment, has resulted in detrimental environmental impacts over recent decades. The systematic increase of nitrogen extracted from the atmosphere and the resulting introduction of active nitrogen compounds into the ecosphere has resulted in a dramatic increase of eutrophication and so-called 'marine dead zones' (i.e. entire patches of marine habitat devoid of any form of higher life) (Schiermeier, 2008). This has led to the setting of targets by the European Commission on the overall reduction of fertiliser use by 20% by 2030 as part of the Farm-to-Fork Strategy[190]. Replacing external inputs based on finite primary fossil resources with secondary recovered nutrients will improve internal cycles of nutrients and reduce the overall external input of nutrients into our overall agro-food system. Current fertiliser producers in Europe will play a key role in this transition towards the substitution of fossil resource-based mineral fertilisers with more bio-based, circular fertilisers.

Development status

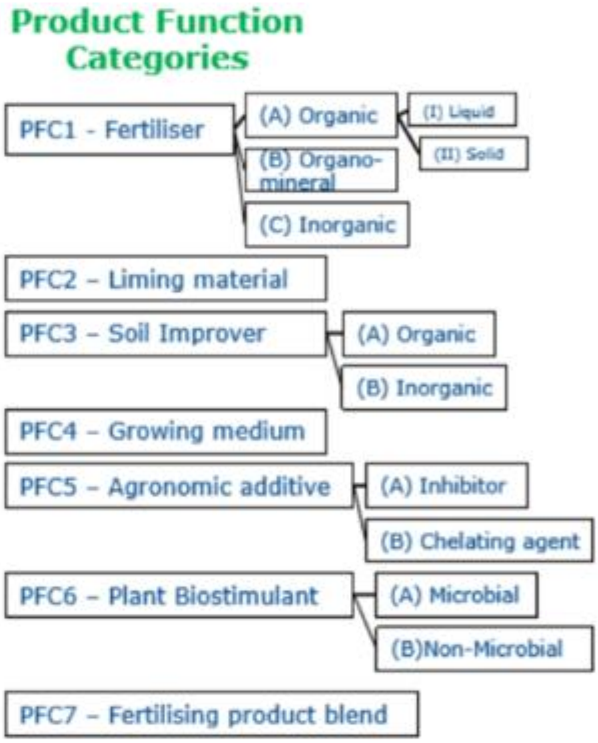
Mineral nutrients (NPK) are present in biomass produced by the anthropogenic food chain; animal manure, crop residues, organic biological waste from the food industry, municipal organic waste and sewage all contain these essential elements. The high demand for these nutrients, combined with the current pressure on natural resources as well as their presence in organic biological waste streams, puts bio-based circular fertilisers high on the political agenda of the European Union. Phosphate rock, for example, the essential ore from which Phosphate is extracted, is virtually absent from the European continent. Considering its vast importance to our food security, it has been designated as a critical raw material ([191]). Moreover, the currently known deposits and reserves are in a handful of countries and regions, making Europe geopolitically vulnerable. These include Morocco, China, Egypt and Algeria, along with less than 1.5% of global reserves in Finland (Statista, 2022a). Natural gas – from which the mineral Nitrogen is produced – has been under increasing scrutiny, first in the fight against climate change, and now also in the drive to reduce EU dependence on imports of natural gas and synthetic fertilisers from Russia. Potassium reserves are also found predominantly outside Europe, in North America, Russia, Belarus and China (Statista, 2022b). Comparable economic and geopolitical drivers therefore apply to all three major nutrients.

The EU has set ambitions towards more nutrient recovery and hence the production of bio-based circular fertilisers from the above-mentioned bio-based waste streams. It has consolidated this drive by including it as a key component in the circular economy package (original in 2015, updated in 2020). In July 2022, the revised Fertilising Product Regulation (FPR) of the EC came into force – three years after its formal adoption by the trilogue of European Council, European Parliament and European Commission. The FPR was revised in the sense that the original regulation only focused on synthetic fertilisers whereas the revised version, implemented in 2022, contains a wide range of recycled raw resources and final products, including those

([189]) https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_6566
([190]) https://ec.europa.eu/commission/presscorner/detail/en/fs_20_908
([191]) The latest EU Critical Raw Material List (2020) available at: https://rmis.jrc.ec.europa.eu/?page=crm-list-2020-e294f6

from bio-based origins. The FPR contains seven product function categories (PFCs) of fertilising products (see **Figure 110**). The current chapter focuses on PFC1, though it should be noted that within the emerging circular bio-based economy related to fertilising products, there are other relevant product categories in addition. For example, biostimulant products can mitigate stress and improve nutrient uptake (and thereby efficiency); inhibitors such as nitrification inhibitors can play a role in the overall nutrient availability and uptake efficiency; and soil improvers can, by increasing soil organic content for example, improve water-holding and nutrient-holding capacity, thereby influencing the effect of mineral and organo-mineral fertilising products. The European Commission has been paying increasing attention to the added value that soil offers for all life on earth – going beyond a singular focus on mineral nutrients to consider soil structure, soil carbon sequestration, soil biodiversity and more. This broadened awareness of the benefits of healthy soil is also evidenced in the EU Mission on Soil Health ([192]).

Figure 110: Product Function Categories



Source: European Commission, 2023

European industry

Two categories of European industry are of interest in terms of investment in bio-based circular fertilisers. Firstly, the conventional chemical industry is investing in more sustainable fertiliser production and the integration of more renewable resources. Some chemical plants try to achieve this by using biomethane or hydrogen produced from renewable energy instead of natural gas for the production of Nitrogen fertilisers (e.g. YARA). Others develop strategies to use recycled Nitrogen, Phosphate or Potassium in their end-products (e.g. ICL, Fertinagro, Fertiberia and ANOREL).

Secondly, existing bio-based sectors, such as agriculture, food and organic waste processing, aim to upcycle bio-based side and waste streams related to their respective processes, improving their sustainability and economic profitability. Both core industries are attracting a fast-growing sector of environmental technology companies which provide processes, products and services. Policy has been (and remains) a major driver for the development of this bio-based economy; the consistent drive by the European Commission to achieve a lower carbon footprint and higher environmental sustainability, resulting in standardised objectives across Member States, has attracted broad interest across both industries. This policy drive is evidenced in goals and obligations relating to carbon footprint (including the EU Emissions Trading System), agriculture (including CAP

([192]) EU Mission on Soil Health, for more information: https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/soil-health-and-food_en reform), the European Green Deal (including farm-to-fork targets), business-oriented measures (such as the Fertilising Product Regulation) and the energy transition (including Fitfor55 and REPowerEU, the last of which affects natural gas consumption and is thereby a major driver in the mineral Nitrogen fertiliser transition).

Existing market

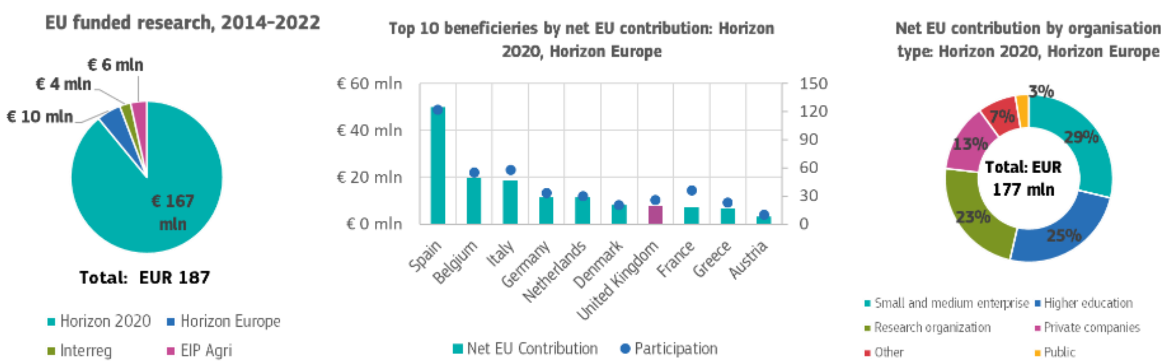
The existing market can be defined as a subset of the fertiliser market, which is currently predominantly fossil resource-oriented. The domestic market can be stimulated directly by European Commission policy measures (incentives and/or obligations) and the export market is subject to alternative drivers which reflect domestic legal obligations in the destination country. Through international trade negotiation, the global export, which is currently EUR 900 million, can also become an important market, as we see a similar drive towards more sustainability in the entire agro-food chain in North-America (US, Canada) and South-East Asia (including China). Moreover, we see an increasing demand for organic soil enhancers in many other parts of the world, based on key agronomic and economic drivers, if not for environmental reasons. In that sense, promoting circular agriculture in Europe can result in more circularity and less export-driven agriculture in those regions as well. For example, increasing local cycling in the EU and reducing dependence on soy-protein imports from South-America to feed our intensive animal production could be transformed into more sustainable local development in those regions.

24.2 EU competitiveness in innovation and future markets

It is difficult to identify the level of investment in R&D related to bio-based circular fertilisers from existing data sources. Nonetheless, we are aware of many initiatives being undertaken at European, Member State and regional levels. Such initiatives include grant applications and various forms of research subsidies, as well as bilateral research between industry and academia, funded by industrial actors. Data on grant applications is fragmented across European, national and regional sources, at times unsuitable for data mining and in multiple languages. Sources on industrial funding for research development are, by default, not made publicly available. While eventual success stories are shared, the efforts and investment taken to get them there are kept behind the scenes.

EU-funded R&I activities in bio-based circular fertilisers are mainly funded through Horizon 2020 and its recent successor, Horizon Europe. Interreg and EIP Agri have also channelled EU funds at a lower level. In total, the EU channelled nearly EUR 190 million into bio-based fertilisers in 2014-2022, with Spain the main beneficiary and the country of most participants in Horizon 2020 and Horizon Europe funds (**Figure 111**). Interestingly, small and medium-sized enterprises (SMEs) constituted the biggest group of beneficiaries, receiving 29% of the funds. Altogether, the private sector received 42% of the funds, while academia, research organisations and universities received another 48%. The high share of SMEs is a positive, considering that the development of bio-based circular fertilisers requires a wide range of local actors in the agro-food ecosystem.

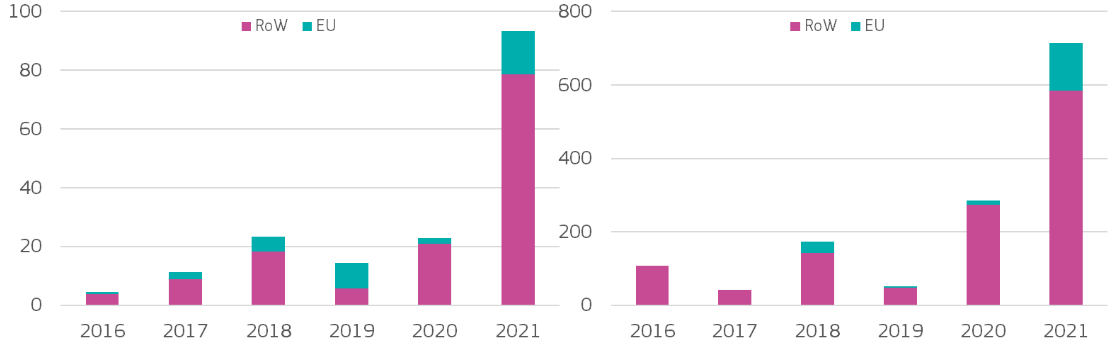
Figure 111: EU-funded research (2014-2022)



Source: JRC based on CORDIS, 2023

Venture capital investment has increased significantly, tripling in 2016-2021 globally compared to 2010-2015, and in the EU, it grew from practically nothing to over EUR 200 million. As **Figure 112** shows, this was largely thanks to a record-breaking year in 2021. In early stage capital, EU-based companies captured 20% of the total investment value, with France, Germany and Sweden leading in the EU but behind the US, Canada and Norway. The EU captured nearly a third of the deals which indicates that deal values were much bigger outside the EU. At later stages, the EU share was weaker, with EU-based scale-ups capturing only 13% of the total investment value. The EU share of deals was 18% which again points to higher deal values outside the EU. France came second only to the US, but overall, only a small number of EU countries (Portugal, Belgium and Spain) managed to raise any later stage investment.

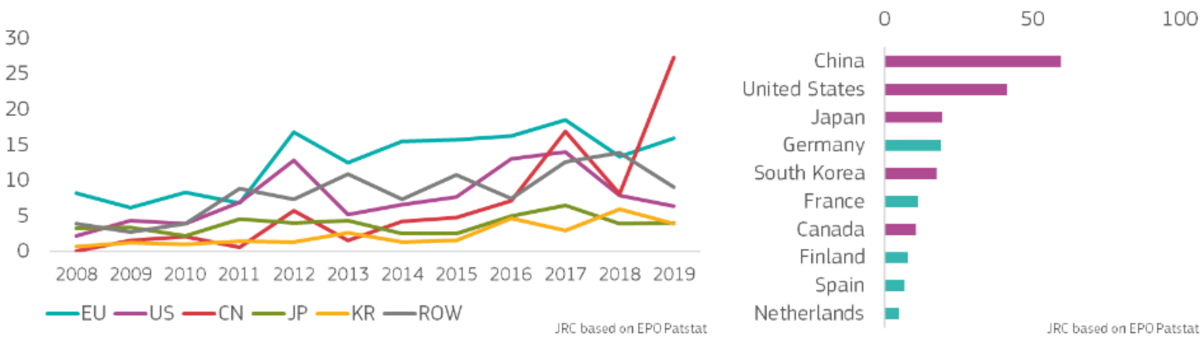
Figure 112: Early stage (left) and later stage (right) investment by region [EUR million]



Source: JRC based on Pitchbook, 2023

Patenting trends reveal that Europe has been dominant among world regions over the last decade (see **Figure 113**). Moreover, the data does not yet reflect the major drive in intellectual property (IP) generated by the adoption of the FPR in 2019 and its entry into force in July 2022, or the renewed Circular Economy plan, adopted in 2020, with 2030 targets for fertilisers. In 2016-2019, the EU accounted for 26% of high-value inventions globally, making it a market-leader in IP generation relating to the relevant patent families. At country level, Germany, France, Finland, Spain and the Netherlands were in the top ten, behind China, the US and Japan. Fertinagro Biotech (Spain) and BASF (Germany) make it to the global top ten companies by patenting activity. Other companies active in patenting in this area are Big Dutchman (Germany), Valio (Finland), Advanced Substrate Technologies (Denmark) and Solar Foods (Finland).

Figure 113: Patenting trends (left) and top ten countries (right)



Source: JRC based on EPO Patstat, 2023

The coming years will reveal whether the new policy framework and ambitions will further boost European patenting applications in the field of bio-based circular fertilisers at home and abroad. Increasing sustainable policies in other parts of the world – including China, the US and Canada – as well a number of important fertiliser production countries (such as Ukraine) may follow and align themselves more with the EU, which would continue to work favourably towards marketability of European R&D and associated IP.

The EU hosts nearly a third of all innovators in this area, with the biggest pool of patenting corporates, while the US has the most venture capital companies. France is behind the US and Japan in terms of the overall number of innovating companies. The geographic spread of venture capital companies is unusually broad in this field, with all continents represented. This may reflect the local embeddedness of circular solutions, which tend to focus on valorising locally available feedstock. The patenting trends also reveal a wide geographical dispersion, with the Rest of the World capturing the third biggest share of high-value patents (18%), behind the EU and China. Canada is the most active country in this group. The Rest of the World is also the biggest recipient of EU and US patenting applications.

Areas of innovation

Innovation related to circular, bio-based fertilisers can be categorised into a number of areas of interest. First are the environmental technologies which enable the selective extraction and upcycling of Nitrogen, Phosphate and/or Potassium from bio-based waste streams – this is a fast-growing category which includes stripping/scrubbing technology, membrane technology, Phosphate leaching & re-precipitation.

Second are the process technologies which allow for the production of new products using recycled nutrients either wholly or partially, including the conditioning of fertilising products, amending additives and the production of novel, tailor-made fertilisers by blending.

Third are the technologies related to the application of novel products, as these deviate from existing formulated products in nature and composition. This category also includes the vast, expanding domain of smart farming (or precision farming) tools, such as online (proximate) sensing of products (e.g. near infrared (NIR) sensors), fertilising standing crop and tele-sensing using drones or other types of imaging.

Finally, there is significant research related to product performance validation – both in agronomic terms (crop yield and quality) and environmental terms (nutrient losses to the environment and GHG emissions). This area has strong forward momentum across sectors, often tempered only where administration and legislation are unable to keep pace with innovation.

24.3 EU competitiveness in current markets

Figure 114 below indicates current employment estimates (including the supply chain) for mineral fertilisers in Europe, given by the sector itself (Fertilizers Europe, 2021) and based on Eurostat data (2017). Of course there is a difference between mineral fertilisers and bio-based circular fertilisers, but the recycled portion of nutrients represents part of this larger market – both in the share of the existing fertiliser market and in the reorientation of that market towards circularity. The estimated number of employees currently ranges between 61 000 and 74 000 (Fertilisers Europe estimate), and from more recent Eurostat data, we can see that employment has been rising in EU Member States consistently over the years, with an annual growth of 4-5%.

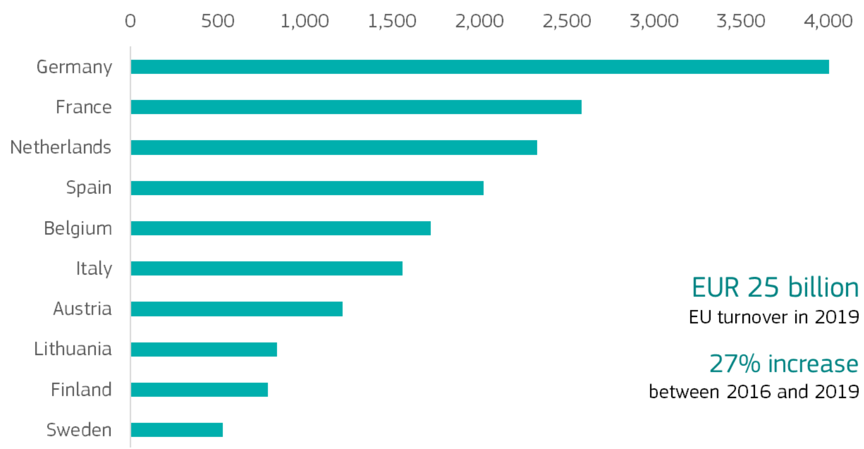
Figure 114: EU employment based on Eurostat by country

Source: JRC based on Eurostat SBS, 2023

Based on the PRODCOM data for all fertilisers, the share of bio-based circular fertilisers is about 5%. Using this as an approximation, bio-based-related employment was 3 000 to 4 000 jobs at EU level in 2017. However, the estimation of employment figures directly linked to bio-based circular fertilisers is more complex than merely anticipating their growing importance in the conventional fertilisers industry. Though it will to some extent evolve as a subsidiary market within the existing chemical fertilisers industry, there is also a strong complementary market developing from side-stream processing. For example, the recovery of nitrogen from manure, and its upcycling into a synthetic fertiliser alternative, has been termed RENURE (REcovered Nitrogen from manURE) by the European Commission. The same emerging markets can be seen as for the biogas industry – which can be profiled as biorefineries, producing recycled fertilising products in addition to renewable energy, as well as for municipal waste treatment facilities which are progressively transitioning from waste disposal (e.g. following the landfill ban in the EU) towards recycling. Putting clear-cut employment figures on agro-processing or municipal waste processing is more difficult than for pre-defined sectors. For example, there is no specific data available in pan-European databases on employment in manure processing, and for the biogas and organic waste sectors there are only industry estimates available

Turnover in the fertiliser manufacturing industry overall was estimated at around EUR 25 billion in 2019, with an increase of 27% between 2016 and 2019. The top ten countries in production (according to value) are depicted in the figure below. Based on the PRODCOM data for all fertilisers, the share of bio-based circular fertilisers is about 5%. Using this again as an approximation, bio-based-related turnover was EUR 1.2 billion at EU level in 2019. As with the employment figures, these numbers are not clear-cut, considering that the actual bio-based circular fertiliser industry consists of two parts: (i) a growing portion of the existing fertiliser industry and (ii) a separate industry processing biological waste streams (manure processing sector, biogas sector, municipal waste processing industry, (municipal) waste water treatment systems). Nonetheless, the turnover of the existing fertiliser industry provides insights into and an indication of the order of magnitude and importance of this sector.

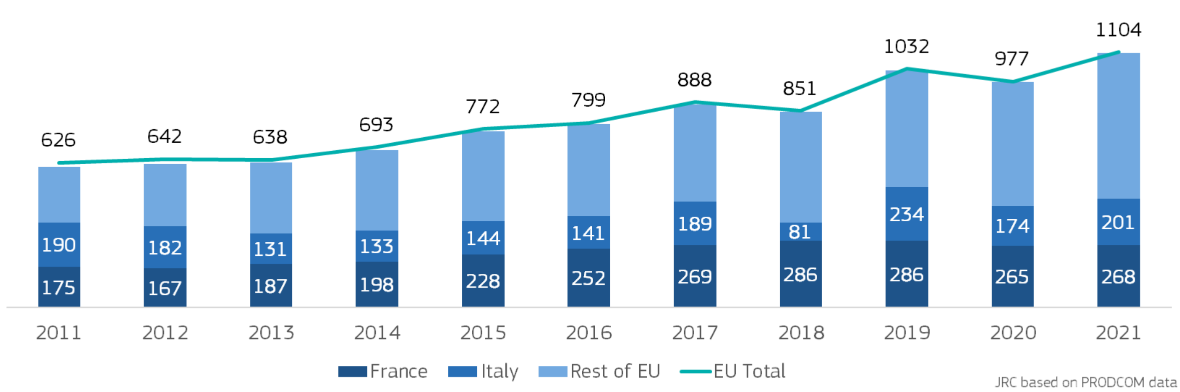
Figure 115: Top ten EU countries by turnover in the fertiliser manufacturing [EUR million] (2019)



Source: JRC based on Eurostat SBS, 2023

The EU production of bio-based fertilisers has grown from a little over EUR 600 million to over EUR 1 billion in 2011-2021. France, Italy and Spain are the top three biggest producers. Spain and Belgium have particularly increased their production in recent years.

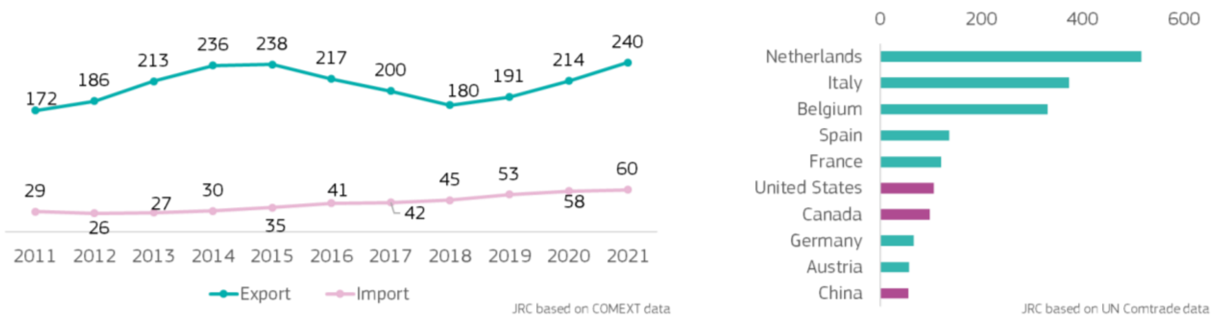
Figure 116: Total production value in the EU and top producer [EUR million]



Source: JRC based on Prodcom, 2023

EU Member States are currently leading in terms of bio-based fertiliser exports. Seven of the top ten countries are from the EU, and all of the top five. In total, the EU generates 46% of global (non-EU) exports. There is also significant intra-EU trade, with the Netherlands exporting to Germany and France, and Belgium exporting predominantly to France. Excluding intra-EU trade, we observe a gradual increase in exports from the EU of bio-based fertilisers, with a 33% rise in the period 2018-2021. The top five importers from the EU are the UK, Vietnam, the US, China and Switzerland. Moreover, the EU enjoys a trade surplus for bio-based fertilisers with three important trade blocs in terms of agricultural products: the UK, China and the US.

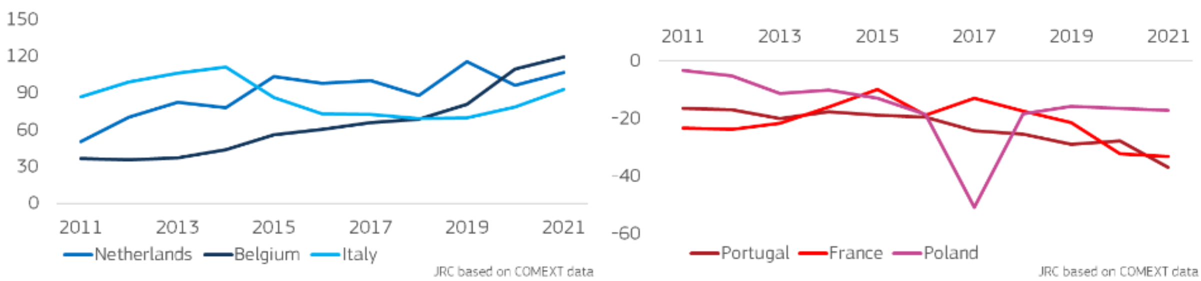
Figure 117: Extra-EU Import & Export (left) and top ten global exporters (right) [EUR million]



Source: JRC based on Comext data, 2023

While France is the biggest producer of bio-based fertilisers, it is also a big importer, reflected by the growing trade deficit. This is probably due to growing demand from France's large agricultural sector. Meanwhile, the Netherlands, Belgium and Italy have a growing trade surplus.

Figure 118: Top 3 countries with positive (left) and negative (right) trade balance [EUR million]



Source: JRC based on Comext, 2023

24.4 Future outlook

The main policy driver in this sector is the Fertilising Product Regulation (FPR). The required certification of novel CE labelled products according to regionally organised notifying bodies may result in delays following implementation. Nonetheless, if the path towards practical commercial applicability of the products can be made clear and transparent from legal perspective, the market will follow. Not least because current fertiliser prices are soaring, following those of raw materials and fossil fuels (including natural gas) as a consequence of Russia's war on Ukraine. This economic driver coincides with an environmental one as many companies – including those in the chemical industry – are subject to carbon footprint quotas under the EU Emissions Trading System (ETS). Moreover, soil carbon build-up related to the use of bio-based fertilising products such as soil improvers or organo-mineral fertilisers can also contribute to soil carbon sequestration. These principals of carbon farming can also enjoy external valorisation benefits, either via certified schemes and/or policy incentives associated with agricultural subsidies, such as the Common Agricultural Policy (CAP).

Barriers to adoption

The EU is playing a leading role in sustainable development, favouring the development and use of bio-based circular fertilisers. Nonetheless, this position is fragile for a number of reasons. First of all, the EU remains very dependent for its overall fertiliser needs and consumption on Morocco, China and the US for phosphate rock imports. European businesses will only be able to make sufficient substitution and achieve market advantage if legal constraints and bottlenecks related to the application of recycled derived fertilisers are sufficiently addressed. In this context, it is important to note that the FPR can continue to be a major driver, nonetheless we need to be aware that this is a product regulation and not a regulation related to the (allowed) application of these products. Within the EU, the (allowed) use of fertilising products falls under a different set of agricultural and environmental legislation (nutrient management plans) which can paradoxically prohibit the free use of products, even if CE-labelled under the FPR. Such legal inconsistencies can be detrimental to the budding circular market and therefore need to be addressed and harmonised at EU level. Numerous examples of such legal inconsistencies requiring harmonisation can be presented – ranging from the need for harmonisation between the Sewage Sludge Directive and allowed use of recycled Phosphate to the Nitrates Directive and allowed use of Recovered Nitrogen from Manure (RENURE) as a synthetic Nitrogen fertiliser. High-value inventions may be rendered void if the policy framework is not sufficiently up to date regarding the allowed application of novel products and processes entering the market. In that sense – although great steps have been taken – the overall feeling is that the state-of-art is developing faster than the state-of-legislation, even though policy ambitions are high and favourable towards IP and market development.

A more pressing and structural delay expected to slow down the market uptake of sustainable bio-based circular fertilisers is related to delays in adopting suitable legislation related to RENURE. Compositional criteria were proposed by the EC to allow for end-of-manure status which would effectively stimulate their use to replace synthetic Nitrogen fertilisers produced from natural gas. However, without the adoption of a suitable legal framework to allow their usage, products upcycled from manure and CE-labelled under the FPR can still not be used as intended to replace synthetic Nitrogen fertilisers, rendering the entire EC move in this direction moot.

The EC has drafted a SWOT analysis based on consultation of the Member States on the best way forward – to either revise the Nitrates Directive (ND) or to follow a system of derogations in frame of the ND for these types of products under agro-environmental legislation (nutrient management plans). The strategy of choice would be to operate via derogations, foregoing the need to revise the ND itself, yet at the moment of writing, the bilateral discussions on derogations for RENURE between DG ENVI and the member states via the Nitrates Committee are proceeding slowly or have even grinded to a (temporary) halt. A large body of European Projects dealing with recycled nutrients has urged the EC (by means of joint policy briefs) to harmonise efforts within the EC with various domains involved (GROW, AGRI, RTD, ENVI and SANTE) so that environmental targets can be reached by 2027 (water quality) or 2030 (agricultural sustainability; GHG abatement goals) respectively.

Future market development

The market is expected to grow gradually in the short term, yet an expected acceleration may occur if the lingering policy constraints can be ironed out at EC level. From sector organisations, EU projects and nutrient platforms operating at European and national or regional level, the transition towards bio-based circular fertilisers has been highlighted as a high-potential development, enjoying high priority both from the existing fertilising industry (aiming to source sustainable domestic resources for continued/consolidated activity on the European continent) as well as the sectors dealing with management of organic waste and side-streams (waste management, manure processing, biogas sector, municipal waste treatment, sewage treatment).

Provided that they have a stable and stimulating policy environment, Member States which have invested in organic biological waste processing over recent years (instead of landfill or incineration) enjoy an advantage in the development of this sector. Countries such as Germany, Italy, Denmark and France have been stimulating the development of the biogas sector – providing suitable conditions to promote nutrient recovery and bio-based fertiliser production associated with these activities. Other Member States have similar potential, provided that they engage local markets with a sufficiently stimulating framework. Likewise, regions with developed agro-industry and particularly intensive animal production have the potential advantage of developing a bio-based fertiliser market based around sustainable manure processing. This includes specific regions around Europe, such as Lombardy (IT), Brétagne (FR), Catalunya (ES), Flanders (BE), Nord-Westfalen (DE), the Netherlands and Denmark (as a whole). However, to upgrade such markets related to manure processing into bio-based fertiliser production, the local and European policy framework needs to mature. In order to optimise nutrient flows throughout the agro-food value chain, less external input is required (as envisaged in the European Green Deal), along with more loop-closing (by means of bio-based fertilisers), in combination with higher nutrient efficiency (in the form of products and precision farming technology) and management systems that allow a more resilient natural removal of nutrients lost from the agricultural system into the environment (nature-based solutions, adapted management techniques, catch crops etc.

However, in the transition to less impactful agriculture (*vis-à-vis* the environment), policymakers tend to rely predominantly in the short term on reducing fertilisation limits and/or imposing constraints regarding licenses to operate (e.g. limiting livestock). Attention should be given to other potential tools at hand which can reconcile agricultural goals with environmental ones. In that sense, in order to move towards more circular and thus sustainable agriculture, the recovery and recycling of nutrients by means of bio-based fertilisers to substitute their fossil-resource based counterparts deserves more attention in the decade(s) to come. Adopting a wider range of tools than merely reducing agricultural activity to reconcile agriculture with nature, by additionally focusing on smarter and more circular sustainability measures (such as bio-based fertilisers replacing synthetic ones) will also result in broader support from the agricultural sector in this much needed transition towards 2030 and beyond.

The resources from which bio-based fertilisers can be produced are present in relative abundance in Europe – for example, manure production within the EU27 amounts to 1.4-1.5 billion tonnes each year (Panagos, et al., 2022; European Soil Data Centre (ESDAC), 2023) in addition to around 118-138 million tonnes of biowaste which are processed into compost or digestates (ECN, 2019) and 9.5 million tonnes of sewage sludge (DW basis) (Buckwell & Nadeu, 2016). The estimated nitrogen and phosphate content in these three streams combined is equivalent to 11.6-12.6 million tonnes of nitrogen and 2.6 million tonnes of phosphate (Buckwell & Nadeu, 2016).

Bio-based fertiliser production from processing such waste streams will in many cases remain a local, decentralised process close to the source of the organic waste stream in question. Decentralised development can yield the benefit of providing job opportunities in rural areas. Nonetheless, business cases taking a more centralised approach by collecting fragmented sources at a single location can also prove viable, with advantages in terms of economies of scale as well as product consistency and homogeneity. The heterogeneous and variable nature of bio-based sources has been mentioned as one of the challenges when moving forward with market development for these products; centralised business concepts to address these challenges may therefore emerge in the coming years. In order for transnational supply chains to be developed, legislation on the trade and transport of Component Material Categories (CMC) under the FPR needs to be sufficiently aligned with Member State legislation on the bilateral trade of goods which are not yet always end-of-waste themselves. National borders – for good reasons – have acted as virtual barriers for the transport of goods falling under waste legislation. However, when organic waste streams under the category of CMCs are transported to final bio-based fertiliser producing facilities, these wastes should be considered to be resources.

The main opportunity for the EU industry is that – by definition – the resources from which bio-based circular fertilisers are produced are local and domestic. Adopting sustainable technology to valorise these waste streams will render the EU more self-reliant and independent with regard to nutrients from imported resources (phosphate rock, potassium ore, natural gas) (Kuokkanen, 2022). Moreover, the technologies for upcycling nutrients from organic waste streams into bio-based circular fertilisers and for their efficient application become export products in their own right. Environmental engineering and sustainability technology providers are important export markets, and by extension promoting sustainable goals globally. The main threat is the risk of delays to progress caused by a legal framework which fails to keep apace with the market.

24.5 Scoreboard and key insights

Although only EU public R&D spending data is available, it shows an increase over the past five years faster than EU GDP. In terms of venture capital investment, the EU captures a fifth of all early stage investment, which is above the EU share of the global economy, and 13% of later stage investment, which is less than the EU's share but above the EU average in clean energy venture capital. The EU is a leader when measured in high-value filings in the area, as it was responsible for 26% of all high-value inventions, but competitors are close behind, especially China, whose activity has peaked in recent years, along with the US and Canada. Overall, the EU hosts 27% of all innovators and as venture capital investment is on the rise, EU companies are well placed to capture risk funding. The solution is characterised by a larger number of start-ups and scale-ups (76% of all innovators) than big corporates, which indicates the emergence of a new ecosystem of solution providers for a growing, yet nascent, market of bio-based fertilisers. As the EU is leading on almost all of the innovation-related indicators (see **Figure 119**), the EU and its companies are well positioned for future markets.

In the existing markets, EU employment and turnover in the manufacture of fertilisers is increasing, and while this is not exclusive to bio-based fertilisers, it indicates the future potential in an already growing industry.

Jobs are expected to transition from the existing fertiliser industry towards more bio-based circular solutions, and jobs will also be created in new businesses based around the bioeconomy. The production of bio-based fertilisers is already increasing in the EU with a compound annual growth rate of 7% in 2016-2021. The EU captures 46% of global exports, with a growing positive trade balance.

The EC has successfully generated interest in society, industry and the agro-food chain in the development and adoption of bio-based circular fertilisers. It is a budding and emerging market, for producers and for agricultural end-users. Although interest has been generated by the adoption of relevant circular economy actions, in combination with sustainability targets, the market is still young and fragile. The EC and Member States need to proceed consistently on the initiated path with policy targets, stimulating end-user adoption and addressing remaining policy constraints at EU level whereas having sufficient attention for national implementation into nutrient management plans.

Figure 119: Scoreboard for bio-based circular fertilisers

Scoreboard	**Bio-based circular fertilisers**	EU performance in the reference period		
Public R&D			2016-2020	EU CAGR
Early Stage	●	20%	2016-2021	EU share of global total value
Later Stage	●	13%	2016-2021	EU share of global total value
Patents	●	26%	2016-2019	EU share of global total HVI
Companies	●	27%	2016-2021	EU share of innovating companies
Employment			2016-2020	EU CAGR
Production	●	7%	2016-2021	EU CAGR
Turnover	●	8%	2016-2019	EU CAGR
Imports & Exports	●	46%	2019-2021	EU share of global exports
Trade Balance	●	High	2016-2021	EU trade balance trend

Source: JRC, 2023

25 Battery recycling

The development of the batteries value chain is well under way in the EU (Bielewski, et al., 2022). With more batteries being used, and manufacturing capacity increasing, sustainability is ever more important, in the value chain and in the treatment of spent batteries. One of the key aspects in this regard is the development of recycling value chains for end-of-life batteries. A well-developed recycling sector would reduce the environmental impact of battery production and utilisation, and decrease the EU's import dependency on valuable raw materials like cobalt, lithium and nickel, which can be recovered from spent batteries.

Demand for batteries in the EU will grow significantly, mostly driven by the e-vehicles sector. Massive new production plants – gigafactories – will supply lithium-ion (Li-ion) batteries for e-vehicles. For the other types of battery, demand is expected to remain stable or to decrease (in the case of lead-acid batteries) (European Commission, 2020d). This chapter will therefore focus on the recycling of Li-ion batteries which are used in the e-mobility sector, portable electronics and industrial energy storage batteries. A strong legislative framework, based on the revamped Batteries Regulation, aims to incentivise the development of the batteries recycling sector in the EU([193]).

25.1 Overview of the solution and current status

The increasing production of batteries in the EU and, in the longer term, the growing number of batteries reaching end-of-life in the e-mobility sector, will generate a large feedstock of spent batteries available for recycling. Taking into account the average lifetime of the Li-ion battery, of between eight and 15 years, and the growing EV fleet in the EU, it is estimated that approximately 4 GWh of EV batteries will reach their end of life annually in Europe by 2025, and more than 200 GWh by 2040. In the shorter term, production scrap from the production of Li-ion batteries should be recycled – 70 GWh of such material is expected to be available for recycling by 2025 (Navarro, et al., 2022).

Battery recycling is a highly complex process. It can be divided into pre-treatment steps and material extraction steps. The first is the physical collection and sorting of spent batteries, based on various chemistries used. The logistics of the collection and transport process are one of key challenges at this point due to the technological variety of batteries (shape, size, chemistries used etc.) and to safety issues regarding the high flammability of Li-ion batteries. The next step involves discharging and dissembling batteries, and may also involve a combination of thermal, mechanical, physical or chemical actions (Fédération Internationale de l'Automobile, 2022).

The extraction of materials usually involves one of the two main technologies, which are pyrometallurgical and hydrometallurgical. The former uses high-temperature melting (±1 500°C) to extract valuable elements like cobalt, nickel and copper. It requires few pre-treatment actions and allows for the combined recycling of various battery types with different chemistries. Its drawback is that many materials (such as lithium and aluminium) are lost in the process, and it generates CO_2 emissions. The latter uses aqueous solutions – inorganic acids to leach metals from the cathode. This can be followed by solvent extraction and/or chemical precipitation to recover aluminium, lithium, manganese, graphite, nickel and cobalt. This method requires more pre-treatment steps and is more complex but enables the extraction of materials of higher purity. Direct recycling is another innovative method currently under development. Direct recycling separates the active material from the collector at cathode level, which enables the extraction of a wider range of materials. This method is not yet commercialised and requires complex pre-treatment (Fédération Internationale de l'Automobile, 2022).

One of the key challenges for the development of the recycling industry in the EU is a lack of standardised design for Li-ion batteries. Designs should allow for the easy deconstruction of battery packs and there should be clear labelling of the chemistry used. However, the development of batteries is pursued by a range of private companies and is confidential, resulting in a variety of designs and cathode chemistries. Such diversity is a barrier to the development of automated recycling processes, which are currently based on manual labour and require skilled workers. This complexity therefore reduces the profitability of recycling. The economic viability of recycling lithium batteries is mainly determined by the value of the valuable metals in the specific types of batteries (Fédération Internationale de l'Automobile, 2022).

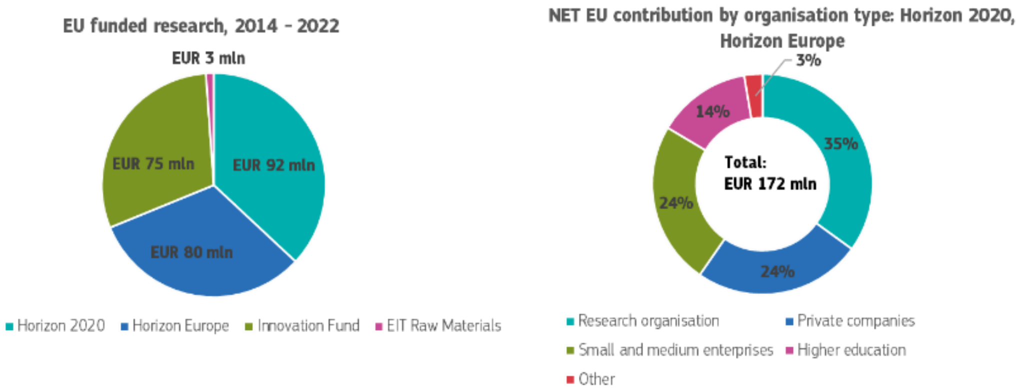
([193]) Proposal for a Regulation concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020, available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020PC0798

It is estimated that end-of-life recycling input rates[194] for several of the raw materials used in Li-ion batteries are relatively low: only 12% for aluminium, 22% for cobalt, 8% for manganese, and 17% for nickel. The recycling input rate for lithium is less than 1% – it is not considered cost-effective in comparison with primary supplies, leading lithium-ion battery recycling plants to prioritise the recovery of more valuable materials (cobalt, nickel and copper) (European Commission, 2020d). Overall though, recycling efficiencies for Li-ion batteries are higher, at approximately 95% for cobalt and nickel, 80% for copper and 50% for aluminium. There are also increasing numbers of factories focusing on lithium recovery (Trinomics, 2018).

25.2 EU positioning in innovation

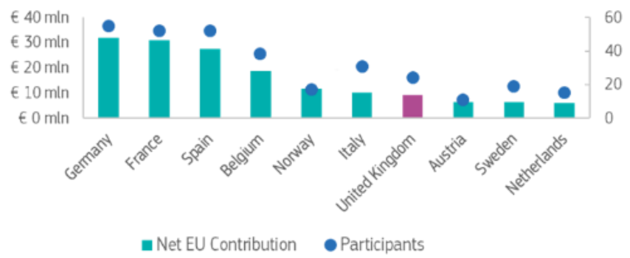
The EU has invested in batteries recycling R&D through various instruments: Horizon 2020 (2014-2020), Horizon Europe (2020-2027), the Innovation Fund (first calls for proposals in 2020) and EIT Raw Materials. The allocation of research funds confirms increasing interest in this sector. Since 2020, Horizon Europe and the Innovation Fund have provided grants totalling EUR 155 million, up from EUR 92 million in the period 2014-2020 (see **Figure 120**). One of the flagship projects (ReLieVe), supported by the Innovation Fund (with a grant of EUR 67 million), is the development of an innovative recycling factory with a capacity of 50 000 tonnes of end-of-life Li-ion batteries and production scrap, expected to become operational in 2027. The factory will be located in northern France, in the proximity of batteries manufacturing plants – the European "battery hub" – near the port of Dunkirk. It will use hydrometallurgical refining to produce high quality recycled metal salts, which can be used for production of new Li-ion batteries. Among the beneficiaries of Horizon Europe and Horizon 2020, the most active entities were research organisations, which received 35% of all funding. Private companies and SMEs, each accounting for 24% of funds, also play an important role in R&D in this sector, with almost half of all funding. On top of EU investment, Member States fund R&D through their national programmes, but this data is not available. Germany was the biggest recipient of EU research support from Horizon 2020 and Horizon Europe with EUR 32 million, and had the biggest number of participants, followed by France and Spain (see **Figure 121**).

Figure 120. EU Horizon 2020 and Horizon Europe funded research 2014-2022 (left) and net EU contribution by organisation type (right)



Source: JRC based on CORDIS and other sources, 2023

Figure 121. Top ten beneficiaries in Horizon 2020 and Horizon Europe programmes (2014-2022)



Source: JRC based on CORDIS and other sources, 2023

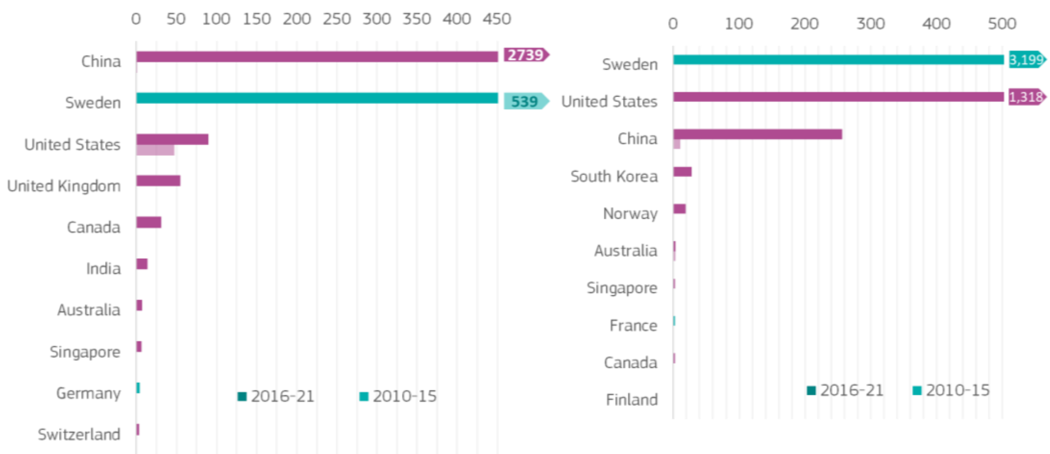
(194) The end-of-life recycling input rate (EOL-RIR) reflects the total material input into the production system that comes from recycling post-consumer scrap (Talens Peiró L., et al., 2018)

The main recipients of early stage investment are Chinese VC companies, followed by Sweden and the United States. Overall, there has been a strong increase in early stage investment: the total value for the period 2010-2015 was EUR 49 million, almost entirely accounted for by the USA (followed by China and the Netherlands), but for the period 2016-2021, this shot up to almost EUR 3.5 billion. China recorded the most dynamic growth, and the number of countries receiving early stage investment rose from three to 15. The share of investment received by EU companies rose from only 0.6% in the period 2010-2015 to almost 16% in the following period.

Sweden took the lead in later stage investment, followed by the USA and China. As with early stage investment, amounts grew substantially from EUR 14 million (mostly from China) to almost EUR 5 billion. The EU share grew from zero to 66%, outperforming other major economies. Sweden played a key role in this change.

It is, however, important to note that there is data overlap, as the key companies involved are also manufacturers of batteries, with a tendency to develop industrial clusters with recycling segments. For example, Swedish company Northvolt is responsible for all of the EU's early stage investment in 2020 and almost all of its later stage investment in 2019 and 2021. In 2021, Northvolt developed new batteries with nickel-manganese-cobalt (NMC) cathodes which are 100% recycled from other batteries. According to its recycling programme launched in 2021, Northvolt plans to scale up recycling to 125 000 tonnes of batteries per year, meeting its production target of making batteries with 50% recycled material by 2030. Another key player on the recycling market is Umicore, which is planning increased investment in recycling capacity. Outside the EU, China's SVOLT accounted for almost all early stage investment in the rest of the world in 2021. Northvolt is almost single-handedly responsible for the EU's investment figures (see **Figure 122**), with most of its equity coming from investors located in Sweden, followed by the United States, Germany and the Netherlands.

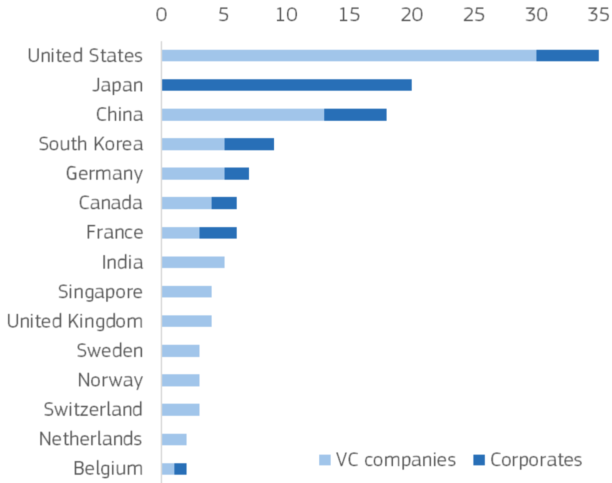
Figure 122. Early stage (left) and later stage (right) investment [EUR million]



Source: JRC based on Pitchbook, 2023

The leader in the field of innovating companies is the USA, with a total of 35 companies, followed by Japan with 20 (all corporate) and China with 18. The best performer within the EU was Germany, with seven innovating companies. The EU as a whole has 23 innovating companies (18 VC and six corporate) an 18% share of the world's innovating companies. See **Figure 123**.

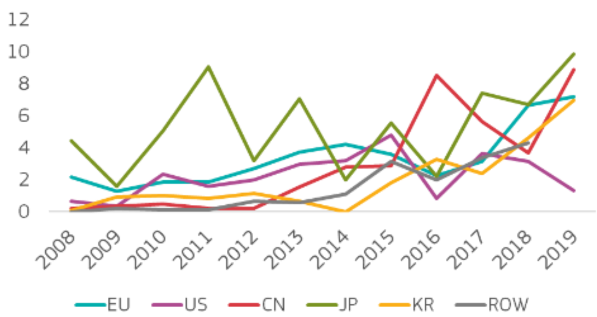
Figure 123. Number of innovating companies (2016-21)



Source: JRC based on various sources, 2023

The EU has a relatively high share of high-value inventions, putting it in third place after China and Japan. The EU's annual number of patents rebounded in 2016 and in 2019 was three times higher than in 2008 (see **Figure 124**). However, in terms of private companies, most high value inventions in the period 2016-19 were developed by Asian companies, Korea's SK Innovation, and Japan's Nippon Mining Metals and Toyota Jidosha Kabushiki Kaisha. The EU's counterparts are some distance behind, with Germany's BASF leading the pack. Data on patenting activities confirm the role of Asia as the powerhouse of the batteries industry and related R&D.

Figure 124: Number of high-value inventions



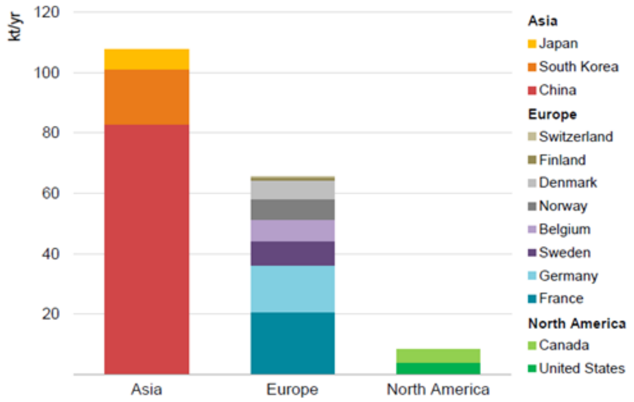
Source: JRC based on EPO Patstat, 2023

25.3 EU competitiveness in the current market

According to the International Energy Agency (IEA), global recycling capacity in 2019 reached 180 kilo-tonnes per year (kt/yr). China accounts for almost 50% of this capacity and is expected to retain its dominant position. The concentration of battery production in Asia is interconnected with the highest recycling capacity, highlighting the importance of logistics – as top producers, Asian countries are able to recycle large amounts of production scrap (see **Figure 125**). Another estimation puts China and South Korea in control of 80% of the Li-ion batteries recycling market (Bielewski, et al., 2022).

The EU's recycling value chain is at an early stage of development, but a number of existing and planned projects are set to ramp up European capacities. The European Battery Alliance estimates that there are currently 35 lithium-ion battery recycling projects either in the planning or development phase in the EU, with numerous facilities starting operations before 2025 (Molina, 2022). Umicore, one of the leading companies worldwide, operates a facility in Belgium with an installed capacity of 7 000 tonnes per year. Northvolt's recycling plant with capacity of 12 000 tonnes of battery packs per year (25 000 EV batteries) opened in 2022. Limited recycling capacity wes added in 2021 through the VW pilot recycling plant in Salzgitter (1 200 t/year) and Fortum's plant in Ikaalinen (3 000 t/year). Others include Nickelhütte Aue (3 000 t/year), Accurec (4000 t/year) and Redux (2 000 t/year) in Germany, with smaller recyclers (of less than 1 000 t/year), SNAM, EDI and TES-AMM (formerly Recupyl) in France, AkkuSer in Finland, and Duesenfeld and Promesa in Germany. In May 2022, Hydrovolt, a battery recycling joint venture between Northvolt and Hydro, started commercial recycling operations at its plant in Fredrikstad, Norway, with capacity to process 12 000 tonnes of battery packs a year (Bielewski, et al., 2022).

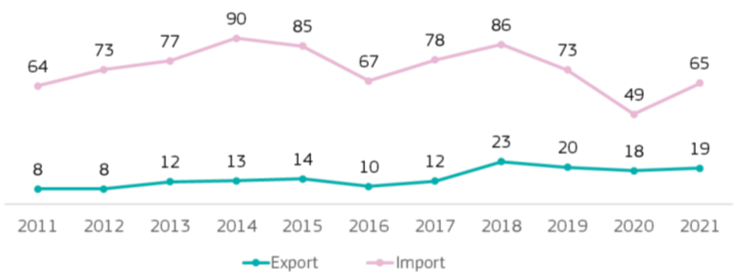
Figure 125. Existing and announced Lithium-ion battery recycling capacity to come online by 2021, by region



Source: *IEA (International Energy Agency, 2021)*

Over the last 10 years, the EU trade deficit has incrementally decreased in the category 'Waste and scrap of primary cells, primary batteries and electric accumulators; spent primary cells, spent primary batteries and spent electric accumulators'. Extra-EU exports have more than doubled since 2008 from EUR 8 million to EUR 19 million, while imports, though fluctuating, have slightly decreased (see **Figure 126**). This unfortunately means that the EU is losing the chance to recover valuable materials from scrap and spent batteries. However, the EU's global share of exports is only 3%. The US is the biggest global exporter, while South Korea and Mexico are the biggest global importers. The UK is the biggest exporting and importing partner of the EU. France, the Netherlands and Germany are the biggest EU exporters. An important characteristic of trade in this category is the high share of trade flows within the EU. Overall, intra-EU imports account for 83% of all EU imports in this category.

Figure 126. The value of the extra-EU import and export [EUR million]



Source: *JRC based on COMEXT data, 2023*

25.4 Future outlook

Scenarios diverge on the exact scale of future end-of-life Li-ion battery supplies, but they all project the exponential growth of spent EV battery supplies in the period 2030-2040. The IEA estimates that globally, the number of spent EV and storage batteries will rise from 100 GWh in 2030 to between 600 GWh and 1.3 TWh by 2040 (International Energy Agency, 2021). Arthur D. Little foresees that by 2030, the total annual European Li-ion battery recycling market will reach about 130 GWh, which will require more than 700 kilo-tonnes (kt) of recycling capacity. It will then triple by 2040, as more EV batteries reach their end of life (Navarro, et al., 2022).

Estimations also vary on the potential of materials recovery. The IEA assumes that by 2040, the recycling and reuse of EV and storage batteries could reduce the primary supply requirement for minerals (lithium, cobalt, copper and nickel) by up to 12%, assuming a collection rate of 80% (International Energy Agency, 2021). The EU's recycling capabilities will grow in the 2030 horizon in particular, reaching 40% of needs in 2025 and 70% in 2030 (Bielewski, et al., 2022).

One of the key factors supporting the development of the EU recycling sector will be a strong legislative framework provided by a recast of regulation 2019/1020, concerning batteries and waste batteries. At the time of writing, the final shape of the regulation is in tripartite negotiations, but it will certainly introduce targets for the collection and recycling of all batteries in the EU. New targets will include mandatory minimum levels of recycled content for new batteries, recycling efficiencies for Li-ion and other types of batteries, material recovery targets for particular materials and labelling with information necessary for the identification of batteries. Development of the recycling industry is also one of priorities of the European Battery Alliance.

The EU batteries recycling market, though currently small, has strong potential for growth. Cooperation is important between the different stages of the value chain, to facilitate industrial convergence and the emergence of companies specialising in recycling. It is also expected that the recycling market will attract an increasing number of non-European entrants (Navarro, et al., 2022). Key to the future recycling market will be the question of profitability. This will partly depend on the price of raw materials, which is expected to increase due to pressures on supply and increased international competition.

25.5 Scoreboard and key insights

The EU batteries recycling sector is in its early days and attracting increasing amounts of early and late stage investment, particularly in Sweden. The EU share of global investment has increased to 16% and 66% for early and late stage, respectively, resulting in medium and high scores. EU spending on R&D has also gone up. While public spending data on R&D is not available at Member State level, investment reached EUR 250 million at EU level in 2014-2022, with the majority of grants signed in the last three years. 18% of innovating companies are headquartered in the EU, which places it in the medium range. Several new recycling plants are expected to become operational in the EU in the coming years, under the auspices of Umicore, Northvolt, Volkswagen, BASF and a number of smaller companies (Molina, 2022). EU patenting activity has increased since 2016, placing it third, with 17% of high value inventions, after Japan and China. Only one EU-based company, the German BASF, featured in the global top ten. This results in a medium score.

EU production volumes are not included in the scoreboard due to a lack of reliable data. Nevertheless, recycling capacity is increasing, with 35 developed and planned recycling facilities underway. Overall capacity should grow significantly after 2025. The trade balance indicators are reversed, because improved circularity means exporting less battery waste outside the EU, with a negative or zero trade balance therefore rated as high performance. The EU accounts for only 3% of global battery waste exports, indicating a limited waste stream so far, and some domestic recycling. Performance on this is therefore ranked high. The EU imported more battery waste than it exported in 2011-2021, which indicates that the EU recycles more than its own battery waste. However, the trade deficit is shrinking due to growing exports, which is a concerning trend, and therefore the performance here is ranked as medium.

Figure 127. Scoreboard ([195]) for batteries recycling

Scoreboard	**Battery recycling**	EU performance in the reference period		
Public R&D			2016-2020	EU CAGR
Early Stage	●	16%	2016-2021	EU share of global total value
Later Stage	●	66%	2016-2021	EU share of global total value
Patents	●	17%	2016-2019	EU share of global total HVI
Companies	●	18%	2016-2021	EU share of innovating companies
Employment			2016-2020	EU CAGR
Production			2016-2021	EU CAGR
Turnover			2016-2020	EU CAGR
Imports & Exports	●	3%	2019-2021	EU share of global exports
Trade Balance	●	Medium	2016-2021	EU trade balance trend

Source: JRC, 2023

([195]) Scoring criteria for Imports&Exports and Trade balance are reversed for the circularity solutions because exporting waste streams outside the EU, implies a loss of circularity opportunity and a possibility to recover valuable materials.

26 Plastics recycling

Synthetic plastic materials entered the market in the early 20th century and became ubiquitous thanks to their low weight and variable shape. Whereas the majority of plastics are used for packaging, plastics also play an important role in the sectors of construction, electric and electronic appliances, automotive industries and agriculture (European Commission, 2018).

In 2021, global plastics production reached more than 390 million tonnes, and European ([196]) production more than 57 million tonnes (Plastics Europe, 2022). However, more than 90% of plastics produced worldwide are fossil-based. In Europe, only about 10% of all plastics produced in 2021 were derived from post-consumer recycled plastics. Considering that almost 40% of plastics are used for packaging, the actual lifetime of plastic articles is often very short, resulting in the generation of large amounts of plastic waste. Of the ~30 million tonnes of plastic waste produced in Europe in 2021, two thirds ended up in incineration or landfill and only one third was collected for recycling. Some waste plastics are not properly discarded or collected and end up in the ocean. This is estimated to be 1.5 to 4% of the global plastics production.

26.1 Overview of the solution and current status

The high dependence on a steady supply of fossil resources for the manufacturing of plastics represents a major challenge to the European economy in terms of climate change, sustainability and strategic autonomy. Hence, policymakers and actors in the European plastics value chain are looking for ways to boost recycling.

Mechanical recycling constitutes the majority of the present-day plastics recycling landscape. The main value chain steps involved in mechanical plastics recycling are waste collection (either as mixed waste or separately collected waste), sorting, actual recycling (shredding, cleaning, melting) to produce new pellets and conversion of recycled pellets to new plastic products. However, as recycling ambitions are growing, new physical and chemical recycling technologies are entering the market (see **Box 3**).

According to the Waste Framework Directive (2008/98/EC)([197]), the scope of plastics recycling is strictly limited to the conversion of plastics into new plastic materials or other materials. The conversion of plastics to energy, e.g. in waste incineration plants, or into fuels, is excluded from the scope. This is important to note as many new technologies branded as recycling in reality constitute a combination of material recovery and energy recovery, or even plain energy recovery. Moreover, although ranked higher in the waste hierarchy, the scope of plastics recycling does not include the reduction of plastic waste (e.g. by reducing the weight of packaging), re-use of plastic items (e.g. sales of second-hand plastic toys) or preparation for re-use (e.g. repairing a discarded fridge). Technologies that break down plastics into innocuous components without making use of the resulting materials are not considered recycling either (e.g. biodegradation of plastics). Finally, replacing fossil-based plastic materials with bio-based plastics or other alternative materials equally falls out of scope.

26.2 EU competitiveness in innovation and future markets

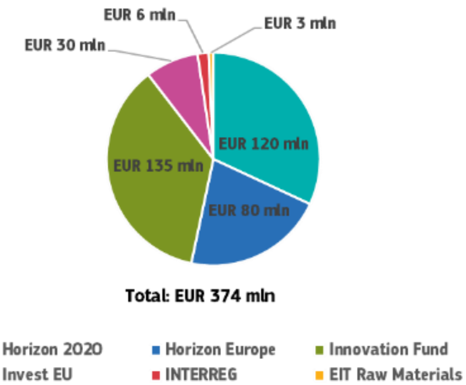
The EU has invested in plastic recycling R&D through various instruments, with Horizon 2020 (2014-2020) and Horizon Europe (2020-2027 ([198])) contributing the biggest share of research funding. EUR 80 million has already been allocated within the first two years of the Horizon Europe programme period, indicating a potential growth of investment compared to the previous programme period (Horizon 2020). The Innovation Fund, which focuses on the demonstration of innovative low-carbon technologies, was the second biggest source (see **Figure 128**).

([196]) European data includes EU27, UK, Norway and Switzerland

([197]) Directive 2008/98/EC. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02008L0098-20180705

([198]) Projects funded until 2022 are included.

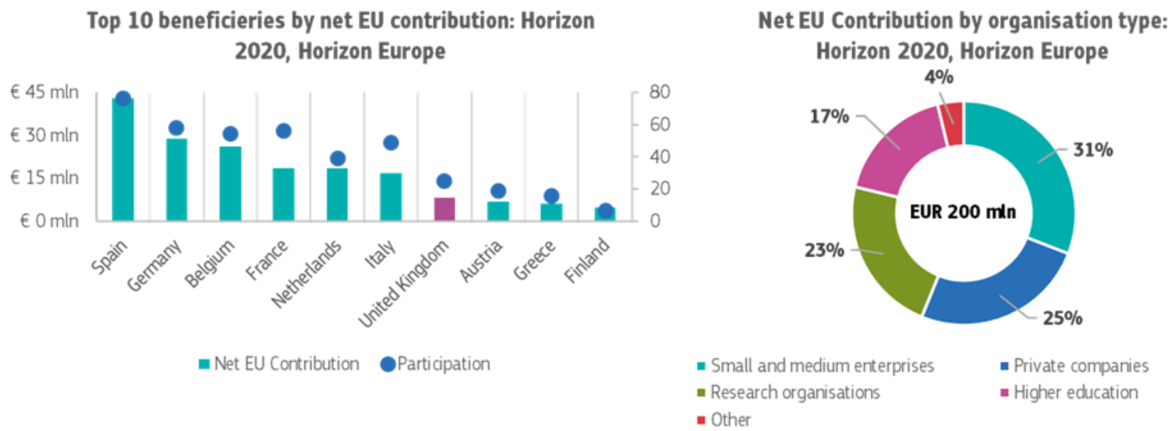
Figure 128: EU-funded research and development (2014-2022)



Source: JRC based on CORDIS data, 2023

Spain has been the biggest recipient of EU Horizon funds since 2014 and has had the biggest number of participants (see **Figure 129**). The same figure also shows that private companies and SMEs play a significant role in plastics recycling R&D, together receiving well over half of EU funds. This is not surprising given that companies have an incentive to develop recycling techniques in order to comply with EU legislation. Nevertheless, a big share of SMEs is a positive sign for emergence of an innovative ecosystem. Member States also fund R&D through their national programmes, but this data is not available.

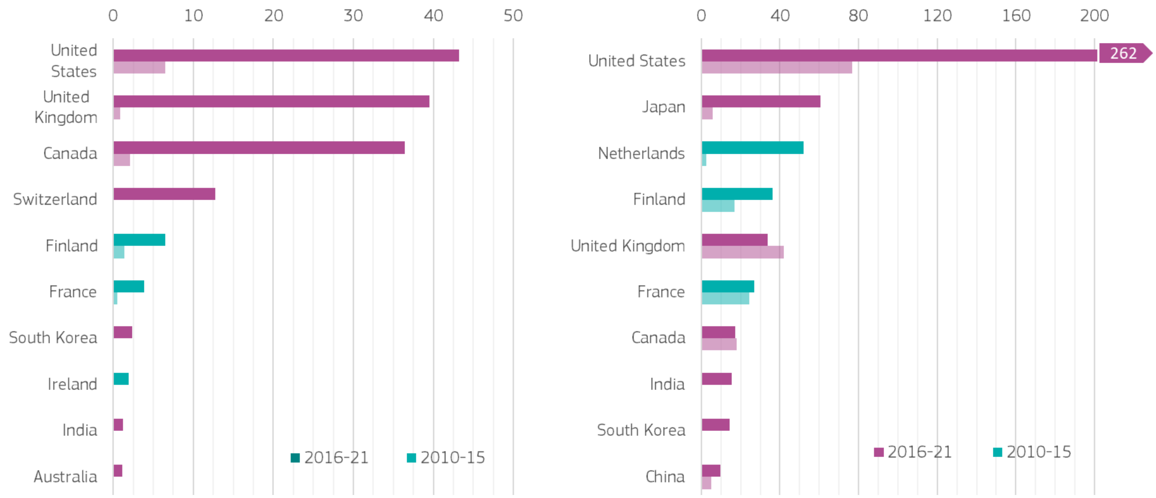
Figure 129: Top ten beneficiaries by net EU contribution (left) and net EU contribution by organisation type (right) (Horizon 2020, Horizon Europe 2014-2022)



Source: JRC based on CORDIS data, 2023

Early stage investment in the field of plastics recycling is dominated by the US, UK and Canada, which together accounted for almost four fifths of worldwide early stage investment in the past decade (see **Figure 130**). Whereas global early stage investment saw more than a twelve-fold increase from EUR 12 million in the period 2010-15 to EUR 152 million in the period 2016-21, the share of EU countries dropped from 16% to less than 10% over the same period. Finland, France and Ireland were the top EU countries in terms of early stage investment.

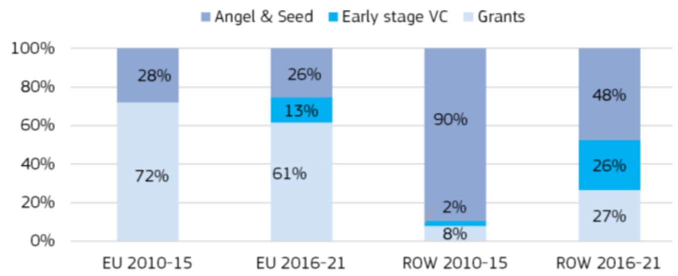
Figure 130: Top countries by early (right) and later (left) stage investment [EUR million]



Source: JRC based on Pitchbook, 2023

Grants outweighed angel and seed investment as well as early stage VC investment in the EU, with shares of more than 60% of overall early investment over the periods 2010-15 and 2016-21 (see **Figure 131**). By contrast, angel and seed investment played a key role in early stage investment in the rest of the world, varying between 48% and 90% over the same periods.

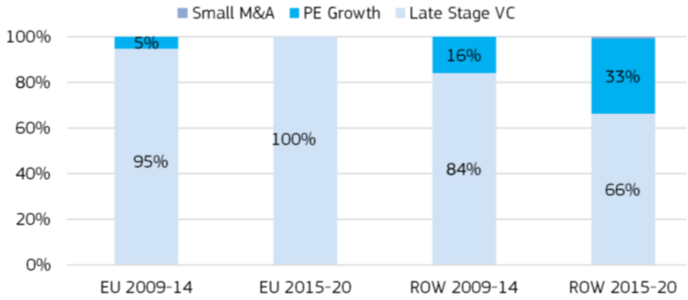
Figure 131: Share by investment type and region



Source: JRC based on Pitchbook, 2023

In later stage investment (see **Figure 130**), the trio, the US, UK and Canada, maintain an important role, representing together 43% of the global EU 315 million investment in the period 2010-2015, and 58% of the global EU 539 million investment in 2016-2021. However, this is mainly thanks to the top position of the US, which alone represented 24% of worldwide later stage investment in 2010-2015 and 49% of worldwide later stage investment in 2016-2021. Japan became a major player in later stage investment in 2016-2021, claiming the second position with 11% of global later stage investment. The EU's share in global later stage investment grew slightly from 20% in 2010-15, to 23% in 2016-21, led by the Netherlands, Finland and France. Late stage VC was the predominant type of later stage investment around the world, especially in the EU, with a share of 100% over the period 2016-21, whereas private equity growth complemented the later stage investment spectrum (see **Figure 132**). Small mergers and acquisitions played almost no role anywhere.

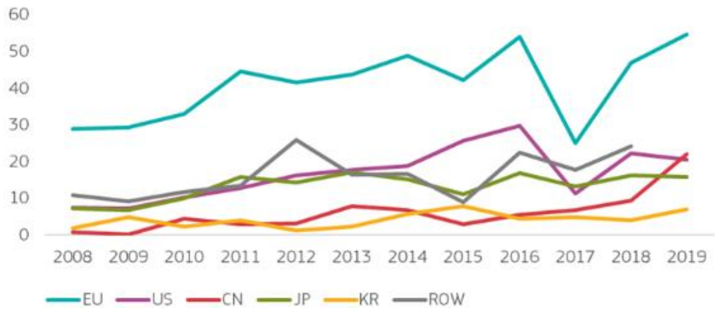
Figure 132: Share by investment type and region



Source: JRC based on Pitchbook, 2023

Seen through the prism of patenting activity, the EU has been leading the world for many years (see **Figure 133**), in line with its overall leadership in inventions related to circularity (Grassano, et al., 2022). This is mainly thanks to a strong performance by Germany, France, Italy and the Netherlands, who occupy spots four to seven in the individual country ranking, after the US, Japan and China and followed by Canada, South Korea and Taiwan. In the period 2016-2019, the EU share of high-value inventions amounted to 37% of the worldwide total. In general, global circular economy technology inventions are concentrated in the Chemicals & Plastics sector, which generates the biggest share of circular inventions, especially in the EU and US (Grassano, et al., 2022).

Figure 133: Number of high-value inventions



Source: JRC based on EPO Patstat, 2023

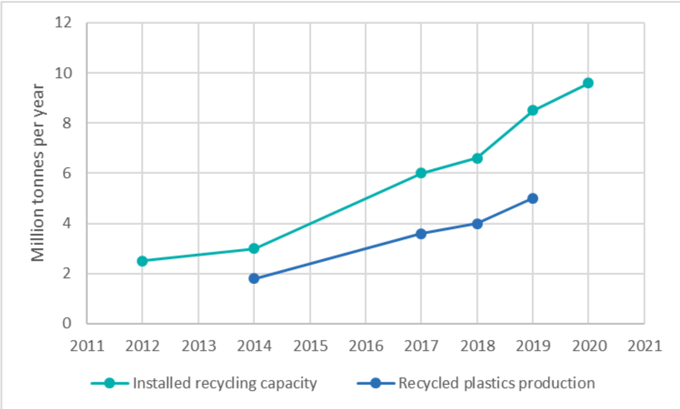
The US, Japan and the UK host the largest number of innovating companies, followed by France, the Netherlands and Germany. Italy, Austria, Sweden, Belgium and Finland also appear in the top 15 countries worldwide in terms of the number of innovating companies. With 78 companies, the EU holds one third of the world's 233 innovating companies in plastics recycling. Both globally and in the EU, the number of VC companies outweighs the number of corporates and they are more evenly spread geographically than the corporates, with coverage in developing countries in Africa.

Investment in plastics recycling is expected to grow substantially in the future. In the short term, the Circular Plastics Alliance, an alliance of organisations across the plastics value chain focussed on increasing the circularity of plastics, expects to boost the output of recycled plastics in the EU27+UK from 6.3 million tonnes in 2020 to 9.6 million tonnes in 2025, by investing between EUR 7.6 and EUR 9.3 billion (Circular Plastics Alliance, 2021). In the longer term, recycling will play an even bigger role in the plastics sector. The European plastics umbrella trade organisation, Plastics Europe, estimates that by 2050, nearly 60% of global plastics production could be based on reuse and recycling (Plastics Europe, 2023). Many in the recycling sector are especially betting on chemical recycling as the new breakthrough technology (see **Box 3**). In May 2021, Plastics Europe announced a significant increase in planned chemical recycling investment by its members, from EUR 2.6 billion in 2025 to EUR 7.2 billion in 2030. By doing so, it expects to produce 1.2 million tonnes of recycled plastics in 2025 and 3.4 million tonnes in 2030.

26.3 EU competitiveness in current market

Plastics recycling in Europe [199] is an important industry, representing over EUR 7.7 billion in turnover, 9.6 million tonnes of installed recycling capacity, more than 650 recycling facilities and over 20 000 employees, as of 2020 (Plastics Recyclers Europe, 2023). In the last decade, the industry has been growing rapidly, both in terms of recycling capacity and actual production of recycled plastics (see **Figure 134**).

Figure 134: Evolution of plastics recycling capacity and recycled plastics production in EU27+UK, Norway and Switzerland



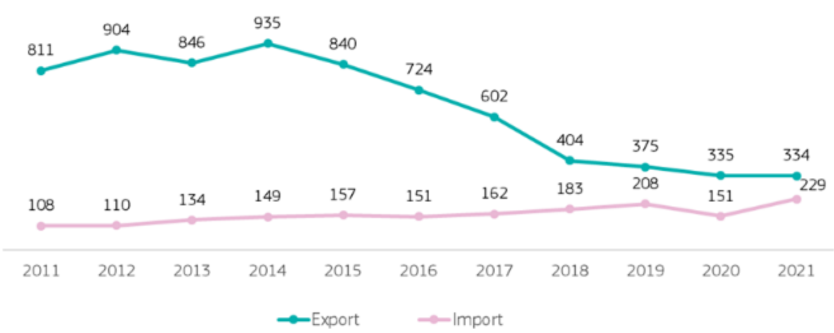
Source: JRC based on Plastics Recyclers Europe data (Plastics Recyclers Europe, 2022; Plastic Recyclers Europe, 2022)

About 80% of the total recycling capacity in Europe relates to the recycling of the polymers, polyethylene terephthalate (PET), low density polyethylene (LDPE) and rigid polyolefins (high density polyethylene – HDPE and polypropylene-PP) (Plastics Recyclers Europe, 2020). Five European countries cover two thirds of all recycling capacity, namely Germany, Italy, Spain, France and the UK.

The growth in the industry is partly due to a favourable policy climate that has been advocating more sustainable plastic management, from the 2013 Green Paper on a European Strategy on Plastic Waste in the environment, the Circular Economy Action Plan in 2018 and its successor in 2020, to the Single Use Plastics Directive in 2021. Furthermore, exports of low quality plastic waste outside Europe have decreased over time due to international awareness of the actual fate of these plastics, as they often ended up on (illegal) landfills or being dumped in river ways and oceans. Moreover, China, which was previously a large importer of plastic waste from around the world, enacted a de facto ban on the import of low quality plastics in 2018, under Operation National Sword.

This growing domestic EU demand for recycled plastics is reflected in EU trade. The trade balance in recycled plastics has been steadily decreasing over the past decade, with exports decreasing and imports increasing at the same time (see **Figure 135**), clearly indicating increased circularity in Europe.

Figure 135: Extra-EU Import & Export [EUR Million]



Source: JRC based on Comext data, 2023

(199) European data includes EU27, UK, Norway and Switzerland

26.4 Future outlook

With the focus on achieving net-zero carbon emissions by 2050, and a drive towards a more circular economy, plastics recycling is expected to continue to grow substantially in the EU, as well as globally. The Single Use Plastics (SUP) Directive (2019/904)([200]), in force since 2021, sets ambitious targets for collection and recycled content for single use plastic bottles, as well as a series of measures for other single use plastic articles. In November 2022, the Commission tabled a proposal for a new Packaging and Packaging Waste Regulation (European Commission, 2022d), to substantially reduce, reuse and recycle packaging materials, in particular plastic packaging. The proposals promote a substantial increase in recycled content for plastic packaging materials, up to 35% by 2030 and up to 65% by 2040 for certain types of plastic packaging, thus transposing the objectives set out in the European Green Deal (European Commission, 2019b). The European Green Deal advocates more recycled content in others sectors as well. As a result, proposals have been brought forward to require, for example, a mandatory recycled content for plastics used in new cars (European Commission, 2021b).

With a long-standing tradition in recycling, the EU has built up considerable expertise in recycling technology. Current recycling technology can still be expanded and improved, e.g. by design-for-recycling standards, which ensure that plastic products put on the market are suitable for recycling, but also by expanding the separate collection of plastic waste and further deployment of recycling infrastructure. New technologies like digital watermarking (AIM, 2021) and artificial intelligence coupled with optical detection technologies, ensure better sorting of plastic materials and hence the improved quality of plastics sent for recycling, with fewer losses. These new technologies may also affect the types of jobs on offer in the waste management sector. At present, many jobs in the recycling sector involve manual, unskilled labour (Politico, 2018), but this could change.

However, with ever higher demands for recycled plastic content, some believe that mechanical recycling might at some point meet its limitations. They see chemical recycling as a way to unlock more recycling potential (see **Box 3**).

Box 3: Is chemical recycling the panacea for our future recycling challenges?

Mechanical recycling dominates today's plastic recycling technology landscape. It is in essence a relatively simple process in which plastic materials are separated by type of polymer and colour, shredded, cleaned and then remelted into new plastics. It is particularly efficient for plastic materials from waste fractions that have been separated at source. According to Plastics Europe, plastic waste recycling rates are 13 times higher when plastic waste is collected separately, compared to plastic waste recovered from mixed waste collection schemes (Plastics Europe, 2022). However, substantial proportions of plastics are still lost in the mechanical recycling process due to the impossibility of separating them from other plastics (e.g. in multi-layered plastics) and other materials (e.g. glued to metal), contamination with chemicals (e.g. solvents) or the presence of certain pigments (e.g. carbon black). Moreover, plastics tend to degrade during use (e.g. due to exposure to sun) or in the actual recycling process (e.g. due to remelting). It should also be noted that plastics are complex materials that consist of a synthetic polymer with a certain structure and chain length and a series of additives that attribute specific physical and chemical properties, such as physical strength, colour and transparency. Hence, when plastics from different sources are recycled together, this results in a new plastic material with different properties and colour, which are difficult to predict beforehand. As a result, mechanical recycling has its limitations and few polymers will be recycled more than once or twice.

Chemical recycling may provide the answer at least to some of these limitations. Chemical recycling is not a single technology but a comprehensive technical term for a series of technologies that alter the chemical structure of the plastic (Crippa, et al., 2019). To start with, chemical recycling of plastics may either refer to processes that are considered physical recycling, in which the chemical composition of the *plastic matrix* is altered but without changing the chemical structure of the embedded *polymer*, or to processes that are considered actual chemical recycling, in which the chemical structure of the polymer is altered.

Physical recycling removes the plastic polymer from its matrix of additives by dissolving the plastic in a solvent and recovering the pure polymer. Physical recycling is therefore also called solvent-based purification. It is a relatively mild process in terms of energy and chemical usage and produces high-purity polymers. It can also be used to separate various types of polymers from a multi-layered plastic material, e.g. the films used to pack food in a protective gas atmosphere.

([200]) Directive (2019/904). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32019L0904

Chemical recycling distinguishes between depolymerisation and feedstock recycling technologies. Depolymerisation technologies split the polymer into shorter chain molecules (oligomers) or monomers, using a solvent and heat. The generic term is solvolysis and the so-called solvolytic processes include glycolysis, hydrolysis and methanolysis. Feedstock recycling technologies turn the polymer into feedstock chemicals such as pyrolysis oil (via pyrolysis) or syngas (via gasification), which can be used to synthesise new plastics or other chemical compounds.

The advantages of chemical recycling include the possibility of certain processes to treat mixed polymers or slightly contaminated polymers, thereby producing high-quality new polymers, including possible food-contact materials. Disadvantages include the technical complexity of many processes, often requiring large-scale installations in order to be economically viable. Furthermore, compared to mechanical recycling, several chemical recycling processes have higher energy and chemical demands. Finally, in many chemical recycling processes, and in feedstock recycling in particular, not all plastic material input is recycled, and some of it is recovered only in the form of energy or fuels, or lost as emissions. These technical challenges linked to chemical recycling explain why plastics recycling has traditionally been dominated by mechanical recycling with only a few chemical recycling installations active in the EU and worldwide at present.

26.5 Scoreboard and key insights

The EU performs strongly on all innovation-related indicators and therefore seems to have sufficient preconditions to capture future market opportunities. In patenting, the EU has an upward trend and generates 37% of all high value inventions (2016-2019), far outperforming its economic size. The EU accounts for five of the top ten corporates by patenting activity. The EU corporate base is made up of chemical and material industry companies (e.g. Arkema, Borealis, Lenzing), technology providers (e.g. Ioniqa Technologies and Previero) and the end-use sector. Complemented by a growing number of VC companies, the EU hosts 33% of all identified innovators in the area, which again outweighs its economic size. EU companies captured 23% of later stage investment but only 10% of early stage investment (bearing in mind that a significant number of EU deals have not been disclosed). While Member State public R&D investment data is not available, at EU level, investment was nearly EUR 400 million in 2014-2022. A significant share of this went towards demonstration, as was also manifested by a high share of grants in early stage financing compared to the rest of the world. Thus, the EU perform well, but so does the US, especially in venture capital investment.

The data related to current markets is scarce. The plastics recycling industry in Europe ([201]) is an important sector, which is set to grow rapidly in the coming years with the development of chemical recycling technologies beside the more established mechanical recycling. It should be noted that the ranking of criteria for Imports & Exports and Trade balance indicators is reversed, because improved circularity results in fewer exports of plastic waste outside the EU. To be rated as high performance, the trade balance should therefore be negative or close to zero. The EU generated 20% of global plastic waste exports in 2019-2021, which is more than its fair share in terms of economic size (18%). Nevertheless, concerted policy action has led to improving circularity in the EU, as seen in the gradual reduction of extra-EU exports. Improving recycling capacity and demand from the end-use industry are, in fact, increasing imports, and the EU is therefore on the way to becoming a net importer, clearly indicating improvements in circularity.

([201]) European data includes EU27, UK, Norway and Switzerland

Figure 136: Scoreboard ([202]) for plastics recycling

Scoreboard	**Plastics recycling**	EU performance in the reference period		
Public R&D			2016-2020	EU CAGR
Early Stage		10%	2016-2021	EU share of global total value
Later Stage		23%	2016-2021	EU share of global total value
Patents		37%	2016-2019	EU share of global total HVI
Companies		33%	2016-2021	EU share of innovating companies
Employment			2016-2020	EU CAGR
Production			2016-2021	EU CAGR
Turnover			2016-2020	EU CAGR
Imports & Exports		20%	2019-2021	EU share of global exports
Trade Balance		Medium	2016-2021	EU trade balance trend

Source: JRC, 2023

([202]) Scoring criteria for Imports&Exports and Trade balance are reversed for the circularity solutions because exporting waste streams outside the EU, implies a loss of circularity opportunity and a possibility to recover valuable materials.

27 Permanent magnets

Green energy technologies – particularly wind energy technology (aerogenerators) and electric mobility (electric traction motors) – require high-performance permanent magnets to operate. Neodymium magnets (Nd-Fe-B) are the best performing magnets in terms of Maximum Energy Product and are the most widely used in the industry.

The EU relies heavily on wind energy to decarbonise its electricity production and deliver on its renewable energy targets. To fulfil the current renewable energy target of at least 42.5%, wind capacity is projected to grow from 204 GW in 2022 by an average of 30 GW per year to 2030 (Wind Europe, 2023). Decarbonisation of the transport sector also relies heavily on electrification. According to the Sustainable and Smart Mobility Strategy, by 2030 there should be 30 million zero-emission vehicles in the EU (European Commission, 2020e). Demand for permanent magnets will therefore increase accordingly.

This chapter will focus on neodymium magnets, which are crucial to the success of the energy transition in the EU. They are of particular concern due to the limited options for technology substitution, the high import dependency (particularly on China), and their critical importance to the functioning of several advanced technologies. It will also address possible measures to support EU autonomy foreseen in the Critical Raw Materials Act, in the form of investment in the *domestic value chain* and increased *recycling* of permanent magnets. Ferrite magnets will also be discussed, as a possible *substitution option for* neodymium magnets in certain e-mobility applications.

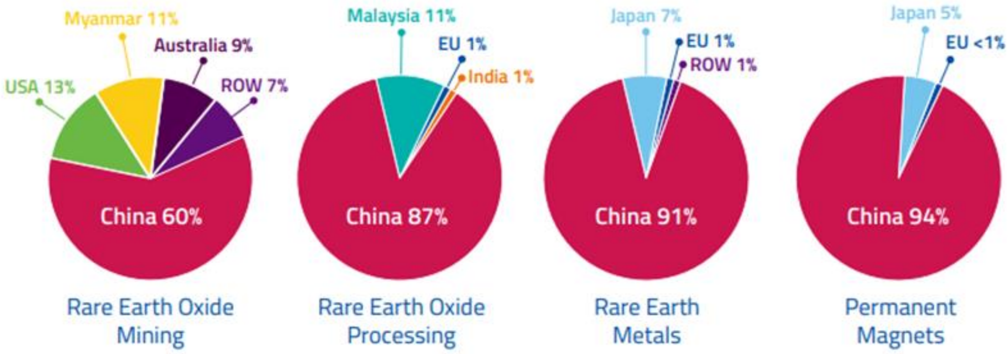
27.1 Overview of the solution and current status

There is only one material available on the market capable of delivering the energy density required to guarantee the efficient working of wind turbines (with capacity exceeding 2.5 MW): neodymium magnets (Nd-Fe-B). In 2019, neodymium magnets represented almost 70% of the permanent magnets market, with ferrite magnets (non-rare earth) taking up the other 30% (Rizos, et al., 2022). Neodymium magnets maximise the electricity generation capacity, decrease the maintenance costs and improve the reliability of wind turbines. Depending on the size and type of turbines, 1 MW of wind generation requires up to 600 kg of neodymium magnets. Permanent magnets are also widely used by the automotive sector for both conventional vehicles and electric vehicles (and other forms of e-mobility such as e-bikes and e-scooters). The high performance of neodymium magnets gives e-cars a longer driving range. It is estimated that each electric car contains 2-2.5 kg of Nd-Fe-B magnets.

About 30% of the weight (wt%) of neodymium magnets is made up of a range of rare earth elements. Nd-Fe-B actually has a more complicated composition than the name suggests. In addition to iron (Fe) and boron (B), the alloy includes light rare-earths (LREs), neodymium (Nd) and praseodymium (Pr), and heavy rare-earths (HREs), dysprosium (Dy) and terbium (Tb). Rare-earth elements are classified as critical raw materials (CRMs). There are additional CRMs also used in magnets, typically cobalt (Co). All of them are used with specific objectives, such as increased operation temperature or enhanced coercivity, to guarantee the best performance for their application.

Extracted ores containing neodymium and other minerals are separated and refined to obtain individual oxides or metals, which are then used for different manufacturing processes. In the case of permanent magnets, the required metals are melted together in a vacuum to obtain an alloy, which is then transformed into a powder. At this stage, there is a choice of two manufacturing processes to create the magnet. The bonded magnet approach developed by General Motors involves mixing the alloy powder with polymers to create a mouldable putty. The sintered magnet approach developed by Sumitomo requires the powder to be pressed together under a specific heat profile. In both cases, magnetisation can be induced either during the treatment of the powder or in a separate phase. Sintered magnets are usually more compact and have stronger magnetic properties, and therefore account for over 90% of today's Nd-Fe-B magnet production.

Figure 137: From rare earths mining to permanent magnets manufacturing: estimated market shares in 2019



Source: ERMA 2021 – Rare Earth Magnets and Motors: A European Call for Action based on JRC and others

The challenge faced by the EU is that the entire value chain of permanent magnets production is concentrated in China. China accounts for 60% of raw materials mining, and dominates the midstream and downstream segments of the value chain, with shares above 90%. In comparison, the EU's raw material mining, rare earth oxides processing and metal making capacities are almost non-existent what creates a major bottleneck for the production of wind turbines in the EU. Such near-monopoly is all the more concerning when projections are taken into account of future demand for permanent magnets, in line with the expected growth of wind energy and e-mobility. This demand is expected to triple between 2020 and 2030 in the EU, from 12 000 tonnes to about 36 000 tonnes. In 2030, 32% of permanent magnets are expected to be used for the production of wind turbines and 53% for electric vehicles and e-bikes (Rizos, et al., 2022).

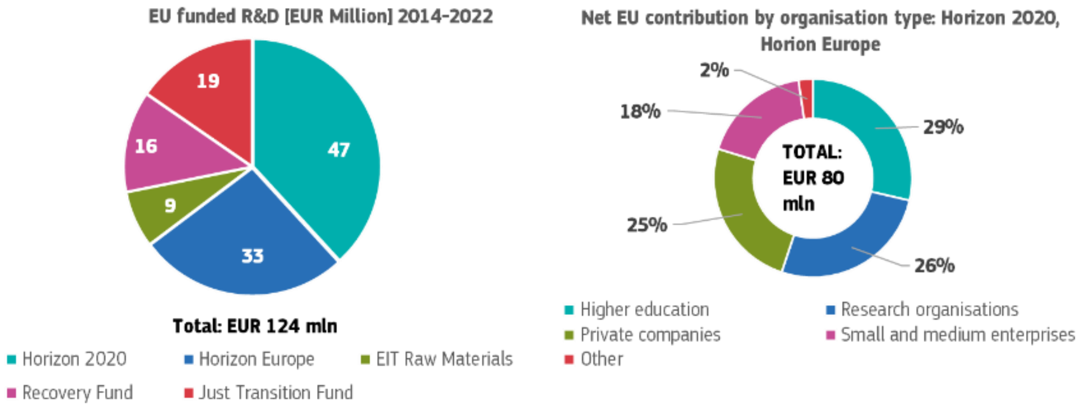
27.2 EU positioning in innovation

EU public R&D expenditure on permanent magnet technologies in the period 2014-2022 was almost EUR 124 million (see **Figure 138**). The main funding instruments were Horizon 2020 (2014-2020) and its successor, Horizon Europe. The top beneficiaries were entities from Germany, which received a net EU contribution of more than EUR 20 million, followed by Spain at EUR 9 million and the United Kingdom at EUR 7 million (see **Figure 139**). Research expenditures reflect a growing interest in this technology, with the funding allocated by Horizon Europe in its first two years almost matching the amount allocated during the entire Horizon 2020 funding period.

The biggest recipients of EU funds (including EIT RawMaterials calls) have focused on recycling (six ongoing projects), innovation in rare earth-based magnets (three ongoing projects), and rare earth-free permanent magnets (one project involving a consortium and one individual ERC grant). More than half of all beneficiaries in Horizon Europe and Horizon 2020 came from academia and research organisations, with private companies next in line.

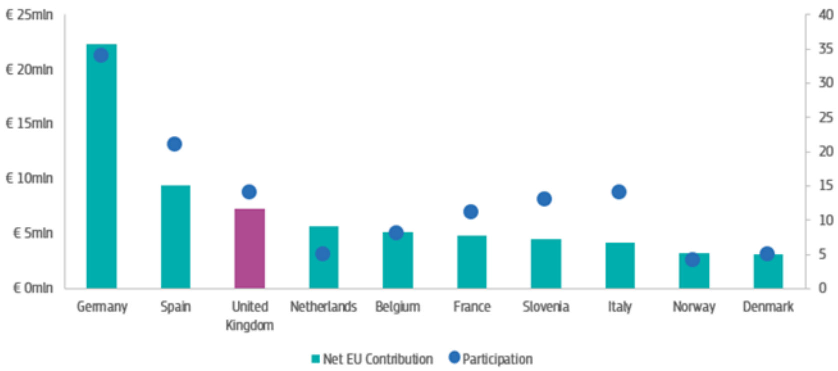
Funding from other programmes not primarily focusing on R&D – the Just Transition Fund and the EU Recovery and Resilience Facility – have also been included in this section. Under the Just Transition Fund, the Government of Estonia provided a grant of EUR 18.7 million to Neo to support the construction of a state-of-the-art rare-earth permanent magnet manufacturing facility in Estonia. The Recovery fund provided grants for two projects related to magnets recycling in France, including EUR 15 million for the construction of an innovative plant for recycling rare-earth minerals such as neodymium from end-of-life products. Data was not available on EU Member State R&D funding through national frameworks.

Figure 138. EU research funding in the period 2014-2022 [EUR million] (left) and net EU contribution by organisation type (right) for Horizon 2020 & Horizon Europe (2014-2022)



Source: JRC based on CORDIS data, 2023

Figure 139. Top ten beneficiaries by net EU contribution [EUR million] (Horizon 2020, Horizon Europe 2014-2022)



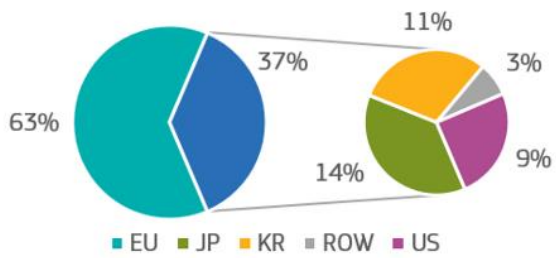
Source: JRC based on CORDIS data, 2023

Bibliometric analysis reveals an interesting research trend. The 'rare-earth crisis' in 2010-2011 – a trade dispute caused by Chinese restrictions on the export of several rare-earth minerals – seems to have triggered a growing number of scientific publications addressing alternatives to rare-earth permanent magnets. Research has focused on ferrites, and on returning to alternatives such as tetrataenit, Mn-Al(-C) and Mn-Bi (though the criticality of bismuth is also a concern)([203]).

Patenting activity in the area of permanent magnets (ferrite and Nd-Fe-B) used for clean energy applications[204] is limited. Most applications were filed by private companies, in Germany, the US, Japan and Korea, with institutes and universities filing in Slovenia and France. Germany is the top patenting country, with four patents: two filled by the Fraunhofer Society, one by the University of Rostock and one by Netzsch, a company which has developed an extremely fine grinding process for the production of rare-earth powders (Powder Metallurgy review, 2018). Despite Chinese market dominance, as observed in most climate change mitigation technologies, China has a high number of inventions but only protected in its internal market. In contrast the EU performs well in terms of inventions protected in more than one markets. The EU accounts for 63% of global high value patents, followed by Japan (14%) and South Korea (11%) (see **Figure 140**).

([203]) Results obtained through an advanced search by keywords ferrite, Mn-Al(-C) and Mn-Bi permanent magnet, from Scopus.
([204]) Ferrite (rare-earth-free permanent magnets) and neodymium (Nd-Fe-B) magnets intersecting with the Y02 classification – technologies or applications for mitigation or adaptation against climate change. The intersection ensures consistency with the rest of the study; however as it limits the results, they have to be interpreted with caution. Future work could expand beyond the Y.

Figure 140. Share of global high value inventions, 2016-2019

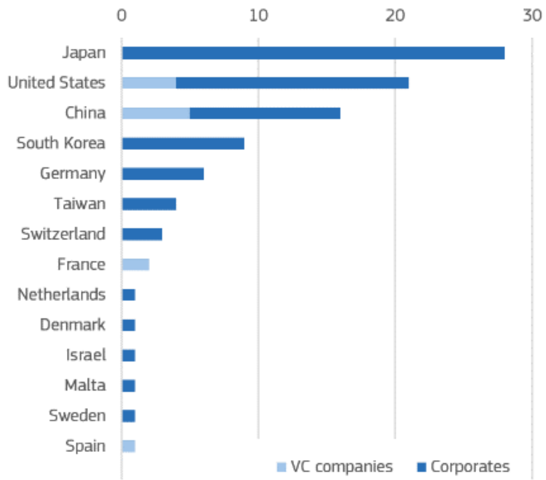


Source: JRC based on EPO Patstat, 2023

In terms of venture capital investment, based on disclosed information, the top EU performer is France, which alone has captured 49% of global early stage investment. This performance can be explained by the EU Recovery fund grants in 2021. In the period 2016-2022, the EU only captured 1% of global late stage investment. Overall, the US leads in early and late stage investment combined, with China coming second.

There are 13 innovating companies in the EU (10 corporate and three venture capital). Germany is the best performing Member State, with six innovating companies (all corporate), followed by France with four (all venture capital). The top performer in this category is Japan with 28 identified companies (all corporate), followed by the United States with 21 companies (four venture capital) and China 16 (five venture capital), (see **Figure 141**). Overall, this solution is dominated by corporates, which explains the limited venture capital investment. The venture capital companies identified are active in the USA, China, France and Spain.

Figure 141. Number of innovative companies, 2016-21



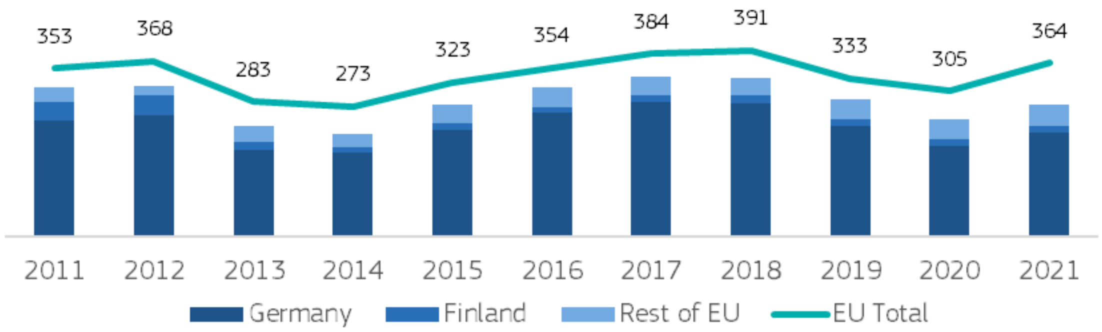
Source: JRC compilation of sources, 2023

27.3 EU positioning in the current market

Globally, in 2019, around 130 000 tonnes of neodymium magnets were produced worldwide, at a market value of about EUR 6.5 billion. Of these, 93% were produced in China (European Raw Material Alliance, 2021). There are eight manufacturing companies in the EU which produce magnets from rare-earth powders or alloys (Carrara, et al., 2023). Four of them operate in Germany (with one production factory located in Slovakia), two in Slovenia and one each in the Netherlands and Finland. However, their production capacities are too low to guarantee EU autonomy in this field, with the EU accounting for only 1% of global neodymium permanent magnet production (Rizos, et al., 2022).

Despite increasing demand, the EU's production value has remained relatively unchanged over the last decade. It has, however, fluctuated in line with rare-earth prices, as a consequence of world events. The rare-earth crisis in 2011 resulted in higher raw materials prices, resulting in decreasing production over the following two years. Another spike in 2017-18 created a similar decrease, which was further aggravated by the COVID-19 economic slowdown. Recent price volatility has affected the confidence of companies which purchase rare earth elements in advance. Overall, Germany is the EU's top producer, followed by Finland, Italy, Czechia, Denmark and Lithuania (included under "Rest of EU", see **Figure 142**).

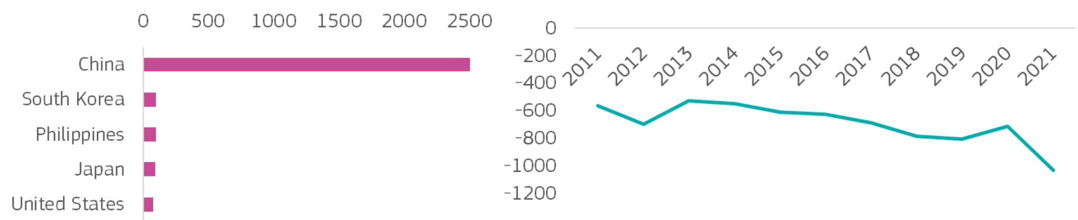
Figure 142: Total production value in the EU and top producer countries 2011- 2022, [EUR million]



Source: JRC based on PRODCOM, 2023

The EU trade deficit has almost doubled within the last decade, reaching EUR 1 billion in 2021 (see **Figure 143**). This reflects increasing EU production of high-tech products containing permanent magnets, and serves to underline the lack of sufficient EU production capacity. Overall, the EU holds a share of only 4% of global exports. China dominates in terms of exports to the EU, with an export value of EUR 2.5 billion in the period 2019-2021 (with minor contributions from South Korea, the Philippines, Japan and the USA). Germany, Italy and Hungary have the highest trade deficits among EU Member States.

Figure 143. Top 5 exporters to the EU [EUR million] (left) and the extra-EU trade balance [EUR million] (right)



Source: JRC based on COMEXT data, 2023

27.4 Future outlook

The EU's increasing dependence on imported neodymium magnets poses a strategic challenge. Any disturbance of supply due to disrupted global value chains, trade disputes or a breakdown in bilateral relations between China and the EU, could undermine the twin green and digital transition. EU demand for such components is projected to grow fast, and the risk is real of replacing one dependency on imported fossil fuels for another on neodymium permanent magnets and other rare earth minerals.

In 2020, the European Commission announced its Action Plan on Critical Raw Materials, proposing a number of actions to resolve current and future supply chain challenges. These include strengthening domestic value chains, increasing recycling rates, developing EU mining capacity and diversifying supply (European Commission, 2020f). One of the outcomes of Action Plan was the launch of the European Raw Materials Alliance, bringing together private companies and public entities active along the entire value chain, in order to increase the EU's supply chain resilience including for rare earth magnets. EIT Raw Materials provides funding for related research projects.

The recently published Critical Raw Materials Act (CRMA) forms a cornerstone of the EU regulatory framework to reduce supply risks structurally across a range of critical raw materials. The proposed legislation aims to strengthen the European value chain of raw materials by introducing Strategic Projects and developing common standards to ensure the smooth functioning of the internal market. It targets key vulnerabilities in terms of import dependencies, risk preparedness and circularity. The CRMA incorporates the fifth list of Critical

Raw Materials updated in 2023, which consists of 34 materials selected on the basis of their economic importance and supply risk.

To develop a European value chain, actions are needed at every stage: from exploration and extraction to recycling. With an investment plan of EUR 1.7 billion, the European Raw Materials Alliance aims to ensure that 20% of Europe's rare earth magnet needs are sourced domestically by 2030 (European Raw Material Alliance, 2021). Discoveries of rare earth deposits were recently confirmed in northern Sweden and the Norwegian continental shelf; it will take an estimated 10-15 years before production can begin.

Alternatives such as ferrite magnets can be used for certain applications in the e-mobility sector to reduce consumption of neodymium magnets. European countries have some of the largest reserves of the minerals necessary for the development of rare earth-free permanent magnets. These include Ukraine (140 000 tonnes of manganese in 2018, about 10% of the world's supply), Norway (1.4 million tonnes of aluminium in 2018), Iceland (870 000 tonnes of aluminium in 2018) and Spain (100 000 kilotonnes of strontium in 2018, about 40% of world production). Beyond Europe, there is an abundance of these materials in various world regions with whom the EU has, or is developing, alliances, making supply possible from a diversity of sources.

Less than 1% of rare earth elements is currently recycled in the EU. Until 2030, it is estimated that recycling could cover between 8% and 19% of the EU's rare earth magnet material requirements, and by 2050, recycling rates could range between 24% and 48% (Rizos, et al., 2022). However, to achieve this, both regulatory and technical advances need to be made, to improve recyclability and traceability.

Box 4: Development of recycling of permanent magnets in the EU: requirements and challenges

To ensure that permanent magnets are recyclable in the EU, it is necessary to:

— Digitalise processes throughout the value chain by developing the tools (e.g., via A.I.). It should result in an efficient digital passport design and certification schemes in line with the call for passports on a product level by the European Resource Efficiency Platform and now, more recently, by the CRMA. Permanent magnets must be traceable, to enable their classification according to different qualities/grades in order to optimise subsequent recycling processes. This will also require policy measures and commitment from industry. Recently started the EU project such as "PLOOTO" focuses on the digitalisation of the processes to foster a more sustainable and circular value chain.

— Design the products with recycling in mind, to facilitate automation of the recovery process. Currently, some car manufacturers fully embed permanent magnets in epoxy in the traction drives of electric vehicles. These are almost impossible, technically and economically, to extract for recycling of the rare earth elements. Addressing practices such as these will require new policies and strong commitment from industry (incentivised by policy). Advances in this field are expected to be slow, nevertheless the Critical Raw Materials Act with Art 28 "Recycled content of permanent magnets" introduces recommendations about the necessary information of permanent magnets in a product including how to remove these from the product.

— Once recyclability is achieved, recycling processes will need to be implemented to "close the loop", making the recovered rare earth elements available for the production of new magnets. Strong regulatory framework and R&D funds are required to address this point. To ensure efficient recycling at industrial scale, it is necessary to:

— Automate processes to make them economically viable (operators are still often required to dismantle
permanent magnets manually, and other valuable metals often fail to be separated due to inefficient processes).

— Reduce environmental impact (most of the procedures used at present involve leaching, with the use of
solvents, generating many residues).

— Guarantee that the recycled material is of sufficiently high quality to be reused without the need for a high content of new feedstock to enhance it.

27.5 Scoreboard and key insights

The EU has become increasingly aware of its high import dependency and lack of supply diversification. Such considerations are reflected in increasing R&D spending in areas such as the recycling of permanent magnets. New financial instruments including the Just Transition Fund and the Recovery and Resilience Facility have also been used to invest in the EU value chain. Based on disclosed data, thanks to the Recovery and Resilience Facility, the EU captured nearly half of all global early stage investment. Global later stage investment gradually increased from zero to EUR 56 million in 2016-2021, with the majority going to US and Chinese companies. Spain is the only EU country with a later stage deal, leaving the the EU with only 1% of all investment in this category. Overall, patenting activity was low. Nevertheless, the EU accounted for 63% of all high-value patents, most of which were filed by the German company Netzsch Trockenmahltechnik. In terms of innovating companies, the EU hosts 25% of all venture capital companies and only 10% of all patenting corporates. Japan, the US and China all host bigger pools of companies. In 2011-2020, EU production fluctuated around the EUR 300 million mark. In 2021 it increased by 20%, reaching 364 EUR million. Germany was responsible for 64% of EU production for 2019-2021. Production grew more slowly, however, than EU GDP over the same period, and is too low to cover increasing EU demand, with Germany being the top importer globally. China was by far the biggest exporter globally and to the EU. The EU captured only 4% of global exports. This is reflected in an increasing trade deficit, which doubled during the last decade, reaching EUR 1 billion in 2021.

Figure 144. Scoreboard for permanent magnets

Scoreboard	**Permanent magnets**	EU performance in the reference period		
Public R&D			2016-2020	EU CAGR
Early Stage	🟢	49%	2016-2021	EU share of global total value
Later Stage	🔴	1%	2016-2021	EU share of global total value
Patents	🟢	63%	2016-2019	EU share of global total HVI
Companies	🔴	14%	2016-2021	EU share of innovating companies
Employment			2016-2020	EU CAGR
Production	🟡	1%	2016-2021	EU CAGR
Turnover			2016-2020	EU CAGR
Imports & Exports	🔴	4%	2019-2021	EU share of global exports
Trade Balance	🔴	Low	2016-2021	EU trade balance trend

Source: JRC, 2023

28 Advanced biofuels

Advanced biofuels are fuels produced without any indirect land use change using specific feedstocks, as listed in Annex IX part A/B of the EU Renewable Energy Directive (RED II) 2018/2001. The list includes many types of wood- and agro-residues, animal manure, sewage sludge, algae and other biowaste-derived materials.

28.1 Overview of the solution and current status

Multiple transformations are possible to obtain advanced biofuels from most biomasses (Hurtig, et al., 2022). The various processes along the conversion chain, from feedstock to advanced biofuel, can be grouped into transformation pathways as follows:

- Pre-treatment and enzymatic hydrolysis convert the lignocellulosic material into sugars;
- Pyrolysis is the thermochemical conversion of biomass into bio-oil, gases and a solid product (biochar) in the absence of oxygen at lower than combustion temperatures;
- Gasification is a high-temperature (700-1 500°C) partial oxidation process through which biomass and a gasifying agent (air, oxygen or steam) is converted into synthesis gas, or syngas, principally CO and H2;
- HydroThermal Liquefaction (HTL), also called hydrous pyrolysis, is the direct thermochemical conversion of wet biomass into a bio-oil (bio-crude) at relatively high temperature (300–350°C) and pressure (10-25 MPa);
- Oil extracting methods from microalgae include mechanical pressing, solvent extraction, supercritical fluid extraction, enzymatic extractions, ultrasonic-assisted extraction and osmotic shock;
- Biological pathways for hydrogen production involve photolytic pathways (direct water splitting with green microalgae or cyanobacteria), photo fermentation ([205]) and dark fermentation ([206]);
- Hydroprocessing (also called hydrotreating) can be applied to oils and fats to produce HVO (Hydrotreated Vegetable Oil), also called HEFA (Hydroprocessed Esters and Fatty Acids) drop-in biofuels;
- Gas fermentation through microorganisms to alcohols can produce intermediates such as ethanol, butanol and acetic acid from CO and H2-rich gases (syngas) or CO-rich gases via fermentation;
- The Aqueous Phase Reforming (APR) is a process that produces hydrogen from biomass-derived oxygenated compounds such as glycerol, sugars, and sugar alcohols in the aqueous phase in a single-step reactor process;
- Fischer-Tropsch (FT) synthesis can use syngas derived from biomass gasification, in which CO and H2 gases react in the presence of a catalyst.

Bioethanol and biodiesel are by far the most used liquid biofuels produced and consumed in the EU. According to a United States Department of Agriculture Foreign Agricultural Service report, in 2022, EU bioethanol production was estimated at 5.35 billion litres, imports at 538 million litres and bioethanol fuel consumption at 5.5 billion litres (USDA and GAIN, 2022). Currently, the bioethanol blend in gasoline is 6%. However, an estimated 60 million litres of advanced lignocellulose bioethanol are produced in the EU, and 440 million litres of waste bioethanol (ePURE, 2023), together constituting 10% of total bioethanol fuel consumption.

EU biodiesel production was estimated at 15 460 billion litres in 2022, with 23% of that made up of advanced biodiesel from waste oil and fats (3 560 billion litres). Imports were an estimated 3 250 billion litres (European Commission, 2022e). The total EU consumption of diesel for road transport was an estimated 200 billion litres, with biodiesel blended into around 9.5% of that.

([205]) Fermentation is the conversion of organic substrates to hydrogen by bacteria.
([206]) Dark fermentation to hydrogen is an anaerobic process similar to anaerobic digestion involving different bacteria to convert organic substrates to hydrogen, in the absence of light, for further synthesis.

According to the EU agricultural outlook (European Commission, 2022e), consumption of diesel is expected to fall by 21% to 155 billion litres in the decade until 2032, and gasoline consumption by 18%, reaching 63 billion litres. To comply with the RED target of 2.2% advanced biofuel blending by 2030, the share of renewable diesel from waste oils and fats is set to rise from 23% to 26%, and other advanced biodiesels from 6% to 16%. The share of waste and residues in bioethanol could grow from 7% to 15%, and ethanol production from other sources is expected to increase even faster, from 3% in 2019-2021 to 12% by 2032 (European Commission, 2022e).

A sharp increase in demand is expected for lignocellulosic and waste bioethanol, and non-fat and oil biodiesel. To meet this increased demand, the supply chain needs to be redesigned for the usable waste and residues which currently go to landfill or are used in other sectors. This redesign should also seek to reduce capital expenditure through economies of scale and technological innovation.

Renewable diesel industry in the EU

The EU renewable diesel industry is established but developing. The following table indicates the relevant production sites.

Table 4: The EU renewable diesel production sites

Company	Production site	In operation since	Main products	Production capacity (l/a)
Neste	Finland		Renewable diesel	430 million (two lines)
Neste	Rotterdam, Netherlands	2011	Renewable diesel	910 million
Neste	Rotterdam, Netherlands		Renewable naphtha, propane and alkanes	1.28 billion
UPM	Lappeenranta, Finland	2015	HDRD	115 million
Green Fuel Nordic Oy together with BTG	Lieksa, Finland		Pyrolysis oil	25 million
Eni	Venice, Italy	2014	Renewable diesel	325 million
Eni	Sicily, Italy		Renewable diesel	585 million
Preem	Gothenburg, Sweden	2021	Renewable diesel	160 million expanded to 220 million
Pyrocell		2021	Biocrude oil	30 million
Total Energy	La Mede, France	2019	HDRD	385 million (max capacity 640 million)
	Portugal		Renewable diesel	35 million
Unipetrol RPA	Czechia		HDRD	3.2 million

Source: JRC based on (Hurtig, et al., 2022; USDA and GAIN, 2022)

Ethanol industry in the EU

In 2022, Versalis, Eni's chemical subsidiary, restarted the production of bioethanol from lignocellulosic biomass at Crescentino, Italy. The plant can process 200 000 Mt of biomass per year, with a maximum production capacity of approximately 32 million litres of bioethanol per year. Following initial testing, the plant is now fine-tuning its processes and scaling up production.

In Finland, St1 has three concepts for advanced bioethanol production. The first concept, Cellunolix® biorefining, is based on the processing of sawmill by-products such as sawdust and chips from softwood. The pilot plant in Kajaani has an annual production capacity of 10 million litres and started production in 2017. The second concept, Etanolix®, involves the refining of waste and residues rich in starch and sugar into advanced ethanol. There are three operating Etanolix® biorefineries in Lahti, Vantaa and Hamina. The annual production capacity varies from one to nine million litres. The third concept, Bionolix® biorefining, makes it possible to produce advanced ethanol from municipal and commercial biowaste. The Bionolix® technology has been tested and in operation since 2010 in the Karanoja waste treatment area in Hämeenlinna, which has an annual production capacity of one million litres.

In Austria, the cellulose producer, Austrocel, has a plant with a capacity of 30 million litres per year, and Agrana produces 222 million litres per year of bioethanol from residuals of its own starch production. In Romania, Clariant opened an advanced ethanol plant with a capacity of 65 million litres in 2021 (Hurtig, et al., 2022; USDA and GAIN, 2022).

Biomethanol industry in the EU

In the Netherlands, the advanced biofuel plant, BioMCN, produces about 75 million litres per year of biomethanol from biogas. In south east Sweden, Södra began production of biomethanol at a pulp mill in 2020, with a production capacity of 6 million litres per year.

28.2 EU competitiveness in innovation and future markets

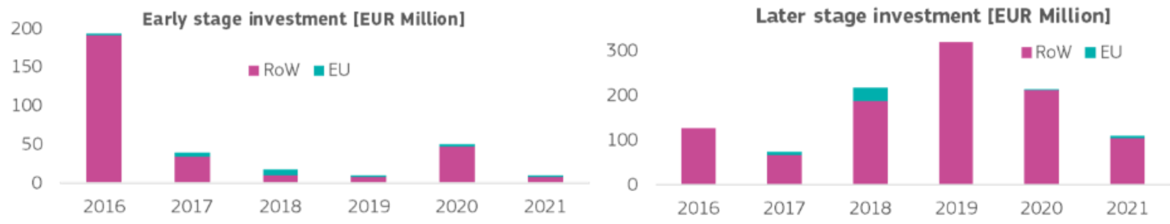
European public funding plays an important role in facilitating the development of R&D activities related to advanced biofuels. Since 2015, Horizon 2020 and Horizon Europe have funded 35 projects – 23 of them in the period 2019-2021. Countries with the highest number of projects are those where biofuel production is already well developed: Germany, the UK, the Netherlands, Italy and Spain. Other important participants include Finland, France, Belgium, Sweden and Austria, likely due to the availability of feedstock or their history of biofuels production. Projects cover various technologies, focusing on areas such as gasification and fuel synthesis, biogas, pyrolysis, fermentation and hydrothermal liquefaction. The whole value chain is represented, from feedstocks such as algae, oil plants and biomass from degraded land, to pre-treatment and intermediate bioenergy carrier production, liquid fuel synthesis, and addressing expansion to road, maritime and aviation fuels (Hurtig, et al., 2022). Another important contributor is the Innovation Fund. This has funded, for instance, the project FirstBio2Shipping with EUR 7 million, to help develop a bio-refinery in the Netherlands converting biogas to renewable, low-carbon, bio-liquefied natural gas (bio-LNG). The bio-LNG is utilised in maritime shipping, where it replaces heavy fuel oil.

As shown in **Figure 145**, after a sharp drop in 2017, global venture capital investment peaked in 2019 and has since decreased to historical levels. Investment since 2016 totals EUR 1.38 billion, which is 18.5% lower than that of 2010-15. The evolution of global VC investment in recent years has primarily been driven by the value of later stage deals realised outside of the EU. The EU, with a weak base of venture capital companies, accounts for only 7% of early stage investment and 4% of later stage investment.

Global early stage investment since 2016 amounts to EUR 321 million and accounts for 23% of all VC investment over the current period. Early biofuel ventures remain largely dependent on public funding (grants account for 85% of investment over the current period) and Canadian company ENERKEM attracted 45% of this in the form of one large grant in 2016.

Later stage investment amounts to EUR 1 billion over the current period, most of which goes to three companies (Canada's ENERKEM with 26%, and US companies LANZATECH with 20% and FULCRUM BIOENERGY with 12%). Later stage investment in the US has significantly decreased compared to the previous period, and large investments in Canada have contributed to reducing the gap. Together, these two countries account for 88% of all later stage investment over the same period.

Figure 145: Early (left) and later (right) stage investment by region [EUR million]

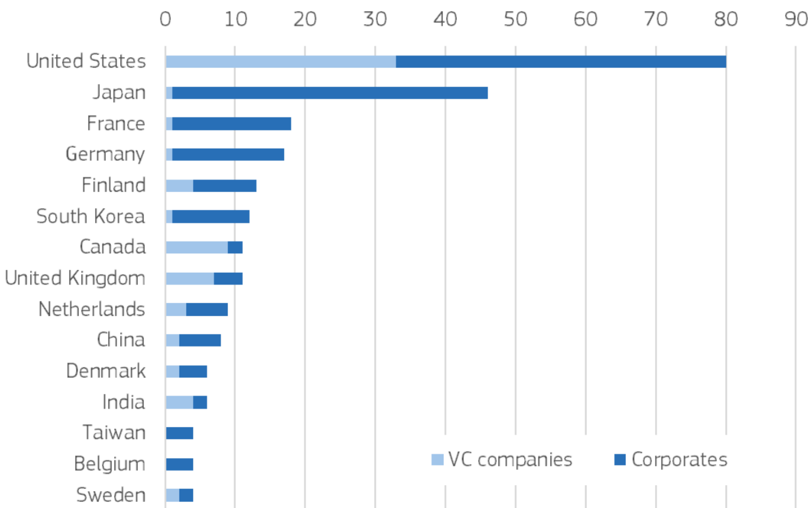


Source: JRC based on Pitchbook, 2023

Patenting activity in advanced biofuels peaked in 2012 and has been decreasing since. However, the decreasing trend was milder for the EU, which has led the patenting activity of high-value inventions since 2014. During 2016-2019, the EU had 41% of the global share in high-value inventions, followed by the US with 23%. For the same period, the US attracted 24% of all international high-value fillings, followed by the EU with 13%.

As shown in **Figure 146**, the US (29%), Japan (17%) and the EU (29%) hosted 75% of active innovators over 2016-2021. Corporates represented 71% of innovators, particularly in the EU (in France, Germany and Finland), Japan and South Korea. Since 2016, only 38% of all identified venture capital companies have actually attracted investment or been funded. Conversely, a few countries such as Canada, the UK and, to some extent, the US, have a strong base of active venture capital companies.

Figure 146: Number of innovating companies by type (2016-21)

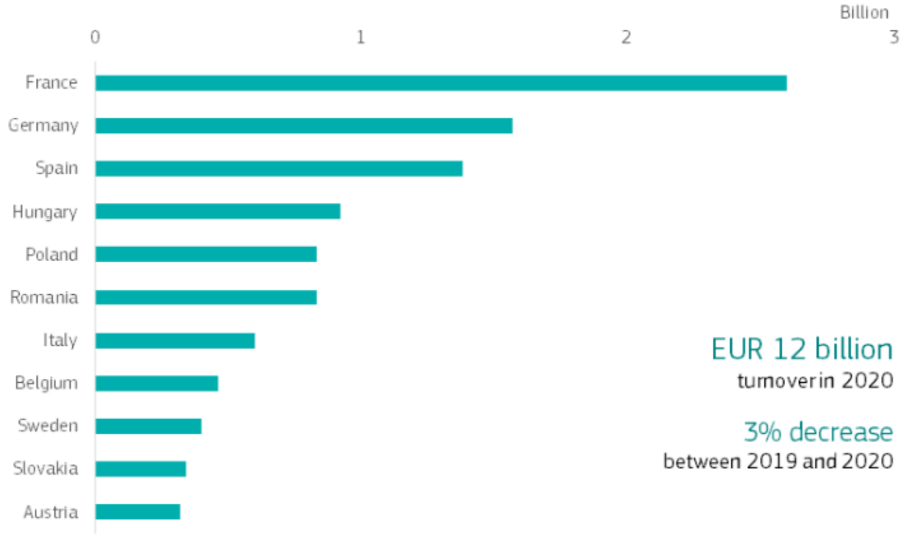


Source: JRC based on Pitchbook, 2023

28.3 EU competitiveness in the current market

According to EurObserver, the biofuel industry in the EU reached a turnover of almost EUR 12 billion in 2020. Of the EU Member States, France had the highest turnover with just over EUR 2 500 million, followed by Germany with over EUR 1 500 million.

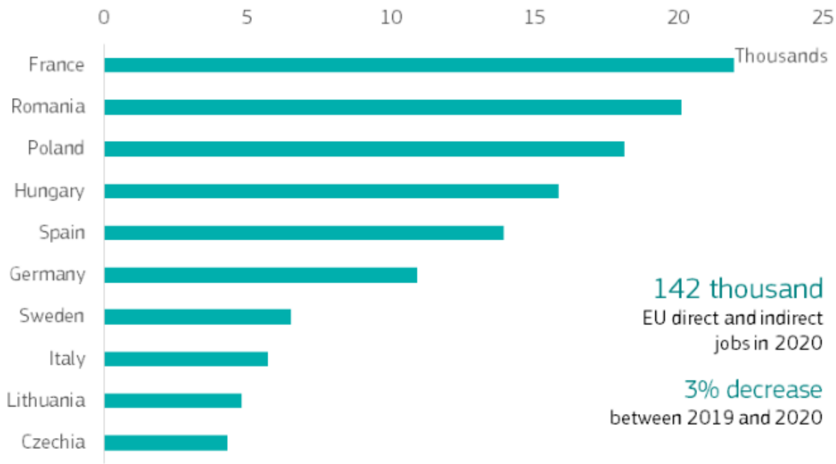
Figure 147: EU turnover in biofuels [EUR billion]



Source: JRC based on EurObserv'ER, 2023

According to EurObserv'ER, the number of direct and indirect jobs generated by the biofuels sector in the EU dropped from 240 000 in 2018 to 142 000 in 2020. However, this drop is associated with updates in methodology rather than actual capacity or market performance[207] (EurObserv'ER, 2022). As shown in **Figure 148**, France, with more than 20 000 jobs, was the Member State with the highest number of biofuel-related jobs in 2020.

Figure 148: Biofuel jobs in the EU

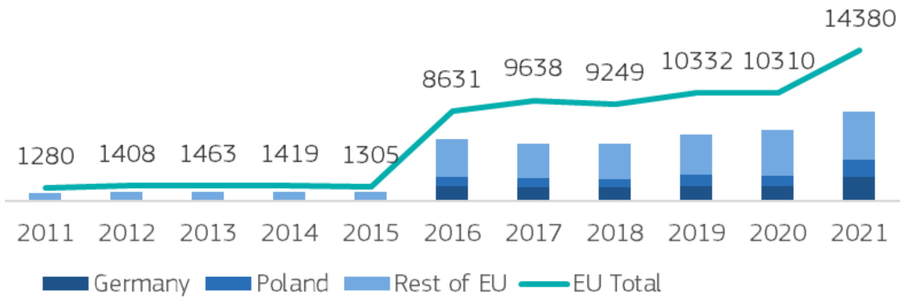


Source: JRC based on EurObserv'ER, 2023

According to **Figure 149**, from 2016 to 2020, the value of biofuel production in the EU remained steady at around EUR 10 billion, and in 2021, it increased to more than EUR 14 billion. Germany and Poland were leading countries, with 15% and 10% of the total EU production value (although data is not disclosed by all Member States).

(207) EurObserv'ER updated data related to biofuels based on insights from H2020 project ADVANCE FUEL, which provides more accurate data than the figures from literature that were used previously. The adjusted feedstock conversion efficiency of biofuel production has had the largest impact on employment and turnover figures. Higher efficiency means that less feedstock is required, affecting employment and turnover estimates.

Figure 149: Total production in the EU and top producers [EUR million]



Source: JRC based on PRODCOM, 2023

The advanced biofuels sector is in its early days, and international trade data is still limited as the number of commercial plants is still quite low. However, the EU is the clear market leader, dominating the list of operational commercial plants for advanced biofuels. As shown in **Table 5**, Sweden and Finland have the highest number of plants inside the EU.

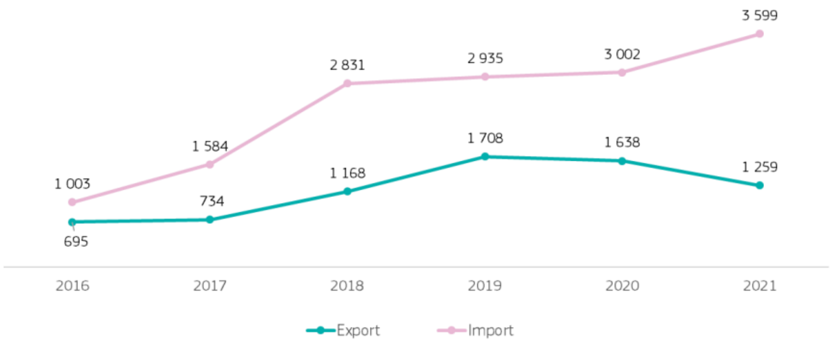
Table 5: List of advanced biofuels plants

Company	Plant	Country	Region
Green Fuel Nordic	GNF Lieksa	Finland	EU
St1	Etanolix Vantaa	Finland	EU
St1	Etanolix Lahti	Finland	EU
St1	Etanolix Hamina	Finland	EU
Total	La Mede	France	EU
Eni SPA	Eni Taranto refinery for co-processing	Italy	EU
Eni SPA	HVO plants in Gela and Venice	Italy	EU
Versalis / Eni	Crescentino Biorefinery	Italy	EU
Twence	Hengelo	Netherlands	EU
Borregaard Industries AS	ChemCell Ethanol	Norway	EU
BP	Co-processing Castellon	Spain	EU
Repsol	Co-processing Puertollano	Spain	EU
Domsjoe Fabriker	Domsjoe Fabriker	Sweden	EU
Honeywell UOP and Preem	Co-processing trial	Sweden	EU
Preem	Preem HVO diesel and biojet	Sweden	EU
Pyrocell (JV of Setra and Preem)	pyrolysis oil upgrading	Sweden	EU
Sodra	Sodra biomethanol	Sweden	EU
St1	Etanolix Gothenburg	Sweden	EU
SunPine	SunPine HVO addition	Sweden	EU
SunPine	SunPine HVO 100 mio l	Sweden	EU

Source: JRC, 2023

The value of biofuel imports from extra-EU countries more than tripled from EUR 1 billion in 2016 to EUR 3.6 billion in 2021, while exports to outside the EU reached EUR 0.7 billion in 2016 and peaked at EUR 1.7 billion in 2019 (**Figure 150**). As a result, the EU trade deficit increased from EUR 3 million in 2014 to EUR 2 billion in 2021.

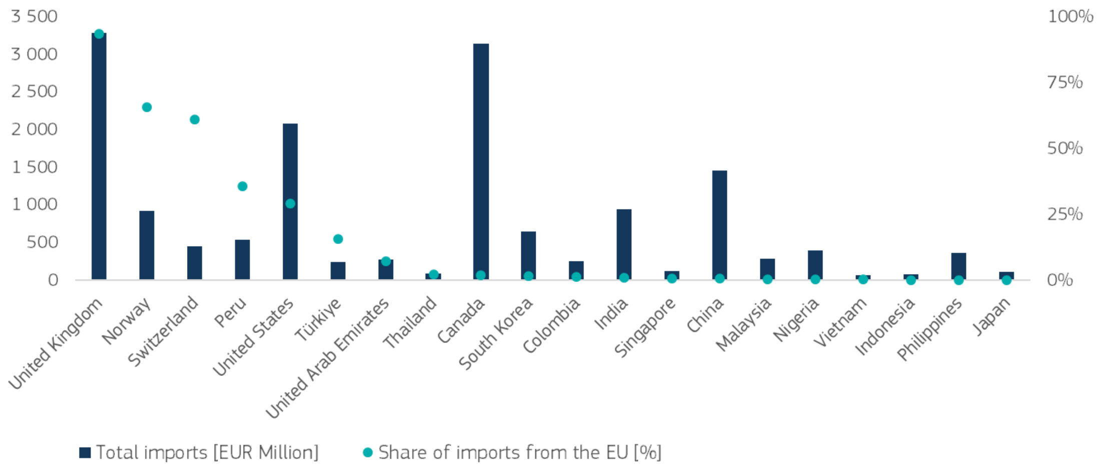
Figure 150: Extra-EU Import & Export [EUR million]



Source: JRC based on Comext, 2023

The Netherlands and Germany were the biggest exporters globally and within the EU. As reported in **Figure 151**, the UK was the biggest importer of EU biofuels, while the US was far behind. The Member States with the biggest trade surplus were Germany, the Netherlands and Spain, while France, Italy and Sweden had the biggest trade deficit. The total value of biofuel exported by Member States, including internal EU trade, rose from EUR 10 billion in 2019 to EUR 18 billion in 2021, while total global exports increased from EUR 15 to EUR 26 billion for the same period. Argentina was the biggest biofuel exporter to the EU, followed by China and Malaysia.

Figure 151: Top 20 non-EU importers (2019-2021)



Source: JRC based on Comtrade, 2023

28.4 Future outlook

Targets for advanced biofuels were recently updated by the European Commission Fit-for-55 package amending RED II and setting the new frameworks towards 2030. The latest revision includes large modifications, such as replacing the primary 14% target for renewable energy in transport (as set by RED II) with a new target of 13% GHG intensity reduction for 2030. Moreover, the updated target for advanced biofuels at 2.2% might appear lower than the 3.5% proposed in RED II, but as it excludes the use of multipliers, it results in a real target that guarantees equal volumes of renewable fuels replacing fossil fuels. REPowerEU prioritises the use of non-recyclable biomass waste and agricultural and forest residues. In this context, REFuelEU Aviation and FuelEU Maritime proposals are designed to ensure that renewable fuels supply 5% and 6.5% of EU jet and shipping fuel consumption, respectively, by 2030.

Overall, in supply chain terms, the feedstock eligible for advanced biofuel production (annex IX, RED II) is widely available in the EU and commonly biodegradable. Local feedstock use and short-distance transport are the best options to minimise storage requirements. Feedstock already has alternative uses such as energy and biomaterials. The competitive use of biomass needs to be assessed from the perspective of multisector use. Moreover, it is necessary to have official statistics to track feedstock streams better, supporting the certification of sustainable biomass.

The EU industry is well-positioned in this area. Regarding technological advances, patents, current facilities and deployment plans, EU companies can also develop new facilities abroad (as seen in the investment plans listed below). However, a stable, long-term policy support framework is needed, along with a certification scheme for feedstock and products. To be price competitive, it is plausible to lower CapEx and OpEx thanks to innovation and an integrated supply chain. Larger advanced biofuel facilities have lower CapEx and more competitive fuel prices and help to recover larger proportions of organic waste (aiding the circular economy). Bigger facilities also help to decarbonise heavy trucks, aviation and maritime transport, where electrification is not a short-term technological solution. Nevertheless, technological advances, waste management and competition for feedstock remain the main challenges.

Renewable diesel

Rotterdam (the Netherlands) is attracting investment related to renewable diesel. Neste is planning another plant with a capacity of roughly 2 billion litres per year. In addition, UPM and Shell plan to build renewable diesel plants of about 640 million litres and one billion litres, respectively. The three prospective plants will partly produce sustainable aviation fuel (SAF) with plans to be fully operational in 2025 or later.

In Finland, Fintoil is building a crude tall oil refinery with a capacity of 100 million litres of renewable diesel. In Italy, ENI Venice's renewable diesel production is forecast to increase to 540 million litres in 2024. In France, the BioTFuel project, a collaboration between Avril, Axens, CEA, IFPEN, ThyssenKrupp and Total Energies, aims to produce 230 million litres of advanced biodiesel and SAF per year. In Portugal, Galp is considering the installation of a second renewable diesel unit in Sines, which could have an annual production capacity of over 345 million litres.

In Sweden, Preem is reportedly planning to expand to 1.3 billion litres in 2023 and 5 billion litres in 2030. To achieve this, a plant with an annual capacity of 950 million litres is expected to become operational in Lysekil in 2024. The company is currently investigating the use and sourcing of other raw materials. St1 plans to produce up to 250 million litres of renewable diesel and SAF in Gothenburg, beginning in 2023. The feedstocks are likely to be UCO and tall oil. St1 is also investigating the construction of another plant with a capacity for biofuels of 500 million litres per year, with operations commencing in roughly five years.

Bioethanol

For Bioethanol, St1 reportedly plans to build three plants in Kajaani (Finland), Pietarsaari (Finland) and Follum (Norway), each with a capacity of 50 million litres. Other companies planning to construct advanced bioethanol plants in Finland are Nordfuel and BioEnergo. Nordfuel intends to build a biorefinery producing 80 million litres of ethanol per year from wood. BioEnergo is planning to build a similar plant with an annual capacity of approximately 60 million litres per year. In Romania and Bulgaria, OMV Petrom is planning an advanced bioethanol plant with wood as feedstock. The projected capacity is 65 million litres per year, and the company plans to inaugurate the plant in 2023. Clariant also plans to build an advanced ethanol plant in Bulgaria, with an annual capacity of 65 million litres per year, using about 250 000 Mt of wheat straw. In Poland, ORLEN Group announced that they will build an installation to produce advanced bioethanol from non-food products, mainly straw, in 2024. Its planned annual capacity is 32 million litres per year. The bioethanol plant will be built together with a biomass-fuelled combined heat and power (CHP) plant (mainly using lignin as a by-product of ethanol production). In the next stage of the project, a biogas plant will be built. It will process stillage, another by-product of bioethanol production.

Biomethanol

For biomethanol, a consortium of Enerkem, Shell, Air Liquide, Nouryon and the Port of Rotterdam is planning to build a waste-to-biomethanol plant in Rotterdam. The facility will convert 360 000 Mt of waste into 270 million litres of biomethanol.

28.5 Scoreboard and key insights

The EU's competitiveness in advanced biofuels is worrying in both early and later stage investment, where EU companies capture global shares of only 7% and 4%, respectively. Nevertheless, the EU has a strong presence in patenting activity, in which it is the global leader, capturing 41% of all high-value inventions. The EU also hosts nearly a third of all innovating companies, thus showing a strong potential for the development of the

EU value chain. EU-funded R&D makes an important contribution with five projects funded on average per year in the period 2015-2022. The main sources were Horizon 2020 and Horizon Europe, though the Innovation Fund supported investment in a scale-up of innovative advanced biofuels production. Trade-related indicators show that the EU has a moderate presence globally, with a 21% share of global exports and an increasing trade deficit. EU production is increasing, making it possible that the EU may cover internal demand and capture some of the growing markets. Comparable employment and turnover data do not go beyond 2019 and it is therefore not possible to determine an overall trend. Nevertheless, the biofuels sector is a significant clean energy employer in the EU.

Figure 152: Scoreboard for advanced biofuels

Scoreboard	**Biofuels**	EU performance in the reference period
Public R&D		2016-2020 EU CAGR
Early Stage	●	7% 2016-2021 EU share of global total value
Later Stage	●	4% 2016-2021 EU share of global total value
Patents	●	41% 2016-2019 EU share of global total HVI
Companies	●	29% 2015-2020 EU share of innovating companies
Employment		2016-2020 EU CAGR
Production	●	11% 2016-2021 EU CAGR
Turnover		2016-2020 EU CAGR
Imports & Exports	●	21% 2019-2021 EU share of global exports
Trade Balance	●	Low 2016-2021 EU trade balance trend

Source: JRC, 2023

29 Biomethane

The REPowerEU plan introduced the Biomethane Action Plan([208]) to increase the EU's annual production of biomethane from 3 billion cubic metres (bcm) in 2020 to 35 bcm by 2030, an equivalent of about 20% of the amount of Russian gas imported in 2021 (European Commission, 2022f). A scale-up of that size requires investment in up to 5 000 new biomethane production units and the collection of up to 200 million tonnes of available sustainable biomass (European Biogas Association, 2021). This challenge is achievable, as only a fraction of biowaste and food waste is currently collected and separated in the EU.

The scope of this solution focuses on the production of biomethane, part of the wider biogas market. These two solutions are intertwined, as approximately 90% of biomethane is currently produced by biogas upgrade (International Energy Agency, 2020). Other biomethane production technologies rely on the gasification of solid biomass followed by methanation. Biomethane, also known as renewable gas, is almost 100% methane, differentiating it from biogas, of which 45-75% is methane and the rest CO_2 (International Energy Agency, 2020). An important advantage of biomethane is that it can be used in the existing natural gas infrastructure (e.g. distribution grid), reducing the need for infrastructure investment to use it more widely. Biomethane can substitute for natural gas in all its end-uses, decarbonising a range of sectors: power and heat production, transport and residential buildings. The development of this value chain will also improve waste management and sustainable agriculture thanks to the valorisation of agricultural waste and soil nutrient recovery after feedstock digestion (Alberici, et al., 2023).

29.1 Overview of the solution and current status

Anaerobic digestion and the upgrade of biogas to biomethane have already been demonstrated successfully. Over the past decade, biogas production has stagnated, but the upgrade of biogas to biomethane is on the increase (European Biogas Association, 2021). It is estimated that biomethane production grew by 20% from 2020 to 2021 (European Biogas Association, 2022).

The main technologies used for upgrading biogas to biomethane include (Motola, et al., 2022):

— Pressurised water scrubbing to dissolve the carbon dioxide from biogas in water at low temperatures and high pressures (5-10 bar);

— Pressure swing adsorption to separate the carbon dioxide from the methane molecules by adsorption on a solid surface (e.g., activated carbon or molecular sieves – zeolites) under elevated pressure (3-10 bar);

— Physical absorption to absorb the carbon dioxide in a liquid under high pressure (5-10 bar) and flash it out in a low pressure flash tank;

— Chemical absorption to dissolve the carbon dioxide into a chemical solvent (e.g., amines, sodium hydroxide, potassium hydroxide) at atmospheric pressure;

— Membrane separation to separate carbon dioxide and methane molecules by a permeable membrane based on their different physical characteristics at high pressure (5–20 bar);

— Cryogenic upgrading to separate the carbon dioxide and methane based on their different boiling points. Methane remains in gaseous form and thus the liquid carbon dioxide stream can be easily separated.

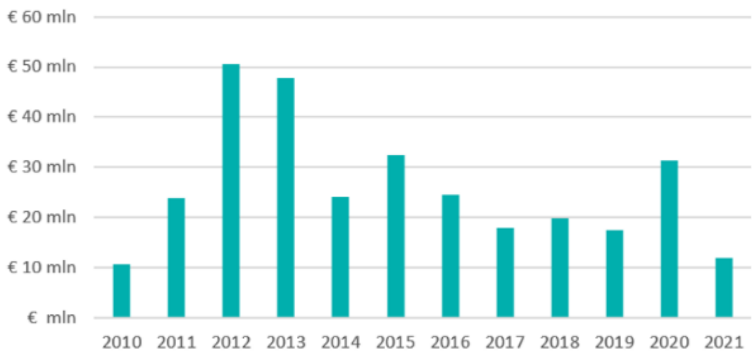
Membrane separation (39%) is the most popular upgrading method, followed by water scrubbing (22%), chemical scrubbing (18%) and pressure swing adsorption (12%), with a limited number of biomethane plants using cryogenic separation (1%) and physical scrubbing (1%) (European Biogas Association, 2021). If biomethane is used to substitute LNG, cryogenic separation has the advantage of benefitting from the integration of methane separation with liquefaction units for the methane.

29.2 EU competitiveness in innovation and future markets

According to data submitted to the International Energy Agency by EU Member States, the EU's collective public spending on biogas-related R&D peaked in 2012 (EUR 51 million) but has decreased ever since, falling to EUR 12 million in 2021. Key technologies that received research funding were thermochemical and biochemical processes – anaerobic digestion. EU Member States provided the majority of public R&D spending during this decade, followed by the US and Canada.

([208]) COM(2022) 230 final, Brussels, 18.5.2022

Figure 153: EU R&D funding – biogases 2010-2021 [EUR million]



Source: *JRC based on IEA, 2023*

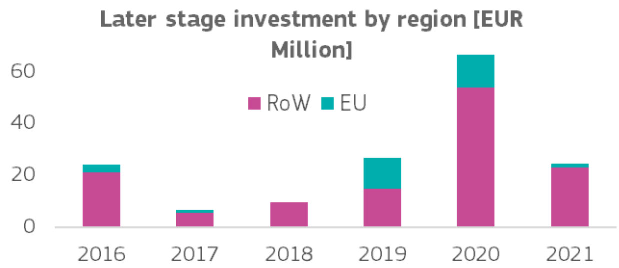
Global venture capital for early and later investment in biomethane activities amounted to EUR 194 million over the 2016-2021 period and is growing (+43%) as compared to the previous five-year period (2010-2015). Since 2016, the EU has attracted 23% of global venture capital investment (37% and 19% of early and late stage investment, respectively) and significantly improved its lagging position over the 2010-2015 period. However, lower levels of early stage investment over recent years and the drop in later stage investment in 2021 indicate that this is not a generalised trend.

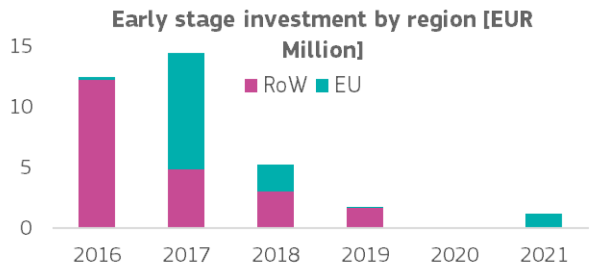
Until 2016, most venture capital investment was realised in businesses founded before or during the early 2010s. Over 2016-2021, later stage investment accounted for 81% of global venture capital investment at EUR 157 million. This was attracted by companies that had not previously raised a significant amount of early stage capital, indicating a potential shift in investors' interest. On the other hand, ventures that raised early stage capital in 2016-2017 have not yet raised a significant amount of later stage capital.

Companies founded after 2016 account for only 13% of identified venture capital companies. This lack of early ventures has led to very low levels of early stage investment since 2017. Early stage investment totals EUR 36 million globally for the period 2016-2021 (making up only 19% of global venture capital investment) and still relies substantially on grants (which represent 29% of early stage investment). EU early stage investment totals EUR 13.5 million for the same period.

Switzerland leads the race in later stage investment mainly thanks to DUCTOR, a producer of biogas from organic waste. While the US can boast higher levels of investment, this has in large part been realised in two companies, one of which does not focus on biomethane or biogas production (but rather on biogas-to-hydrogen processing) and the other of which has now gone out of business. In both early and later stage investment, France ranks second in 2016-2021, helped by the rapid development of WAGA ENERGY (founded in 2015 and a successful IPO in 2021), fast-tracked by the support of EU corporate investors (Air Liquide, CMA CGM). With leading investment levels over 2010-2015, the UK now hosts a strong base of mature companies and still leads the race for early stage investment over 2016-2021.

Figure 154: Early (left) and later (right) stage investment by region [EUR million]

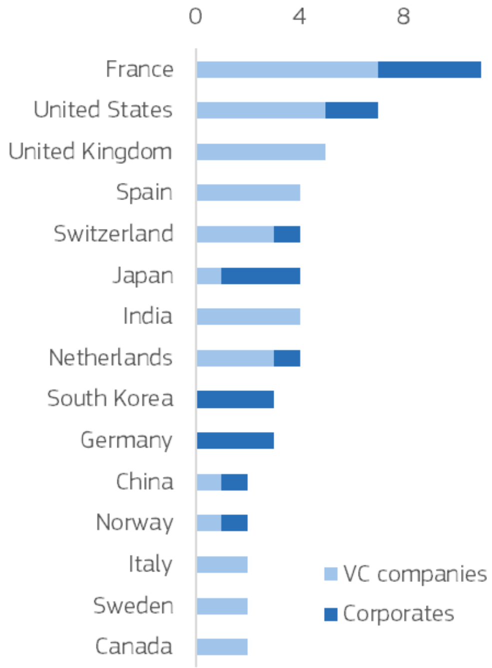




Source: *JRC based on Pitchbook, 2023*

The EU accounts for a significant share (44%) of active venture capital companies over 2016-2021, primarily located in France, Spain and the Netherlands. France takes the lead with 16% of active venture capital companies before the US and the UK (11% each). The number of identified companies remains limited, particularly the number of corporate innovators ([209]) with activity which falls under the selected patent codes.

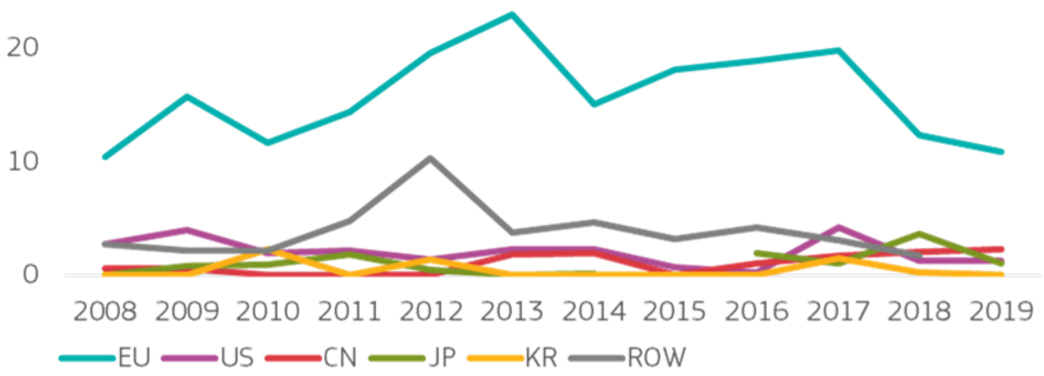
Figure 155: Number of innovating companies by type (2016-2021)



Source: JRC based on Pitchbook, 2023

China had the most patenting activity in total inventions in 2016-2019, followed by the EU. However, only 1% of China's filings were international, and only 2% can be considered high-value. The EU was the leader in high-value patents, with 62% of its filings ranked as high-value and 13% international. France was the top global inventor, followed by Germany and Japan.

Figure 156: Number of high-value inventions



Source: JRC based on EPO Patstat, 2023

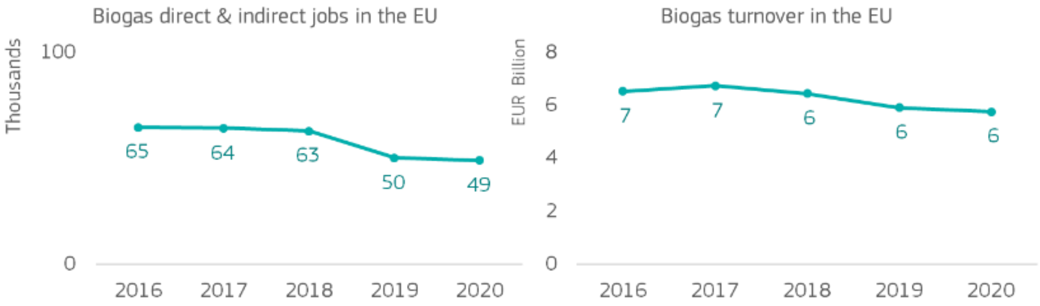
29.3 EU competitiveness in the current market

The number of direct and indirect jobs related to the biogas sector in the EU has remained stable, totalling 49 000 in 2020. While EurObserv'ER statistics appear to show a decrease, this is the result of an update in

([209]) The number of identified corporates with high-value patents is very low over the 2016-2021 period. This can indicate a lower involvement of corporate innovators in the development of bioenergy technologies but can also be related to the selection of patent codes. In the absence of further supporting evidence, this area is not analysed in further detail.

modelling assumptions [210]. Germany, with almost 25 000 employees, was by far the leading EU country, followed by Italy, Czechia, France and Poland. A similar pattern is visible in the case of turnover, which stood at EUR 6 billion in 2020. With almost EUR 4 billion, Germany had the largest share of EU turnover.

Figure 157: EU direct and indirect jobs in biogas (left) and turnover in biogas (right)



Source: JRC based on EurObserv'ER, 2023

Overall, 3.5 billion m^3 of biomethane was produced in Europe (EU27+)([211]) in 2021, of which 2.8 billion m^3 was produced in the EU27. The top producer was Germany, followed by Denmark and France. The speedy growth of biogas production is worthy of note, jumping from 20% in 2019/2020 to almost 30% in 2020/2021. However, biomethane is part of a broader biogas market. In 2021, biogas production in Europe totalled 18.4 billion m^3 (European Biogas Association, 2022), so there is plenty of potential for upgrading larger volumes of biogas to biomethane, as long as existing biogas plants are adapted.

Overall, there are 1 222 biogas plants in the EU (including the estimated increase in 2022). France is leading the development of biogas plants, overtaking Germany. Biogas grew fast in France in 2021, with the deployment of 151 new plants, and in 2022, with an additional 112. Biomethane plants have an average production capacity of 35 GWh per year and are much larger than biogas plants, whose average capacity is 8 GWh. The majority of biogas plants (55%) are directly connected to the distribution grid, while 19% are connected to the transport grid (European Biogas Association, 2022)

29.4 Future outlook

The RepowerEU Plan recognises biomethane as an important alternative to the natural gas imported from Russia and sets an ambitious target of producing 35 bcm by 2030. Diversification of the gas supply and the decarbonisation agenda creates a window of opportunity for the dynamic development of the biogas sector. Furthermore, in order to engage the private sector, the Biomethane Industrial Partnership was launched in September 2022.

The EU legislative framework set out in the revamped Renewable Energy Directive introduces higher targets for renewable energy and sub-targets for the heating and transport sectors. It may incentivise market creation for this solution. Regarding feedstock mobilisation, the Common Agriculture Policy [212] supports farmers while securing food production and assisting the goals of the European Green Deal. The Waste Framework Directive [213] defines the use of organic waste, agricultural residues and the possibility of recovering soil nutrients after digestion, while its 2023 revision is set to target climate and sustainability amendments.

The biogas and biomethane sectors have strong potential for growth. It is estimated that their combined production capacity may increase from 18 bcm in 2021 to approximately 35-45 bcm by 2030 and up to 165 bcm by 2050 (European Biogas Association, 2022). In line with such an assessment, several Member States planned an increase in their production capacity by 2050, including France (22 bcm/year), Germany

[210] Feedstock costs were revised downwards in the model, basing them on the CAPRI dataset in the 2022 report. As the feedstock supply chain represents a large share of employment in the bioenergy sectors, this adjustment led to a significant decrease in the employment and turnover estimates for the biogas sector (EurObserv'ER , 2022).

[211] Europe in this case includes the United Kingdom, the second biggest producer of biomethane after Germany. It also includes data for Switzerland and Norway, though their share is relatively low.

[212] Common agricultural policy (CAP) https://eur-lex.europa.eu/EN/legal-content/glossary/common-agricultural-policy-cap.html

[213] Waste Framework Directive (WFD) https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en

(22 bcm/year), Spain (20 bcm/year), and Italy (14 bcm/year). This target can be achieved with improved waste management and collection programmes and a sustainable sequential cropping system.

Such perspectives open up growth opportunities for European companies, which currently count between 15 000 and 20 000 active jobs in the biogas value chain. Growing biogas and biomethane production may create approximately 460 000 jobs by 2030 and over one million jobs by 2050 (European Biogas Association, 2022).

Key areas of innovation in the sector include the design and operation of the reactor, the employment of innovative substrates, changes in the mixing regime, capture and use of biogenic CO_2, upgrade of the digestate towards alternative fertilisers, the establishment of new end-products and the development of modular units in partnership with farmers and waste handlers. The recovery of CO_2 from the biogas upgrading treatment can play an important role in the future, especially in combination with a methanation [214] process through renewable hydrogen.

29.5 The scoreboard and key insights

The EU is well positioned in investment- and innovation-related indicators but less so in terms of employment and turnover. The EU hosts 63% of high-value inventions and nearly half of all innovative companies (45%), and has maintained a high level of public R&D spending in this field. In terms of venture capital investment, the EU attracted 37% of early stage and 19% of later stage investment in 2016-2021. France was the leading EU country in early and later stage investment, as well as in patenting activity. Germany was the leading EU country in employment and turnover, with over 50% of the EU share, followed by Italy with approximately 14%. Overall, employment and turnover have remained stable in 2016-2020, taking into account the methodological update which suggests otherwise. Nevertheless, the sector has significant job creation potential if current scale-up plans are realised.

Figure 158: Scoreboard for Biomethane

Scoreboard	**Biomethane**	EU performance in the reference period		
Public R&D			2016-2020	EU CAGR
Early Stage		37%	2016-2021	EU share of global total value
Later Stage		19%	2016-2021	EU share of global total value
Patents		63%	2016-2019	EU share of global total HVI
Companies		45%	2016-2021	EU share of innovating companies
Employment		-7%	2016-2020	EU CAGR
Production			2016-2021	EU CAGR
Turnover		-3%	2016-2020	EU CAGR
Imports & Exports			2019-2021	EU share of global exports
Trade Balance			2016-2021	EU trade balance trend

Source: JRC, 2023

[214] Methanation is the conversion of carbon monoxide (CO) and carbon dioxide (CO_2) to methane (CH4) through hydrogenation

30 Small Modular Reactors

Small Modular Reactors (SMRs) are reactor units with power up to 300 MWe that can be manufactured in a factory, and delivered and installed at the site in modules (IAEA, 2022). SMRs are not a technology per se, but rather a technological solution aiming at better integration and at enhancing inherent and/or passive safety features that could improve nuclear safety performance, allowing SMRs to be built closer to agglomerations and on industrial sites. Their lower capital cost requirements enable new delivery models and business cases (such as scalable sources of heat and electricity applications), that would make them more affordable and faster to deploy than large-scale reactors.

The outcome of this study has a preliminary character due to the data sources and the indicators used (listed in **Table 1** of Chapter 2). These have shown some limitations for a thorough analysis of the SMR market and in particular because SMRs encompass a variety of different technologies that are not yet industrially established. A future, more detailed, study with adapted indicators could also address the outcomes of the market analysis for SMRs currently being undertaken by the dedicated European SMR Pre-Partnership.

30.1 Overview of the solution and current status

Though already in operation in China and Russia, SMRs are an upcoming solution not yet industrially established in the Western world. This analysis addresses all SMRs, regardless of their technology type or application. The IAEA listed over 80 SMR concepts from 18 countries worldwide and among them, nine are European. These are at pre-conceptual/conceptual design stage. **Table 6** lists the main SMR technologies with their principal areas of application and key characteristics.

Table 6: Main SMR technologies and characteristics

SMR Type	Applications	Key characteristics
Light Water-cooled Reactor (LWR)	Electricity, hydrogen and heat production, land or marine based	Design simplification; advanced technological readiness level, and similar waste treatment as conventional reactors.
High Temperature Gas-cooled Reactor (HTGR)	Electricity & cogeneration, hydrogen, industrial applications	High temperature heat (>750ºC), enhanced safety, advanced technological readiness levels.
Liquid Metal-cooled Fast Reactor (LMFR)	Electricity, hydrogen and heat production, nuclear fuel breeding and recycling	Medium-to-low technological readiness level; intrinsic safety features, atmospheric pressure, opacity of metal coolant and challenging coolant treatment.
Molten Salt Reactor (MSR)	Electricity and hydrogen production, nuclear fuel breeding and recycling	Low technological readiness level; intrinsic safety features and challenging materials treatment.
Micro Modular Reactors (MMR)	Electrical power below 10MWe, back-up and portable power	Transportable, suitable for small or remote grids and challenging licensing levels (e.g. transportability).

Source: JRC, 2023

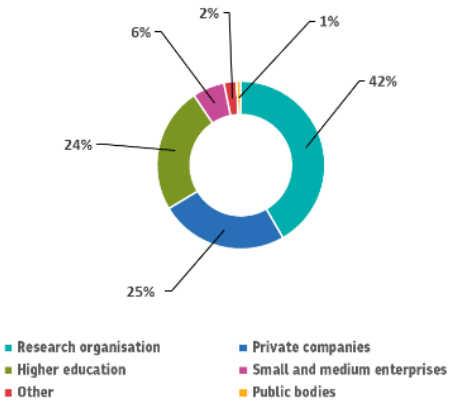
Two SMR types are already in operation (a marine-based LWR in Russia and a HTGR in China). In addition, some LWR and HTGR designs from the US are already in the later stages of licensing and some EU countries are showing an increasing interest in these designs.

The scope analysed for the SMR solution covers EU R&D funding, venture capital investment, patents and companies indicators related to generic SMR technologies (without considering a specific type), but due to the as yet non-existent market for SMRs, the production and trade indicators have been taken from the conventional nuclear reactor industry by dealing with fuel and components separately.

30.2 EU competitiveness in innovation and future markets

Global data on EU Member State public funding for R&I on SMRs is not available. In 2022, France announced it will invest EUR 1 billion through the France 2030 re-industrialisation plan to promote R&D for its LWR SMR design Nuward and for other non-LWR SMR design concepts (IEA, 2022h). Belgium and the Netherlands are making available EUR 100 million and EUR 65 million respectively, for research in SMRs. The European Commission Horizon 2020 framework programme (2014-2020) had a budget of EUR 320 million for fission technologies R&I compared to the EUR 80 billion of the overall R&I programme. Specific SMR projects amounted to a total of EUR 40 million. The biggest recipients of Horizon 2020 funds were France, Germany, Czechia, Italy, Finland and Belgium. Participants from countries that host a nuclear industry (e.g. France) and those phasing out nuclear power (e.g. Germany) captured these funds. As shown in the **Figure 159**, the role of research entities and universities represents 66% of the beneficiaries, and together with big corporates (private companies), gather 91% of the funding. The 6% share of small and medium-sized enterprises (SMEs) is considerably small when compared to other solutions, which is understandable due to the nature and historical evolution of the nuclear industry. The Euratom Research and Training Programme (2021-2025) offers complementary funding; with a total budget of EUR 1.38 billion, there is EUR 266 million dedicated to indirect actions in nuclear fission, safety and radiation protection, including calls specific to SMRs.

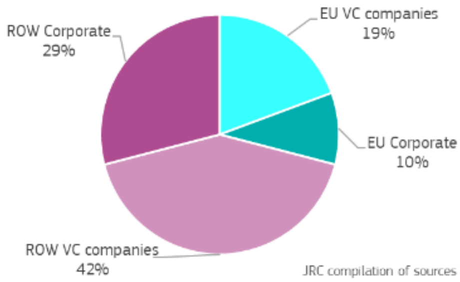
Figure 159: Net EU contribution by organisation type (2020)



Source: JRC based on CORDIS, 2023

As shown in **Figure 160**, the development of SMRs is mostly driven by companies outside the EU with an equal share between Venture Capital (VC) funded companies (start-ups and scale-ups) and corporates. Note that the number of companies does not relate to the number of designs being developed due to the fact that some countries rely more on state-owned companies (such as China and Russia) rather than start-ups or newcomers. The European and worldwide company landscape is changing. Nonetheless, the US is in the lead, hosting 39% of active innovators and a major share of VC-funded companies, whereas traditional nuclear supplier countries like France, Japan and South Korea mostly host corporate innovators. Overall, VC companies represent 61% of active innovators, indicating that corporate incumbents in the nuclear sector are not yet seizing this emerging market opportunity. The EU maintains a competitive position, hosting 29% of active innovators.

Figure 160: Share of EU companies by innovator type (2016-21)



Source: JRC based on Pitchbook, 2023

However, the EU has attracted a limited share of VC investment over the 2016-21 period. The US is strongly in the lead, accounting for 88% of early and later stage investment in 2020-21, mostly via companies such as NuScale Power, Ultra Safe Nuclear, TerraPower and X-Energy (to which the U.S. Department of Energy (DOE) provided over EUR 1 billion in 2020 according to Pitchbook data([215])). However, with VC investment offering a limited budget in exchange for a fast return, the nuclear industry is not an ideal fit, and VC investment represents a fraction of the total investment received globally by SMR companies, mainly led by state funding.

As SMRs are based on a compilation of technologies not exclusively developed or used in small modular reactors, patenting trends are delineated selecting the most relevant patent categories intersecting with the Y02 patent classification dedicated to climate change mitigation and adaption technologies. The number of patents based on this search and on EPO Patstat shows a clear lead by the US among the inventions filed in more than one jurisdiction, although South Korea has the largest number, with a residual share seeking international protection. Patenting activity in the SMR market and the nuclear industry overall is relatively low, as intellectual property is often protected as industrial secrets.

Many of the big actors in SMR development (such as GE-Hitachi, Holtec, Kairos Power and Newcleo) are not on the list. This may indeed be the result of the broad technological base of SMRs, but also the classification logic by which solutions are tagged as 'climate mitigation technologies' in this sector.

30.3 EU competitiveness in current market

Because SMRs are an upcoming technological solution not yet established, the competitiveness in the current market, with no possibility to distinguish between different end-uses and SMR applications, is analysed through the production and trade of the conventional nuclear industry, split between components (parts of nuclear reactors) and fuel (uranium and fuel components) as a proxy of transferable skills and manufacturing capacities. The same cannot be done for employment and turnover because there are no direct similarities between the conventional nuclear industry and SMR markets for these indicators.

30.3.1 Components

The EU production of nuclear reactor parts and machinery for isotopic separation in 2004-2021, as extracted from the Eurostat Prodcom database, showed a distinct peak during the period 2011-2013 for machinery for isotopic separation. In particular, during 2007-2016, the enrichment plant of Orano in France replaced and updated the whole enrichment machinery by building a new facility, which accounts for 12% of global enrichment capacity. The centrifuges for isotopic separation were manufactured by ETC (a Joint Venture between Urenco and Orano) in the Netherlands, for an investment estimated to be EUR 4 billion (European Commission, 2017). Regarding the production of nuclear reactor parts, a trend is observed of EUR 200-300 million per year, with the notable contribution of 32 steam generators manufactured by Areva in France for an order worth EUR 1.1 billion. Investment made in the last decade in Europe, due to long-term operation and post-Fukushima safety upgrades, is not visible, as the data only targets the specific production of nuclear reactor components. The investment made in the EU NPP fleet as a consequence of the EU Stress Tests was in the order of billions of euros, but the majority of safety equipment installed during this period may be recorded under different database codes due to their non-nuclear specific nature (e.g. conventional engineering equipment, civil engineering activities).

30.3.2 Fuel

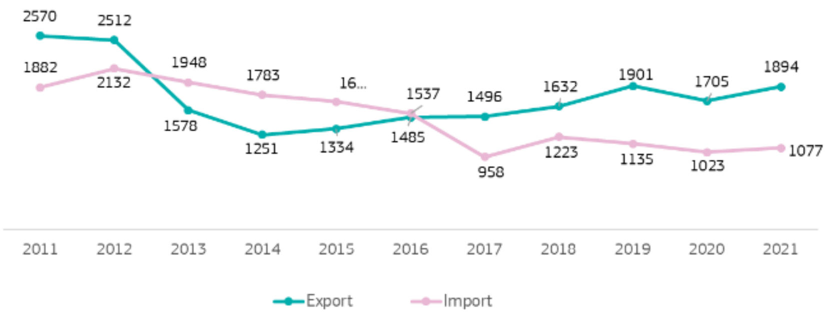
Uranium fuel is a major element of the supply chain of any nuclear reactor operation. The uranium front-end processes involve mining, conversion, enrichment and fabrication, the enrichment being the most critical of all, mainly because of security and safeguarding issues, and only a few countries (FR, NL, DE, UK, US, Russia and China) have the capacity to enrich.

EU industry is active in all segments of the nuclear fuel supply chain. While uranium mining is limited in the EU, its companies have mining operations in several major producer countries. The EU nuclear industry also has significant capacities in conversion, enrichment, fuel fabrication and spent fuel reprocessing, making it a global technology leader (European Commission, 2017). **Figure 161** shows a decrease in imports and exports after 2011, mostly as a consequence of the Fukushima accident that same year, but the return of a positive trade balance after 2016, which has been increasing ever since. During the period 2019-2021, the EU was

(215) While this investment is considered as a grant, it constitutes an outlying value, is dedicated to deployment and therefore not reported as such in the early or late stage indicators.

the main exporter, with 55% of the global share. On the other hand, fuel imported from Russia to the EU is very relevant for the soviet/Russian design reactors (VVER) operational in Europe. However, this situation is under consideration through an agreement between the Swedish subsidiary of Westinghouse (US) and other EU companies, to start fuel deliveries for the European VVER fleet in early 2024. The US shows a clear reliance on the EU for its enriched fuel imports, accounting for 53% of EU exports, making it the biggest importer from the EU.

Figure 161: Extra-EU Import & Export [EUR Million]



Source: JRC based on Comext, 2023

According to the WNA Nuclear Fuel Report 2021, Russia and the EU led in 2020 with 45% and 35% of the world enrichment capacity respectively, but China is expected to grow to 25% of global capacity by 2030.

Moreover, some designs of the upcoming SMR fleet will need fuel with higher uranium enrichment, called High Assay Low Enriched Uranium (HALEU). For the HALEU (also used in research reactors and medical radioisotope production) the EU is nowadays dependent on the US and Russia (ESA, 2022). Even though the EU has the knowledge and expertise to produce this material, Euratom has only launched a research call to the value of EUR 1 million under its 2023-25 work programme, to secure the supply of HALEU for medical radioisotope production and research reactor fuel (Euratom, 2023). This can be measured against US Department of Energy funding, through the Inflation Reduction Act, of USD 700 million to secure a reliable domestic supply.

30.4 Future outlook

As one of the main scalable solutions towards decarbonisation, the SMR market has high potential for growth and is attracting increasing amounts of investment and interest worldwide. Various SMR technologies could fit into different sectors, for example to replace retiring coal power plants in the electricity sector, and to produce low carbon, high-quality process heat for district heating applications and industrial sectors. Potential applications include petroleum-refining, steam reforming of natural gas and large-scale hydrogen production as a feedstock for products such as ammonia or synthetic hydrocarbon fuel, for aviation for example.

Analysing the indicators considered and the database consulted for this study, the main SMR actor appears to be the US, with the largest number of VC and corporate companies, together with a wide range of different technological SMR designs. The advanced level of technological and licensing readiness of the US is shared by China and Russia who rely on their state-owned companies for the design and deployment of SMRs.

Some SMR designs would require HALEU fuel and the US and Russia are currently its sole producers. It appears that only US has an ongoing programme to become self-sufficient. If the EU fails to develop this capability, it risks losing its technological leadership in this field.

In terms of the market outlook, significant uncertainties remain regarding technology- and regulatory readiness. The cost competitiveness of SMRs is intrinsically linked to the robustness and size of the global market and to the level of regulatory and policy support.

Compared to other international actors, the readiness levels of EU designs are relatively low but a resilient, independent industry can be built around a mature design to secure its supply chain. A more detailed study is required, with adapted indicators and an expanded database, including the outcomes of the EU SMR pre-partnership work and the NEA SMR Dashboard ([216]).

([216]) The NEA Small Modular Reactor Dashboard by OECD-NEA. Available at: https://www.oecd-nea.org/jcms/pl_78743/the-nea-small-modular-reactor-dashboard

30.5 Scoreboard and key insights

The assessment performed for this study with the available data shows that the EU competitiveness score raises some concerns regarding VC investment when compared to the US. Even though patenting activity is masked by industrial secrecy, the large contribution from the US shows that its deployment readiness level is more advanced than that of the EU. For that reason, patenting activity is a more reliable indicator than company shares to reflect the performance level for each design.

The EU appears to have a strong trade balance for the nuclear fuel-related industry, with major manufacturing capacity (and related fuel cycle services) and the largest export share. However, commercial-grade dedication for certain components should be considered in future studies.

The SMR industry is highly granular due to the wide range of technologies included, and more specificity may be required when selecting solutions for future assessment. Specific indicators not applicable to other solutions may also be necessary, such as technological and licensing readiness levels or investments communicated under Euratom Art. 41.

Figure 162 shows the summary scoreboard for the SMR solution. As with other emerging solutions examined in this report, this first attempt at an assessment has served to reveal the complexity and data limitations involved. While the Scoreboard must be interpreted with caution due to the latter, future work, by the European SMR Pre-Partnership for example, can take into account the issues identified to provide more informed insights.

Figure 162: Scoreboard for small modular reactors

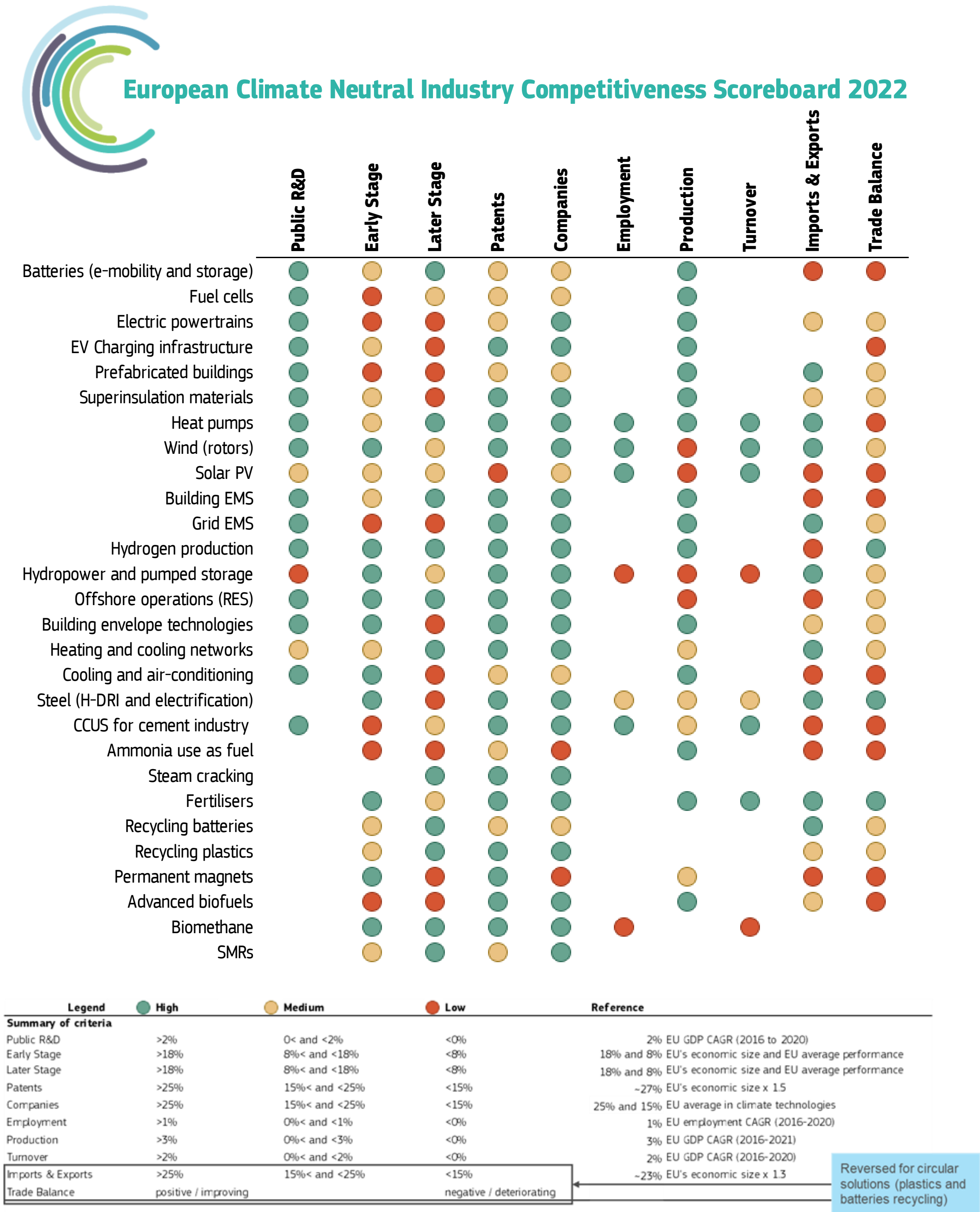
Scoreboard	**Small Modular Reactors**	EU performance in the reference period		
Public R&D			2016-2020	EU CAGR
Early Stage		9%	2016-2021	EU share of global total value
Later Stage		35%	2016-2021	EU share of global total value
Patents		16%	2016-2019	EU share of global total HVI
Companies		29%	2016-2021	EU share of innovating companies
Employment			2016-2020	EU CAGR
Production			2016-2021	EU CAGR
Turnover			2016-2020	EU CAGR
Imports & Exports		19%	2019-2021	EU share of global exports
Trade Balance		High	2016-2021	EU trade balance trend

Source: JRC, 2023

31 Conclusions

European industry plays a central role in delivering the transformational change needed to achieve climate neutrality, reduce energy dependency and ensure European competitiveness in the "net-zero age". In order to succeed, EU industry needs to remain competitive by continuing to innovate. This new scoreboard measures EU progress on the climate neutral solutions key to achieving these goals (**Figure 163**). The summary scoreboard for 2022 provides a snapshot of the EU's competitive position and performance across 28 key climate-neutral solutions, 12 of which are carried over from a previous assessment carried out in 2020, eight of which were added in 2021, and a further eight of which have been added for 2022. The scoring criteria benchmark the values or trends for each indicator in each solution against the performance of the EU economy as a whole, or in terms of 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 the competitiveness analysis of each solution.

Figure 163: European Climate Neutral Industry Competitiveness Scoreboard 2021



Source: JRC, 2023

Overall findings

The EU performs well on innovation-related indicators, especially high-value patents, public R&D investment and the number of innovating companies. EU Member State public R&D investment increased in the period 2016-2020 in all but one solution. Public R&D investment increased most in batteries, offshore operations, hydrogen, grid EMS and CCUS, in which investment grew by an average of 20-30% annually (2016-2020). Based on available data, public R&D investment only decreased in hydropower and pumped storage.

In terms of patenting activity, the EU accounts for over 25% of all high-value filings in 19 of the 28 solutions assessed. In six solutions, the EU dominates innovative activity, representing half of high-value filings globally. Moreover, the EU hosts over 25% - the threshold for strong performance – of identified innovating companies globally in 20 of the 28 solutions. The composition of the innovation ecosystem in the EU is comparable to the rest of the world, with a third of innovators being venture capital companies. Nevertheless, the EU score is average in some strategic net-zero technologies such as batteries and batteries recycling, fuel cells and solar PV.

When it comes to venture capital, investment in climate-neutral solutions continued to rise and had a record year in 2021. Batteries dominate EU venture capital funding, with EUR 0.74 billion of early stage and over EUR 3 billion of later stage investment in 2016-2021. In early stage investment, the EU has captured a lower share globally, compared to the 2015-2020 period, and is therefore less competitive in batteries, solar PV and heating & cooling networks. Nonetheless, with the exception of batteries and batteries recycling, EU early stage investment is increasing and the EU has captured a significant share of all early stage investment in steel, permanent magnets, biomethane, offshore operations, hydropower, wind, bio-based circular fertilisers, cooling and air-conditioning and building envelope technologies. The overall grant intensity in the EU (22%) is comparable to the rest of the world (21%), with the exception of three solutions (fuel cells, hydrogen production and small modular reactors), where the EU ranks markedly lower than the global average.

Overall, the EU has captured a higher share of later stage investment compared to the 2015-2020 period, doing particularly well in batteries and batteries recycling, offshore operations, heat pumps, hydrogen production, heating and cooling networks plastics recycling, building EMS and biomethane. The EU also achieved a strong performance in small modular reactors (supported by corporate investment pledges) and in steam cracking (though through a single venture capital company). However, compared to 2015-2020, it did not perform well in hydropower, fuel cells, CCUS for cement, EV charging infrastructure or steel. Clearly clean energy and climate technologies are witnessing a new wave of venture capital, which is casting its net wider in terms of the spectrum of solutions funded than in the first boom prior to the 2008 financial crisis. Venture capital companies can play an important role in challenging incumbents and catalysing breakthrough innovations in sectors such as steel, fertilisers, buildings and construction. Strong policy support and demand for these solutions may help these ventures succeed.

The green recovery boosted EU production, as an indication of EU manufacturing capacity, which grew faster than EU GDP in 19 solutions in 2016-2021. The most notable compound annual growth rate, at 72%, was in batteries, followed by electric powertrains, prefabricated buildings and hydrogen production to a lesser degree. Production has improved in general compared to 2015-2020, reflecting the economic rebound from the pandemic, with the exception of three solutions: offshore operations, where performance dropped slightly; fuel cells, which maintained a strong performance; and hydropower and pumped storage, whose performance remained weak. Nevertheless, a strong recovery was accompanied by supply chain disruptions and employment shortages, coupled with price volatility. Increased production costs starting in 2021 have affected the indicator to varying degrees across the different solutions.

Regarding EU external trade, the EU performed strongly in 2019-2021, accounting for over 25% of extra-EU exports in eight solutions. The EU largely maintained its position, compared to 2018-2020, apart from in steel, where its performance improved, and in CCUS, where it marginally declined. The majority of EU imports were covered by internal trade except for five solutions: 73% of permanent magnet imports came from China; 70% of ammonia imports came from Algeria, Russia and Trinidad and Tobago; 65% of solar PV imports came from China; 65% of offshore platform and vessel imports came from China, India and South Korea; and 59% of nuclear machinery and 50% of nuclear fuel, both relevant to the small modular reactor (SMRs) value chain, came from Russia.

In 2021, the EU had a positive trade balance in 14 solutions and a trade deficit in 11 solutions: notably several strategic net-zero technologies. China was the main exporter to the EU in seven solutions with a negative trade balance (solar PV; batteries; cooling and air-conditioning; permanent magnets; EV charging; heat pumps; and buildings EMS). Compared to 2020, the EU trade balance deteriorated with the exception of four technologies (wind rotors; hydrogen; offshore operations; and steel). This indicates that EU demand for climate-neutral solutions is growing to the extent that domestic manufacturing is not able to meet all of the demand and an increasing share is met with imports. For instance, in 2020, the trade balance in heat pumps turned negative (EUR 40 million) for the first time, and in 2021, the deficit increased almost tenfold (EUR 390 million). In this context it should be noted that many technologies depend on imported materials, giving impetus to the Critical Raw Materials Act adopted in 2023. Here, circular solutions chosen for the 2022 assessment come into play. Hence, in the case of waste trade, a trade surplus indicates a loss of opportunity for circularity. The EU had a declining trade surplus in plastic scrap, implying improved circularity, while in spent batteries, the volumes of which are still small, exports are on the rise, implying the need to improve recycling within the EU.

There are significant difficulties in consolidating employment and turnover figures, and data is therefore unavailable for the majority of solutions. Nevertheless, renewable energies, for which data is available, show that employment and turnover increased by 12% and 14% respectively in 2021 on 2020 figures. Growth was fuelled particularly by increasing demand for heat pumps and solar PV. At the same time, wind contracted in both jobs and turnover due to a faltering installation rate. A strong bounce-back from the pandemic has been accompanied by employment shortages spilling over from the overall economy, in combination with inertia in the clean energy sector in terms of building the skills capacities required for the green and digital transitions. Therefore, it is of utmost importance to bridge the skills gap and address the supply chain risks identified for (critical) materials to ensure the competitiveness of the EU's climate-neutral industry.

The EU areas of strength

The report confirms EU areas of strength: wind (rotors), heat pumps, offshore operations (for installation of renewables) and heating and cooling networks, where the 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 65% share of all extra-EU exports and hosting a substantial proportion of the global wind energy supply chain. The EU heat pump industry is innovative and well placed to benefit from increasing deployment. Imports from China have, however, increased during recent years. The EU plays host to over 42% 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 are causing bottlenecks for operators, while 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 40% annually in 2016-2020. Early stage investment grew from EUR 5 million in 2010-2015 to over EUR 700 million in 2016-2021, while later stage investment increased from EUR 19 million to EUR 3.5 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. EU production, which increased for the first time since 2016, also shows signs of revival. 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.

Circularity solutions

Bio-based circular fertilisers, batteries and plastics recycling mitigate climate and environmental impacts, while offering new business opportunities and improving security of supply. In bio-based circular fertilisers, the EU shows strong performance in innovation. Supported by an enabling policy framework, such as the Fertilising Product Regulation EU, production is gradually increasing, serving an emerging global market. In terms of plastics recycling, the EU leads in patenting activity and innovating companies, thus being well positioned to capture future opportunities. The EU has already reduced plastic waste export significantly, yet there is still room to improve, as the EU is responsible for 20% of global plastic waste exports. Battery recycling is still a nascent area, but extremely important for the development of an EU-based battery supply chain and access to critical raw materials. Better recycling is also one of the pathways explored for improving security of supply in rare earth-based permanent magnets.

Emerging solutions

Deep decarbonisation will need solutions to address the hard-to-abate emissions of the energy-intensive industries, including steel, cement and chemicals. In steelmaking, the EU has the potential to take the lead in the green hydrogen-based net-zero production route. The EU is already a leader in energy- and CO_2-efficient steel production, and with a 31% share of high-value inventions and 34% of innovating companies, the EU also leads in breakthrough technologies. Thanks to a mega-deal with a Swedish start-up in 2021, the EU has captured nearly three quarters of all early stage investment. In addition, the majority of global steel decarbonisation projects via the H-DRI route are based in Europe. Nevertheless, deep decarbonisation of steel production will depend on the accelerated development and adoption of supporting technologies, such as electrolysers and hydrogen infrastructure, and the availability of renewable energy.

In CCUS technologies, there have been unprecedented advances in recent years. While the EU is behind the US and the rest of the world on some indicators, the situation is improving. EU Member State public R&D funding grew at a CAGR of 18% in 2016-2020 and CCUS received the highest share of EU R&D funding for the decarbonisation of the cement industry.

Steam cracking is the key process in the decarbonisation of the chemical industry, electrification of which could not only drastically reduce emissions but also improve product yield. Several innovative ideas are being developed by the industry and academia, and the EU is a clear leader in patenting activity. The only venture capital deal so far has gone to an EU-based start-up, which is developing a technology that, if successful, can be ground-breaking for the chemical and other energy-intensive industries.

Other important emerging solutions are biomethane and small modular (nuclear) reactors (SMRs). Biomethane can substitute for natural gas, decarbonising a range of sectors, while improving waste management and sustainable agriculture. It can thus contribute to the goals of REPowerEU to reduce the EU's dependence on imported fossil fuels and diversify its energy supply. The EU performs strongly in investment and innovation, but weakly in employment and turnover. Nevertheless, if current scale-up plans are realised, the sector has a significant job creation potential. SMRs can significantly improve nuclear safety performance and lower capital cost requirements, thus offering a solution that can be built closer to industrial sites, while enabling new delivery and business cases (such as scalable sources of zero-carbon heat and electricity applications), that would make them more affordable and faster to deploy than large traditional reactors. As such, they are attracting increasing amounts of investment worldwide, with the US largely leading the way. Several EU countries have shown interest and allocated public funding to the development of SMRs, supported by the EU SMR Pre-Partnership Initiative.

The EU areas in need of attention

This report also reveals areas of weaknesses and potential threats. There are some trends of concern in transport-related solutions, such as fuel cells, electric powertrains, EV charging infrastructure, ammonia as a fuel and advanced biofuels, where EU companies have attracted less venture capital than their global competitors. As clean mobility is one of the fastest growing sectors, there is a risk that innovative EU companies are not able to find adequate financing to scale up and relocate to commercialise their solutions. EU companies also capture less investment than the EU average in climate tech (less than 9%), in grid EMS and prefabricated buildings, which are both very important, the former for enabling smart grids and the latter for decarbonising the building sector. In building EMS, which is closely connected to both, the EU trade deficit is gradually increasing, reflecting the EU's reliance on imports when it comes to digital components and assemblies.

Another concern relates to neodymium magnets (Nd-Fe-B), which are high-performance permanent magnets, indispensable for the production of wind turbines (aerogenerators) and electric vehicles (electric traction motors) as well as a number of other advanced technologies. The EU's increasing trade deficit (EUR 1 billion in 2021) exemplifies the magnitude of the import dependency for this crucial technology. It also raises concerns over the role of China as the most important exporter to the EU (export value of EUR 2.5 billion in the period 2019-2021). The future legislative framework, based on the European Critical Raw Materials Act, will provide incentives to increase the EU's self-sufficiency in this domain and diversify supply. This can be reinforced by the ongoing EU R&D projects (funded by Horizon Europe), which focus on improving circularity and developing rare earth-free magnets.

References

ACEA, 2022. *EV Charging Infrastructure Masterplan 2022,* ACEA.

Acton, M., Bertoldi, P. & Booth, J., 2021. *2021 Best Practice Guidelines for the EU Code of Conduct on Data Centre Energy Efficiency,* Ispra: European Commission.

Alberici, S., Gräf, D. & Aurand, M., 2023. *Beyond energy - monetising biomethane's whole-system benefits,* Netherlands: Guidehouse.

Ammonia Energy Association, 2020. *Wartsila, Repsol, and Knutsen to test ammonia four-stroke engine.* [Online]
Available at: https://www.ammoniaenergy.org/articles/wartsila-repsol-and-knutsen-to-test-ammonia-four-stroke-engine/
[Accessed 4 22 2022].

Ammonia Energy Association, 2022. *Ammonia Energy Association.* [Online]
Available at: https://www.ammoniaenergy.org/articles/haldor-topsoe-and-partners-issue-ammonfuel-report/
[Accessed 22 4 2022].

Asensio Bermejo, J. & Georgakaki, A., 2020. *Competitiveness indicators for low-carbon energy industries,* Luxembourg: Publications Office of the European Union.

Aspen Global Change Institute and Lawrence Berkeley National Lab, 2014. *US Data Center Electricity Use.*

Bednarek, T., Davies, J., Malkow, T. & and Weidner, E., 2021. *Historical Analysis of FCH 2 JU Stationary Fuel Cell Projects: Progress of Key Performance Indicators against the State of the Art,* Luxembourg: Publications Office of the European Union.

Bernreuter Research , 2020 (updated 2022). *Polysilicon Market Reports - Manufacturers,* Bernreuter Research.

Bielewski, M. et al., 2022. *Clean Energy Observatory: Batteries for energy storage in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets,* Luxembourg: Publications Office of the European Union.

Bloomberg Intelligence, 2021. *European Steel-Producer Decarbonisation Plans*.

Bloomberg, 2021. *Global oil giants hunt for that one last big hit along Brazil's offshore fields.* [Online]
Available at: https://www.bloomberg.com/news/features/2021-07-26/global-oil-giants-hunt-for-that-one-last-big-hit-along-brazil-s-offshore-fields

BloombergNEF, 2023. *2023 Hydrogen Market Outlook,* BloombergNEF.

BNEF, 2021a. *Electric Vehicle Cost Competitiveness.*

BNEF, 2021b. *2021 Global EV Public Charging Market Summary*.

BNEF, 2021c. *2H 2021 Hydrogen Market Outlook.*

BNEF, 2021d. *Steel Pins Hopes on Collaboration, Private Sector.*

BNEF, 2021e. *Global Graphite Outlook 2021.*

BNEF, 2021f. *Decarbonising Steel - Technologies and Costs.*

BNEF, 2022a. *Localizing Clean Energy Supply Chains Comes at a Cost.* [Online]
Available at: bnef.com
[Accessed 6 January 2023].

BNEF, 2022b. *1H 2022 Hydrogen Market Outlook.*

Bobba, S. et al., 2020. *Critical materials for stratetic technologies and sectors in the EU - a foresight study,* Luxembourg: Publications Office of the European Union.

BPIE, 2020. *Building Renovation: A Kick-Starter for the EU Economy*, Buildings Performance Institute Europe, Available at: https://www.renovate-europe.eu/2020/06/10/building-renovation-a-kick-starter-for-the-eu-economy/

BPIE, 2021. *Deep Renovation: Shifting from exception to standard practice in EU Policy*, Available at: https://www.bpie.eu/publication/deep-renovation-shifting-from-exception-to-standard-practice-in-eu-policy/

BPIE, 2023. *How to stay warm and save energy – insulation opportunities in European homes,* BPIE (Buildings Performance Institute Europe).

Brinks, H. & Hektor, E., 2020. *Ammonia as a marine fuel,* DNV GL.

Buckwell, A. & Nadeu, E., 2016. *Nutrient Recovery and Reuse (NRR) in European agriculture. A review of the issues, opportunities, and actions.,* Brussels: RISE Foundation.

Bundesverband Warmepumpe (BWP), 2022. [Online]
Available at: https://twitter.com/BWPev/status/1569623749627985920

Buttler, A. & Spliethoff, H., 2018. Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews,* 82(P3), pp. 2440-2454.

Capdevila-Cortada, M., 2019. Electrifying the Haber-Bosch. *Nature Catalysis,* p. 1055.

Carrara, S. et al., 2023. *Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU - A foresight study,* Luxembourg: Publications Office of the European Union.

Chandler, D., 2022. Evaporation and Radiation cooling: no power required (but the aerogel must get cheaper). *Energy Post*, 28 September.

Chatzipanagi, A. et al., 2022. *Clean Energy Technology Observatory: Photovoltaics in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets,* Luxembourg: Publications Office of the European Union.

Cheliotis, M. et al., 2021. Review on the Safe Use of Ammonia Fuel Cells in the Maritime Industry. *Energies,* 14(11), p. 3023.

Circular Plastics Alliance, 2021. *Circular Plastics Alliance - Roadmap to 10Mt recycled content by 2025,* Brussels: European Commission.

Climate Neutral Data Centre, 2020. [Online]
Available at: https://www.climateneutraldatacentre.net/
[Accessed 12 1 2022].

Crippa, M. et al., 2019. *A circular economy for plastics: insights from research and innovation to inform policy and funding decisions,* Brussels: Publications Office.

Davies, J., Dolci, F. & Weidner, E., 2021. *Historical Analysis of FCH 2 JU Electrolyser Projects: Evaluation of contributions towards advancing the State of the Art,* Luxembourg: Publications Office of the European Commission.

DCD, 2021. *Data center dynamics.* [Online]
Available at: https://www.datacenterdynamics.com/en/news/svenska-kraftn%C3%A4t-and-stockholm-exergi-plan-heat-recovery-from-huge-swedish-substation/
[Accessed 11 2 2022].

DNV-GL, 2019. *Maritime Forecast to 2050.*

Dolci, F. et al., 2022. *Clean Energy Technology Observatory: Water Electrolysis and Hydrogen in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets,* Luxembourg: Publications Office of the European Union.

E4tech, 2021. *Fuel Cell Industry Review 2020.*

ECN, 2019. *European Bio-waste Management - Overview of Bio-waste Collection, Treatment & Markets Across Europe,* Brussels: ECN.

ECSO, 2021. *Renovating the building envelope - Quo vadis?,* s.l.: European Construction Sector Observatory.

EEA, 2021. *New registrations of electric vehicles in Europe,* Copenhagen: EEA.

EEA, 2022. *New registrations of electric vehicles.* [Online]
Available at: https://www.eea.europa.eu/ims/new-registrations-of-electric-vehicles

EIT, 2018. *Innoenergy -Top-10 innovators, Heat pumps report.*

EMSA, 2022. *Potential of ammonia as fuel in shipping.*

Englert, D., Losos, A., Raucci, C. & Smith, T., 2021. *The Role of LNG in the Transition Toward Low- and Zero-Carbon Shipping,* Washington, DC: World Bank.

EPO and OECD/IEA, 2023. *Hydrogen patents for a clean energy future - A global trend analysis of innovation along hydrogen value chains,* Hague: EPO.

ePURE, 2023. *ePURE: European renewable ethanol.* [Online]
Available at: https://www.epure.org/

ESA, 2022. *Securing the European Supply of 19.75% Enriched Uranium Fuel,* Paris: ESA.

ESTEP, 2021. *Clean Steel Partnership - Strategic Research and Innovation Agenda (SRIA),* Brussels: ESTEP AISBL.

ETIPWind Executive Committee, 2020. *Floating Offshore wind - Delivering Climate Neutrality.*

Euratom, 2023. *Euratom Research and Training Programme Work Programme 2023-2025,* Brussels: Euratom.

EurObserv'ER, 2019. *The State of Renewable Energies in Europe - Edition 2019.*

EurObserv'ER, 2022. *The State of Renewable Energies in Europe - Edition 2021 20th EurObserv'ER Report.*

EurObserv'ER, 2023. *The state of renewable energies in Europe - edition 2022. 21st EurObserv'ER report,* Paris: EurObserv'ER.

Eurofer, 2021. *European Steel in Figures 2021,* Eurofer.

European Biogas Association, 2021. *EBA Statistical Report 2021,* Brussels: EBA.

European Biogas Association, 2022. *Statistical Report 2022,* Brussels: European Biogas Association.

European Commission, 2016. *The European Code of Conduct for Energy Efficiency in Data Centres.*

European Commission, 2017. *Nuclear Illustrative Programme (PINC),* Luxembourg: European Commission.

European Commission, 2018. *COM(2018) 28 final. A European Strategy for Plastics in a Circular Economy,* Luxembourg: European Commission.

European Commission, 2019a. *Strengthening Strategic Value Chains for a future-ready EU Industry - report of the Strategic Forum for Important Projects of Common European Interest.*

European Commission, 2019b. *COM(2019) 640 final,* Brussels: European Commission.

European Commission, 2020a. *Climate neutral market opportunities and EU competitiveness,* Luxembourg: Publications Office.

European Commission, 2020b. *Hydrogen generation in Europe: overview of costs and key benefits,* Luxembourg: Publications Office of the European Union.

European Commission, 2020c. *Progress of clean energy competitiveness SWD(2020) 953 final,* Brussels: European Commission.

European Commission, 2020d. *Impact Assessment Report SWD(2020) 335 final,* Brussels: European Commission.

European Commission, 2020e. *Sustainable and Smart Mobility Strategy – putting European transport on track for the.*

European Commission, 2020f. *Communication - Resilience: Charting a Path towards greater Security and Sustainability.*

European Commission, 2021a. *Digital technologies and use cases in the energy sector,* Brussels: Publications Office.

European Commission, 2021b. *SWD(2021) 60 final. Evaluation of Directive (EC) 2000/53 of 18 September 2000 on end-of-life vehicles,* Brussels: European Commission.

European Commission, 2022a. *Hydrogen: Commission supports industry commitment to boost by tenfold electrolyser manufacturing capacities in the EU. Press release.* [Online]
Available at: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_2829
[Accessed 5 May 2022].

European Commission, 2022b. *District heating and cooling in the European Union : overview of markets and regulatory frameworks under the revised Renewable Energy Directive,* Bacquet, A.; Galindo Fernández, M; Oger, A: European Commission, Directorate-General for Energy.

European Commission, 2022c. *European Commission, DG Trade.* [Online]
Available at: https://policy.trade.ec.europa.eu/news/eu-counters-dumped-imports-graphite-electrodes-china-2022-04-07_en

European Commission, 2022d. *COM(2022) 677 final. Proposal for a regulation on packaging and packaging waste,* Brussels: European Commission.

European Commission, 2022e. *EU agricultural outlook for markets, income and environment, 2022-2032,* Brussels: European Commission, DG Agriculture and Rural Development.

European Commission, 2022f. *'REPowerEU Plan'. COM(2022) 230 final,* Brussels: European Commission.

European Commission, 2023. *Recovery and Resilience Scoreboard.* [Online]
Available at: https://ec.europa.eu/economy_finance/recovery-and-resilience-scoreboard/index.html
[Accessed 28 June 2023].

European Court of Auditors, 2021. *Special Report 05/2021: Infrastructure for charging electric cars is too sparse in the EU,* Brussels.

European Heat Pump Association, 2022. *European Heat Pump Market and Statistics Report 2022,* Brussels: The European Heat Pump Association AISBL (EHPA).

European Institute of Innovation and Technology, 2022. *EIT News and Events.* [Online]
Available at: https://eit.europa.eu/news-events/news/tuv-sud-and-eit-innoenergy-launch-partnership-combat-skills-shortage-battery-sector
[Accessed 6 January 2023].

European Parliament, 2022a. *EU ban on the sale of new petrol and diesel cars from 2035 explained.* [Online]
Available at: https://www.europarl.europa.eu/news/en/headlines/economy/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained

European Parliament, 2022b. *Car-recharging stations should be available every 60 km, say MEPs.* [Online]
Available at: https://www.europarl.europa.eu/news/en/press-room/20221014IPR43206/car-recharging-stations-should-be-available-every-60-km-say-meps

European Raw Material Alliance, 2021. *Rare Earth Magnets and Motors: A European Call for Action*.

European Round Table for Industry, 2020. *Putting the EU Industrial Strategy into action: KPIs for tracking progress and benchmarking competitiveness,* Brussels: ERT.

European Soil Data Centre (ESDAC), 2023. *Joint Research Centre, European Commission.* [Online]
Available at: esdac.jrc.ec.europa.eu
[Accessed 13 January 2023].

Eurostat, 2022. *Mineral fertiliser consumption remained high in 2020.* [Online]
Available at: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20220628-1#:~:text=Mineral%20fertiliser%20consumption%20remained%20high%20in%202020%20%2D%20Products%20Eurostat%20News,-Back%20Mineral%20fertiliser&text=The%20amount%20of%20mineral%20fertilise
[Accessed 23 February 2023].

Fahnestock, J. et al., 2021. *NoGAPS: Nordic Green Ammonia Powered Ship - Project Report.*

Falck, O., Czernich, N. & Koenen, J., 2021. *Auswirkungen der vermehrten Produktion elektrisch betriebener Pkw auf die Beschäftigung in Deutschland,* München: Ifo Institut.

FBI, 2022. *Fortune Business Insights.* [Online]
Available at: https://www.fortunebusinessinsights.com/industry-reports/smart-building-market-101198

FCH 2 Joint Undertaking, 2019. *Hydrogen roadmap Europe: a sustainable pathway for the European energy transition,* Luxembourg: Publications Office.

FCH 2 JU, 2020. *Opportunities arising from the inclusion of Hydrogen Energy Technologies in the National Energy & Climate Plans,* Brussels: FCH 2 JU.

FCH 2 JU, 2021. *Programme Review Report 2020-21,* Luxembourg: Publications Office of the European Union.

FCH 2 JU, 2022. *Programme review report 2022,* Luxembourg: Publications Office of the European Union.

FCHO, 2022a. *Technology and Market, Fuel Cell Market data,* Brussels: Fuel Cells and Hydrogen Observatory.

FCHO, 2022b. *2022 EU and National Policies Report,* Brussels: Fuel Cells and Hydrogen Observatory.

FCHO, 2023. *Policy and Regulation Codes and Standards.* [Online]
Available at: https://www.fchobservatory.eu/observatory/policy-and-rcs
[Accessed 1 April 2023].

Fédération Internationale de l'Automobile, 2022. *FIA Region I - Expert study on guidance and recommendations regarding electric vehicle propulsion battery end-of-life policies,* FiA.

Fertilizers Europe, 2021. *Industry Facts and Figures.*

Financial Times, 2022. Carmakers to suffer chip shortages until at least end of 2023. *Financial Times*, 20 December.

Fiorini, A., Georgakaki, A., Pasimeni, F. & Tzimas, E., 2017. *Monitoring R&I in Low-Carbon Energy Technologies,* Luxembourg: Publications Office of the European Union.

Fleet Europe, 2021. *How Europe aims to achieve battery independence from China.* [Online]
Available at: https://www.fleeteurope.com/en/new-energies/europe/features/how-europe-aims-achieve-battery-independence-china

Fleet Europe, 2022. *Renault, Valeo and Valeo Siemens form electric motor partnership.* [Online]
Available at: https://www.fleeteurope.com/en/new-energies/europe/article/renault-valeo-and-valeo-siemens-form-electric-motor-partnership
[Accessed 15 2 2022].

Fraunhofer, 2021. *The world's first high-temperature ammonia-powered fuel cell for shipping.* [Online]
Available at: https://www.fraunhofer.de/en/press/research-news/2021/march-2021/worlds-first-hightemperature-ammonia-powered-fuel-cell-for-shipping.html
[Accessed 22 4 2022].

Frelle-Petersen, C., Howard, A., Hjorth Poulsen, M. & Hansen, M., 2021. *Innovation Needs for Decarbonisation of Shipping,* Mission Innovation and Danish Maritime Authority.

Fry, J. & Schleiss, A. M. M., 2022. Hydropower as a catalyst for the energy transition within the European Green Deal Part I: urgency of the Green Deal and the role of Hydropower. *E35 Web of Conferences, Sharing Water: Multi-purpose of reservoirs and innovations,* Volume 346, p. 04015.

Fuel Cells and Hydrogen Observatory, 2021a. *Chapter 1 2021 Technology & Market Report,* Brussels: FCH 2 JU.

Fuel Cells and Hydrogen Observatory, 2021b. *2021 Hydrogen supply and demand Chapter 2,* Brussels: FCH 2 JU.

Gardarsdottir, S. et al., 2019. Comparison of Technologies for CO2 Capture from Cement Production—Part 2: Cost Analysis. *Energies,* 10 February, 12(3), p. 542.

Global CCS Institute, 2021. *Technology readiness and costs of CCS*.

Global Cooling Prize, 2021. *Breakthrough, climate-friendly ACs: winners of the Global Cooling Prize announced*.

GMF, 2022a. *Mapping of zero emission pilots and demonstration projects (third edition)*.

GMF, 2022b. *Annual Progress Report on Green Shipping Corridors 2022*.

Grassano, N. et al., 2022. *The 2022 EU Industrial R&D Investment Scoreboard,* Luxembourg: Publications Office of the European Union.

Gross, S., 2021. *The Challenge of Decarbonizing Heavy Industry,* Foreign Policy at Brookings Institution.

GWO, G., 2022. *Global Wind Workforce Outlook 2022-26*.

Hurtig, O. et al., 2022. *Clean Energy Technology Observatory: Advanced biofuels in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets,* Luxembourg: Publications Office of the European Union.

Hybrit, 2018. *Summary of findings from HYBRIT Pre-Feasibility Study 2016-2017*.

Hydrogen Europe, 2022. *Clean Hydrogen Monitor 2022*.

IAEA, 2022. *Advances in Small Modular Reactor Technology Developments,* Paris: IAEA.

IEA, 2019. *Transforming Industry through CCUS,* Paris: IEA.

IEA, 2020. *Energy Technology Perspectives 2020.* [Online]
Available at: https://www.iea.org/reports/energy-technology-perspectives-2020
[Accessed 22 4 2022].

IEA, 2021a. *Hydrogen,* Paris: IEA.

IEA, 2021b. *Global Hydrogen Review 2021 (Revised version November 2021),* Paris: IEA.

IEA, 2021c. *Hydropower Special Market Report Analysis and Forecast to 2030,* Paris: IEA.

IEA, 2021d. District Heating, Paris: IEA.

IEA, 2021e. *Cooling,* Paris: IEA.

IEA, 2021f. *The Role of Low-Carbon Fuels in the Clean Energy Transitions of the Power Sector,* Paris: OECD Publishing.

IEA, 2021h. *Ammonia Technology Roadmap: Towards more sustainable nitrogen fertiliser production,* Paris: OECD Publishing.

IEA, 2022a. *Tracking Clean Energy Innovation: Focus on China,* Paris: IEA.

IEA, 2022b. *Global EV Outlook 2022,* Paris: IEA.

IEA, 2022c. *The Future of Heat Pumps,* Paris: OECD/IEA.

IEA, 2022d. *Special Report on Solar PV Global Supply Chains,* Paris: IEA.

IEA, 2022e. *Global Hydrogen Review 2022,* Paris: IEA.

IEA, 2022f. *Space Cooling,* Paris: IEA.

IEA, 2022g. *World Energy Outlook,* Paris: OECD/IEA.

IEA, 2022h. *"France 2030 Investment Plan" - Small Modular Reactor investment.* [Online]
Available at: www.iea.org/policies/15028-france-2030-investment-plan-small-modular-reactor-investment

IMO, 2021. *Marine Environment Protection Committee (MEPC) 77, 22-26 November 2021.* [Online]
Available at: https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MEPC77.aspx
[Accessed 22 4 2022].

International Energy Agency, 2020. *Outlook for biogas and biomethane: Prospects for organic growth,* Paris: IEA.

International Energy Agency, 2021. *The Role of Critical Materials in Clean Energy Transitions,* Paris: International Energy Agency.

International Hydropower Association (IHA), 2022. *Hydropower Status Report Sector trends and insights,* United Kingdom: IHA Central Office.

IRENA, 2021. *Renewable Power Generation Costs in 2020,* Abu Dhabi: International Renewable Energy Agency.

IRENA, 2022a. *Renewable Energy and Jobs - Annual Review 2022,* Abu Dhabi: IRENA.

IRENA, 2022b. *Geopolitics of the Energy Transformation: The Hydrogen Factor,* Abu Dhabi: International Renewable Energy Agency.

IRENA, 2022c. *Innovation Outlook - Renewable Ammonia,* Abu Dhabi: International Renewable Energy Agency.

IRENA, 2023. *Renewable capacity statistics 2023*, Abu Dhabi: International Renewable Energy Agency.

Jager-Waldau, A., 2022. Snapshot of photovoltaics - February 2022. *EPJ Photovoltaics,* p. 9.

Jakubcionis, M. & Carlsson, J., 2017. Estimation of European Union residential sector space cooling potential. *Energy Policy,* Volume 101, pp. 225-235.

JRC, 2020. *Deep decarbonisation of industry: The cement sector*.

Kapetaki, Z. et al., 2022. *Clean Energy Technology Observatory: Carbon Capture Utilisation and Storage in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets,* Luxembourg: Publications Office of the European Union.

Kim, D. et al., 2022. Design and Implementation of Smart Buildings: A Review of Current Research Trend. *Energies,* p. 15(12):4278.

Kivlehan, P. N., 2022. *What are the latest trends in modular construction?.* [Online]
Available at: https://ww3.rics.org/uk/en/modus/built-environment/construction/modular-construction.html
[Accessed 09 02 2023].

Koot, M. & Wijnhoven, F., 2021. Usage impact on data center electricity needs: A system dynamic forecasting model. *Applied Energy,* Volume 291, p. 116798.Kougias, I. et al., 2019. Analysis of emerging technologies in the hydropower sector. *Renewable and Sustainable Energy Reviews,* Volume 113, p. 109257.

Kuokkanen, A., 2022. *The next-generation of sustainable fertilisers: a win-win solution,* Petten: European Commission.

Kuokkanen, A. et al., 2022. *European Climate Neutral Industry Competitiveness Scoreboard (CINDECS) - Annual Report 2021,* Luxembourg: Publications Office of the European Union.

Kurmayer, N. J., 2023. *Growing demand puts EU electricity grid under pressure.com.* [Online]
Available at: EURACTIV.com

Liu, F. & van den Bergh, J., 2020. Differences in CO2 emissions of solar PV production among technologies and regions: Application to China, EU and USA. *Energy Policy ,* 138(111234).

Ludwig, M. et al., 2021. *The Green Tech Opportunity in Hydrogen,* Boston Consulting Group.

Lyons, L. et al., 2022. *Clean Energy Technology Observatory: Heat Pumps in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets,* Luxembourg: Publications Office of the European Union.

Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, 2021. *Industry Transition Strategy*.

Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, 2022. [Online]
Available at: https://www.zerocarbonshipping.com/
[Accessed 21 4 2022].

Magagna, D. et al., 2017. *Supply chain of renewable energy technologies in Europe: An analysis for wind, geothermal and ocean energy,* Luxembourg: Publications Office of the European Union.

MAN Energy Solutions, 2020. *MAN Energy Solutions to Lead Danish Consortium Developing Ammonia-Fuelled Engine for Maritime Sector.* [Online]
Available at: https://www.man-es.com/company/press-releases/press-details/2020/10/21/man-energy-solutions-to-lead-danish-consortium-developing-ammonia-fuelled-engine-for-maritime-sector
[Accessed 22 4 2022].

MarketResearchFuture, 2019. *Zero Energy Buildings Market: Information by Equipment, Application and Region - Forecast to 2030.* [Online]
Available at: https://www.marketresearchfuture.com/reports/zero-energy-buildings-market-5325

MarketResearchFuture, 2022. *Prefabricated Buildings Market Research Report Information By Product, By Module Type, By Application, and By Region – Market Forecast Till 2030..* [Online]
Available at: https://www.marketresearchfuture.com/reports/prefabricated-buildings-market-5171
[Accessed 09 02 2023].

MarketsandMarkets, 2023. *Building Thermal Insulation Market by Material, Application, Building Type, and Region - Global Forecast to 2027.* [Online]
Available at: https://www.marketsandmarkets.com/Market-Reports/building-insulation-materials-market-510.html.

Marmier, A., 2023. *Decarbonisation options for the cement industry,* Luxembourg: Publications Office of the European Union.

Matson, J., 2021. *Super-efficient space cooling can mitigate 0.5 degree of warming by 2100,* Energy Post.

Mission Innovation, 2022. *Action plan for the zero-emission shipping mission.*

Mission Possible Partnership, 2022. *Making net-zero Ammonia possible.*

Molina, L., 2022. *The sustainable future of batteries in Europe rests on a developed recycling industry,* Brussels: European Battery Alliance.

Motola, V. et al., 2022. *Clean Energy Technology Observatory: Bioenergy in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets,* Luxembourg: Publications Office of the European Union.

Motorship, 2020. *MAN ES unveils 2025 ammonia retrofit target.* [Online]
Available at: https://www.motorship.com/news101/alternative-fuels/1265564.article
[Accessed 4 22 2022].

Nakano, J., 2022. China's Hydrogen Industrial Strategy. *Center for Strategic & International Studies*, 3 February.

Navarro, R. P. et al., 2022. *European Battery Recycling: an emerging cross-industry convergence,* s.l.: Arthur D. Little.

Oceans of Energy, 2021. *North Sea 1.* [Online]
Available at: https://oceansofenergy.blue/north-sea-1/

Offshore Energy, 2021. *Floating solar power set for trials off Canary Islands.* [Online]
Available at: https://www.offshore-energy.biz/floating-solar-power-set-for-trials-off-canary-islands/

Panagos, P. et al., 2022. European Soil Data Centre 2.0: Soil data and knowledge in support of the EU policies. *European Journal of Soil Science,* 73(6), p. e13315.

Pei, M., Petajaniemi, M., Regnell, A. & Wijk, O., 2020. Toward a fossil free future with HYBRIT: Development of iron and steelmaking technology in Sweden and Finland. *Metals,* 10(7), p. 972.

Pezzutto, S. et al., 2022. Recent Advances in District Cooling Diffusion in the EU27+UK: An Assessment of the Market. *Sustainability,* Volume 14.

Plastic Recyclers Europe, 2022. *25 years of making plastics circular,* Brussels: Plastics Recyclers Europe.

Plastics Europe, 2022. *Plastics - The Facts 2022*.

Plastics Europe, 2023. *European plastics manufacturers plan 7.2 billion euros of investment in chemical recycling.* [Online]
Available at: https://plasticseurope.org/media/european-plastics-manufacturers-plan-7-2-billion-euros-of-investment-in-chemical-recycling-2/
[Accessed 25 January 2023].

Plastics Recyclers Europe, 2020. *Report on Plastics Recycling Statistics 2020 (Update 2021),* Brussels: Plastics Recyclers Europe.

Plastics Recyclers Europe, 2022. *Plastics Recycling Industry in Europe: Mapping of installed plastics recycling capacities, 2020,* Plastics Recyclers Europe.

Plastics Recyclers Europe, 2023. *Plastics Recyclers Europe.* [Online]
Available at: https://www.plasticsrecyclers.eu/about/
[Accessed 25 January 2023].

Plaza, M., Martínez, S. & Rubiera, F., 2020. *CO2 Capture, Use, and Storage in the Cement Industry: State of the Art and Expectations.* [Online]
Available at: https://www.mdpi.com/1996-1073/13/21/5692

Politico, 2018. Hope for circular economy jobs could be a waste. *Politico*, 4 April.

Powder Metallurgy review, 2018. Netzsch offers grinding and classifying of rare earth powders for PM magnet production. *Powder Metallurgy review*, 10 September.

Precision Reports, 2023. *Global Building Envelope Industry Research Report 2023.* [Online]
Available at: https://www.precisionreports.co/global-building-envelope-industry-research-report-2023-competitive-landscape-market-22380090

Quanranta, E. et al., 2022. Is there a residual and hidden potential for small and micro hydropower in Europe? A screening-level regional assessment. *Water Resources Management,* 36(6), pp. 1745-1762.

Quaranta, E. et al., 2021. Assessing the energy potential of modernizing the European hydropower fleet. *Energy Conversion and Management,* Volume 246, p. 114655.

Quaranta, E. et al., 2020. Hydropower case study collection: innovative low head and ecologically improved turbines, hydropower in existing infrastructures, hydropeaking reduction, digitalisation and governing systems. *Sustainability,* Volume 12, p. 8873.

Quaranta, E. & Davies, P., 2021. Emerging and innovative materials for hydropower engineering applications: turbines, bearings, sealing, dams and waterways, and ocean power. *Engineering,* Volume 8, pp. 148-158.

Quaranta, E. et al., 2022. *Clean Energy Technology Obersveatory: Hydropower and Pumped Hydropower Storage in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets,* Luxembourg: Publications Office of the European Union.

Quaranta, E. & Muntean, S., 2023. Wasted and excess energy in the hydropower sector: A European assessment of tailrace hydrokinetic potential, degassing-methane capture and waste-heat recovery. *Applied Energy,* Volume 329, p. 120213.

Ratka, S. & Boshell, F., 2020. The nexus between data centres, efficiency and renewables: a role model for the energy transition. *Energy Post*, 26 June.

ReportLinker, 2021. *Global Li-ion Battery Industry*.

RHC and EHPA, 2021. *Strategic Research and Innovation Agenda for Heat Pumps: Making the technology ready for mass deployment*.

Ritchie, H., Roser, M. & Rosado, P., 2022a. *Fertilizers.* [Online]
Available at: https://ourworldindata.org/fertilizers

Ritchie, H., Roser, M. & Rosado, P., 2022b. *Energy*. [Online]
Available at: https://ourworldindata.org/energy-production-consumption#citation

Rizos, V., Righetti, E. & Kassab, A., 2022. *Developing a supply chain for recycled rare earth permanent magnets in the EU,* Brussels: CEPS.

RVO, 2018. *Contribution of Renewable Cooling to the Renewable Target of the EU,* Dutch Ministry of Foreign Affairs.

Saputra, P. C. & Ramadhan, A., 2023. Smart building trend, role, and position: a systematic literature review. *International Journal of Reconfigurable and Embedded Systems (IJRES),* March.pp. 12(1), 29-41.

Savchina, O., Pavlinov, D., Bobkov, A. & Konovalova, N., 2022. Comparative analysis of the financial stability of renewable-based electricity companies: the case of hydroelectric organizations. *International Journal of Energy Economics and Policy,* 12(5), pp. 392-408.

Schiermeier, Q., 2008. Marine dead zones set to expand rapidly. *Nature,* Volume 126.

Schmidt, D., 2021. Digitalization of district heating and cooling systems. *Energy Reports,* p. 458–464.

Seemungal, L. et al., 2021. *Decarbonisation of Heavy Duty Vehicle Transport: Zero emission heavy goods vehicles. Workshop summary report (28 October 2020, JRC Petten, Netherlands),* Luxembourg: Publications Office of the European Union.

SI Ocean, 2013. *Ocean Energy: Cost of Energy and Cost Reduction Opportunities.*

Simon, F., 2019. *Smart meter woes hold back digitalisation of EU power sector.* [Online]
Available at: https://www.euractiv.com/section/energy/news/smart-meter-woes-hold-back-digitalisation-of-eu-power-sector/

Smith, T. et al., 2021. *A Strategy for the Transition to Zero-Emission Shipping - An Analysis of Transition Pathways, Scenarios, and Levers for Change, Getting to Zero Coalition,* UMAS.

SolarPower Europe, 2021. *Solar PV manufacturing industry*.

SolarPower Europe, 2022. *EU Market Outlook for Solar Power 2022-2026*.

Somers, J., 2021. *Technologies to decarbonise the steel industry,* Luxembourg: Publications Office of the European Union.

Statista, 2022a. *Phosphate rock reserves worldwide in 2021, by country.* [Online]
Available at: https://www.statista.com/statistics/681747/phosphate-rock-reserves-by-country/
[Accessed 13 January 2023].

Statista, 2022b. *Distribution of potash reserves worldwide in 2020, by select country.* [Online]
Available at: https://www.statista.com/statistics/604174/distribution-of-potash-reserves-worldwide-by-select-country/
[Accessed 13 January 2023].

T&E, 2020. *Recharge EU: How many charge points will Europe and its Member States need in the 2020s*.

Telsnig, T. et al., 2022a. *Clean Energy Technology Observatory: Wind Energy in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets,* Luxembourg: Publications Office of the European Union.

Telnsig, T., 2022b. *Mapping and analysis of current circular economy approaches in the wind energy sector,* Petten: European Commission.

The Climate Group, 2020. *The Climate Group SteelZero.* [Online]
Available at: https://www.theclimategroup.org/steelzero
[Accessed 20 12 2021].

The Royal Society, 2020. *Ammonia: zero-carbon fertiliser, fuel and energy storage,* London: The Royal Society.

The White House, 2021. *Carbis Bay G7 Summit Communique*.

Topsoe, 2021. *Haldor Topsoe and Aquamarine enter into a Memorandum of Understanding with the purpose of building a green ammonia facility based on SOEC electrolysis.* [Online]
Available at: https://blog.topsoe.com/haldor-topsoe-and-aquamarine-enters-into-a-memorandum-of-understanding-with-the-purpose-of-building-a-green-ammonia-facility-based-on-soec-electrolysis
[Accessed 22 4 2022].

Trinomics, 2018. *Study in support of evaluation of the Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators*.

UK for Business, Energy & Industrial Strategy, 2021. *CCUS Supply Chains: a roadmap to maximise the UK's potential*.

USDA and GAIN, 2022. *Biofuels Annual,* The Hague: USDA.

Vogl, V., Ahman, M. & Nilsson, L., 2021. The making of green steel in the EU: a policy evaluation for the early commercialization phase. *Climate Policy,* 21(1), pp. 78-92.

Volt, J. et al., 2022. *A. Clean Energy Technology Observatory: District Heat and Cold Management in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets,* Luxembourg: Publications Office of the European Union.

Wagner, B., Hauer, C. & Habersack, H., 2019. Current hydropower developments in Europe. *Current Opinion in Environmental Sustainability,* Volume 37, pp. 41-49.

Weidner, E., Ortiz Cebolla, R. & Davies, J., 2019. *Global deployment of large capacity stationary fuel cells - Drivers of, and barriers to, stationary fuel cell deployment,* Luxembourg: Publications Office of the European Union.

Wind Europe/Wood Mackenzie, 2020. *Wind energy and economic recovery in Europe - How wind energy will put communities at the heart of the green recovery*.

Wind Europe, 2023. *Wind energy in Europe: 2022 Statistics and the outlook for 2023-2027*.

WIPO, 2022. *Hydrogen fuel cells in transportation,* Geneva: World Intellectual Property Organization.

World Economic Forum, 2021. *Decarbonizing shipping – why now is the time to act.* [Online]
Available at: https://www.weforum.org/agenda/2021/05/decarbonising-shipping-the-time-to-act-is-now/
[Accessed 4 21 2022].

World Steel Association, 2020. *Steel Statistical Yearbook 2020 concise version*.

Yara, 2021. *Ammonia bunkering technology company Azane Fuel Solutions and project partners receives public funding for World's first green ammonia bunkering terminal.* [Online]
Available at: https://www.yara.com/news-and-media/news/archive/2021/ammonia-bunkering-technology-company-azane-fuel-solutions-and-project-partners-receives-public-funding-for-worlds-first-green-ammonia-bunkering-terminal/
[Accessed 22 4 2022].

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 furnaceEMS Energy Management System
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

List of boxes

List of figures

List of tables

Annexes

Annex 1. Climate neutral solutions assessed

	Public R&D	Early and later stage investment	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		Based on consolidated and validated list of VC companies.	Y02B 30/17			28251130		841950
17 Cooling and air-conditioning	144		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
21 Electrification of steam cracking	EU funded projects with key word search and expert validation	Based on consolidated and validated list of VC companies.	Y02 AND (C01B 2203/085 or C07C 5/333 or C10G 9/00 or C10G 9/18 or C10G 9/24 or C10G 9/36 or C10G 15/08 or C10G 47/02 or C10G 51/023 or B01J 3/08 or B01J 2219/00135)	Keywords and expert validation for VC companies and corporates through patenting activity.	N/A	N/A	N/A	N/A
22 Bio-based circular fertilisers	EU funded projects with key word search and expert validation		Y02A 40/20, Y02W 30/40		NACE 20.15 (a share of)	20158000	NACE 20.15 (a share of)	310100
23 Batteries recycling	EU funded projects with key word search and expert validation		Y02W 30/84		N/A	N/A	N/A	854810
24 Plastics recycling	EU funded projects with key word search and		Y02W 30/62, Y02P 20/143		N/A	N/A	N/A	391510, 391520, 391530,

	expert validation							391590
25 Permanent magnets	EU funded projects with key word search and expert validation		Y02 AND [(H01F 1/00 or H01F 1/057) AND (H01F 1/032 or H01F 1/053 or H01F 1/0571 or H01F 1/0577 or H01F 1/08)] OR [(H01F1/00 or H01F1/10) AND (H01F1/11 or C01G49/00 or C01G49/0054 or C01G51/40 or C01G51/68 or C04B35/01 or C04B35/26 or C04B35/2633 or C04B35/2641)]		N/A	25992995, 23441230	N/A	850511, 850519
26 Advanced biofuels	N/A		Y02P 30/20, Y02E 50/00, Y02E 50/10, Y02E 50/30		EurObserv'ER	20147500, 20595800, 20142230, 20147130	EurObserv'ER	220720, 382600, 290513, 380300
27 Biomethane	N/A		Y02E 50/30 AND (C12M 21/04 OR C02F		EurObserv'ER	N/A	EurObserv'ER	N/A

			3/00 OR C02F 11/02 OR A01C 3/023)					
28 Small modular reactors	EU funded projects with key word search and expert validation		Y02 AND (G21C 1/32 OR G21C 1/322 OR G21C 1/324 OR G21C 1/326 OR G21C 1/328 OR G21C 1/02 OR G21C 1/24 OR G21C 1/088 OR G21C 3/52 OR G21C 3/54 OR G21C 19/31)		N/A	28993910, 25302200	N/A	284420, 840120, 840130, 840140

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