European Commission

ERA

Industrial technology roadmap **for low-carbon technologies**

in energy-intensive industries

Research and Innovation

ERA industrial technology roadmap for low-carbon technologies in energy-intensive industries

European Commission
Directorate-General for Research and Innovation
Directorate E — Prosperity
Unit E.1 — Industrial research, innovation and investment agendas

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ERA INDUSTRIAL TECHNOLOGY ROADMAP FOR LOW-CARBON TECHNOLOGIES

in energy-intensive industries

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FOREWORD

At the time of this publication and for several months, Europe has been facing high and volatile energy prices. After Russia's unprovoked invasion of Ukraine, a spike in conventional energy prices and security of supply concerns have exacerbated the situation.

The Commission decided to act decisively and presented a Joint European action for more affordable, secure and sustainable energy: 'REPowerEU'. While Europe is looking at short-term solutions to cater for the current needs, we remain more than ever bound to the objectives of the EU Green Deal. The EU transition to clean energy has become even more urgent and the case has never been stronger and clearer.

Implementing the European Green Deal goes hand in hand with making the EU independent from Russian gas imports. Looking at the impact on industry, Russia's invasion of Ukraine hits the EU's energy-intensive industries' ecosystem hard. The REPowerEU plan of March 2022 shows confidence in our capability to accelerate the switch to renewable electrification and green hydrogen.

Meeting the objectives of the Green Deal requires some changes of paradigm, climate mitigation measures and a strong research-based energy sector. Accelerating the implementation of our goals requires even bolder and stronger innovations.

That is why, in complement to the new Emissions and Pollutants package of proposals, we publish the first industrial technology roadmap for low-carbon technologies in energy-intensive industries. We renewed the European Research Area with the objective of increasing the impact of research and innovation and to speed up the transfer and uptake of research results by industry in the economy. This roadmap delivers on this objective.

It provides a synthesis on the state of play in the development of low carbon technologies across energy-intensive sectors and points to critical investment needs. These needs appear not yet fully covered in existing investment agendas and support mechanisms.

This roadmap is drawing a pathway for more synergies in the use of existing mechanisms and cooperation instruments. The roadmap is addressed to policy makers at EU level and in the Member States and regions, but also to decision makers in the industry, and all stakeholders having a stake in the development of low-carbon technologies. The roadmap is there to help Member States to maintain their trajectory towards climate neutrality and to team up with researchers, innovators and the industry for concrete action.

I thank all who have contributed to this report and I am confident that you find it informative and inspiring. I am looking forward to continuing and deepening our cooperation, joint action and investments to live up to our commitments for a sustainable, fair, secure and climate-neutral Europe.

Mariya Gabriel

Commissioner for Innovation, Research,
Culture, Education and Youth

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EXECUTIVE SUMMARY

The EU has to drastically accelerate the clean energy transition and increase Europe's energy independence from fossil fuels – and from Russia. This focus is not new: decarbonisation of industry is a key element on the EU's path to achieving the objective of climate neutrality by 2050 and an intermediate target of reducing greenhouse gas emissions by at least 55% by 2030, as laid down in the European Climate Law. However, bringing innovative low-carbon industrial technologies quickly to the market has become more urgent than ever. The European Research Area (ERA) industrial technology roadmap sketches out the key technologies and the means to transfer them to the industrial ecosystem for energy-intensive industries at EU and national level.

Key findings

Scaling up and deploying the – manageable – number of innovative low-carbon technologies currently at high technology readiness is needed to reach the 2030 emission objectives and to further reduce industry dependence on gas. Technologies that are still in pilot and demonstration phase and at an even lower development levels are crucial for reaching the 2050 emission targets. The challenge is to speed up innovation projects at scale to reach the market.

- There is a gap between the current overall research and innovation (R&I) investments across energy-intensive sectors and the amount needed to reach Green Deal emission targets. The biggest investment gap concerns investments in the coming years for first-of-a-kind (FOAK) installations and further deployment of technologies currently at high technology readiness levels. While EU co-programmed public-private partnerships provide a strong forum for cross-sector cooperation, there is no broad and open platform to establish efficient coordination of research, development and innovation investment plans for low-carbon industrial technologies.

- Several Member States have developed national sector-specific or even cross-sectoral strategies towards decarbonisation in energy-intensive industries, co-created with relevant stakeholders (such as in Finland, Germany, Slovenia and Sweden). These are important instruments designing a detailed process with milestones towards commonly agreed emission reduction (and other) targets. Nevertheless, not all Member States with high CO_2 emission (per capita) have had high European regional development fund (ERDF) allocations for low-carbon projects during the programming period 2014-2020.

- A key barrier to rollout are the uncertainties around authorisations of FOAK installations. Designing and building a pilot or demonstration plant at scale is one of the major challenges for the development of many decarbonisation technologies on the regional level and across borders.

- Patenting filings in green inventions, which give early indications of technological and economic developments, continue to increase globally and patents by major EU companies still play a key role in energy-intensive industries. However, the role of small and medium-sized enterprises (SMEs) in energy-intensive industries' inventions remains unclear.

- EU green standards for several low-carbon technologies appear to be underdeveloped in areas such as carbon capture and storage, hydrogen and industrial symbiosis. As compared to other green technologies like biomass, their number of referenced policy documents and EuroVoc descriptors is significantly lower.

Key opportunities for action

In order to make best use of the public toolbox to leverage private R&I investment, to increase cross-sector cooperation and accelerate deployment, the following opportunities for action arise:

- Assess the potential for establishing an industrial alliance or similar initiative for low-carbon technologies in energy-intensive industries based upon the Processes4Planet and the Clean Steel Partnerships, as referred to in the 2020 New Industrial Strategy. Such initiatives should have a special focus on cross-sectoral technologies linked to the energy efficiency of the industrial processes and use and integration of renewables. Implementing this cross-sectoral approach and the synergies identified by the roadmap would allow a more efficient use of the public toolbox to accelerate decarbonisation and independence from gas towards clear targets. In this context, relevant hub structures could facilitate investment into development and uptake of cross-sectoral low-carbon industrial technologies. Awareness raising actions and expert discussions about private R&I investment under the EU taxonomy for sustainable finance and about existing national support structures for uptake could help increasing R&I investments.

- Facilitate specific national sectoral and cross-sectoral strategies or programmes with key stakeholders as part of ERA policy agenda. This can include joint discussions between the ERA Forum and the Strategic Energy Technology (SET)-Plan's working party on energy efficiency in industry and/or peer counselling and working under the policy support facility and mutual learning exercise. R&I input into the European Semester could facilitate better matching of ERDF and national funding by Member States with a focus on the highest emitting Member States and regions.

- Establish a community of practice to facilitate authorisation for FOAK installation for low-carbon industrial technologies, building upon similar approaches under the European Chips Act, the Regulatory Hubs Network (RegHub) under the regulatory fitness and performance programme (REFIT), EU recommendations for approval processes for renewable energy installations, the Hubs4Circularity community of practice and involvement of existing networks of relevant agencies.

- Improve the knowledge on patenting for green technologies and for energy-intensive industries, such as cement and steel, through more granular sector analysis, and through enabling simpler online searchers for existing green patents.

- Facilitate further valorisation by exploring with industry the opportunity to open up IP on central (cross-sectoral) green inventions, widening the access to IP for licensing (e.g. patent pool) and knowledge transfer.

- Cooperate with European standardisation organisations (e.g. CEN, CENELEC) and industrial partnerships to identify and fill main standardisation gaps for innovative low-carbon industrial technologies.

INTRODUCTION

Policy context

This industrial technology roadmap for low-carbon technologies in energy-intensive industries is published at a moment, when the Commission and EU leaders have launched strong measures to respond to Russia's unprovoked invasion of Ukraine and to break the EU's dependence on Russian gas imports. Very high energy prices and the need to strongly accelerate the clean energy transition call for a combination of pragmatic short-term solutions and determined first steps to implement ambitious medium- and long-term strategies.

This technology roadmap highlights the technological options for low-carbon technologies in energy-intensive industries, including the use of green electricity and hydrogen, it points to available support instruments, synergies and action to accelerate the transition. It is a call for a dialogue with Member States and regions on their specific as well as common and cross-border interests and needs, and provides comprehensive input for Europe's decision makers.

As a cornerstone of the European Green Deal[1], the European Climate Law[2] sets in legislation the EU's objective of climate neutrality by 2050 with an intermediate target of reducing greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. Climate neutrality by 2050 means achieving a balance between anthropogenic economy-wide emissions by sources and removals by sinks of greenhouse gases domestically within the EU by 2050, mainly by cutting emissions. The law aims to ensure that all EU and national policies contribute to achieving this goal and that all sectors of the economy and society play their part in doing so. It steps up efforts to tackle climate change and to deliver on implementation of the Paris Agreement adopted under the United Nations Framework Convention on Climate Change and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

The European Climate Law takes on board the European Council's[3] emphasis on the key role of forward-looking research, development and innovation in achieving climate neutrality. Its accompanying impact assessment emphasises the key role research and innovation (R&I) plays in achieving the EU's climate goals and show that R&I will determine the speed at which decarbonisation can take place, at what cost and with what accompanying benefits.

An upcoming OECD report advocates the role that R&I need to play as part of the transition to a climate-neutral economy[4]. The report shows that the scale of the current innovation response is not in line with the climate neutrality targets. The empirical evidence points to a stagnation in public spending for low-carbon R&D as a share of GDP and a worrisome decrease in climate-related innovation as measured by patent filings, along with a stable share of global VC funding directed at climate-related start-ups. Therefore, the report explores the possibilities towards more ambitious R&I policies for climate neutrality, including interactions with other policy areas.

In this context, Russia's invasion of Ukraine is a stark reminder that the EU has to drastically accelerate the clean energy transition and increase Europe's energy independence from fossil fuels – and from Russia[5].

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[1] COM/2019/640 final, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions The European Green Deal.

[2] Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (European Climate Law).

[3] European Council conclusions, 12 December 2019 (europa.eu).

[4] OECD (2022), Driving low-carbon innovations for climate neutrality, OECD Publishing, Paris. *Forthcoming.*

[5] See RePowerEU: https://energy.ec.europa.eu/repowereu-joint-european-action-more-affordable-secure-and-sustainable-energy_en.

Box 1 | **IMPACT OF A GAS SHORTAGE AND GAS PRICE RISE ON THE DECARBONISATION OF INDUSTRIAL PROCESSES IN EU ENERGY-INTENSIVE INDUSTRIES DUE TO RUSSIA'S INVASION OF UKRAINE**

Compared with coal and oil, natural gas has lower CO_2 emissions in relation to its respective calorific value and is therefore an important transitional energy source on the road to climate neutrality. In the chemical industry for example, it accounted for 35.6% of the energy consumption in 2019[6].

Replacing Russian natural gas poses a major challenge, particularly in the generation of process heat and heating. The heating effect of natural gas can be replaced in the medium to long-term by a combination of renewable electricity and hydrogen. However, this also requires enormous additional quantities of energy generated in Europe or imported, as well as a conversion of industrial plants and storage and supply infrastructures[7]. Existing transformation paths must therefore be looked at considering the new framework conditions.

Against the background of the scarcity of natural gas, - also as a "transition fuel", natural gas should play only a minor or no role in future technological solutions/R&I projects for emission reduction of industrial processes[8]. The implications of reduced availability and higher cost of gas on the technology pathways analysed in this industrial technology roadmap will be be summarised under Chapter 2.

The purpose of this first ERA industrial technology roadmap for low-carbon technologies in energy-intensive industries is to help aligning and linking key partnerships under Horizon Europe with the industrial ecosystem for energy-intensive industries, so as to ensure that efforts team up and that research results are known and rolled out faster in the economy[9].

The roadmap pulls together analysis and stakeholder feedback on the state of play and future needs in R&I to develop and take up key low-carbon technologies. With this comprehensive overview, including the available policy toolbox, it will facilitate an efficient use of the full set of support mechanisms to crowd in private investments in key cross-border projects. The roadmap provides the basis for action at EU and national level to speed up the transfer of research results into the economy with R&I investment agendas from basic research to deployment[10]. The new ERA policy agenda incorporates the two green industrial technology roadmaps on low-carbon and circular industrial technologies together with complementary action to accelerate the twin green and digital transition for key industrial ecosystems[11].

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6 2022 Facts and Figures of the European Chemical Industry, https://cefic.org/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/.

7 Please see also: Leopoldina, Akademie der Wissenschaften: Ad-hoc-Stellungnahme | 8. März 2022, Wie sich russisches Erdgas in der deutschen und europäischen Energieversorgung ersetzen lässt; https://www.leopoldina.org/publikationen/detailansicht/publication/wie-sich-russisches-erdgas-in-der-deutschen-und-europaeischen-energieversorgung-ersetzen-laesst-2022/.

8 As a feedstock for materials/chemicals (especially in the chemical industry) it is difficult to substitute and might continue to play a key role in smaller quantities.

9 COM(2020)628 final, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions *A new ERA for Research and Innovation* (A new ERA). A second industrial technology roadmap will address circular industrial technologies and will be published before end of 2022.

10 Action 5 of the New ERA for Research and Innovation, COM(2020)628.

11 European Commission (2021), *European Research Area Policy Agenda – Overview of actions for the period 2022-2024*, p.15 and following. Council Conclusions 26 November 2021 (14308/21).

The EU's updated industrial strategy from May 2021[12] defines 14 industrial ecosystems, one of which being energy-intensive industries (EIIs)[13]. Following this strategy, the findings from this industrial technology roadmap for low-carbon technologies feed into the upcoming transition pathway for the energy-intensive industries ecosystem, which the European Commission is co-creating with stakeholders to facilitate the green and digital transition and to increase resilience. It contributes the R&I elements to the envisaged actionable plan, which the transition pathway is designed to deliver for the energy-intensive industries industrial ecosystem.

An industrial technology roadmap for low-carbon industrial technologies

This ERA industrial technology roadmap for low-carbon technologies in EIIs provides an evidence base to underpin R&I action for accelerated development and uptake of these technologies, building on the Horizon Europe Processes4Planet and Clean Steel partnerships. It comprises input from several Commission services concerned, while providing complementary analysis of technology development and existing EU-wide R&I action to support it.

World-leading research on low-carbon industrial technologies is being carried out at EU level and at national and regional levels within the EU. The Horizon 2020 and Horizon Europe programmes are funding cutting-edge R&I in these areas, including partnerships with industry to help move low-carbon technologies for energy-intensive industries from basic research to deployment. The European Commission regularly collects and assesses evidence on the development and uptake of low-carbon industrial technologies. This includes industry's focus on R&D investment, Member States' engagement in relevant R&I, and local action to support industrial transformation. Relevant monitoring tools include the EU Industrial R&D Investment Scoreboard, the Strategic Energy Technology Information System (SETIS), the Science, research and innovation performance of the EU (SRIP) reports[14], the Horizon Europe Results Platform, the Innovation Radar, policy mechanism projects[15], the Global Industrial Research & Innovation Analyses (GLORIA) project, the progress report on competitiveness of clean energy technologies, etc. They continuously improve their monitoring and assessment work including on breakthrough industrial technologies and innovation ecosystems, in collaboration with the European Innovation Council (EIC).

The Commission's work with industry experts has identified specific (groups of) technologies expected to have a particularly high potential to lower EU carbon emissions in EIIs[16]. These technologies also play a key role in greenhouse gas emission reduction

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[12] COM(2021)350 final, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions *Updating the 2020 New Industrial Strategy: Building a stronger Single Market for Europe's recovery* (Updated industrial strategy).

[13] The energy-intensive industries (EII) ecosystem covers the chemicals, steel, paper, plastics, mining, extraction and quarrying, refineries, cement, wood, rubber, non-ferrous metals, ferro-alloys, industrial gases, glass and ceramics industries, as defined by the Commission in SWD(2021) 277, Commission Staff Working Document *For a resilient, innovative, sustainable and digital energy-intensive industries ecosystem: Scenarios for a transition pathway* (Transition pathway for the EII ecosystem). The sectors included in the ecosystem are characterised by high energy intensity and by being at the starting point of most value chains, providing raw, processed and intermediate materials rather than finished goods. In this document, the focus is on the following sectors: cement and lime, chemicals, iron and steel, pulp and paper, ceramics, glass, non-ferrous metals.

[14] European Commission, DG R&I (2022), Science, Research and Innovation performance of the EU 2022 report. Forthcoming.

[15] Horizon Results Platform (europa.eu); https://www.innoradar.eu; Projects for policy (P4).

[16] Processes4Planet Strategic Research and Innovation Agenda (SRIA); Clean Steel Partnership SRIA; European Commission (2019), Masterplan for a competitive transformation of EU energy-intensive industries enabling a climate-neutral, circular economy by 2050; COM(2020) 953 final REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL on progress of clean energy competitiveness.

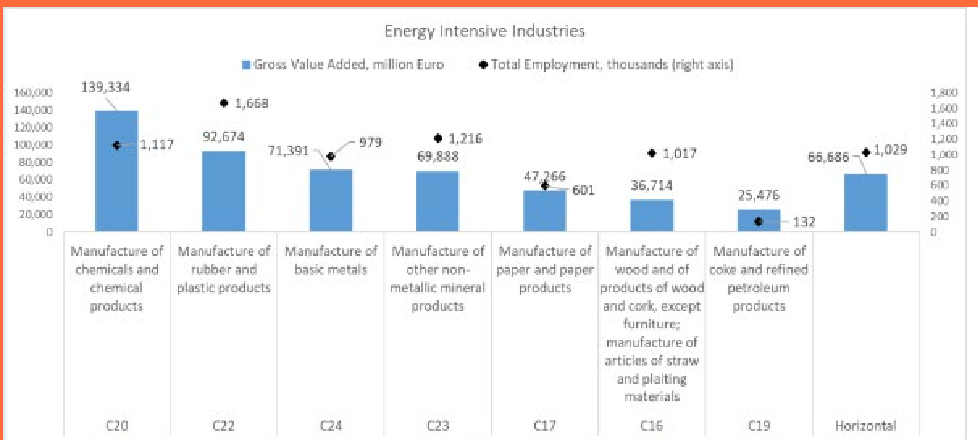
scenarios referred to in the EU's first *Strategic foresight report*[17]. This analysis suggests, that scaling up existing innovative technologies as well as developing new breakthrough technologies is crucial to achieve both the 2030 and the 2050 objectives[18]. For mature technologies, the necessary investment into large-scale demonstration and deployment might require increased pooling of resources[19]. The industrial technology roadmap for low-carbon industrial technologies aims to substantiate the R&I needs to bring industry on the path for transition to reach both objectives and to provide a basis for common action with industry, member states and other stakeholders.

Box 2 | **THE ENERGY-INTENSIVE INDUSTRIES ECOSYSTEM IN THE EU**

Energy-intensive industries accounted for 17% of the EU's total greenhouse gas emissions in 2019[20]. These emissions mainly come from (fossil) energy use or from emissions from processes. That makes the decarbonisation of industry crucial for EU and global pathways towards carbon neutrality[21]. Without further major steps in industrial innovation for low-carbon technologies, the EU will not be able to reach its climate goals[22]. Industries producing key materials (steel, refinery products, fertilisers and cement) and chemicals emit around 500 million tonnes of CO_2 a year, 14% of the EU total[23].

The EII ecosystem is made up of around 548 000 companies across the EU, employing around 7.8 million people and providing a value added of EUR 549 billion (4.55% of the EU total)[24], with different sectors accounting for different proportions (see **Figure 1**). The EII ecosystem has a high percentage (99.4%) of SMEs, which represent 31.3% of the EII ecosystem's turnover and 36.9% of its value added.

Figure 1 Energy-intensive industries ecosystem



Note: The bar labelled Horizontal refers to activities which contribute to all ecosystems such as professional services and utilities; see Annex of the SWD on Monitoring the Implementation of Industrial Policy.
Source: Eurostat, National Accounts. Data from 2018 (or latest year available).

Source: European Commission, Annual Single Market Report 2021 (COM(2021) 351 final).

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17 COM(2021) 750 final, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL, *2021 Strategic Foresight Report: The EU's capacity and freedom to act*, key point III.2 "Securing decarbonised and affordable energy".

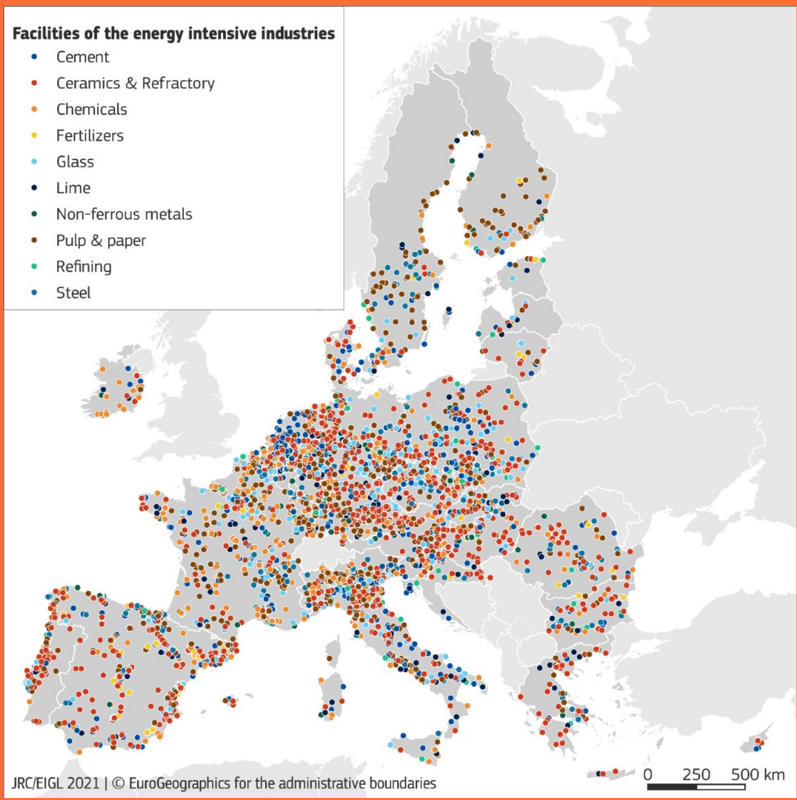
18 A clean Planet for All, p.157; European Commission (2020), Science, Research and Innovation Performance of the EU 2020: A fair, green and digital Europe, p.38; see also industry priorities in Masterplan for EII a Competitive Transformation of EU energy-intensive industries, p.25, and Capgemini, Fit For Net-Zero.

20 According to Emission Trading System (ETS) greenhouse gas inventories, 2019.

21 Capgemini Invent (2020), Fit for Net-Zero: 55 Tech Quests to accelerate Europe´s recovery and pave the way to climate neutrality ('Fit for Net-zero'), p.58 and following; International Energy Agency (2021), Net Zero by 2050: A Roadmap for the Global Energy Sector ('Net-Zero by 2050'), p.121 and following.

This industrial ecosystem is present in production facilities in all Member States and is particularly relevant for decarbonisation, due to its high energy usage, emission rates, and its spread across the EU (see **Figure 2**).

Figure 2 Production facilities of the EIIs ecosystem in the EU



Source: Energy and Industry Geography Lab (Joint Research Centre).

Low-carbon industrial technologies for energy-intensive industries are currently at very different levels of market readiness, often lagging behind what is required to contribute to decarbonisation pathways in order to achieve 2030 and 2050 climate objectives[25]. However, it is important to assess and mitigate risks before beginning large-scale deployment[26] and to provide a synthetic view on industrial transformation through advanced technologies in order to embed it in the broader vision of systemic change to

21 Capgemini Invent (2020), Fit for Net-Zero: 55 Tech Quests to accelerate Europe´s recovery and pave the way to climate neutrality ('Fit for Net-zero'), p.58 and following; International Energy Agency (2021), Net Zero by 2050: A Roadmap for the Global Energy Sector ('Net-Zero by 2050'), p.121 and following.

22 SWD(2020) 176, COMMISSION STAFF WORKING DOCUMENT IMPACT ASSESSMENT Accompanying the document COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Stepping up Europe's 2030 climate ambition - Investing in a climate-neutral future for the benefit of our people, p.31, p. 211 and following. The European Commission had also carried out in-depth analysis exploring how climate neutrality can be achieved across the key economic sectors in the SWD In-depth analysis in support on the COM(2018) 773, A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy ('A clean planet for all'), p.241 and following.

23 According to ETS greenhouse gas inventories, 2019.

24 SWD(2021) 277, Transition pathway for the EII ecosystem.

25 Throughout this report we use the term decarbonisation to mean aiming to reduce greenhouse gas emissions in industrial processes. The term decarbonisation does not, in the case of this report, mean substituting carbon as an essential element of most chemicals and polymers.

26 A clean planet for all, p. 243.

ensure the overall sustainability of our economies and societies. To avoid risks of technological lock-in and stranded technologies, thorough consideration of R&I results - as with industry in Horizon Europe partnerships such as Processes4Planet and Clean Steel - plays a crucial role in enabling efficient investment in future technologies. Therefore, the development and implementation of a common EU vision for R&I action and investment in EU technology roadmaps put together with industry, Member States and other stakeholders are essential for the EU to achieve its policy objectives[27].

[27] SET Plan; European Parliament, 2020, Study on energy-intensive industries; A new ERA; Fit For Net-Zero, p.18.

CHAPTER 1: TRANSITION OF ENERGY-INTENSIVE INDUSTRIES TO CLIMATE NEUTRALITY

Energy-intensive industries (EIIs) are a major contributor to EU's greenhouse gas (GHG) emissions. This chapter provides an overview of the EU industrial ecosystem for EIIs and the emission footprint generated by its facilities in the EU. It then looks into specific scenarios towards net zero emission in energy-intensive industries.

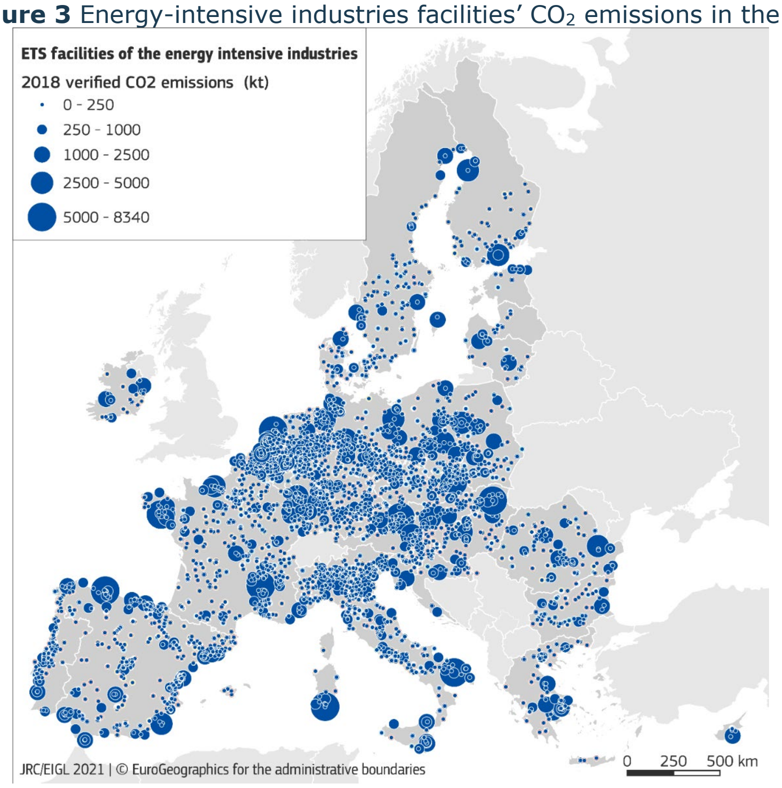
1 Decarbonisation of energy-intensive industries

1.1 *The greenhouse gas emissions of energy-intensive industries*

The EII ecosystem, present in all Member States, is particularly relevant for decarbonising and transforming EU industry, due to its significant share of EU's total GHG emissions[28].

According to Eurostat's energy balances, energy-intensive industries consumed 83% of the final energy used by EU industries in 2018. Based on greenhouse gas emission inventories[29], energy-related emissions (all gases) of EU manufacturing industries and construction amounted to 448 metric tons of carbon dioxide (Mt CO_2) in 2018, while emissions associated to industrial processes were 349 Mt CO_2 (56% and 44% of industry-related emissions respectively).

Figure 3 Energy-intensive industries facilities' CO_2 emissions in the EU



Source: Energy and Industry Geography Lab (Joint Research Centre).

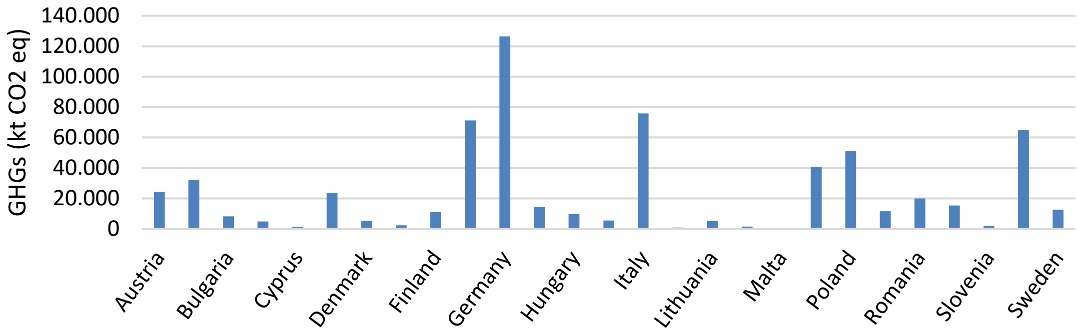
[28] According to ETS greenhouse gas inventories, 2019.

[29] European Environment Agency, https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-17

While emissions generated by energy-intensive industry plants come from all Member States, there is a correlation between emission intensity and share of national Gross Domestic Product (GDP) in EU's GDP. The top four Member States in terms of GDP (Germany, France, Italy and Spain), with an overall share of 63% of EU27 GDP[30], account for more than half of all EU greenhouse gas emissions originating in energy-intensive industries plants.

This trend is confirmed if the next two Member States with the highest emissions are included – the Netherlands and Poland. This results in the top six Member States accounting for almost 73% of EU27 GDP[31], and their combined share of greenhouse gas emissions originating from EII installations making up two thirds (66.9%) of total EU EII greenhouse emissions.

Figure 4 Distribution of EII greenhouse gas emissions by Member State



Source: European Environment Agency, GHG Data Viewer.

However, data on EII plants' CO_2 emissions per capita reveals that several Member States have a CO_2 intensity per capita that is more than double the EU average: Belgium, Slovakia, and Austria. The countries with a CO_2 intensity per capita almost double the EU average are Finland, Netherlands and Luxembourg. Other Member States with a CO_2 intensity per capita considerably higher than the EU average are Lithuania and Estonia.

Table 1 EIIs CO_2 emissions per capita

Country	CO_2 emissions from EII per capita	Country	CO_2 emissions from EII per capita	Country	CO_2 emissions from EII per capita
Belgium	2.7	Germany	1.5	Poland	1.0
Slovakia	2.4	Cyprus	1.4	Ireland	1.0
Austria	2.4	Greece	1.3	France	0.9
Finland	2.3	**EU27 - average**	1.3	Bulgaria	0.9
Netherlands	2.2	Spain	1.2	Slovenia	0.9
Luxembourg	2.1	Sweden	1.2	Romania	0.8
Lithuania	1.8	Croatia	1.2	Hungary	0.8
Estonia	1.7	Portugal	1.0	Denmark	0.7
Czechia	1.6	Italy	1.0	Latvia	0.5

Note: ERDF projects refer to the period 2014-2020 and CO_2 emissions to the year of 2018. Malta is not reported in the table because there are no facilities of the EII in the country covered by the ETS. Source: Marques Santos, A., Reschenhofer, P., Bachtrögler-Unger, J., Conte, A., and Meyer, N., 2022, 'Mapping Low-Carbon Industrial Technologies projects funded by European ERDF in 2014-2020', *Territorial Development Insights Series*, JRC128452, European Commission.

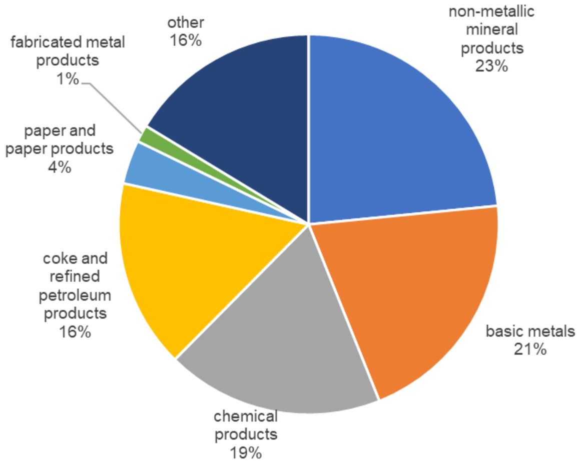
[30] DG R&I calculations based on Eurostat data on GDP and main components, https://ec.europa.eu/eurostat/databrowser/view/nama_10_gdp/default/table?lang=en
[31] Ibid.

For more information on the link between CO2 emissions per capita and European regional development fund (ERDF) funding in low-carbon projects by Member State, see subchapter 3.4: EU programmes.

1.2 *Concentration of emissions in the main sectors*

There is an uneven distribution of emissions not only at national level, but also at sector level. Three of the sectors in the energy-intensive industries ecosystem – non-metallic mineral products, basic metals, chemical products – account for 63% of EII greenhouse gas emissions, making them particularly relevant in the EU's quest for reducing greenhouse gas emissions.

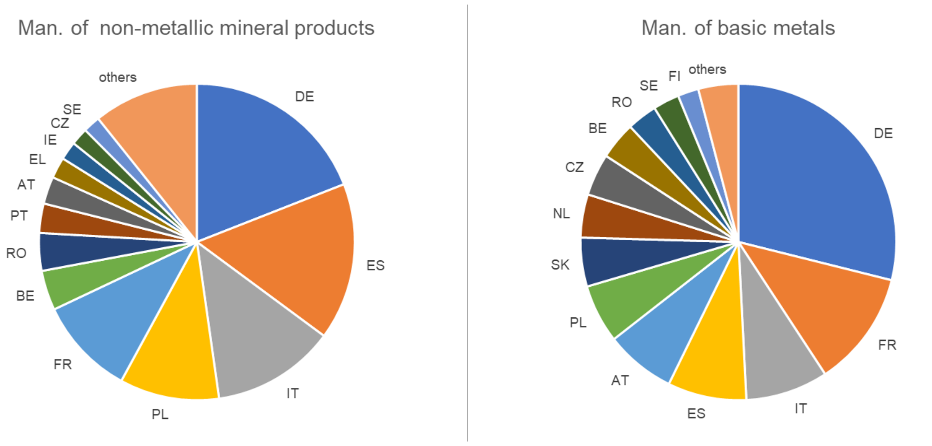
Figure 5 Concentration of greenhouse gas by sector



Source: ETS & Eurostat data, processed by the Austrian Institute of Technology.

Looking at the most emission-intensive sectors of the EIIs (non-metallic mineral products and basic metals), there are differences between Member States' emission levels: While Germany expectedly ranks first, the second and third ranks differ between these two sectors.

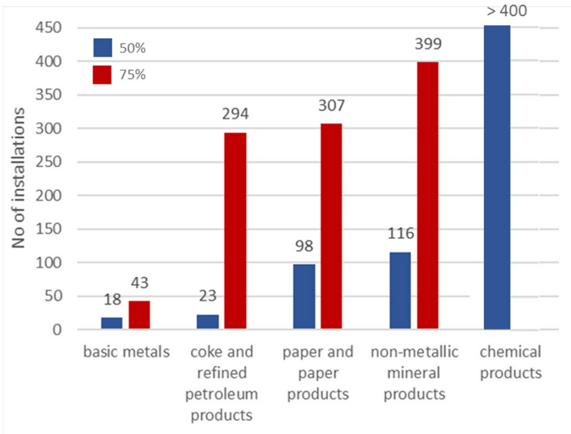
Figure 6 Concentration of GHG emissions at national level for the two most emission-intensive sectors



Source: ETS & Eurostat data, processed by the Austrian Institute of Technology.

Combined ETS and Eurostat data shows that there are different emission concentrations by sector. For instance, in the basic metals sector (e.g. steel, iron, aluminium), just the 18 most emitting industrial plants in the EU are responsible for 50% of the sector's emissions; and 43 plants for 75% of the sector's emissions. By contrast, emission concentration is much lower in the chemical sector, where more than 400 of the most emitting plants account for 50% of the sector's emissions.

Figure 7 Concentration of greenhouse gas emission plants



Note: data for chemicals is not displayed to scale on the graph because of the very high number of plants in the sector. The blue bar refers to the number of plants accounting for 50% of greenhouse gas emissions in the sector, the red bar for 75%.
Source: ETS & Eurostat data, processed by the Austrian Institute of Technology.

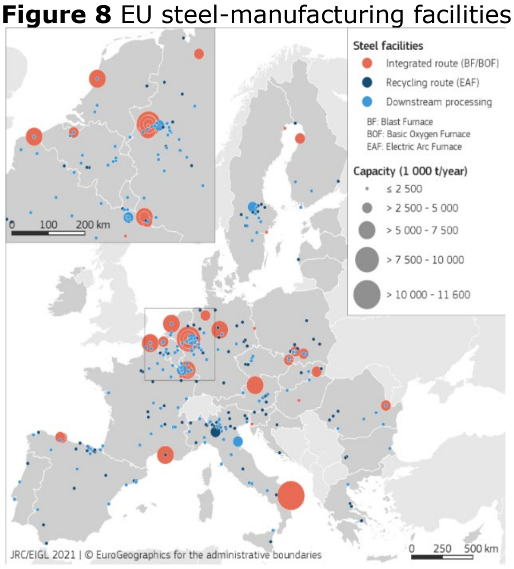
1.3 *Focus on steels, chemicals and cement*

These sectors are energy-intensive industries, which the Commission included in its 2022 Annual Single Market report[32] as specific 'areas of relevance' for the EU's green, digital and resilient transformation.

FOCUS SECTOR | STEEL

There are more than 500 steel production facilities across 23 Member States. The steel industry is responsible for 2.6 million direct, indirect and induced jobs across the EU (of which 330 000 are direct jobs)[33].

Figure 8 EU steel-manufacturing facilities



Source: Energy and Industry Geography Lab (Joint Research Centre) based on Plantfacts.

The EU is the second-largest steel producer in the world, and it produced approximately 160 million tonnes in 2020[34]. China is the top producer, with production exceeding 1 billion

32 Annual Single Market Report 2022 – SWD(2022) 40 final.
33 SWD (2021) 353 final, Towards a Competitive Clean European Steel.
34 European Steel Association (EUROFER), https://www.eurofer.eu/about-steel/learn-about-steel/#Facts-at-a-glance

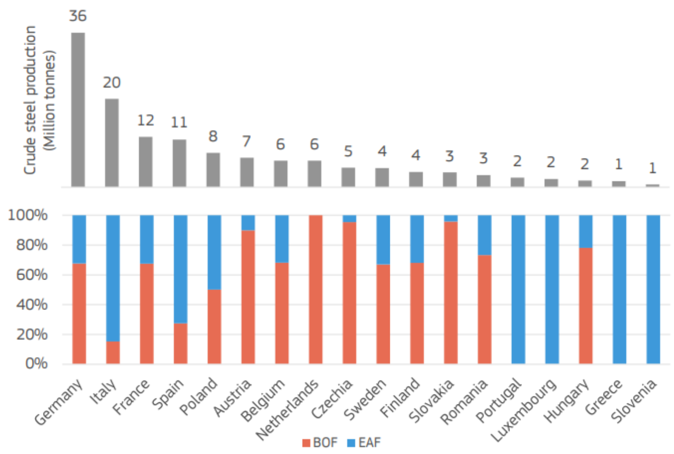
tonnes a year, representing roughly half the world's annual production (53%). There has been a recent move in the industry to decarbonise steel production. The five biggest steelmakers (by production in 2019) have announced net zero targets by 2050. All the biggest EU steelmakers have set targets to be carbon neutral or close to carbon neutral by 2050 (with reductions of 80%)[35].

Steel production in the EU is mainly divided into two major routes[36].

- The blast furnace-basic oxygen furnace (BF-BOF) route relies on coal as the main carbon-bearing material for steelmaking, and it mostly creates new steel. This route accounts for around 60% of the steel produced in the EU.

- The electric arc furnace (EAF) route, which largely relies on scrap steel as the main feedstock. It accounts for just over 40% of EU steel production.

Figure 9 Steel production by Member State



Source: JRC based on World Steel Association (2021), *2021 World Steel in Figures.*

CO_2 emission intensity of steelmaking varies greatly across the world. The main factor influencing the average CO_2 intensity is the share of steel coming from each country's different production routes, i.e. the amount of steel made from iron ore through the BF-BOF route versus the share of steel made though the EAF route, which mainly uses steel scrap. The materials used in each process also affect the average CO_2 intensity. Steelmakers add steel scrap to BF-BOFs to control the reaction temperature, but the amount added depends on the availability and price of scrap and the desired characteristics of the final product. Increasing the amount of scrap reduces the amount of hot metal (from the blast furnace) needed per final tonne of steel, thus lowering the CO_2 intensity. Similarly, EAFs can be loaded with iron feedstock such as direct reduced iron (DRI), liquid hot metal or pig iron (from a blast furnace) in addition to scrap, depending on local availability, cost and the desired quality of the crude steel.

Comparing steel production's average CO_2 intensity by country (combining all production routes), the USA has the lowest, followed by Turkey and Europe (EU27, UK and Norway). This is because the first two countries (USA and Turkey) produce around 70% of their steel through the EAF route. EU countries have the lowest CO_2 intensity out of those countries with over 50% of BF-BOF steel production.[37]

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[35] Somers, J., Technologies to decarbonise the EU steel industry, EUR 30982 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-47147-9, doi:10.2760/069150, JRC127468.

[36] EUROFER, https://www.eurofer.eu/about-steel/learn-about-steel/what-is-steel-and-how-is-steel-made/

[37] Ibid; Somers, J., *Making the EU's steel industry fit for carbon neutrality*, Publications Office of the European Union, Luxembourg, 2021, JRC127468.

Table 2 Announced or ongoing hydrogen-DRI steel decarbonisation projects in the EU

Country	Project (site)	Company	Reductant/fuel	Technology	Technology description	Timeline	Status
Belgium	(Ghent)	ArcelorMittal	NG, then H_2	H-DRI	2.5 Mt DRI plant and two EAFs	2030: Operational 2.3 Mt DRI	Letter of intent signed
Germany	H2Steel (Duisburg)	Thyssenkrupp	H_2 (electrolysis)	H-DRI	DRI with submerged arc furnace and BOF	2024: Commission first large-scale DRI 2025: Produce 0.4 Mt green steel with H_2 2030: Produce 3 Mt of green steel	Announcement
Germany	H2morrow (Duisburg)	Thyssenkrupp	Blue H_2	Blue H_2	Supply of blue H_2 (offshore CCS storage)	2021: Feasibility study completed	Feasibility study
Germany	H2Hamburg	ArcelorMittal	Grey H_2 then H_2 (electrolysis)	H-DRI	Grey H_2, then green H-DRI	2023: Produce 0.1 Mt (grey) H-DRI	Plant design commissioned
Germany	HyBit (Bremen)	ArcelorMittal	NG, then H_2 (electrolysis)	Electrolyser and H-DRI	24 MW H_2 electrolyser	2026: commercial DRI	MoU signed
Germany	(Eisenhüt-tenstadt)	ArcelorMittal	NG then H_2 (pyrolysis)	H_2 pyrolysis and H-DRI	H_2 from pyrolysis	2026: pilot innovative DRI	Announcement
Germany	(Wilhelms-haven)	Uniper and Salzgittter	H_2 (electrolysis)	Electrolyser and H-DRI	2 Mt DRI plant with upstream electrolyser	n/a	Feasibility study
Germany	SALCOS (Salzgitter)	Salzgitter	NG then H_2	Wind, electrolyser and H-DRI	Wind park, electrolyser and H-DRI	2020: Commissioned 30 MW wind park and electrolyser 2022: DRI plant	Construction started
Spain	(Gijon)	ArcelorMittal	NG, then H_2 (electrolysis)	H-DRI	2.3 Mt DRI plant and 1.1 Mt EAF	2025: Operational 2.3 Mt H-DRI	MoU signed
France	(Dunkirk)	ArcelorMittal	NG then H_2	H-DRI	Initially NG, then H-DRI with submerged arc furnace	2021: MoU signed with Air Liquide	MoU signed
France	(Dunkirk)	Liberty Steel	NG then H_2	H-DRI	Initially NG, then H-DRI	2021: MoU signed	MoU signed
Austria	HYFOR (Donawitz)	voestalpine	H_2 (electrolysis)	H-DRI	H-DRI using fine ores	2021: Pilot plant operational	Pilot
Austria	H2Future (Linz)	voestalpine	H_2 (electrolysis)	Electrolyser	6 MW H_2 electrolyser for steel	2020: PEM 6 MW electrolysis plant operational	Pilot
Netherlands	H2ermes (IJmuiden)	Tata Steel	NG, then H_2 (electrolysis)	Electrolyser and H-DRI	H_2 production for H-DRI	2021: Final investment decision 2025: Start H_2 production	Feasibility study
Romania	(Galati)	Liberty Steel	NG then H_2	H-DRI	NG then H-DRI	2023-2025: commercial with NG (2.5 Mt)	MoU signed
Sweden	Hybrit (Luleå)	SSAB	H_2 (electrolysis)	Electrolyser and H-DRI	Decarbonisation of full steelmaking value chain	2021: pilot plant operational 2026: commercial demonstration plant	Pilot plant
Sweden	LKAB (Kiruna)	LKAB	H_2 (electrolysis)	Electrolyser and H-DRI	Ore miner shift to H-DR	2029: DRI plant in Malmberget	Announcement
Sweden	H2green Steel (Svartbyn)	Northvolt team	H_2 (electrolysis)	Electrolyser and H-DRI	Greenfield plant	Before 2030: 5 Mt capacity	Announcement

Source: Somers, J., Making the EU's steel industry fit for carbon neutrality, Publications Office of the European Union, Luxembourg, 2021, JRC127468.

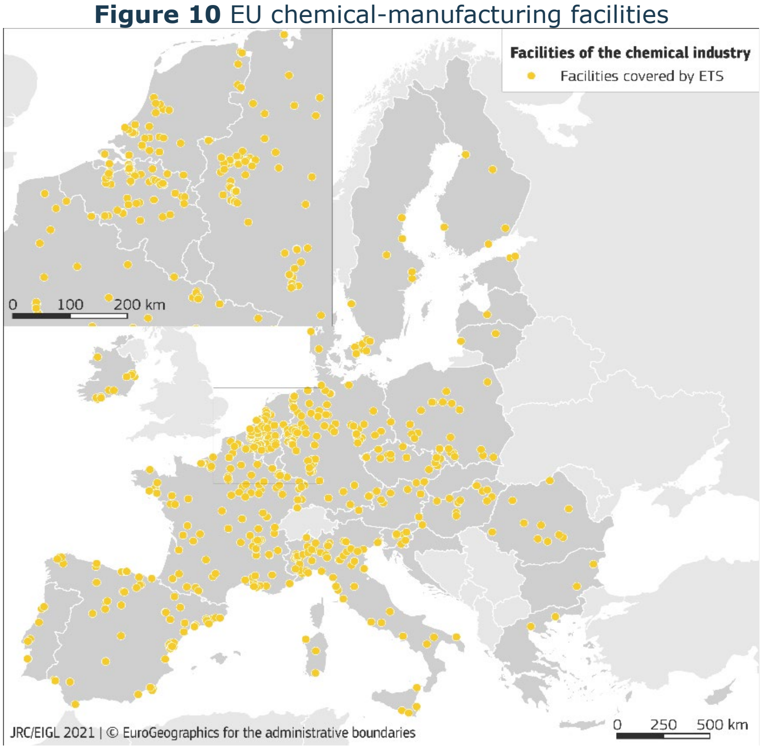
FOCUS SECTOR | CHEMICALS

The chemical sector has production facilities across 23 Member States, according to data from the JRC's Energy and Industry Geography Lab. The EU chemical industry is the second-largest producer in the world, after China, based on total sales[38]. However, the overall share of the EU chemical industry in the world market has been declining, falling from 26.7% in 1999 to 14.8% in 2019.

The total volume of chemicals produced in the EU increased between 2004 and 2007, peaking at 314 million tonnes in 2007. Following a decrease in production during the financial crisis of the late 2000s, production levels resumed after 2010. However, they remain lower than the pre-crisis record, in spite of an increase of more than 10 million tonnes in 2017[39].

The chemical industry is concentrated in a few Member States. In 2018, around 70% of EU chemical sales came from just five countries: Germany, France, Italy, the Netherlands and Belgium[40].

Figure 10 EU chemical-manufacturing facilities



Source: Energy and Industry Geography Lab, Joint Research Centre.

[38] Cefic, Facts and Figures 2021, https://cefic.org/app/uploads/2021/02/FactsFigures2021_Leaflet_V05.pdf

[39] Eurostat, Chemicals production and consumption statistics, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Chemicals_production_and_consumption_statistics#Total_production_of_chemicals

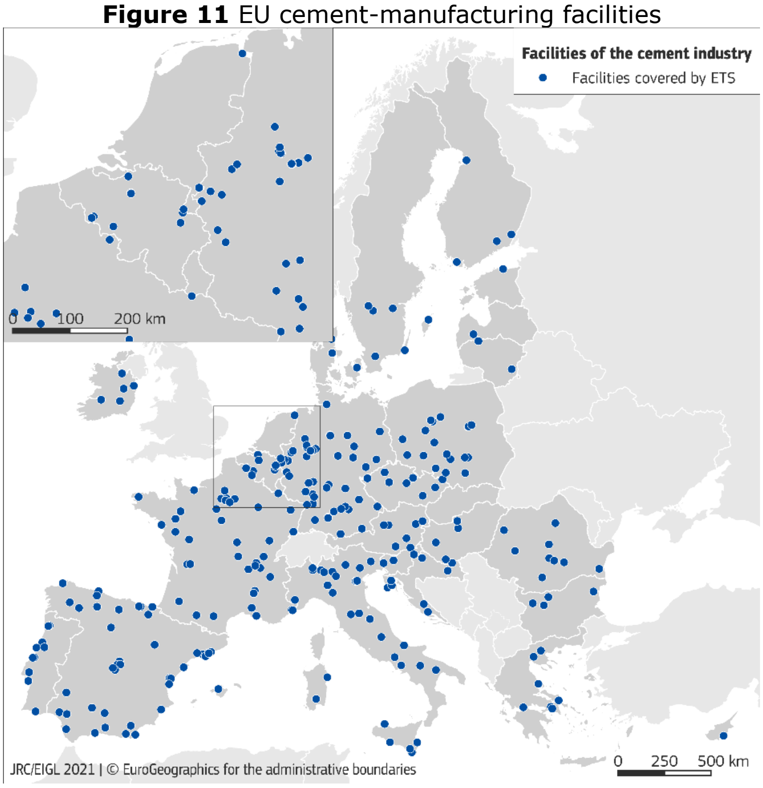
[40] Cefic, 2020 Facts and Figures of the European Chemical Industry, https://www.francechimie.fr/media/52b/the-european-chemical-industry-facts-and-figures-2020.pdf (data reported for EU28)

FOCUS SECTOR | CEMENT

The EU was the world's third-largest producer of cement in 2019, producing over 182.1 million tonnes. This was approximately 4.3% of the world's production, after China (2 300 Mt) and India (320 Mt)[41]. However, EU cement production has declined by 19.2% since 2001, when 225.5 Mt was produced. The sector employed 35 169 people in 2019 across the EU.

Overall, there were around 350 EU companies active in the cement-manufacturing sector in 2015, with an estimated turnover of EUR 15 billion and a value added of EUR 4.8 billion[42]. Based on the total number of companies, most were active in Spain (22%), followed by Italy (20%), Poland (11%), Germany (9%) and France (4%). However, looking at the companies' turnover, Germany had the biggest share (19%), followed by France (18%), Italy (10%), Spain (10%) and Poland (8%).

Figure 11 EU cement-manufacturing facilities



Source: Energy and Industry Geography Lab, Joint Research Centre.

[41] CEMBUREAU, Global Cement Production, https://cembureau.eu/media/zutk4pir/global-cement-production-2019.png [data reported for EU28]

[42] European Commission (2018) Competitiveness of the Cement and Lime Sectors, http://publications.europa.eu/resource/cellar/07d18924-07ce-11e8-b8f5-01aa75ed71a1.0001.01/DOC_1

2 Current decarbonisation scenarios

Several research consortia, agencies and two Horizon Europe partnerships investigate the potential of decarbonisation through the use of innovative industrial technologies and the relevant R&I investment needs in energy-intensive industries, including process industries. There is broad consensus on the key types of technologies and the level of maturity they have reached today thanks to R&I efforts in recent years. There is also growing consensus about the relative importance of innovation at low, medium and high technology readiness levels (TRLs)[43], from the perspective reaching the EU's 2030 and 2050 climate targets while ensuring the competitiveness of EU energy-intensive industries[44].

The Processes4Planet Partnership (P4P) and the Clean Steel Partnership (CSP) under Horizon Europe have developed specific roadmaps – Strategic Research and Innovation Agendas (SRIAs) – for industrial decarbonisation with their respective partners. These are mainly driven by private engagement leveraged through Horizon Europe work programmes (and the Research Fund for Coal and Steel (RFCS) in the case of the CSP). In the context of the SET plan[45], Member States and associated countries, industry and research stakeholders, coordinated by the European Commission, updated the Implementation Plan[46] of the SET Plan Action on 'Energy Efficiency in Industry' in 2021. The SET Plan prioritises specific industrial decarbonisation R&I activities, including aspects of clean energy production outside the scope of this roadmap. It also sets concrete targets to be reached in their development within a fixed time horizon reflecting the EU's climate and energy objectives for 2030 and 2050. Complementary and relevant analysis has been done by the High-Level Group on Energy-Intensive Industries (HLG EII), the International Energy Agency (IEA), Capgemini Invent, Material Economics, the European Parliament, Fraunhofer and NGOs, who have published important studies and specific roadmaps. Based on these, this analysis highlights how new low-carbon technologies can best contribute to decarbonisation in energy-intensive industries.

2.1 *Need for accelerated innovation – the IEA Net Zero by 2050 Scenario*

In its latest decarbonisation scenario ('net zero emission' – NZE) and publication on (industrial) technological perspectives, the IEA emphasises the urgent need to speed up innovation and the introduction of new low-carbon technologies in the coming decades[47].

According to the IEA's calculations and empirical findings, a major acceleration in clean energy innovation, including its production, will be necessary to reach net zero emissions by 2050 (up to 40% quicker than in the past few decades). In the NZE scenario, innovative technologies that are on the market today (TRL 9-10) provide nearly all of the emissions reductions required by 2030. However, after 2030 reaching net zero emissions will require

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[43] Description of technology readiness levels as per EC, Horizon Europe 2020 – work programme 2018-2020, general annexes:
TRL 1: basic principles observed;
TRL 2: technology concept formulated;
TRL 3: experimental proof of concept;
TRL 4: technology validated in laboratory;
TRL 5: technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies (KETs));
TRL 6: technology demonstrated in relevant environment (industrially relevant environment in the case of KETs);
TRL 7: system prototype demonstration in operational environment;
TRL 8: system complete and qualified;
TRL 9: actual system proven in operational environment (competitive manufacturing in the case of KETs; or in space).

[44] See chapter 2.

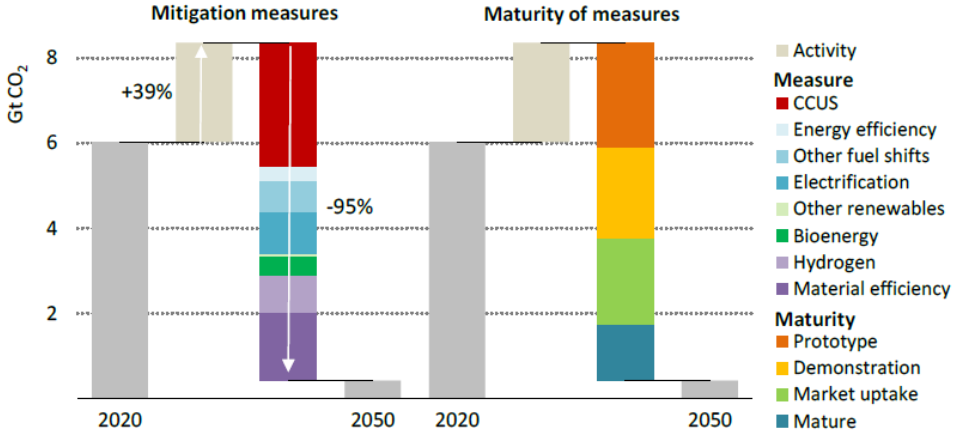
[45] Strategic Energy Technology Plan (europa.eu)

[46] https://setis.ec.europa.eu/system/files/2021-12/SET%20Plan%20Action6%20on%20EE%20in%20industry-Implementation%20Plan-Rev2021-final-endorsed.pdf

[47] IEA, Net Zero by 2050.

the widespread use of technologies still being developed today and therefore at lower TRLs. In 2050, almost 50% of CO_2 emissions reductions in the NZE scenario come from technologies currently at demonstration or prototype stage (TRL 4-8). This figure is even higher in energy-intensive sectors (see figure below).[48]

Figure 12 Global CO_2 emissions in heavy industry and reductions by technological options (mitigation measures) and technology maturity level, in the NZE of the IEA



Note: CCUS stands for carbon capture, utilisation and storage.
Source: IEA, 2021, all rights reserved.

A range of measures can help reduce emissions in heavy industry[49], with innovative decarbonisation technologies such as carbon capture and utilisation (CCU), carbon capture and storage (CCS), fuel shift, electrification, hydrogen and material efficiency/circular economy. The role of CCS might be more important globally than in Europe, as Europe is aiming for leadership in decarbonisation and thus innovative, non-carbon production processes that require no or fewer carbon capturing measures.

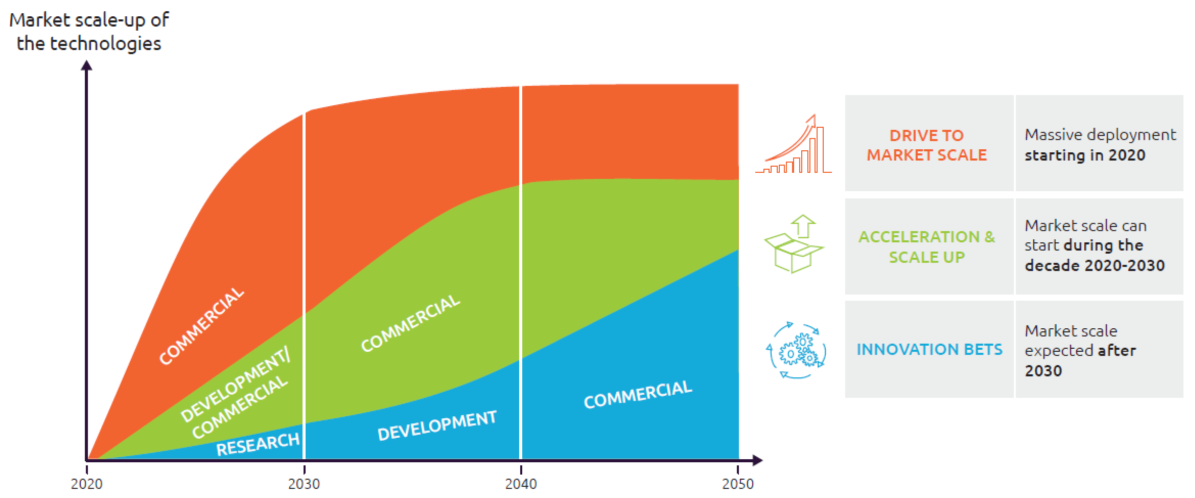
For investment decisions in heavy industries, the long investment cycles mean that clean technologies will have to be made ready quickly for large-scale deployment. Therefore, the challenge – in Europe and globally – is to ensure that innovative low-carbon industrial technologies that are at large prototype and demonstration stage today reach market within the next decade, when around 30% of existing assets will be 25 years old and therefore require an investment decision[50].

2.2 *Market scale-up trajectories*

The recent Capgemini Invent study[51] confirms the need for accelerated innovation for industrial decarbonisation and the need to get more innovative low-carbon technologies to market-readiness stage. The figure below shows three different mass market trajectories for 2020 and 2050, addressing different levels of maturity of low-carbon technological options (see also Chapter 2).

[48] Ibid, p. 123
[49] Heavy industries: energy-intensive process industries + shipbuilding, manufacturing etc.
[50] IEA, *Net Zero by 2050*, p. 124.
[51] Capgemini, Fit for Net Zero.

Figure 13 Industrial low-carbon technologies mass market trajectories



Source: Capgemini, 2020.

The orange diffusion curve 'Drive to market scale' comprises innovative technologies of TRL9-10. Mass deployment of such (niche) technologies must be achieved by 2030+. These technologies are ready to be deployed on the mass market. Short-term acceleration of relatively mature technologies, scaling up, and quick replication are the priorities.

The green trajectory 'Acceleration & scale up' covers technologies that could reach mass deployment by 2040+, and the early market adoption (TRL 9) phase from 2024 onwards. They have reached TRL 4-8 now, are still in pilot or demonstration phase and are crucial for reaching emission targets after 2030. Kickstarting innovation for several, existing large-scale pilot sites (TRL 7-8) to become profitable in mass market deployment until 2025 is crucial. The ambition here is for the predominant share of invested R&D to contribute to reaching TRL 8 by 2030 latest.

The blue mass market trajectory, 'Innovation bets' comprises breakthrough technologies for decarbonisation that are still emerging (TRL 1-3). They have the potential to reach mass deployment by 2050+, an early market adoption phase from around 2035 onwards, and EU-wide replication by 2040. The mission is to speed up such innovation projects on a scale enabling them to reach TRL 9 in this timeframe, and to enable breakthrough technologies for sector-wide use also beyond 2050. While these technologies might not be able to influence decarbonisation up to 2050 significantly, given the long investment cycles in energy-intensive industries, they are highly relevant from the perspective of continued global decarbonisation and competitiveness after 2050.

2.3 *Three high-level pathways to net zero emissions for EU heavy industry*

In their study 'Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry'[52], a research consortium led by Material Economics explored three general pathways to net zero emissions for EU heavy industry (in their publication this, refers to steel, plastics, ammonia and cement sectors). The approach taken in this study recognises that EU industry and society can choose different ways and that views differ on the most promising solution. All three pathways have in common that they leave no or very few emissions in place in 2050, and use the range of possible technological and non-

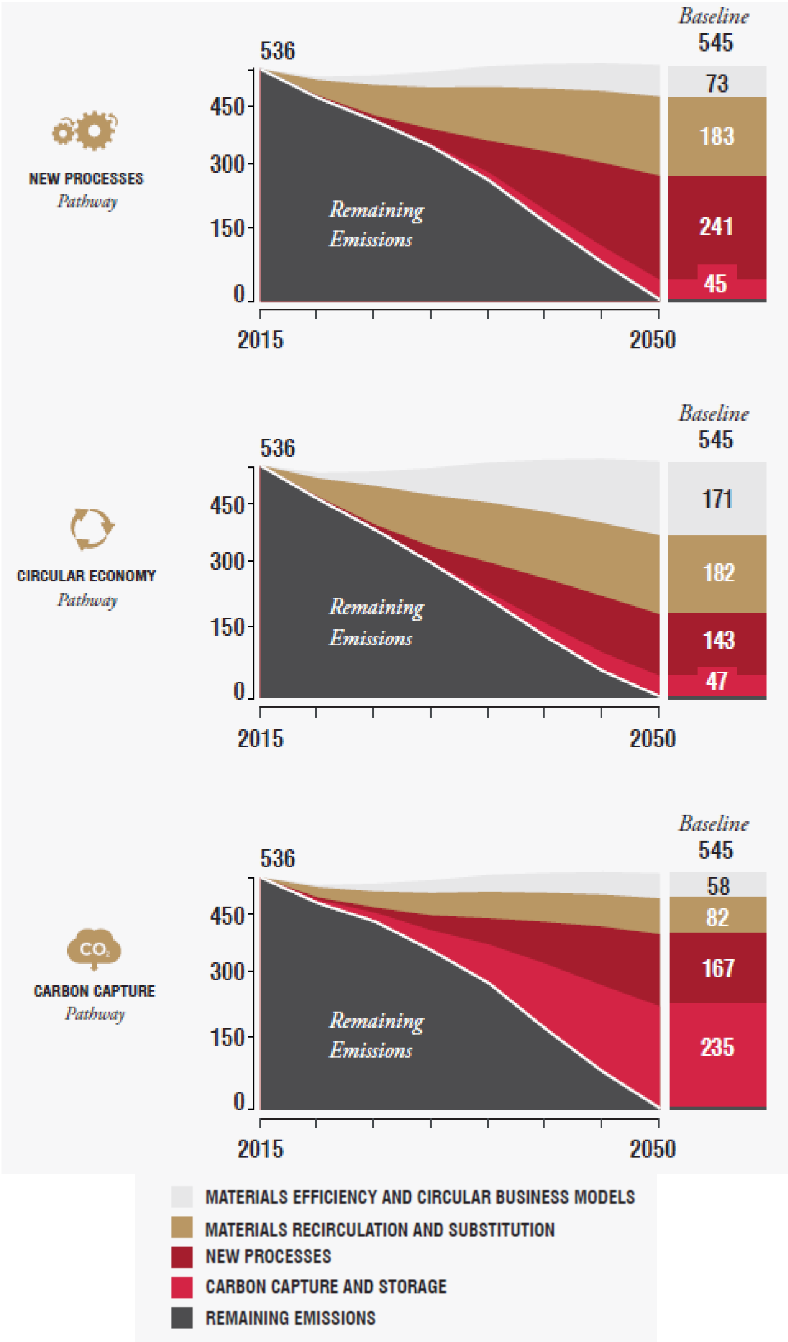
[52] Material Economics (2019), *Industrial Transformation 2050, Pathways to Net-Zero Emissions from EU Heavy Industry*, p.36 and following, https://materialeconomics.com/publications/industrial-transformation-2050 ('Industrial transformation 2050).

technological solutions for net zero (see next chapter on technologies), but each with a different emphasis.

The figure below visualises the three pathways proposed, 'New Processes', 'Circular Economy', and 'Carbon Capture'. These three high-level pathways group together a number of more specific solutions (referred to as "technological pathways" in Chapter 2): materials efficiency and circular business models; materials recirculation and substitution; new processes; CCS.

In each of the three net zero pathways the mitigation share of the distinctive four solutions (including business models) is calculated, with different weight given to each of them, the most important one giving the name to the pathway.

Figure 14 Potential emission reductions from EU steel, chemicals, and cement (Mt CO_2/year), by means of different pathways to net zero emissions



Source: Material Economics (2019), *Industrial transformation 2050*, p.37.

In the 'New Processes' pathway, most emission reductions are achieved by introducing new core production processes and new feedstock. This is a high electricity demand scenario that emphasises new, alternative feedstock. Key themes are innovation, electrification and investment. This scenario therefore relies heavily on new core industrial processes driven by electricity, either directly or using hydrogen. Key enablers are electricity supply and the rapid commercialisation of new processes.

In the 'Circular economy' pathway, the EU succeeds in making the transition to a circular economy, harnessing much of the potential for materials recirculation, materials efficiency and new business models. Jointly, these account for nearly 50% of the emissions abatement in this scenario. It relies on the realisation of the potential for a more circular economy for materials recirculation and greater materials efficiency. Key enablers in this case are new business models, digitisation and extensive coordination across the entire value chain.

In the 'Carbon capture' pathway, a critical mass of carbon capture infrastructure is a key enabler of major emissions cuts. In this scenario, most of the 235 Mt of captured CO_2 is stored underground. This reduces this pathway's social acceptability however. CCU can nevertheless play a role as an intermediate step in accelerating carbon emission reduction, notably in the sector coupling of steel and chemicals production. Key enablers are a critical mass of CCS infrastructure and risk distribution, and the reconfiguration of production processes to allow for high CO_2 capture rates. Extensive carbon capture in this pathway provides early emissions reductions, buying time for a more gradual introduction of new processes. It also requires less electricity than the 'New Processes' pathway[53].

3 Conclusions on the transition of the EII ecosystem to climate neutrality

- The reduction of greenhouse gas emissions in energy-intensive industries is a cornerstone for achieving the EU's climate goals for 2030/2050 under the European Green Deal. The concentration of these emissions facilitates a significant impact from R&I policy action to support the development and uptake of low-carbon industrial technologies for energy-intensive industries.

- Energy-intensive industries accounted for 17% of the EU's total greenhouse gas emissions in 2019. Three sectors (non-metallic mineral products, basic metals, and chemical products) accounted for almost two thirds (63%) of all greenhouse gas emissions from the energy-intensive industry ecosystem.

- Within some EII sectors, installations are highly concentrated. For basic metals (steel, iron, aluminium etc.), the 18 most-emitting installations account for half of the sector's total emissions. In the chemicals sector, the more than 400 most installations account for the same share. The different degree of concentration in the sectors will be an important element of the decarbonisation approach, and have an impact on the need for knowledge dissemination.

- While EII facilities are present in all 27 Member States, there is a concentration of greenhouse gas emissions at territorial level. Data on CO_2 emissions from EII facilities per capita reveals that a number of Member States (Belgium, Slovakia, Austria and Finland) have an emission intensity almost double the EU average, while other Member States (Netherlands, Luxembourg, Lithuania and Estonia) register significantly higher rates than the average. This is a call for national policy action to support the development and/or uptake of low-carbon industrial technologies.

[53] See also Material Economics, *Industrial Transformation 2050*, p. 38.

CHAPTER 2: KEY TECHNOLOGICAL PATHWAYS

This chapter describes the key technological pathways identified for reaching decarbonisation of energy-intensive industries in the EU and gives an overview of the state of play of decarbonisation of energy-intensive industries in the EU.

1 Synthesis of pathways, technologies and levels of maturity

The following overview of technological decarbonisation pathways is based on a deep-dive analysis and assessment of technological options for the decarbonisation of industrial processes. It was put together by the European Commission in collaboration with its contractor, the Austrian Institute of Technology (AIT), based on several current reports, studies and roadmaps, including those of the P4P and CSP[54].

The most important studies on which this synthesis is based, are referenced in the following sections of this chapter.

The synthesis table shows the main technological pathways with relevant TRLs, and in all pathways, most technological options have already reached medium and/or higher TRLs, except in the 'Electrification of production and processes' pathway, where there are more lower TRLs than in other pathways.

According to the the study and masterplan of the High-Level Group on energy-intensive industries and the feedback of business associations during the consultation phase, the application potential of the different pathways and options identified is 'high' for most of the eight industrial sectors investigated[55]. Exceptions are 'Use of hydrogen' and 'CCS/CCU'. In these pathways application potential is high particularly in the 'chemicals' and 'iron & steel' sectors.

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[54] The detailed analysis of this summary is available in a separate annex. The main studies included in this in-depth analysis, overview and assessment are:
- European Commission (2021), Pilot industrial technology prospect report – R&I evidence of EU development of low-carbon industrial technologies*;*
- P4P SRIA and CSP SRIA;
- High-Level Group on energy-intensive industries (HLG EII) (2018), Masterplan, Study and Addendum;
- European Parliament, Committee on Industry, Research and Energy (ITRE) (2020), *Roadmap on Energy-Intensive Industries;*
- European Parliament, Panel for the Future of Science and Technology (STOA), *Carbon-free steel routes*
- IEA (2020), *Energy Technology Perspectives 2020*; IEA, *Net Zero by 2050;*
- Capgemini, *Fit for Net Zero* ;
- Material Economics, *Industrial Transformation 2050;*
- ICF & Fraunhofer ISI (2019), *Industrial Innovation: Pathways to deep decarbonisation of Industry;*
- Exponential Roadmap Initiative (2019, revised 2020), *Exponential roadmap 2030: Scaling 36 solutions to halve emissions by 2030;*
- Energy Transitions Commission (2018), *Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century;*
- Written input/feedback on draft technology assessment from energy-intensive industries business associations representing the sectors at EU level.

[55] Industries included in the analysis are: cement & lime, chemicals, iron & steel, ferroy-alloys & silicon, pulp & paper, aluminium & non-ferrous metals, ceramics, and glass.

Table 3 Overview of technological pathways, TRLs and application potential by sector

Technological decarbonisation pathways in EII **High** priority in Material Economics pathways[56] **P4P innovation area**	**Assessment of technology readiness (i) and application potential by sector[57] (ii)**	**Prioritised R&I activities in the SET Plan – Action 6 on energy efficiency in industry, in each thematic group (in bold)**
Electrification **'Processes'**, 'Circular economy', 'Carbon capture' Electrification of thermal processes Electrically driven processes	(i) **low/medium**/high (ii) **High:** chemicals, non-ferrous metals; iron & steel, ceramics, glass	**Heat & cold**: 1.1. Heat upgrade from low to high grade **Chemicals**: 4.1. Electrification **Iron & steel**: 5.2. CO_2 emissions avoidance through direct reduction iron using electricity **Pulp & paper**: 6.3. Process optimisation and electrification (modular approach) **Systems**: 2.2. Non-conventional energy sources in process industry including CCU
Use of green[58] hydrogen **'Processes'**, 'Circular economy', 'Carbon capture' Hydrogen integration as energy source and as reductant	(i) low/**medium**/high (ii) **High**: chemicals, iron & steel and non-ferrous metals	**Chemicals:** 4.2. Integrated production of hydrogen with low carbon footprint **Iron & steel:** 5.1. CO_2 emissions avoidance through direct reduction of iron using hydrogen
CCS **'Carbon capture'** CO_2 capture and concentration	(i) low/**medium/high** (ii) **High:** cement & lime, chemicals, iron & steel	**Cement**: 3.3. CCUS
CCU **'Carbon Capture'** CO_2 capture for utilisation CO_2 utilisation in minerals CO_2 & CO utilisation in chemicals and fuels	(i) low/**medium**/high (ii) **High:** cement & lime, chemicals, iron & steel; but also for all other EII	**Systems**: 2.2. Non-conventional energy sources in process industry including CCU **Cement**: 3.3. CCUS **Iron & steel**: 5.5. CCU **Chemicals:** 4.4. CO_2 / CO as an alternative feedstock
Alternative fuels and feedstocks (excl. H2), bio-based resources, and integration of renewable energy **'Processes'**, 'Circular economy', 'Carbon capture' Integration of renewable energy and circular feedstock as energy source	(i) low/**medium/high** (ii) **High:** cement, chemicals, pulp & paper, non-ferrous metals, glass; but also for all other EII	**Heat & cold:** 1.4. Polygeneration (heat, cold, electrical power) and hybrid plants integrating renewable heat **Chemicals:** 4.3. Plastic waste as an alternative feedstock; 4.5. Biomass as an alternative feedstock **Pulp & paper**: 6.6. Biomass as alternative feedstock
Alternative materials and more energy efficient processes **'Processes'**, 'Circular economy' Integration of renewable energy and circular feedstock as energy source Energy and resource efficiency Heat reuse	(i) low/**medium/high** (ii) **High:** cement & lime, chemicals, iron & steel, pulp & paper, non-ferrous metals, ceramics; but also for all other EII	**Heat & cold:** 1.2. Waste heat to power (low and high temperature); 1.3. Waste heat to cold generation **Cement**: 3.1. Resource efficiency; 3.2. Energy efficiency **Chemicals**: 4.6. Process efficiency **Iron & steel**: 5.3. Process integration: HIsarna smelting reduction process for lowering energy consumption and CO_2 emissions of steel production; 5.4. Process integration: top gas recycling – blast furnace using plasma torch **Pulp & paper**: 6.1. Integral drying and heat recovery processes; 6.5. Onsite renewable energy conversion
Materials efficiency, secondary resources and waste valorisation (incl. recycling/CE and industrial symbiosis) **'Circular Economy'** Energy and resource efficiency Circularity of materials Industrial-urban symbiosis Circular regions	(i) low/**medium/high** (ii) **High:** in all EII	**Iron & steel:** 5.6. Circular economy **Systems**: 2.1. Industrial symbiosis **Pulp & paper**: 6.2. Paper making without water evaporation

Notes: In the central column, phrases highlighted in bold mean that in this technology pathway most technological options are at this/these TRLs.
Source: In-house by the European Commission (DG R&I) in collaboration with AIT.

56 See the description of the three Material Economics overall pathways, under the section on scenarios.
57 According to the HLG EII as well as feedback from business associations.
58 'Green' means fully renewable sources to produce hydrogen; stakeholders highlighted the emphasis on renewables but also 'low-carbon' hydrogen.

Box 3 | **IMPACT OF A GAS SHORTAGE AND GAS PRICE RISE ON THE DECABONISATION OF INDUSTRIAL PROCESSES IN EU ENERGY-INTENSIVE INDUSTRIES DUE TO RUSSIA'S INVASION OF UKRAINE**

The current geopollitical situation makes it necessary to drive and accelerate the transformation of energy supply and industrial processes even more vigorously than before[59].

In general, this means that technological solutions for decarbonisation that are already on the market (best available techniques (BAT)) or are in the successful demonstration stage (TRL 7-9) must be quickly brought to the market of the user process industries and implemented competitively to achieve short-term and medium-term effects on emission reduction. Existing R&D projects and activities, especially from the medium TRL (4) onwards, must also be brought towards innovation and market transfer more quickly than before through a joint public and private effort. To achieve synergy effects and dissemination as quickly as possible, cross-sector solutions and technologies are a key lever for that acceleration.

That urgency may lead to a stronger emphasis on dissemination and replication, and on R&D needs that focus even more on non-technological issues.

Against the background of the price hike of natural gas and the dependency on natural gas imports and supply cuts due to Russia's invasion of Ukraine, gas should play only a minor or no role in future key technologies for decarbonisation of energy-intensive industries. The implications of reduced availability and higher cost of gas on the technology pathways identified in Table 3 can be summarised as follows:

- Electrification: The electrification of industrial processes (heat, mechanical, electrochemical) is becoming even more important. Decarbonisation requires that the electric power is produced as clean energy.
- Use of green hydrogen: Since the production of hydrogen with natural gas not only leads to greenhouse gases, but natural gas could also become a (expensive) scarce commodity, hydrogen must be produced from water, with the aid of electrolysis fuelled by 'green' electricity, in particular from renewables. Dispensing with natural gas seems feasible as soon as corresponding quantities of hydrogen produced with low CO_2 emissions are available.
- Materials efficiency, secondary resources and waste valorisation: The shortage of natural gas will significantly increase the importance of recycling materials and secondary raw materials as waste products containing carbon (e.g. slag). In addition, waste gases will be used as raw materials for the production of materials and chemicals where natural gas was used previously (see also CCU). In addition, the importance of steel scrap could increase, as industry might prioritise processes, which use more scrap but require no or less natural gas (e.g. scrab-based EAF).
- Alternative fuels and feedstocks, bio-based resources, and integration of renewable energy: Alternative feedstocks/fuels must be promoted even more. In addition to renewable, bio-based feedstocks/energy carriers, the production of synthetic fuels/energy carriers (e.g. synthetic natural gas) is gaining importance. The integration of electric power from renewable energy sources (wind, hydro, solar) has very high priority to enable emission-free electrification of industrial processes (see above). An increased use of heat pumps, also in industry, and an intensified use of biogas (besides hydrogen) becomes more urgent[60].
- Alternative materials and more energy efficient processes: increasing the energy efficiency of industrial production processes is necessary to reduce the importance of natural gas as a "transition fuel" and to use natural gas more efficiently than before in industry (both as a feedstock for chemical products (e.g. hydrogen) and as a fuel/reduction agent). Short-term and low-cost efficiency measures in industry gain in importance.
- 'Carbon capture & utilisation' (CCU): if less natural gas as a hydrocarbon source is available as fuel, reducing agent and raw material, the utilisation and valorisation of CO_2/CO as feedstock for fossile based chemicals and the production of synthetic fuels or plastics becomes more important. However, the question arises whether the use of green hydrogen as a feedstock/reactant for CO_2/CO valorisation is sufficiently energy efficient, as it has to be produced via electrolysis before.
- 'Carbon capture & storage' (CCS): storing CO_2 in the ground is related to the reduced use of natural gas to the extent that less storage capacity for CO_2 emissions from natural gas use may be required. The prerequisite for this is that natural gas is not replaced by other fossil fuels in industrial processes (oil/coal). The latter would also be counterproductive for European emission targets.

Several technological options[61] and R&D&I topics can be applied across (several) industrial sectors[62]. Examples across the above pathways include the following:

- electrification of thermal processes (furnaces) and process steps; heat pumps for low/medium and high temperature processes; electrically driven separation; electrochemical processes;

- use of hydrogen for better combustion in furnaces of high temperature process industries;

- capture and storage of CO_2 from process emissions and combustion processes;

- CO_2 capture and purification technologies for CO_2 valorisation;

- integration of alternative fuel (mixes) and renewables; processing of (non-recyclable) waste and of biomass in high temperature furnaces; direct use of bio-based resources as feedstock in industrial applications/processes; hybrid systems, e.g. hybrid kilns;

- new kiln technologies, installing heat exchangers; energy/waste heat recovery (also between sectors[63]) and optimal combustion processes; drying technologies; process intensification, e.g. through next-gen catalysis;

- industrial and industrial-urban symbiosis and reuse; innovative materials for better life cycle performance; inherent recyclability of materials; upgrading of secondary resources; better separation and sorting technologies.

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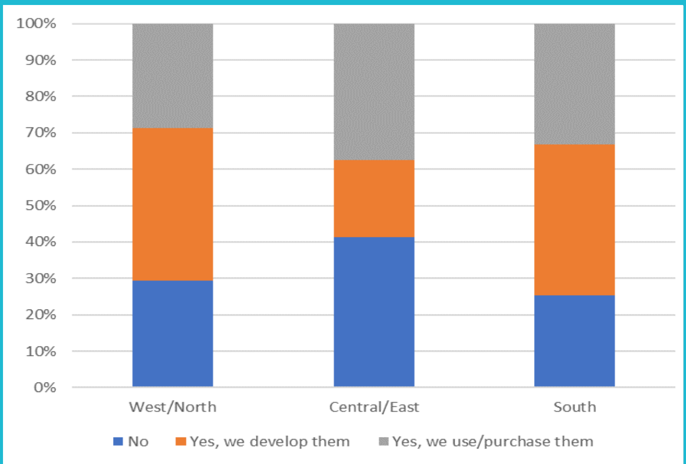
[59] Leopoldina, Akademie der Wissenschaften: Ad-hoc-Stellungnahme | 8. März 2022, Wie sich russisches Erdgas in der deutschen und europäischen Energieversorgung ersetzen lässt.
[60] See RePowerEU.
[61] For technological options and R&D&I topics that could be used across factories and sectors boundaries see also P4P cross-sectoral innovation areas, P4P SRIA p.73
[62] See also P4P cross-sectoral innovation areas.
[63] Being also part of "industrial symbiosis".

SME Focus 1 | **POTENTIAL ROLE IN DEVELOPING AND ADOPTING NEW TECHNOLOGIES**

Small and medium-sized enterprises (SMEs) can play a significant role in creating further synergies at industry level to develop and mainstream the use of new industrial technologies aiming to decarbonise EIIs. Around 38% of SMEs reported to not yet use environmental technologies, with an ever higher share of SMEs not using low-carbon technologies (49%), according to consultations ran by DG Research and Innovation (survey results[64]).

Among the respondents to the survey, the share of firms which use environmental technologies is highest in southern Europe, followed by western/northern Europe and Central/Eastern Europe. At the same time, the share of companies which develop new technologies or solutions is the lowest among SMEs located in central/eastern Europe.

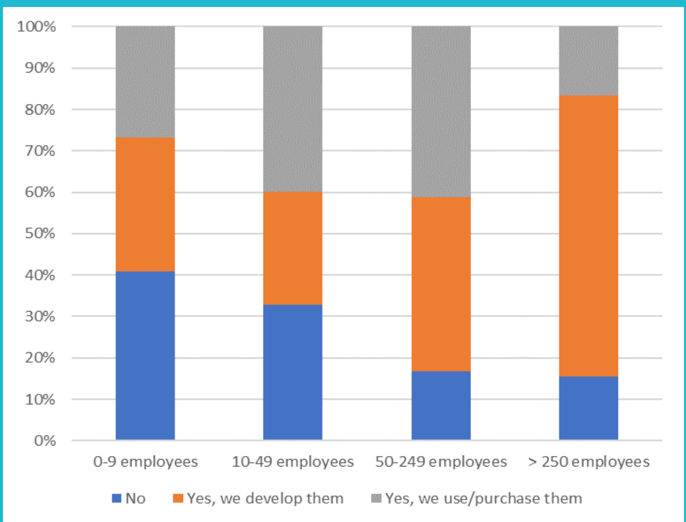
Figure 15 Development or use of environmental technologies at regional level



Note: West/North: BE, DE, DK, FI, IE; Central/East: BG, CZ, PL, RO; South: ES, GR, IT, PT.
Source: European Commission / Enterprise Europe Network SME Survey, conducted from November 2021 to January 2022 (see Annex 1).

The survey further indicates that the development of technologies is influenced by the size of a company. Therefore, larger companies are expected to develop new technologies in a considerably higher share than their SME counterparts.

Figure 16 Development or use of environmental technologies and firm size



Source: European Commission / Enterprise Europe Network SME Survey, conducted from November 2021 to January 2022 (see Annex 1).

2 The innovation areas and the approach of the Processes4Planet Partnership

The EU co-programmed public-private partnership Processes4Planet (P4P) - successor to Horizon 2020 SPIRE Partnership - which covers ten leading sectors[65] of the European process industries (cement, steel, ceramics, chemicals, engineering, minerals and ores, non-ferrous metals, steel, water, refineries, pulp/paper) is the only European level cooperation involving industry and research organisations in the development of cross-sectoral low-carbon technologies for energy-intensive industries in the EU.

Through innovation in decarbonisation technologies and processes as well as non-technological innovations, the P4P Partnership aims to bring European process industries on a transformation pathway to make them circular and achieve overall climate neutrality at EU level by 2050, while enhancing their global competitiveness. For this reason, the partnership emphasises the need for crosscutting and cross-sectoral innovation.

Through technological and non-technological innovations, cross-sectoral collaboration and engagement with the local ecosystem, P4P process industries aim to develop and deploy sustainable circular business models and will move towards resource circularity and resource efficiency. To accelerate the GHG emission reduction, cross-sectoral coupling, for example by combining fossil-based process integration with CCUS, will be encouraged.

The cross-sectoral dimension of innovation challenges must also be considered at regional level: process industries are often clustered in industrial parks in the interests of better energy, services, infrastructure and material flows. There is still a significant opportunity to further develop this approach, enabling the circularisation of value chains across industrial sectors and in the urban environment, triggering the development of regional circularity hubs.

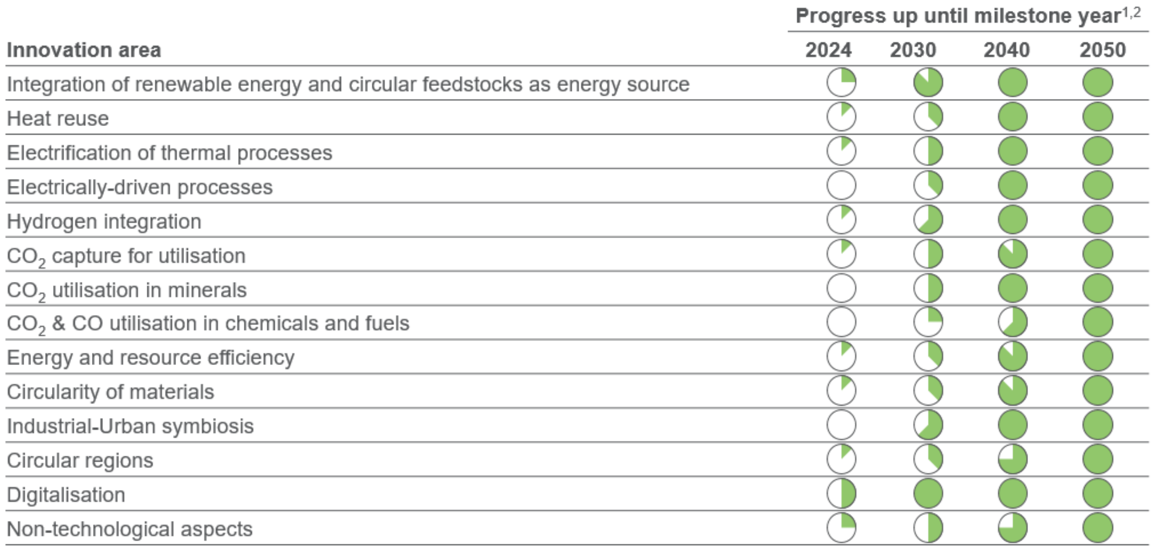
In this context, industrial symbiosis and cross-sectoral cooperation mean a long-term commitment across the boundaries of individual companies in dealing with waste and the use of by-products. Currently, this often fails due to numerous barriers between companies, even if the technologies exist and could in principle be adapted and used. This is why the P4P Partnership urgently calls for more integrated approaches between sectors and companies, supported by circularity hubs and cross-sectoral and cross-organisational cooperation.

The P4P Partnership defines 36 detailed innovation programmes to turn this vision into reality. They are clustered in 14 innovation areas. The three high-level pathways outlined in the Material Economics study cover these innovation areas. As the backbone of the P4P approach, the innovation areas are expected to collectively deliver the necessary technological and non-technological solutions up to the market readiness stage.

[64] DG R&I has run a series of consultations targeting SMEs, and their findings will be indicated throughout the roadmap. For methodology indications and more details, please consult Annex 1 of the report, describing the results of the SME surveys.

[65] Largely but not precisely corresponding to energy-intensive industries.

Figure 17 Estimate of the progression of P4P innovation area level



[1] Progress is depicted here as % of total TRL9 projects programmed in each area, and for circular regions, digitalisation, and non-technological aspects % of total investment needs until 2050.
[2] It is extremely difficult to foresee future technological developments and related innovation opportunities over a 5- to 10-y horizon. This Table outlines the foreseeable progress of each innovation area based on best available knowledge about technologies under development.

Source: Processes4Planet SRIA, October 2021.

According to the P4P roadmap, about 50% of the technologies in question, which the partnership addresses, could be applied by 2030, and 100% by 2050 (entering the TRL9 phase). Up to 2024, less than a quarter of technological options proposed by P4P will have entered their first deployment stage. P4P's innovation programmes are designed to push multiple technologies towards commercial application (TRL 9), starting with low (TRL 1-3), medium (TRL 4-6) and high (TRL 7-8) TRLs in the different innovation areas, depending on existing levels of maturity.

P4P explicitly follows a cross-sectoral approach to generate synergies for technology development between industries and to create conditions conducive to technology transfer. Its three main goals are:

- developing and deploying climate-neutral solutions;
- closing the energy and feedstock loop;
- global leadership in climate-neutral and circular solutions to accelerate innovation and unlock public and private investments.

As does the CapGemini report, P4P stresses the need for technological development to happen within and between process industries as quickly as possible in order to reach climate neutrality by 2050[66], and the additional systemic challenges integrating process industries into the new value chains and a low-carbon energy system entails. To reach these goals, P4P emphasises the role of enablers such as digitalisation and the establishment of 'hubs for circularity' to enable the fast development of new materials and processes as well as industrial-urban symbiosis, which in turn makes a major contribution to improving the energy and resource efficiency of plants and value chains. P4P also aims to promote non-technological innovation and its implementation, particularly addressing

[66] See also IEA, Net Zero by 2050.

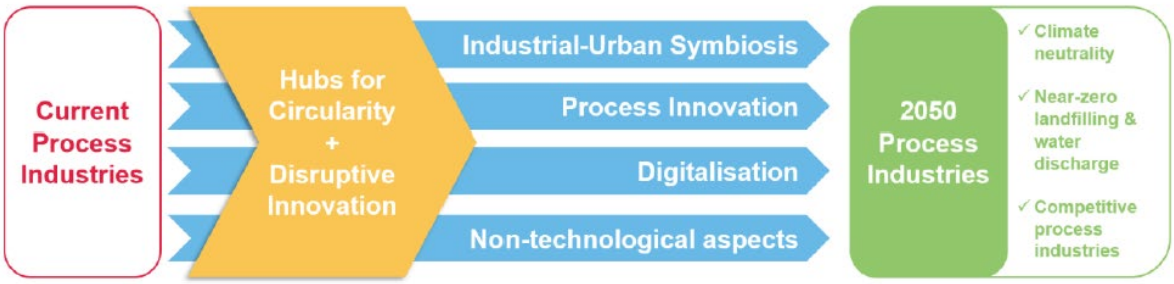
the non-technological aspects of efficient and effective technology take-up and diffusion, as well as the need to upskill and re-skill the workforce, and social acceptability.

Process industries are facing industrial competitiveness issues in terms of access to affordable climate-neutral energy and due to the absence of a carbon pricing level playing field with non-European competitors[67]. These factors hinder the transition to climate-neutral solutions. However, the potential for digitalising the industry is a way to boost competitiveness. European process industries have not yet exploited the potential of digital technologies for resource efficiency and productivity gains. In fact, ICT currently invests very little in low-carbon innovation. However, it does contribute by developing enabling technologies, such as AI. According to a recent Joint JRC and Organization for Economic Cooperation and Development (OECD) study (2021), 20% of climate-related patents have a digital component, creating more potential for the digital transformation to enable the green transition across many carbon-intensive sectors, and that 60% of climate-related trademarks are also ICT-related. The use of digital solutions is therefore widespread at the commercialisation stage[68].

According to the P4P Partnership, many challenges faced by several sectors can be addressed through cross-sectoral collaboration, e.g. sharing information in the value chain quickly and safely, with the help of digital technologies. The effectiveness and efficiency of innovation programmes can be increased by developing such innovation jointly, enabling technology transfer and mutual learning. Cross-sectoral innovation also has the advantage of faster deployment and greater impact at scale, as well as common risk sharing.

The following figure summarises the partnership's vision of how to achieve the transformation of process industries. Industrial-urban symbiosis, process innovation, digitalisation and non-technological aspects are crucial for transforming process industries. Process innovation includes innovation in the pathways of electrification, renewables, fuel and feedstock shift and hydrogen, the capture and use of CO_2, and energy and resource efficiency. Industrial symbiosis as part of a circular economy, digitalisation and non-technological aspects support and accelerate the digital transformation and will integrate the process industries of the future into a climate-neutral and circular society.

Figure 18 P4P approach to achieving its ambitions and goals



Source: Processes4Planet SRIA, October 2021.

[67] Draft proposal for a European Partnership under Horizon Europe Processes4Planet, https://ec.europa.eu/info/sites/default/files/research_and_innovation/funding/documents/ec_rtd_he-partnerships-industry-for-sustainable-society.pdf (underpinning the Memorandum of Understanding for the Co-programmed European Partnership Processes4Planet, approved and signed on 14 June 2021).

[68] See Amoroso, S. et al (2021), *World Corporate Top R&D Investors: Paving the way for climate neutrality. A joint JRC and OECD report*, Publication Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-43373-6, doi:10.2760/49552, JRC126788.

Box 4 | **CROSS-CUTTING AND CROSS-SECTORAL INNOVATION UNDER P4P**

Cross-cutting and cross-sectoral innovation, including circular business models, technologies to increase resource efficiency and (urban) industrial symbiosis are at the heart of the EU co-programmed public private partnership Processes4Planet. This partnership encompasses ten leading sectors of the European Energy Intensive Process Industries (cement, steel, ceramics, chemicals engineering, minerals and ores, non-ferrous metals, steel, water, refineries, pulp/paper) and is successfully showing the way forward on how innovation challenges common to several sectors can be addressed through cross-sectorial collaboration.

Many similar innovation challenges are encountered across energy intensive industrial sectors such as, achieving high temperatures using electricity, integrating renewable energy in the process, making more efficient use of resources including energy, materials and water, developing CO_2 capture and use, demonstrating industrial symbiosis, or addressing non-technical e.g. skills, data sharing or standards, related challenges. The effectiveness and efficiency of the innovation pathways can be increased by developing such innovations jointly and by putting learnings in common. Cross-sectoral innovation offers the advantage of faster deployment and impact at scale. Processes4Planet (former SPIRE) has shown the effectiveness of its unique cross-sectoral innovation approach and aims to find more synergies in the coming period.

Industrial-Urban Symbiosis, CO_2 Carbon Capture and Use and Digitalisation achievements are some of the Processes4Planet (former SPIRE) process industries successful cross-cutting, cross-sectoral innovations [69,70].

Industrial symbiosis is the process by which wastes or by-products of an industry or industrial process become the raw materials for another. This includes all resources: waste, by-products, residues, energy and water. In addition, symbiotic industrial clusters can share logistics, capacity, expertise, equipment and materials, and investments. Industrial symbiosis is an important element contributing to establishing a circular economy that goes beyond the optimisation of processes at the single value chain level. The potential has been expanded towards industrial-urban symbiosis involving also municipalities and regions on issues like waste, energy and water allowing such industries to develop and anchor in these regions. This is the foundation for the hubs for circularity (H4C), an initiative put forward under the Green Deal under the umbrella of the partnership.

Beside others, the P4P Partnership also emphasises the urgent need to develop and transfer technological solutions for the decarbonisation of industrial processes in a cross-sectoral approach to accelerate the pace of decarbonisation and dissemination of appropriate and promising solutions, and thus also to exploit synergy potentials between sectors of the process industry. Many challenges e.g. related to the integration of alternative raw materials and fuels, the improvement of energy efficiency, the valorisation of CO_2, the increased use of secondary materials or the electrification of processes are in principle the same between sectors. Technological solutions that address these common challenges have the potential to be relevant for several sectors, even if at the end of the day sector-specific adaptations and further developments have to be made. The examples given above can serve as a starting point for such common, cross-sectoral solutions and applications, which can subsequently be defined jointly and more precisely by the participating sectors.

For example, one sector could take the lead together with the equipment industry in such a pilot and demonstration project (e.g. in integration of renewables for electrification, new kiln technologies, CO_2 purification and valorisation, or biomass in high temperature furnaces), further develop the required technological solutions surrounding this challenge

[69] European Commission, Directorate-General for Research and Innovation, Sommer, K., *Study and portfolio review of the projects on industrial symbiosis in DG Research and Innovation : findings and recommendations*, Publications Office, 2020, https://data.europa.eu/doi/10.2777/381211.

[70] SPIRE Trends Report 2020.

together with representatives from other sectors up to TRL9, and in this way secure and shape the know-how transfer to these other relevant sectors. This would also increase the chance that these sectors take up the results and technologies and in turn further develop them into viable sector-specific solutions and demonstration projects of their own.

Therefore, this kind of industrial development and demonstration projects require mechanisms and formats that enable cross-sectoral cooperation and a transfer of solutions between locations and different sectors efficiently and effectively. Trust-based mutual learning and the readiness for deep cooperation must be in the foreground and realised through transfer mechanisms at the right time along the ladder of technological development.

The ‘marbles’ proposed by P4P[71] could in one or the other case be an effective way to realise such cross-sectoral projects up to first-of-a-kind (FOAK) and thus TRL9.

For instance, one of the marbles identified in the P4P roadmap 2050 as M33 "New era for electrical & electrochemical processes" is very relevant both for ceramics and for minerals sectors; M25 and M26 referring to CO_2 capture, purification and utilisation, for cement, lime and ceramics; M49 "Biomass and Biowaste as renewal energy - Torrefaction of biomass" for steel and ceramics. In all these examples, cross-sectoral cooperation will enable actors across industries to optimise research results, reach economies of scale, accelerate the uptake and widen the deployment of these technological pathways.

3 The Clean Steel Partnership approach and technological pathways

EU Emissions Trading System (ETS) data put the steel industry’s degree of responsibility for the industrial CO_2 emissions the ETS covers at about 20% to 25%[72]. Steelmakers show a high commitment to reducing their emissions, thereby contributing to the achievement of the EU’s climate and energy targets. The steel industry has been at the forefront of R&D&I into breakthrough technologies to reduce its climate footprint for many years[73]. The establishment of the European Clean Steel Partnership (CSP) and the development of its innovation roadmap is a further, important step in this process.

The CSP’s long-term vision is to support the drive for European leadership in transforming the steel industry into a climate-neutral sector. Six specific objectives, to be achieved in seven to 10 years, will support the achievement of the general objective. These specific objectives are:

- enabling steel production by means of carbon direct avoidance (CDA) technologies at demonstration scale;
- promoting smart carbon usage (SCU) - CCUS technologies in steelmaking routes at demonstration scale, thereby cutting CO_2 emissions from the burning of fossil fuels (e.g. coal) in existing steel production routes;
- developing deployable technologies to improve energy and resource efficiency (SCU - process integration (PI));
- increasing the recycling of steel scrap and residues, thereby improving the use of smart resources and further supporting a circular economy model in the EU;

[71] See P4P SRIA, chapter 5.5. A.SPIRE members have coined the term “marbles” to describe a first-of-a-kind (FOAK) large scale application of one or more new technologies, deployed by the process industry. They indicated their intention to invest in marbles to bring them to TRL 9.
[72] See CSP SRIA, p. 12.
[73] European Commission (2018), European Steel: The Wind of Change.

- demonstrating clean steel breakthrough technologies contributing to climate-neutral steelmaking;

- strengthening the global competitiveness of the EU's steel industry in line with the EU industrial strategy for steel.

To achieve these objectives, R&D&I activities supported by the CSP will revolve around the following main intervention areas:

- two technology pathways: carbon direct avoidance (CDA) and SCU, further divided into SCU-CCUS and SCU-PI;

- circular economy (CE) projects broadly supporting technology pathways;

- possible combinations of the different pathways and CE projects;

- enablers and support actions, i.e. activities that can support the implementation of solutions developed in the other intervention areas, as well as the global competitiveness of the EU's steel industry.

The CSP's general objective is to develop technologies at TRL 8 to reduce CO_2 emissions from EU steel production by 80-95% from 1990 levels, ultimately leading to climate neutrality.

Increasing circularity through the use of recycled steel and reducing steel demand are important levers for the decarbonisation of EU steelmaking. However, virgin steel will continue to be needed in the future. This requires the deployment of new steelmaking technologies to replace the coal-based blast furnace - basic oxygen furnace (BF-BOF) route.

The steel sector is currently exploring various strategies to reduce CO_2 emissions. In the short term, extensively modifying processes and switching from fossil fuels to low-CO_2 energy sources can enable some limited CO_2 mitigation. Combined with CCUS technologies, deeper emissions cuts can potentially be made. A different pathway, which seems to be emerging as the principal strategy for most European steelmakers, is to fully replace existing processes with breakthrough technologies that rely on hydrogen or electricity to reduce iron ore, making it possible to produce steel with little to no CO_2 emissions. Deploying these technologies would require the replacement of existing steel processes with new steel plants. Key technologies include the following.

1. The direct reduction of iron ore (DRI) to iron using hydrogen (H-DRI), thereby completely avoiding the use of fossil fuels. This process could already be deployed by 2030, but relies on the availability of low-CO_2 hydrogen and electricity in large quantities and at low cost. Several steelmakers are exploring the use of natural gas as a transition fuel until enough hydrogen is available at an acceptable cost.
2. Electrolytic processes, whereby iron ore is reduced using only electricity, at high temperature (molten oxide electrolysis) or low temperature (electrowinning). While these technologies are potential game changers, they are not expected to be deployed before 2040.
3. The smelting reduction of iron ore to steel with fossil free inputs, such as hydrogen plasma in a single reactor. This technology is highly integrated and potentially very efficient, but is also at an early stage of development and not expected to be available before 2040[74].

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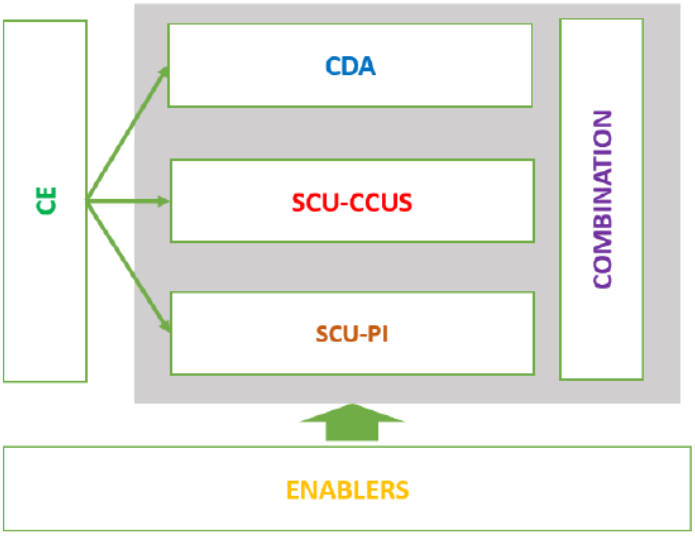
[74] Greensteel for Europe Project (2021), *Decarbonisation Pathways 2030 and 2050*, Somers, J. (2021), *Technologies to decarbonise the steel industry*, Publications Office of the European Union, JRC127468.

The following graph from the CSP roadmap shows the six areas of intervention and how they relate to each other.

Figure 19 Technological pathways and enablers to reduce the EU's steel industry's CO_2 emissions



Source: CSP Roadmap, 2020.

Carbon Direct Avoidance (CDA) includes technologies that avoid carbon emissions during steelmaking. CDA mainly relies on steel production processes based on hydrogen and green electricity, i.e. produced without carbon emission. SCU-CCUS encompasses technologies that help avoid carbon emissions to the atmosphere. This pathway supports all the options for utilising the CO and CO_2 in steel plant gases or fumes as raw material to produce valuable products. Smart carbon usage, in the form of process integration (SCU-PI), enables the reduction of fossil fuel (coal, natural gas, etc.) used in both BF-BOF and electric arc furnace (EAF) steel production, and the curtailment of CO_2 emissions.

The CSP maintains that the viability of both steelmaking routes (as described also above, under the SPIRE/P4P partnerships) - the BF-BOF and EAF - must be preserved, as they remain necessary to ensure the EU steel sector's capacity to deliver high-quality steel grades using different raw materials, thereby ensuring strategic capability. Hence, R&D&I needs to focus on both production routes.

The share of production between the two routes in the EU is split with roughly 60% produced via the BF-BOF route and about 40% via the EAF route. Production using the EAF route is less CO_2 intensive than the BF-BOF route. For each tonne of crude steel produced with the BF-BOF process, about 1.3 to 1.8 tonnes of CO_2 are created. One tonne of steel produced with the EAF process requires about 400-500 kWh (kilowatt-hours) of electricity, and 80-120 kg of direct and 250-350 kg of indirect CO_2 emissions. In the future, the primary steelmaking route will also have direct reduction plants.

Box 5 | **EXAMPLES OF BREAKTHROUGH TECHNOLOGIES BY STEELMAKING ROUTE**[75]

BF-BOF route

Process integration (to be combined with CCU and/or CCS):

- Top Gas Recycling-BF using plasma torch (project: IGAR)
- Carbon Valorisation/CCU (projects: Steelanol, Carbon2Chem, FReSMe)

CDA via hydrogen/electricity:

- CO_2 emission avoidance through direct reduction of iron ore using hydrogen and natural gas (projects: HYBRIT, SALCOS/MACOR, H2Steel (H2Future + SuSteel))
- Electrowinning of iron metal from iron oxides (SIDERWIN)
- Other projects: Primary Energy Melter (PEM), Stepwise

CCU projects:

- Gas fermentation processes to reduce CO_2 emissions and produce low carbon liquid fuels and chemicals (project: Steelanol)
- Use gases from steel production processes, including CO_2, as a starting material for chemical products and use surplus energy from renewable source in the process (project: Carbon2Chem)
- EAF steelmaking projects, using EAF as a breakthrough technology for CDA BOF, by direct reduction of iron ore using hydrogen and natural gas (project examples: GreenEAF2, OSCANEAF, OXYMON, SuperChargeEAF, Fines2EAF, and RINFOAM)

Source: Clean Steel Partnership.

EAF route

The EAF route will be fundamental in Clean Steel Partnership to reinforce the position in the circular economy of EU steel industry.

In this context, both primary steelmaking and scrap-based steelmaking must be in symbiosis: the majority of long steel products in the EU (79%) is produced by EAF, while 91% of flat products is produced by BF/BOF.

Moreover, the EAF is an important element in the mentioned breakthrough technologies for CDA.

EAF steelmaking projects in the RFCS framework like GreenEAF2, OSCANEAF, OXYMON, SuperChargeEAF, Fines2EAF, and RINFOAM provided the base for scaling up of the process and generating a new framework for development of the future strategies/plane from EAF route.

The H2020 Retrofeed project includes the development of tools and equipment to allow the use of renewable feedstock and industrial residues in the steel sector.

The CSP's main circular economy (CE) target is to extract fewer raw materials and recycle and recover more existing materials, and have a significant impact on resource efficiency. Doing so will require fewer natural resources and raw materials and less energy, creating up to 50% CO_2 savings in the steelmaking process[76]. CE approaches enhance the recycling of steel and resource efficiency through scrap utilisation, scrap sorting and better removal of scrap pollution with new detecting technologies. It also includes the utilisation of all residues from steel production internally or in other sectors (industrial symbiosis). CE will also support the substitution of fossil materials with alternative carbon-bearing materials

[75] See also EUROFER for more detailed overviews. Cf the map accessible on https://www.eurofer.eu/assets/Uploads/Slide1.PNG

[76] CSP SRIA, p. 70 and following.

and alternative reductants (e.g. biomass, syngas from wastes), and encompass technologies that identify and use waste heat sources.

The CSP emphasises that the combination of technological pathways is important for the steel sector to increase its CO_2 reduction potential. For example, SCU-PI technologies alone can help reduce CO_2 by up to 65%. If combined with CCUS technologies, this can increase up to 100%[77].

4 The SET Plan approach and prioritised R&I activities

SET Plan Action 6 on energy efficiency in industry aims to make energy-intensive industries less energy-, resource-, and emissions-intensive and more competitive. Member States and non-EU SET Plan associated countries, industry and research stakeholders, together with the Commission, identified technological options and R&I activities to increase energy and resource efficiency and drastically reduce GHG emissions in European process industries. The resulting implementation plan was revised and endorsed by the Member States and associated countries on 7 December 2021. The plan specifically addresses four sectors – cement, chemicals, iron and steel and pulp and paper – while the areas of heating and cooling and system integration are applicable to all sectors. The objective is to facilitate the development, deployment and market penetration of emerging technologies.

In this implementation plan, six thematic groups spanning four industrial sectors and two crosscutting technological fields are defined and described by the SET Plan action members, comprising representatives from 19 SET Plan countries, industrial stakeholders from four sectors and cross-cutting technology areas, as well as research institutions. Each thematic group presents their sector-level ambitions, which the SET Plan Action 6 R&I priorities aim to contribute to. Targets corresponding to each R&I priority activity area for all thematic groups are also presented[78]. For each of these six thematic groups and the R&I activities they consist of, operational implementation plans with targeted TRLs, a timeline, expected deliverables and the budget required were drawn up.

The following table gives an overview of these six thematic groups and the R&I activities prioritised and planned in them with a view to developing relevant low-carbon industrial technologies.

Table 4 Thematic groups and prioritised R&I activities in the SET Plan – Action 6

TG	No.	Title
Heat & Cold	1.1	Heat upgrade from low to high grade
	1.2	Waste heat to power (low and high temperature)
	1.3	Waste heat to cold generation
	1.4	Polygeneration (heat, cold, electrical power) and hybrid plants integrating renewable heat
Systems	2.1	Industrial symbiosis
	2.2	Non-conventional energy sources in process industry, including carbon capture and use
	2.3	Digitalisation
	2.4	Knowledge exchange, training and capacity building
Cement	3.1	Resource efficiency*
	3.2	Energy efficiency*
	3.3	Carbon capture storage and usage (CCS/U)*
	3.4	Recarbonation and mineralisation*

77 Ibid, p. 35.
78 See SET Plan action 6, Revision 2021, page 23 and following.

Chemicals	4.1	Electrification
	4.2	Integrated production of hydrogen with low carbon footprint*
	4.3	Plastic waste as an alternative feedstock*
	4.4	CO_2/CO as alternative feedstock*
	4.5	Biomass as alternative feedstock *(shared activity, see Pulp & Paper 6.6)**
	4.6	Process efficiency
Iron & Steel	5.1	CO_2 emissions avoidance through direct reduction of iron using hydrogen
	5.2	CO_2 emissions avoidance through direct reduction of iron using electricity*
	5.3	Process integration: HIsarna smelting reduction process for the lowering energy consumption and CO_2 emissions of steel production
	5.4	Process integration: top gas recycling -blast furnace (TGR-BF) using plasma torch
	5.5	Carbon capture and usage (CCU)*
	5.6	Circular economy*
Pulp & Paper	6.1	Integral drying and heat recovery processes*
	6.2	Paper making without water evaporation*
	6.3	Process optimisation and electrification (modular approach)*
	6.4	Mild pulping processes *
	6.5	Onsite renewable energy conversion*
	6.6	Biomass as alternative feedstock *(shared activity, see Chemicals 4.5)**

Note: * Indicates activities that are new to the 2021 SET Plan.
Source: SET Plan – Action 6 on energy efficiency in industry.

The prioritised R&I topics in the implementation plan for SET Plan Action 6, as well as the technological options for industrial decarbonisation described in other roadmaps and studies, were analysed in detail and systematised along different technological pathways and sectors.

In the six thematic areas of SET Plan Action 6, the focus is on R&I activities that aim for higher TRLs to enable the market scale-up of technological and non-technological solutions necessary for the decarbonisation of European process industry[79].

Two thematic groups take a cross-cutting approach ('Heat & Cold' and 'Systems') to leverage synergies and potential between industrial sectors, based on common challenges and technological options for low-carbon solutions.

The cross-cutting thematic group 'Heat & Cold' targets development up to TRL 7 in a timeframe of 5 to 10 years. Heat and cold generation, upgrade and recovery technologies are being developed, or they already exist but are not yet sufficiently economically viable to be deployed in all industrial processes. This thematic group therefore includes R&I activities for heat upgrade, waste heat to power and to cold generation, polygeneration and hybrid plants integrating renewable heat.

The thematic group 'Systems' targets development up to TRL 7-8, except training and capacity building, for which TRL 9 is envisaged. This thematic group's timeframe is also 5-10 years. 'Systems' focuses on the integration of concepts (based on technologies), the overall systems needed, embedded in a regional setting and encompassing training and education (including raising the public's awareness of what is at stake here). For this integration to work, strong digital tools are needed to manage data flows, improve processes and guarantee the quality of products and services. R&I activities consist of

[79] See Set Plan Action 6, Revision 2021, page 10 and following.

industrial symbiosis, non-conventional energy sources including CCUS, digitalisation and knowledge sharing, training and capacity building.

In 'Cement', the existing TRL is medium/high in the case of most technological options, except for electrification. SET Plan Action 6 focuses on R&I activities that are already at medium/high TRLs and therefore have the potential to reach demonstration and early market adoption phase (TRL 7-9). Cement-related R&I topics include energy and resource efficiency, CCUS and recarbonation and mineralisation.

'Chemicals': in the prioritised R&I activities the existing TRL is mainly medium and/or high, except for electrification and CCU. They will now need to be brought to demonstration stage and scaled up for market adoption, so the target in this case is TRL 7-9. R&I activities consist of electrification and process efficiency, integrated production of low-carbon hydrogen, plastic waste and CO_2/CO as an alternative feedstock. A cross-cutting topic is the use of biomass as alternative feedstock (shared activity with pulp and paper).

The 'Iron & Steel' thematic group follows mainly the CSP roadmap. Its aim is to bring low-carbon technologies to TRL 7 and above 8, so it will start mostly with medium TRLs. Proposed R&I activities are the direct reduction of iron using hydrogen and electricity, Hlsarna smelting reduction, top gas recycling-blast furnace, carbon capture and usage (CCU). The new cross-cutting topic is the circular economy.

In 'Pulp & Paper' R&I activities range from TRL 2 to TRL 8, covering both long-term research and short-term application-driven demonstration projects. Proposed R&I activities are integral drying and heat recovery, papermaking without water evaporation, process optimisation and electrification, mild pulping processes, onsite renewable energy conversion, and biomass as alternative feedstock (shared activity with 'Chemicals').

SET Plan implementation plans are prepared by Member States and associated countries in collaboration with industry, research organisations and the European Commission. They do not include a funding commitment for their execution. Some of the actions identified in the SET Plan implementation plans are being executed mobilising Member States' and associated countries' national public and private funding, as well as funding from the European Innovation Fund and the European Investment Bank (EIB).

Some examples:

- The Horizon 2020 CO2OLHEAT project[80] is a direct result of the implementation plan's heat and cold priority. The project focuses on developing the supercritical CO_2 (sCO_2) cycle, so it can be deployed in energy-intensive industries with the main objective of unlocking the potential of unused industrial waste heat and transforming it into power. The development of innovative, cutting-edge sCO_2 technologies will be used to design and demonstrate in a real industrial environment the first-of-a-kind sCO_2 plant in the EU.
- The HYBRIT[81] project, co-funded by Sweden, was launched in 2016 as a joint venture between Vattenfall, LKAB and SSAB, working together to develop the first fossil-free steel. HYBRIT technology has the potential to reduce Sweden's total carbon dioxide emissions by 10%.
- The STEELANOL[82] project focuses on the production of sustainable, advanced bioethanol with an innovative gas fermentation process that uses exhaust gases emitted by the steel industry. Starting in May 2015, the project received funding

[80] https://cordis.europa.eu/project/id/101022831
[81] https://www.hybritdevelopment.se
[82] http://www.steelanol.eu/en

from Horizon 2020's R&I programme and benefited from an EIB loan under the InnovFin Energy Demonstration Projects Facility.

- The Horizon Europe Clean energy transition co-funded Partnership is a transformative R&D&I programme across Europe to boost and accelerate all aspects of the energy transition so Europe can become the first climate-neutral continent. The partnership's total indicative budget is EUR 210 million, EUR 70 million of which is an EU top-up, committed under Horizon Europe budget in annual instalments over 2021-2022.

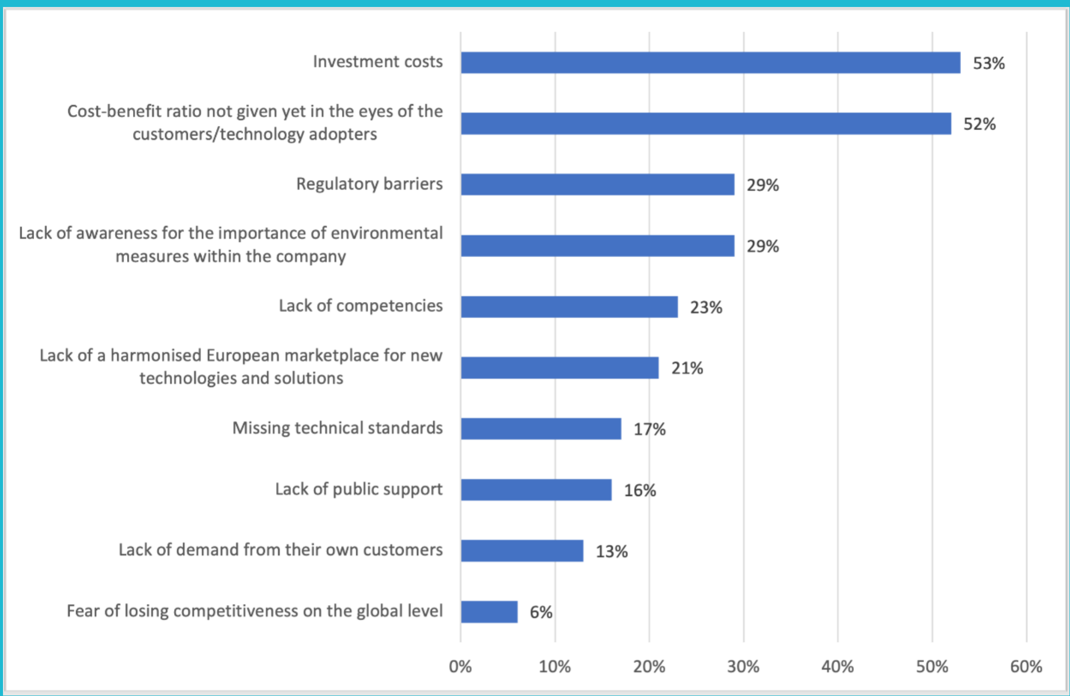
SME Focus 2 | **THE ROLE OF SMES IN DEVELOPING TECHNOLOGIES**

Small technology developers are engaged in developing various technologies covering the entire spectrum of low-carbon technologies, such as clean energy, waste recycling, carbon capture and storage, material efficiency, hydrogen, biomass, sector coupling, and digital business models. About half of the firms have already been granted patents demonstrating their technology leadership ambitions, and about two thirds of the firms claimed to spend more than 25% for R&D&I, further highlighting their focus on innovation.

Most of the startups (73%), both small and large firms, serve the B2B market. In DG R&I's survey, these firms were asked to assess the willingness of their customers to become more environmentally friendly. The overall mark given for this was 7.4 on a scale between 1 (very low) to 10 (very high). This indicates that small high-tech companies often serve customers who are very willing to reduce their CO2 emissions.

However, when it comes to assessing the main barriers which small technology developers encounter from their customers (usually other companies), the survey indicates that high investment costs (53%) are perceived as the most significant barrier in adopting the technologies supplied by the small technology developers. Other barriers include the unknown cost-benefit ratio (52%), a lack of awareness for the importance of environmental measures within the company (29%) and regulatory barriers (29%).

Figure 20 Barriers encountered by respondents' customers to adopt environmental technologies or solutions



Source: survey on small technology developers, conducted in November 2021 and January 2022 (see Annex 1).

5 Enablers including circularity

In line with these considerations, following the different roadmaps and studies, two enabling pathways can be defined: 'Digitalisation' and 'eco systems and support actions for non-technological innovation and drivers'. They are very important for speeding up emission reductions in process industries and for achieving a circular economy, cross-sectoral cooperation and industrial symbiosis. Identified topics in this context include, for digitalisation:

- AI, machine, and deep learning;
- 3D printing and digital fabrication, including with new materials;
- digitalisation of the design phase of processes and materials;
- traceability of raw materials and products;
- digital twins;
- strategic scheduling tools for industrial transition processes, etc.[83]

Identified topics in the 'eco systems and support actions for non-technological innovation and drivers':

- integrating non-technological aspects in R&I activities to improve the technological solution's effectiveness;
- creation of 'European Community of Practices' and hubs for circularity;
- proactive adjustment of human resources and (digital) skills for technological development and implementation;
- support actions for creating synergies between projects, upskilling the industrial workforce, fostering R&D&I collaboration, creating new markets, taking up successful technologies developed and the global competitiveness of the EU industries.

A similar approach on potential technological pathways has been at the core of the work carried out by A.SPIRE, within the SPIRE Partnership, under Horizon 2020. Energy usage and access to renewables, coupled with the electrification of industrial processes, is seen as key for the way forward, alongside further pathways (i.e. CCU, circularity).

[83] Some more examples could be taken from P4P SRIA, emphasising the role of digitalisation and non-technological innovation: page 57 and following, page 61 and following.

Box 6 | **CIRCULARITY AS AN ENABLER OF DECARBONISATION**

Studies indicate that, beyond technologies that reduce CO_2 emissions produced by current processes or new production pathways with lower CO_2 footprints, a more circular economy approach can make deep cuts to emissions from heavy industry. For instance, the electric arc furnace (EAF) method used in the steel industry has been identified as a valid way to decrease the sector's emissions[84]. Furthermore, as the EII ecosystem is so deeply linked to all other economic sectors, indirect actions linked to limiting the use of virgin steel, cement or concrete in new buildings can significantly reduce emissions. Consequently, it is possible to reduce emissions by 12% through overspecifying concrete in building plans, 16% through using innovative and alternative cement types and 15% through reusing structural steel[85].

The increased circularity of materials is expected to boost the importance of circularity in reducing emissions from the energy-intensive industries ecosystem, in order to optimise raw material use and to contribute to the security of supply[86]. Raw materials represent one of the highest cost categories for the EIIs ecosystem, which makes them a key element to address in the pathway to net zero. Furthermore, availability of critical raw materials is key in the overall green transition of Europe's energy-intensive industries, especially given the high dependence on non-EU trading partners for a number of critical raw materials.

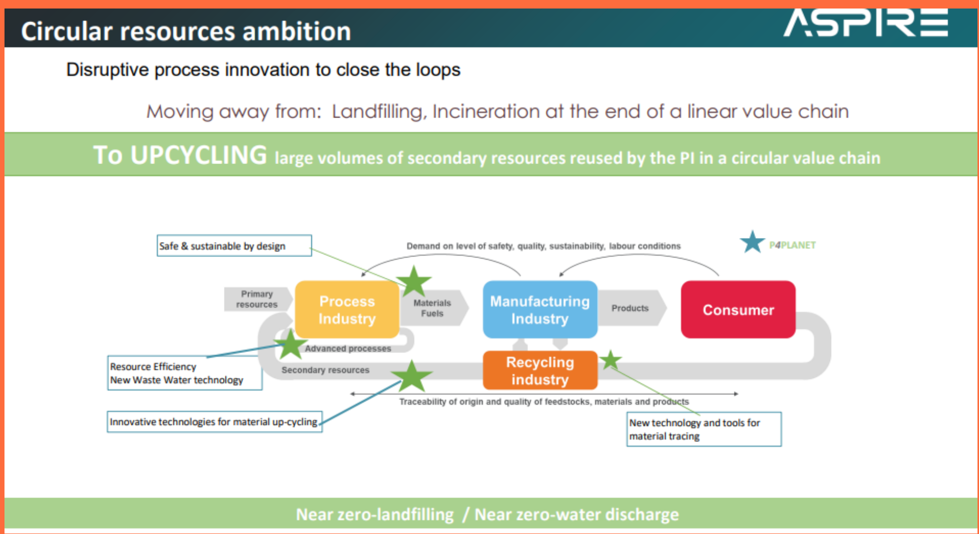
Part of the solution is **industrial symbiosis**, which can ensure that EIIs benefit from parallel material flows. This option benefits from the overall landscape of EU's big production facilities, which are sometimes located in the same industrial zone as other plants, thus being able to share similar infrastructure, logistics and resources.

A specific waste that needs to be valorised in the energy-intensive industries ecosystem is **carbon waste**, which should become a *valuable resource* with an increased productivity[87]. However, circularity of carbon requires improvement in waste collection and sorting, as a means to enable innovative recycling solutions for carbon.

Estimates indicate that, at a global level, the circular economy can reduce global CO_2 emissions from just four sectors – steel, cement, aluminium and plastic – by 40% by 2050[88]. The wide applicability of materials from these industries, e.g. to buildings or mobility, make them highly relevant for global supply chains. By eliminating waste and circulating products and materials, an overall emissions reduction of up to 2 billion CO_2 tonnes per year could be registered worldwide.

The Commission, with Member States and stakeholders, is working on a further ERA industrial technology roadmap on circular industrial technologies. It will address, among other things, the circularity of various EIIs, such as steel, chemicals or ceramics.

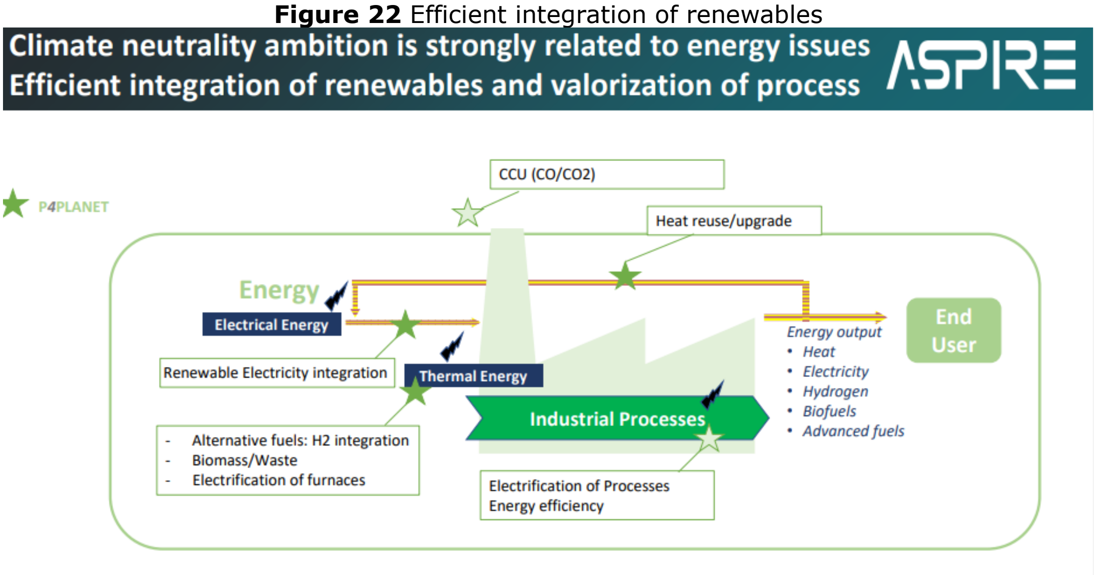
Figure 21 Circularity in the A.SPIRE roadmap



Source: A.SPIRE roadmap 2050.

Furthermore, the pathway to decarbonisation is strongly related to the supply and use of energy, and notably electricity. The access and use of renewable green energy is a major determinant, along with related questions on infrastructure, notably for the increased use of electricity and hydrogen[89].

Figure 22 Efficient integration of renewables



Source: A.SPIRE roadmap 2050.

As part of the development of the ERA roadmap, a stakeholder consultation was conducted in summer 2021[90], addressing experts from industry, research organisations and industry interest groups. In total, 83 experts from different organisations across Europe participated in the survey. The experts were asked, among other things, to assess the highest potential of the different technologies to reduce carbon emissions in energy-intensive industries.

The feedback reveals that on overall electrification, the use of biomass and other biofuels, green hydrogen, and recycling were considered as the most promising solutions. However, the other pathways such as carbon capture and storage, industrial symbiosis and alternative solutions (e.g. digitalisation) were also considered to have a high potential. There were small differences concerning the assessment of experts from different groups of stakeholders, i.e. firms, research and industry interest groups (see Figure 23, top). Recycling was considered important, particularly by 'other' stakeholders. Furthermore, there were hardly any differences between large and small firms (not disclosed here), nor between different country groups (see Figure 23, bottom).

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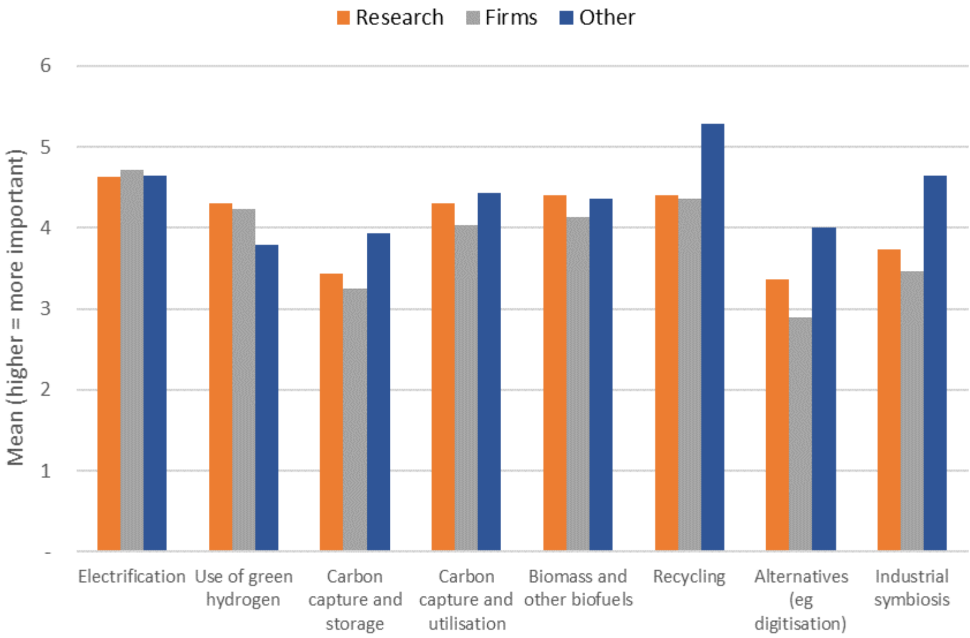
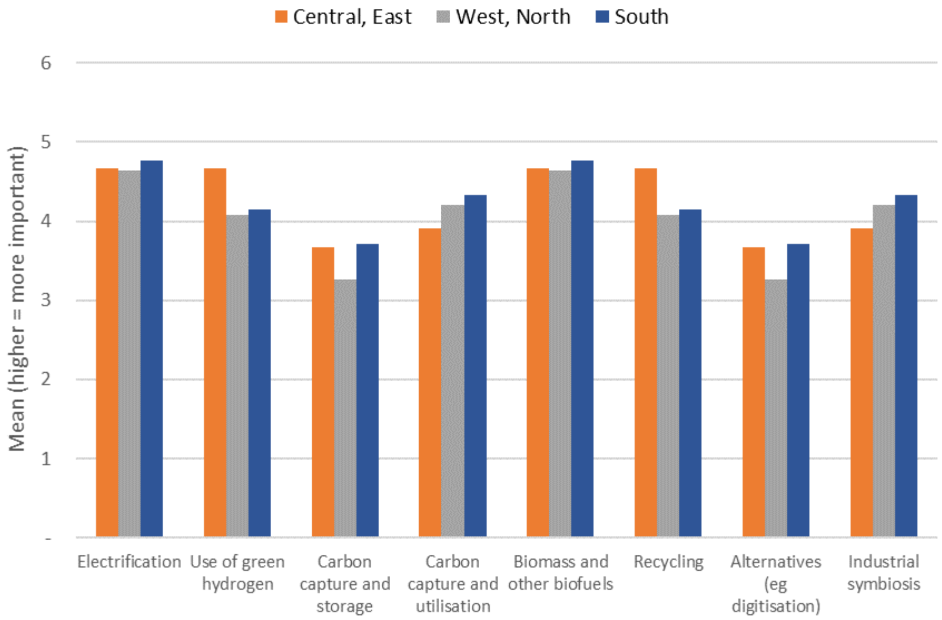
84 SWD (2021) 353 final, Towards a Competitive Clean European Steel.
85 European Environment Agency (2020), Cutting greenhouse gas emissions through circular economy actions in the buildings sector.
86 HLG EII (2018), Masterplan for a Competitive Transformation of EU Energy-intensive Industries – Enabling a Climate-neutral, Circular Economy by 2050.
87 Ibid.
88 Ellen MacArthur Foundation & Material Economics (2021), Completing the Picture: How the circular economy tackles climate change.
89 However, this roadmap does not cover energy (including electricity) or hydrogen production.
90 Consultation open from 23 July to 30 September 2021.

Figure 23 Assessment of the potential to reduce emission in energy-intensive industries by type of organisation and by group of country





Note: West, North: AT, BE, FI, FR, DE, IE, NL, SW; Central, East: BG, CZ, PL, SK; South: GR, IT, PT, ES.
Source: ERA roadmap stakeholder consultation, open from July to September 2021.

6 Conclusions on key technological pathways

- The analysis results in a list of most relevant technological pathways (groups of similar technologies) needed for decarbonisation of the energy-intensive industries ecosystem. These are: electrification; use of green hydrogen; carbon capture and storage and utilisation; alternative feedstock and integration of renewables; alternative materials and processes; energy and materials efficiency including circularity; and industrial symbiosis.

- There is a converging view about a – manageable – number of low-carbon industrial technologies, which are needed to achieve EU climate objectives in the energy-intensive industries ecosystem.

- Low-carbon industrial technologies for energy-intensive industries, which have a high potential for reducing greenhouse gas emissions, are currently at varying technology readiness levels (TRLs) in their development curve. Their technological readiness is decisive for their impact on reducing carbon emissions in the market by 2030 or 2050 and for R&I investment needs for further development, as the latter vary greatly between low or high TRLs.

- Scaling up and deploying existing innovative low-carbon technologies currently at high TRLs is crucial for reaching the 2030 emission objectives. This is particularly so for the 'big three' sectors (steel, chemicals and cement) but also in other energy-intensive industry sectors.

- At the same time, technologies that are still in pilot and demonstration phase and technologies that are now at an even lower development levels will need to be developed for reaching emission targets after 2030 in the horizon 2050. The challenge is to speed up such innovation projects to reach the market in this timeframe.

- Because of their cross-sectoral nature, a number of low-carbon industrial technologies can be applied or adapted in several energy-intensive industries. This also includes circular and digital industrial technologies. In addition, actions to support ecosystems and non-technological innovation are important for speeding up emission reductions in process industries and to mobilise the added value of cross-sectoral cooperation and industrial symbiosis.

- The different scenarios described in the chapter, including Commission analysis under the Strategic Energy Technology Plan, point to the need to strengthen the development of relevant technologies, both at low and high TRLs, and simultaneously to pursue alternative technology pathways.

- The cross-sector and cross-border collaboration on large-scale R&D&I projects deployed by the process industry ('marbles'), namely bringing a number of key technologies to the level of first-of-a-kind large-scale application, mitigates high costs and uncertainty of return on investment.

- Among the key technologies, electrification and use of green hydrogen depend on the availability of affordable clean energy.

- Therefore, to ensure development and uptake of low-carbon technologies in the energy-intensive industries ecosystem, there is a need to ensure in parallel the availability and affordability of such clean energy.

- Funding of relevant R&I and infrastructure investment should therefore complement and not compete with R&I investments in low-carbon industrial technologies. This can best be ensured through integrated approaches for industrial R&I development.

- EU co-programmed public-private partnerships under Horizon Europe provide a strong forum for cross-sector cooperation. They are the largest European initiatives in this industrial ecosystem to develop and implement transformation strategies to support the European Green Deal and implement them through joint R&I actions. They cover several sectors concerned and bring together Europe's key companies, associations and R&I stakeholders. For steel, several relevant developments are concentrated or connected to the Clean Steel Partnership.

CHAPTER 3: R&I INVESTMENTS

This chapter first gives an overview of the R&I investment needs for the decarbonisation of energy-intensive industries, providing estimates of active public-private partnerships and the SET-Plan Action 6 on energy efficiency in industry, followed by estimates on three pathways for net-zero emissions by Material Economics. Second, it presents available public and private R&I data and also develops trend analysis of companies' R&D expenditures in EU-27, USA, UK, China and Japan for 2012-2020. The third section gives a snapshot on overall trends in green patenting activity and on the patenting of specific energy-intensive industries. The fourth section looks at EU public investments and programmes, while the final section develops understanding of investments in national schemes and programmes.

Overall, the chapter offers the opportunity to compare needed efforts and actual as well as potential funding and investments towards EU's climate-neutrality targets.

1 R&I needs for decarbonising energy-intensive industries

This section follows the same logic as the one on technologies; it describes the R&I funding estimations by Processes4Planet (P4P), Clean steel, the SET plan, and it also gives the projections of Material Economics that were already described under Chapter 1.

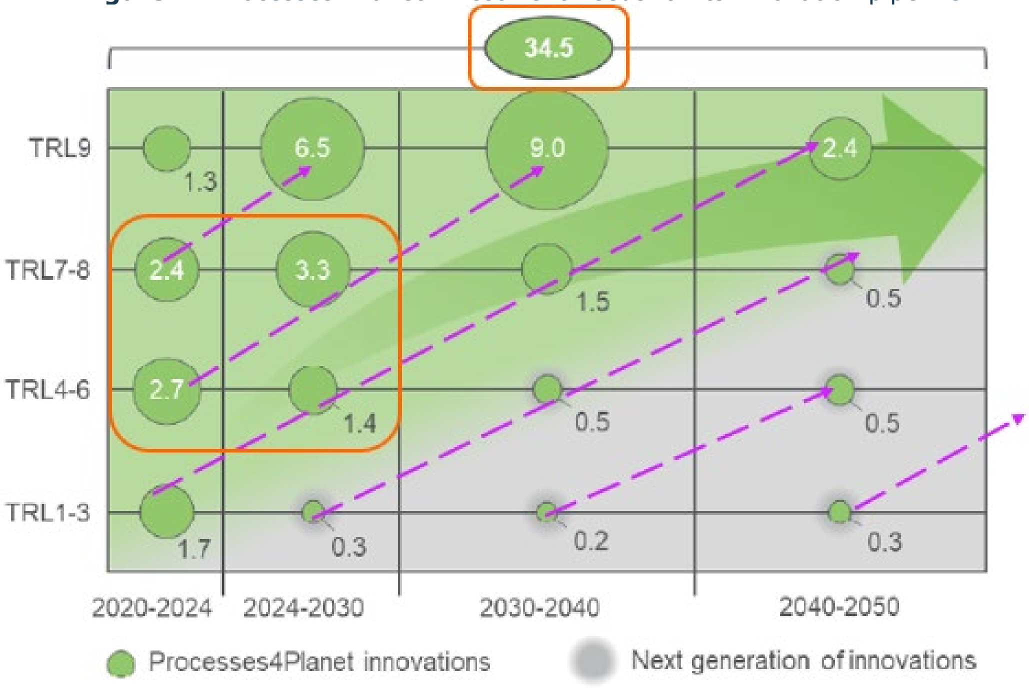
1.1 *The Processes4Planet Partnership: funding and investment needs along the timeline*

The P4P Partnership estimates EUR 34.5 billion in investment is needed until 2050 to develop and advance its innovation pipeline as described above, comprising 36 distinct detailed innovation programmes clustered in 14 innovation areas. This estimation includes the total investments of the projects from TRL1 to TRL9, namely FOAK demonstration plants (the 'marbles' described above)[91]. It also includes funding for non-technological activities.

For the 2020-2030 period, investments are estimated at EUR 19.8 billion, of which EUR 10.1 billion are in the expected TRL range of Horizon Europe (i.e. TRL4 to 8) and in the proposed non-technological activities of Horizon Europe. The following figure depicts a more detailed breakdown of the technological investment needs. Estimates for investments after 2030 are more uncertain than those for before 2030. The non-technological investments amount to EUR 303 million until 2050.

[91] For a detailed quantification of investment needs by different project types and TRLs, see P4P SRIA, Annex E-5.

Figure 24 Processes4Planet investment needs for its innovation pipeline



Source: P4P SRIA, Roadmap.

The estimated investments are highest in the first decade (2020-2030), as most innovation must be in place during this period to reduce GHG emissions in time. The investments needed decrease in the second decade and third decade. In Figure 24, highlighted in the orange frame on the left is Horizon Europe's focus.

The arrows within the graph visualise the stepwise approach of the innovation programme and the corresponding investment needed, building upon each other, moving the ladder up to higher TRLs. Most investments needed in TRL 9 will be required in the first and second decades, also highlighting the increased need for private investments, complemented by funding means outside Horizon Europe (e.g. ETS Innovation Fund, EIB, private equity and debt). On the other hand, investments required for TRL 4-8 are most needed in the first decade, what underlines the particular importance of EU, but also national and regional R&D funding instruments within this timeframe.

The investments for deployment are substantial and estimated to be about 24 times higher than the estimated EUR 34.5 billion investment needed for developing the technologies (TRL 1-9), thus overall above EUR 800 million until 2050. The projected cumulative capital investment needed by 2050 to convert the steel industry alone to carbon-neutral production in the EU has been estimated at between EUR 70 billion and EUR 100 billion[92]. EU wide investments for deployment in the chemical industry are estimated to be in the range of EUR 220-240 billion[93].

[92] Somers, J., Technologies to decarbonise the EU steel industry, EUR 30982 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-47147-9, doi:10.2760/069150, JRC127468.

[93] See P4P SRIA, October 2021, p. 82. The SRIA mentions that a more accurate estimation of investment needs for deployment would require more detailed analysis, further the overall figure will depend on the investments included. For example, for full deployment across Europe additional investments, also into electricity power production and indirect investments in the supply chains or transport, are needed that are estimated to exceed €3 trillion based on the limited information available currently. (p. 13, 83)

1.2 *The Clean Steel Partnership – funding & investment needs along the timeline*

The R&I investment timeline developed by the P4P Partnership is largely reflected also in the work of the Clean Steel Partnership (CSP) in its multi-stage R&D&I approach to accelerate carbon mitigation in the steel industry. This approach provides the rationale for the way in which the budget is split over time.

- stage 1 (short- to medium-term impact measures) targets projects that generate 'immediate' CO_2 reduction opportunities;

- stage 2 (medium-term impact measures) focuses on those projects that may not be implemented 'immediately' in the installed base, but allow for a quick evolution towards improved processes;

- stage 3 (medium- to long-term impact measures) looks at those projects that can 'revolutionise' the steel industry through breakthrough development and require significant capital investment in new processes.

The total resource requirement for the R&D&I projects falling within the scope of the CSP roadmap is estimated at EUR 3 billion during 2021-2030. This R&D&I investment will then have to be followed up by a multiple of these resources, to ensure that the technologies are deployed and rolled out.

Thanks to the collaboration within the partnership, a reasonable amount of synergy is expected, thus reducing the investment need to about EUR 2.55 billion. The investment needed from the public and private side for the 2021-27 period, is estimated at EUR 2 billion. The remaining EUR 0.55 billion will be allocated to the 2028-2030 period, during which time projects will still be completed. The expected investments to be managed within the scope of the Clean Steel Partnership are around EUR 1.4 billion for 2021-27. Major private funding will match EU public funding, such as Horizon Europe and the Research Fund for Coal and Steel. The partnership's activities will mobilise further resources from other EU funded programmes and the Member States.

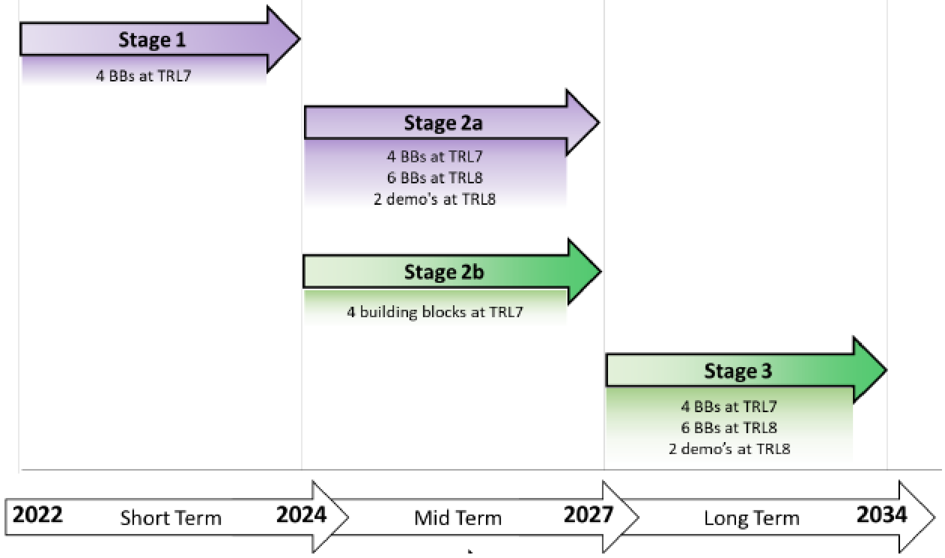
As shown in the next Figure, the budget is expected to finance 16 projects resulting in building blocks at TRL7 (EUR 10-30 million each), 12 projects resulting in building blocks at TRL 8 (EUR 30-60 million each) and 4 demonstration projects at TRL8 (up to EUR 100 million each). These four demonstrations, which will combine different technological building blocks, will be launched in 2023, 2024, 2026 and 2027. Two of them are target technologies that have up to 50% CO_2 mitigation potential by 2027, and the other two support technologies with up to 80% of CO_2 reduction by 2030[94].

Because of the scale and complexity of the technologies, the maturity of the industry and the high costs associated with innovation, progress in the steel sector has been slow in developing these breakthrough technologies, and advancing them towards demonstration levels and subsequent commercialisation[95].

[94] See CSP Roadmap, p. 57.

[95] Somers, J., Technologies to decarbonise the EU steel industry, EUR 30982 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-47147-9, doi:10.2760/069150, JRC127468.

Figure 25 Budget distribution along the multi-stage approach of the CSP



Source: CSP Roadmap.

While already in this timeline R&I investment needs peak around 2030, the investment needs for full-scale industrial production plants are also kicking in with the market-readiness of the relevant technologies (above TRL 9). Notably, most of the overall investment needs for the steel sector from 2020 onwards will be concentrated in the 2030-2050 period[96].

Beyond the proposed R&D&I projects, the European Commission, Member States, and European steel industry are also expected to invest massively in the market deployment of low-carbon steelmaking technologies developed. Instruments outside of the CSP like the EU-ETS-Innovation Fund, the ongoing work for developing hydrogen technologies and their deployment including the steel sector under both the IPCEI instrument and the Climate, Energy and Environmental Aid Guidelines and national decarbonisation funds will contribute to support the roll-out of breakthrough technologies in the steel industry in the coming years.

1.3 *SET Plan Action 6 on energy efficiency in industry: estimations of funding needs*

The implementation plan of the SET Plan Action 6 on energy efficiency in industry, lists funding requirement estimations by thematic groups, projects and TRLs. Budgets for medium TRL projects are in the range of EUR 2-5 million each; for higher TRL projects, the budgets are between EUR 7 and 30 million, but sometimes amount to EUR 50 million. When reaching large-scale demonstration plants and first market deployment, the investments needed amount to several hundreds of millions of euros, and can also reach billions of euros[97]. The SET Plan indicates specific funding requirements, e.g. in the two cross-cutting thematic groups 'Heat & Cold' and 'Systems'. Similarly to the P4P assessment, the SET plan sees the most pressing short-term R&I investment need in those technologies, which are currently at high TRLs to bring them to the market. This is combined with the need to bring breakthrough R&I on board now to mature in time to unfold its impact over the next decades[98].

On investment needs, the implementation working group of the SET Plan Action 6 (IWG6) concludes that EU level funds should be guaranteed to achieve true a cross-sectorial EU dimension for technology development and demonstration. In all TRL development phases, the projects should be co-financed via public grants (national and/or EU) and private funds.

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96 Green Steel for Europe project, Investment Needs, June 2021.
97 See SET plan Action 6 implementation plan, Revision 2021, and Annex 2: R&I activity fiches.
98 The funding requirements for sector specific solutions sometimes can be even higher. For large-scale demonstration plants and FOAK in particular, the required budget can add up for several 100 million euros. This applies for all four industrial sectors in the SET plan Action 6.

Other complementary funds or tools will cover specific territorial interests (e.g. national or regional funds) or support deployment (e.g. investment and financial instruments from the EIB, the ETS Innovation Fund). In addition, according to IWG6, risk-sharing measures through appropriate financial instruments for high TRL demonstration plants and FOAK plants will be put in place.

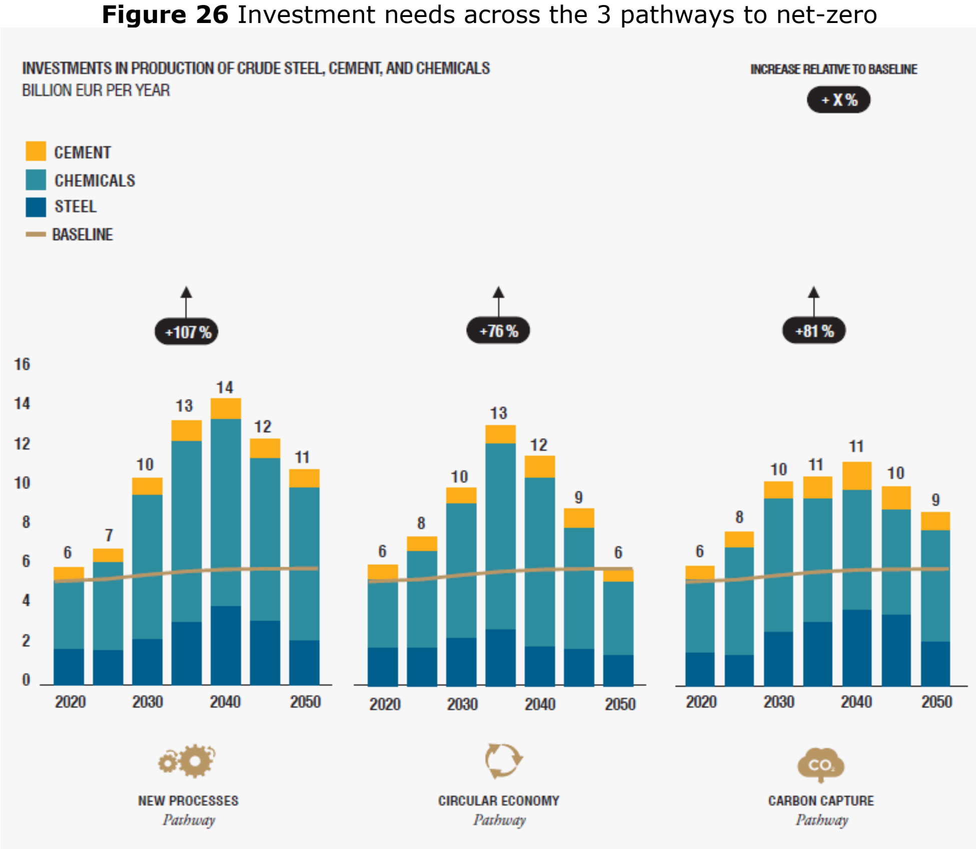
1.4 *Three pathways to net-zero emissions – R&I funding & investment needs*

All three pathways proposed by Material Economics research consortia require an increase in capital expenditure (all investment expenditure) to ensure the operation of industrial plants based on low-carbon technologies. Similar to the investment timelines developed by P4P and Clean Steel Partnerships, the baseline rate of investment in the core industrial production processes is around EUR 5.1 billion per year, rising by up to EUR 5.5 billion per year in the net-zero pathways, reaching EUR 11–14 billion per year in the 2030s.

Investments are highest in the 'New Processes' pathway. In the 'Circular Economy' pathway, less investment capital is needed because many solutions are less capital-intensive than new production. In the 'Carbon Capture' pathway, somewhat less investment is required because more of the existing production assets can be maintained, but from a long-term 2050 perspective, the effect is relatively modest. Over the three pathways, investments increase by 76–107% on a baseline scenario where current production routes are maintained[99].

Overall, chemicals, iron & steel and cement are the sectors with the biggest investment needs whose transition will on average require additional investments of EUR 3.9-5.5 billion per year.

Figure 26 Investment needs across the 3 pathways to net-zero



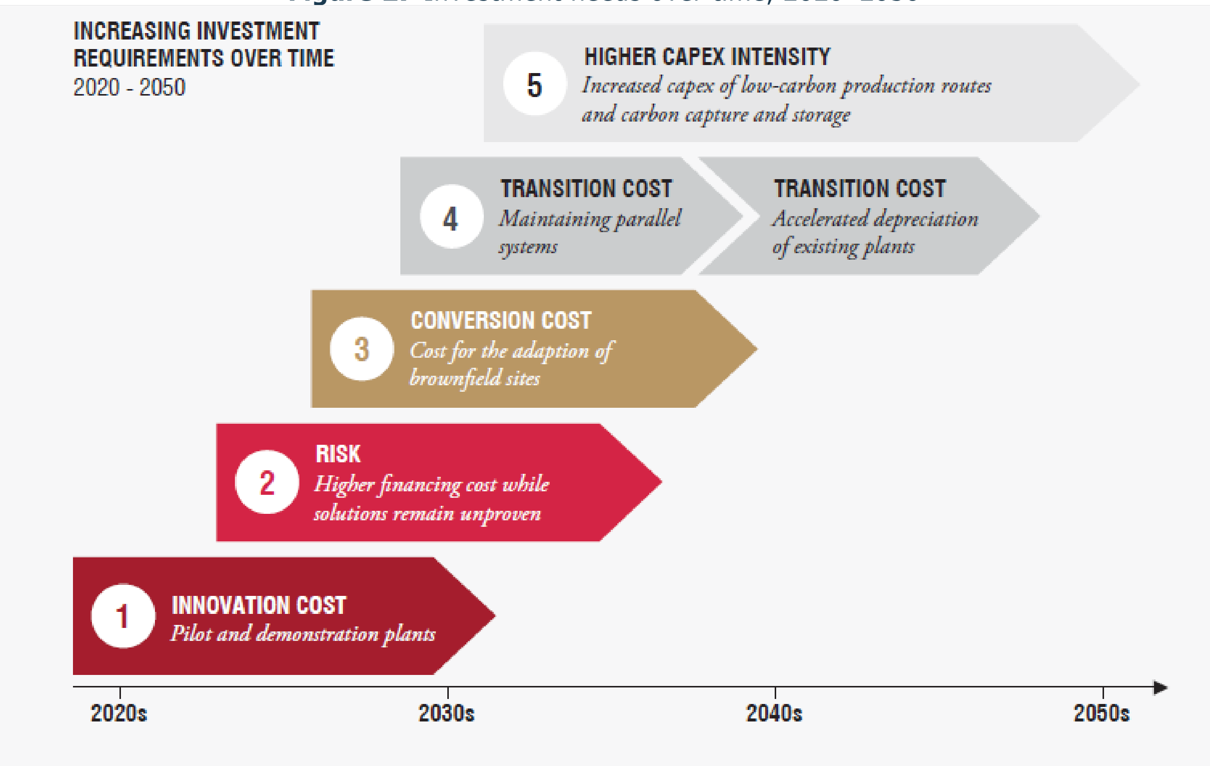
Source: Material Economics, 2019.

[99] Material Economics, *Industrial Transformation 2050*, p. 47

Early in the transition, investments in pilot and demonstration plants are needed (TRL 4-8). For individual companies this investment can be a big challenge, as demonstration rarely offers a real business case and a return in its own right. As much of the benefit from these innovations go to society, there is a high risk of underinvestment without policy (funding) support.

The investments in the early deployment of new technologies (FOAK, TRL 9) will still be undertaken in a situation of significant uncertainty about technical viability, future availability and cost of new fuels and feedstocks, and the degree of policy support. Increased risk in turn increases the bar for raising capital, and the cost of both debt and equity.

Figure 27 Investment needs over time, 2020–2050



Source: Material Economics, 2019.

Additional investments will be necessary to adapt current production sites (conversion costs). Switching the process then requires investment not just in the core production machinery, but also in a range of supporting and integrating functions. These costs arise when the new technologies are first put in place and can be substantial in the steel and chemicals sector.

According to the analysis of Material Economics, many companies will keep their options open and maintain some degree of redundancy, to avoid fully committing themselves to a risky solution. The gradual transition from one system to another will thus require some degree of parallel production systems, with dual investment requirements as a result (transition costs). In addition, unless all investments are perfectly timed, there is a risk that existing assets must be written off before the end of their technical lifetime.

From the mid-2030s, the main reason for increased investment will be the intrinsic higher capex associated with some low-carbon processes and with carbon capture and storage. This is particularly marked in the chemicals sector, where there is a need to replace a single core process (steam crackers) with alternatives containing multiple loops to achieve a high carbon balance and very low CO_2 emissions[100].

The authors of the study conclude with regard to investments needed, that 'the most important policy instrument for investment in low-CO_2 production is to ensure a future business case for higher-cost production routes[101].'

Box 7 | **FINANCING R&D&I– RESULT OF STAKEHOLDER WORKSHOP**

Designing and building a demonstration plant is one of the major challenges for developing many decarbonisation technologies and solutions and often requires collaboration between different industries and partners on a regional level and across borders. The investment returns are uncertain and there is the risk of technological lock-in and stranded investments. The subsequent transition from pilot phase to industrial-scale deployment is still associated with risks and requires even larger investments.

The participants in the workshop with stakeholders, organised in November 2021, stressed the challenge posed to both small and large companies in financing R&D&I projects. A lack of access to finance for FOAK innovation was perceived as a key barrier for innovation and deployment. Furthermore, financing the take-up of new technologies with the need to test the solutions at higher TRL requires huge investments and is a major barrier as there is a lack of subsidies. If a FOAK is successfully installed, there is a lack of transfer to the others (appliers, machining industry) as well as a lack of processes and measures to support such a transfer.

The lack of funding opportunities and risk-sharing possibilities throughout upscaling and integration into existing systems and value chains results directly from the lack of a market for technology deployment. Therefore, no relevant financial payback from decarbonisation investments can be expected in the short and medium term.

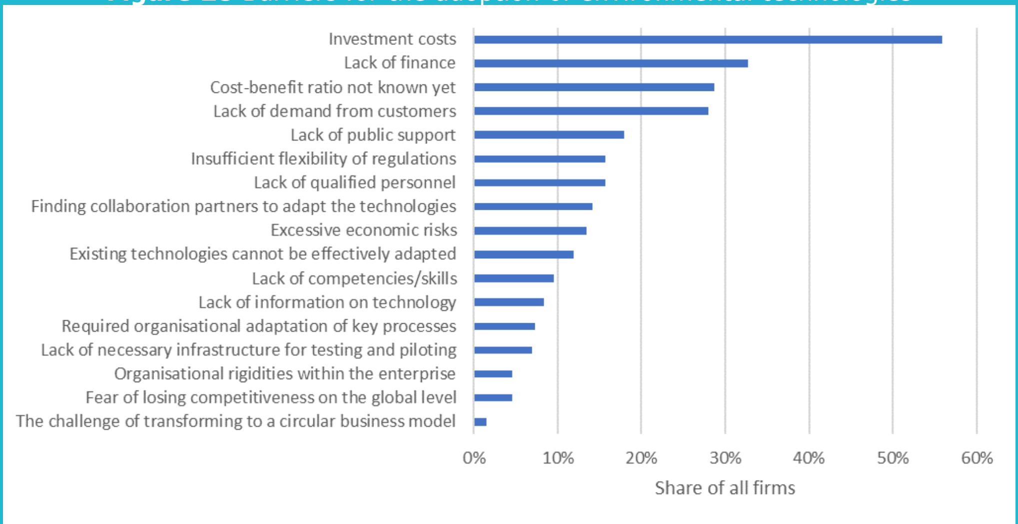
In addition, new forms of cross-sectoral collaboration are needed. However, new value chains and business models are just emerging and investment decisions in such an environment are associated with high uncertainty, which can slow down decision-making on R&D&I investments.

[100] Ibid, p. 49.
[101] Ibid. p. 48.

SME Focus 3 | **FINANCING THE DEVELOPMENT AND UPTAKE OF NEW TECHNOLOGIES**

The analysis carried out by DG R&I reveals that too high investment costs are the most frequent barrier to adopting new environmental technologies by SMEs, followed by a lack of finance. Losing competitiveness or the challenge of transforming to a circular business model are rarely regarded as barriers by SMEs when making a business decision on investing in new environmental technologies.

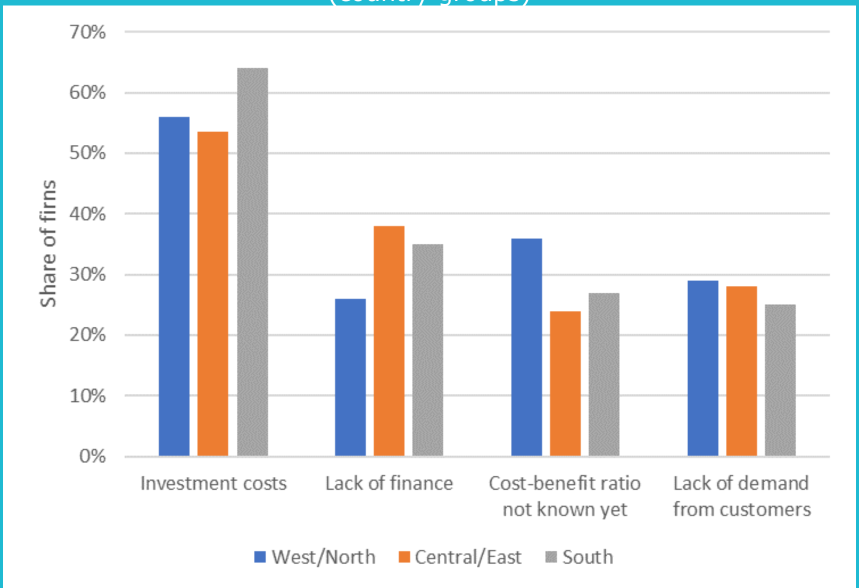
Figure 28 Barriers for the adoption of environmental technologies



Source: European Commission / Enterprise Europe Network SME Survey, conducted from November 2021 to January 2022 (see Annex 1).

The survey further shows the existing some regional differences, with SMEs in southern Europe claiming more often that they face challenges in relation to high investment costs. An unknown cost-benefit ratio is particularly relevant for SMEs in western/northern Europe, where companies less often have to deal with challenges related to financing the adoption of environmental technologies.

Figure 29 Major barriers for the adoption of environmental technologies at the regional level (country groups)



Source: European Commission / Enterprise Europe Network SME Survey, conducted from November 2021 to January 2022 (see Annex 1).

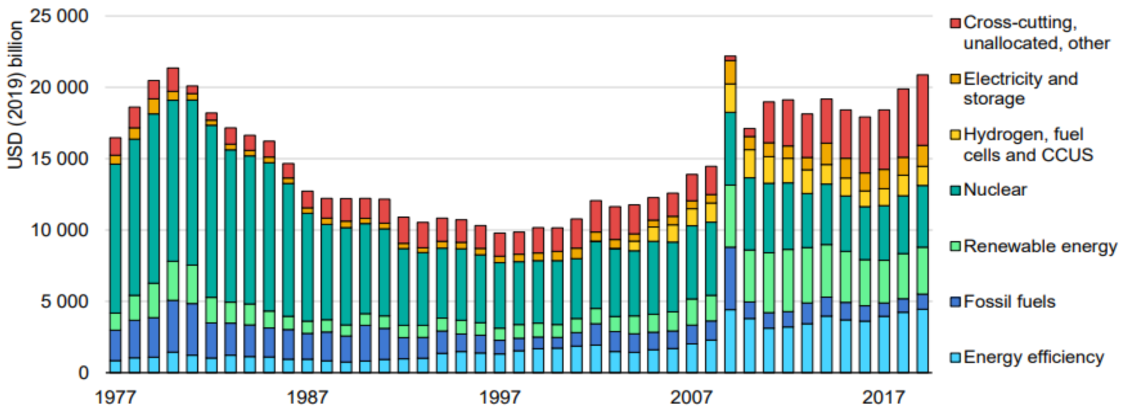
2 Estimated public and private R&I investments

R&I investments play a key role in achieving the European Green Deal objectives and making Europe the first climate-neutral continent in the world in a fair, resource-efficient, cost-effective and competitive way. The EU Green Deal is supported by an unprecedented EU budget under the 2021-2027 multiannual financial framework (EUR 1 074 billion) and the NextGenerationEU recovery and resilience package (agreed in 2020 for the amount of EUR 750 billion)[102]. A total of 30% of the overall budget is earmarked for climate spending; Horizon Europe's climate spending target is 35%, while that set in national recovery and resilience plans is 37%.

2.1 *Public*

Global government energy-related R&D spending in 2019 increased by 3% to around EUR 27.3 billion[103], of which approximately 80% was directed to low-carbon energy technologies[104]. The growth rate for 2019 remained above the annual average recorded since 2014. In China, the low-carbon component of energy R&D rose by 10% in 2019, with big increases in R&D for energy efficiency and hydrogen in particular. In both Europe and the United States, spending on public energy R&D rose by 7%, an increase above the recent annual trend. Nuclear R&D spending has decreased over time, as shown in the figure below.

Figure 30 Public energy technology R&D and demonstration spending by International Energy Agency (IEA) member governments by technology, 1977-2019



Notes: CCUS = carbon capture, utilisation and storage. Peak in 2009 was due to post-2007-08 financial crisis stimulus, especially in the USA.
Source: IEA (2020), *Energy Technology Perspectives 2020*, IEA, Paris, https://www.iea.org/reports/energy-technology-perspectives-2020.

When adjusted for inflation, IEA reports that the data show that spending on low-carbon energy R&D in IEA member countries almost doubled between 2000 and 2012, but has since then been broadly stable. Global energy efficiency R&D spending (including energy efficiency in industry) has not changed much since 2009, when it doubled compared to the previous decade.

102 The budget is estimated at 2018 prices.
103 Based on national data submissions, the dataset covers IEA member countries plus the EU and is open to any country wishing to participate. Its scope includes spending allocated to demonstration projects. In general, countries report energy-specific research-programme spending regardless of the sponsoring government department, but differ in reporting budgets versus actual spending and in the extent to which they include basic research on energy-related topics or demonstration project funds (see IEA 2020, p. 318, footnote 6).
104 See IEA (2020, p. 318).

Overall, IEA concludes that although energy R&D budgets are growing in the aggregate, including for developing low-carbon technologies, they are not growing as a share, and in most cases they account for a shrinking proportion of total government R&D spending[105].

In the EU, in spite of global and European initiatives, the EU-27's reported rate of public investment in clean energy technologies needed for decarbonisation was the lowest of the major economies (0.027% of GDP in 2019)[106] before the current multiannual financial framework and NextGenerationEU. This rate is not fully representative for the EU, as only 20 EU Member States report public investment figures regularly and the level of technological detail varies[107].

At the global level, the Mission Innovation initiative was launched in 2015 by 22 leading countries (including 8 EU Member States) and the European Commission with the aim of doubling their public investment in clean energy R&D over 5 years. The goal was to catalyse action and investment in research, development and demonstration so as to make clean energy affordable, attractive and accessible by 2020. The initiative increased annual investments by EUR 5 billion from members, which represent over 90% of global public investments in clean energy innovation. Mission Innovation 2.0 was launched on 2 June 2021 to accelerate progress towards the Paris climate goals.

At the EU level, the SET Plan was launched in 2007 by the European Commission in cooperation with EU Member States and associated countries. It aims to speed up the development and deployment of low-carbon technologies through cooperation between EU countries, companies, research institutions and the EU itself. The private sector is an important partner, for example, as strategic alliances mean the burden and benefits of research and demonstration can be shared. In 2015, the Commission established a new integrated SET Plan for all energy sectors, including energy efficiency in industry (action 6)[108]. A number of actions have been co-funded by the Commission and national R&I programmes under the Horizon 2020 programme and specific implementation plans have been approved. To step up cooperation among EU-wide research and innovation sectors for the improvement of energy efficiency and cost-effectiveness in industry, an energy efficiency in industry working group was created in 2016 under the SET Plan. However, it includes only 16 EU Member States, besides industry associations, and two associated countries (Norway and Turkey)[109]. By recognising that the transition to a more sustainable EU economy needs to protect the competitiveness of energy-intensive industries, the working group aims to design a common R&I strategy, develop R&I activities to be financed either through national or EU support, and identify potential funding sources, among other things. In Horizon Europe, the objectives of the SET Plan are supported by a new partnership (Clean Energy Transition)[110].

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105 See IEA (2020, p. 319).

106 Energy Union R&I priorities (based on COM(2015)80): renewables, smart system, efficient systems, sustainable transport, CCUS and nuclear safety.

107 The IEA statistics are the main source of data for public investment figures. There is a 2-year time delay in reporting for most Member States. Data gaps are supplemented by the Member States through the SET Plan Steering Group and/or through targeted data mining. Additional estimates are provided based on the correlation of macroeconomic indicators such as GBAORD and/or GDP.

108 C(2015)6317 final Communication from the Commission, Towards an Integrated SET Plan: Accelerating the European Energy System Transformation.

109 The working group helps implement the SET Plan strategy and European Green Deal strategy on energy system integration. The group focuses on the most energy-intensive sectors, such as iron & steel, chemicals, pulp & paper and cement, while also addressing cross-cutting themes – heating & cooling, systems and industrial symbiosis – that are relevant to all industrial sectors. It includes the following EU Member States: AT, BE, CY, CZ, FI, FR, DE, IR, IT, LV, NE, PO, PT, SK, ES, SE.

110 More information at https://setis.ec.europa.eu/implementing-actions/energy-efficiency-industry_en.

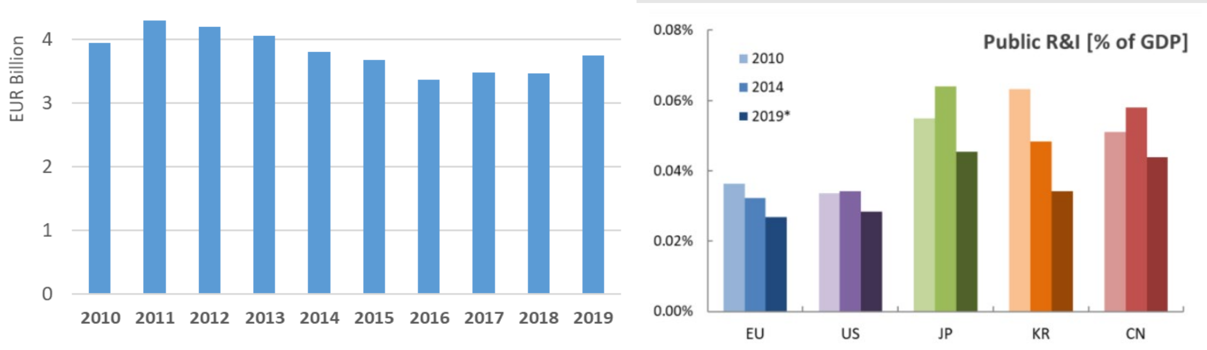
During SET Plan implementation, public R&I investments of EU Member States in energy efficiency for industry was at 10% of their budgets on Energy Union R&I priorities in 2014-2018.

The current geopolitical developments and the evolving policy landscape call for redirecting the SET Plan's objectives and scope, as well as remodelling its governance in order to increase impacts. As a result, there is a proposed revision of the SET Plan, foreseen for publication in November 2022.[111]

Overall, public investments in R&I prioritised by the Energy Union[112,113] went into decline for half a decade between 2010-2019, only showing signs of recovery after 2016 when EU Member States invested on average EUR 3.5 billion per year. Spending still remains lower than that observed a decade ago.

Although the EU compared well with the USA in terms of public R&I financing in Energy Union R&I priorities as a share of GDP between 2010 and 2019, Japan, Korea and China provided more public funding on average throughout the years (see figure below).

Figure 31 Public R&I financing of Energy Union R&I priorities in the EU in EUR billion (on the left) & as a share of GDP in major economies (on the right)



Note:*Public R&I figures for Italy refer to 2018.
Source: JRC in COM (2021)952 final, p.9-10.

As regards R&I spending in energy efficiency in industry (specifically energy-intensive industries), EU Member States invested on average EUR 360 million per year between 2014 and 2018. Although this is less than the average R&I investments in energy efficiency in industry before then (EUR 435.8 million per year between 2009 and 2013), it is higher

[111] The main aims of the revision of the SET Plan are as follows:
- Deliver on the ambitious goals of the Green Deal (its strategies, implementation of the Fit for 55 package and the 2050 climate neutrality objective), the Energy Union and Recovery, and the ERA Policy Agenda;
- Strengthen the EU's strategic energy value chains to increase our energy and technology independence, global competitiveness, geo-political resilience and security of energy supply, in particular in view of the current crisis with Russia;
- Adapt the governance of the SET Plan to ensure the delivery on issues of strategic importance for the Union while keeping an optimal flexibility and agility;
- Strengthen the anchoring in the ERA. Support the development of research and/or technology infrastructures, including pilot lines and Open Innovation Test Beds. Involve the European Energy Research Alliance (EERA) in aligning education and training with the needs of the SET Plan priorities;
- Give more consideration to hydrogen and key enabling technologies such as advanced materials and digital solutions, and continue the Implementing Working Group on nuclear safety;
- Prepare for and support the deployment of clean energy technologies by promoting synergies between different programmes and leveraging national financing; consider capitalising on the increased revenues of the Emission Trading Scheme;
- Increase visibility and political support for the SET Plan through regular interventions in the Competitiveness Council and the Energy Council, and raising the profile of the annual SET Plan conference.

[112] COM(2015)80; renewables, smart system, efficient systems, sustainable transport, CCUS and nuclear safety.

[113] JRC SETIS, https://setis.ec.europa.eu/publications/setis-reseach-and-innovation-data_en.

than the equivalent amounts reported for other major economies, such as Japan (average EUR 290 million) and the United States (average EUR 165 million). Overall, a small number of Member States provided the bulk of overall public R&I funds[114]. The amount accounts for roughly 15% of the EU's R&I spending on Energy Union R&I priorities, given that EU funds contributed another EUR 200 million per year on average[115].

These figures represent the best currently available estimates of past public investments when looking for R&I investments in the decarbonisation of energy-intensive industries[116]. At the same time, compliance with Regulation (EU) 2018/199 on Energy Union and Climate Action Governance, the EU's Energy Union Strategy on energy security, internal energy market, energy efficiency, decarbonisation and research, innovation and competitiveness requires EU countries to produce integrated national energy and climate plans and include integrated reporting on research, innovation and competitiveness[117].

2.2 *Private*

Private R&I investments will be crucial to bring technologies currently under development to maturity or deploy them by 2030 and beyond, and to develop systems changes and breakthrough technologies which enable the contribution of energy-intensive industries to climate neutrality. While the Conference of the Parties of the United Nations Framework Convention on Climate Change, which took place in November 2021, saw a number of corporate pledges for climate action and net-zero targets, there is widespread understanding that the investments announced will not be sufficient to keep the average temperature increase at the 1.5 °C maximum set by the Paris Agreement.

While in general classified as low to medium-tech industries, energy-intensive industries do invest in research and development. The 2021 Industrial R&D Investment Scoreboard[118] shows that private R&D investment by energy-intensive industries is the fifth largest investment by the top 2 500 R&D companies in the world, behind the digital, health, mobility and electronics ecosystems which together account for about 64% of the total investment in 2020. The chemicals sector has been the most prominent R&D investor among energy-intensive industries, although it has registered a slowdown in the global ranking of the top 2 500 R&D investors as 4 companies from EU and USA, 1 from China and 2 from the rest of the world exited the ranking. The EU is well represented in the energy sector, including companies producing renewable energy technologies. However, Japan leads in terms of R&D investments by its companies in the chemicals sector.

The recently published 2021 SET Plan Progress Report noted that for 2018, an estimated EUR 28.7 billion was invested in the clean energy technology R&I priorities of the Energy Union. Most of the investment comes from the private sector (83%)[119], while 12%

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[114] For example, Finland was the top public investor in 2010 with EUR 103.6 million, followed by the Netherlands (EUR 87 million), Germany (EUR 61 million), Hungary (EUR 38.56 million), France (EUR 33.4 million) and Italy (EUR 25 million), providing 82% of total public investment in the EU. In the period 2014-18, Germany, Finland, Italy, France and the Netherlands together provided around 60% of R&I investment in energy efficiency in industry. Data is available at https://setis.ec.europa.eu/publications/setis-research-and-innovation-data_en.

[115] Public (national) investment: IEA's R&D&I online data service; public (EU) investment: Directorate-General for Research & Innovation and SETIS/Joint Research Centre. In fact, EU funding for SPIRE projects alone came to EUR 532 million for projects under Horizon 2020 by 2018, while R&I funding programs for the steel industry generated EUR 268 million under H2020 and an additional EUR 16 million under the Research Fund for Coal and Steel (RFCS) by 2020.

[116] Data collection relies on voluntary sharing by countries. This is why the data mentioned in this chapter address different scopes of activities, depending on the granularity of reporting: R&D for energy in general, low-carbon energy, energy efficiency in general, energy efficiency in industry.

[117] See article 25 of Regulation EU 2018/1999.

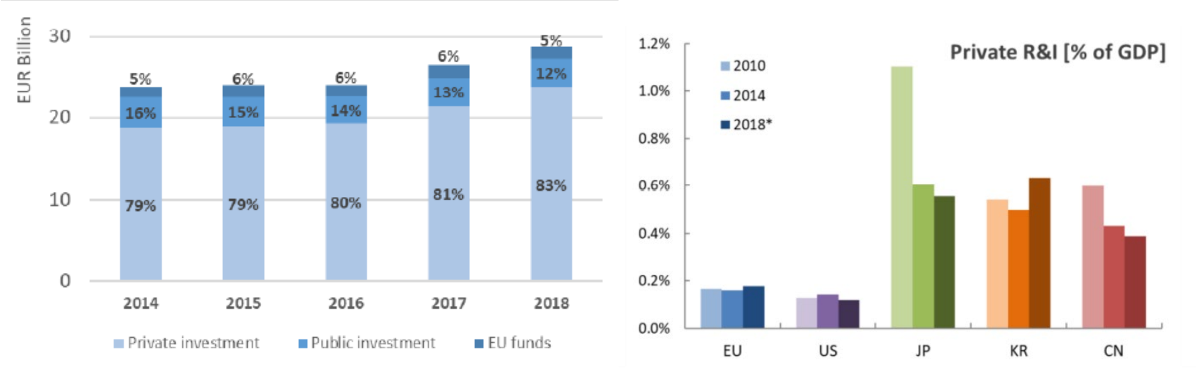
[118] See the report at https://iri.jrc.ec.europa.eu/scoreboard/2021-eu-industrial-rd-investment-scoreboard.

[119] Private R&I investment is estimated using patents as a proxy, resulting in a longer time lag for data availability. See COM (2021)952 final, p.9, footnote 40.

constitutes public funding from Member States and 5% EU funds[120]. According to the report, R&I investment increased by more than 24% in the period 2015-2018, mostly driven by the private sector and, to a lesser extent, by EU funds. Within this, private spending in the EU for Energy Union R&I priorities is estimated at an annual average of EUR 20 billion in 2014-2018[121].

Private investment in the Energy Union R&I priorities in the EU is estimated at 0.18% of GDP in 2018, above the USA but lower than other major competing economies (Japan, Korea, China). Private spending in Korea alone is more than 3 times higher as % of GDP in 2018 (see figure below).

Figure 32 Private R&I financing of Energy Union R&I priorities in the EU in EUR billion (on the left) & as a share of GDP in major economies (on the right)



Note:* Private data for 2018 are provisional.
Source: JRC in COM (2021)952 final, p.9-10.

The estimated private spending on energy efficiency in industry over the period 2014-2018 averages just over EUR 3 billion per year. Almost half comes from companies headquartered in Germany (49%), followed by companies headquartered in the Netherlands (11%), France (10%), Italy, Denmark and Finland (5%). Therefore, around 85% of the private investment is concentrated in companies headquartered in 6 EU Member States.

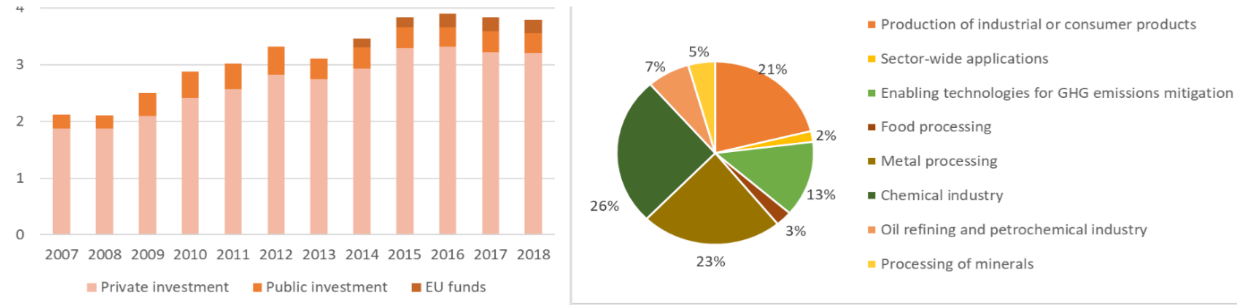
The figure below (on the left) shows that EU private funding of energy efficiency in industry increased from less than EUR 2 billion in 2007 to over 3 billion in the period 2014-2018, which correlates with the trend of global spending on energy efficiency as per IEA data. Technologies to improve processes in the chemicals sector alone account for 26% of overall private R&I investment, while metal processing constitutes another 23% and production of industrial or consumer products consolidates another 21% of overall share in private R&I investment for 2014-2018 (see figure below right).

[120] Shtjefni, D., Kuzov, T., Clocchiatti, A., Lecomte, E., Lonning, E.V.W., Baleva, S. and Tzimas, E., SET Plan Progress Report 2021, Black, C., Ruehringer, M. and Andre, S. editor(s), Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-43092-6, doi:10.2760/804820, JRC126881. See the report at https://op.europa.eu/en/publication-detail/-/publication/6e4c3e5a-5259-11ec-91ac-01aa75ed71a1/language-en/format-PDF/source-244850864.

[121] See COM(2021)952 final, Progress on the Competitiveness of clean energy technologies, p.9.

Figure 33 R&I investment in energy efficiency in industry (EUR billion)

Share in private R&I investment (2014-2018)

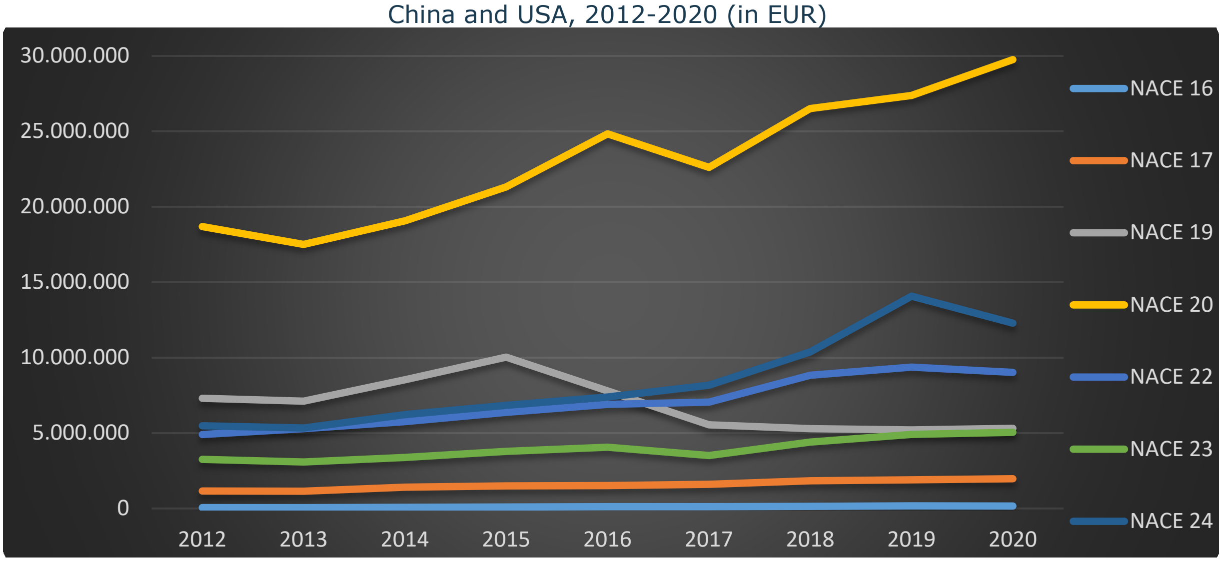


Source: JRC SETIS (2021)[122].

Information on R&I investment at highly disaggregated level in energy efficiency in industry is not readily available. Private R&I investments are estimated based on financial information from publicly available company statements and patent data from PATSTAT. As with patent data, complete data series have a 4-year delay. Estimates with a 2-year time lag are made for each EU Member State[123]. Private R&I data from Member States are in general not readily available at nomenclature of economic activities (NACE) 4-digit numerical codes.

To provide a better understanding, available data on R&D expenditure by companies from energy-intensive industries at NACE 2-digit numerical codes in the EU-27, UK, Japan, China and the USA is analysed for 2012-2020[124].

Figure 34 R&D expenditure of companies per energy-intensive industry in EU-27, UK, Japan, China and USA, 2012-2020 (in EUR)



Note: NACE 16 (wood), NACE 17 (paper), NACE 19 (coke and oil), NACE 20 (chemicals), NACE 22 (rubber and plastic), NACE 23 (non-metal minerals), NACE 24 (basic metal).
Source: PPMI calculations for DG R&I, based on data from the ORBIS database of Bureau Van Dijk.

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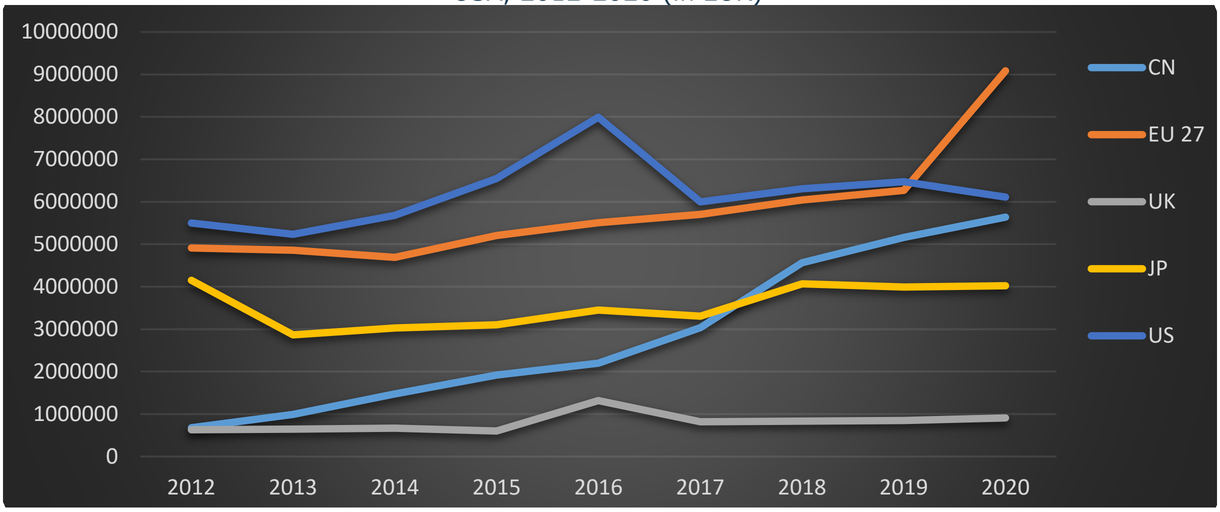
122 Data for EU funding only available 2014 onwards; private investment estimates only available to 2018. EU and Public (MS) R&I funding maintained similar levels in 2019.

123 Fiorini, A., Georgakaki, A., Pasimeni, F., Tzimas, E (2017). Monitoring R&I in low-carbon energy technologies. JRC 105642. Publications Office of the EU.

124 The sample of energy-intensive industries included 2 996 companies as follows: wood (59 companies), paper (204), coke and oil (55), chemicals (1 370), rubber and plastic (466), non-metal minerals (357), basic metal, which includes steel companies (485). The sample consists of companies in existence over the period 2012-2020 and they had at least 10 employees in 2020, or at least EUR 1 million of turnover, or at least EUR 1 million in total assets in 2020 in all NACE codes relevant to energy-intensive industries.

As seen from the figure above, most of the global R&D expenditure of companies was concentrated in the chemicals sector (45% of total investment over 2012-2020); the basic metal sector comes second (16.6%), followed by rubber and plastic (14%). It is interesting to note that EU-27 companies took the lead in 2020 in terms of R&D expenditure by the chemicals sector (see figure below). In the analysis sample, EU-27 companies in the chemicals sector were leaders between 2012 and 2014 in terms of R&D intensity, but slowed down in 2018 and eventually took last position in 2019 and 2020 vis-à-vis comparators.

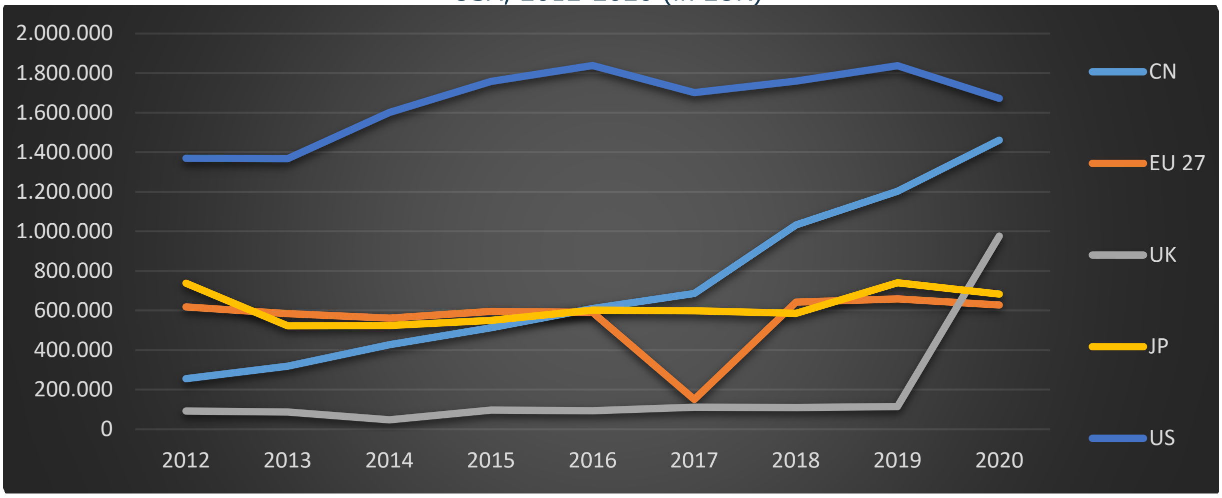
Figure 35 R&D expenditure of companies in the chemicals sector in EU-27, UK, Japan, China and USA, 2012-2020 (in EUR)



Note: 1 008 companies fall in the sample as follows: CN (608), UK (131), JP (122), EU-27 (82), USA (65).
Source: PPMI calculations for DG R&I, based on data from the ORBIS database of Bureau Van Dijk.

Unlike the chemicals sector, R&D expenditure of companies in the basic metal sector in the EU-27 is lower compared with China, UK, Japan and USA. This is the sector where global R&D intensity has increased continuously on an annual basis since 2012.

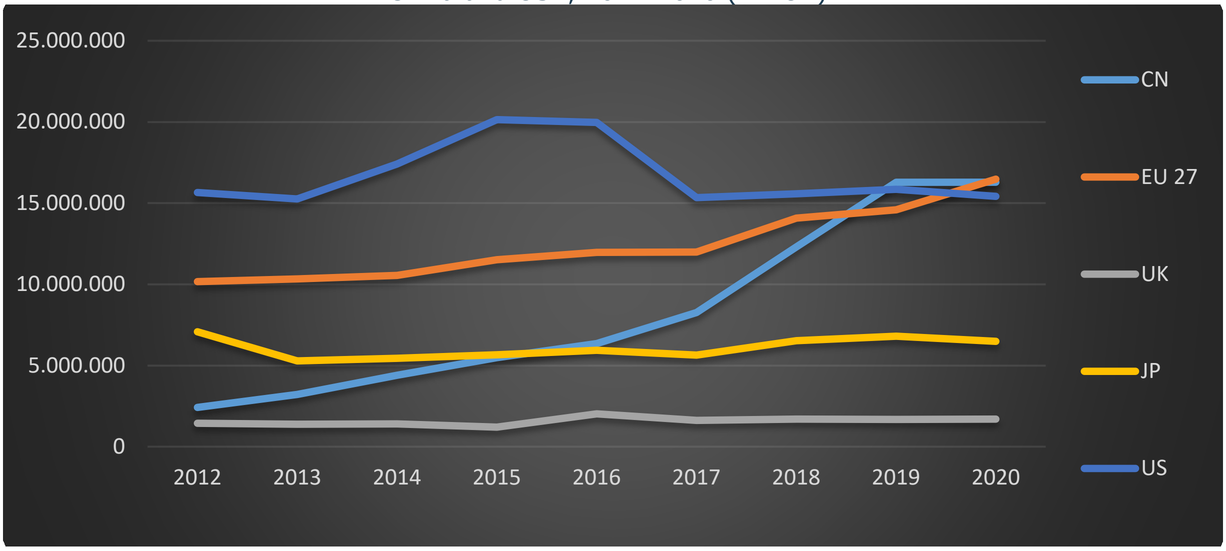
Figure 36 R&D expenditure of companies in basic metal sector in EU-27, UK, Japan, China and USA, 2012-2020 (in EUR)



Source: PPMI calculations for DG R&I, based on data from the ORBIS database of Bureau Van Dijk.

The total investment of companies in all EU-27 energy-intensive industries in the analysis sample is estimated at EUR 111.7 billion in the period 2012-2020 (see Figure 37). This places EU-27 companies in second position after the USA (EUR 150.6 billion) and ahead of companies from China (EUR 75 billion), Japan (EUR 54.8 billion), and the UK (EUR 14.2 billion).

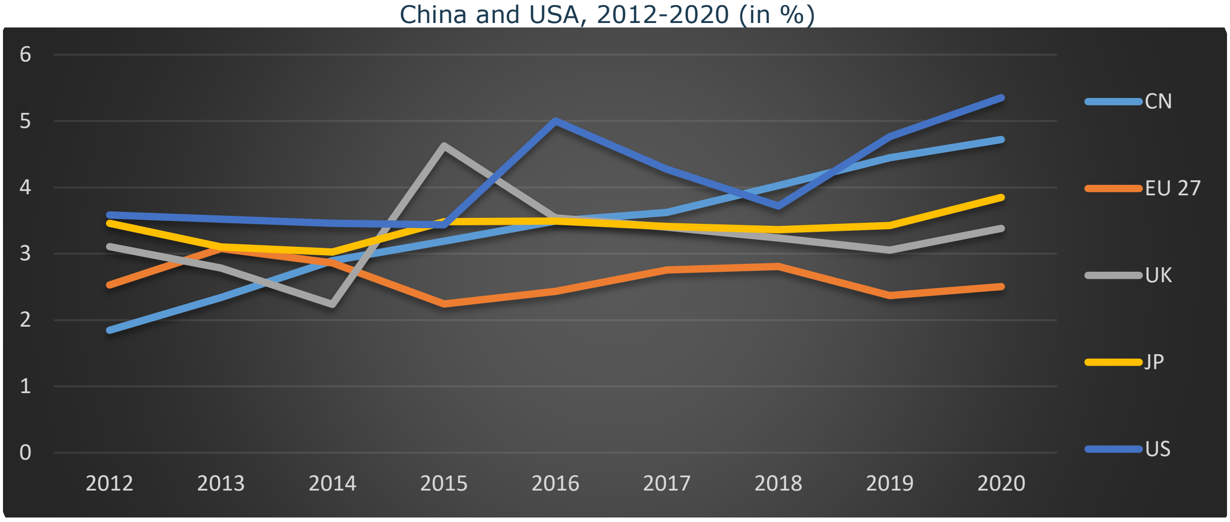
Figure 37 Total R&D expenditure of companies in energy-intensive industries in EU-27, UK, Japan, China and USA, 2012-2020 (in EUR)



Source: PPMI calculations for DG R&I, based on data from the ORBIS database of Bureau Van Dijk.

In 2012-2017, EU-27 companies invested between EUR 10.2 and EUR 12 billion; in the past 3 years of sample analysis investments increased, reaching EUR 14 billion in 2018, EUR 14.58 billion in 2019 and EUR 16.5 billion in 2020. However, EU-27 companies in energy-intensive industries were continuously in last place between 2015 and 2020 as regards R&D intensity of all energy-intensive industries, with USA and Chinese companies having become the top performers since 2016 (see Figure 38).

Figure 38 Average R&D intensity of companies in energy-intensive industries in EU-27, UK, Japan, China and USA, 2012-2020 (in %)



Source: PPMI calculations for DG R&I, based on data from the ORBIS database of Bureau Van Dijk.

The sample analysis has limitations, as there is no full dataset for R&I investments in low-carbon technologies of energy-intensive industries. The trend analysis for 2012-2020 shows that the level of R&D expenditure of EU-27 companies in energy-intensive industries compares well with R&D expenditure of companies from China, Japan, the USA, and the UK. However, the performance of EU-27 companies vis-à-vis comparators in terms of R&D intensity is the lowest, which means that EU-27 companies in energy-intensive industries need to invest more in R&D if they are to catch up with the main global competitors.

3 Patents and bibliometrics in climate change mitigation technologies

This section provides analysis of the evolution of general trends in patenting for climate change mitigation technologies, covering data to 2018, and a deeper analysis of such 'green inventions' for energy-intensive industries (EIIs). It builds on data and information in the EU Industrial R&D Investment Scoreboard 2021[125] which pioneered a deeper investigation of relevant patenting activities. Focusing on the climate change mitigation technologies addressing the production or processing of goods[126], it covers eight energy-intensive industries in more detail. Box 8 below shows the relevant industries (cement, ceramics, chemicals, fertiliser, glass, lime, refining, steel) and the corresponding Cooperative Patent Classification (CPC) codes.

For both climate change mitigation technologies and the focus section in energy-intensive industries, analysis is split into overall patenting activity (companies and other players) and then the patenting activity of EU Scoreboard companies[127].

3.1 *Update on trends in green patenting overall*

In the period 2000 to 2018, the average annual share of green inventions[128] in all patenting activity amounted to 8%. The global number of green inventions has been increasing constantly, driven by China's green inventive activity, however mostly focused on its domestic market (Figure 39). This is spurred by intellectual property laws that incentivise patenting activity via grants and a large, rapidly growing internal market in China.

Considering patent protection beyond the own domestic market of major economies, the picture changes: the EU had the second highest share of high-value inventions[129] (57%) just below the US (58%). Among major economies, South Korea and the EU have the largest share of green technologies in all inventions (over 11%).

Large companies play an important role. The world's top R&D investors are key contributors to global climate-related innovation. They own 70% of global climate change mitigation or adaptation patents and over 10% of global climate-related trademarks, which is larger than their contribution to overall patents and trademarks across all fields.[130]

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[125] Grassano, N., Hernandez Guevara, H., Fako, P., Tuebke, A., Amoroso, A., Georgakaki, A., Napolitano, L., Pasimeni, F., Rentocchini, F., Compaño, R., Fatica, S. and Panzica, R. The 2021 EU Industrial R&D Investment Scoreboard – Executive Summary, EUR 30902 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-44455-8, doi:10.2760/248161, JRC127360. Chaper 4.

[126] Section Y02P of the CPC classification.

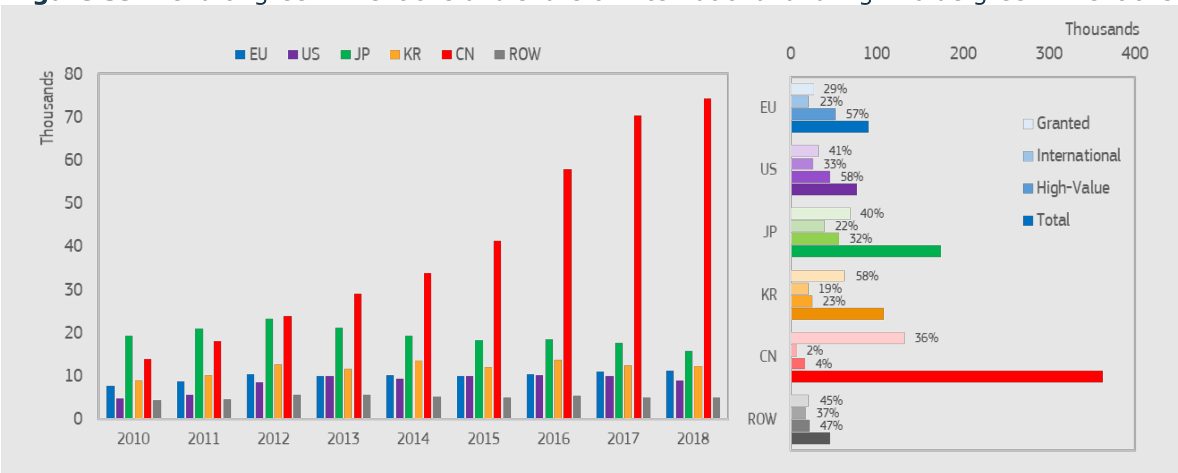
[127] The 2021 EU Industrial R&D Investment Scoreboard provided an extensive analysis on patenting trends in climate change mitigation technologies (CCMTs, also referred to as 'green patents') for the EU, compared with other major economies, and insights on the performance of EU Scoreboard companies (2 500 companies investing the largest sums in R&D in the world) and subsidiaries in green innovation. In addition, it offered a short, broad look into the decarbonisation of key industries, such as metal processing, cement and chemicals.

[128] We use patent families as a proxy for inventions (see also Box 13).

[129] An invention / patent family is considered of high-value when it contains patent applications to more than one office (see also Box 8 on Methodology).

[130] Amoroso, S. et al (2021), World Corporate Top R&D Investors: Paving the way for climate neutrality. A joint JRC and OECD report, Publication Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-43373-6, doi:10.2760/49552, JRC126788.

Figure 39 Trend of green inventions and share of international and high-value green inventions



Note: On the left: annual trend in the period 2010-2018 of green inventions for major economies. On the right: total green inventions for major economies in the period 2010-2018 (dark colours) and high-value inventions, international inventions and granted inventions (lighter colours) with label indicating the share of total inventions. Source: JRC.

Box 8 | **METHODOLOGY**

Patenting trends are produced following the methodology developed by the JRC[131] to derive indicators on global inventive activity in **clean energy technologies**[132]. Patent data are retrieved from PATSTAT 2020 Autumn Edition, and analysis is restricted to climate change mitigation technologies (CCMTs). CCMTs – referred to as **green technologies** in the context of this study - are identified through the Y02 and Y04 schemes of the Cooperative Patent Classification (CPC). Note that due to the time lag, datasets for 2018 are provisional and we are not able to take full account of the effects of the COVID-19 pandemic.

The JRC methodology uses **patent families** as a proxy for **inventions**; the two terms are used interchangeably in the text. Patent families include all documents relevant to a distinct invention, including patent applications to multiple jurisdictions, and those following regional, national and international routes. Statistics are produced based on applicants only (as the owners of the patent and, thus, directly financing R&D activities) and considering different categories of applicants, namely companies, universities and non-profit organisations. In the case of multiple documents per invention, and when more than one applicant or technology code is associated with an application, fractional counting is used to proportion effort between applicants or technological areas, thus preventing multiple counting. An invention is considered of **high-value** when it contains patent applications to more than one office, as this entails longer processes and higher costs and thus indicates a higher expectation of the prospects in international markets.[133,134]. Within a patent family, only patent applications protected in a

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[131] JRC publications:
- Pasimeni, F., Fiorini, A., and Georgakaki, A. (2021). International landscape of the inventive activity on climate change mitigation technologies. A patent analysis. Energy Strategy Reviews, 36, 100677. https://doi.org/10.1016/j.esr.2021.100677
- Pasimeni, F. and Georgakaki, A. (2020). Patent-Based Indicators: Main Concepts and Data Availability. JRC121685, https://setis.ec.europa.eu/patent-based-indicators-main-concepts-and-data-availability_en
- Pasimeni, F., Fiorini, A., and Georgakaki, A. (2019). Assessing private R&D spending in Europe for climate change mitigation technologies via patent data. World Patent Information, 59, 101927. https://doi.org/10.1016/j.wpi.2019.101927
- Pasimeni, F. (2019). SQL query to increase data accuracy and completeness in PATSTAT. World Patent Information, 57, 1-7. https://doi.org/10.1016/j.wpi.2019.02.001
- Fiorini, A., Georgakaki, A., Pasimeni, F. and Tzimas, E. (2017). Monitoring R&I in Low-Carbon Energy Technologies. EUR 28446 EN, Publications Office of the European Union, Luxembourg. ISBN 978-92-79-65591-3, https://doi.org/10.2760/434051

[132] SETIS Research & Innovation data: https://setis.ec.europa.eu/publications/setis-research-innovation-data

[133] Dechezleprêtre, A., et al., (2011) Invention and transfer of climate change–mitigation technologies: a global analysis. *Review of environmental economics and policy*.

[134] Dechezleprêtre, A. et al., (2015) Invention and International Diffusion of Water Conservation and Availability Technologies. *OECD Environment Working Papers, No. 82*.

country different to the residence of the applicant are considered as **international**. High-value considers EU countries separately; for international inventions, European countries (European Patent Office Members) are viewed as one macro category. For example, a patent family protected in two EU countries (e.g. Germany and France) is considered high-value, while a patent application by a French applicant to the German patent authority (or to the European Patent Office) is not considered international. In addition, international patents denote efforts to protect solely outside the country of residence of the applicant. A **granted invention** only sums fractional counts of the patent family related to granted patent applications.

Fractional counting is also used to quantify international collaborations in patenting activity. Co-inventions are calculated based on a matrix of all combinations among co-applicants, for inventions that have been produced by at least two entities resident in two different countries. Shares of co-inventions in the same country are not considered.

The analysis of EU Scoreboard companies focuses on companies headquartered in the EU. The portfolio of inventions of these companies includes inventions produced by all subsidiaries, irrespective of their location. The matching of subsidiaries to applicant names in PATSTAT currently covers 70% of the EU Scoreboard companies, which however account for 90% of R&I investments.

The selection of CCMTs relevant to **energy-intensive industries (EII)** is done through the codes shown in Table 5. In the case of fertiliser and steel industries, it is necessary to cross-reference the Y02P with codes from the technology classification to restrict the scope of the CCMT class. For example, the Steel EII includes those patent families that are tagged with Y02P 10 (Metal processing) and also have at least one tag in C21B (Manufacture of iron or steel), C21C (Processing of pig iron) or C21D (Ferrous metals).

Table 5 Concordance of CPC classes and EII technologies

EII Industries	Y02P classes	Extra filter
Cement	Y02P 40/10, Y02P 40/12, Y02P 40/18	
Ceramics	Y02P 40/60, Y02P 40/69	
Chemicals	Y02P 20 and subclasses	
Fertiliser	Y02P 60 and subclasses	C05
Glass	Y02P 40/50, Y02P 40/57	
Lime	Y02P 40/40, Y02P 40/45	
Refining	Y02P 30 and subclasses	
Steel	Y02P 10 and subclasses	C21B or C21C or C21D

3.2 *Patenting trends in green inventions relevant to energy-intensive industries*

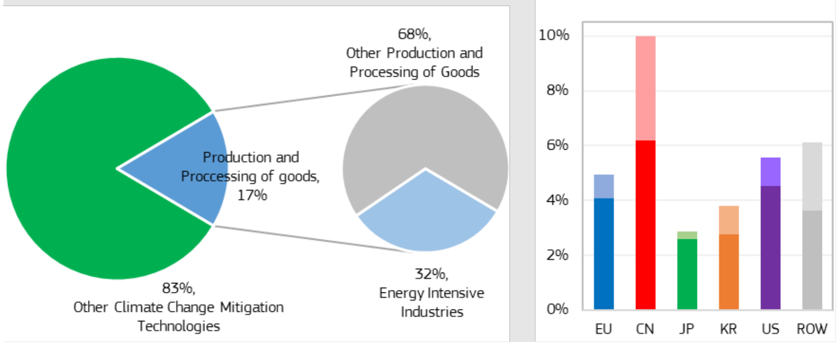
The innovation needed to reach EU climate goals in the EU industrial ecosystems for energy-intensive industries is capital and technology intensive, and may require large-scale infrastructure to establish; it is thus not easily undertaken by start-ups or small companies outside the field. The innovative capacity of EU leading companies is therefore crucial for the industry to remain competitive. The energy-intensive industry sector is dominated by large, multinational incumbents, which may be more likely to develop and keep knowledge in-house and thus have varying propensity to patenting, whereas other inventors, such as young firms, may develop more radical innovations[135].

Globally, EII inventive activity accounts on average for about 5% of the constantly increasing number of total green inventions, and it is about a third of filings in the area of

[135] Amoroso, S. et al (2021), World Corporate Top R&D Investors: Paving the way for climate neutrality. A joint JRC and OECD report, Publication Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-43373-6, doi:10.2760/49552, JRC126788.

production or processing of goods, which in turn represents 17% of total green inventions (Figure 40). This share has been almost constant over the last 10 years. Nonetheless, the levels of activity are quite different among major economies. The share is highest for China, where there is also a much more significant contribution from non-business sectors.

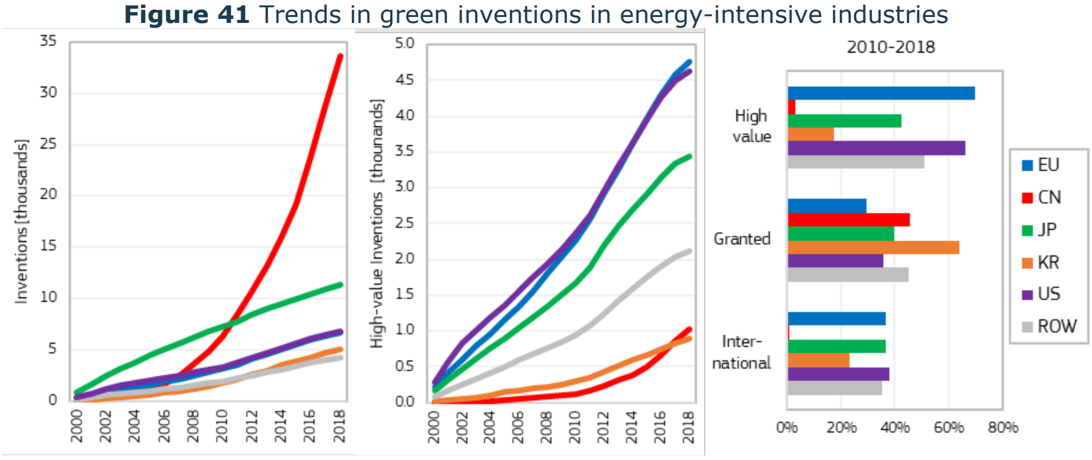
Figure 40 Share of green inventions in energy-intensive industries (2010-2018)



Note: On the left: share over the inventions in production and processing of goods and green inventions. On the right: share by major economies. Dark colours represent the contribution of companies.
Source: JRC.

In line with the above figures on overall green patenting, China also ranks first in total number of green inventions in energy-intensive industries, with a cumulative number of inventions equivalent to those produced by all other actors put together. However, when it comes to inventions protected in multiple jurisdictions (i.e. high-value inventions), again the EU and USA are in the lead, followed by Japan. In summary, Figure 41 shows that – as in the case of overall green inventions – Chinese applicants mostly protect inventive activity related to energy-intensive industries in the national jurisdiction. In contrast, applicants from the EU, the USA and Japan have a more international focus, indicating the readiness of innovative technologies in their portfolio to flow across borders and capture emerging markets.

Figure 41 Trends in green inventions in energy-intensive industries

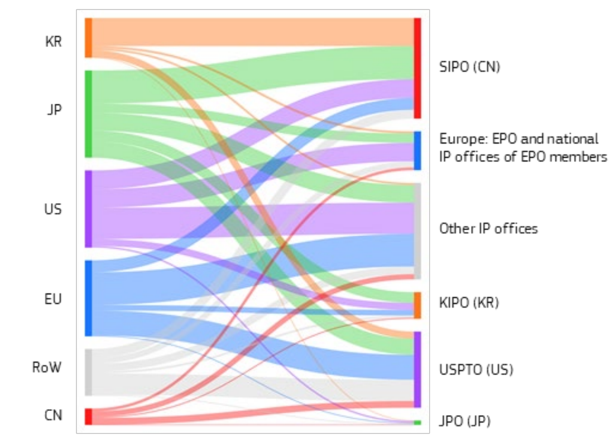


Note: Cumulative inventions (left), high-value inventions (centre), and share of high-value, granted and international inventions (right) for major economies in the period of 2010-2018.
Source: JRC.

Taking the country perspective, Figure 42 shows that China is the jurisdiction attracting the most foreign-originating inventions in energy-intensive industries (29%), followed by the USA (28%). The EU is the third most targeted geographical area where foreign applicants decide to protect inventions in energy-intensive industries (11%). Note that Japan features very little as a destination for the protection of inventions by foreign applicants. Its strong industry and technology base, coupled with the particularity of regulations that apply, tend to make this a rather difficult and insular market for foreign technology providers.

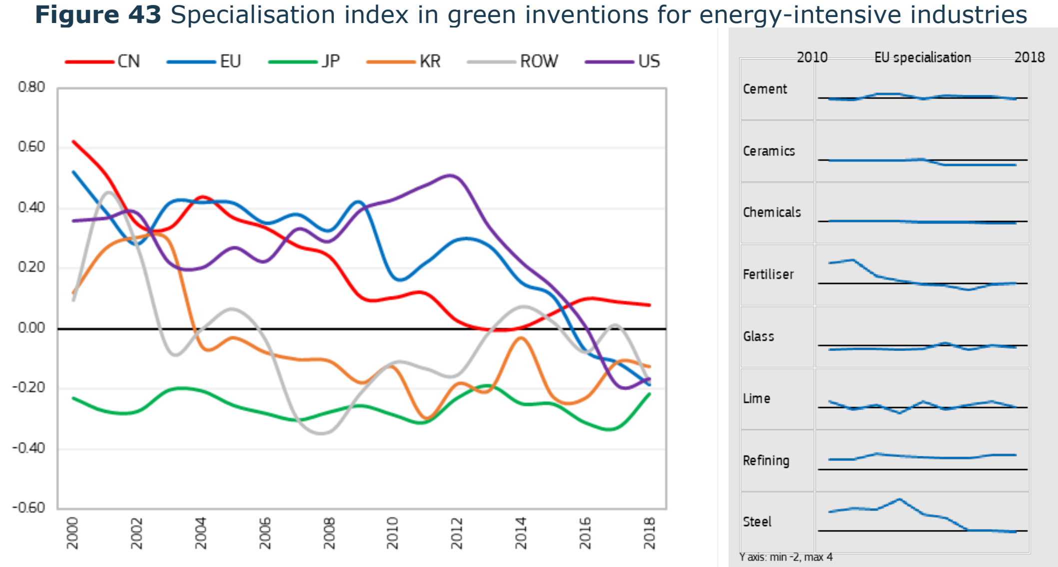
Among major economies, over recent years, China shows the highest specialisation in inventive activity in energy-intensive industries, meaning a relative concentration of capabilities in this specific area. The USA and the EU were leading in this indicator since 2007 but have since gradually lost this advantage and were overtaken by China in the period 2015-2016 (Figure 43). Japan and South Korea maintain their level of specialisation, which is however lower than the world average. Between 2010 and 2018, the EU has more or less maintained the same level of specialisation in the energy-intensive industries in focus, with the exception of the fertiliser and steel industries where there has been a marked drop, and the refining industries where the already strong specialisation has increased slightly further. Given that the specialisation of an economy reflects the weight of inventions in energy-intensive industries as compared to other major economies, the drop can either signal a decrease in patenting activity in the EU or the increase in other major economies, such as China's exponential increase in filings due to policy support. They do however provide an idea on the change of relative importance of subject areas of innovative activity within each economy – irrespective of whether or not this aims to serve the national or international market.

Figure 42 Flow of green inventions in energy-intensive industries



Note: Country of applicant (left) and foreign authorities targeted for protection (right) in the period 2010 onwards.
Source: JRC.

Figure 43 Specialisation index in green inventions for energy-intensive industries



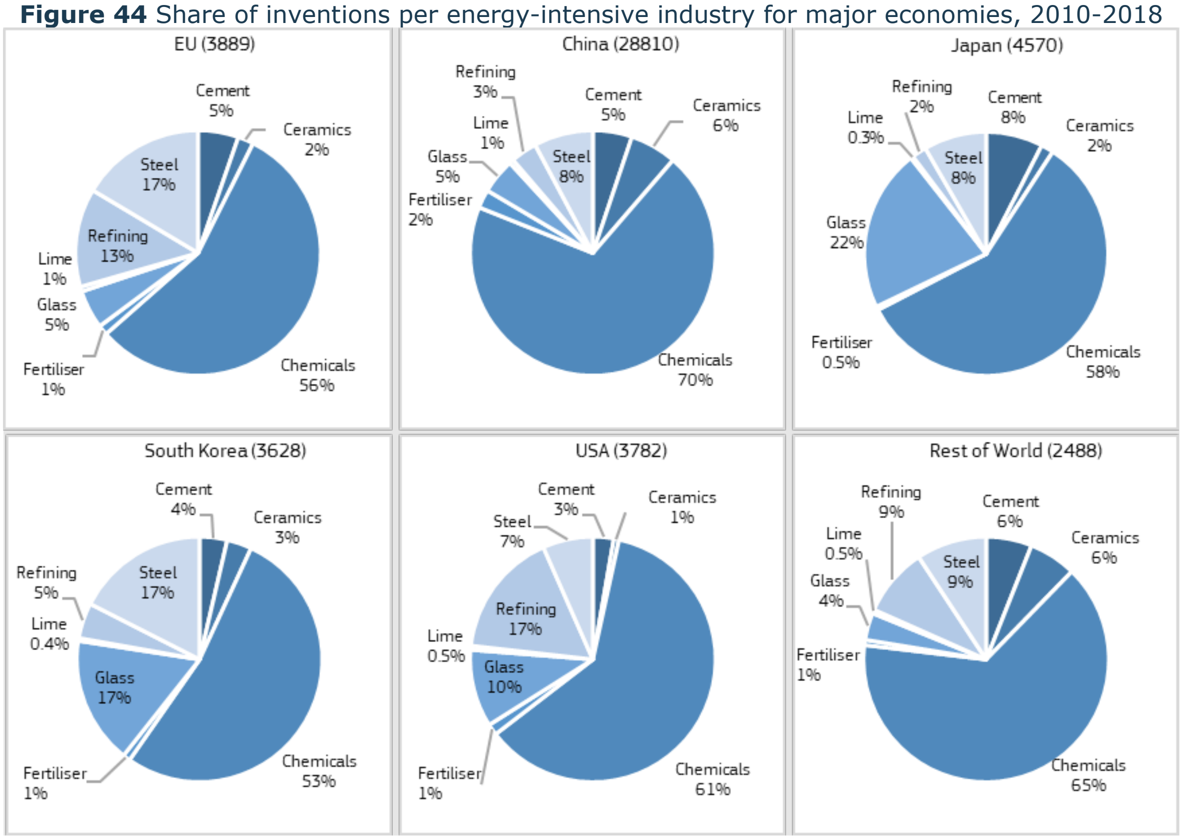
Note: On the left, the share of inventions relevant to energy-intensive industries within CCMTs for the production and processing of goods for major economies. On the right, the trend in EU specialisation by energy-intensive industry between 2010 and 2018. The horizontal axis denotes the world average.
Source: JRC.

Figure 44 provides a breakdown of the portfolio of inventions in energy-intensive industries based on the filings of entities headquartered in each major economy[136]. The numbers and shares reflect both the R&D effort carried out and the propensity to patent, which may vary significantly between industry sectors and technologies.

It is notable that, on average, inventions related to the chemical industry account for about 60% of the portfolio of inventions in energy-intensive industries across all major economies.

In the period 2010-2018, and consistent with ongoing specialisation in this area, the EU has one of the highest shares of inventions related to refining (13%), second to that of USA (17%). Similarly, and despite the decreasing specialisation of the EU on the steel sector, the EU still has the second highest share of inventions related to steel (16%), following that of South Korea (18%). The drop in relative specialisation in EU could be rather due to the relatively high share of relevant inventions from China than to decreased EU efforts. Some 23% of Japanese inventions in energy-intensive industries relate to the production of glass, the highest among all portfolios.

Figure 44 Share of inventions per energy-intensive industry for major economies, 2010-2018



Note: The number in brackets shows the number of inventions.
Source: JRC.

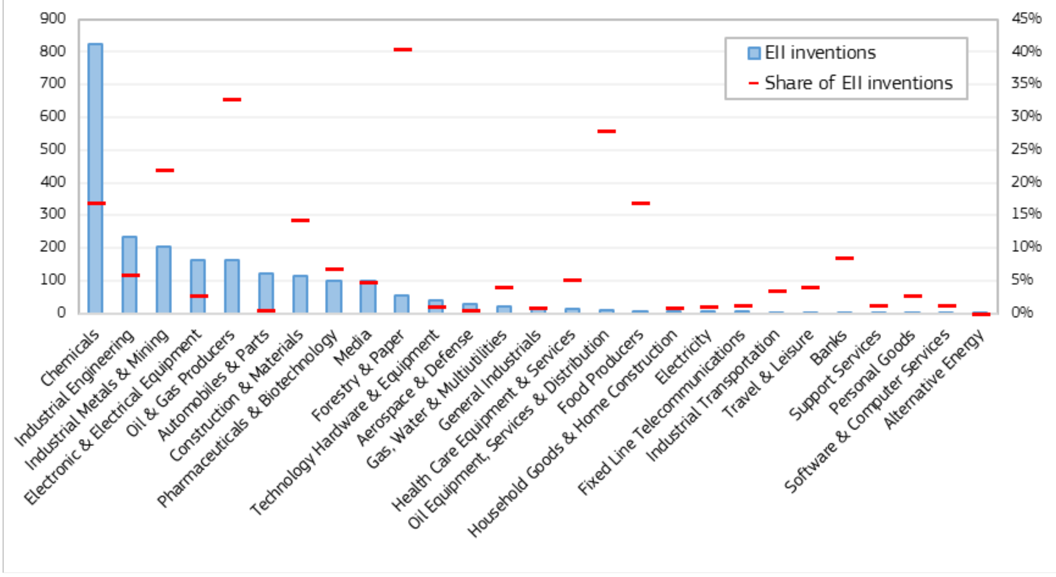
3.3 *EU Scoreboard companies in green inventions for energy-intensive industries*

The EU Scoreboard companies, including the inventive activity of subsidiaries located outside the EU, account for about a third of global green inventive activity in energy-intensive industries from 2010 onwards. Consistent with the figures in the previous sections, the EU Scoreboard companies in the ICB chemicals sector are those with the highest number of inventions in EIIs (Figure 45). This accounts for the 17% of green inventions produced by EU Scoreboard companies in the Chemicals sector (in red in Figure

[136] For activity in different EU Member States, see figure 51 in following sub-chapters.

45). The ICB sectors of Forestry & Paper, Oil & Gas Producers, Oil Equipment, Services & Distribution, Industrial Metals & Mining, and Food Producers all have a share of 17% or higher in terms of inventions for energy-intensive industries in their green inventive activity. All these sectors are predominantly active in green inventions related to the chemicals industry, except for Forestry & Paper, which focuses half of the activity towards solutions for the refining industry and Industrial Metals & Mining, which addresses over a third of inventions to the steel sector. Notably, the Forestry & Paper sector mostly comprises Scandinavian companies, most prominent among them UPM-Kymmene.

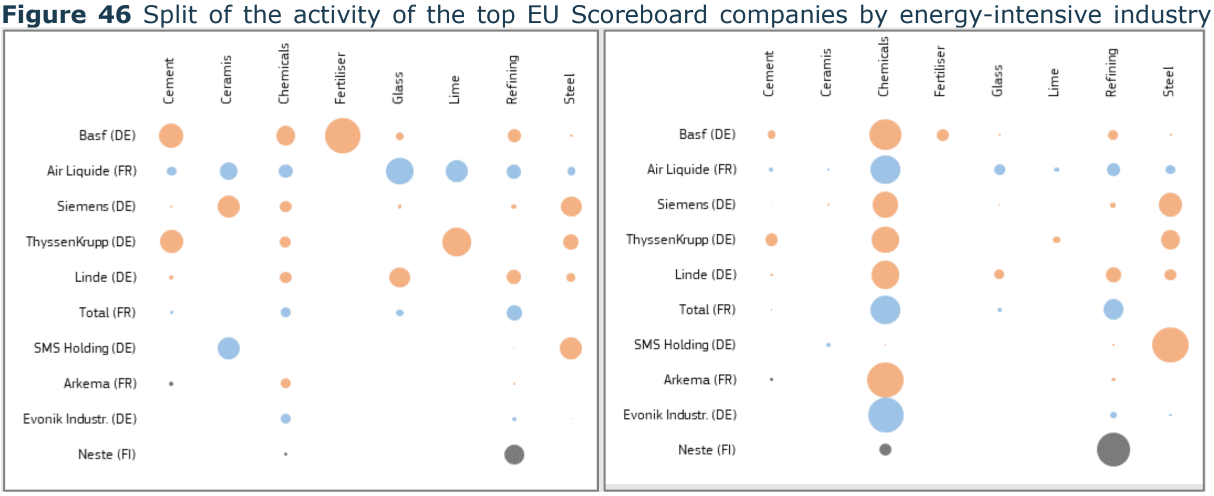
Figure 45 EU Scoreboard companies' green activity in energy-intensive industries by ICB sector



Note: Number of inventions in energy-intensive industries (blue, left axis), and share of inventions in energy-intensive industries in green inventive activity by ICB sector (red, right axis) for EU Scoreboard companies in the period 2010-2018.
Source: JRC.

Figure 46 shows the split of activity per industry for the top 10 Scoreboard companies with the highest number of inventions. Apart from Neste (refining) and SMS Holdings (steel), all companies have a strong focus on chemicals (over half of their EII portfolio) and share inventions equally among them in the top 10. BASF also has a presence in cement, fertilisers and refining, Air Liquide in glass and refining, and Siemens in steel. Fertilisers, ceramics and lime are the industries less addressed by the top 10 – but also those with the lowest numbers of inventions, often produced by smaller, regional entities.

Figure 46 Split of the activity of the top EU Scoreboard companies by energy-intensive industry



Note: The bubble size represents the share of inventions for each industry, within the top 10 (left), and within the company's activity in energy-intensive industries (right).
Source: JRC.

3.4 *Top Scoreboard innovators per energy-intensive industry*

Patent analysis allows to highlight specific technologies, which stand in the focus of EII companies' green patenting activity including some low-carbon industrial technologies.

Green inventions related to the cement industry

Over 80% of green patenting activity in the cement industry is classified under generally improving or optimising production methods. Some 15% addresses energy efficiency measures and the use of renewable energy sources, and 5% involves innovations introducing carbon capture and storage (CCS) in the production process. While Japan leads in all areas, except for CCS where the EU has an advantage, the EU has a higher share of inventions protected internationally. With the exception of Vicat, all of the EU top 5, along with Vinci and Air Liquide, have a strong presence in CCS, which is one of the main solutions for decarbonisation of the industry. Prominent non-EU innovators in this field are Holcim in Switzerland, along with Schlumberger and Calix from the US.

Considering inherent patent quality[137] based on citation analysis (technology relevance), the top company is Arelac, a US company. Most of the R&D appears to take place in China. Focussing on R&D for patents in the EU, US, Japan or South Korea, most research takes place in Japan and the US. If we look at specialisation within the sector, while overall leadership is with US and Japanese firms, Holcim, Knauf and Heidelberg are strong in admixtures and Holcim and Heidelberg are in strong positions in molten slag and calcination respectively.

Green inventions related to the ceramics industry

The selection of codes describing green inventions in the ceramics industry is not broken down further to technological aspects; this is not surprising given the limited activity in the field. Chinese Scoreboard companies (mainly ZTE) account for more than half of the activity in filings; however, EU Scoreboard companies still account for over a third of high-value patents, with the main contributor being Saint-Gobain, followed by Siemens, SMS Holdings, STMicroelectronics, and Bosch.

Green inventions related to the Chemicals industry

About 38% of green inventions in the chemical industries are dedicated to improvements in the production of bulk chemicals using selective catalysts, with an additional 18% looking into innovations in recycling unreacted materials or catalysts. A further 10% is dedicated to improving process efficiency. In all these three areas, China Petroleum & Chemicals shows the most activity by far in selective catalysts, followed by PetroChina, Exxon Mobil, Samsung Electronics and Saudi Basic Industries. Nonetheless, China Petroleum is joined by a different selection of companies when it comes to recycling; Dow Chemical, BASF, Honeywell, and Arkema make up the top 10, indicating a higher focus on circularity from EU and US companies. Chinese companies also top the activity in process efficiency inventions. Siemens and ThyssenKrupp are among the top 5 in energy recovery (e.g. by cogeneration, hydrogen recovery or pressure recovery turbines), with Siemens also third in inventions incorporating renewable energy sources, two fields not dominated by Chinese companies to the same degree. EU companies lead inventions on the reduction of greenhouse gases from the chemical industry (an area with markedly less activity by China), through Air Liquide and Linde, the latter also in the top 5 for feedstock innovations. EU companies are prominent in innovation related to chlorine production.

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[137] Based on DG R&I analysis in PatentSight, a software solution that provides insights into the patent landscape.

Considering inherent patent quality[138] based on citation analysis (technology relevance), the top companies overall are Exxon and Dow with BASF in the area of greenhouse gases. Most of the R&D appears to take place in China. Focussing on R&D for patents in the EU, US, Japan or South Korea, most research takes place in Japan and the US.

Green inventions related to the fertiliser industry

In the Fertiliser EII, about 92% of total inventions relate to the reduction of greenhouse gas emissions in agriculture, mostly dinitrogen oxide (N_2O) using aquaponics, hydroponics or efficiency measures. The EU leads with about 54% of total inventive activity, followed by the USA (about 22%). BASF, Solvay, Dow Chemical and Saudi Basic Industries are key Scoreboard innovators in this technology area.

Green inventions related to the glass industry

In glass production, the focus is on improving the yield, e.g. by reduction of reject rates. Even if Japanese Scoreboard companies collectively account for about half of all inventive activity, Corning (USA) has the highest number of inventions ahead of the Japanese Asahi Glass and Nippon Electric Glass.

In regard to specialisation[139] within the sector, Corning is strong in all areas and the EU firms Heraeus, St. Gobain and Schott have good positions in some niche areas.

Green inventions related to the lime industry

In the production or processing of lime, most patents are filed under the generic code, addressing for example limestone regeneration of lime, with less than 2% of inventive activity dedicated to using fuels from renewable energy sources. EU Scoreboard companies take the lead in this area with nearly half of the (limited) inventive activity, with UPM-Kymmene (Finland), ThyssenKrupp (Germany), and Andritz (Austria) sharing the top spot.

Green inventions related to the refining and petrochemical industry

Over 70% of green inventive activity in the refining and petrochemical industries relates to technologies using bio-feedstock, with another 25% addressing ethylene production. The USA (25% of the total) is the most active country, followed by the United Kingdom (22%) and China (22%). Neste and UPM-Kymmene (both from Finland) together make up a third of EU inventions related to bio-feedstock.

Green inventions related to the steel industry

Recycling and process efficiency are the two most prominent areas in green innovation for the steel industry, accounting for 52% and 40% of activity respectively. EU Scoreboard companies lead in process efficiency with about 38% of the total inventive activity, while South Korean companies lead in recycling (40% of the total). Daimler, ThyssenKrupp, Siemens and SMS Holdings (all from Germany) are the most prominent EU companies in producing inventions related to process efficiency; nonetheless, the lead in this area goes to Nippon Steel and POSCO. Siemens and SMS Holdings are also very active in recycling. Very little activity is recorded in other areas, such as using renewable energy sources or reducing greenhouse gas emissions.

Looking at specialisation within the sector, notwithstanding the overall Asian leadership, ThyssenKrupp has a strong position in connecting rods and ArcelorMittal in hot rolled steel[140].

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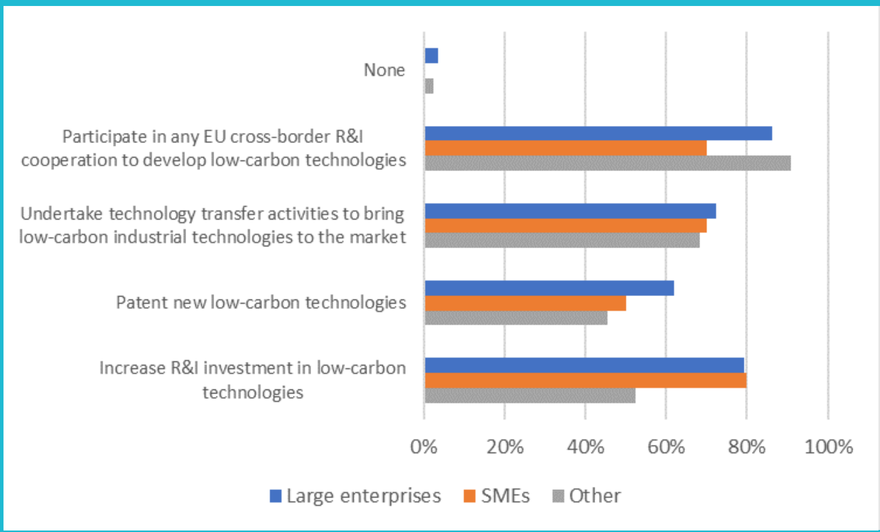
[138] Ibid.
[139] Ibid.
[140] Ibid.

SME Focus 4 | **PATENTING ACTIVITY AT SME LEVEL**

Evidence collected through a dedicated stakeholder consultation indicates that companies have put in place various mechanisms to cope with the required transformations by the green transition. One of the respective activities refers to patenting new low-carbon technologies, besides participating in EU cross-border R&I projects, increasing R&I spending and undertaking technology transfer to bring low-carbon industrial technologies to the market.

The survey showed that SMEs are less likely to patent new low-carbon technologies compared to larger firms, but it does not reflect the significant difference suggested by the strong activity of large incumbents. Still, except for increasing R&I investments in low-carbon technologies, SMEs are expected to perform less than larger companies in most of the measures indicated in the consultation.

Figure 47 Planned measures in the next 5 years to cope with the challenges



Source: ERA roadmap stakeholder consultation, open from July to September 2021.

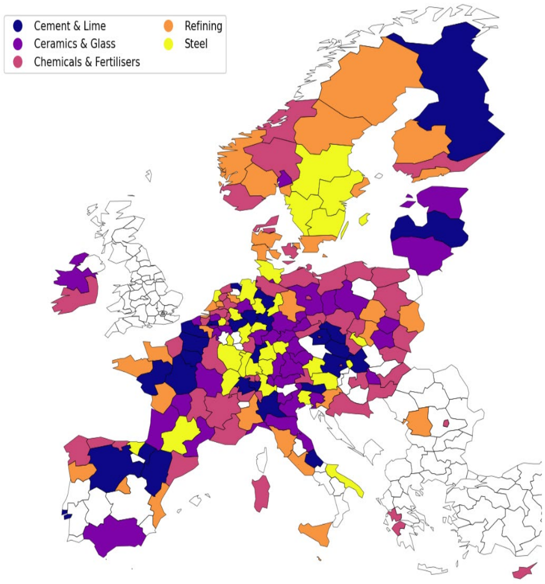
3.5 *Geography of patents : regional technology hotspots*

This section provides a mapping of the geographical localisation of technological developments for EEIs, which can be useful for clustering activity and R&I dissemination activities for low-carbon industrial technologies.

The analysis of EIIs relies on patent data extracted from the 2020 Autumn Edition of the PATSTAT database. The backbone of the findings consists in identifying the number of patents in the domain of energy-intensive industries, that can be attributed to geographical regions. In the case of patenting activity, which tends to be 'lumpy' over brief time windows, this implies that it is necessary to consider how many patents have been produced in a region over a sufficiently prolonged period. To clarify, a company that invests consistently to innovate in a set of technologies will not necessarily produce a stable number of patents every year; it will reap the benefits of several years of work into a single patented invention. Overall, considering also the technical constraints imposed by the patent data, the selected data is the pooled set of patents filed during the period 2010-2018.

The relevant green technologies come from the Y02 and Y04 schemes of the Cooperative Patent Classification (CPC). Patents are assigned to NUTS2 (2013) regions based on available applicant information; the rationale for this choice being that applicants are the original owners of the patents and, thus, those who directly financed the underlying R&D activities. The objective is to provide preliminary insights on the relevance and geographical distribution of technological inventions aimed at reducing CO_2 emissions for selected EIIs.

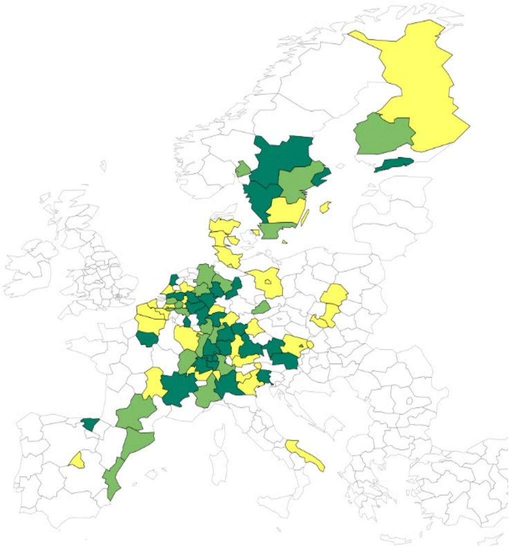
Figure 48 Top EII-related technologies by NUTS2 region



Note: The colour of each region in the map reflects the EII-related CCMT technology in which the region performed best in terms of patenting output over the period 2010-2018. The attribution of patents to geographical region is based on applicant information.
Source: JRC SETIS elaboration of PATSTAT data for the EU Industrial R&D Investment Scoreboard.

In the first map (Figure 48) eight patent groups are aggregated into five groups. It highlights for each European region at the NUTS level the EII-related patent group in which the region ranks highest in terms of measured patenting activity. The development of climate change mitigation technologies (CCMTs) for ceramics & glass seems to be mostly based in areas of Northern Italy, Germany, and some Eastern European regions. Germany, some regions in Eastern France and Sweden are highly active in CCMTs for related to steel. CCMTs for cement & lime, refining, and chemicals & fertilizers are instead much more scattered across European regions.

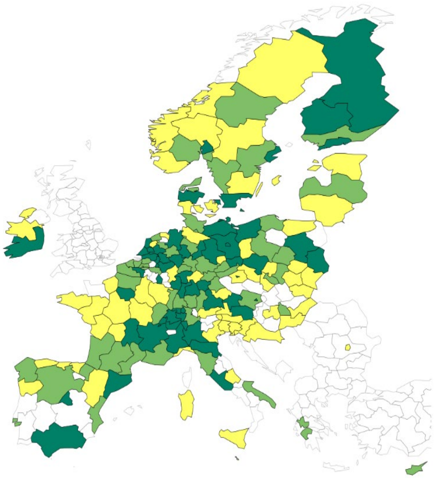
Figure 49 Patenting activity in CCMTs relevant for Steel



Note: The colour of each region reflects the global patenting output of applicants based therein over the period 2010-2018. Regions ranked in the top third of the ranking patent output ranking are dark green; regions in the middle third are light green; regions in the bottom third are yellow.
Source: JRC SETIS elaboration of PATSTAT data for the EU Industrial R&D Investment Scoreboard.

Figure 49 zooms in to show the geographical distribution of CCMT for the steel sector only. The map shows a high concentration in the development of these technologies in the industrial belt of North-West Europe encompassing Western Germany, Northern France, Northern Spain, and Northern Italy.

Figure 50 Patenting activity in CCMTs that are relevant for Chemicals & Fertilisers



Note: The colour of each region reflects the global patenting output of applicants based therein over the period 2010-2018. Regions ranked in the top third of the ranking patent output ranking are dark green; regions in the middle third are light green; regions in the bottom third are yellow.
Source: JRC SETIS elaboration of PATSTAT data for the EU Industrial R&D Investment Scoreboard.

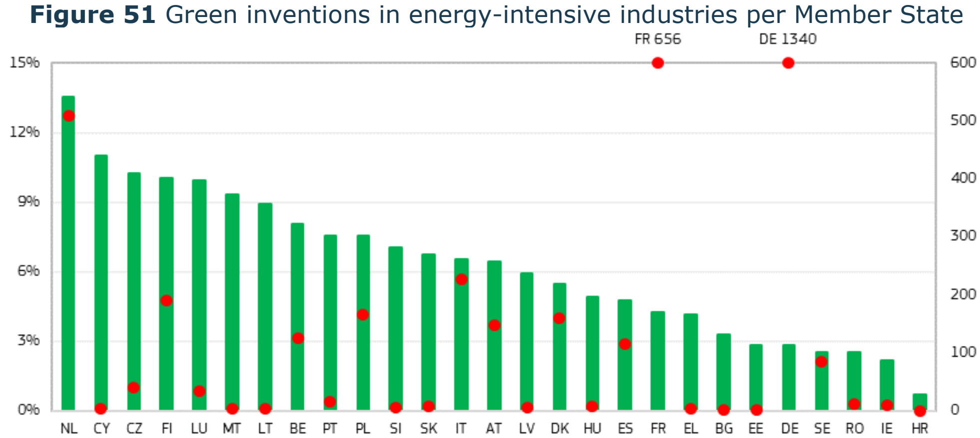
Figure 50 focuses on the CCMT for Chemicals & Fertilisers. Here the geographical distribution is much more widespread showing that the development of technological capabilities for the abatement of CO2 emissions in the chemical sector is spread across several European countries and regions.

3.6 *National and regional performance in the EU*

Among EU member states, Denmark remains the country with the highest share of green inventions overall over total inventions (21%, nearly 3 000 patent families) in its national portfolio. Not surprisingly, due to the size of their economies, Germany continues to rank first in terms of the total number of green inventions (over 47 000) followed by France (over 15 000).

Over the period 2010-2018, among the EU member states, the Netherlands had the highest share of green inventions addressing the energy-intensive industries in focus (14%) (see Figure 51).

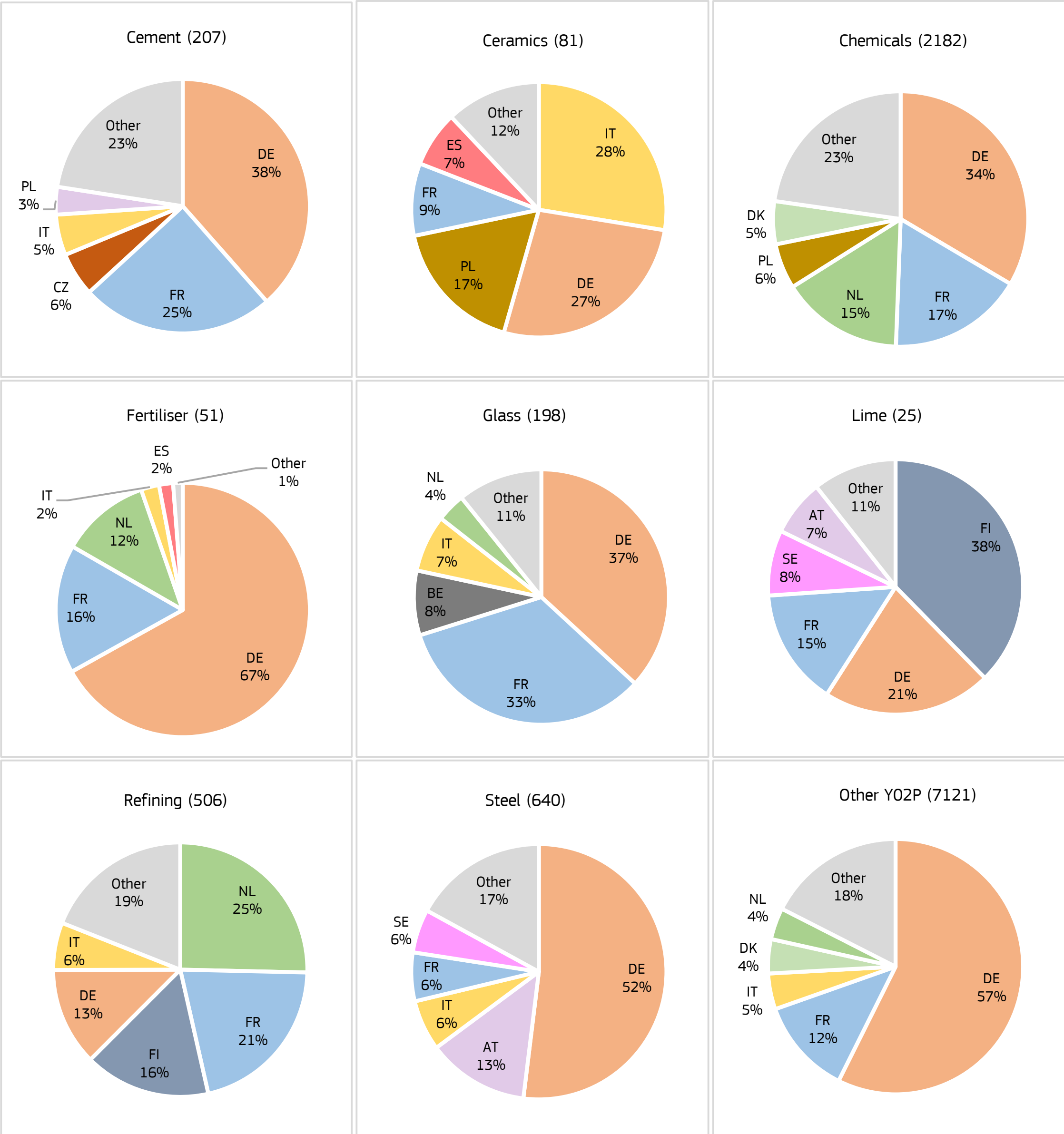
Figure 51 Green inventions in energy-intensive industries per Member State



Note: Share of EEI in green inventions (bars coloured in green, left axis) and number of inventions in EIIs (dots in red, right axis) per EU Member State in the 2010-2018 period.
Source: JRC.

Germany ranks among the top five in each of the energy intensive industries examined in terms of share of inventions in the EU (Figure 52). While it leads in six out of nine industries, it just loses out to Italy on Ceramics and ranks second and fourth in green inventions related to the lime and refining industries, led by Finland and the Netherlands respectively. France is second highest in the number of inventions and the only other EU country that ranks in the top five in all the industries in focus. Italy and Poland are second and third in the number of inventions related to ceramics, accounting respectively for 24% and 20% of the total EU inventive activity in this area.

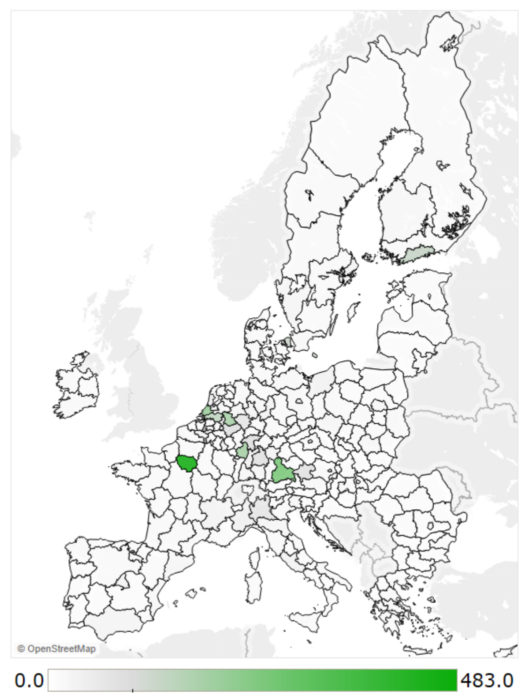
Figure 52 Share of green inventions and champions per industry and Member State, 2010-2018



Note: The number in brackets shows the number of inventions.
Source: JRC.

There is coherence that companies leading in patenting are located in the countries as described above, and even more, they are concentrated in specific regions, making them stand out as innovation hotspots for the energy-intensive industries. Île de France is the EU region with the highest number of inventions (Figure 53). The Oberbayern region in Germany follows, while four more German regions are in the EU top 10. The Netherlands has two, Zuid-Holland and Noord-Brabant, in the top 10 regional list, and Finland and Denmark one region (Helsinki-Uusimaa and Hovedstaden, respectively). Three of these regions, namely Île de France, Oberbayern and Noord-Brabant also feature in the top 10 as the hosts of innovators in all climate change mitigation technologies.

Figure 53 Regional distribution of green inventions in energy-intensive industries and key industrial players resident in the top 5 NUTS regions (2010 onwards)



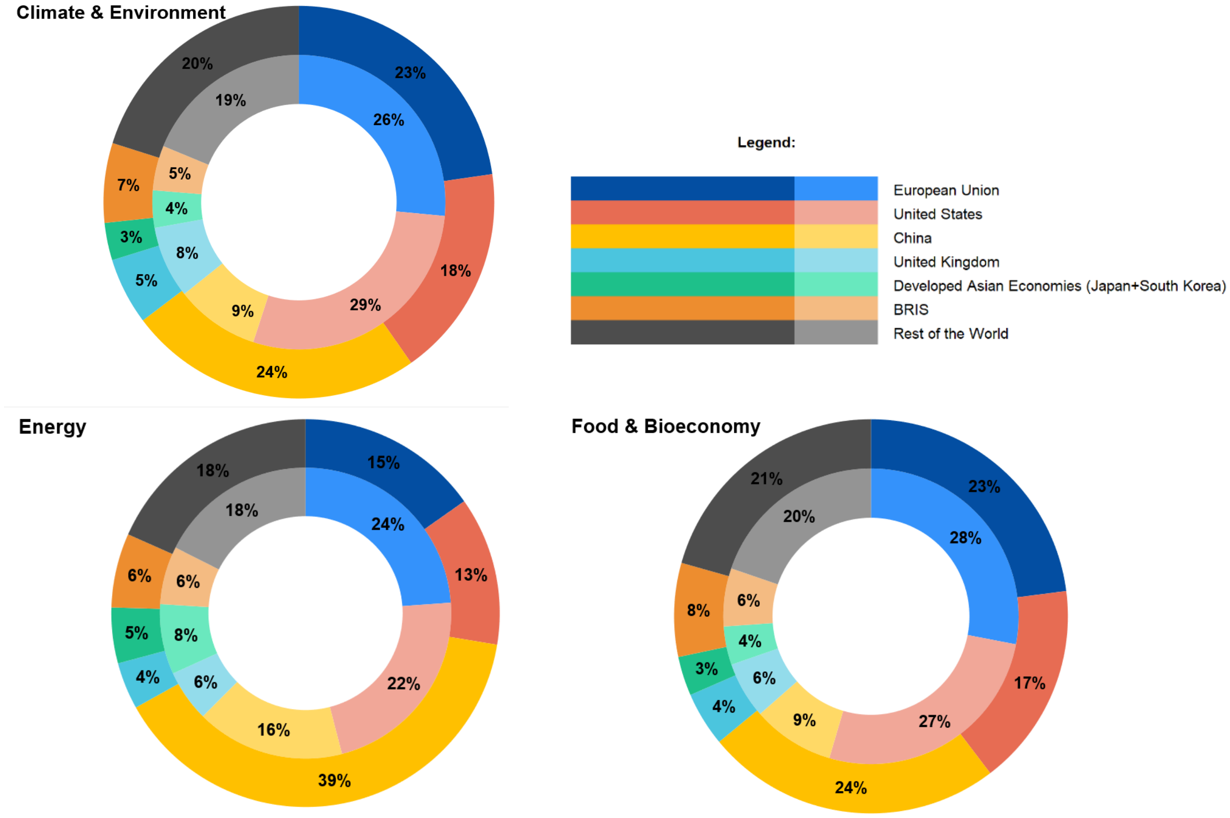
Source: JRC.

NUTS region	Inven-tions	Major industrial players
Île de France (FR10)	333	IFP Énergies nouvelles, Air Liquide, Arkema, Commissariat à l'Énergie Atomique et aux Énergies Alternatives, Saint-Gobain Glass, Centre national de la recherche scientifique
Ober bayern (DE21)	200	Linde AG, Siemens AG, Fraunhofer Society
South Holland (NL33)	184	SHELL Internationale Research Maatschappij B.V.
Rhein hessen-Pfalz (DEB3)	173	BASF SE
Düsseldorf (DEA1)	70	Evonik Industries, ThyssenKrupp AG

3.7 *Bibliometrics*

China and the EU are the global leaders in terms of scientific output on climate and environment, followed by the United States. In terms of scientific quality, while the United States was clearly in the lead before 2018, China has now the highest share of highly cited publications (top 10%), but the United States is still leading on the top 1% cited publications. Output from Chinese researchers has risen exponentially in the last two decades to finally overpass the EU's. In the EU, research intensity varies and there is a positive correlation between scientific quality and investment in most countries.

Figure 54 Shares (%) of top 10 % of scientific publications on climate and environment, 2008 (interior) and 2018 (exterior)



Note: Data produced by Science-Metrix based on Scopus database. The data is for the EU27.
Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit.

In terms of high-quality scientific publications, China has overall increased its shares exponentially between 2008 and 2018 and has overpassed both the EU and the USA . In 2018, the EU is no more in the lead in top cited scientific publications relating to food & bioeconomy and climate & environment, while China takes the lead for food & the bioeconomy with 24,4% of the total share of top cited publications in the field), followed closely by the EU (23%). In the field of climate & environment, China is in the lead with 24,5 % of the top cited publications and the EU follows with 22,7%. As regards energy, the EU share dropped from 24% in 2008 to 15% in 2018. The share of China in energy-related top cited publications is close to 40% in 2018. It is still worth noting that many of the lagging regions (mostly in eastern and southern Europe) improved their performance on scientific output, which indicates improved returns on R&D investment.

In 2019, the EU contributed only 17% of the published scientific articles relating to the low-carbon energy sector. The leading countries in this more specific field of science were China, the USA and India. Nevertheless, the EU did show specialision in energy efficiency in industry.

However, the EU's share of international co-publications in both climate change, environment, resource efficiency, raw materials and secure, clean and efficient energy is above the world average for the period 2000-2020. The best performing countries for climate change, environment, resource efficiency and raw materials were Luxembourg, Cyprus and Denmark, and, for secure, clean and efficient energy, Luxembourg, Cyprus and Belgium. EU also has more open access publications in 2019 than the world average.

4 EU public investments and programmes

This section outlines the support the EU public toolbox provides for R&I on low-carbon industrial technologies. It reviews the period 2014-2020 and looks forward to opportunities under the current multi-annual financial framework 2021-2027 with its new tools, such as the Innovation Fund.

The EU budget is a tiny fraction (2%) of combined national budgets of all EU countries[141]. The European R&I funding programmes, including Horizon 2020, are however responsible for 7.2% of public funding for R&I in 2019 in Europe and a significantly higher percentage when looking only at competitive funding.[142] Even if specifically for low-carbon technologies for energy-intensive industries the share has been higher than the average, the framework programmes cannot be expected to cover the major investments in the development and especially deployment of low-carbon technologies that are needed to reach the 2030 emissions reduction target and climate neutrality in 2050.

In the multiannual financial framework (MFF) for 2021-2027 of EUR 1.2 trillion, EUR 95.5 billion is dedicated to Horizon Europe for R&I. R&I and market uptake are funded, among others, under InvestEU (Sustainable infrastructure policy window: EUR 9.9 billion; Research, innovation and digitisation policy window: EUR 6.6 billion) and the Innovation Fund (EUR 25 billion, depending on CO_2 price). The European Fund for Strategic Investments (EFSI), through the European Regional Development Fund (ERDF) (EUR 215.2 billion), also support R&I and industrial investments in regions. 30% of the EU budget will be spent to fight climate change.

In addition, the Recovery and Resilience Facility (RRF), the key instrument at the heart of NextGenerationEU makes available EUR 723.8 billion (in current prices) in loans (EUR 385.8 billion) and grants (EUR 338 billion).

Member States have allocated almost 40% of the spending in their Recovery and Resilience Plans (RRPs) to climate measures across the 22 plans approved so far. This exceeds the agreed targets of 37% for climate spending. It is estimated that 6% of the RRPs expenditure supporting the green transition will go to R&I in green activities.

The MFF and RRF provide an unprecedented opportunity for Member States and industry to accelerate the development and uptake of low-carbon technologies.

EU CENTRALISED FUNDS

EU programmes managed centrally by the Commission finances low-carbon technologies projects. Through Horizon Europe, the Innovation Fund and other instruments, more funding is available in 2021-2027 for low-carbon technologies projects.

4.1 *Horizon 2020 and Horizon Europe*

Horizon Europe, the current EU R&I programme, has a budget of EUR 95.5 billion for 2021-2027. This represents a 30% increase vis-à-vis Horizon 2020, its predecessor, and makes it the most ambitious R&I programme in the world. Over 35% of Horizon Europe spending will contribute to climate objectives.

The Horizon 2020 and Horizon Europe programmes are funding cutting-edge R&I, including partnerships with industry to help moving low-carbon industrial technologies for energy-intensive industries from basic research to deployment (e.g. SPIRE/Processes4Planet and

[141] https://ec.europa.eu/info/strategy/eu-budget/eu-budget-added-value/fact-check_en

[142] European Commission. Directorate-General for Research and Innovation. (2022). Science, Research and Innovation performance of the EU 2022 report. forthcoming

Clean Steel Partnerships) as well as the European Innovation Council (EIC) and the European Institute of Innovation and Technology (EIT).

4.1.1. European Partnerships

- SPIRE/Processes for Planet (P4P)

SPIRE has been the contractual public-private partnership active between 2014 and 2020 under Horizon 2020 and dedicated to innovation in resource and energy efficiency enabled by the process industries. SPIRE has brought together companies, world-leading universities and research organisations and other stakeholders involved in several energy-intensive industry sectors, namely cement, ceramics, chemicals, engineering, minerals and ores, non-ferrous metals, steel and water.

The partnership helped integrating, demonstrating and validating systems and technologies for achieving reductions of up to 30% in fossil energy intensity, and reductions of up to 20% in non-renewable and primary raw material intensity. The aim has been a drastic overall efficiency improvement of up to 40% in CO_2-equivalent footprints.

Significant SPIRE innovations concerned three main areas at all TRLs, namely efficient processes, sustainability and circular economy, and enabling sustainable industry development (see Chapter 2). The relevant projects pointed to a 38% reduction of dependency on fossil fuels, 31% reduction of dependency on non-renewable, primary resources and 29% reduction of emissions. While the partnership agreement with SPIRE covered innovations up to TRL 7, some projects have managed to go beyond this level, showing the level of stakeholder commitment and the innovation potential in process industries.

The partnership has achieved a private investment leverage factor of 8.5, with a total investment by private companies of EUR 4.52 billion. SME members have seen a 40% growth in turnover (double the EU average).

Since its launch, SPIRE has inspired and initiated nearly 50 programme calls under Horizon 2020, covering topics such as efficient processes, circular economy and the development of technologies and innovations that enable sustainable industrial development. By 2020, around 125 projects had been supported through Horizon 2020.

The successor of SPIRE is Processes4Planet (P4P), the co-programmed partnership launched by A.SPIRE and the European Commission in June 2021.

The overall budget of the partnership is EUR 2.6 billion (EUR 1.3 billion from Horizon Europe and EUR 1.3 billion for the private partners). The partnership will continue working on emerging technologies and on the scaling up of already developed technologies at higher technology readiness levels (TRLs) to deliver expected CO_2 emission reductions by 2030 and achieve their full impact by 2050. 14 Innovation Areas and 36 Innovation Programmes moving from TRL 1 to 9 have been identified (see Chapter 2). P4P aims to bring technologies to a higher TRL until market deployment.

As a concrete tool to improve synergies, P4P has set up an Impact Panel, which aimed at facilitating the launch and market uptake of projects by public or private investors by establishing links with national programmes and interested Member States, the Innovation Fund and the European Investment Bank.

SPIRE and Processes4Planet have shown the effectiveness of cross-sectorial innovation.

- Clean Steel Partnership/RFCS

Building on the work already carried out under Horizon 2020 and with the help of the Research Fund for Coal and Steel (RFCS), the EC launched the Clean Steel Partnership in 2021, which specifically supports the transformation of the steel industry into a carbon-neutral sector. The Clean Steel Partnership provides funding through Horizon Europe and through the RFCS for an EU contribution of EUR 700 million. It will implement, by 2027, at least two demonstration projects leading to 50% CO_2 emission reduction and achieving TRL 8 by 2030 in at least 12 building blocks funded by the partnership. The final ambition is reducing CO_2 emissions by 80-95% by 2050, ultimately achieving carbon neutrality. The Clean Steel Partnership aims to establish synergies through links with the Innovation Fund in view of ensuring follow-up investments for deployment of innovative clean steel technologies.

The RFCS is a EU funding programme supporting research projects in the coal and steel sectors. The two big tickets funding opportunities for coal and steel (EUR 104 million) opened on 18 February 2022 and have a deadline for submission on 3 May 2022. For steel, the big tickets call provides support for projects that aim to develop and demonstrate clean steel breakthrough technologies leading to near-zero-carbon steel making. Proposals must be in line with the general and specific objectives of the Clean Steel Partnership.

Under both Horizon 2020 (and predecessor programmes) and the RFCS, direct development of low-carbon steel technologies has been undertaken by a limited number of projects as indicated in Table 6.

Table 6 Projects in R&D funding programmes for the steel industry focusing on CO_2 emissions reduction

Funding programme	Selected funding period	No. of projects	Total budget	EU contribution	TRL
ULCOS (FP6)	2004-2010		€ 35 m	€ 20 m	
RFCS	2011-2020	16	€ 24 m	€ 16 m	2-5
H2020	2014-2020	42	€ 331 m	€ 268 m	2-7
Clean Steel Partnership	2021-2030	tbd	€ 1.4 bn	€ 700 m (Horizon Europe + RFCS)	5-8

Source: Somers, J., Technologies to decarbonise the EU steel industry, EUR 30982 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-47147-9, doi:10.2760/069150, JRC127468.

4.1.2. Other R&I activities and partnerships funded under Horizon 2020 & monitoring tools

Horizon 2020 had 1522 projects related to low-carbon technologies in energy-intensive industries, excluding SPIRE projects, starting between 2014 and 2022, amounting to EU support of EUR 3.86 billion, including 117 coordination & support actions and 487 under the SME instrument. Projects addressing lower TRLs appear to have a greater participation of SMEs.

The European Commission's Horizon Results platform[143] and the Innovation Radar[144] are useful monitoring tools presenting some relevant EU-funded research and innovation projects, among others in the field of low-carbon technologies.

[143] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/horizon-results-platform
[144] https://www.innoradar.eu/

The Horizon Results platform enables all stakeholders in R&I, and more broadly any citizen, to learn more about EU-funded projects, by making results available to the public and giving them the possibility to enter into contact with their creators.

The Innovation Radar is a European Commission initiative to identify high potential innovations and innovators in EU-funded R&I projects, give visibility to these projects and make the outputs of EU innovation funding available to the public. This database does not give an overall overview of the projects, as only some of them are selected by independent experts. When looking up 'low-carbon', 23 projects can be found, 10 of them are 'market ready' or 'business ready', and 13 in the 'exploring' phase. SMEs are involved in 4 of them.

Box 9 | **3D CARBON CAPTURE PILOT, A HORIZON-FUNDED DEMONSTRATION PROJECT**

The '3D' carbon capture pilot plant is the brainchild of a consortium including Totalenergies, Arcelor Mittal, Axens and IFP Energies Nouvelles. The plant has started up at Arcelor Mittal's Dunkirk site in France and is an important step in decarbonising the steelmaking industry, but not only: the pilot can also be applied to refining processes.

This demonstration, which is scheduled to last for 12 to 18 months, is the final stage before the technology's full-scale deployment. During the demonstration stage, it will capture 0.5 tons of CO_2 an hour, i.e. more than 4,000 tons a year.

The EUR 14.7 million EU-funded project is considered by the consortium as a 'vital driver' for reaching Paris Agreement targets and includes twelve partners from research and industry in six European countries.

Further to the above-mentioned partnerships with industry, other partnership address the the production of clean energy and the wider energy transition, which is closely linked to the development and uptake of low-carbon technologies.

The Hydrogen and Fuel Cells public-private partnership (Joint Undertaking) under Horizon 2020 and the new Hydrogen Partnership under Horizon Europe support the development of green hydrogen production in Europe and reach out to key user sectors including energy-intensive industries, notably the steel industry.

Horizon Europe will also co-invest with Member States in the new Clean Energy transition co-fund Partnership of Horizon Europe. This is a transformative R&D&I programme across Europe boosting and accelerating a just energy transition in all its dimensions for Europe to become the first climate-neutral continent. It aims at bringing together national funding with a top–up contribution from the EU. The total indicative budget for the co-funded European partnership is EUR 210 million.

4.1.3. InnovFin

InnovFin was launched in 2014 by the EIB Group in cooperation with the Commission under Horizon 2020, with a budget of EUR 2.7 billion for 2014-2021. Until 2020, it offered a range of tailored products, which provided financing in support of research and innovation by SMEs and large companies and the promoters of research infrastructure. Its goal was to help bridge the 'valley of death' from demonstration to commercialisation, supporting the further rollout of innovative technologies to the market.

InnovFin Energy Demonstration has supported projects related to low-carbon technologies, including the Steelanol project mentioned in Chapter 2. InnovFin has become part of InvestEU for the programming period 2021-2027.

4.1.4. European Innovation Council

The European Innovation Council (EIC) supports breakthrough and transformative innovation under Horizon Europe. Since its inception in late 2018 – building on the already existing SME Instrument – the EIC has taken decisive steps towards funding promising technological breakthroughs.

- Pilot phase 2018-2020

In its pilot phase (2018 to 2020), the EIC provided finance for green technologies, as part of EU's focus on the European Green Deal. In July 2020 alone, 64 start-ups were awarded funding of more than EUR 300 million for European Green Deal innovations. Overall, the EIC's green technologies portfolio includes 1 600 companies, with EIC funding of EUR 1 billion, complemented by follow-up investments of EUR 1.15 billion. EIC-funded innovative new technologies offer ways of replacing combustion engines with electric batteries, and fossil fuels with renewable energy, and of lowering the carbon footprint of various industries.

Box 10 | **HIGH-POTENTIAL SME/EIC PROJECTS FOR INDUSTRIAL LOW-CARBON TECHNOLOGIES**

Low TRL projects

The low TRL projects are mainly in four areas: electrification of industry; use of green hydrogen, biomass and other biofuels; CCS & CCU; and recycling. Most projects develop technologies at TRL 3 to 4, with some technologies aimed at TRL 5.

Project examples include:

- Electrification of industry: AMADEUS (end TRL 3), QuIET (end TRL 2-3), HAVERSTORE (end TRL 3-4), UncorrelaTEd (end TRL 2), MAGENTA (end TRL 3), TPX-Power (former WASTE-NOT – end TRL 3), CATCHER (end TRL 5), ESiM (end TRL 3), ThermoDust (end TRL 3), or MeBattery (end TRL 3).
- Use of green hydrogen, biomass and other biofuels: 112CO2 (end TRL 4).
- CCU & CCS: DIACAT (end TRL 3) and FuturoLEAF (end TRL 3).
- Recycling: EcoPlastiC (end TRL 3).

While the funded projects and the developed technologies can be relevant for the energy-intensive industries ecosystem, their applicability for the market remains limited. Further development of the respective technologies is needed in order to determine exact applicability in the energy-intensive industries ecosystem.

High TRL projects

The high TRL projects relevant for energy-intensive industries funded by the EIC are in four main areas: electrification of industry, recycling, industrial symbiosis and other topics. The average TRLs of the developed technologies are between TRL 6 and 8.

Various projects funded through the EIC, at high TRLs, were recipients of the 2020 European Green Deal Call, in areas such as recycling, industrial symbiosis, energy efficiency or reducing carbon footprint of specific industrial sectors (e.g. cement).

Project examples include:

- Electrification of industry: HEAT2VALUE and DUSTCOMB.
- Recycling: SENS (TRL 5/6 to 8).
- Industrial symbiosis: Proton (TRL 7 to 8).
- Other topics: CemShale CemTower (TRL 5/6 to 8), CRCP (TRL 6 to 8), Glazer, CO2Catalyst (TRL 6 to 7) or Willpower.

- 2021-2027

The overall funding of the EIC for this programming period 2021-2027 is EUR 10.1 billion, including EUR 3 billion for the EIC fund. The EIC opens funding opportunities worth over EUR 1.7 billion in 2022.

Through its tailored approach for start-ups and SMEs, the EIC manages to address innovators regardless of the maturity of the technologies developed:

- **low TRL**: the EIC Pathfinder (worth EUR 350 million in 2022) provides grants of up to EUR 3-4 million for early stage research on breakthrough technologies;
- **medium TRL**: the EIC Transition instrument (worth EUR 131 million in 2022) provides grants of up to EUR 2.5 million for technology maturation from proof-of-concept to validation;
- **high TRL**: the EIC Accelerator (worth EUR 1,16 billion in 2022) provides grants of up to EUR 2.5 million, combined with equity investments of up to EUR 15 million, for development and scale-up of deep-tech or disruptive innovations.

Figure 55 Main financing tools of the European Innovation Council

The majority of funding will be awarded through open calls with no predefined thematic priorities (‘EIC Open’). The EIC Open funding is designed to enable support for any technologies and innovations that cut across different scientific, technological, sectoral and application fields or represent novel combinations. The challenge driven approach (‘EIC Challenges’) provides funding to address specific technological and innovation breakthroughs. These challenges take into account EU priorities for transitioning to a green, digital and healthy society, including the development and take up of low-carbon technologies (for 2022: EIC Pathfinder ‘EIC Challenge’ (EUR 167 million indicative budget): includes ‘Mid-long term, systems-integrated energy storage’; EIC Transition ‘EIC Challenge’ (EUR 60.5 million indicative budget): includes ‘Process and system integration of clean energy technologies’; EIC Accelerator ‘EIC Challenges’ (EUR 536.9 million) includes ‘Technologies for ‘Fit for 55’’)[145].

The EIC also links with other components of Horizon Europe, including the European Research Council (ERC), the European Institute of Innovation and Technology (EIT) and its Knowledge and Innovation Communities (KICs), and with other Commission funding programmes, such as InvestEU.

New synergies include:

- The EIC ‘Fast Track’ scheme, a novelty under Horizon Europe and a specific process applicable to the EIC Accelerator. It provides for a specific treatment of proposals that result from existing Horizon Europe or Horizon 2020 projects.
- The EIC pilot ‘Plug-in’ scheme, which is also a novelty under Horizon Europe and a specific process applicable to the EIC Accelerator. It applies to applications that result from existing national or regional programmes certified by the European Commission.

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[145] EIC Work Programme 2022 (europa.eu)

The EIC Accelerator focusses on innovators and entrepreneurs, and complements InvestEU, which is investor and financial intermediary driven. It aims at directly de-risking selected operations in order to better bridge these two worlds and crowd-in investors. For that purpose, the EIC Accelerator is designed to fulfil the role of initial or first risk-taker, where needed.[146]

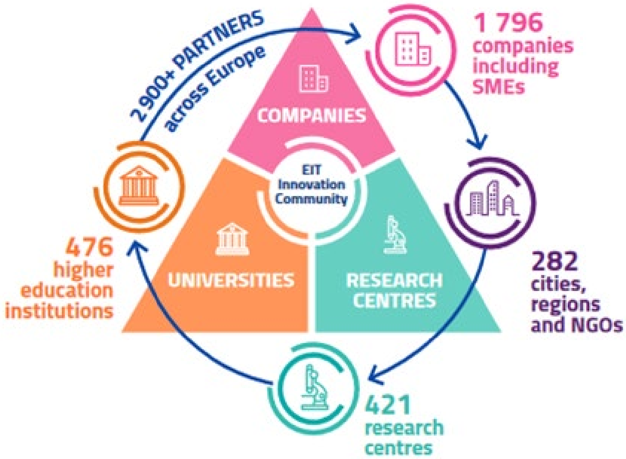
4.1.5. EIT: enabling knowledge & innovation in the EU

The European Institute of Innovation & Technology (EIT) creates an architecture to promote innovation in the EU, through its operational arms, the Knowledge and Innovation Communities (KICs). There are currently eight KICs, of which four are particularly relevant for R&I in the area of low-carbon industrial technologies: EIT Climate KIC, EIT InnoEnergy, EIT Raw Materials and EIT Manufacturing.

The KICs are dynamic and creative partnerships that bring together businesses, research centres and universities (the 'knowledge triangle') in order to develop new innovative products and services, to train a new generation of entrepreneurs and to support new companies in their start-up and scale-up phase. With this, they can play an important role in supporting the development of pan-European clusters for the development and uptake of low-carbon industrial technologies.

Overall, in 2021, an estimated EUR 115 million was spent by relevant EIT KICs across the industrial value chains for the development and uptake of green technologies.

Figure 56 EIT's knowledge triangle: businesses, research centres and universities



Source: European Institute of Innovation & Technology.

Besides the KICs, the EIT also established the Regional Innovation Scheme (RIS), for EU Member States with lower innovation performance[147] and non-EU Horizon Europe associated countries, where EIT KICs disseminate knowledge and promote a broader participation in their projects across Europe. The RIS's aim is to raise the capacity of innovation players and facilitate their access to services and programmes offered by the EIT KICs[148], effectively increasing the chances for wider uptake of innovative green

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[146] https://eic.ec.europa.eu/system/files/2021-05/EIC%20Fund%20Investment%20Guidelines%20-%20Horizon%20Europe.pdf.

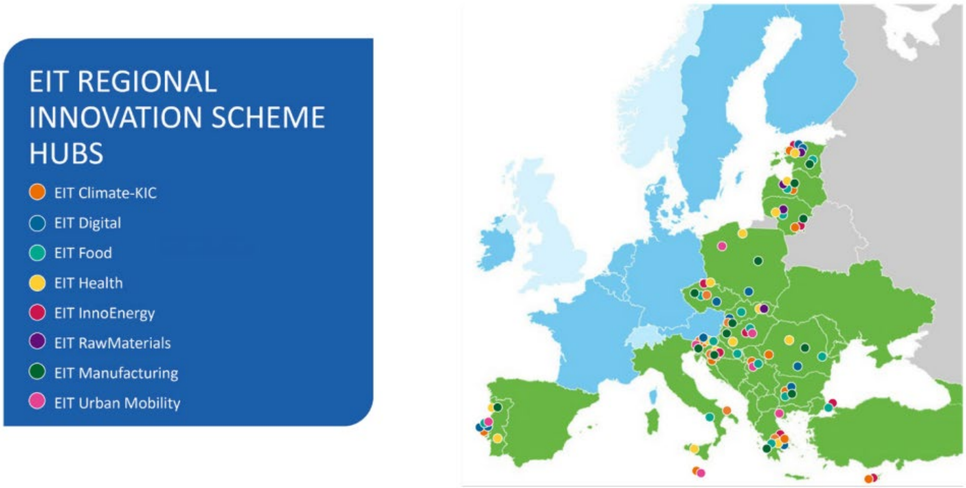
[147] Based on the European Innovation Scoreboard, https://ec.europa.eu/info/research-and-innovation/statistics/performance-indicators/european-innovation-scoreboard_en.

[148] EIT RIS Activity Report 2019-2020, https://eit.europa.eu/sites/default/files/eit_ris_activity_report_-_final.pdf.

technologies in widening countries[149]. EIT RIS is building on synergies and complementarities with national, regional and EU programmes such as European Structural and Investment Funds (ESIF) or Smart Specialisation Strategies. Close collaboration of EIT KICs with local authorities and innovation players is helping to operationalise local sector-specific plans and strategies using good practices, experiences and know-how arising from KIC activities elsewhere and offering tailor-made services to address identified innovation gaps in local sector-specific ecosystems.

EIT KICs engage local organisations to serve as EIT Hubs (see Figure 57) with the ambition of scaling them into regional and national innovation hubs. The aim is to enable them to spark the desired cooperation and co-creation among local business, research, academia and public sector players with a view to facilitating the use of local competences and resources for a better innovation output. By 2020, EIT KICs had established 64 EIT Hubs in 18 EIT RIS countries, and as well as 12 Co-location Centres in 5 EIT RIS countries.

Figure 57 EIT Regional Innovation Scheme Hubs



Source: EIT RIS Activity Report 2019-2020.

The participation of partners in EIT RIS increased from over 40 to over 300 partners between 2014 and 2020, while funding received by partner organisations tripled in the same period. These figures increased further in 2021.

For the period 2021-2027, the EIT will receive EUR 2.96 billion to continue strengthening Europe’s ability to innovate.

[149] The phrase ‘widening countries’ designates the Member States that have joined the EU most recently: Bulgaria, Croatia, Cyprus, Czechia, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Portugal, Romania, Slovakia and Slovenia.

Box 11 | **EIT KICS: GRANTS & NON-FINANCIAL SUPPORT FOR INNOVATION NETWORKS**

EIT Raw Materials funded projects dealing with reducing energy consumption in energy-intensive industries (i.e. mineral and hydrometallurgy processing for primary and secondary raw material sourcing) with approximately EUR 39 million. Furthermore, the KIC's projects dealing with the CO2 footprint of industrial processes received a total funding of EUR 8.5 million up to 2021.For example, the SAMOA project aims to upscale the process chain of raw aluminium alloys from material efficient powder production, energy efficient laser and arc wire additive manufacturing to material recycling in order to reduce the material need by up to 50%.

EIT InnoEnergy KIC's portfolio addresses relevant thematic fields for the decarbonisation of industry, such as energy efficiency or the circular economy. Relevant projects funded through the EIT InnoEnergy KIC include innovations related to the electrification of linear motion in heavy machines used in industrial processes. This is expected to contribute to an annual avoidance of 33 million tonnes of CO2 equivalent emissions by 2030.

EIT Climate KIC RIS Accelerator, operational since 2016, has supported clean tech entrepreneurs in RIS countries and regions on a variety of actions, including through grants for climate change adaptation and mitigation.

One of its beneficiaries, the Estonian start-up Ascalia, created a platform to collect and analyse data using artificial intelligence, resulting in detailed analytics and optimisation of processes, which helps reducing energy and raw materials usage, as well as the environmental impact of industry.

Since 2019, EIT Climate KIC, in cooperation with EIT Raw Materials KIC and partnering up with the governments of Bulgaria, Italy and Slovenia, supported the implementation of 'A Deep Demonstration of a Circular, Regenerative and Low-Carbon Economy'. This aims to harness circularity to transform and decarbonise industrial value chains by designing and delivering the smart transition of regions through a coordinated systemic approach where innovation and green technologies are embedded in production and waste flows across key economic systems and selected value chains, including transport, forestry, the agri-food sector or raw materials. This project covered the development and uptake of low-carbon technologies in industry through its support for the creation of a living laboratory to foster innovation, with cross-sectoral and cross-disciplinary approaches and working with stakeholders from local communities, businesses, research organisations and policymakers. Iterative development of designing innovative solutions based on existing projects and experiences will take place until 2025.

4.1.6. Synergies

Building synergies within Horizon Europe and between Horizon Europe and other programmes are essential, for their effectiveness and for the efficient use of R&I investments, but also to achieve the best possible impact of other programmes.

Annex IV of the Horizon Europe Regulation[150] sets out a framework to develop strategic synergies with all other main EU programmes. This should ensure primarily that, on the one hand, research and innovation activities inform the development of EU policies and programmes and, on the other hand, that R&I ideas and results receive the support necessary for their deployment and market uptake.

A dedicated Commission guidance document will promote synergies between Horizon Europe and the European Regional Development Fund (ERDF), such as:

- The Seal of Excellence, a quality label awarded by the Commission to proposals which have been assessed in a call for proposals under Horizon 2020 or Horizon Europe and comply with the quality requirements but could not be funded due to budgetary constraints. These projects are judged to deserve funding and might

[150] EUR-Lex - 52018PC0435 - EN - EUR-Lex (europa.eu)

receive support from national sources of funding. The Seal of Excellence is currently awarded notably to proposals that apply under the EIC Accelerator and the EIC Transition;

- Support for European partnerships: under certain conditions, financial contributions from programmes co-financed by the ERDF may be considered as a contribution of the participating Member State to European partnerships ('Co-funded European partnerships'; 'Institutionalised European partnerships');

- Support to Teaming actions: 'Teaming' supports centres of excellence in certain eligible countries; beneficiaries are mostly universities and research organisations, sometimes also regional authorities and SMEs. It facilitates the funding from the ERDF to co-finance a Teaming action with Horizon Europe, and to support investment in Teaming-related research infrastructure;

- The option, for Member States, to transfer cohesion policy funds to Horizon Europe (and transfer back if not fully used): Member States may transfer up to 5% of their initial cohesion policy allocations to any other EU fund or instrument under shared, direct or indirect management.

4.2 *Financial instruments: European Fund for Strategic Investment (EFSI)/InvestEU.*

4.2.1. European Fund for Strategic Investment (EFSI)

Low investment levels following the 2007/2008 financial crisis prompted the Commission to launch the Investment Plan for Europe, also known as the Juncker Plan, in 2014. One pillar of the Investment Plan for Europe was EFSI (European Fund for Strategic Investments), a guarantee mechanism that enhanced the EIB Group's risk-bearing capacity. Its aims were to help finance operations that address market failures and suboptimal investment situations and to mobilise private investment.

EFSI comprised the EIB-managed Infrastructure and Innovation Window (IIW), which aimed to mobilise investment in infrastructure and innovation, and the EIF-managed SME Window (SMEW), which sought to enhance access to finance for SMEs and small mid-cap companies.

With the EFSI support, the EIB Group provided funding for economically viable projects, especially for projects with a higher risk profile than those usually financed by the EIB. The focus was on sectors of key importance for the European economy, including:

- strategic infrastructure including digital, transport and energy;

- education, research, development and innovation;

- renewable energy and resource efficiency; and

- support for small and mid-sized businesses.

As of 31 December 2020, the EFSI portfolio comprised 733 operations approved under the IIW totalling EUR 69.8 billion (EUR 314.5 billion investment mobilised), and 816 operations approved under the SMEW totalling EUR 33 billion (EUR 232 billion investment mobilised). Together, these operations are expected to mobilise EUR 546.6 billion of investment across the European Union. EFSI has thus exceeded its target volume of investment mobilised from operations approved up to year-end 2020[151].

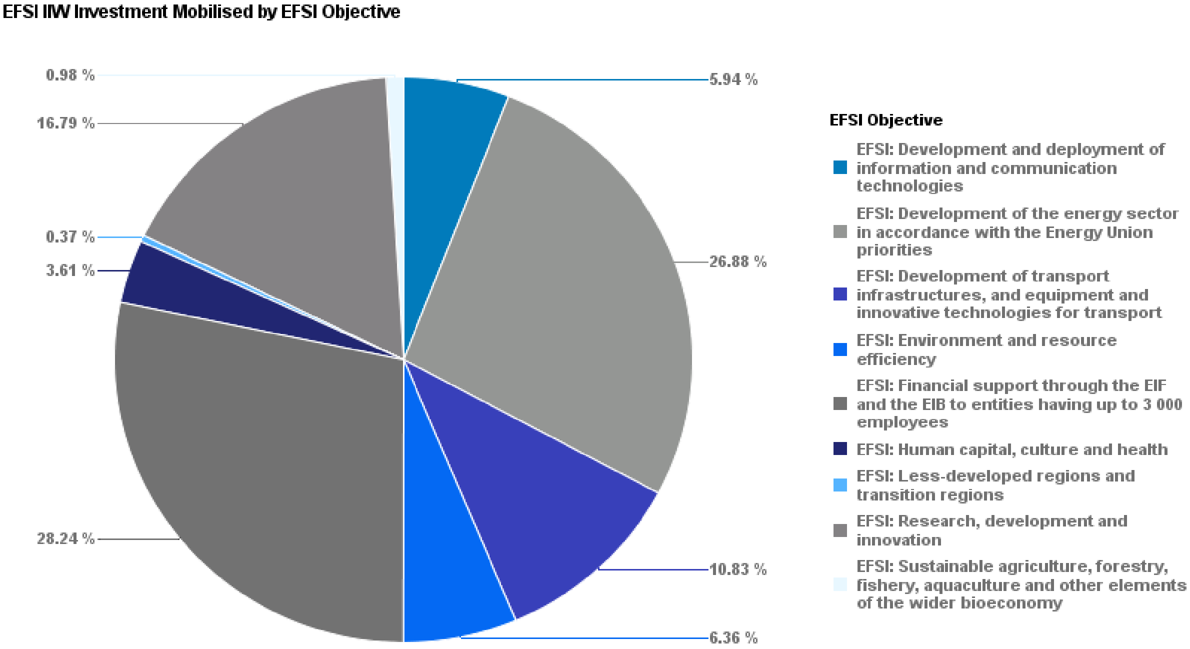
[151] 2020 EFSI report from the European Investment Bank to the European Parliament and the Council on 2020 EIB Group Financing and Investment Operations under EFSI.

EFSI | Sectors

The nine general objectives eligible under EFSI were: R&D&I (RDI), Energy, Transport, Smaller companies, Digital, Environment and resource efficiency, Social infrastructure, and, since the extended EFSI, Bioeconomy and Regional development.

As illustrated in Figure 58 below, the RDI objective represents 16.79% of the investments mobilised by approvals under the EFSI Infrastructure and Innovation Window (IIW) (234 projects and EUR 52.8 million) and the Environment and resource efficiency objective 6,36% (87 projects and EUR 20 million).

Figure 58 EFSI IIW investment mobilised by EFSI objective



Source: EIB REPORTING: EFSI IIW / SMEW / EIB GROUP Operations Approved as at 31/12/2020.

RDI and Environment and resource efficiency objectives under the IIW are the most relevant categories for low-carbon industrial technologies projects. However, current EIB reporting does not allow to break down such support to RDI-relevant support for low-carbon (or climate mitigation) technologies.

Relevant projects to support R&D&I activities for the decarbonisation of EII include the following[152]:

- A EUR 280 million loan granted to ArcelorMittal in Belgium, France, Luxembourg and Spain, to help fund the group's European research and development programme between 2021 and 2023. This funding will allow significant expansion of ArcelorMittal’s research and development activities on decarbonisation.
- A EUR 290 million loan to Wacker Chemie AG., a German technological leader in the chemical industry. The financing supports Wacker's research and development programme with a strong focus on sustainability and energy efficient economy, and is part of the company’s shift to become a climate-neutral chemicals organisation.

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[152] EFSI project list – EIB website.

- A EUR 40 million loan to global chemicals company Kemira Oyj, headquartered in Finland, to boost its investments in research, development and innovation in chemical applications and technical solutions for water treatment, pulp and paper chemicals, and other chemicals.

- A EUR 82 million loan to Sustainable Cement RDI. The project comprises the modernisation of the promoter's production sites in France and Switzerland as well as its EU-based RDI activities related to cement products and production technologies in 2021-2023.

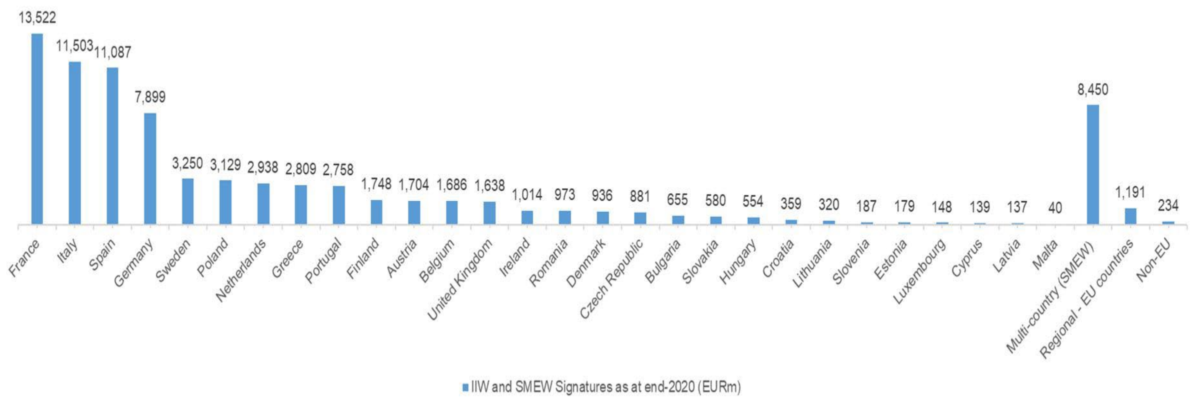
In December 2017, EFSI stipulated that at least 40 % of projects under the Infrastructure and Innovation Window must contribute to climate action, in line with the commitments made at the UNFCCC's COP21 climate change conference.

As of 30 June 2021, 386 operations with climate action components[153] have been supported under the EFSI IIW for an amount of some EUR 20.5 billion.

EFSI | Geographical distribution

All EU Member States and the United Kingdom (former Member State) benefited from the support of EFSI, as illustrated in Figure 59. France, Italy, Spain and Germany have benefited the most from EFSI funding, while there is also funding channelled to central and eastern European Member States. The share of the EFSI signatures in EU13 (13 Member States that joined the EU in 2004, 2007 and 2013) has consistently improved thanks to various measures since the start of EFSI in mid-2015, although in absolute figures EFSI support remains relatively less predominant in this region[154]. The extended EFSI (December 2017) brought amendments including with a view to further contributing to the geographical spread.

Figure 59 Geographical coverage of EFSI signed operations as of the end of 2020



Source: 2020 EFSI REPORT From the European Investment Bank to the European Parliament and the Council on 2020 EIB Group Financing and Investment Operations under EFSI.

In 2021, InvestEU took over as the new long-term financing programme of the EU, building on the success of EFSI.

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153 In order to identify climate action project components, EIB uses its internationally agreed methodology as foreseen in the EFSI Agreement.

154 2020 EFSI REPORT From the European Investment Bank to the European Parliament and the Council on 2020 EIB Group Financing and Investment Operations under EFSI.

4.2.2. InvestEU Fund

The InvestEU Fund focusses on addressing the large investment gaps in key areas of the future through an EU budget guarantee of EUR 26.2 billion. It will thus further boost job creation and support investment and innovation in the EU. It is expected to mobilise at least EUR 372 billion of private and public investment across the EU by end-2027. At least 30% of the InvestEU Fund is expected to contribute to fighting climate change[155].

Due to InvestEU targeting higher risk innovation projects and SMEs, as well as the greater focus on EU policy objectives, a slightly more conservative multiplier effect than under EFSI is expected: 11.4 rather than 15.[156]

The guarantee will be implemented by the EIB (at 75%) and, for the first time, by implementing partners: national promotional banks and international financial institutions such as the European Bank for Reconstruction and Development (EBRD), the Council of Europe Development Bank (CEB) and the Nordic Investment Bank (NIB).

A guarantee agreement with the EIB group was signed in March 2022 so that companies and project promoters can start applying for financing. Guarantee agreements with other implementing partners will follow in the course of 2022. Other implementing partners have been selected through the call for expression of interest. The first call was concluded in 2021. Guarantee agreement negotiations with the selected other implementing partners are ongoing.

Compared with EFSI, InvestEU is more targeted to specific policy objectives, through its four policy windows. It remains a market/demand driven instrument but with a stronger policy focus.

The InvestEU Fund operates through the following four policy windows that are to address market failures or sub-optimal investment situations within their specific scope:

- Sustainable Infrastructure Policy Window, which comprises inter alia the deployment of innovative technologies that contribute to EU environmental or climate resilience or social sustainability objectives and that meet EU environmental or social sustainability standards (EUR 9.9 billion);

- Research, Innovation and Digitisation Policy Window, which comprises research, product development and innovation activities, the transfer of technologies and research results to the market to support market enablers and cooperation between enterprises, the demonstration and deployment of innovative solutions and support for the scaling up of innovative companies, and digitisation of EU industry (EUR 6.6 billion);

- SME Policy Window, which comprises access to and availability of finance primarily for SMEs, including for innovative SMEs and SMEs operating in the cultural and creative sectors, as well as for small mid-cap companies (EUR 6.9 billion); and

- Social Investment and Skills Policy Window (EUR 2.8 billion).

The InvestEU Fund, with its four priority policy windows, has a strong focus on financing investments that have a positive climate impact. The Sustainable Infrastructure Policy Window supports investments in sustainable industrial applications which help reduce greenhouse gas emission. The Research, Innovation and Digitisation Policy Window supports new environmentally sustainable technologies that lead to the reduction of

[155] InvestEU Programme statement.
[156] https://europa.eu/investeu/investeu-fund/frequently-asked-questions-about-investeu-fund_en.

greenhouse gas emissions of industries. Both policy windows are relevant for low-carbon technologies.

The InvestEU guidelines indicate under the Sustainable Infrastructure Policy Window that "support from the InvestEU will also promote the deployment of low-emission technologies: projects that include carbon capture, transport, storage and/or use (CCUS) technologies and infrastructure for the production of renewable electricity, heat and cold, low-carbon gases (such as hydrogen) or industrial processes, as well as bio-energy plants and manufacturing facilities enabling the energy transition, or carbon removals"[157].

The InvestEU Fund features the option of establishing Member State compartments for each policy area, meaning that EU countries may add to the EU guarantee's provisioning by voluntarily channelling a part of their cohesion policy funds to these compartments. In this way, EU countries benefit from the EU guarantee and its high credit rating, giving national and regional investments more firepower and higher multiplying effect.

In the Members State compartments, EU countries can also use InvestEU as a tool to implement their recovery and resilience plans under the recovery and resilience facility, if they so wish.

The reinforced implementation of InvestEU through national promotional banks might yield opportunities for future synergies with national funds channelled by the same banks.

The EIB also finances research and development of low-carbon technologies through its own resources. In 2021, the share of EIB investments that went to climate action and environmental sustainability projects amounted to EUR 27.6 billion[158].

4.3 *Innovation Fund*

The Innovation Fund will provide around EUR 25* billion of support over the period 2020-2030, depending on the carbon price (* at EUR 50 / tCO2), for the commercial demonstration of innovative low-carbon technologies, aiming to bring to the market industrial solutions to decarbonise Europe and support its transition to climate neutrality. The Fund is financed by auctioning of a small part of emission allowances from the EU's Emissions Trading System and any unspent funds from the NER300 programme. The goal is to help businesses invest in clean energy and industry to boost economic growth, create local future-proof jobs and reinforce European technological leadership on a global scale.

This is done through calls for large and small-scale projects focusing on:

- innovative low-carbon technologies and processes in energy-intensive industries, including products substituting carbon-intensive ones;
- carbon capture and utilisation (CCU) and carbon capture and storage (CCS);
- innovative renewable energy generation; and
- energy storage.

[157] InvestEU investment guidelines.
[158] European Investment Bank, EIB climate action explained, https://www.eib.org/en/about/priorities/climate-action/explained/index.htm

As the successor of the NER300 programme[159], the Innovation Fund improves risk-sharing for projects by giving more funding in a more flexible way through a simpler selection process and is also open to projects from energy-intensive industries. It operates via grants for large-scale and small-scale projects.

Innovation Fund | Large-scale projects

The results of the first call for large-scale projects were published in November 2021. Seven projects aiming to bring breakthrough technologies to the market in energy-intensive industries, hydrogen, carbon capture, use and storage and renewable energy were pre-selected for grant agreement preparations. Grants for EUR 1145 million will be awarded for the seven projects in the first quarter of 2022.

These projects are:

- in Sweden, to entirely eliminate greenhouse gas emissions from steel production by using renewable hydrogen in Gällivare and Oxelösund (Hybrit project); another project on bio-energy carbon capture at a combined heat and power plant and storage in North Sea, thus creating negative emissions;

- in Finland, to demonstrate two ways of producing low-carbon hydrogen at a refinery in Porvoo, through renewable energy and by capturing CO_2 and permanently storing it in the North Sea;

- in France, to capture unavoidable emissions in a cement plant and in part store the CO_2 geologically in the North Sea and in part integrate it into concrete;

- in Belgium, to develop a complete carbon capture, transport and storage value chain in the Port of Antwerp so as to reduce emissions in the production of hydrogen and chemicals;

- in Spain, to produce bio-based methanol from non-recyclable municipal waste; and

- in Italy, on bifacial heterojunction photovoltaic cells production at gigawatt scale.

These projects will therefore cover most of the technological pathways, with the exception of energy storage, included in the scope of the Innovation Fund. These seven projects together have a potential to avoid 72.8 megatonnes CO_2-equivalent over the first 10 years of operation.

The Innovation Fund will provide funding for the demonstration plant of the Swedish Hybrit project, whose initial R&D stages were partly funded by the Swedish government. The Clean Steel Partnership will also provide funding to address the gap at demonstration stages.

Looking at the full pipeline of projects 311 proposals were submitted for the call and 70 best-ranking proposals were invited to the second stage of the call. This shows that there is high demand for financing innovative low-carbon technologies at the stage of commercial

[159] The NER 300 is a funding programme for innovative low-carbon energy demonstration projects in the EU linked to renewable energy technologies and environmentally safe carbon capture and storage (CCS) on a commercial scale. The programme is funded from the monetisation of emission allowances from the New Entrants Reserve. In total, 39 projects have been awarded EUR 2.1 billion of funding in 20 Member States. Projects are at different stages but 23 were withdrawn due to difficulties in raising sufficient equity and/or attracting additional financial support. These withdrawals led to a release of almost EUR 1.5 billion. The amended NER 300 Decision allowed to reinvest EUR 708.7 million of unused funds through the existing financial instruments: the InnovFin Energy Demonstration Projects (InnovFin EDP) and the CEF Debt Instrument, both managed by the EIB. The remaining unspent funds will be channelled to the Innovation Fund with the perspective of full allocation of undisbursed funds by the end of 2022.

deployment. Under the ETS revision proposal, the Commission proposed an increase in the resources available under the Innovation Fund, larger sectoral scope and to explore competitive bidding for the allocation of support.

The Commission launched the second call for large-scale projects on 26 October 2021, with a deadline for 3 March 2022 and a budget of EUR 1.5 billion, which is increased by 50% compared with the previous call.

Innovation Fund | Small-scale projects

A total of 30 projects signed their grant agreements[160] under the first call for small-scale projects. They will implement innovative technologies focusing on the decarbonisation of energy-intensive industries (iron and steel, biofuels and biorefineries, pulp and paper, refineries, non-ferrous metals, glass, ceramics and construction material, hydrogen) and the energy sector (innovative production and use of renewable energy or storage solutions).

The second call for small-scale projects was launched in March 2022 with a budget of EUR 100 million and submission deadline in August 2022.

Innovation Fund grants can be combined with funding from other support programmes, for example:

- InnovFin Energy Demo Projects
- Connecting Europe Facility
- Horizon 2020 and Horizon Europe
- InvestEU
- Modernisation Fund
- Just Transition Fund
- European Innovation Council (EIC)
- Private capital

In view of creating synergies with other instruments, the Innovation Fund can scale-up to commercial size clean tech innovations developed at early stage by the EIC, Horizon 2020 and Horizon Europe with its partnerships, or Member State's R&D programme. The infrastructure part can be supported by Connecting Europe Facility, Member State’s programme or InvestEU guarantee[161].

4.4 *Breakthrough Energy Catalyst partnership*

The EU-Catalyst partnership, launched on 3 November 2021, is an example of a new blending approach (Bill Gates Foundation Catalyst, Horizon Europe and Innovation Fund) with the objective to accelerate the deployment of low carbon breakthrough technology. DG CLIMA, DG R&I, DG ENER, EIB and Catalyst have worked together and a call for proposals was launched on 11 January 2022 for large-scale deep green tech projects based in Europe. The request will trigger investments in a portfolio of high-potential projects in the areas of clean hydrogen, sustainable aviation fuels, direct air capture, and long-duration energy storage. The partnership will mobilise USD 1 billion (around EUR 820 million) between 2022 and 2026 to accelerate the deployment and commercialisation of innovative technologies. EU funding for the EU-Catalyst partnership comes from Horizon

[160] https://ec.europa.eu/clima/eu-action/funding-climate-action/innovation-fund/small-scale-projects_en
[161] innovation_fund_cumulation_public_en.pdf (europa.eu).

Europe and the Innovation Fund, managed under InvestEU, creating additional synergies. Each euro of public funds is expected to leverage three euros of private funds.

4.5 *Modernisation Fund*

The Modernisation Fund is a dedicated funding programme to support 10 lower-income Member States in their transition to climate neutrality by helping to modernise their energy systems and improve energy efficiency. The beneficiary Member States are Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania and Slovakia.

The revenues of the Modernisation Fund come from the auctioning of ETS allowances for 2021-2030.

The Modernisation Fund supports investments in: generation and use of energy from renewable sources; energy efficiency; energy storage; modernisation of energy networks, including district heating, pipelines and grids; and just transition in carbon-dependent regions: redeployment, re-skilling and upskilling of workers, education, job-seeking initiatives and start-ups.

Industry can benefit from the Modernisation Fund if their investments fall into the category 'energy efficiency' or 'RES production or use'.

4.6 *LIFE Clean Energy Transition sub-programme*

Building on the success of the Horizon 2020 Energy Efficiency (2014-2020) programmes, the LIFE Clean Energy Transition sub-programme continues to support the delivery of EU policies in the field of sustainable energy.

It has a budget of nearly EUR 1 billion over the period of 2021-2027 and aims at facilitating the transition towards an energy-efficient, renewable energy-based, climate-neutral and resilient economy by funding coordination and support actions across Europe. The programme finances networks, which provide support services for the uptake of clean energy technologies.

4.7 *COSME*

COSME, the EU programme for the Competitiveness of Small and Medium-Sized Enterprises, ran from 2014 to 2020 with a budget of EUR 2.3 billion. According to the COSME data hub[162], EUR 3.3 million has been allocated to projects with the keyword "low-carbon". In the 2021-2027 period, the programme has been incorporated to InvestEU and the SMEs Policy Window.

4.8 *The 'Ideas Powered for business SME Fund'*

The 'Ideas Powered for business SME Fund' is a new grant scheme designed to help EU SMEs intellectual property rights. The SME Fund is a Commission initiative implemented by the European Union Intellectual Property Office and will run from 10 January 2022 to 16 December 2022. It could help SMEs to take the lead in new low-carbon technologies by supporting the protection of their inventions.

DECENTRALISED FUNDS (SHARED MANAGEMENT)

Over half of EU funding is channelled through the five European Structural and Investment funds (ESIF). They are jointly managed by the European Commission and the EU countries. The selection, monitoring and evaluation of projects to be financed are performed by

[162] https://cosme.easme-web.eu/?mode=7#.

Member States and their regions. The purpose of these funds is to invest in job creation and a sustainable and healthy European economy and environment. The ESIF mainly focus on five areas: research and innovation; digital technologies; supporting the low-carbon economy; sustainable management of natural resources and small businesses.

Regions are encouraged to use ESIF to contribute to reinforcing the innovation eco-system both in the upstream and/or downstream of the innovation process or the value chain. ESIF can support innovation by building capacity, such as R&I infrastructure, equipment and skills – pre-conditions for successful engagement in subsequent R&I activities (upstream investments). Moreover, ESIF can complement Horizon 2020 and Horizon Europe initiatives, which are usually more focused in basic and applied research, by providing financial support for technology development or to launch products in the market (downstream investments).

The European Regional Development Fund (ERDF), which promotes balanced development in the different regions of the EU, is one of the ESIF funds. It has financed low-carbon technologies projects in 2014-2020 and will continue to do so in this programming period. Under the ERDF, the new Interregional Innovation Investment (I3) enables the commercialisation and scale-up of interregional innovation projects, which could include low-carbon technologies projects. The Just Transition Fund (JTF) will also finance the decarbonisation of the industry, within its ressources.

4.9 *European Regional Development Fund (ERDF) in 2014-2020*

The following analysis on low-carbon industrial technologies projects under ERDF in 2014-2020 is based on the most recent release of the JRC-WIFO ERDF database[163.] This database comprises around 600 000 observations on ERDF project beneficiaries during the 2014-2020 period, providing a unique coverage and level of details on the ERDF operations.

By means of text analysis techniques, it is possible to extract relevant information on the territorial allocation of beneficiaries, projects and investments under the different areas relevant to the broad category of low-carbon industrial technologies.

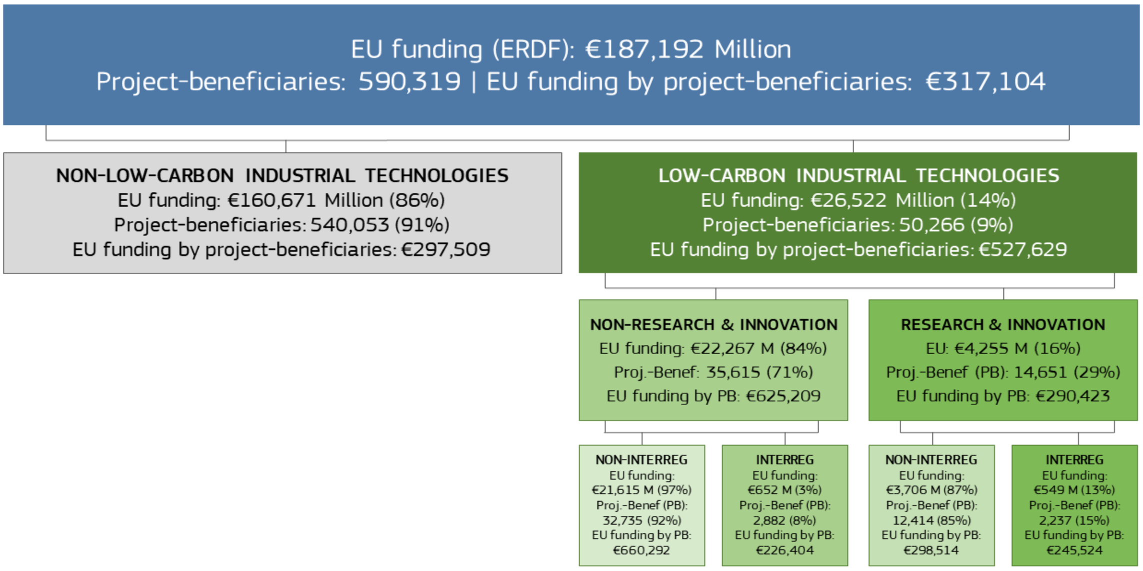
4.9.1. Main results of the ERDF

Around 14% of total ERDF funding in the programming period 2014-2020 is linked to projects related to low-carbon industrial technologies, which represents EUR 26.5 billion of EU co-funding. The average size of projects under the low-carbon category (EUR 527 000) are much bigger than those classified outside this category (EUR 298 000).

16% of low-carbon project funding is associated with R&I funding (EUR 4.3 billion), of which 13% are transnational and interregional cooperation projects (EUR 549 million) under the Interreg programme. R&I projects are related to the development and implementation of technologies with a focus on low carbon economy. Non-R&I projects are mainly associated with capacity building (e.g. energy and environmental infrastructures and business development) to support climate change objectives (see Figure 60).

163 https://publications.jrc.ec.europa.eu/repository/handle/JRC127403.

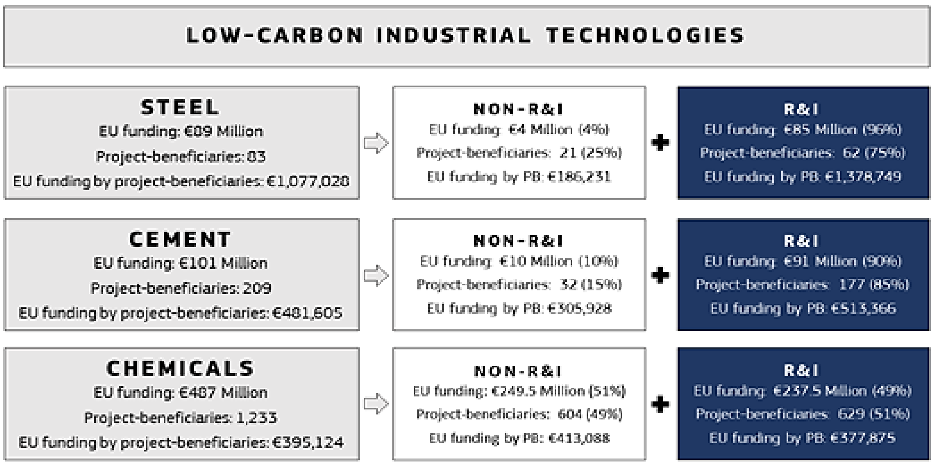
Figure 60 Low-carbon industrial technologies projects over the total ERDF projects, 2014-2020, EU27 + UK, by innovation and cooperation typologies



Note: Projects relating to low-carbon technologies were identified through text analysis. The classification of Research & Innovation projects is associated with the ERDF intervention fields. Interreg refers to transnational and interregional cooperation projects.
Source: JRC- Territorial Data Analysis and Modelling (TEDAM) analysis based on JRC-WIFO database.

Chemicals-related projects account for more than steel- and cement-related projects. The former have a relatively smaller average funding size and are almost equally divided into R&I and non-R&I investments. In contrast, steel- and cement-related projects under ERDF are almost entirely R&I related (see Figure 61).

Figure 61 Low-carbon industrial technologies by industry, 2014-2020, EU27 + UK

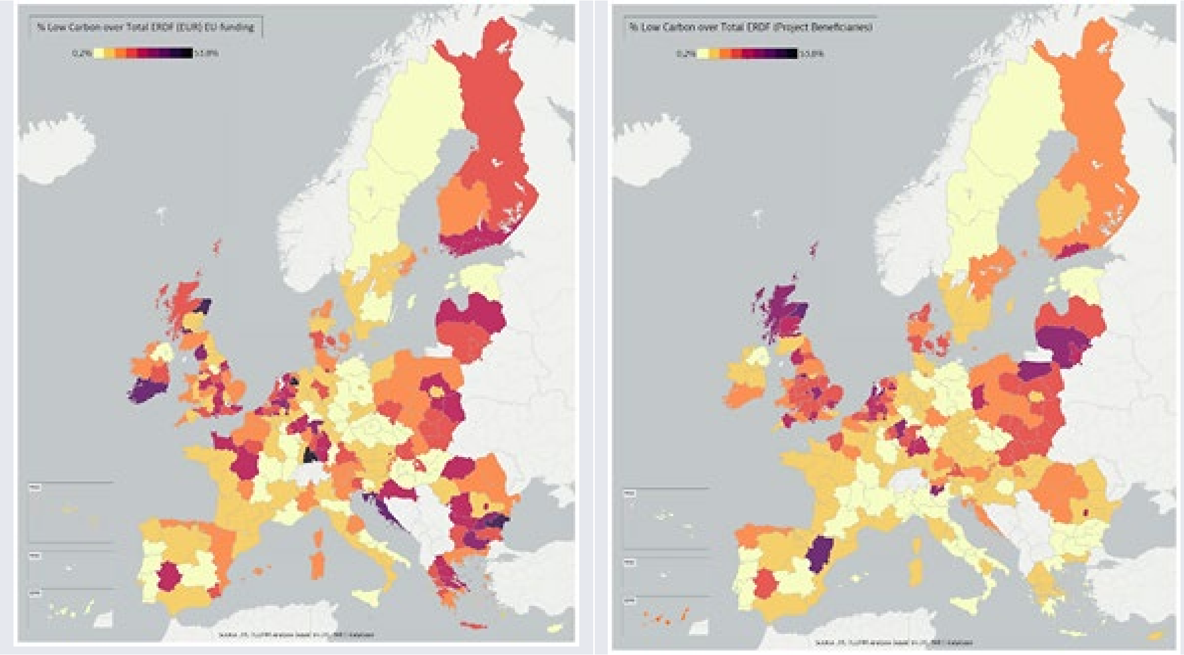


Note: Projects relating to low-carbon technologies were identified through text analysis. The classification of Research & Innovation projects is associated with the ERDF intervention fields.
Source: JRC-TEDAM analysis based on JRC-WIFO database.

In terms of geographical patterns (see Figure 62), the relative share of funding (left) and beneficiaries (right) of low-carbon projects over the total ERDF regional allocation allows to identify specialisation patterns across Europe. Indeed, a relatively higher share towards low-carbon projects seems to appear in central and eastern Europe (as well as in the UK) over the period 2014-2020.

Figure 62 Specialisation patterns: EU regions investing ERDF co-funding in low-carbon industrial technologies, 2014-2020, EU27 + UK

% of total EU funding in low-carbon technologies	% of total project beneficiaries in low-carbon technologies

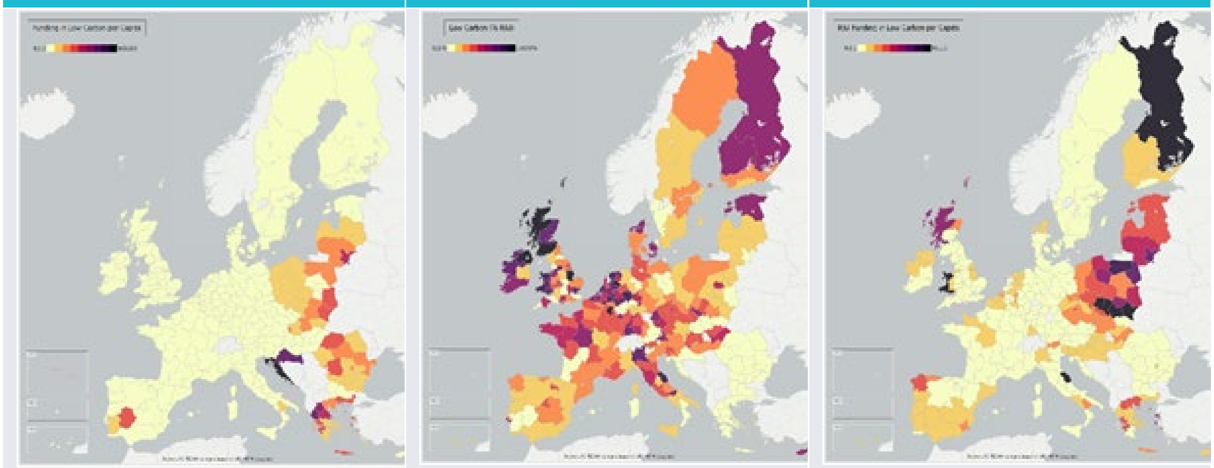


Note: Projects relating to low-carbon technologies were identified through text analysis.
Source: JRC TEDAM analysis based on JRC-WIFO database.

The funding intensity, measured by the amount of ERDF per capita associated with low-carbon projects (Figure 63 - left), shows a higher volume in some regions of Croatia, Greece, Poland, Romania and Lithuania. Concerning the share of R&I funding of these projects (Figure 63 - centre), they are higher in some regions of Belgium, UK and the Netherlands. The R&I funding intensity of low-carbon projects, expressed in per capita (Figure 63 - right), appears to be more concentrated in some regions of UK, Poland and Finland.

Figure 63 Funding intensity: EU regions investing ERDF co-funding in low-carbon industrial technologies, 2014-2020, EU27 + UK, Total and R&I

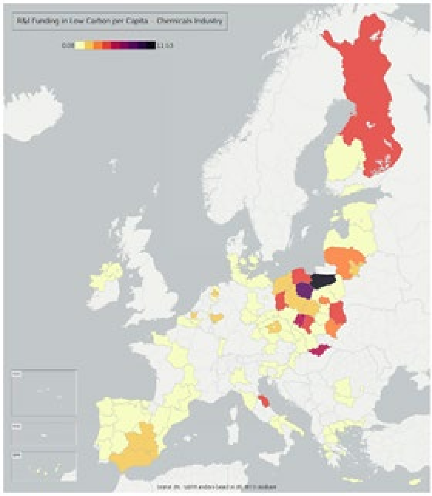
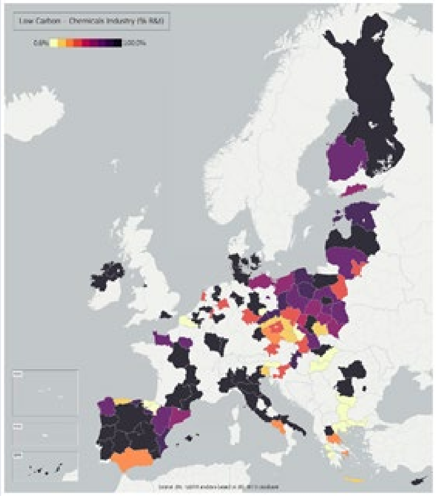
Funding (EUR) in low-carbon per capita	Funding in low-carbon (% R&I)	R&I funding (EUR) in low-carbon per capita



Note: Projects relating to low-carbon technologies were identified through text analysis. The classification of Research & Innovation projects is associated with the ERDF intervention fields.
Source: JRC TEDAM analysis based on JRC-WIFO database.

R&I low-carbon industrial technologies projects in chemicals industries are concentrated in EU regions/countries (Figure 64). For instance, the intensity of R&I funds per capita is particularly high in some regions of Poland, Hungary and Finland (Figure 64 – left). Furthermore, the share of R&I projects in chemicals industries (Figure 64 – right) is 100% (or close to) in most regions with low-carbon projects in this specific industry.

Figure 64 EU regions investing R&I ERDF co-funding in low-carbon industrial technologies, 2014-2020, EU27 + UK, in chemicals industry

R&I funding (EUR) in low-carbon per capita in chemicals industry	**Funding in low-carbon in chemicals industry (% R&I)**
	

Note: Projects relating to low-carbon technologies in chemicals industry were identified through text analysis and the NACE code of the beneficiaries (manufacturing industries related to chemicals with projects in low-carbon technologies). The classification of Research & Innovation projects is associated with the ERDF intervention fields.
Source: JRC TEDAM analysis based on JRC-WIFO database.

4.9.2. Matching emission data and ERDF allocations for low-carbon projects

Data indicates that the most CO_2 intensive Member States are not necessarily the ones investing most funds into low-carbon projects through ERDF allocations. As such, while the most CO_2 intensive countries are Belgium, Slovakia, Austria and Finland, the highest share of low-carbon projects from ERDF is observed in Croatia, Bulgaria, Latvia and the Netherlands.

At the same time, while Estonia has a significantly higher than EU average CO_2 intensity per capita, it spends the lowest share of ERDF on low-carbon projects in the EU. On the contrary, Latvia registers the lowest CO_2 intensity per capita in the EU, but it allocates the third highest share of low-carbon projects within its ERDF allocation.

Table 7 EII installations' CO_2 emissions & share of low-carbon projects (% total ERDF) in EU Member States

Country	CO_2 emissions from EII per capita	Low-carbon projects (% total ERDF amount)	Country	CO_2 emissions from EII per capita	Low-carbon projects (% total ERDF amount)
Belgium	2.7	12%	Spain	1.2	12%
Slovakia	2.4	20%	Sweden	1.2	5%
Austria	2.4	12%	Croatia	1.2	33%
Finland	2.3	21%	Portugal	1.0	6%
Netherlands	2.2	25%	Italy	1.0	8%
Luxembourg	2.1	20%	Poland	1.0	18%
Lithuania	1.8	21%	Ireland	1.0	21%
Estonia	1.7	2%	France	0.9	10%
Czechia	1.6	4%	Bulgaria	0.9	27%
Germany	1.5	8%	Slovenia	0.9	5%
Cyprus	1.4	4%	Romania	0.8	18%
Greece	1.3	18%	Hungary	0.8	4%
EU27 average	**1.3**	**14%**	Denmark	0.7	13%
			Latvia	0.5	26%

Note: ERDF projects refer to the period 2014-2020 and CO_2 emissions to the year of 2018. Malta is not reported in the table because there are no facilities of the EII in the country covered by the ETS.
Source: JRC calculations based on: Marques Santos, A.; Reschenhofer, P.; Bachtrögler-Unger, J.; Conte, A and Meyer, N. (2022). Mapping Low-Carbon Industrial Technologies projects funded by ERDF in 2014-2020. Territorial Development Insights Series, JRC128452, European Commission.

4.9.3. National and regional Smart Specialisation Strategies (2014-2021)

Smart Specialisation is a place-based approach characterised by the identification of strategic areas for intervention based both on the analysis of the strengths and potential of the economy and on an Entrepreneurial Discovery Process with wide stakeholder involvement. It is outward looking and embraces a broad view of innovation including, but certainly not limited to, technology-driven approaches, supported by effective monitoring mechanisms.

Smart Specialisation Strategies have been an integral part of cohesion policy in the multiannual financial framework 2014-2020, as an *ex-ante* condition related to R&D ERDF investments. EU Member States and regions have developed over 120 Smart Specialisation Strategies (S3), driving research and innovation investments of overall over EUR 40 billion provided by the EU (EUR 68 billion including national co-financing). These strategies have been implemented by national and/or regional managing authorities through collaborative processes involving stakeholders, such as universities and other research and higher education institutions, businesses, industry and social partners.

In the following section, the territorial spread of smart specialisation priorities related to steel, chemicals and energy will be considered. Note that information on national and regional priorities should be considered together with actual spending on those priorities, as calls implementing the smart specialisation strategies usually address all priorities in a certain territory jointly (Gianelle et al, 2020)[164].

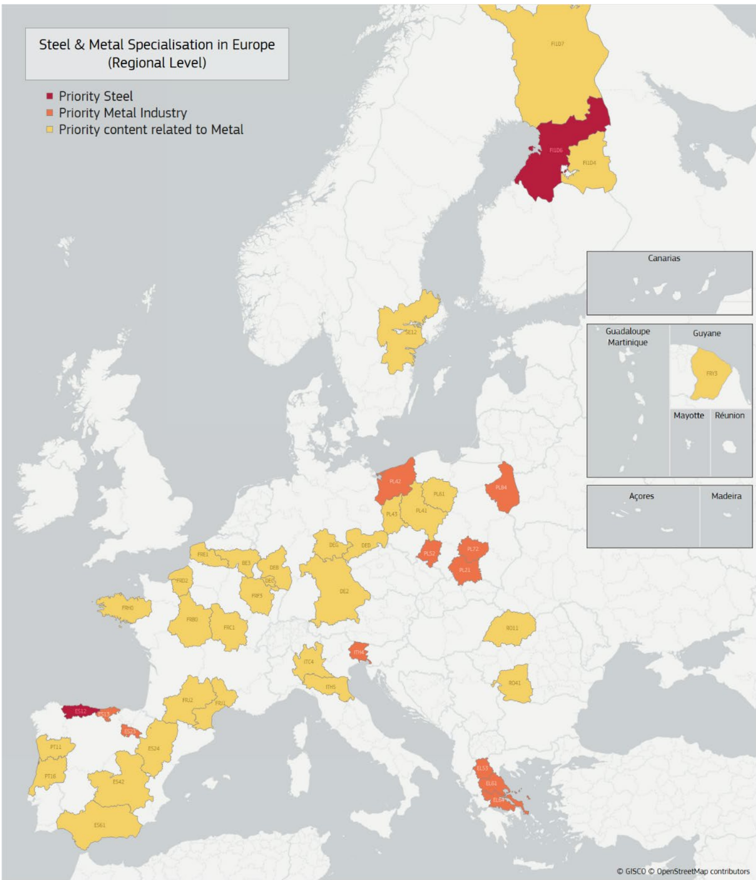
[164] Carlo Gianelle, Fabrizio Guzzo & Krzysztof Mieszkowski (2020) Smart Specialisation: what gets lost in translation from concept to practice?, Regional Studies, 54:10, 1377-1388, DOI: 10.1080/00343404.2019.1607970.

S3 | Territorial strategies targeting steel, chemicals and energy

- Steel and metal

When considering territories with traditional heavy industries, such as steel and metal among the core activities, their priorities often refer to the development and adoption of new technologies, capacities and processes addressing sustainability and competitiveness.

Figure 65 Regions with priorities on steel, metal and other activities related to metal



Source: JRC based on data from DG REGIO/Prognos, 2021.

Two European Regions, Northern Ostrobothnia and Principado de Asturias, have chosen 'Steel' as the higher level of their specialisation strategies. Additionally, 11 regions consider metal industries among their main level priorities and 43 others have, in different ways, included metal industries in the description of activities included in their prioritisation process.

In Finland, Oulu[165] in the Northern Ostrobothnia region is a clear example where the objective of innovation is to decrease the carbon footprint of the metal industry and to improve its global competitiveness by integrating the principles of digitalisation. Its research programme is built around steel refinement chains. The key technology involves corrosion- and wear-resistant steels and durable and lightweight steels, and their application in various product solutions related to, for example, the maritime industry and offshore operations. Cooperation is extensive and well networked.

Another interesting regional example is the RIS3 of Asturias, with open innovation centred on an integrated process of steel production (see Box 12).

[165] Oulu Region's Smart Specialisation.

Box 12 | **OPEN INNOVATION IN STEEL – THE ASTURIAS EXPERIENCE**

Principado de Asturias, in Spain, has been historically a steel production centre. The manufacture of steel in Asturias is responsible for the contemporary industrial profile of the region. ArcelorMittal Asturias is the only steel plant in Spain where the integral process of steel production is carried out. Downstream, the branch of manufacture of metal products registers the greatest volume of employment and companies of the region's manufacturing sector.

Asturias' 2014-2020 RIS3 Priority 'Asturias Industrial Steel Hub' has defined two main objectives: diversification for the markets by R&D and industrial leadership through technology. To these aims, ERDF Asturias OP has funded grants directed towards the execution of differential or leading R&D&I projects[166] and Primas Proof of Concept Programme[167].

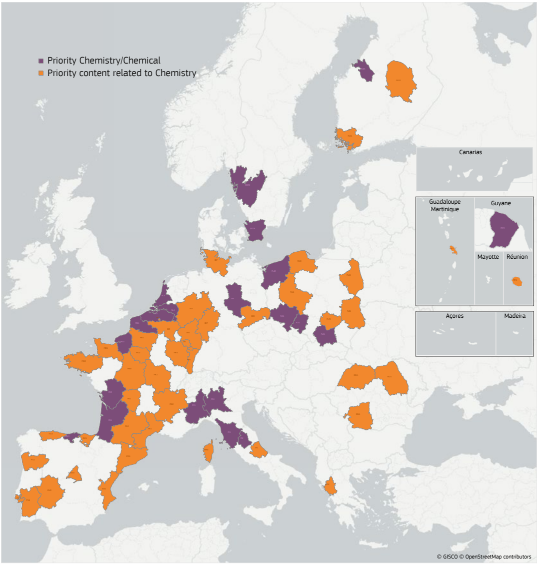
The R&D Centre of ArcelorMittal is developing an infrastructure, known as the Steel Square (S2) project, that consists of an integral steel process reproduction through pilot plants. This project will be an open innovation set of facilities for promoting a step forward in the steel value chain. To foster this facility, in the 2014-2020 framework the project 'Asturias Industrial Steel Hub' was carried out, co-funded by ERDF, aiming at the formalisation of a cluster focused on the development of R&D activities for the improvement of products and processes associated with steel.

- Chemicals

Chemical innovations are important for many downstream industries and foster solutions for societal challenges such as environmental protection, energy, and new materials. 'Chemicals' or 'chemistry' has been mentioned as part of the priorities of 66 European regions, and 7 countries contain this domain among the details of the description of their smart specialisation strategies.

Figure 66 indicates the regions with priorities on chemistry and other activities related to chemicals.

Figure 66 Regions with priorities on Chemistry and other activities related to Chemicals



Source: JRC based on data from DG REGIO/Prognos, 2021.

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[166] All projects funded under ASTURIAS RIS3 can be found at https://www.idepa.es/innovacion/asturias-ris3 duly classified by priority and topic.

[167] https://www.idepa.es/documents/20147/67715/dipticoris3steel.pdf/2e5e487d-12ee-6872-1dc4-c036a57ac1fa.

An interesting illustration is the smart chemistry specialisation strategy of Saxony-Anhalt (see Box 13).

Box 13 | **SMART CHEMISTRY SPECIALISATION STRATEGY OF SAXONY-ANHALT**

The RIS3 Saxony-Anhalt has defined the chemistry and bioeconomy sectors as an important innovation priority. To support the development of tangible innovation projects, a technology roadmap has been implemented. A first estimation of investment costs is also included.

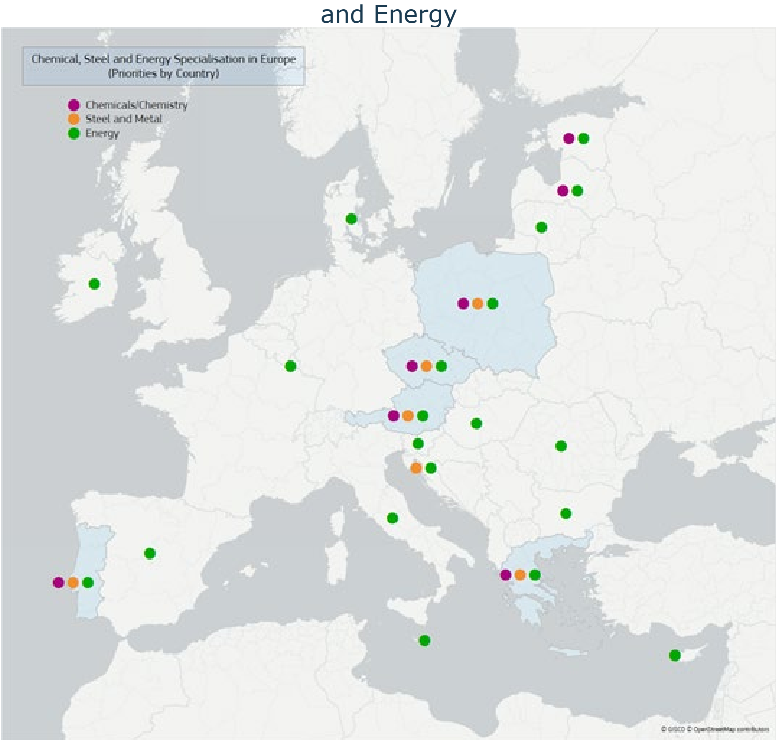
Over 100 stakeholders have been involved in this process. A questionnaire was developed and completed in order to identify the needs of the innovation players. The final technology roadmap contained several innovation project proposals for each sub-theme with a description of the partnership, thematic focus and financial estimates. These results have been discussed and adopted in coordination with the Ministry of the Economy, Science and Digitalisation. Based on the roadmap, the companies and research entities have developed specific project applications to be funded by ERDF[168].

- Energy

Energy is the most popular priority in S3. Most of the territories that mention energy in their priorities are focusing on developing processes and environmental techniques for the energy transition. Numerous regions and countries mention fuels as a sustainable option among the contents of their priorities related to energy. Three French regions consider hydrogen as a RIS3 priority. It is also interesting to note that two French regions have prioritised systems design for energy storage.

At national level, there are also countries with selected Chemical, Steel and Energy priorities domains, as illustrated in Figure 67.

Figure 67 Countries with priorities related to Chemistry, Steel and Other activities related to metal and Energy



Source: JRC based on data from DG REGIO/Prognos, 2021.

[168] Smart Chemistry Specialisation Strategy. Final Brochure of Phase 1.

4.9.4. Smart specialisation platforms and low-carbon technologies

Building on the international dimension of Smart Specialisation and based on their local priorities, EU regions have set up partnerships on areas of common interest and joined forces to exploit complementary strengths across Europe and build synergies with other regional, national and EU networks and initiatives. Those EU regions are committed to enhancing the development of EU value chains in new growth areas, and to generating a pipeline of investment projects implemented by using interregional cooperation, cluster participation, and the involvement of industry. Some 37 interregional S3 partnerships are running under the three thematic S3 platforms on Agri-Food, Energy and Industrial Modernisation, with almost 200 territories participating (at city, local, regional or country level), from more than 30 different EU and non-EU countries, engaging different typologies of stakeholders both from public and private sectors[169].

S3 | Industrial Modernisation partnerships

Almost 150 regions and countries have engaged in 24 interregional partnerships, with shared S3 priorities, intending to develop investment projects for industrial modernisation.

- Chemicals

The main objective of this partnership is the modernisation of the chemical industry to a sustainable, energy- and resource-efficient sector that is globally competitive and that provides innovative solutions.

Led by the regions of Limburg (Netherlands) and Lombardy (Italy), this partnership counts on the participation of Catalonia (Spain), Central Ostrobothnia (Finland), Mazowieckie (Poland), Saxony-Anhalt (Germany), Usti region (Czechia) and Wallonia (Belgium).

Within this partnership, the Interreg Europe project 'Smart Chemistry Specialisation Strategy' (S3Chem)[170] has been developed. From 2016 to 2021, the regions cooperated to strengthen smart specialisation strategies in the chemical and bioeconomy sectors.

The S3Chem project has looked at different dimensions for the improvement of ERDF policy instruments: better involvement of regional stakeholders and governance, project generation, funding instruments, and evaluation and monitoring. Based on good practices identified in several regions, an interregional learning process has been initiated. After three years of intensive exchange of experience, the partners developed an action plan that describes further concrete actions to improve their policy instruments for the promotion of innovation in the chemical and bioeconomy sectors.

- Metal

There is one relevant interregional partnership related to metal machinery, equipment: Sustainable Manufacturing, led by Auvergne Rhone-Alpes (France), Catalonia (Spain) and Lombardy (Italy). It is a pilot project born in the framework of the Vanguard Initiative. It is focused on technologies that aim at increasing throughput, quality, and environmental and social sustainability of manufacturing activities while reducing costs. Reducing emissions, energy, resources and materials consumption and increasing the inclusion of human people in factories are also targets of this partnership of 18 regions.

S3 | Energy and the Smart Specialisation Platform on Energy (S3PEnergy)

S3PEnergy promotes activities for achieving a shared vision on knowledge-based energy policy, accompanying European territories in the implementation of energy-related

[169] https://s3platform.jrc.ec.europa.eu/s3-thematic-platforms
[170] https://www.interregeurope.eu/s3chem/

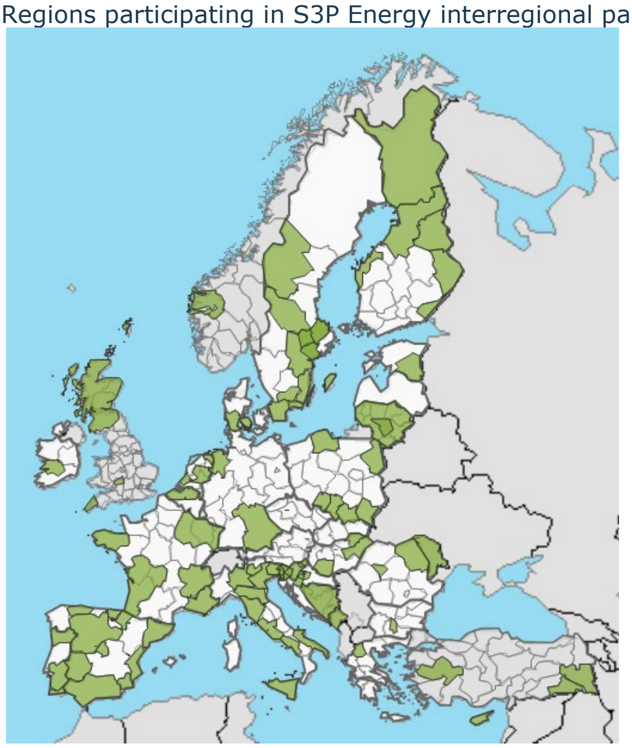
innovation strategies and supporting them with the appropriate methodological development and related tools, with regard in particular to benchmarking, mutual learning and interregional cooperation.

The goal of S3PEnergy is to set up a collaborative framework that will accelerate the development and deployment of innovative low-carbon technologies in the EU in the framework of Smart Specialisation. The participating regions in the S3PEnergy Interregional Partnerships are presented in Figure 68.

The list of interregional partnerships created under S3PEnergy are:

- Advanced Materials for Batteries, fully supported by Alliance for Batteries, is led by Andalusia and Castilla-Leon (Spain), together with Slovenia;
- Sustainable Building, led by Andalusia (Spain), North Great Plain (Hungary) and North-Croatia (Croatia) with more than 20 regions involved;
- Hydrogen Valley, a partnership that involves more than 50 regions and is led by Aragon (Spain) and Auvergne Rhone Alpes (France);
- Solar Energy, led by Alentejo (Portugal) and Extremadura (Spain);
- Smart Grids, led by Basque Country (Spain) and Provence-Alpes-Côte d'Azur (France); and
- Geothermal, led by Scotland (United Kingdom) and Tuscany (Italy).

Figure 68 Regions participating in S3P Energy interregional partnerships



Source: S3 thematic platforms, https://s3platform.jrc.ec.europa.eu/s3-thematic-platforms.

4.10 *European Regional Development Fund (ERDF) in 2021-2027*

In 2021-2027, the European Regional Development Fund (ERDF) (EUR 215.2 billion) will continue enabling investments into research and innovation to develop or take up low-carbon industrial technologies under its policy objectives. The aim is to make Europe and its regions more competitive and smarter - through innovation and support to SMEs, and digitisation and digital connectivity - and greener, low-carbon and resilient[171].

Based on their prosperity, all regions and Member States will focus their support on a more competitive and smarter Europe (first policy objective), as well as greener, low-carbon transitioning towards a net-zero carbon economy and resilient Europe (second policy objective), through the mechanism known as 'thematic concentration'. All regions and Member States will concentrate at least 30% of their allocation to become greener, low-carbon and resilient. More developed regions or Member States will dedicate at least 85% of their allocation to both objectives; transition regions or Member States will reserve at least 40% to the first objective and less developed regions or Member States at least 25%.

Operations under the ERDF are expected to contribute 30% of the overall EU financial support to reach climate objectives.

The Interregional Innovation Investments (I3) is a new funding instrument under the ERDF regulation (EUR 570 million for 2021-2027), implemented by the European Innovation Council and SMEs Executive Agency (EISMEA). It supports the commercialisation and scaling-up of interregional innovation projects having the potential to encourage the development of European value chains, and could be used to deploy low-carbon technologies across regions.

4.11 *Just Transition Fund*

The Just Transition Fund is one of the elements of the Just Transition Mechanism for a transition towards climate neutrality. It is implemented under shared management, under the overall framework of cohesion policy. The Commission provides grants to Member States having identified the territories expected to be the most negatively impacted by the green transition. The Just Transition Fund supports economic diversification and reconversion of the territories concerned. This means:

- investments in SMEs;
- creation of new firms;
- research and innovation;
- environmental rehabilitation;
- clean energy;
- up- and reskilling of workers;
- job-search assistance; and
- transformation of existing carbon-intensive installations.

It is expected to mobilise close to EUR 30 billion in investments from 2021 to 2027.

In order to unlock and implement Just Transition Fund resources, Member States are preparing strategic territorial just transition plans. These identify the eligible territories that are expected to be the most negatively impacted by the climate transition. The territorial just transition plans have to be prepared together with the relevant internal partners, in dialogue with the Commission, and must be consistent with the smart specialisation strategies and National Energy and Climate Plans.

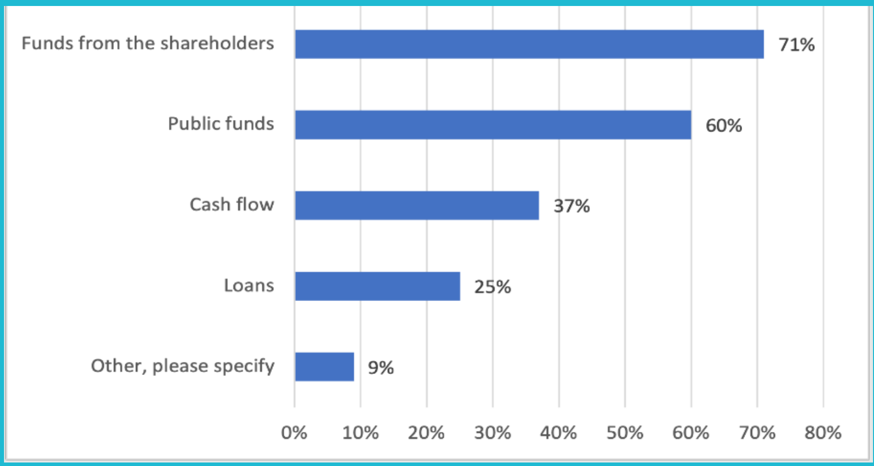
Territorial just transition plans have not yet been adopted by Member States but companies and sectors active in or comprising carbon-intensive industries will be beneficiaries of the Just Transition Fund for their transition to low-carbon technologies.

[171] Other priorities aim to make EU regions more connected (mobility), more social, supporting effective and inclusive employment, education, skills, etc., and closer to citizens.

SME Focus 5 | **RELEVANCE OF PUBLIC FUNDS & EU'S FRAMEWORK PROGRAMMES FOR FINANCING R&I**

Funding R&D activities performed by SMEs relies on two major sources: funds from shareholders and public funds (60%) and cash flow (37%).

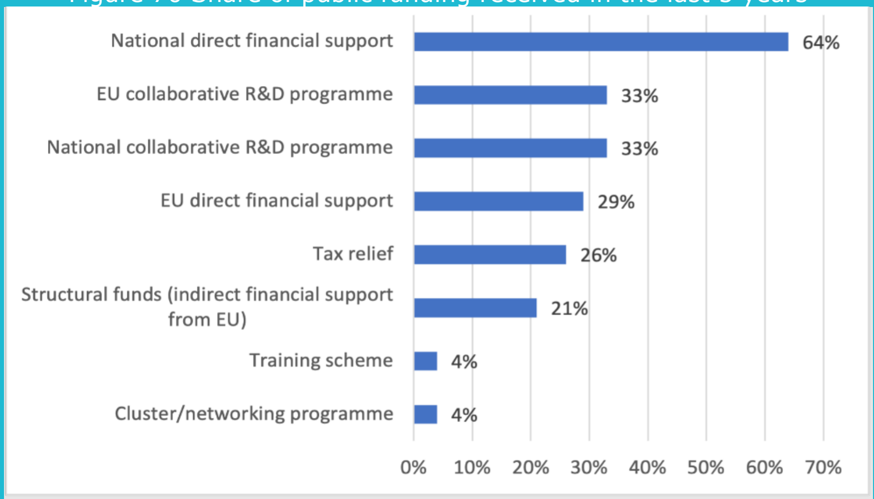
Figure 69 Share of R&D finance sources



Source: survey on technology developers, conducted from November 2021 to January 2022 (see Annex 1).

SMEs were further asked to give more information about the type of public funds available. For 64% of the companies, national direct financial support is the most important followed by projects funded within EU R&D programmes (33%). For 29% of companies, direct financial support from the EU is the most important, while for 33% it is funding from national R&D programmes.

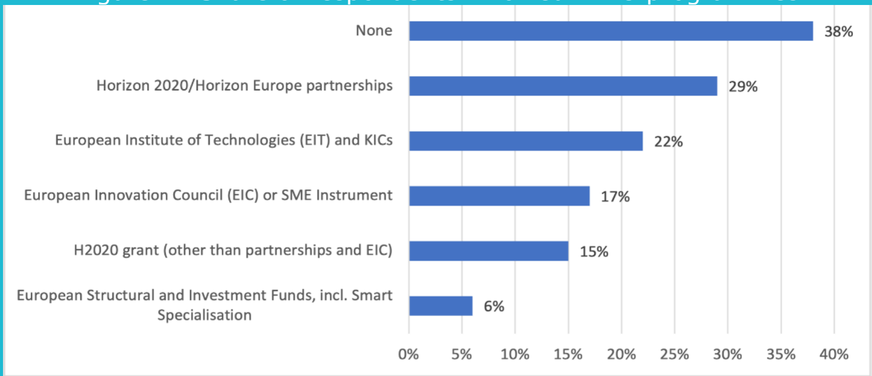
Figure 70 Share of public funding received in the last 5 years



Source: survey on technology developers, conducted from November 2021 to January 2022 (see Annex 1).

Respondents have mostly participated in the 'Horizon 2020/Horizon Europe partnerships' (29%). The most relevant programmes according to respondents are those provided through 'the EIT and KICs' (22%). However, 38% of the respondents claimed not to have participated in any EU funded programme. Thus, small technology developers are, as expected, involved in EU programmes more often compared to traditional SMEs (see below).

Figure 71 Share of respondents involved in EU programmes



Source: survey on technology developers, conducted from November 2021 to January 2022 (see Annex 1).

5 National investments and programmes

This section is the outcome of a series of meetings with Member States' representatives under the ERA Forum for Transition[172], in a subgroup 'Industrial technology roadmaps' created in March 2021. The meetings took place between July 2021 and January 2022. The subgroup was composed of 20 Member States: Austria, Belgium, Denmark, France, Finland, Germany, Slovenia, Sweden, Netherlands, Poland, Spain, Slovakia, Ireland, Czechia, Estonia, Malta, Greece, Italy, Portugal, Bulgaria, plus Norway as an associated country.

This overview of the existing initiatives for national support in research & innovation (R&I) towards industrial decarbonisation is based on the analysis of:

- Member States' recovery and resilience plans (RRPs) under the recovery and resilience facility[173];
- their national energy and climate plans (NECPs) submitted to the European Commission;
- the Commission's assessment of these RRPs and NECPs;
- and the own voluntary contribution from Member States.

5.1 *Recovery and resilience plans & national energy and climate plans: Member States' action towards climate neutrality under the scrutiny of the Commission*

The recovery and resilience facility (RRF) allows the Commission to raise funds to help Member States implement reforms and investments that are in line with the EU's priorities and address the challenges identified in country-specific recommendations under the

[172] The ERA Forum for transition was set-up as a governance structure to start implementing the renewed ERA strategy. The sub-group on industrial technology roadmaps was one of three sub-groups dedicated to specific actions. Following the adoption of the ERA Pact on research and innovation and the ERA Policy Agenda.

[173] The recovery and resilience facility is at the core of *NextGenerationEU*, a financial instrument that allows the Commission to raise funds to help repair the immediate economic and social damage caused by the coronavirus pandemic. RRF is closely aligned with the Commission's twin transition – the green and digital transformation of economies.

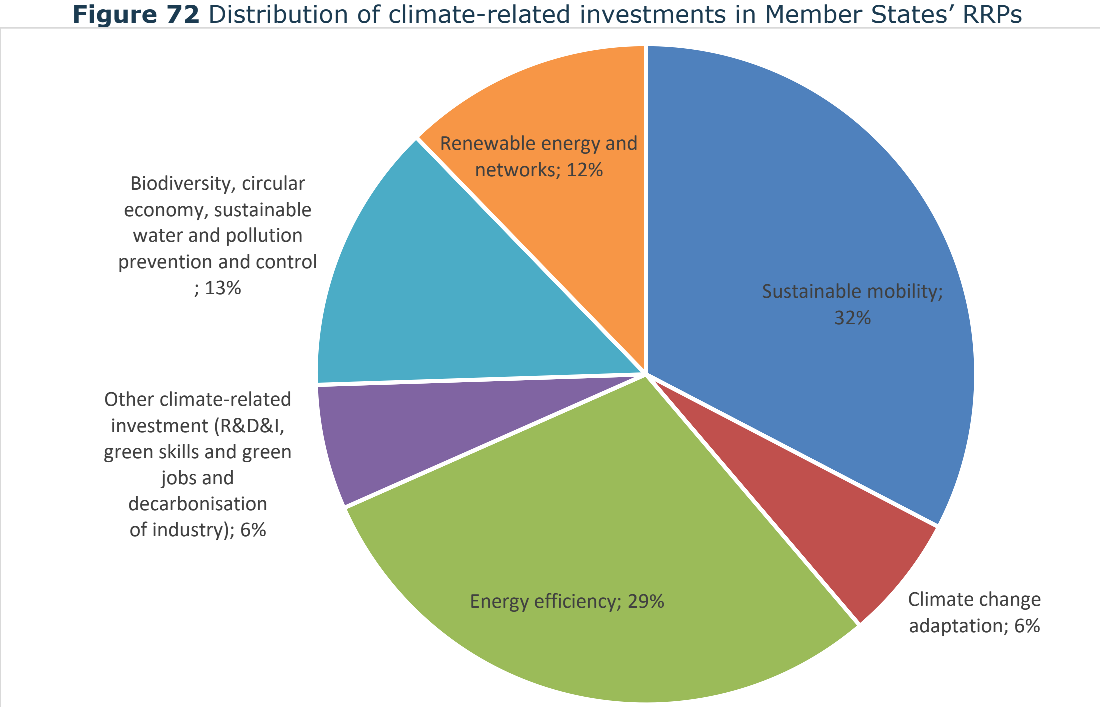
European Semester framework of economic and social policy coordination. It makes available EUR 723.8 billion in loans and grants for that purpose.

Member States' RRPs are expected to boost climate-related investments by at least EUR 177 billion (which represents a total of 40% of the total allocation in grants and loans) and strengthen necessary reforms in order to support the climate and energy transition[174]. In October 2021, the Commission approved 22 RRPs that have allocated 40% of their spending to climate measures. This goes beyond the 37% climate target (mainly in the areas of sustainable mobility, energy efficiency in building renovation, renewable energy and networks). About 43% of this amount (EUR 76 billion) is dedicated to energy efficiency[175]. However, it is expected that the bulk of the funds will go on energy renovations in private buildings and public infrastructure and construction of buildings, and only part will cover energy efficiency in industry, including SMEs.

The RRF is meant to accelerate the green transition of European industry. It will directly target sustainable industry (including support schemes for industry in key green areas, industrial applications of hydrogen and remanufacturing measures), but will also go beyond that. Investments in the circular economy, renewable energy and networks will contribute to more resource- and energy-efficient industrial production. Hydrogen-related measures, which may provide a useful industrial feedstock and are particularly relevant for energy-intensive industries, or the construction of industrial sites using renewable energy fall under the categories of renewable energy, R&I and energy efficiency, depending on the type of measure.

The overall volume of RRF-funded R&I investment is in the order of EUR 44 billion, of which about 37% tagged as contributing to the green transition. Although there is further scope for deepening the R&I reform efforts, we also need to consider the development and uptake of low-carbon industrial technologies.

Figure 72 Distribution of climate-related investments in Member States' RRPs



Source: Report on the implementation of the Recovery and Resilience Facility COM(2022) of 1.3.2022.

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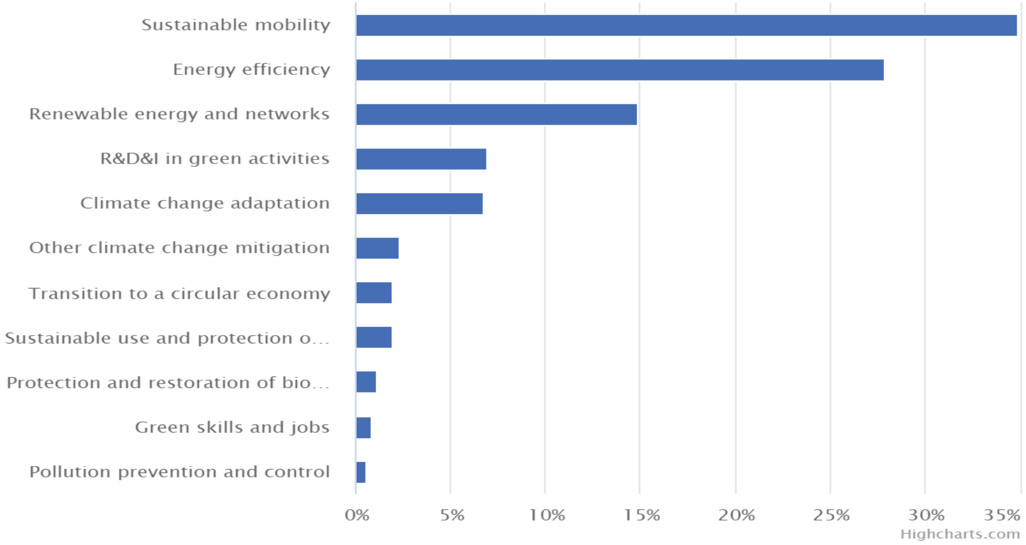
[174] State of the Energy Union Report 2021.
[175] See COM(2021) 952 final, 26 October 2021, Report from the Commission to the European Parliament and the Council. Progress on competitiveness of clean energy technologies, p. 6.

According to the Commission's analysis[176], 6% of the RRPs overall address R&D&I in green activities under the Green transition pillar.

Figure 73 Breakdown of expenditure in terms of climate objectives per policy area



Note: Each recovery and resilience plan has to include at least 37% of the plan's total allocation supporting climate objectives. To this end, the plans had to specify and justify to what extent each measure contributes fully (100%), partly (40%) or has no impact (0%) on the climate objectives. The contributions to climate objectives have been calculated using Annex VI of the RRF Regulation. Combining the coefficients with the cost estimates of each measure allows the Commission to assess to what extent the plan contributes to the 37% climate target.
Source: European Commission, Recovery and Resilience scoreboard.

In general, the RRPs complement or are linked to the NECPs[177]. These plans give an overview of how Member States are approaching their transition towards climate neutrality for 2021–2030 in non-ETS sectors across five areas: decarbonisation, energy efficiency, energy security, internal energy market, research and innovation and competitiveness, as well as R&I in support of these policies. Low-carbon technologies used in ETS sectors (incl. energy-intensive process industries) are not in their focus.

The Commission's overall assessment of the NECPs in 2020[178] concluded on research, innovation and competitiveness, that there was a lack of detail and underlines the importance of linking R&I policies to match the energy and climate ambitions. Some progress is noted in terms of regional cooperation and by linking energy and climate policies to environment policies, though there is still space for improvement.

In both cases of the RRPs and NECPs, the level of details provided by the Member States dos not enable the Commission to properly monitor and map the national support, all the less the amounts, dedicated to development and uptake of low-carbon technologies.

The European network of energy agencies (EnR), currently under the presidency of the French Agency for ecological transition (ADEME), has also published a comparative study on the role of the European energy network agencies in the implementation of industry decarbonisation public policies[179]. The study finds out that national energy agencies have a wide range of tools at their disposal. The main ones used are grants, R&D and training

[176] Recovery and Resilience Scoreboard (europa.eu)
[177] National energy and climate plans (NECPs) ; https://ec.europa.eu/info/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en.
[178] EU-wide assessment of National Energy and Climate Plans, COM(2020) 564 final.
[179] https://librairie.ademe.fr/energies-renouvelables-reseaux-et-stockage/5298-comparative-study-on-the-role-of-the-european-energy-network-agencies-in-the-implementation-of-industry-decarbonisation-public-policies.html.

programmes, database management and communications campaigns. One third of agencies are also conducting forecasting studies or implementing certification programmes.

The study also highlights the driving role played by EnR, establishing itself as a platform that the various agencies can use for sharing knowledge and good practices, as well as discussing experiences. In the same direction, the ERA subgroup members have underlined during the various discussions the need for better knowledge sharing across the EU.

5.2 *Strategies related to industrial decarbonisation and R&I*

In the requirements for the recovery and resilience plans, Member States were asked to allocate a minimum of 37% of investments to the green transition. For many EU countries, industry makes up a significant share of their greenhouse gas emissions. Some of them have set up national targets to reduce these emissions. Therefore, most of the subgroup members have a dedicated programme for industry decarbonisation that often also focuses on energy-intensive industries. However, most of these programmes mainly address the production of clean energy for industry (including hydrogen). Their contribution to the development and uptake of industrial technologies for the use of clean energy in energy-intensive industries remains unclear.

Below are listed the main programmes that were described in the NECPs and RRPs:

- New Energy for Industry & Wasserstoffinitiative Vorzeigeregion Austria Power & Gas (Austria);
- Vlaanderen CO2-neutraal (Belgium);
- Roadmap for the decarbonisation of energy-intensive industries (Estonia);
- Long-Term Decarbonisation Strategy 2050 (Spain) & Spain 2030 Industrial Policy;
- Decarbonisation of industry strategy & National Low-Carbon Strategy (France);
- Fund for the decarbonisation of the enterprise sector (Ireland);
- Electricity & industry plan (Netherlands);
- 2050 Carbon Neutrality Roadmap (Portugal);
- Industriklivet initiative (Sweden): SEK 300 million per year for R&I&D funding in 2018-2040;
- Slovenian Industrial Strategy;
- Low-carbon development strategy of Slovakia until 2030 with a view to 2050.

However, a few RRPs and NECPs do not cover industry at all (Malta, Greece) or only a little (Italy).

Similarly, most of the R&I programmes described or mentioned in the RRPs and NECPs focus on energy. Below are listed most of them:

- Innovation Strategy for Smart Specialisation, 2021-2027 (Bulgaria);
- THETA programme for 2018-2025 (Czechia);
- 7th Energy Research Programme (Germany) from 2018, which provides annual funding of EUR 1.301 billion, including for overarching, cross-sector issues such as sector coupling, digitisation, energy efficiency, reduction of consumption at different TRLs;
- Research, development, innovation and entrepreneurship 2021-2035 (Estonia);

- The Spanish Pact for Science and Innovation has earmarked EUR 81 million for climate change, new energy sources and materials for energy transition, including some projects for the development and upgrade of pilot plants for CO_2 recovery in energy-intensive industries, in particular steel and cement, based on technologies developed by the National Council for Research;
- Smart and clean energy, sustainable manufacturing & smart industry (Finland);
- National Energy Research Strategy (France);
- National Energy Research Development & Demonstration Funding Programme (Ireland);
- National research programme on climate (Sweden);
- Research and Innovation Strategy (Slovenia).

When not part of a dedicated strategy, some Member States also invest in this topic under the recovery and resilience facility, such as Slovakia with their component 'Research and innovation for the decarbonisation of the economy' (component C9, Investment 4), which amounts to EUR 79 million; or Denmark with their component 'Green research and development', which promotes green R&D projects. It will fund four R&D missions, including carbon capture, utilisation and storage. Around 25% of the budget appears to go to the 'Power Up' flagship area[180], and a significant amount supports the manufacturing sector.

Although most Member States cover energy aspects under their R&I plans, in the RRPs and NECPs they often fail to explain the ultimate purpose of these investments in energy, in particular their use, as well as clear targets.

5.3 *Specific schemes for development and towards deployment of green technologies*

One of the most frequent outcomes of the series of meetings is the acknowledgement that there are no dedicated schemes for the specific technologies or specific stages of development.

As regards hydrogen as a source of energy, almost all Member States plan to focus on it in their decarbonisation plans (except for Bulgaria, Czechia, Malta and Slovenia, at least not in their RRPs and NECPs) but not necessarily in order to use it in energy-intensive industries. Often the focus is on transport and the production of energy for consumption. The Member States that specifically mention industry in their hydrogen strategy are mostly western European countries: Austria, Belgium, Germany, Spain, Finland, France, the Netherlands and Sweden, together with Poland and Slovakia.

Apart from hydrogen — which is not a technology but an important component of some major decarbonisation technologies — there is no dedicated investment scheme for a specific technology considered key for decarbonising energy-intensive industries.

However, some Member States do have some dedicated funds for green technologies in general: the *Green Technology Investment Programme* in Estonia, the *National Energy Research Development and Demonstration Programme* in Ireland and the *National Growth Fund* in the Netherlands.

Although Member States insist on the importance of being technology-neutral, some focus on specific low-carbon technologies in their decarbonisation strategies. This is the case in particular in the Nordic countries: for instance, Denmark puts the emphasis on the Power-to-X technology (falls under the pathway 'electrification'); Finland on electrification of processes and Sweden has a dedicated programme HYBRIT (*HYdrogen BReakthrough*

[180] https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1658.

Ironmaking Technology) focused on the use of green hydrogen in the steel and iron sector. Elsewhere in the EU, it is worth highlighting the emphasis that Spain puts on the CO_2 capture and calcium looping technology. The Netherlands has given priority to the use of biomass in the chemical industry with its *Agri-Based Chemicals* programme (see Box 14). This aims to set up a sustainable sugar-based chemical and materials manufacturing industry.

Box 14 | **AGRI-BASED CHEMICALS PROGRAMME (NL)**

This programme aims to make plastics produced from biological raw materials available on a large scale. The programme will act as a catalyst to expand the bio-based agrochemical materials industry in the Netherlands. The expected annual GDP, high-quality jobs and CO_2 sequestration effects for 2050 amount to EUR 2.7 billion, 4,800 jobs, and 4 to 6 Mton CO_2 respectively.

Some Member States have chosen to develop sector-specific decarbonisation programmes. The pioneer here is Finland and its 13 sectoral low-carbon roadmaps, which have been developed by each sector. These involve all stakeholders and take into account the specifics of each industry. Similarly, the *Fossil free Sweden* initiative launched in 2015 invited all business sectors to produce roadmaps on how to become climate-neutral by 2045 while increasing their competitiveness: 22 industry roadmaps are being developed, including the energy-intensive industries. Following those paths, Estonia is preparing sectoral development plans; while Germany is working on carbon-neutral production processes in 56 hard-to-decarbonise industrial sectors.

On a smaller scale, Spain is developing *Strategic projects for recovery and economic transformation* that build public-private partnerships in certain technologies and sectors. Under the *Polish Hydrogen Strategy,* Polish companies and industrial associations, universities, RTOs and non-governmental organisations have signed sectoral partnerships on hydrogen.

In general, public-private partnerships are a convenient way of working towards industrial decarbonisation. Other examples across the EU include two large-scale private-public initiatives in the chemicals sector in the Netherlands: *Groene Chemie Nieuwe Economie* and the Advanced Research Center Chemical Building Blocks Consortium. Spain has large-scale projects partnering with the private sector in the steel and cement sectors with ArcelorMittal and LafargeHolcim. Finland has a joint project between companies and universities on carbon-neutral steel production (*Towards Carbon-neutral Metals*, see Box 15).

Box 15 | **TARGETED SUPPORT IN FINLAND FOR LOW-CARBON ROADMAPS & PROJECTS**

In Finland, 13 industries have developed their low-carbon roadmaps in close cooperation with key companies, public authorities and other stakeholders. Electrification of processes has been identified as the key tool.

In parallel, many joint projects under private-public partnerships have been funded. These include:

- Joint project between companies and universities: carbon-neutral steel production (Towards Carbon-neutral Metals,);
- LUT (Lappeenranta-Lahti University of Technology) University Research Platform: Green Hydrogen and CO2 for Industry Renewal (GREENRENEW);
- GreenE2: building innovation ecosystem between different sectors to facilitate a carbon-neutral industry through electrification and green hydrogen.

The national innovation agency Business Finland supports business-driven research, innovation and business development through several programmes, including smart and clean energy, sustainable manufacturing and smart industry.

5.4 *Schemes on specific stages of technology development*

Most countries focus on all stages of technology development. But some have specific programmes for R&D and demonstration (lower TRLs), or focus instead on development and uptake (higher TRLs).

Some examples of research & demonstration:

- Denmark set up a fund of EUR 17 million to support demonstration projects in energy storage.
- The Austrian *Klima- und Energiefonds* funds projects in applied research & innovation, testing and implementation of low-carbon technologies.
- The German *Energy Research Programme* supports application-based research. SPRIN-D, the federal agency for disruptive innovation, supports projects with the potential for breakthrough technologies (see below).
- The Finnish Innovation Agency supports business-driven research, innovation and business development through several programmes.
- France funds research and demonstration projects focused on hydrogen for industry.
- The Swedish *Industriklivet* initiative provides support to companies at every step, from R&I projects to pilot and full-scale plants.
- Slovenia encourages investment in green R&D&I demonstration and pilot projects.
- Bulgaria has introduced incentives to encourage the private sector to invest in R&D&I in widely used production methods aimed at optimum resource efficiency.

Box 16 | **SPRIN-D, FEDERAL AGENCY FOR DISRUPTIVE INNOVATION: THE GERMAN EIC?**

This agency provides targeted support to scientific experts and entrepreneurs to help bring breakthrough innovation to the market.

The innovations need to have breakthrough potential and already be at TRL 3 or 4.

In 2021, the agency received 375 applications. After an initial in-depth analysis, around 7% of the projects were found to have the potential for disruptive innovation. After further analysis and a decision based on the findings of the agency's experts, around 3.5% of the projects were pursued further.

More info: https://www.sprind.org/en/

Here are a few examples of national programmes that focus on uptake & deployment:

- Denmark will support and develop research on power-to-X development and upscaling.
- The Estonian *Green Fund* supports the development and uptake of green technologies.
- The Dutch *National Growth Fund* supports the application of green hydrogen in chemistry, heavy transportation and process industries.
- Spain will upscale pilots of CO_2 capture and calcium looping.

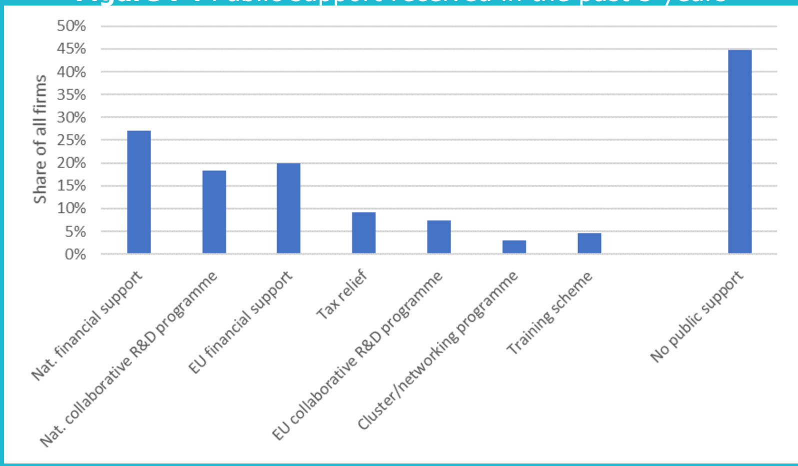
There are also some schemes that look at the entire value chain. The French *Future Investments* programme covers the entire innovation value chain, including priority research programmes and equipment (TRL 1-4) & maturation (TRL 3-7), and has earmarked EUR 20 billion in R&I for 2021-2025. The Swedish *Industriklivet* initiative provides support to companies at every step – from R&I projects to pilot and full-scale plants. In Slovakia, EUR 78.7 million from the RRP will be directed towards the entire R&I cycle (TRL 1 to 9). The largest allocation will be channelled to demonstration projects and more advanced TRLs on green decarbonisation themes.

One final scheme of interest is the one set up by the Sustainable Energy Authority of Ireland. This provides market support to the energy/low-carbon technology sector and technology-related policy support.

SME Focus 6 | **SMES' RELIANCE ON NATIONAL FUNDING FOR R&D&I**

DG R&I's survey analysed the role of public funding and its relevance for SMEs. According to the participating companies, national financial support is the type of public funding most availed of. More than a quarter of the responding companies indicated national financial support as the most relevant type of public support received in the past five years to deal with developing or adopting new environmental technologies. Around one fifth of the firms use financial support from the EU.

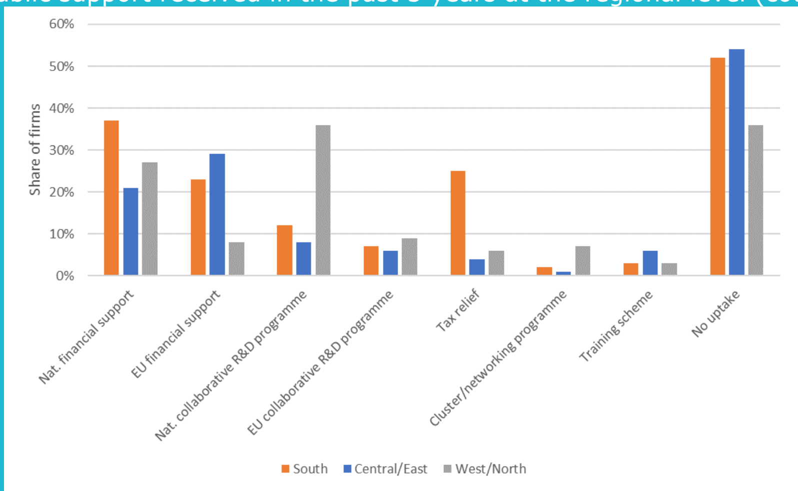
Figure 74 Public support received in the past 5 years



Source: European Commission / Enterprise Europe Network SME survey, conducted from November 2021 to January 2022 (see Annex 1).

Regarding the company's location, the survey illustrates various differences between EU regions. SMEs in southern Europe seem to have the easiest access to national financial support, while SMEs in central/eastern Europe find it easiest to get funding from the EU. National collaborative R&D funds are particularly relevant for SMEs in western/northern Europe.

Figure 75 Public support received in the past 5 years at the regional level (country groups)



Source: European Commission / Enterprise Europe Network SME survey, conducted from November 2021 to January 2022 (see Annex 1).

6 Conclusions on R&I investments

6.1 *R&I needs and public and private investments*

- Overall, the transition will require investments estimated at more than EUR 800 bn until 2050. The biggest investment needs will be in the chemical sector, followed by steel and cement, estimated at additional EUR 3.9-5.5 billion per year on average.

- Scenarios, studies and R&I investment trends show that there is a gap between current overall R&I investments across sectors and the amount needed to reach European Green Deal emission targets. This requires major acceleration in low-carbon innovation and a significant rise in R&I investments.

- The highest R&I investments should happen in the coming years (estimated at somewhat above EUR 20 billion until 2030), together with increasing deployment investments with a peak around the mid- to end 2030s.

- The biggest investment gap concerns R&I investments over the coming eight to twelve years for first-of-a-kind installations, large-scale demonstration and deployment of technologies currently at high TRLs. Given the risks associated with the needed large investments, risk sharing and public support are needed.

- Most EU R&I investments in energy efficiency in industry are private (around 80%). They need to be further increased to match the substantial R&I investment needs, especially by 2030. Relevant R&I investments have to be ensured in the short term, given the long investment cycles of energy-intensive industries.

- Although public funding for energy-related R&D increased from 2014 to 2018, it has still not reached the level of 2010.

- Greater participation by Member States in energy efficiency in industry under the revised Strategic Energy Technology Plan and the European Research Area policy agenda could facilitate increasing R&I investments in development and uptake of low-carbon technologies across the EU.

- More specific estimations on existing and needed investments and funding, and regular monitoring of data on low-carbon industrial technologies in different sectors of energy-intensive industries will require more systematic availability of annual data with sufficient quality and granularity. The Energy Union and Climate Action Governance Regulation and its reporting provisions could be used as to promote the provision of better data, monitor the impact of policies and adjust investments.

6.2 *Patents*

- Patent filings in green inventions across industrial sectors continue to increase globally, which gives an early indication of continuing technological and economic developments towards the green transition of industry. Patents, which address energy-intensive industries account for about 5% of these green inventions on average.

- Among the EU Member States, the Netherlands had the highest share of green inventions addressing the energy-intensive industries in focus (14%), while Denmark leads on overall green patenting (21%).

- The propensity of patenting in the area of EIIs may be related to the importance of large incumbents such as the companies in the Industrial R&D Investment Scoreboard which may be more likely to develop and keep knowledge in-house.

- The role of SMEs in energy-intensive industries' inventions remains unclear, as the roadmap analysis reveals only the top patenting positions taken by large incumbents. Considering that other inventors, such as young firms, may develop more radical innovations[181], this suggests the need to analyse further the opportunity to strengthen their contribution to innovation in low-carbon technologies.

- Between 2010 and 2018 the EU has more or less maintained the same level of specialisation in the energy-intensive industries in focus, meaning that EU industry puts a constant level of capacities into green energy-intensive industries' inventions. An exception are the fertiliser and steel industries where there has been a marked drop in inventive activity. While the EU still has the second highest share of inventions related to steel (16%), this suggests the need to verify the main drivers for the clear negative trend in these two EII sectors.

- Regional hotspots in EII green patenting show potential for a leading role in low-carbon industrial technology clusters for Île de France, South-Holland, Oberbayern and four other German regions. Maps of hotspots show a varied leadership across several specific EII sectors.

6.3 *EU programmes addressing low carbon industrial technologies*

Centrally managed programmes

- Horizon Europe, including the newly established European Innovation Council (EIC) and the European Institute of Innovation and Technology, support the development of breakthrough low-carbon technologies. European partnerships with industry, funded by Horizon Europe (Processes4Planet and Clean Steel Partnership), create a critical mass of funding with industry partners.

- InvestEU is expected to mobilise, by the end of 2027, substantial private and public investment (with a multiplier effect of 11.4) including for the development and deployment of low-carbon technologies (Sustainable infrastructure window: EUR 9.9 billion; R&I window: EUR 6.6 billion). The Innovation Fund will also provide support over the period 2020-2030 for the commercial demonstration of innovative low-carbon technologies (EUR 25 billion* depending on the carbon price (* at EUR 50 / tCO_2)).

- European R&I funding programmes support important stakeholder cooperations and set directions with a relative small part of overall public funding for R&I in Europe. Even if specifically for low-carbon technologies for energy-intensive industries the leverage has been higher than the average, the framework programmes cannot be expected to cover the major investments in the development and especially deployment of low-carbon technologies that are needed to reach the 2030 emissions reduction target and climate neutrality in 2050.

Programmes under shared management

- In the last programming period (2014-2020), regions used approximately 15% of ERDF funding to finance projects related to low-carbon industrial technologies (EUR 26.5 billion). In the current programming period (2021-2027), all regions will devote at least 30% of their allocation to priority 2 (a low-carbon transitioning towards a net zero carbon economy and resilient Europe).

- The Interregional Innovation Investments (I3) instrument is a new EUR 563.5 million funding instrument under the ERDF. It supports the

[181] Amoroso, S. et al (2021), World Corporate Top R&D Investors: Paving the way for climate neutrality. A joint JRC and OECD report, Publication Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-43373-6, doi:10.2760/49552, JRC126788.

commercialisation and scaling-up of interregional innovation projects and can be used to fund low-carbon technologies.

- Not all Member States with high emission intensity allocate significant ERDF funding to low-carbon projects. For example, overall ERDF funding intensity for low-carbon projects (R&I and beyond) is comparatively low across all regions in Belgium and Austria and Estonia. Some Member States have national R&I schemes, which also support decarbonisation investments in energy-intensive industries, but their relevance and magnitude for development and uptake of low-carbon technologies is difficult to gauge.

- Most widening countries have smaller shares of overall greenhouse gas emissions at European level (see Chapter 1). Nevertheless, for their national emissions, energy-intensive industries still play a significant role (especially in Czechia, Romania and Slovakia), making support for decarbonisation an important element to consider in national policies.

- However, overall ERDF funding intensity for low-carbon projects is higher in several regions of widening countries, such as Croatia (across the country), Lithuania, Poland, Romania and Slovakia, as compared with regions in more innovative Member States.

- In terms of closing the innovation divide in the area of low-carbon technologies, it is notable that R&I investment per capita under the ERDF in low-carbon projects is higher than average in several regions of central & eastern European Member States, such as Czechia, Estonia, Hungary, Latvia, Lithuania and Poland (alongside Finland).

- Interregional projects as part of the Smart Specialisation Platforms (for industrial modernisation) have generated cross-border investment in low-carbon projects. This is especially so in regions from Member States with high emissions per capita and lower than EU average ERDF investment in low-carbon projects, such as Belgium, Austria, Estonia, Czechia, Germany and Cyprus (as shown in Table 7).

SMEs

- The biggest barrier for SMEs in developing or adopting new environmental technologies comes from investment costs. Other major barriers identified by SMEs in developing and/or adopting environmental technologies include the unknown cost-benefit ratio, lack of demand from customers and regulatory barriers.

- Most SMEs involved in technology development expect the EU to provide better access to venture capital funds to support innovation and deliver environmental technologies. For the uptake of technologies, SMEs in all EU regions expect more research funds from the EU to support the adoption of environmental technologies.

- A stricter environmental regulation and the reduction of regulatory barriers are considered as important. SMEs that are not particularly active in technology development often called for raising awareness and providing training and education.

6.4 *National support schemes and strategies*

National schemes

- Under the Recovery and Resilience Facility, an estimated 6% of expenditure supporting the green transition goes to R&I. A variety of support instruments tackles the decarbonisation of energy-intensive industries as part of national recovery and resilience plans and infrastructures.

- The 22 recovery and resilience plans approved so far go beyond the requirement of at least 37% of climate investment of the total allocation of EUR 177 billion. Overall, total estimated expenditure in clean power – renewables and networks - is around EUR 26.7 billion, with the largest amount for renewable energy generation, and important investments in the hydrogen value chain and energy networks.

- All Member States with energy-intensive industries have put their decarbonisation in their industrial, green and R&I agendas.

- Also, in most Member States, some support instruments are available to tackle the decarbonisation of energy-intensive industries. However, it is a challenge to identify the actual budgetary resources, partly because some support schemes take a cross-cutting approach for R&D support, or technologies for energy-intensive industries are addressed in energy-related programmes.

- Several Member States have developed sector-specific roadmaps towards decarbonisation, in cooperation with relevant stakeholders (such as in Finland, Sweden, Germany and Slovenia). These are important instruments designing a detailed process with milestones towards commonly agreed emission reduction (and other) targets.

Synergies between EU instruments and national funding schemes

- Several EU support instruments provide funding opportunities for R&I and innovation for the decarbonisation of energy-intensive industries. They are mostly complementary with their specific priorities and have their own rules. The Commission is engaging in improving the links and cooperation between services and institutions in order to implement and capitalise on synergies.

- The EIC Plug-in scheme enables projects selected by national and regional programmes to apply faster to the EIC Accelerator.

- A guidance document on synergies between Horizon Europe and the ERDF will promote synergies, including the Seal of Excellence that allows Member States to take advantage of the Horizon Europe evaluation process.

- Potentially, national programmes under the ERDF and the Recovery and Resilience Facility could also benefit further from the selection process of other EU instruments, such as the Innovation Fund.

- Horizon Europe partnerships or InvestEU can be used as a vehicle for funding under the Recovery and Resilience Facility. National promotional banks will be involved in InvestEU as implementing partners, which might yield opportunities for future synergies with national funds.

- The Processes4Planet Partnership has set up an impact panel to facilitate the launch and market uptake of projects by public or private investors. It does this by establishing links with national programmes and interested Member States, the Innovation Fund and the European Investment Bank.

- The available information on national and regional strategies and programmes gives a rather fragmented picture with limited synergies between EU and national and regional instruments. The gap as regards synergies between support instruments at EU and the national level could be explained by the lack of any broad and open platform to establish strategic roadmaps and efficient coordination of research, development and innovation investment plans for low-carbon industrial technologies.

CHAPTER 4: FRAMEWORK CONDITIONS

Besides funding and performing R&D&I (as presented in previous chapters), there are various conditions covering non-technological, organisational and economic factors that enable the development and uptake of low-carbon technologies.

This chapter looks at the EU regulatory framework conditions and describes the relevant legislation for the energy-intensive industries (EII) ecosystem. It addresses enabling framework conditions for research and innovation (R&I) activities targeting the development and uptake of new low-carbon technologies. It matches barriers, identified through consultations, to existing EU initiatives that address similar barriers in related sectors. The chapter looks at the role of digital technologies in decarbonisation, State aid rules and their relevance for R&I, and sustainable taxonomy.

Building on the regulatory conditions, the chapter explains the valorisation of R&I results, analyses available tools at EU level for knowledge valorisation and looks in detail at one of its key parts – the role of standards.

1 Regulatory framework conditions

The existence of multiple barriers and market failures faced by low-carbon innovation, requires policy action to address those[182]. Regulation plays a crucial role for the development and uptake of new low-carbon technologies. The EU and Member States' regulatory frameworks are expected to be essential in the successful green transition of the energy-intensive industries ecosystem.

1.1 *EU regulatory framework for energy-intensive industries*

The EU regulatory framework is important for research and innovation in energy-intensive industries, as technology development and uptake is crucial for transforming the industrial ecosystem and contributing to emissions reduction targets set out in the European Green Deal. Energy-intensive industries are high emitters and so are directly targeted by a series of EU legislative packages. Since 2019, the regulatory framework has shifted radically to reflect the EU's ambition to be the first climate-neutral continent by 2050, through a total reduction of greenhouse gas emissions, and to reduce emissions by at least 55% (compared to 1990) by 2030. The European Green Deal sets a new vision for European industry to achieve climate neutrality by 2050 by looking to new and low-emission technologies, sustainable products and services[183].

The 2021 Autumn Package of the European Semester[184] highlighted that a significant investment is required to meet the European Green Deal's ambitions. An additional EUR 520 billion will be needed every year to cater for the green transition. A large portion of this amount will need to be provided through private investment, including in R&D and new technologies. Regulatory frameworks, at both EU and national level, are therefore designed to support the necessary ambitions for decarbonising and transforming EU industry.

[182] On a range of barriers and market failures, please see OECD (2022, pp.14-16), *Forthcoming*.
[183] A European Green Deal, https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/industry-and-green-deal_en.
[184] COM(2021) 740 final, https://ec.europa.eu/info/system/files/economy-finance/2022_european_semester_annual_sustainable_growth_survey.pdf.

Long before the European Green Deal, energy-intensive industries were regulated through different EU laws to make industry more sustainable and to tackle the effect of emissions on the environment. The applicable legislation includes the EU Emissions Trading System (EU ETS) Directive[185], the Industrial Emissions Directive (IED)[186], the Extractive Waste Directive[187], and the Environmental Impact Assessment Directive[188].

One of the most prominent and important laws is the EU ETS, which concerns CO_2 emissions from energy-intensive industries. These industries include steel works, oil refineries, and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals. All plants must participate in the EU ETS, with some exceptions (i.e. smaller plants, installations used for research, innovation and testing of new products and processes). The ETS Directive was revised in 2018 to ensure emissions reductions of at least 40% compared to 1990 (as part of the EU's contribution to the 2015 Paris Agreement). The Commission proposed a further revision of the ETS Directive in 2021 as part of the Fit for 55 legislative package, in order to bring it in line with the overall Green Deal target of reducing emissions by at least 55% compared to 1990[189].

Box 17 | **FIT FOR 55**

The Fit for 55 package, adopted in July 2021, is a comprehensive legislative mix, which covers the energy system, industry, transportation and buildings. With Fit for 55, the Commission ensures that the decade until 2030 creates the premises needed not only to reduce emissions by at least 55% in the next 10 years, but also that the EU is on the right track to achieve climate neutrality by 2050.

Without the Fit for 55 package, the EU would not be ready to achieve climate neutrality in 2050 solely based on the 2014 target to reduce emissions by 40% by 2030. Data shows that a greenhouse gas emissions reduction of only 60% would be achieved by 2050 under previous targets (SWD (2020) 176 final).

Figure 76 Fit for 55 elements

Source: European Commission.

[185] European Emissions Trading System, https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets_en
[186] Directive 2010/75/EU, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32010L0075
[187] Directive 2006/21/EC, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32006L0021
[188] Directive 85/337/EC, https://ec.europa.eu/environment/eia/eia-legalcontext.htm
[189] Proposal for a Directive to amend Directive 2003/87/EC, https://ec.europa.eu/info/sites/default/files/revision-eu-ets_with-annex_en_0.pdf

Main legislation and relevance for industry

- **Revised EU Emissions Trading System (ETS)**

The proposed revision of the EU ETS should lead to reducing overall emissions by 61% in the sectors concerned by 2030 (compared to 2005). This will contribute significantly to the EU's overall emissions reduction target of 55%[190]. The revised annual emission reduction from sectors covered by the EU ETS sees an increase from the average 1.74% reduction rate a year (pre-2018) to around 2.2% a year (from 2021). To meet the increased ambition and to support companies, new instruments are available. These include the Modernisation Fund (designed for investments in energy system modernisation, just transition and energy efficiency in the 10 Member States with the lowest income) and the Innovation Fund (available for all Member States, supporting investments in breakthrough low-carbon technologies).

Stakeholder consultation: identified barriers in relation to the ETS

According to feedback from DG Research and Innovation's (DG R&I) consultations when drafting this roadmap, stakeholders argued that carbon pricing instruments are necessary and seen as a way to encourage investment and support market creation, but current market mechanisms are not working properly.

Nevertheless, participants involved in DG R&I's stakeholder consultation in 2021 saw the need for a change to the EU ETS benchmark design over the entire sector and business activities through the life cycle, without differentiating between various process or technology options. It has also been argued that carbon leakage protection from both direct and indirect costs of the EU ETS supports the development of low-carbon R&I in EU industry. They also commented that the ETS and related monitoring and reporting legislation does currently not recognise CO^2 emission avoidance resulting from the use of captured CO^2 as alternative carbon feedstock in the production of chemicals and polymers.

- **Industrial Emissions Directive (IED)**

The IED regulates pollutant emissions of industrial plants in the EU. Around 50 000 industrial plants must adhere to the IED. Many activities covered by the Directive are directly related to the energy-intensive industries ecosystem (including energy industries, production and processing of metals, mineral industries, chemical industries, waste management – including waste from EIIs, and production of pulp, paper, and cardboard)[191]. The Directive is implemented through regulations on sector-specific best available techniques (BATs) that EU industrial plants must apply to provide a high level of environmental protection.

The Commission proposed a revision of the IED in April 2022, in line with the European Green Deal's roadmap on key measures to be taken.

Stakeholder consultation: identified barriers in relation to the IED

The stakeholder consultation revealed that the revision of the IED should look at existing BATs and give insights into forward-looking techniques.

In this regard, the Commission is proposing the Novel Techniques Innovation Observatory, which deals with industrial emissions, BATs, BATs reference documents (BREFs), and emerging techniques. Emerging techniques could ensure an equivalent or higher level of environmental protection but with lower costs than existing BATs.

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190 COM(2021) 551 final, https://ec.europa.eu/info/sites/default/files/revision-eu-ets_with-annex_en_0.pdf

191 Annex I to Directive 2010/75/EU, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0075&from=EN

- **New Carbon Border Adjustment Mechanism (CBAM)**

Stakeholder consultation: identified barriers in relation to the proposed CBAM

DG R&I's stakeholder consultation indicated concerns about the new Carbon Border Adjustment Mechanism because it would need further development to serve as a robust mechanism to support a global environmental level playing field for EU industries.

Promoting voluntary standards, labelling and certifications might also encourage creating markets for low-carbon products. Representatives from different organisations (industry, research, interest groups etc.) all agreed that public support is needed in the pre-commercialisation phase and until established levers are in place (e.g. CO_2 price, carbon-free product bonus, border tax), which would allow the sectors to stay economically viable.

1.2 *R&I enabling framework conditions*

The updated 2021 industrial strategy outlines significant action for industries across the EU and paves the way for their green and digital transition. It proposes co-creating transition pathways for industrial ecosystems, which will offer a better understanding of the scale, cost and conditions for industry to help companies' sustainable competitiveness.

To support industries in their transformation, the industrial strategy proposes to continue supporting industrial alliances as a tool to accelerate coordination of research, innovation and development of new industrial technologies. Industrial alliances are designed as complementary to public-private partnerships, such as Horizon Europe partnerships. Member States are also preparing an important project of common European interest (IPCEI) addressing the decarbonisation of energy-intensive industries to bring companies together with the expertise, knowledge and financial resources to address, for example, technological and societal challenges such as those in the European Green Deal. The Commission will examine these project plans attentively and, where the criteria are met, will accompany them as they reach maturity.

Particularly relevant for the energy-intensive industries ecosystem, the updated industrial strategy aims to create a level playing field, an effective framework to prevent carbon leakage, and measures to create markets for sustainable products. The strategy states that, in most cases, there is still no business case for transformative investments in the EII ecosystem.

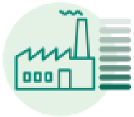
To respond to the increasing demand for R&I in the decarbonisation of the energy-intensive industries ecosystem, DG R&I carried out consultations in 2021 to identify the main barriers in developing and adopting new low-carbon technologies. The main findings indicate that framework conditions are key to deploying R&I to further decarbonise the sector. This R&I includes large-scale demonstration projects, access to clean energy sources and implementing circular economy principles. The Commission and Member States can build on several existing EU initiatives to address the main barriers identified.

Table 8 Key barriers and related EU initiatives

Main barriers	EU initiatives addressing similar challenges
Setting up first-of-a-kind (FOAK) installations Performing R&D&I is often associated with setting up pilot installations, new infrastructures and similar investments that require legal approval. Permits granted on time, which do not compromise health, safety and environmental standards, can support and accelerate the R&I process. New technological and organisational solutions also require changes to existing locations, building up new sites for on-site energy harvesting and storage, or providing additional space for stockpiling, embedded in local energy and material cycles. Designing and building a pilot or demonstration plant at scale is one of the major challenges for developing many decarbonisation technologies at regional and cross-border level. In the consultation, stakeholders mentioned a lack of access to finance for first-of-a-kind installations as a significant barrier for innovation and deployment. They also argued that running such big low-carbon pilot projects requires public co-funding to reduce the investment risk (particularly also beyond TRL 6). However, funding decisions often take too long for innovative players competing at a global level. In addition, the EU and national public support strategies and programmes are not yet fully aligned.	• **EU Chips Act** The new EU Chips Act, adopted by the Commission in February 2022, proposes 'pilot lines for preparing innovative production and for testing and experimentation'. The Act proposes extended pilot lines to prototype and scale up innovation, which act as a bridge from demonstration in a lab to production in a manufacturing facility. • The EU Chips Act defines 'first-of-a-kind' for State aid assessment, while providing several benefits for FOAKs. Such benefits include granting fast-track permits and prioritised access to pilot lines set up under the Chips Act. • **REFIT RegHub** The new Regional Hubs Network (RegHub) monitors how EU policies are implemented on the ground and at local and regional levels. Such hubs, part of the Fit for the Future platform, ensure that regional and local stakeholders provide feedback on EU policies and further streamline processes at local level on matters such as authorisations and licensing for FOAKs. The RegHub identifies potentially burdensome procedures that delay building infrastructures across the EU and propose ways to speed up permit procedures. • **State aid** Please see below for detailed information on State aid.
Access to clean energy Integrating (supporting) new technologies into a full production system is a key organisational challenge. Examples include producing hydrogen, transforming biomass into fuels, chemicals and polymers, and technologies to capture CO_2 in the production process. Reducing greenhouse gas emissions also requires increasing quantities of zero-carbon electricity, hydrogen and the related infrastructure (e.g. electricity, hydrogen, CO_2 transport and storage). Geological storage of CO_2 is also required for using CCS technologies. In the consultation, experts identified storage, access, and the cost of green energy as major barriers. This goes hand in hand with large infrastructure needs if there is a switch to green energy sources, i.e. big power lines, pipelines, and modifying existing infrastructure (e.g. natural gas pipelines). The experts called for freedom in the legislation for energy grid operators to have the possibility to invest in innovative technology that makes their operations more flexible and leaves room to anticipate extensions needed in the future.	• **REPowerEU** Please see below for detailed information on REPowerEU. • **EU Renewable Energy Directive** Since 2018, the EU Renewable Energy Directive already lays down that permits must be approved within two years of the permit request. The Commission will provide, by June 2022, further guidance on good practices to address the complex and long administrative procedures for authorising new renewable energy plants. • **Revised rules for Trans-European Networks for Energy (the TEN-E Regulation)** The new rules, which should be adopted in April 2022, will ensure cross-border cooperation on energy infrastructures in line with the European Green Deal. The new TEN-E Regulation will help deliver cross-border infrastructures on time, by proposing ways to simplify and accelerate permit and authorisation procedures.

Other obstacles were raised: the lack of any real sectoral integration and an increased competition for resources/energy, together with an unknown time frame of availability and price (e.g. large-scale green hydrogen availability at competitive prices). According to the experts, this requires a balanced approach and using multiple energy sources to ensure a sustainable and affordable transition.	
Access to circular raw materials and sectoral integration Industries are increasingly dependent on recycled materials to use as raw materials. For the most basic materials, more circularity will become even more critical over the next decades. More circular material and energy flows can contribute to reducing greenhouse gas emissions, reducing energy use and maintaining supply security. The sustainable supply of alternatives for emission intensive feedstock is essential. This includes biomass, waste, and CO_2 (and carbon from industrial waste gases). Several factors limit the potential, including new limits on the use of forest raw material, export of waste outside Europe and no legally binding EU targets on reducing resource use. In the steel industry, for instance, the availability of pure high-quality scrap is limited. Impurities are also accumulated often due to ineffective or inefficient sorting and separation technologies. When fossil carbon is to be reduced, then the alternatives are waste, recycled materials, biomass and CO_2 (CCU). However, getting the required amount of circular carbon is difficult as these carbon sources are less concentrated or polluted than oil and gas. According to stakeholders, there is no cost truth in individual sectors and many environmental costs are externalised. Cheap waste exports and resources are also still left in Europe. In this context, the stakeholders also raised the issue that, in many cases today, there are legal barriers to recycling and reusing and producing new products in the same site, e.g. processing primary and secondary raw materials in the same facility is not allowed. Furthermore, participants in the consultation argued that circularity design is not yet rewarded in markets (especially for manufactured products; cradle to cradle approach). There is not enough focus on circular business models and innovation, which can influence both product design and demand for sustainable products. In general, weak existing market tools lead to a weak business case for the circular economy, which is characterised by very diverse solutions and approaches.	• **EU circular economy action plan** The Commission adopted the circular economy action plan in 2020 to enable greater industrial circularity, with a focus on 'facilitating industrial symbiosis by developing an industry-led reporting and certification system, and enabling the implementation of industrial symbiosis'. • **ERA circular industrial technologies roadmap (due in Q4 2022)** DG R&I will deliver a roadmap for circular industrial technologies in Q4 2022 that addresses the circularity of energy-intensive industries (steel, chemicals, ceramics). The roadmap will dive into circularity and how it can contribute to achieving the EU's climate objectives.

REPowerEU: EU joint action for more affordable, secure and sustainable energy



Decarbonising Industry by accelerating the switch to electrification and renewable hydrogen and enhancing our low-carbon manufacturing capabilities.

Following Russia's invasion of Ukraine in February 2022, the EU initiated joint efforts to ensure Member States have access to energy sources and reduce their dependency on Russian gas, which represents roughly 45% of EU gas consumption[192]. In this regard, industrial transformation is one of the key measures, with energy-intensive industries at the forefront for decarbonising EU industry.

REPowerEU highlights the need for EIIs to accelerate the switch to electrification and renewable hydrogen, while further improving low-carbon manufacturing capabilities.

By 2030, the objective is to ensure front-loading electrification and renewable hydrogen uptake by energy-intensive industries. The measures announced through REPowerEU to meet this objective are to front-load the Innovation Fund and extend its scope to carbon contracts.

Furthermore, to ensure the decarbonisation of EU industry, the REPowerEU plan could strengthen the EU's manufacturing capabilities of innovative zero- and low-carbon equipment, such as electrolysers, next generation solar/wind equipment, and other technologies.

Other barriers at EU level

- For the selection of promising low-carbon technologies and (pre-)assessing technology performance, the stakeholders consulted mentioned that having to evaluate many factors (environmental, economic, etc.) is challenging. In the chemical industry, for instance, the impact of individual technologies depends on specific processes or target molecules. It also depends on the geographical location because different company sites have specific constraints and different access to resources and/or infrastructure. Thus, developing and diffusing standard methods to assess the potential and impact of technologies over the entire life cycle could help develop and diffuse technologies in different industries. The assessment should look into economic, environmental and social factors (e.g. impact on climate and other emissions, health, safety, costs, business case). Such an assessment also reduces companies' uncertainties about their investment decisions.

- The stakeholders confirmed the importance of collaborative projects. However, changing value chains, cross-sectoral and intra-sectoral collaboration, and new business models bring uncertainty, which can slow down decision-making and investments in R&D&I. It is important to remember that energy-intensive industries are changing in many ways at the same time. This requires a system perspective and a collaborative approach with new stakeholders. Such processes take time, and there is also a limited window of opportunity to stay competitive and adapt to changing market conditions.

- Collaboration among competitors can provide big opportunities for synergies. Flexibility in the legislation for energy grid operators would be a major enabler. This would give them the possibility to invest in innovative technologies that gives them flexibility in their operations and leaves room for any necessary extensions in the future (otherwise the grids will be a serious bottleneck for decarbonisation). The

[192] COM(2022) 108 final.

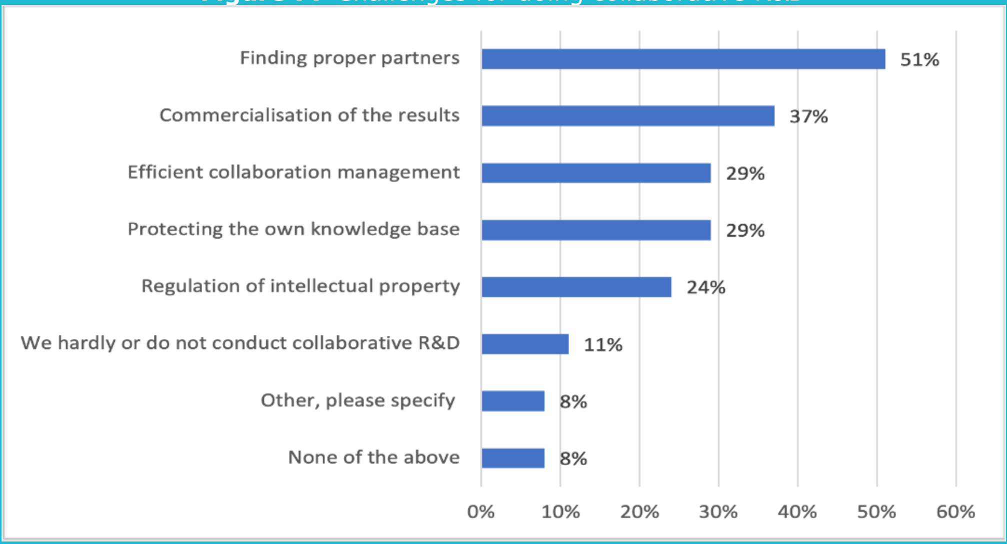
presence of some negative views on wind and PV parks, amongst others, is also a significant barrier.

- Some EII sectors have an older workforce with a low level of education and a lack of interest among young people. A skills mismatch has been identified in several sectors and demand for skilled people is growing, due to digitalisation and changes in data analysis, robotics, resource efficiency, recycling, business processes and overall transition, both in products and processes of the EII ecosystem[193]. In addition, the wide deployment of decarbonisation technologies entails the integration of workers, customers, and the public. In fact, the adequate provision of green skills is highly relevant for firms engaging in low-carbon technology deployment and scale-up, and likely to promote investment.[194] The transformation of the industry requires a well-designed transfer of existing skills and adapting to new skills. It also needs education, communication and discussions with the public to position the industry as a major solution provider. Public acceptance is essential for a successful industrial transformation.

SME Focus 7 | **SME SPECIFIC CONDITIONS FOR R&D&I ACTIVITIES**

The development and deployment of low-carbon technologies often requires collaborative projects to be carried out. Around half of the small technology developers which participated in the survey argued that finding a suitable partner is a challenge. However, the translation of the findings from collaborative projects into innovation, i.e. the commercialisation, is a problem for one third of the companies.

Figure 77 Challenges for doing collaborative R&D



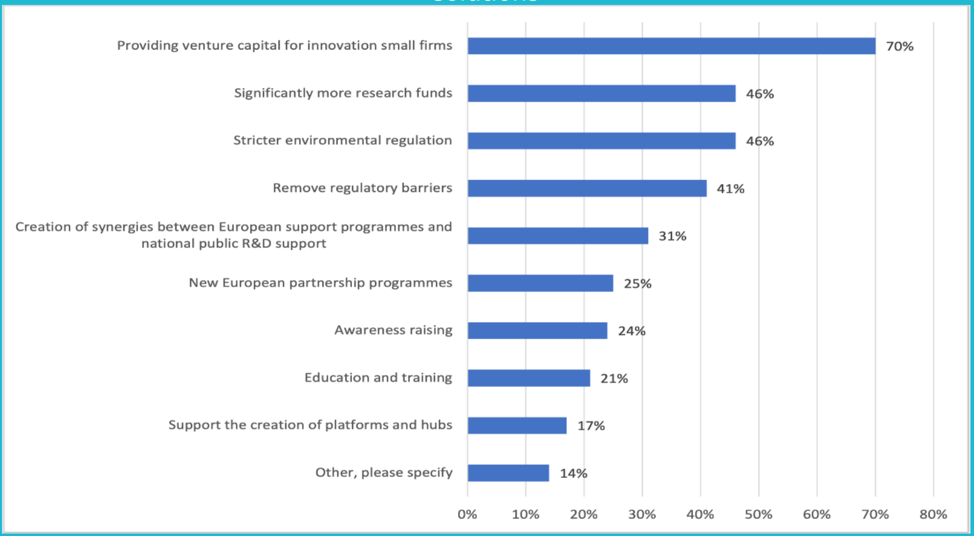
Source: survey on technology developers, conducted from November 2021 to January 2022 (see Annex 1).

193 The conclusions on skills in the EII sectors came from a roundtable event on 7 June 2021. This was organised by Commissioner Schmit and Commissioner Breton to promote engagement in the pact for skills and shape a sectoral pact. The event brought together representatives of the steel, ferro-alloys, non-ferrous-metals, ceramics, pulp and paper, chemicals sectors, as well as representatives from local authorities, social partners and vocational education and training providers. For information about the EU's initiative on the pact for skills, see https://ec.europa.eu/social/main.jsp?catId=1517&langId=en.

194 OECD (2022, p.36), *Forthcoming.*

When it comes to **developing new technologies,** the survey reveals that providing venture capital was considered the most important measure, followed by stricter environmental regulation and significantly more funding for research. In fact, a forthcoming OECD study confirms that there has been a declining trend of global venture capital investment in 2019-2020 for clean tech start-ups, although investments have grown from USD 4 billion in 2010 to USD 26 billion in 2020.[195]

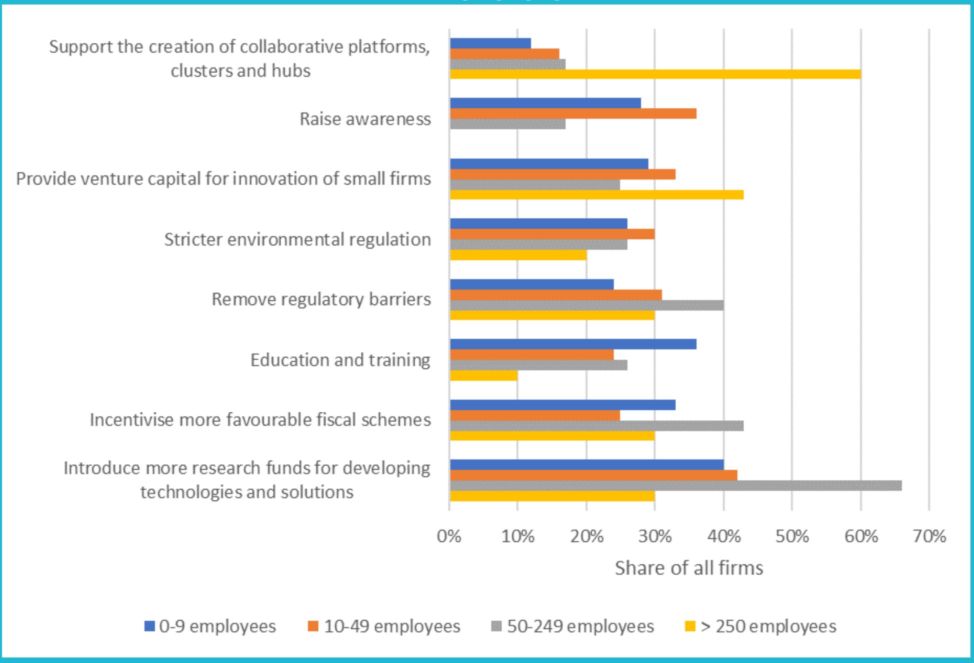
Figure 78 European policy support for the development of sustainable technologies & solutions



Source: survey on technology developers, conducted from November 2021 to January 2022 (see Annex 1).

On the other hand, on the topic of adopting new technologies, the survey shows that very small firms called for better or more education and training. Larger firms, more so than smaller firms, consider the support of collaborative platforms and clusters, as well as the provision of venture capital.

Figure 79 How EU policy can support the adoption of environmental technologies, analysis at firm size level

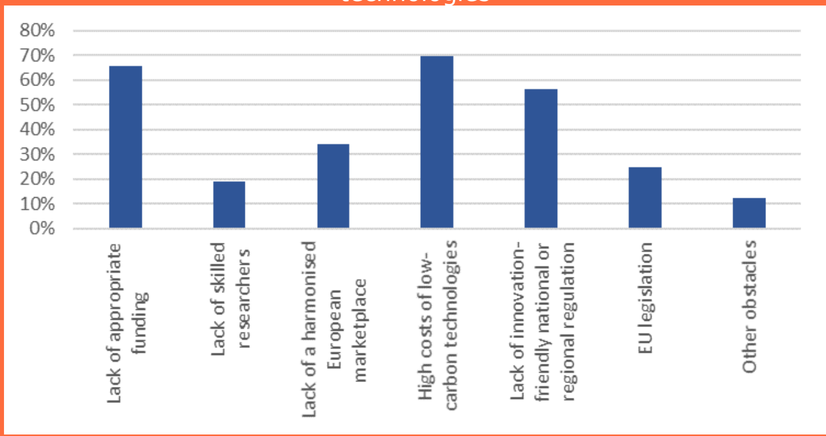


Source: European Commission/Enterprise Europe Network SME from November 2021 to January 2022 (see Annex 1).

Box 18 | **NATIONAL ACTION TO IMPROVE FRAMEWORK CONDITIONS**

Discussions with Member States in the ERA subgroup and feedback from the online consultation (referred to above) highlighted possible national action to address barriers for innovation.

Figure 80 Obstacles delaying the development or uptake of low-carbon industrial technologies



Source: ERA roadmap stakeholder consultation, open from July to September 2021.

Framework conditions are an important feature to stimulate R&I and development of low-carbon technologies. Spain is a good example with a set of instruments in the following areas described below.

- **Dissemination and valorisation**: in Spain, *technology platforms* have a key role creating technology communities and disseminating results, best practices and raising awareness among the public with publications, events, and other activities. Examples are the CO2 platform (about technologies for capture, transportation, storage, and use of CO2) and the Energy Efficiency, Platea (for the steel sector).
- **Skills**: the Spanish annual employment policy plans will have specific national and regional programmes launched to promote green jobs.
- **Standardisation**: the Spanish Association for Standardisation (UNE) has established a technical committee on 'Energy efficiency, climate change and renewable energies (CTN 216)', which is developing standards in this area.
- **Support to SMEs**: the CERVERA programme has special assistance for SMEs using the services of the RTOs networks established for certain technologies.

1.2. *Policy framework for digital technologies to enable green transformation*

Digital technologies (including artificial intelligence (AI), cloud, edge computing, 5G, the internet of things) and digitisation are key for all industries and can accelerate the sustainable transformation[196]. Climate neutrality, as a forthcoming OECD report claims, will rely on digital technologies. For example, AI can help forecast weather and electricity prices, thus mitigating intermittency problems in the system and increasing energy efficiency.[197] A study by the JRC and the OECD[198] indicates that 20% of climate-related patents have a digital component, and 60% of climate-related trademarks are related to

[195] OECD (2022, p.10), *Forthcoming.*
[196] COM(2021) 574 final, https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0574
[197] OECD (2022, p.7), *Forthcoming.*
[198] JRC & OECD, 2021, *World Corporate Top R&D Investors: Paving the Way for Climate Neutrality*, https://www.oecd.org/sti/world-corporate-top-rd-investors-paving-the-way-for-climate-neutrality.pdf

ICT. Nonetheless, the study highlights that this proportion of new climate-related patents with a digital component is rather low in energy-intensive industries.

In the EU, the 2030 Digital Compass[199] sets the goal that 75% of EU businesses should use digital technologies such as AI, cloud computing services and big data by 2030. This will also concern the energy-intensive industries ecosystem.

For instance, estimates indicate that process optimisation through digital technologies (such as cloud-based data, digital platforms, AI-driven cost and emissions optimisation) can reduce CO_2 emissions by an average of 5% to 10%. Furthermore, carbon data transparency (through digital technologies such as the internet of things, blockchain tracking solutions, data visualisation and impact reporting) can reduce CO_2 emissions by an average of 30% to 40%[200].

1.3. State aid for R&D and innovation in the area of low-carbon technologies – overview of applicable EU State aid rules

EU State aid rules only allow granting aid if it does not adversely affect trading conditions contrary to the common interest. For R&D&I-aid, the exemptions are set out in Article 107(3)(b) and (c): basically, if State aid is to be allowed, its benefits must outweigh any distorting effects.

This means that the measure taken must:

- facilitate the development of a product or service, for instance researching carbon-capture technology;
- encourage the beneficiary to carry out additional activities, which it would not have carried out or it would have carried out in a restricted or different manner without the aid;
- not be in breach of EU law (and this also applies to the activity supported by the measure).

While EU State aid rules lay down conditions for the compatibility of aid, they do not favour any particular technology – they are technology neutral.

For RDI in a broader sense, criteria for State aid are set out in the texts below.

- General Block Exemption Regulation[201] (EU) No 651/2014 (GBER) is the fast way to implement necessary aid measures. Today, Member States implement most new State aid measures – 95.5%[202] - under this Regulation. This means without formal assessment and approval by the Commission. Member States are not obliged to notify State aid to the Commission for assessment (under the principles mentioned above) and formal approval (if the aid meets all the criteria set out in the GBER). The GBER presumes that the positive effects of such aid prevail over the negative effects. This Regulation is under revision and an update is expected in 2022.

- In all other cases, where aid exceeds the limits set out in the GBER, the Commission must be notified before implementation, under Article 108(3) of the Treaty. Member States must demonstrate that the aid is in line with the applicable compatibility

[199] COM(2021) 118 final, https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021DC0118
[200] Boston Consulting Group, https://www.bcg.com/publications/2021/how-technology-helps-sustainability-initiatives; estimates refer to all industrial sectors.
[201] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02014R0651-20210801
[202] European Commission, State Aid Scoreboard 2020, p.37.

criteria. If an aid measure meets these criteria, the Commission will approve it. The criteria for aid measures that must be notified are set out in the following texts.

- Framework for State aid for research, development and innovation[203] (RDI-framework): this applies to certain RDI-aid measures that, before their implementation, must be notified to the Commission for approval by decision. This framework is under revision and an update, adapted to recent market and technological developments and the EU's policy objectives, is expected in the first half of 2022.

- Communication on State aid for Important Projects in the Common European Interest[204] (IPCEI-Communication): this applies to notifiable large collaborative cross-border projects and large R&D&I projects even up to first industrial deployment, i.e. the upscaling of pilot facilities and the testing phase.

- Guidelines on State aid to promote risk-finance investment[205] (RFG): these apply to certain aid measures to facilitate access to finance for SMEs and mid-caps. Before implementation, the Commission must be notified about the measures and approve them.

- Guidelines on State aid for climate, environmental protection and energy 2022[206] (CEEAG): these apply to aid for a wide variety of environmental protection projects, including demonstration projects and eco-innovation. Before implementation, the Commission must be notified about the measures and approve them.

Table 9 Overview of eligible activities and investments and market failures that RDI-aid can address (and a selection of applicable texts)

<table>
<tr><th>Eligible activities and investments</th><th>Market failure</th><th>Applicable conditions set out under</th></tr>
<tr><td>Aid for R&D projects –fundamental research, industrial research, experimental development, and feasibility studies. In general, this means that R&D-aid for projects must not go beyond technology readiness level 8</td><td rowspan="5">Positive externalities/knowledge spill-overs leading to an unattractive rate of return from a private perspective

Imperfect and asymmetric information leading to a high degree of uncertainty on the risks/benefits of the investment or hampering access to finance

Coordination and network failures, e.g. in collaborative projects these are caused by difficulties in coordinating a large number of partners, diverging interests, contractual issues, and difficulties in sharing sensitive information</td><td rowspan="5">– GBER (Article 25 – 25d)
– RDI-framework
– GBER (Article 26)
– RDI-framework
– GBER (Article 27)
– RDI-framework
– GBER (Article 28)
– RDI-framework
– GBER (Article 29)
– RDI-framework</td></tr>
<tr><td>Investment aid for construction or upgrade of research infrastructures</td></tr>
<tr><td>Aid for innovation clusters</td></tr>
<tr><td>Innovation aid for SMEs</td></tr>
<tr><td>Aid for process and organisational innovation</td></tr>
</table>

[203] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.C_.2014.198.01.0001.01.ENG
[204] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.C_.2021.528.01.0010.01.ENG&toc=OJ%3AC%3A2021%3A528%3ATOC
[205] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.C_.2021.508.01.0001.01.ENG&toc=OJ%3AC%3A2021%3A508%3ATOC
[206] https://ec.europa.eu/competition-policy/sectors/energy-and-environment/legislation_en

Risk-finance aid for SMEs	Capital market failure preventing supply from meeting demand at a price acceptable to both sides. This results in a 'financing gap' affecting SMEs (and in certain situations small mid-caps and innovative mid-caps)	– GBER (Article 21) – RFG
Risk-finance aid for mid-caps		– RFG
Aid for small innovative enterprises		– GBER (Article 22(5))
Aid for demonstration projects to reduce greenhouse gas emissions	Negative externalities: when pollution is not adequately priced	– CEEAG
Eco-innovation: any innovation activity resulting in or aimed at significantly improving environmental protection	Positive externalities: when market participants other than the investor benefit from an investment Asymmetric information on the likely returns and risks of the project Coordination failures: due to diverging interests and incentives, costs of contracting, uncertainty about the collaborative outcome and network effects	
Major projects in the common European interest: this includes aid for first industrial deployment as long as the deployment follows on from an R&D&I activity and contains a major R&D&I component that is an integral and necessary factor in successfully implementing the project. Aid for mass production or commercial activities is excluded.	Major market or systemic failures and societal challenges that otherwise cannot be addressed	IPCEI-Communication

1.4. Sustainable Finance and EU Taxonomy

The EU taxonomy is a classification system of environmentally sustainable economic activities. It will play a major role in helping the EU scale up sustainable investment and implement the European Green Deal. The EU taxonomy will provide companies, investors and policymakers with definitions for which economic activities can be considered environmentally sustainable. Listed under 'climate mitigation' in the taxonomy's environmental criteria are the manufacturing of low-carbon technologies and the reduction of carbon emissions in the production of cement, aluminium, iron, steel, and organic basic chemicals. R&D in these areas is considered an enabler for sustainable investments.

2 Valorisation and standardisation for low-carbon industrial technologies

2.1 Valorisation of R&I results

Valorisation of research and innovation in low-carbon industrial technologies, as in other fields, often relies on the collaboration of many players in the socio-economic ecosystem. It is a multidirectional, iterative process in which major new research topics and innovations emerge through interaction between academia, industry, the public sector, the financial sector and civil society. It is important to improve this collaboration and optimise the use of public knowledge and research in the green transition. Exploitation patterns are vast, and they are generally supported by a policy mix based on a toolbox of instruments that acknowledge different valorisation channels and ecosystems, which vary across countries that have varying strengths, not only in science and industry, but also in other areas.

As one of the priority actions of the new ERA for research and innovation, guiding principles for knowledge valorisation will be developed to shape a broad approach to knowledge valorisation and provide directionality. The guiding principles constitute a political commitment co-designed with and endorsed by Member States. The aim is to achieve a common line on measures and policy instruments for improving knowledge sharing and valorisation in Europe. They will also help to address gaps across Member States and help more and more countries to better benefit from R&I results. A key element will be smart knowledge asset management and an intellectual property culture that enables open science, open innovation and entrepreneurship while taking account of the highly competitive global environment.

In addition, codes of practice will provide guidance for R&I practitioners on how to implement certain elements of knowledge valorisation, such as smart intellectual property management and standardisation for knowledge uptake[207]. The codes of practice will be bottom-up initiatives co-created with R&I stakeholders and will provide practical guidance and concrete best practice examples for all R&I ecosystem players. On 28 January 2022, the Community of Practice was launched, with the task of working on a code of practice for the smart use of intellectual property[208]. This initiative will provide a general framework that will benefit the uptake of low-carbon industrial technologies and may be a starting point for more sector-specific activities if considered useful.

The EU Knowledge Valorisation Platform[209] will support this process by promoting and supporting cross-border peer learning and sharing of best practices[210] and lessons learned. The platform provides an interactive forum to stimulate cooperation across borders and sectors by involving all players of knowledge valorisation, from academia and industry to public policy and civil society. It enables the exchange of knowledge and expertise to support the design, implementation and evaluation - including in specific areas like green technologies - of policies, investments and measures.

Box 19 | **BEST PRACTICE EXAMPLES FROM THE EU KNOWLEDGE VALORISATION PLATFORM THAT PROMOTE AN ECOSYSTEM APPROACH INVOLVING SEVERAL TYPES OF STAKEHOLDERS TO PROMOTE THE DISSEMINATION AND UPTAKE OF SUSTAINABLE AND LOW-CARBON TECHNOLOGIES**

- The University of Antwerp, Belgium, wants to be the driving force of innovation in knowledge-intensive ecosystems in a region that is characterised by its world port, a large chemical cluster and a strong creative sector. Based on the University of Antwerp's own strengths combined with the peculiarities of Antwerp's ecosystem, the University of Antwerp decided to focus on three priority areas of valorisation, one of which is sustainable chemistry & materials.
- In Amsterdam, Netherlands, a multi-stakeholder cooperation addresses sustainability issues focusing on the realisation of blue-green roofs delivered by a consortium of the city government, private companies, housing corporations, the water board, and knowledge institutions.
- The University of Applied Science in The Hague, Netherlands, develops, in cooperation with potential users, a sustainable protocol for (facility) professionals in order to stimulate sustainable behaviour and reduction of raw material flows in facility management.

207 For more information: Standards drive innovation | European Commission (europa.eu).
208 Code of Practice for the smart use of intellectual property | European Commission (europa.eu)
209 Knowledge Valorisation Platform | European Commission (europa.eu)
210 Repository of best practice examples is available on the Knowledge Valorisation Platform, which is continuously open for submissions of new best practice examples.

2.2 *Standardisation as an important aspect of knowledge valorisation*

Standards and standardisation are recognised as a tool for promoting innovation, both for policymakers and businesses, as standards allow to codify knowledge and make it available to a wide range of stakeholders.

A standard is a formal, voluntary document that sets the specifications for a terminology, a product, a system, a process or a service. Standards can help to make different parts of an infrastructure work together or to systematise processes, e.g. energy efficiency or waste reduction. Standards can lift barriers to the uptake of environmentally friendly technologies and materials, by specifying tests, or provide robust definitions that avoid misleading environmental claims[211].

Typically, standards are developed and published in cooperation by many different groups and organisations using various degrees of consensus in their preparation and approval. Formal standards are standards that are approved or adopted by national, regional or international standards bodies, whilst informal standards are published by other standards development organisations. At the European level, standards are developed by the European standardisation organisations officially recognised under Regulation (EU) No 1025/2012: CEN, CENELEC, and ETSI[212].

It is important that scientists can communicate and exchange their research results by using agreed vocabulary, definitions and units. It is essential to undertake repeatable measurements and comparable experiments. As standards are voluntary, the reduction of diversity should not limit scientific development. Looking from this angle, one can say that scientists are among the first clients of standardisation in the low-carbon industrial technologies value chain.

For example, if a research activity develops a specific procedure or protocol to overcome a particular issue, this can represent the basis of a standard. To be suitable for providing the basis of a standard, a research output needs to be applicable to, and be of use for, one or more established groups of stakeholders: researchers, industry and/or regulators.

Transferring research results into one or more standards can have a significant impact on the subsequent use of the results by industry and other researchers, by making clear not only what the research outputs are but also how to implement them[213].

Standardisation can be relevant for innovative results at different maturity levels. Although standards become more important when an innovation matures (and thus reaches a higher technology readiness level (TRL)), standards can support all stages, from knowledge creation to technology and business development. As shown in 81, different standards can provide support to development: semantic standards (TRL 1-3); measurement and testing standards (TRL 3-5); interface standards (TRL 5-7); and product and service standards (TRL 7-9).

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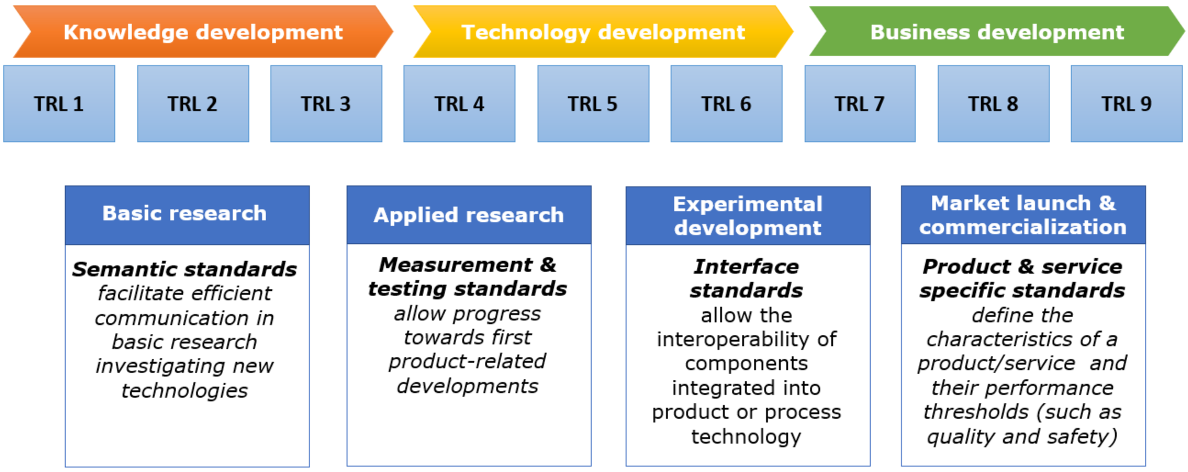
[211] https://www.cencenelec.eu/media/CEN-CENELEC/Areas%20of%20Work/CENELEC%20sectors/Accumulators,%20Primary%20cells%20and%20Primary%20Batteries/Documents/standardsinsupporteuropeangreendealcommitments.pdf

[212] European Committee for Standardisation (CEN), European Committee for Electrotechnical Standardisation (CENELEC), European Telecommunications Standards Institute (ETSI).

[213] https://op.europa.eu/en/publication-detail/-/publication/db289e47-140b-11eb-b57e-01aa75ed71a1/

Figure 81 Technology readiness levels, linked to typical research types and standardisation deliverables



Source: CEN-CENELEC.

Standards, in contrast to patents, are accessible to all at low cost and are more likely to be broadly implemented because all (interested) stakeholders have reached a consensus. Furthermore, standardisation is a cooperation and transfer process, because it represents a common platform for different players with heterogeneous backgrounds, i.e. research, industry, public administration, and social interest groups, e.g. consumers[214].

Due to the level of transparency and the involvement of the public, the development time of national standards takes on average 18 months. For European and international standards, the time needed increases to more than 2 years. This is because national standardisation bodies have to develop a national position in their national mirror committees, that vote at national level to support a European or international standard. Due to the high degree of consensus, standards have a high level of acceptance in society.

Standardisation activities in research projects usually focus on the creation of pre-standards (such as the CEN/CENELEC Workshop Agreement). A pre-standard is a public, freely available document that describes products, systems or services by defining characteristics and requirements. A pre-standard is characterised by the fact that, compared with a standard, it reflects the consensus of interested parties and is not developed based on the national delegation principle. In contrast to a standard, the pre-standard is developed in a workshop (temporary committee) with advice from a standardisation organisation. After the committee adopts the pre-standard, the standardisation organisation publishes the pre-standard.

2.3 *Standardisation use cases as examples for valorisation of research results*

Materials efficiency

Materials efficiency aspects in European standardisation are covered by CEN-CENELEC Joint Technical Committee 10 'Material efficiency aspects for products in scope of Ecodesign legislation'. CEN-CLC/JTC 10 developed eight standards containing generic principles to consider when addressing the material efficiency of energy-related products. These standards address the exact same aims of the European Commission to: i) extend product lifetime; ii) re-use components or recycle materials from products at end-of-life; iii) use of re-used components and/or recycled materials in products. These are all horizontal guidance documents, which means that there is still a gap to fill between the guidance

[214] https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1527333

provided and the needs of specific products (or groups of products). Examples of specific standards are:

- EN 45555 elaborates on recyclability and recoverability in a horizontal, cross-product way. This standard defines a series of parameters that may be considered to calculate product-specific recycling and recoverability rates. However, a correct assessment can only be done in a product-specific way, taking into account specific parameters of a specific product group.

- EN 45558 covers the general method to declare the use of critical raw materials in energy-related products, for recyclers and other interested parties. This standard is considered to be directly applicable, although more specific references can be made by product-specific technical committees.

Moreover, CEN-CLC/JTC 10 has just started the development of a standard that proposes detailed principles, requirements and guidance for a method to achieve circular-ready designs of products falling under the scope of the Ecodesign Directive.

Low-carbon cements

The cement industry emits approximately 8% of global CO_2. The majority of these emissions come from the calcination of clinker, the most prevalent component of cement (which is itself the essential binding agent in concrete). Cement and concrete emissions can be reduced by: deploying concretes with better performance (i.e. less concrete needed in construction); using concrete with alternative compositions (i.e. less cement needed in concrete); and reducing the clinker content of cement (i.e. less clinker needed in cement).

Standardisation can help[215,216] to facilitate the market uptake of low-carbon cements and concretes, thereby reducing the greenhouse gas intensity of this industry. This calls for standards aimed at: a) specifying alternative concrete and cement compositions; b) setting requirements for physical characteristics of the – then newly developed – products (be it concrete or cement); or c) harmonising products and testing methods.

European standard EN 197 addresses the composition of most common cements. EN 197 accounts for alternative cements with substitutes to clinker, such as granulated blast furnace slag, pozzolanic materials, fly ash, limestone, and silica fume. The latest update (EN 197-5:2021) allows further reduction of the clinker content of cement by increasing the share of these alternative materials.

Regarding concrete, requirements on specification and performance are provided by European standard EN 206:2013+A2. This standard is not harmonised at European level, weakening the EU market for concrete. Furthermore, it does not explicitly address cements newly covered by standard EN 197-5. These cements may nonetheless be used providing that suitability is demonstrated. Standards thus need to be continuously updated to allow easier use of new clinker substitutes in cement and of admixtures as cement substitutes in concrete[217].

Alternatives to ordinary Portland cement with lower CO_2 intensities are being developed through different processes and chemistries[218]. Belite-Ye’elimite-Ferrite and calcium

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[215] Ecostandard, Breaking down barriers to lower-carbon cements – ECOS brings solutions to concrete problems
[216] Cembureau, Cementing the European Green Deal.
[217] New Climate, decarbonisation pathways for the EU cement sector: Technology routes and potential ways forward.
[218] E. Gartner, T. Sui, Alternative cement clinkers, Cement and Concrete Research 114 (2018) 27–39.

silicate clinkers are deemed promising chemistries[219,220], although they do not yet comply with EU (composition) standards for cements[218,220]. Yet substitutes to clinker do exist at varying phases of technological development[220,221] (such as Celitement[222], Futurecem[223], and Solidia[224]). There is thus room for further specification of cement compositions in standards.

Carbon capture and storage

ISO currently leads carbon capture and storage (CCS) standardisation with ISO/TC 265 regarding carbon dioxide capture, transportation, and geological storage. Standards such as ISO 27913:2016 on geological storage or ISO 27916:2019 on CO_2 storage using enhanced oil recovery, lay the foundation for deploying decarbonising technologies in carbon-intensive industries.

At the European level, Italy's national standardisation body, UNI, has published a pre-standard PdR 99:2021 on requirements for carbon credit generation projects. The British Standards Institution (BSI) is actively exploring links between CCS and green hydrogen production. Establishing a European-level technical committee on CCS is currently being considered.

Green hydrogen

International and European standards can support the increased uptake of hydrogen in energy systems. CEN-CLC/JTC 6 'Hydrogen in Energy Systems' and the 'CEN-CENELEC Sector Forum Energy Management / Working Group Hydrogen' are active at a European level.

The existing standard EN 16325 on Guarantees of Origin for Electricity is being revised by CEN-CLC/JTC 14 'Energy management and energy efficiency in the framework of energy transition'. The aim is to extend the scope to include hydrogen, as well as biomethane and other gases for heating and cooling.

Hydrogen technologies also have applications as replacements for natural gas home heaters/boilers. European projects, such as the THyGA project (Testing Hydrogen Admixtures for Gas Appliances), develop a detailed understanding of the impact of blends of natural gas and hydrogen on end-use applications. CEN/TC 109 'Central heating boilers using gaseous fuels' has a range of standards and pre-standards under development addressing these aspects of hydrogen technology, such as prEN 15502-2-1.

Energy grid and system efficiencies

The CEN-CLC/JTC 14 'Energy management and energy efficiency in the framework of energy transition' spearheads European standards on optimising existing European energy grids in light of the green transition. JTC 14 has developed standards for energy efficiency benchmarking methodologies (EN 16231:2012) and energy auditing of buildings, processes and transport (EN 16247 series).

CEN-CENELEC Sector Forum Energy Management also prioritises the high quality and performance of energy grids with a large share of renewables. Standardisation can support the challenges of energy storage and conversion. It can provide tools to improve

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[219] ETH, A sustainable future for the European Cement and Concrete Industry - Technology assessment for full decarbonisation of the industry by 2050.
[220] Chatham House, Making Concrete Change Innovation in Low-carbon Cement and Concrete.
[221] Worldcement, CO2 Reducing Cement, Part One: Solidia Cement Composition and Synthesis
[222] Celitement - A novel cement based on hydraulic calcium hydrosilicates (hCHS).
[223] https://www.cementirholding.com/en/our-business/innovation/futurecemtm
[224] https://www.solidiatech.com/accomplishments.html

sustainability to policymakers, efficient and sustainable financing schemes to investors and interested organisations, and efficient and affordable energy to the general public.

The CEN-CENELEC-ETSI Coordination Group on Smart Grids advises on European standardisation requirements relating to smart electrical grid and multi-commodity smart metering standardisation. While the Coordination Group itself does not develop standardisation deliverables, it can provide to, and receive from, the European Commission input for developing informative material for the public domain beyond the reach of traditional standards.

Box 20 | **EXAMPLES OF PROJECTS CO-FUNDED BY HORIZON 2020 THAT USED STANDARDISATION FOR DISSEMINATING AND VALORISING R&I RESULTS**

- NEXTOWER: Over the course of the project, NEXTOWER contributed with a CEN Workshop Agreement proposal for setting up a test platform for an upcoming ISO standard for high-tech components (CWA225 17726 'High temperature accelerated ageing of advanced ceramic specimens for solar receivers and other applications under concentrated solar radiation'). The project also drafted and submitted to the ISO Standardisation Body an amendment to the current standard ISO 18755:2005 on thermal diffusivity determination with the laser/light flash method (LFA), an ISO that was received and which also started a new process for extending this ISO at the European level and for it to be endorsed by CEN-CENELEC226. Both standardisation aspects are seen as important in ensuring that advanced ceramics enter the market and bring both societal and environmental benefits. See CORDIS: https://cordis.europa.eu/project/id/721045. Project website: https://www.h2020-nextower.eu/
- Innovative multi-functional vacuum-insulation-panels for use in the building sector (INNOVIP): Over the course of the project, the committee CEN/TC 88/WG 11 further developed the draft standard: Draft EN 17140 Thermal insulation products for buildings - Factory-made vacuum insulation panels (VIP) – Specification. This was used in the project to determine mechanical properties and the performance over time for the new panels. See Cordis:https://cordis.europa.eu/project/id/723441.

2.4 *Standardisation gaps*

This section presents the fields and technologies that are currently lacking standardisation initiatives and that offer potential opportunities where standardisation can benefit their dissemination and market uptake.

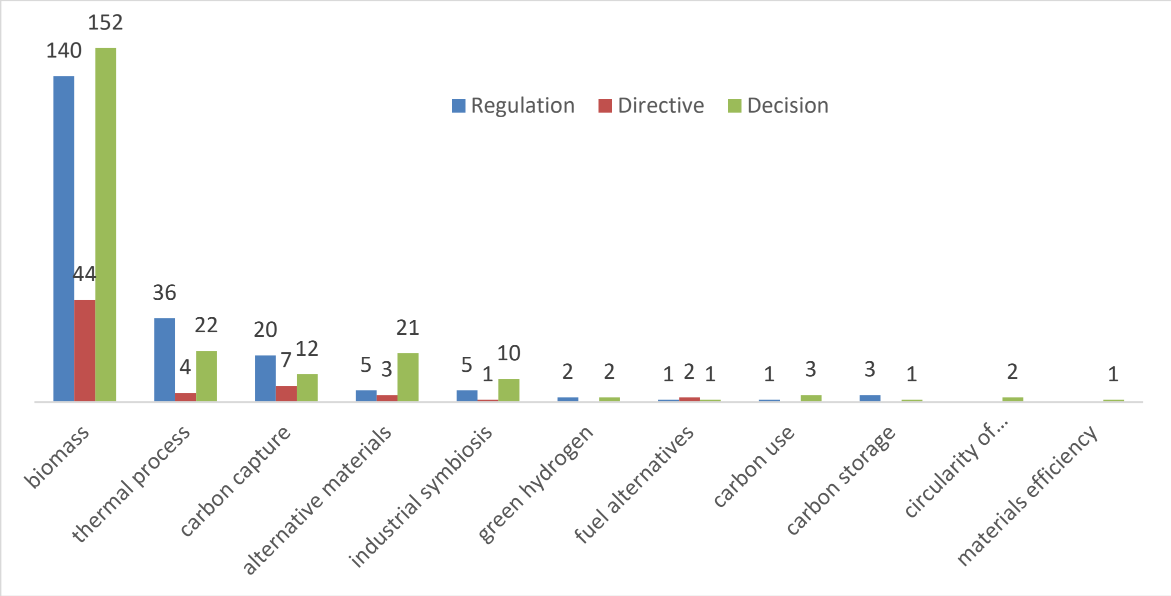
One way of assessing the gaps between R&I and standardisation is by examining the EUR-Lex database. The analysis consists in identifying policy documents (directives, decisions, and regulations) containing keywords – denominators – associated with the topics of low-carbon industrial technologies as given in Figure 82. These denominators are: biomass, thermal process, carbon capture, alternative materials, industrial symbiosis, green hydrogen, fuel alternatives, carbon use, carbon storage, circularity of materials and materials efficiency, together with the word 'standard*' using the Boolean operator "AND". A list of documents was extracted from the analysis, with their corresponding EuroVoc descriptor[227] and the subject matters to which they are associated.

The analysis also showed that there are few policy documents that focus specifically on low-carbon industrial technologies. Figure 82 presents the frequency and the types of policy document that contain the word standard or standards in combination with the 11 denominators related to low-carbon industrial technologies. Biomass, as a keyword in

[225] CEN Workshop Agreement (commonly abbreviated CWA) is a reference document from the European Committee for Standardization (CEN).
[226] European Committee for Electrotechnical Standardization
[227] EuroVoc is the EU's multilingual and multidisciplinary thesaurus. It contains keywords, organised in 21 domains and 127 sub-domains, which are used to describe the content of documents in EUR-Lex.

combination with standards, is the most frequently mentioned, followed by thermal process, carbon capture, alternative materials and industrial symbiosis.

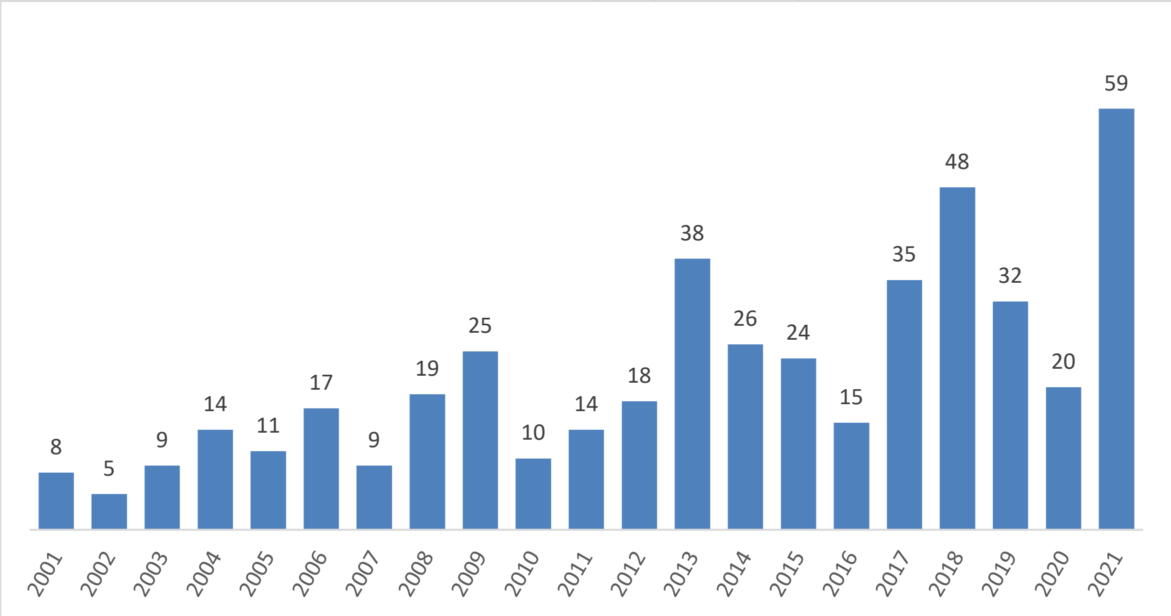
Figure 82 Data-mining in EUR-Lex: Type of policy documents and frequency of EuroVoc descriptors that relate to low-carbon industrial technologies for the 11 denominators (+ standard*)



Source: own elaboration by JRC based on EUR-Lex.

The results from the analysis are shown in Figure 83 for the screening of 452 policy documents between 2001 and 2021. The figure shows a tendency over time of an increased frequency of policy documents containing standards in combination with the 11 denominators considered. This can be an indicator of an increased societal demand for regulating aspects associated with low-carbon industrial technologies. The analysis also showed that there are few policy documents that focus specifically on low-carbon industrial technologies.

Figure 83 Data-mining in EUR-Lex: Frequency of publication of policy documents (Directives, Regulations, Decisions) containing the 11 denominators (+ standard*) related to low-carbon industrial technologies (2001–2021)



Source: own elaboration by JRC based on EUR-Lex.

The preliminary analysis carried out with EUR-Lex indicates that standardisation could benefit several areas of low-carbon industrial technologies in which, currently, standardisation requests or references in policy documents are under-represented. These areas are:

- green hydrogen;
- fuel alternatives;
- carbon use;
- carbon storage;
- circularity of materials; and
- materials efficiency.

3 Conclusions on framework conditions

3.1 *Regulation*

- Designing and building a pilot or demonstration plant at scale is one of the major challenges for the development of many decarbonisation technologies at regional level and across borders. A key barrier to rollout are the uncertainties around authorisations of first-of-a-kind installations. A community of knowledge and practice, with know-how on authorisation processes, and obtaining permits and licences etc., could support the creation of new demonstration plants across the EU.
- There are several models at EU level for facilitating authorisation processes. These include efficient set-up of semi-conductor production facilities (European Chips Act), the network of regional hubs for better regulation (RegHub) or recommendations from the Commission to Member States on how to speed up approval processes for renewable energy installations.
- Specific State aid rules (i.e. direct support for R&D&I activities, intellectual property transfer) allow SMEs to better protect their intellectual property, given that they are less likely to patent new low-carbon technologies compared with their larger counterparts.

3.2 *Valorisation and standardisation for low-carbon industrial technologies*

- Standards can provide agreed vocabulary, definitions and units. The development of low-carbon technologies from basic research to deployment, at every stage, requires the use of standards.
- Bridging the gap between R&I and standardisation requires strengthening the links between science communities, in particular those in emerging technologies, and standardisation organisations.
- Similarly, knowledge sharing and valorisation in Europe helps addressing gaps across Member States and to help widening countries to better benefit from R&I results.
- Current analysis indicates that further action on standardisation could help promoting innovation for several low-carbon industrial technologies in which, currently, standardisation requests or references in policy documents are under-represented. These areas are: digitalisation, green hydrogen; fuel alternatives; carbon use; carbon storage; circularity of materials; and materials efficiency. While it is possible and useful to assess standardisation gaps using data-mining in Euro-Lex and EuroVoc descriptors, more work is needed to identify gaps and prioritise standard setting.

INPUT TO THE TRANSITION PATHWAY

The updated Industrial Strategy confirms R&I as a key factor to accelerate the twin transitions and in co-creating transition pathways across relevant industrial ecosystems, which should take into account relevant inputs such as industrial technology roadmaps announced in the Communication on the European Research Area (ERA).

The table below summarizes the R&I input from the industrial technology roadmap to the upcoming transition pathway for the energy-intensive industries' ecosystem.

The inputs from the industrial technology roadmap will also support the follow-up work with Member States, industry and other stakeholders on the ERA Policy Agenda 2022-2024 to accelerate the digital and green transition of Europe's key industrial ecosystems.

Table 10 Key R&I findings and ways forward for the transition pathway on energy-intensive industries' ecosystem

Findings	Actions	Responsible Actors
• There is a converging view about a – manageable – number of low-carbon industrial technologies, which are needed to achieve EU climate objectives in the energy-intensive industries' ecosystem. • Scaling up and deploying existing innovative low-carbon technologies currently at high TRLs is crucial for reaching the 2030 emission objectives. • At the same time, technologies that are still in pilot and demonstration phase and technologies that are now at an even lower development levels will need to be developed for reaching emission targets after 2030 in the horizon 2050. The challenge is to speed up such innovation projects to reach the market in this timeframe. • Scenarios, studies and R&I investment trends show that there is a gap between the current overall R&I investments across energy-intensive sectors and the amount needed to reach EU emission objectives. This requires major acceleration in low-carbon R&I and a significant rise in R&I investments. The highest R&I investments should happen in the coming years (estimated at somewhat above EUR 20 billion until 2030), together with increasing deployment investments with a peak around the mid- to end -2030s. • The biggest investment gap concerns R&I investments over the coming eight to twelve years for first-of-a-kind (FOAK) installations, large-scale demonstration and deployment of technologies currently at high TRLs. • Overall, the transition will require investments estimated at more than EUR 800 b. until 2050. The biggest investment need will be in the chemical sector, followed by iron & steel and cement. • EU co-programmed partnerships with industry under Horizon Europe and EIT KICs provide a strong forum for cross-sector cooperation. They are the largest	1. Assess the potential for establishing an industrial alliance or similar initiative for low-carbon technologies in energy-intensive industries based upon P4P and Clean Steel partnerships, as referred to in the 2020 New Industrial Strategy. Such initiatives should have a special focus on cross-sectoral technologies linked to the energy efficiency of the industrial processes and use and integration of renewables. 2. Develop relevant hub structures to increase investment into development and uptake of cross-sectoral low-carbon industrial technologies. 3. Organise awareness raising actions and expert discussions about private R&I investment under the EU taxonomy for sustainable finance and about existing structures to support uptake, like the European Energy Network agencies.	Industry, Member States and other stakeholders, EC EC, Industry, Member States, regional authorities &other stakeholders EC in cooperation with Member States, industry and other stakeholders

European initiatives in this industrial ecosystem to develop and implement transformation strategies to support the European Green Deal and implement them through joint R&I actions. They cover several sectors concerned and bring together Europe's key companies, associations and R&I stakeholders. For steel, several relevant developments are concentrated or connected to the Clean Steel partnership.		
• Not all Member States with high CO_2 emission from energy-intensive industries (including per capita), have made high ERDF allocations for low-carbon projects during the programming period 2014-2020. Some of them have national R&I schemes, which provide (parts of) the relevant funding support, but their relevance and magnitude for development and uptake of low-carbon technologies is difficult to gauge. • Fragmented reporting and data pose a challenge to anticipate and estimate R&I investments and their effects on emission reduction. Links between different monitoring mechanisms, coherence and completeness of indicators and data are missing in order to get the needed oversight and to plan and adapt investments.	4. Facilitate better matching of ERDF/National transition strategies with emission patterns in energy-intensive industries. 5. Develop key indicators and data sets for monitoring of industrial R&I in the EU industrial ecosystems for energy-intensive industries also through better use of existing data, including from Energy Union reporting, in the context of the new ERA policy agenda and linked to the revised SET-Plan (working group on energy efficiency in industry) and other relevant monitoring tools.	Member States, regional authorities, EC EC, industry, Member States and other stakeholders
• There is a gap as regards synergies between support instruments at EU level and with the national level, which is also due to the lack of a broad and open platform to establish strategic roadmaps and efficient coordination of research, development and innovation investment plans for low-carbon industrial technologies.	6. Extend and strengthen synergies between Horizon Europe partnerships with industry and other EU instruments as well as with national instruments. This should be based on good practices like the Impact Panel of the P4P partnership, facilitating the launch and market uptake of projects at TRL 9 through links with the Innovation Fund and the European Investment Bank. The objective should be stronger complementarity and links between the instruments. 7. Discuss opportunity of targeted low-carbon R&I funding instruments with specialized national or international promotional banks in implementation of InvestEU. see also action 1	EC EC, specialized national or international promotional banks
• Several Member States have developed sector-specific or even cross-sectoral strategies towards decarbonisation, co-created with relevant stakeholders (such as in Finland, Sweden, Germany and Slovenia). These are important instruments designing a detailed process with milestones towards commonly agreed emission reduction (and other) targets.	8. Facilitate developing integrated low-carbon technology or sector-specific roadmaps at national level with key stakeholders as part of ERA policy agenda 2022-2024. 9. Consider joint discussions between ERA Forum and SET-Plan Implementation Working Group on Energy Efficiency in Industry) and/or peer-counselling groups. 10. Launch action under policy support facility (PSF)-Country and Mutual learning exercise.	EC, Member States, Industry & other stakeholders EC, Member States, Industry EC, Member States, Industry

• Patenting filings in green inventions, which give early indications of technological and economic developments, continue to increase globally. Among the EU Member States, Denmark remains the country with the highest share of green inventions (21%) in its national portfolio. • SMEs appear to play a minor role in energy-intensive industries' inventions, suggesting the need to strengthen their possibilities to create innovation markets for breakthrough low-carbon technologies.	11. Explore further the role of start-ups in patenting of green inventions, including innovation for energy-intensive industries. 12. Improve the knowledge on patenting for green technologies and for energy-intensive industries, such as cement and steel, through more granular sector analysis, and through enabling simpler online searchers for existing green patents 13. Facilitate further valorisation by exploring with industry the opportunity to open up IP on central (cross-sectoral) green inventions, widening the access to IP for licensing (e.g. patent pool) and knowledge transfer.	EC with relevant partners/agencies EC with relevant partners/agencies EC
• Current analysis indicates that further action on standardisation could help promoting innovation for several low-carbon industrial technologies in which, currently, standardisation requests or references in policy documents are under-represented. These areas are: digitalisation, green hydrogen; fuel alternatives; carbon use; carbon storage; circularity of materials; and materials efficiency. While it is possible and useful to assess standardisation gaps using data-mining in Euro-Lex and EuroVoc descriptors. More work is needed to identify gaps and prioritise standard setting.	14. Cooperate with CEN/CENELEC, DG JRC, DG GROW and industrial partnerships to identify and fill main standardisation gaps for innovative low-carbon industrial technologies (incl. next Standardisation Work Programme).	EC, CEN/CENELEC, European partnerships and Member States
• A key barrier to rollout are the uncertainties around authorisations of FOAK installations.	15. Establish a community of practice to facilitate authorisation for FOAK installations for low-carbon industrial technologies, building upon similar approaches under the European Chips Act, the Regulatory Hubs Network under REFIT (RegHub), EU recommendations for approval processes for renewable energy installations, the Hubs4Circularity Community of Practice and involvement of existing networks of relevant agencies.	EC with Member States, Industry & other stakeholders

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ABBREVIATIONS & ACRONYMS

ADEME: French Agency for ecological transition

AI: Artificial intelligence

AIT: Austrian Institute of Technology

AT: Austria

BE: Belgium

BF: Blast furnace

BOF: Basic oxygen furnace

BG: Bulgaria

CBAM: Carbon Border Adjustment Mechanism

CCMT: Climate change mitigation technologies

CCS: Carbon capture and storage

CCU: Carbon capture and utilisation

CCUS: Carbon capture, storage and utilisation

CEEAG: Climate, environmental protection and energy guidelines

CEN: European Committee for Standardization

CENELEC: European Committee for Electrotechnical Standardization

CN: China

CO_2: Carbon dioxide

CPC: Cooperative Patent Classification

CSP: Clean steel partnership

CY: Cyprus

CZ: Czechia

DE: Germany

DG CLIMA: Directorate-General for Climate Action

DG EAC: Directorate-General for Education and Culture

DG ENER: Directorate-General for Energy

DG ENV: Directorate-General for Environment

DG GROW: Directorate-General for Industry, Internal market and SMEs

DG R&I: Directorate-General for Research and Innovation

DG REGIO: Directorate-General for Regional Policy

DK: Denmark

DRI: Direct reduced iron

EAF: Electric Arc Furnace

EC: European Commission

EE: Estonia

EEI: Energy-efficient industry(ies)

EGD: European Green Deal

EIC: European Innovation Council

EII: Energy-intensive industry(ies)

EISMA: European Innovation Council and SMEs Executive Agency

EIT: European Institute of Innovation and Technology

EnR: European network of energy agencies

EPO: European Patent Office

ERA: European Research Area

ERC: European Research Council

ERDF: European Regional Development Fund

ES: Spain

ESIF: European Structural and Investment Funds

ETS: Emission Trading System

EU: European Union

EUR: Official currency of the European Union (Euro)

FI: Finland

FOAK: First-of-a-kind

FOD: Foresight on Demand

FR: France

GBER: General Block Exemption Regulation

GDP: Gross Domestic Product

GHG: Greenhouse gas

GR: Greece

H2020: Horizon 2020

HLG EII: High-Level Group on Energy-Intensive Industries

HR: Croatia

HU: Hungary

ICB: Industry Classification Benchmark

ICT: information and communications technology

IE: Ireland

IEA: International Energy Agency

IED: Industrial Emissions Directive

IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IPCEI: Important Project of Common European Interest

IT: Italy

JP: Japan

JRC: Joint Research Centre

JTF: Just transition fund

KICS: Knowledge and Innovation Communities

LT: Lithuania

LU: Luxembourg

LV: Latvia

MFF: Multiannual financial framework

MT: Malta

Mt: Metric ton

Mt CO_2: Metric ton of carbon dioxide

NACE: Nomenclature of economic activities

NECP: National energy and climate plan

NL: Netherlands

NUTS: Nomenclature of territorial units for statistics

NZE: Net Zero Emissions

OECD: Organisation for Economic Cooperation and Development

P4P: Processes4Planet

PATSTAT: Patents statistics, a tool of the European Patent Office

PL: Poland

PPMI: Public Policy and Management Institute

PT: Portugal

RD&I: Research, Development & Innovation

R&D: Research & Development

R&I: Research & Innovation

REFIT: Regulatory Fitness and Performance Programme

REGHUB: Regional Hubs Network

RFCS: Research Fund for Coal and Steel

RFG: Risk-finance guidelines

RIS: Regional Innovation Scheme

RO: Romania

RRF: Recovery and resilience facility

RRP: Recovery and resilience plan

RTO: Research and Technology Organisation

SE: Sweden

SET Plan: Strategic energy technology plan

SETIS: Strategic Energy Technology Information System

SI: Slovenia

SK: Slovakia

SME: Small and medium-sized enterprise

SPIRE: Sustainable Process Industry through Resource and Energy Efficiency (Horizon 2020 Partnership)

SRIAs: Strategic Research and Innovation Agendas

SRIP: Science, research and innovation performance of the EU

SWD: Staff Working Document

TEDAM: Territorial Data Analysis and Modelling

TEN-E: The Trans-European Networks – Energy

TRL: Technology readiness level

UK: United Kingdom

USA: United States

USPTO: United States Patent and Trademark Office

FIGURES, TABLES AND BOXES

ANNEXES

Annexes are available in a separate document on the EU Bookshop.

Annex 1: Summary of SMEs surveys.

Annex 2: Workshop Report: ERA industrial technology roadmap for low-carbon industrial technologies in energy-intensive industries - Online Workshop, 24.11.2021, 14:00-17:00.

Annex 3: Assessment of technological options for decarbonisation of energy-intensive industries by pathways.

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The energy crisis resulting from Russia's invasion of Ukraine only underlines the urgency for the EU to reduce its dependency on fossil fuel, in order to reach climate neutrality by 2050, which is at the core of the European Green Deal. Decarbonising the industry, responsible for 17% of greenhouse gas emissions in the EU, is therefore key.

This first industrial technology roadmap under the new European research area (ERA) provides an evidence base on the state of play of low-carbon technologies in energy-intensive industries in the EU and available support instruments, and points to possible research and innovation action in view of accelerating development and uptake of these technologies. These possible ways forward build on contributions from industry, other research and innovation stakeholders, Member States, and relevant European partnerships.

This roadmap will feed into the transition pathway for the energy-intensive industries ecosystem under the EU industrial strategy and supports the work to accelerate the green and digital transitions under the ERA policy agenda.

Research and Innovation policy

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