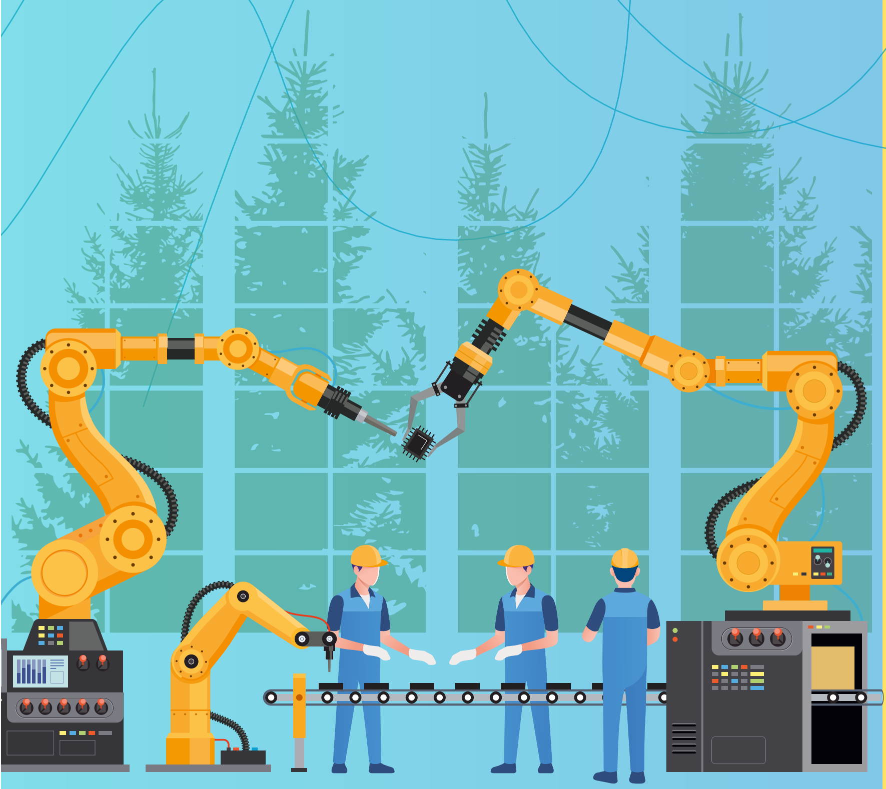
European Commission

Pilot Industrial technology prospect report:

R&I evidence on EU development of low-carbon industrial technologies



Pilot - Industrial technology prospect report: R&I evidence on EU development of low-carbon industrial technologies

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EUROPEAN COMMISSION

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DG RTD.E.1 & JRC.B.3, JRC.C.7

Directorate-General for Research and Innovation
Directorate Prosperity

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2021

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INTRODUCTION

As a cornerstone of the European Green Deal[1], the EU Climate Law[2] sets in legislation the EU's objective of climate neutrality by 2050. This is in line with scientific findings reported by the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and contributes to the implementation of the Paris Agreement on climate change.

The EU Climate Law takes on board the European Council's[3] emphasis of the key role of forward-looking research, development and innovation (RD&I) in achieving climate neutrality. To help implement the Green Deal's growth agenda, the EU's industrial strategy 2020[4] announced a New European Research Area (ERA) to map out a new approach to innovation and ensure the EU budget is used with maximum impact. The ERA will involve the development of common EU technology roadmaps implementing a joint vision for the development of industrial technologies based on research and innovation (R&I) in a 'renewed partnership' with industry and national/regional stakeholders. Through the industrial strategy and the new ERA, the EU will be able to use its excellent R&I results and cooperation more effectively, to push innovation as a basis for strengthening its industrial alliances and ecosystems.

The European Commission has carried out in-depth analysis exploring how climate neutrality can be achieved across the key economic sectors, including energy, transport, industry and agriculture. This has shown that R&I will determine the speed at which decarbonisation can take place, at what costs and with what co-benefits. Without further major steps in industrial innovation for low-carbon technologies, the EU will not be able to reach its climate goals[5].

Energy-intensive industries accounted for roughly 15% of the EU's total greenhouse gas (GHG) emissions in 2015 (18.4% in 1990)[6]. Among the energy-intensive sectors, steel, chemicals and cement account together for more than two-thirds of all industrial CO_2 emissions in the EU, while directly employing nearly 2 million workers and generating an annual turnover of about €750 billion[7]. To address this state of affairs, the Commission announced the establishment of a low-carbon industrial alliance in the industrial strategy.

The Commission's work with industry experts has identified a number of specific technologies that are expected to have a particularly high potential to lower EU carbon emissions in energy-intensive industries[8]. These technologies also play a key role in the scenarios for GHG-reduction referred to in the EU's first *Strategic foresight report*[9].

The Commission's analysis shows that new and promising low-carbon technologies will need to be developed further if EU industry is to achieve the required emissions reductions. Existing technology will not deliver the full reductions required to achieve EU's climate objectives and new technologies should ideally be brought to market by

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1 COM/2019/640 final, 11.12.2019.

2 Provisional agreement between the Council and the European Parliament from 21 April 2021 on the Commission proposal for a Regulation of the European Parliament and of the Council establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (COM/2020/80 final).

3 EUCO Conclusions 12 December 2019.

4 COM(2020) 102 final, 10.3.2020.

5 *A clean planet for all*, staff working document accompanying COM(2018) 773 (in-depth analysis serving as impact assessment for the 2020 Climate Law), p. 243.

6 This excludes land use, land-use change and forestry (LULUCF); see High-Level Group report, *Masterplan for a competitive transformation of EU energy-intensive industries enabling a climate-neutral, circular economy by 2050*.

7 Report from the Strategic Forum for Important Projects of Common European Interest; https://ec.europa.eu/docsroom/documents/37824

8 *Masterplan for energy-intensive industries* (see above); *Commission report on progress of clean energy competitiveness* (COM(2020) 953 final, adopted 14 October 2020).

9 https://ec.europa.eu/info/sites/info/files/strategic_foresight_report_2020_1.pdf

2030, to allow for scaling-up and deployment across the EU by 2050[10]. In the case of more mature technologies, the necessary investment into large-scale demonstration and deployment will require increased pooling of resources[11].

Technologies are currently at very different levels of market readiness, often lagging behind what is required to contribute to decarbonisation pathways. However, it is important to assess and mitigate risks before large-scale deployment[12]. To avoid risks of technological lock-in and stranded technologies, thorough consideration of R&I results 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 established with industry and other stakeholders are key to achieving EU policy objectives[13].

World-leading research on low-carbon industrial technologies is being conducted at EU level and at national or 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, and producing a wealth of evidence on the state of play and the industrial potential of innovative low-carbon technologies. The Commission's Joint Research Centre (JRC) and Directorate-General for Research and Innovation (DG R&I) regularly collect and assess the evidence. They manage complementary monitoring tools such as the EU Industrial R&D Investment Scoreboard[14], the Strategic Energy Technologies Information System (SETIS)[15], the *Science, research and innovation performance of the EU, 2020* report[16], the Innovation Radar[17], the GLORIA project[18], the projects for policy mechanism[19] etc. They continuously improve their monitoring and assessment work including on breakthrough industrial technologies and innovation ecosystems under the European Innovation Council (EIC).

This first pilot 'industrial technology prospect report' aims to provide an insight into the state of play on R&I in low-carbon industry technologies, which are key for emissions reductions in energy-intensive industries, such as steel, cement and chemicals, covered by the upcoming EU low-carbon industrial alliance[20]. It concentrates on the maturity of relevant technologies and their potential to help industry reach the EU climate targets. It provides an overview of relevant production costs in industrial sectors, potential cost reductions through new technology and insights into current public and private sector R&D investment and related patenting developments. The report also provides a snapshot of green R&I development and patents in EU regions.

This report is the outcome of a model of cooperation between services that will help to provide a strong evidence base to inform future roadmaps supporting R&I in industrial ecosystems and alliances. The approach will be further developed in other areas through the exploitation of existing analytical capacities, targeted use of Horizon Europe results

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10 Clean Planet for All, SWD In-depth analysis, page 157 and SRIP Report 2020, p. 38. See also industry priorities in Masterplan for a Competitive Transformation of EU energy-intensive industries, page 25.

11 The EU hydrogen strategy for a climate-neutral Europe aims for 40 GW of renewable hydrogen electrolysers and significant production of renewable hydrogen in the EU energy system by 2030, with direct investment of €24-42 billion; https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

12 *A clean planet for all*, p. 243.

13 European Parliament, *Study on energy-intensive industries* (July 2020); Communication *A new ERA for research and innovation* (COM(2020) 628 final); see also successful examples under the energy union SET plan.

14 https://ec.europa.eu/info/news/2019-eu-industrial-rd-investment-scoreboard-report-2019-dec-18_en

15 Strategic Energy Technologies Information System (SETIS) https://setis.ec.europa.eu/index_en

16 *SRIP report 2020*; https://ec.europa.eu/info/research-and-innovation/strategy/support-policy-making/support-national-research-and-innovation-policy-making/srip-report_en#srip2020

17 https://www.innoradar.eu/faq

18 https://cordis.europa.eu/project/id/811163

19 https://ec.europa.eu/info/research-and-innovation/strategy/support-policy-making/scientific-support-eu-policies/p4p_en;

20 Future areas could include resilient manufacturing, bioeconomy and bio-based industries, and pharmaceuticals.

and greater involvement of the European Institute for Innovation and Technology (EIT) in analysing the territorial dimension of R&I.

1 Relevant Key Technologies

In order to gauge the state of play in R&I that can help industry to develop and deploy technologies enabling achievement of the EU's climate objectives, we need to understand:

- which technologies can best address the key factors driving emissions in a sector;
- their potential in reducing those emissions; and
- their level of development.

This part of the report gives an overview of available or future technologies that can help to reduce GHG emissions in the main energy-intensive industries. The results also form the basis for the analysis of investment and patenting activity and for the data mining across Horizon 2020 projects in subsequent chapters.

Table 1 is based on the scientific study underpinning the 'masterplan for a competitive transformation of EU energy-intensive industries enabling a climate-neutral, circular economy by 2050'. The technologies are classified by category and by the sector(s) for which they are relevant. Some play a cross-cutting role for all three main (and other) energy-intensive industries, while others are used in a more specific context.

Table 1: Overview of relevant key technologies by industry and category

<table>
<tr><th>Industry
Category</th><th>Cement</th><th>Chemicals</th><th>Steel</th></tr>
<tr><td>Electrification</td><td>Cement kiln electrification</td><td>• Electrochemical processes
• Ultrasounds
• Steam cracker electrification</td><td>• Electric arc furnace (EAF) in combination with hydrogen — direct reduced iron (H-DRI)
• Iron ore electrolysis</td></tr>
<tr><td rowspan="2">Use of green hydrogen</td><td>Use of hydrogen and biomass fuel mix as a replacement for fossil fuels</td><td>Use of low-CO_2 hydrogen for chemical production (ammonia, methanol)</td><td>• Hydrogen as a reducing agent in DRI
• Hydrogen-plasma smelting processes</td></tr>
<tr><td colspan="3">• Alkaline electrolysis hydrogen
• Polymer electrolyte membrane (PEM) electrolysis hydrogen
• Methane pyrolysis</td></tr>
<tr><td>Carbon capture and storage (CCS)</td><td>• Post-combustion technologies
• Oxyfuel combustion
• Calcium-looping
• Direct separation technology</td><td>Capture of CO_2 (amine based, adsorption, physical absorption)</td><td>• Generation of CO_2-rich waste gas to facilitate carbon capture
• DRI + carbon capture
• HIsarna steelmaking process</td></tr>
<tr><td rowspan="2">Carbon capture and utilisation (CCU)</td><td>Carbonation of solid raw material</td><td>Use of CO_2 as carbon feedstock for many base chemicals (alcohols, polymers, acids…)</td><td>Valorisation of waste gases from the blast furnace (e.g. to produce chemical raw materials)</td></tr>
<tr><td colspan="3">CO_2 separation and purification technologies</td></tr>
</table>

<table>
<tr><td rowspan="2">Biomass and other biofuels</td><td></td><td>Use of biomass as a raw material
Bio-ethanol for high added value chemicals value chain</td><td>Torrefied biomass partially replacing injected coal</td></tr>
<tr><td colspan="3">Use of biomass as an energy source
Production of biofuels</td></tr>
<tr><td rowspan="2">Recycling</td><td>Recycling and re-use of concrete</td><td>Conversion of mixed plastic wastes into synthetic fuels
Chemical recycling of plastics as feedstock</td><td>Recycling of process gases
Recycling high-quality steel / separation of contaminants from scrap
Valorisation of scrap metal</td></tr>
<tr><td colspan="3">Valorisation of waste streams</td></tr>
<tr><td rowspan="2">Alternatives</td><td>Clinker substitutes
New cements with low clinker content
Alternative binders
Improving concrete mix design
Advanced grinding technologies (contact-free grinding systems, ultrasonic-comminution, high-voltage power-pulse fragmentation, low temperature comminution)</td><td>Membrane reactor technologies</td><td>Avoidance of intermediate process steps</td></tr>
<tr><td colspan="3">Enhanced digitalisation</td></tr>
<tr><td rowspan="3">Industrial symbiosis</td><td>Recycling and recovering waste and by-products from other energy-intensive industries, such as steel slag</td><td colspan="2">Waste gases from primary steel production can become the feedstock for the production of high added value chemicals</td></tr>
<tr><td></td><td></td><td>Delivering granulated blast furnace slag for the cement industry</td></tr>
<tr><td colspan="3">Delivering waste heat to other industries</td></tr>
</table>

Adapted from: *VUB-IES, Industrial value chain: A bridge towards a carbon-neutral Europe — Europe's energy-intensive industries' contribution to the EU strategy for long-term EU greenhouse gas emissions reductions (2018).*

2.1 Key determinants for relevance of R&I action to develop low-carbon technologies: technological-readiness and GHG reduction potential

Experts consider the low-carbon technologies in the table above as particularly relevant, either because of their advanced level of development or because of their high emissions-reduction potential, or both. Mature low-carbon technologies can unfold their positive impact on EU industry where R&I action helps to bring them to the market, e.g. through large-scale demonstration and deployment. Lower technological readiness levels (TRLs) mean that further R&I action is required to push the technologies closer to widespread application in the market. Understanding the technological readiness of relevant technologies and assessing their potential contribution to emissions reductions is key to designing effective R&I policies to drive industrial innovation.

For instance, **hydrogen-based technologies** (a key route to lower emissions in the EU) are supported by the July 2020 EU hydrogen strategy, national strategies in countries such as France and Germany, and the launch of an EU Clean Hydrogen Alliance. New steelmaking technologies aim to replace the natural gas currently used in the direct reduction of iron by green hydrogen. If renewable electricity is used both by the hydrogen plant and the electric arc furnace (which further processes the iron to steel), CO_2 emissions could be cut by up to 95%. The Commission aims to facilitate large-scale demonstration of the relevant technologies in the context of the Clean Hydrogen Alliance[21].

The direct electrolysis of iron ore ('electrowinning') to produce raw steel is still at an early stage of development and has been proven at laboratory scale only. However, by using solely renewable electricity, steel production could emit up to 87% less CO_2 than the current integrated route[22]. Evidence and experience as to how R&I can help with the further development of such technologies is therefore equally important.

2.2 Technological readiness levels and CO2 reduction potential: technology groups

This section groups the current main technologies according to their TRLs, with reference to their perceived potential for reducing CO_2 emissions in the cement, steel and chemicals industries.

TRLs are a widely used indicator of the maturity of a technology from inception (TRL 1) to deployment (TRL 9)[23]. Although the TRL scale is a very valuable tool in that respect, it cannot always capture the precise state of development of a technology. It is sometimes difficult to assign an overall TRL index to complex technologies made up of many different components. This is often the case, for example, with wider technological approaches in energy-intensive industries (e.g. overall control systems, process optimisation and integration, catalysis, etc.). In this context, when using TRLs to estimate the readiness for deployment of a certain 'technology', factors other than purely technical/technological considerations, such as scale, requirement for concomitant technologies, investments, existing technologies, investments, existing technologies etc. play a particularly important role[24].

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[21] *EU hydrogen strategy*, 8 July 2020.

[22] European Commission, *Strengthening strategic value chains for a future-ready EU industry* (2019), Annex II.

[23] Description of levels:
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).
Source: European Commission, *Horizon 2020 — work programme 2018-2020*, general annexes.

[24] The Innovation Radar introduces complementary indicators to gauge technological maturity; https://ec.europa.eu/jrc/sites/jrcsh/files/booklet-a4_innovation_radar.pdf

Low TRL (1-4):

- In the steel industry, **iron ore electrolysis** could emit up to 87% less CO_2 than the current integrated route (if electricity is fully decarbonised), but it has been proven at laboratory scale only (TRL 4).

- In the cement industry, technologies for providing decarbonised heat — such as substituting fossil fuels fully with **biomass** (possibly mixed with hydrogen) or **electrification of heat via plasma generators** — can reduce GHG emissions by up to 35% (without addressing the process emissions of clinker making). These technologies have not been proven outside the laboratory (TRL 3).

- **Hydrogen plasma reduction** (Susteel project) is at TRL 4-5 and aimed at zero CO_2 emissions[25].

- Also in the cement industry, **kiln electrification** (CemZero project) is at TRL 3-4; the project aims to achieve zero emissions.

- In the chemicals industry, **steam cracker electrification** ('cracker of the future' project) is at TRL 3. One of the project participants, BASF, envisions cutting CO_2 emissions per cracker by 90% (i.e. by 750 000 tonnes annually across the company).

Medium TRL (5-7):

- In the steel industry, **hydrogen steelmaking** (currently at TRL 5-7) could emit up to 95% less CO_2 than the current integrated route (if electricity is fully decarbonised).

- The new **'HIsarna' smelting technology** (new ironmaking concept that uses fine coals and fine ores directly without any preparation) could reduce emissions by up to 35% and is at TRL 7. Due to the high CO_2 concentration of the waste gases, this technology is particularly suited to being combined with carbon capture and storage (**CCS**), in which case emissions could be reduced by up to 80%.

- In the cement industry, several **carbon capture technologies** are being explored. They can capture 95% of total (process + fuel) CO_2 emissions when fossil fuels are still used for heat (oxyfuel or calcium-looping technology), or can be combined with a zero-CO_2 heat process to capture 95% of process emissions (post-combustion or direct-separation technology). These CCS technologies are currently at TRL 6.

- There is considerable ongoing research on **alternative clinkers and low-carbon cements** using alternative cement binders at a wide range of TRLs (5-7), which could achieve around 30% CO_2 reduction versus ordinary Portland cement.

High TRL (8-9):

- In the steel industry, **carbon capture and re-use technologies** (valorising the waste gases of blast furnaces) can reduce emissions by up to 65% if fully deployed (the CO_2 reductions also depend on the full lifecycle of the resulting chemical products). Several are at a more advanced stage of development — the Steelanol demonstration plant (currently under construction — TRL 9) uses waste gas to produce bio-ethanol and the Carbon2Chem project (TRL 7-8) aims to use waste gas as a raw material for chemicals.

- In the chemicals industry, the use of **membrane reactor technologies** could reduce emissions significantly by enhancing process efficiency. For example, the H2020 'reactor optimisation by membrane enhanced operation' (ROMEO) project aims to

[25] https://www.k1-met.com/en/research_programme/susteel/

reduce energy consumption by up to 80% and emissions by up to 90% in industrial catalytic gas-phase reactions. Currently, work is focusing on demonstrating the technical feasibility of this approach.

2.3 European Innovation Council: identifying breakthrough technology and bringing it from inception to deployment

Since its inception in late 2018 and now in the context of the Green Deal, the **EIC** has funded promising technological breakthroughs contributing to the decarbonisation of energy-intensive industries.

The **EIC Pathfinder** supports low-TRL research projects. Building on the 'future and emerging technologies' (FET) programme for inter-disciplinary, cross-border advanced research, it has been supporting a number of consortia-led projects developing breakthrough innovation. Although not specifically targeting the cement, chemical and steel industries, these projects might have a significant impact in terms of their decarbonisation:

- AMADEUS (TRL 1 to 3) is developing **novel materials and devices that enable storage** of any kind of energy (waste heat, sunlight) in the form of latent heat, and conversion to electricity on demand. Possible future applications are in the field of photovoltaics, thermal storage, silicon casting and metallurgy disciplines;

- HARVESTORE (TRL 1 to 3-4) is developing a new family of nano-enabled miniaturised energy sources able to **harvest and store energy from heat and light sources** in a single device. This new paradigm is based on intelligent materials able to harvest and store ambient energy (thermal gradient or light) and smartly release it when needed. The project includes an application scenario on industrial and energy-network monitoring covering tests in exhaust gas chimneys and gas-management networks with harsh conditions and temperatures of up to 350 °C. This could enable the deployment of 'internet of things' technologies in these sectors;

- UncorrelaTEd (TRL 1-2) is testing the application in materials for thermoelectric devices of a new paradigm in thermoelectricity, capable of significantly improving overall **thermoelectric efficiency**. The project is important *inter alia* for applications in the metals sector, e.g. the steel industry;

- MAGENTA (TRL 1 to 3) is developing **magneto-thermoelectric materials** and devices based on ionic ferrofluids for the waste-heat recovery industries. The technology is potentially scalable to specific industrial sectors using waste heat energy;

- TPX-Power (TRL 1 to 3) is developing a new **heat engine technology for thermal energy recovery** allowing high power density and competitive energy-harvesting efficiency even for low-temperature energy streams;

- 112CO2 (TRL 1 to 4) aims to develop new material for a methane decomposition reactor for **CO_x-hydrogen free production**;

- DIACAT665085 (TRL 1 to 3) is developing a new technology for the **direct photocatalytic conversion of CO_2 into fine chemicals** and fuels using visible light and the unique properties of man-made diamond. The chemicals industry could use the technology for the direct transformation of CO_2 into organic chemicals using illumination with light; and

- FuturoLEAF (TRL 1 to 3) involves a new generation of **photosynthetic cell factory** for chemical industries, with a tailored solid-state biocatalyst architecture for efficient biological carbon capture and sustainable bio-production of a wide spectrum of chemicals, from active pharmaceutical ingredients and fine/special chemicals to commodity chemicals and biofuels.

The **EIC Accelerator** supports the scale-up of innovative start-ups and SMEs, along with the market uptake of higher-TRL transformative technologies. As the successor to the SME Instrument, it funds projects involving promising technologies that address key issues in the decarbonisation of heavy industry:

- CemShale CemTower (TRL 5/6-8) involves reducing the carbon footprint of the cement industry by using **'supplementary cementitious materials'** based on pre-calcined shale granule material, and vertically integrated equipment (preheater, kiln and cooler) for optimised treatment of the material. The combination of new materials and equipment improves process efficiency and substitution rates, and (if fully implemented across the cement industry) could lower worldwide CO_2 emission by nearly 5%;

- CRCP (TRL 6-8) is the first **liquid-tolerant 'centric reciprocating compressor enabled to pump'** (**CRCP**) allowing for the energy- and cost-efficient compression and large-scale deployment of 'wet gas' across several industries. It promises energy savings of at least 30% and an almost 45% reduction in CO_2 emissions, thus contributing an estimated GHG emissions reduction of 4 million tonnes CO_2-equivalent by 2030;

- Sens (TRL 5/6-8) involves **smart, sensor-with-radar waste management technology** that can detect methane emission and contribute an overall 60% reduction in CO_2 emissions from waste treatment. The project relies on 'internet of things' technologies to deliver a solution that, while primarily targeting cities and urban spaces, could be adopted by heavy-polluting industries; and

- Proton (TRL 7 to 8) is bringing circularity to industries through the **recycling of industrial CO_2 and its conversion into proteins for animal feed**. The technology is based on gas fermentation that, when scaled up, can turn large volumes of CO_2 into single-cell proteins. As part of its business and commercialisation plan, the SME carrying out the project intends to establish a joint venture with a carbon-intensive industrial company.

2.4 Decarbonisation scenarios

Box 1: Decarbonising the steel sector[26]

- The steel sector accounts for **4%** of all EU emissions and is one of the hardest industrial sectors to decarbonise.
- Currently, the recycled steel route emits around 80% less CO_2 than the integrated route (emissions would be close to zero if electricity were to be fully decarbonised), but is limited by the availability of high-quality scrap.

An analysis of 2050 decarbonisation scenarios published by various sources[27] shows that:

– most scenarios that achieve deep decarbonisation of the sector use new steelmaking processes based on **hydrogen reduction** or **direct electrolysis** of iron;

[26] JRC, *Decarbonisation of industrial heat: The iron and steel sector*, 2020.
[27] For this analysis the JRC has analysed eight scenarios from four publications:
European Commission, *A Clean Planet for all -A European long-term strategic vision for a prosperous, modern, competitive and climateneutral economy*, 2018;
Material economics, *Industrial Transformation 2050 -Pathways to Net-Zero Emissions from EU Heavy Industry,* 2019;
ICF & Fraunhofer ISI, *Industrial Innovation: Pathways to deep decarbonisation of Industry*, 2018;
International Energy Agency, *Energy Technology Perspectives 2017*, 2017.

– **carbon capture and storage/utilisation** are heavily deployed in carbon capture scenarios, by valorising waste gases from the current integrated route to produce chemical raw materials, or associated with new technologies (smelting or top gas recycling);
– including the production of hydrogen, the sector's annual electricity demand could grow by up to **three times** the current demand in the Commission's 1.5 °C scenarios; and
– the proportion of **recycled steelmaking** (currently 40%) could increase by improving the **quality of scrap**; for instance, the downstream recycling process or the upstream design of products could be optimised to allow better disassembly and re-use of materials.

Box 2: Decarbonising the cement sector[28]

- The cement sector accounts for about **4%** of all EU emissions.
- The combustion of fuels to **heat cement kilns** is responsible for about 35% of the sector's carbon footprint. The other 65% are **process emissions**, released during the calcination reaction involved in the production of clinker.

An analysis of 2050 decarbonisation scenarios published by various sources[29] shows that:

– all scenarios achieving deep decarbonisation include some form of **carbon capture technology** (post-combustion, oxyfuel combustion, calcium-looping, direct-separation);
– greater use of **sustainable biomass** (and possible negative emissions when combined with CCS) is proposed as a measure to reduce GHG emissions in several scenarios, including as a bridging measure until breakthrough technologies are ready to be deployed. However, its role is **uncertain** due to increased **competing demand** for biomass from other sectors;
– **electrification** of cement production (electrification of heat) is deployed in high-electrification/low-CCS scenarios; and
– **clinker substitutes** (supplementary cementitious materials) and **new cements** are deployed to varying degrees.

2.5 Sustainable Process Industry through Resource and Energy Efficiency (SPIRE) partnership

Under Horizon 2020, the EU supports the **SPIRE R&I partnership** with industry, which was launched in December 2013. SPIRE supports R&I in the field of sustainable process industries through resource and energy efficiency. It brings together companies, world-leading universities and research organisations, and other stakeholders in the cement, ceramics, chemicals, engineering, minerals & ores, non-ferrous metals, steel and water sectors. It helps to integrate, demonstrate and validate systems and technologies to achieve reductions of up to 30% in fossil-energy intensity and up to 20% in non-renewable and primary raw material intensity. The aim is a drastic overall efficiency improvement of up to 40% in CO_2-eq. footprints.

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[28] JRC, *Deep decarbonisation of industry: The cement sector*, 2020.
[29] *Ibid 26*

In terms of technological capacity to reduce GHG emissions, SPIRE projects reported in 2019 that their innovations could make significant improvements in energy and raw materials efficiency in line with SPIRE's contractual targets, including a reduction of 28.53% CO_2-eq. ('up to 40%' target).

The significant innovations concern three main areas at all TRLs:

- efficient processes;
- sustainability and circular economy; and
- enabling sustainable industry development.

The relevant projects have achieved:

- ✓ 38% reduction of dependency on fossil fuels;
- ✓ 31% reduction of dependency on non-renewable, primary resources; and
- ✓ 29% reduction of emissions.

Projects reported that participants planned to invest in taking almost 54% of innovations up to a higher TRL after the end of the project, which exceeds the 2014 baseline value in this area by almost 25 percentage points. While contractually SPIRE concerns innovations up to TRL 7, the fact that some projects have managed to go beyond this level shows the stakeholders' commitment and the innovation potential in the process industries.

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

2.6 Research Fund for Coal and Steel (RFCS)

The European **Research Fund for Coal and Steel (RFCS)** supports the development of technologies to reduce emissions in the steel industry. In order to pave the way for future applications, several research activities have focused on the development of alternative carbon carriers originating from renewable sources and new breakthrough processes for iron ore reduction and smelting.

Under RFCS-supported projects[30]:

- tests on top gas recycling in blast furnaces have shown that it is possible to operate the process and the gas separation plant in a closed loop, with a 25% reduction in carbon consumption;
- trials on HIsarna have demonstrated that the process works effectively and has now reached TRL 7 (see above);
- a study on the use of electricity to directly decompose iron oxide into metal and oxygen by electrolysis of iron ores has demonstrated a very high capacity for CO_2 mitigation;
- material tests and pilot trials on the substitution of carbon and oxygen with industrial and/or municipal waste have shown that the liquid steel quality can be preserved and the environmental footprint kept low; and

[30] *RFCS monitoring and assessment report (2011-2017).*

- a thermoelectric power generation system has been used for the first time to convert exhaust heat above 550 °C into electricity, and its feasibility has been demonstrated. The potential energy savings of direct use are 0.6-2.8% of total energy input.

To date, the EU has funded 16 relevant projects, with a total budget of €24 million, to which the EU contributed €16 million.

It has funded an additional 42 relevant projects, with a total budget of €331 million, to which the EU contributed €268 million.

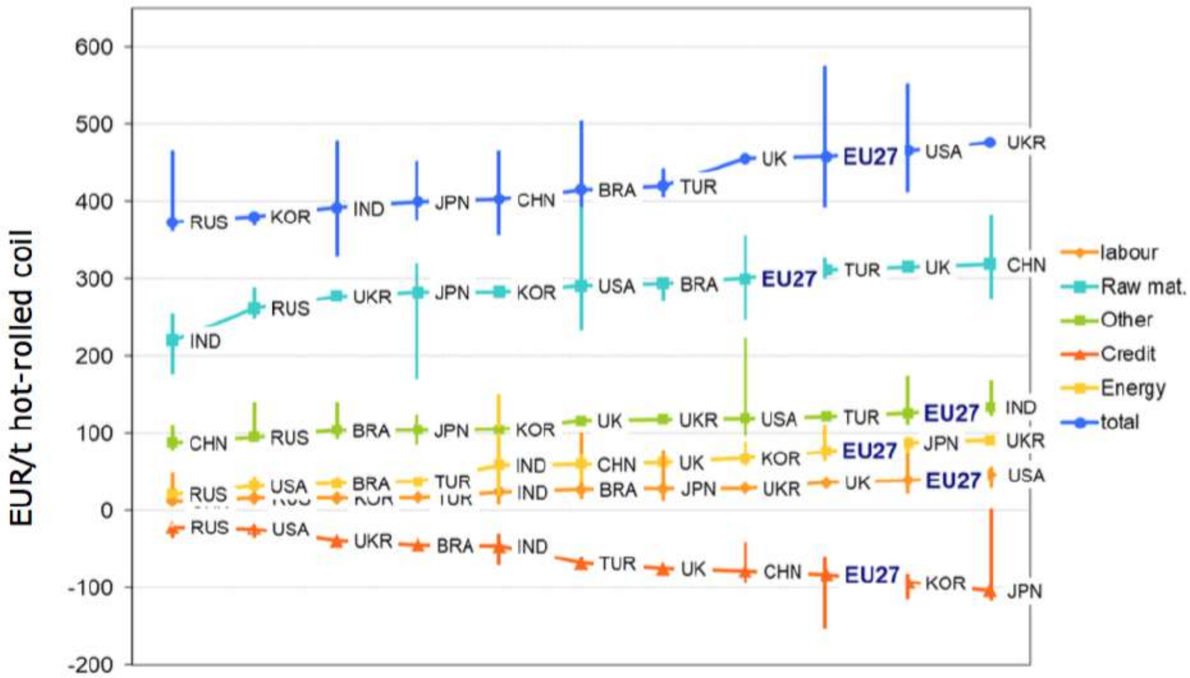
2 EU worldwide productivity and cost efficiency through R&I

R&I is crucial for the EU's productivity. It can increase firms' efficiency through process innovation and improve the goods and services they produce, thus raising demand and reducing production costs. Also, firms that innovate are also likely to grow more and new entrants with better products should displace inefficient firms. Overall, this contributes to higher aggregate productivity: new ideas help to generate greater (or the same) output with the same (or less) input, for companies and the whole economy. This, in turn, should positively affect wages and business profitability. A significant proportion of productivity performance can be ascribed to R&I and intangible investments (see patent section below)[31].

Production costs are a key factor in industrial companies' decision-making about the application of new low-carbon technologies. While the technologies require investment, they can also reduce production costs compared to a baseline scenario in which industries have to reach their climate objectives without the technology. In order to gauge the crucial (potential) interest of industry in the development of new low-carbon technologies through R&I, it is useful to look at production cost patterns in key energy-intensive industries in the EU and competing regions.

Figure 1 shows the cost components in the production of steel (hot-rolled coil) through the blast furnace-basic oxygen furnace (BF-BOF) route (the most carbon-intensive production method, as used for 60% of steel in the EU)[32].

Figure 1: Hot-rolled coil production costs in the BF-BOF process in 2019



Source: JRC

The 'credit' cost element shows cost savings generated by efficiency measures, notably the recycling of waste gases for power self-generation. These represent the accumulated effect of investments in R&I in the sector, for technologies that have now achieved commercial maturity. The figure shows that the EU is among the world leaders (with South Korea and Japan) in this respect, thus improving its global competitiveness.

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[31] *SRIP report 2020*, pp. 97 & 105.

[32] Medarac, H., Moya, J.A. and Somers, J., *Production costs from iron and steel industry in the EU and third countries* (Publications Office, Luxembourg, 2020; ISBN 978-92-76-20887-7; doi:10.2760/145957, JRC121276).

2.1 Production costs and breakthrough technologies

The Climate Law will enshrine the 2050 climate-neutrality objective in EU law. Against this backdrop, the energy-intensive industries are faced with the formidable challenge of decarbonising within 30 years. However, they are already working at virtually maximum energy efficiency and further incremental improvements will not allow them to meet the EU's climate and energy targets. In the steel industry, for instance, current best available technologies promise further CO_2 emissions reductions of only 10% at most%[33], while 65% of emissions in the cement industry are due to reactions that are inherent and unavoidable in the current production process. If the EU is to meet its ambitious climate targets while maintaining its industrial capacity, it will need to deploy breakthrough climate-neutral technologies enabled by a coordinated RD&I effort.

Three recent studies by the International Energy Agency (IEA)[34], Material Economics[35] (ME) and Agora *Energiewende* / Wuppertal Institut[36] (A-EW & WUI) have estimated production costs with breakthrough technologies in the steel, cement and chemicals industries by 2050 (see Table 2):

Table 2: Estimates of production costs with breakthrough technologies in the steel, cement and chemicals industries by 2050

Technology	IEA (USD/t)*	A-EW & WUI (€/t)	ME (€/t)
Steel			
Current BF-BOF route	330-450	391	371
Hydrogen direct reduction	500-850	532-630	403-470
Iron ore electrolysis		645-828	
Smelting reduction + CCS	350-500	427-454	427
Blast furnace + CCU (waste gas valorisation)		637-858	
Gas-based DRI-EAF with CCUS	420-620		
Avg. cost increase of low-CO2 tech.	**+10% to +50%**	**+10% to +112%**	**Up to +20%**
Cement			
Current cement production	50	46	51
CCUS - oxyfuel		82-94	88

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33 JRC, *Decarbonisation of industrial heat: The iron and steel sector*; https://setis.ec.europa.eu/publications/relevant-reports/decarbonisation-of-industrial-heat-iron-and-steel-sector

34 International Energy Agency (2020), *Energy technology perspectives*; https://www.iea.org/reports/energy-technology-perspectives-2020

35 Material Economics (2019), *Industrial transformation 2050 — pathways to net-zero emissions from EU heavy industry*.

36 Agora Energiewende and Wuppertal Institut (2019), *Klimaneutrale Industrie: Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement* (Berlin, November 2019).

CCUS – direct separation + electrification		80-101	94-109
Low-cost CCUS	± 100		
High-cost CCUS	± 110-140		
Avg. cost increase of low-CO2 tech.	**+60% in 2070**	**+74% to +105%**	**+70% to +115%**
Chemicals			
Plastics			
Current steam cracking		842	842
Steam cracker electrification		968-993	
Steam cracker electrification + EoL CCS			1253
Chemical recycling		890-1050	1320
Alternative routes (green methanol)		1223-3176	
Avg. cost increase of low-CO2 tech.		**+6% to +277%**	**+20% to +45%**
Ammonia			
Current steam methane reforming	±260	1.8€/kg H2	354
Steam methane reforming with CCS	± 350-600		418-553
Water electrolysis	± 350-600	2.8-5€/kg H2	553-747
Avg. cost increase of low-CO2 tech.	**+20% to +230%**	**+56% to +178%**	**+15% to +111%**

Source: JRC (IEA, ME, A-EW & WUI) *Estimates

The studies show that production costs of low-CO_2 technologies are highly uncertain. While continued R&I plays a role in making them more competitive in the future, they are currently more expensive than fossil-fuel based production pathways. The renewable electricity price is a determining factor for technologies relying on direct electrification, but it is also the major cost component of green hydrogen production. The price of biomass is a determining input for a fuel switch route in the cement sector and new feedstock routes in the chemicals sector. The capital-intensive carbon capture technologies and the cost of CO_2 transport and storage determine the competitiveness of CCS routes in all sectors.

Box 3: Electrolysis

Water electrolysis for the production of green hydrogen is a key horizontal technology for greening energy-intensive industries such as the chemicals and steel sectors, and enabling the deployment of a fully renewables-based energy system[37]. Currently, several water and steam electrolysis demonstration projects are operational for alkaline electrolyser (AEL), proton exchange membrane electrolyser (PEMEL) and solid oxide electrolyser (OEL) technologies up to 10 MW. Projects on a scale of 20 to > 100 MW are under development.

Electrolysis is currently more expensive than other methods of producing hydrogen — due to the capital costs and dependence on electricity costs. The costs (€5-8/kg H_2) are well above those for the commercially established technologies (e.g. small modular reactor), i.e. less than €2/kg H_2.The key steps needed to realise the 2030 vision are reducing electrolyser cost and improving efficiency, with high durability and reliability, by increasing the scale of deployments or through production in series, for both water and steam electrolysis.

The capital and fixed **operational costs** of electrolysers have been reduced considerably since 2012, but additional improvements are needed[38]. Especially when electrolysers are operated exclusively on renewable electricity, their limited use increases the impact of these two cost factors on commercial viability. A second objective is to improve the **efficiency** of electrolyser systems so as to reduce the cost of hydrogen production. The aim should be to install 40 GW of electrolysis in the EU by the end of 2030. Together with improvements in efficiency, the resulting cost reductions should mean that the cost of electrolyser-produced net-zero hydrogen can be kept below €3/kg. This will be the focus of the new R&I partnership on hydrogen under Horizon Europe[39].

Under Horizon 2020, the **'Fuel Cell and Hydrogen' R&I partnership** (FCH2 joint undertaking) is supporting a series of projects to increase the efficiency of electrolysis[40].

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37 See also *EU hydrogen strategy*, 8 July 2020.

38 IEA; https://www.iea.org/data-and-statistics/charts/hydrogen-production-costs-using-natural-gas-in-selected-regions-2018-2

39 Draft strategic research and innovation agenda for upcoming Horizon Europe 'Clean Hydrogen for Europe' R&I partnership.

40 DJEWELS, a 20 MW AEL to be installed at Nouryon's Delfzijl (Netherlands) site, to produce green methanol; REFHYNE, a 10 MW PEMEL to be installed at Shell's Cologne refinery; MULTIPLHY, a 2.6 MW SOEL to be installed at NESTE's Rotterdam biorefinery; DEMO4GRID (4MW AEL) and HYBALANCE (1.25 MW PEMEL) for grid balancing.

3 R&I investments and patenting

As the Commission has pointed out in its communication ***A clean planet for all***[41], further developing the most relevant technologies to reduce carbon emissions from energy-intensive industries, so as to allow their deployment, will require significant public and private investments in R&I at both EU and national levels.

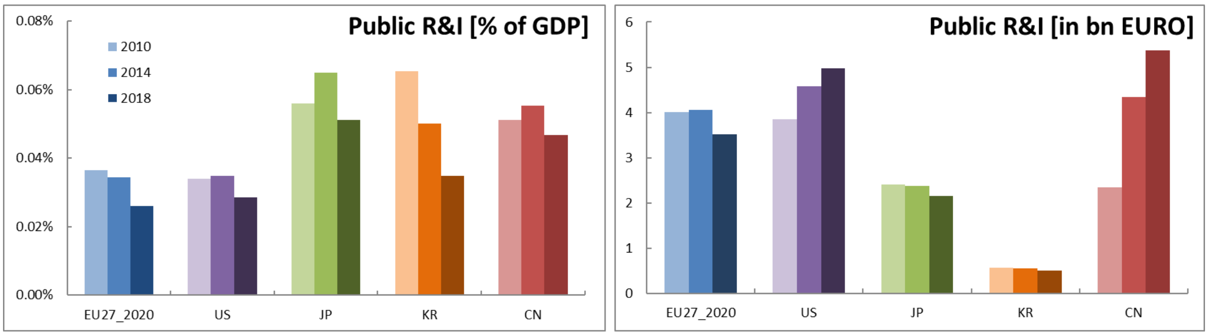
The Commission's recent ***Report on progress of clean energy competitiveness***[42] found that, in recent years, an average of nearly €20 billion a year has been invested in clean energy R&I in the EU[43,44]. Of this, EU funds have contributed 6%, national governments 17% and businesses around 77%.

3.1 Public R&I investment in energy efficiency in industry[45]

In 2014-2018, Member States invested €360 million a year on average (10% of their budgets for energy union R&I priorities) in areas relating to energy efficiency in industry. This is higher than the amounts reported for other major economies, such as Japan (€290 million) and the United States (€165 million). The major public investors among the Member States are Germany (30% of the total), Finland (11%), Italy (10%), France and the Netherlands (both 9%). EU funds contributed another €200 million a year on average.

The R&I budget allocated to energy overall in the EU-27 represents 4.7% of total R&I expenditure[46]. In absolute terms, however, Member States have decreased their national R&I budgets for clean energy (see **Error! Reference source not found.**); in 2018, the EU-27 spent around €0.5 billion less than in 2010 (in line with the global trend).

Figure 2: Public R&I financing - energy union R&I priorities[47]



[41] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. COM/2018/773 final

[42] COM(2020)953 final and accompanying SWD, 14 October 2020.

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

[44] JRC SETIS; https://setis.ec.europa.eu/publications/setis-research-innovation-data
JRC112127 Pasimeni, F.; Fiorini, A.; Georgakaki, A.; Marmier, A.; Jimenez Navarro, J. P.; Asensio Bermejo, J. M. (2018), *SETIS research & innovation country dashboards* (JRC) [Dataset] PID: http://data.europa.eu/89h/jrc-10115-10001, according to:
JRC105642 Fiorini, A., Georgakaki, A., Pasimeni, F. and Tzimas, E., *Monitoring R&I in low-carbon energy technologies* (Publications Office, Luxembourg, 2017);
JRC117092 Pasimeni, F., Letout, S., Fiorini, A., Georgakaki, A., *Monitoring R&I in low-carbon energy technologies – revised methodology and additional indicators, 2020* (forthcoming).

[45] *Ibid*.

[46] Eurostat, Total GBAORD by NABS 2007 socio-economic objectives [gba_nabsfin07]. The Energy socio-economic objective includes conventional energy R&I; the Energy Union R&I priorities would also fall under other the socioeconomic objectives

[47] Excludes EU funds.

This trend is the opposite of what is needed if the EU is to finance the R&I required to support the development of the key low-carbon technologies that will help industry achieve the EU's climate objectives. The EU (and others) needs to invest more in R&I on clean technologies if it is to meet its decarbonisation commitments. Today, among the major global economies, the EU has the lowest investment when measured as a proportion of GDP (**Error! Reference source not found.**). EU research funds have been contributing a larger proportion of the public funding and have been essential in maintaining R&I investment levels over the last 4 years.

3.2 Private R&I investment in energy efficiency in industry[48]

According to the Commission's report, only a small share of private sector revenues is currently being spent on R&I in the sectors that need to adopt low-carbon technologies on a large scale[49]. Estimated EU-27 private investment in the energy union R&I priorities has been decreasing and now amounts to around 10% of companies' total R&I expenditure[50]. This is higher than the USA's figure and comparable to Japan's, but lower than China's and South Korea's.

The financial sector plays a critical role in enabling the decarbonisation transition and funding the appropriate types of investment at the scale required. Fulfilling this role will require a transformation of the sector itself[51]. The necessary adaptations will be facilitated by the implementation of the EU's sustainable finance legislation, including the recent Sustainable Finance Taxonomy Regulation[52].

On average, major listed companies and their subsidiaries make up 20-25% of the main R&I investors, but account for 60-70% of patenting activity and investments. In the EU, the automotive sector is the biggest investor in absolute terms, followed by biotechnology and pharmaceuticals. Among the energy industries, the oil & gas sector is the largest investor in R&I. Other energy sectors, such as electricity and alternative energy companies, have much lower R&I budgets, although they spend more of it on clean energy. It is estimated that oil & gas producers, the construction & materials and the industrial metals & mining sectors invest a fifth to a quarter of their budget in clean R&I. The figure is just under one sixth for the chemicals sector.

The EU and Japan lead the international competition in high-value patents[53] in clean energy technologies. Clean energy patents account for 6% of all high-value inventions in the EU; this share is similar to Japan's and higher than China's (4%), the USA's and rest of the world's (5%), and second only to South Korea's (7%) among the competing economies. The EU is host to a quarter of the top 100 companies in terms of high-value patents in clean energy.

The majority of inventions funded by multinational firms headquartered in the EU are produced in Europe and, for the most part, by subsidiaries located in the same country.[54] The main intellectual property offices (IPOs) — and, by extension, markets — targeted for the protection of EU inventions are in the USA and China.

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[48] JRC SETIS; https://setis.ec.europa.eu/publications/setis-research-innovation-data
(JRC112127) *SETIS research & Innovation country dashboards*, according to:
(JRC105642) *Monitoring R&I in low-carbon energy technologies* and (JRC117092) *Monitoring R&I in low-carbon energy technologies – revised methodology and additional indicators, 2020* (forthcoming).

[49] IEA, *Energy Technology Perspectives,* https://www.iea.org/reports/clean-energy-innovation/global-status-of-clean-energy-innovation-in-2020#government-rd-funding

[50] Contrasted with BERD statistics (Eurostat/OECD, *Business expenditure on R&D (BERD) by NACE Rev. 2 activity and source of funds* [rd_e_berdfundr2]). The utilities sector includes water collection treatment and supply services. Data not available for all countries.

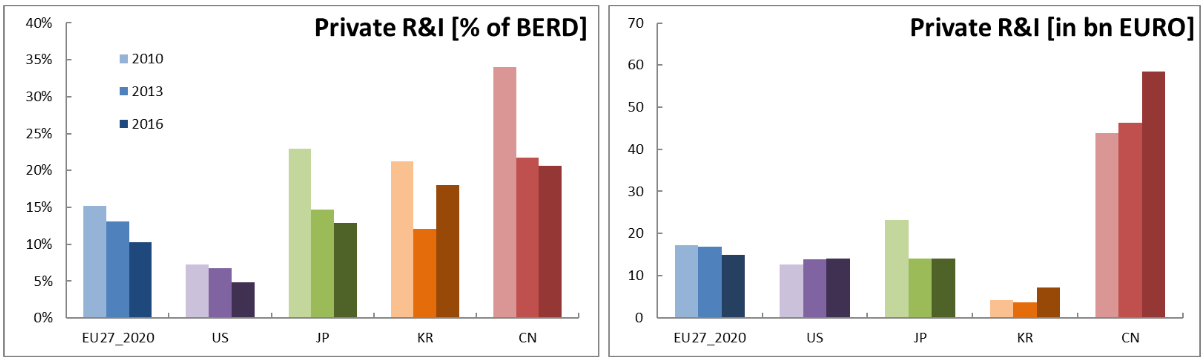
[51] *A clean planet for all*, p. 235.

[52] Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088 (OJ L 198, 22.6.2020, p. 13).

[53] High-value patent families (inventions) are those containing applications to more than one IPO, i.e. seeking protection in more than one country/market.

[54] Incentives, language and geographical proximity explain the major exceptions.

Figure 3: Estimated private R&I financing in the energy union R&I priorities



Notes: BERD stands for Business enterprise expenditure on R&D. Estimates for China are particularly challenging and uncertain, given the differences in Intellectual Property protection (see also https://chinapower.csis.org/patents/), and the difficulty in mapping the company structure (e.g. state backed companies) and financial reporting.

Average private sector spending on energy efficiency in industry is estimated at €3 billion a year[55], which is comparable with estimates for Japan and the United States, and twice as much as that for South Korea[56]. Almost half comes from companies headquartered in Germany (49%), followed by companies headquartered in the Netherlands (11%), France (10%), Italy, Denmark and Finland (all 5%).

Of the actions in the strategic energy technology (SET) plan, 'making EU industry less energy-intensive and more competitive' accounts for the highest number of inventions. Nonetheless, the EU overall does not display 'specialisation' in this subject area (i.e. its share in total patenting activity) compared with the rest of the world.

3.3 In-depth analysis of relevant private-sector R&D investments: companies from energy-intensive sectors in the EU Industrial R&D Investment Scoreboard[57]

Progress in the development of low-carbon technologies in the EU depends largely on investment in relevant R&D by industry itself. On the basis of the EU Industrial R&D Investment Scoreboard, this part of the report looks at patterns of investment and green patent activity by **the main global companies**[58] **investing in R&D** in the energy-intensive industries[59].

In 2018, the 2 500 Scoreboard companies in all sectors invested a total of **€823 billion** in R&D, **8.9% more** than in 2017. In the energy-intensive industries, the total (**€61 billion**) grew at a similar rate (8.7%). However, **global R&D of the top 2 500 was driven by other sectors**: ICT services (€127 billion/17%), ICT producers (€192 billion/8.2%) and health (€170 billion/7.6%).

The Scoreboard shows an **intensifying race for global technological leadership** over the past decade:

– **EU companies** are still in the lead in sectors such as automobiles, traditional health and aerospace & defence, but losing ground in ICT industries and biotech health;

– **US companies** have bolstered their position in high-tech sectors, especially ICT services and health;

[55] Data available for 2014-2016.
[56] China also invests significantly in this area, especially in 'clean coal' technologies.
[57] https://ec.europa.eu/info/news/2019-eu-industrial-rd-investment-scoreboard-report-2019-dec-18_en
[58] For this purpose, a subset of 276 companies closely associated with the chemicals, metals and energy sectors was selected from the 2 500 Scoreboard companies.
[59] There is often no exact overlap of sector definitions and actual company activities, which may relate to very different industrial sectors and change over time.

- **Japanese companies** have proportionally even more of their R&D in medium/high-tech sectors and less in high-tech than companies in the EU (where the medium/high-tech group has grown significantly, but the size of the high-tech group has barely changed); and
- **Chinese companies'** global shares in ICT industries and low-tech sectors have increased substantially, albeit from a lower base.

A Scoreboard subsample covering energy-intensive industries shows specific R&D investment dynamics and relative trends (see Table 3).

Table 3: R&D investment, capital expenditure (capex) and patents by sector and main region (2018)

Region	No. of companies	R&D (€bn)	Capex (€bn)	Net sales (€bn)	R&D intensity (%)	Capex intensity (%)	Share of green patents (%)	Share of Y02P[60] patents (%)
Chemicals								
EU	32	11.0	18.6	330.8	3.3	5.6	11.6	3.9
USA	37	4.0	8.5	147.5	2.7	5.8	6.6	2.7
Japan	36	8.0	15.0	216.3	3.7	6.9	8.5	3.3
China	19	1.3	8.9	53.1	2.4	16.8	9.9	7.2
RoW	28	5.0	25.3	332.4	1.5	7.6	20.3	5.3
Metals & related companies								
EU	14	1.7	15.0	254.2	0.7	5.9	13.8	6.3
USA	1	0.1	0.7	12.2	0.7	5.5	15.2	15.2
Japan	8	1.4	8.7	124.9	1.1	6.9	8.7	4.5
China	15	2.2	6.5	110.0	2.0	5.9	9.5	6.5
RoW	6	1.0	11.0	145.5	0.7	7.5	14.3	8.0
Energy related companies								
EU	29	10.8	112.1	1458.5	0.7	7.7	20.2	6.1

[60] The Y02 scheme of the Cooperative Patent Classification (CPC) regroups the following subcategories related to climate change mitigation technologies (CCMTs):
Y02A: Technologies for adaptation to climate change:
Y02B: CCMTs related to buildings
Y02C: Carbon capture storage (CCS), sequestration or disposal of greenhouse gases
Y02D: CCMTs related to information and communication technology (ICT)
Y02E: Reduction of greenhouse gas emissions, related to energy generation, transmission or distribution
Y02P: CCMTs in the production or processing of goods
Y02T: CCMTs related to transportation
Y02W: CCMTs related to wastewater treatment or waste management

US	10	6.5	46.9	580.0	1.1	8.1	17.0	3.8
Japan	14	1.2	24.3	330.0	0.4	7.4	17.2	6.1
China	15	4.8	62.8	797.9	0.6	7.9	11.8	5.1
RoW	10	1.7	39.3	378.8	0.4	10.4	27.2	4.5

Note: Patent shares refer to annual averages for 2010-2016. Data on patents available for 223 of the 274 companies in the sample, representing 94.9% of total R&D in the sample.
Source: JRC

Among the Scoreboard companies and the 274 companies covered here, **those in the chemicals sector show the highest R&D intensity** (2-4% of net sales), followed by metals and energy. EU, US and Japanese companies' capital expenditure (capex) intensity is about five times greater than their R&D intensity. For companies from China and the rest of the world (RoW), **it is almost 10 times greater**. This may be because these companies invest more in capital goods, as infrastructure still needs to be built up. However, it might also be triggered by policy initiatives in the countries in question that incentivise participation in infrastructure investment. For the Scoreboard companies, analysis of corporate accounting indicators at firm level does not suggest substitution between R&D and capex, but a positive effect of R&D on subsequent capex[61].

The **EU chemicals companies in the subset of energy-intensive industries have the second highest overall R&D intensity** (after Japan, but ahead of the USA). Overall, chemicals R&D investment is concentrated in EU, US, Japanese and RoW (Swiss) companies constituting several dimensions that of their Chinese counterparts. **Chinese chemicals companies also stand out in terms of capex investment** (Figure 6), with more than twice the capex intensity of their competitors. This is the result of a sustained increase in capex by Chinese companies in the subsample in 2010-2018 (from €1.3 billion to €8.9 billion), with substantial variation across individual companies. For the EU sample, the R&D performance of the largest R&D investor, BASF (-11.6% in financial year 2018) had a big impact. These examples underline the importance of the investment dynamics of individual top companies for innovation, even in large geographical areas.

R&D investment by the **top EU metals companies**[62] **was similar to that of their Japanese counterparts** (almost €1.5 billion) but **less than the Chinese figure** (almost €2.1 billion) in 2018. In terms of capex and net sales, EU metals companies are ahead of their peers. Chinese companies have relatively low capex, leading to a **high R&D/capex ratio** overall. This appears to be the opposite of the picture in the **chemicals sector**, where Chinese companies focus more on capex than R&D.

Based on the current sample, it remains unclear at this stage whether it is due to individual companies' specificities or to a strategic choice that Chinese chemicals and metals companies' approach to R&D and capex differs from that of their peers in the Scoreboard.

Energy-related companies[63] **in the EU are ahead of their peers from the other regions** in R&D investment, capex and net sales. The **overall low R&D intensity** of the

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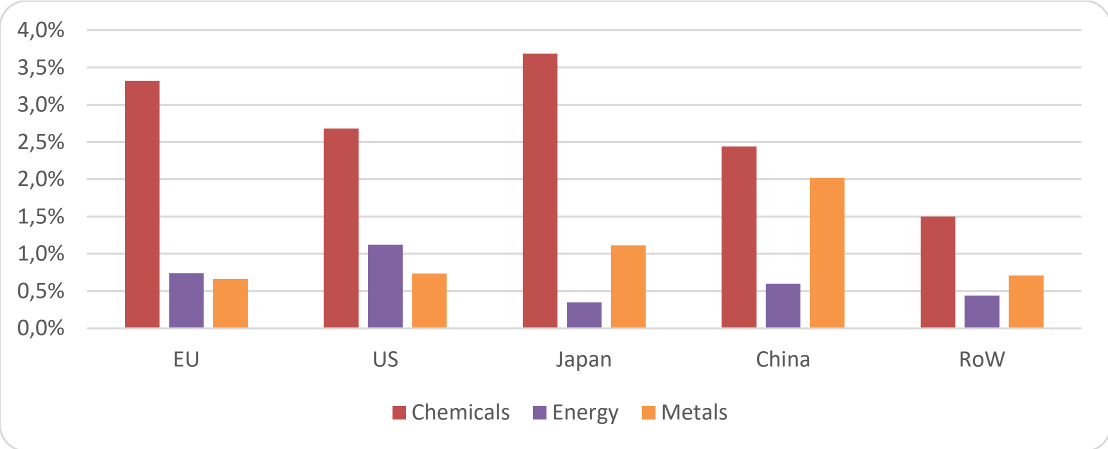
[61] Coad, A. and Grassano, N., *Disentangling the processes of firm growth and R&D investment*, JRC Policy Brief JRC103175 (November 2016); https://iri.jrc.ec.europa.eu/sites/default/files/contentype//publication//policybriefs//1568801206//Disentangling%20the%20processes%20of%20firm%20growth.pdf

[62] Metals companies' business is more capital- than R&D-intensive, so they are not as well represented in the subsample as chemicals companies.

[63] Due to the more capital- than R&D-intensive nature of the energy business, 'pure' energy companies are not well represented in the Scoreboard, so the subsample was enriched with a few companies with substantial energy activities.

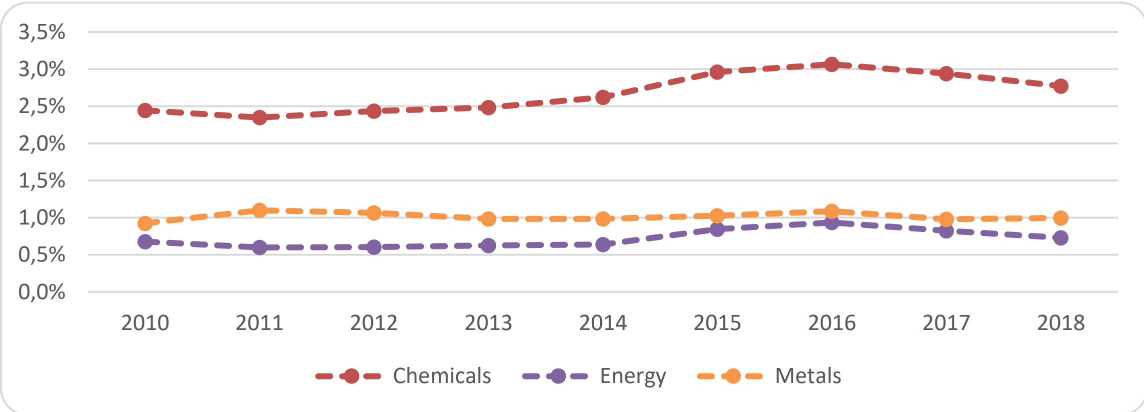
subsample's energy companies is due to very high net sales, especially for oil-related companies. Also, among the three subsectors considered here, energy is the sector with the highest capex intensity. Other parts of this report offer further insight into the energy sector (see Section 4).

Figure 4: Average R&D intensity, by selected sectors and main regions (2016)



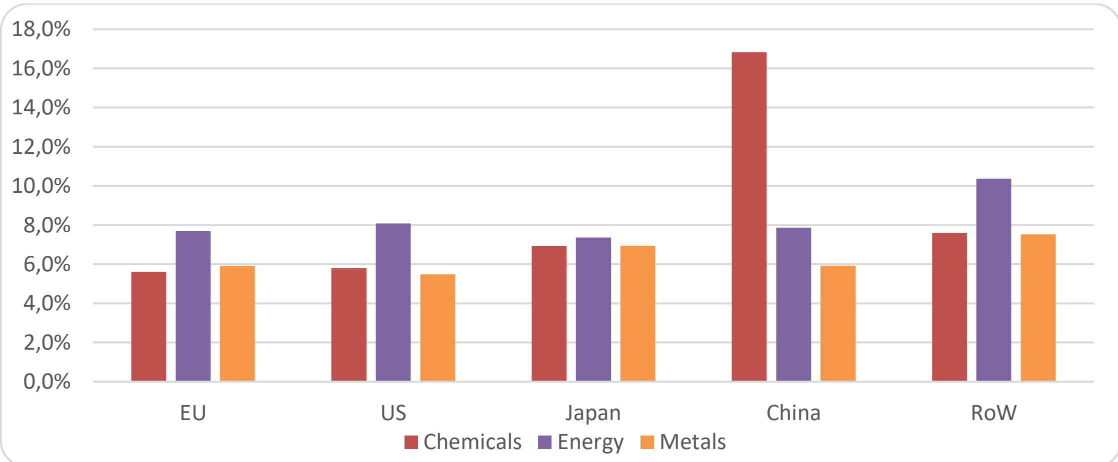
Source: *The 2019 EU R&D Investment Scoreboard* and JRC patent analyses.

Figure 5: Average R&D intensity in selected sectors- trends



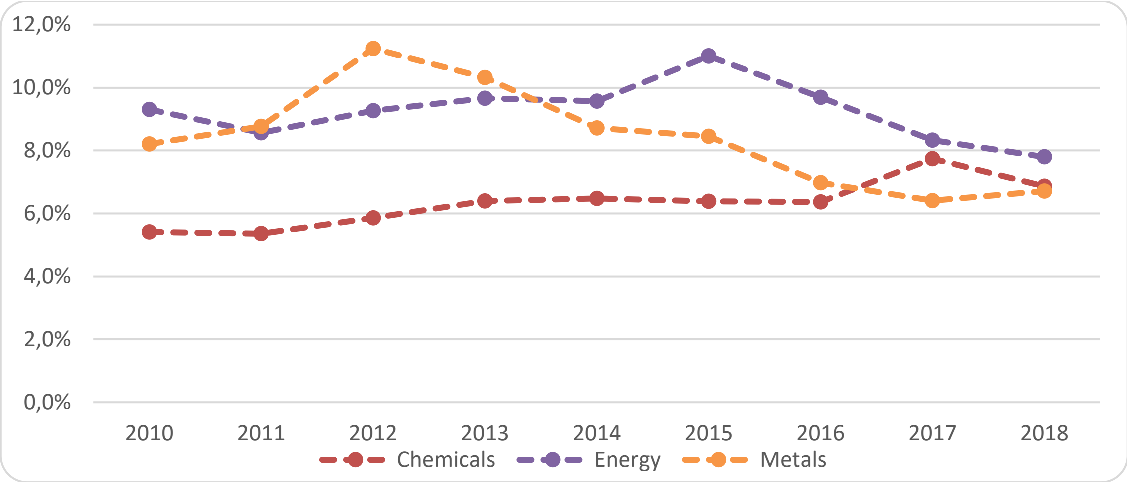
Note: Trend data on patents available for 232 of the 274 companies in the sample, representing 92.9% of total R&D in 2018 in the sample.
Source: *2019 EU R&D Investment Scoreboard* and JRC patent analyses.

Figure 6: Average capex intensity, by selected sectors and main regions (2016)



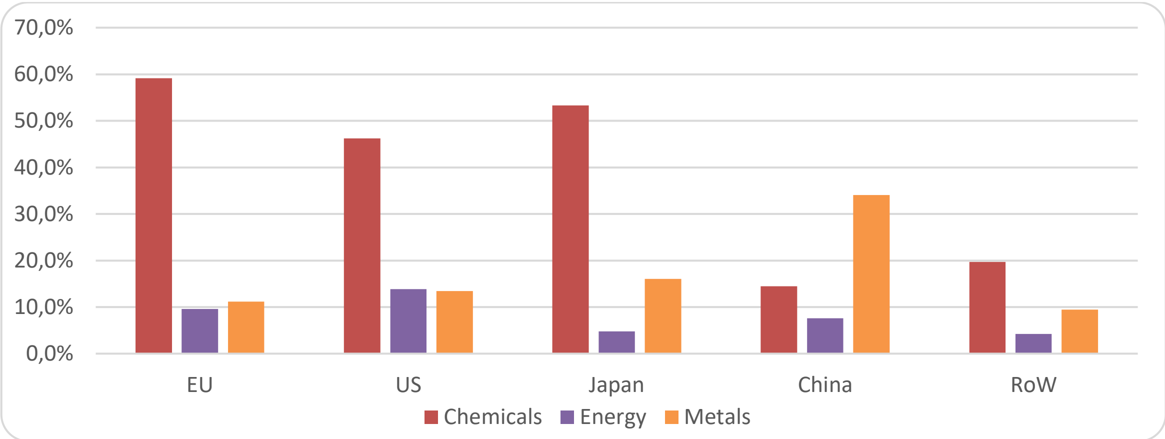
Source: *2019 EU R&D Investment Scoreboard* and JRC patent analyses.

Figure 7: Average capex intensity of selected sectors — trends



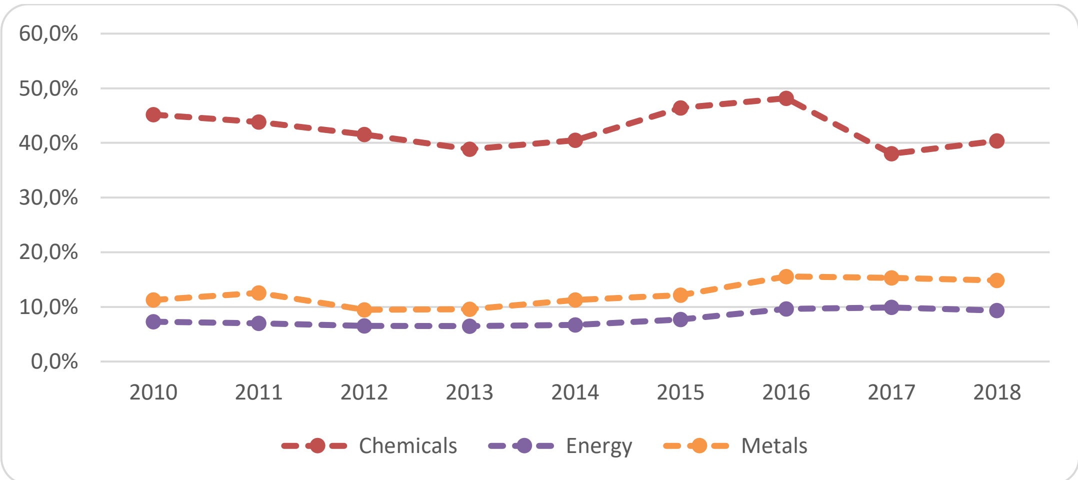
Note: Trend data on patents available for 232 of the 274 companies in the sample, representing 92.9% of total R&D in 2018 in the sample.
Source: *2019 EU R&D Investment Scoreboard and* JRC patent analyses.

Figure 8: R&D/capex ratio, by selected sectors and main regions (2016)



Source: *2019 EU R&D Investment Scoreboard and* JRC patent analyses.

Figure 9: R&D/capex ratio of selected sectors — trends

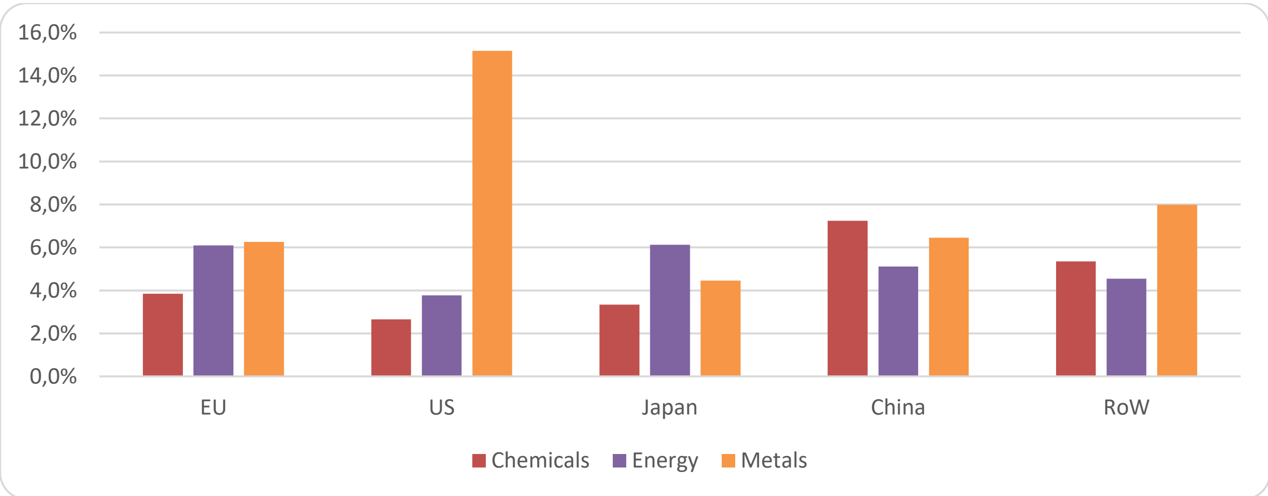


Note: Trend data on patents available for 232 of the 274 companies in the sample, representing 92.9% of total R&D in 2018 in the sample.
Source: *2019 EU R&D Investment Scoreboard* and JRC patent analyses.

As regards the **patenting activity** of the subsample of energy-intensive industries from the Scoreboard[64], 4.7% of all patent applications relate to green technologies (patent subclass YP02). The region with the lowest percentage of green patent applications is the USA (3.6%), while that with the highest is 'RoW' (6.0%). The EU is above the overall average (5.1% of YP02 applications) and has the highest absolute number of green applications per year over the period. There are two EU companies in the top 5 companies in terms of share of green patents in the chemicals sector, three in the metals sector and four in the energy-related sectors[65]. More detailed analyses on green patenting activities are presented in other parts of this report (see Section 4).

Patenting activity in the Scoreboard top 2 500 sample of all sectors shows that patents in the global **automotive sector**, which accounts for 13% of the total, are mostly in current automotive technologies. However, an increasing proportion relate to green technologies, including electric and autonomous vehicles and newer components such as novel batteries and fuel cells. EU companies hold around a third of these patents, which includes around a quarter of green patents, and appear highly diversified and competitive in most technological fields. However, in green technologies relating to hybrid cars, batteries and fuel cells, their Japanese counterparts are leading the race. The automotive sector is being joined in patent filing by software, technology hardware, electronics and chemicals. This is challenging EU companies, whose lead in the automotive sector may be eroded as digital technologies take a higher proportion of the added value in the automotive sector, with new developments such as electric self-driving cars fitted with more electronics and communications accessories.

Figure 10: Share of Y02P patents, by selected sectors and main regions (average 2010-2018)



Note: Patent shares refers to annual averages for the period 2010-2016. Data on patents available for 223 out of the 274 companies in the sample, representing 94.9% of the total R&D in 2018 in the sample. The data for US metals sectors refer to the one company for which patent data are available
Sources: 2019 EU R&D Investment Scoreboard and JRC patent analyses.

[64] See JRC patent analyses based on JRC SETIS methodology;
https://setis.ec.europa.eu/publications/setis-research-innovation-data
https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/monitoring-ri-low-carbon-energy-technologies
https://ec.europa.eu/jrc/en/publication/assessing-private-rd-spending-europe-climate-change-mitigation-technologies-patent-data

[65] Three of these companies are based in the UK.

Table 4: Top 5 companies (in terms of share of YP02 patent applications), by sector

Company	Country	R&D-2018 (€ m)	Capex-2018 (€ m)	Net sales 2018 (€ m)	Green inventions share – avg 2010-2016 (%)	YP02 inventions share – avg 2010-2016 (%)
Chemicals						
AIR PRODUCTS AND CHEMICALS	US	56.3	1 369.8	7 799.3	30.0	13.3
SAUDI BASIC INDUSTRIES	SA	271.0	3 299.0	39 389.4	14.4	9.9
LINDE	DE	113.0	n.a.	13 370.3	21.8	9.1
ASAHI GLASS	JP	360.6	1 665.6	12 000.8	13.9	8.3
JOHNSON MATTHEY	UK	195.1	238.4	11 913.8	40.4	7.7
Metals						
HERAEUS	DE	153.9	n.a.	20 295.1	19.4	8.2
POSCO	KR	412.2	2 022.1	50 864.1	14.6	8.1
UMICORE	BE	196.4	466.0	13 716.7	38.7	8.1
JFE	JP	293.7	2 463.2	30 525.2	9.9	6.3
THYSSENKRUPP	DE	416.0	801.0	42 745.0	10.8	5.4
Energy						
FIRST SOLAR	US	73.8	646.1	1 959.9	70.4	24.8
VESTAS WIND SYSTEMS	DK	325.0	312.0	10 134.0	89.0	22.7
NORDEX	DE	56.7	113.7	2 459.1	91.3	21.4
ROYAL DUTCH SHELL	UK	861.1	20 096.9	339 195.5	25.7	20.7
BP	UK	374.7	14 591.3	260 922.1	32.2	12.7

Note: Data refer to applications belonging to IP5 families for 2010-2016. Only companies with an average of at least 10 green patent applications per year were considered.
Sources: 2019 EU R&D Investment Scoreboard and JRC patent analyses.

3.4 *Other aspects of R&I activity: start-ups and venture capital*

Start-up formation can be used as an indicator of innovation, future technologies and competitiveness[66]. Start-ups are mostly in digital technologies and are less common in more capital-intensive industrial sectors such as steel, chemicals and energy. Those sectors require high up-front capital investment, while in the start-up business model in other sectors (such as software-based businesses), knowledge and human capital are leveraged to take on larger and more established incumbents (or carve out a market niche). However, steel, chemicals and energy start-ups are a critical ingredient of innovation and help us to understand the digitalisation of business models. The EIC is supporting and monitoring such start-ups and the development of their innovation ecosystems[67].

Although they account for a small percentage of all new businesses, start-ups in the chemical, steel and energy-related sectors represent a significant area of innovation that is worth exploring, e.g. by drawing country comparisons and assessing how the EU is performing.

It seems that the steel and chemicals sectors are less suitable for the start-up business model, accounting for fewer than one in a thousand start-ups (the United Nations Industrial Development Organization (UNIDO) database has figures of 3.3% for chemicals and 1.7% for metals, although its 'metals' category covers more than just steel[68]). On the other hand, 3% of start-ups are in energy, which may reflect the sector's greater amenability to the start-up model. This is much more than the share of energy-related establishments/firms in UNIDO, which may reflect Dealroom's broader definition of the sector.

Table 5: Sector shares in UNIDO and Dealroom

Sector	No. of establishments/ firms (UNIDO)	Share	No. of start-ups (Dealroom)	Share	Share ratio
Chemicals	21 575	3.25%	81	0.01%	0.004
Energy	2 727	0.41%	17 200	2.99%	7.28
Steel	11 119	1.67%	65	0.01%	0.006
Others	628 841	94.67%	558 193	96.98%	1.02
Totals	*664 262*	*100.00%*	*575 587*	*100.00%*	*1*

Steel and chemicals

The EU has the same number of start-ups in chemicals as the USA, and a third fewer in steel. As regards value (funding for start-ups), the EU is behind the USA and, in the case of steel, also China, which has very few highly valued start-ups.

The EU has only 0.3% of start-ups in steel and 16% in chemicals. The latter figure, while small in absolute terms, is relatively large compared with the proportion in core start-up sectors such as robotics and artificial intelligence (around 8% in both cases).

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66 This section uses the Dealroom dataset of global start-up activity; https://dealroom.co/
67 See section 2.3
68 More details about the UNIDO methodology available at: https://stat.unido.org/pdf/Inst32-online-UserGuide_2402619451797638449.pdf

Table 6: Start-ups in steel, chemicals and energy sectors

Region	No. of start-ups	Share	Funding (€ m)	Share
Steel				
EU	18	27.69%	2.42	0.29%
US	27	41.54%	116.55	13.92%
Japan	0	0.00%	0	0.00%
China	3	4.62%	716.24	85.53%
RoW	17	26.15%	2.18	0.26%
Totals	*65*	*100.00%*	*837.39*	*100.00%*
Chemicals				
EU	24	30.38%	281.83	16.24%
US	24	30.38%	1 244.4	71.72%
Japan	1	1.27%	8.83	0.51%
China	2	2.53%	12.73	0.73%
RoW	28	35.44%	187.24	10.79%
Totals	*79*	*100.00%*	*1735.03*	*100.00%*
Energy				
EU	4 698	27.31%	7 460.73	8.15%
US	7 594	44.15%	57 750.2	63.05%
Japan	43	0.25%	8.83	0.01%
China	287	1.67%	12 737.36	13.91%
RoW	4578	26.62%	13 634.61	14.89%
Totals	*17 200*	*100.00%*	*91 591.7*	*100.00%*

Energy

While there is no shortage of innovative ideas in the EU (there are almost as many start-ups as in the USA), EU start-ups lack risk capital – the EU is lagging behind as regards the proportion of total funding made up of venture capital. In the EU, Germany, France and Sweden account for the biggest proportions of the funding (Table 7).

Table 7: EU energy start-ups, by Member State

Country	No. of start-ups in energy	Start-up funding >€1 m	Start-up value €200–800 m	Start-up value >€800 m	Total funding (€ m)
Germany	771	89	7	0	1 413.67
France	753	116	7	1	1 494.16
Netherlands	704	67	4	0	968.26
Spain	399	43	2	0	259.71
Italy	310	36	0	1	380.62
Sweden	276	66	1	1	1 511.17
Ireland	228	25	3	0	430.89
Denmark	206	27	0	0	209.84
Finland	206	38	0	0	275.24
Belgium	155	23	0	0	108.96
Poland	97	6	0	0	58.68
Portugal	93	13	0	0	27.04
Austria	84	9	0	0	53.85
Lithuania	58	1	0	0	5.99
Estonia	49	3	0	0	56.65
Slovenia	44	4	0	0	12.85
Greece	41	1	0	0	5.34
Czechia	39	1	0	0	6.9
Hungary	39	4	0	0	11.17
Romania	34	0	0	0	1.06
Slovakia	25	4	0	0	19.74
Latvia	23	3	0	0	14.06
Croatia	15	3	0	0	4.81
Bulgaria	12	0	0	0	0.77
Luxembourg	11	3	1	0	129.1
Malta	9	1	0	0	0.05
Cyprus	7	0	0	0	0.15
EU	***4 688***	***586***	***25***	***3***	***7 460.73***

3.5 Patents for climate change mitigation technologies in goods production or processing

As part of the picture on progress in R&I on low-carbon industrial technologies, developments regarding patents[69] provide information on technological inventiveness, based on an established methodology[70].

Clean energy technologies account for a higher share of overall patenting activity in the EU than in other major economies. Just over 20% of all inventions in climate change mitigation technologies (CCMTs) relate to goods production or processing. As regards CCMTs in these areas[71], the EU has a relative advantage[72] in the fields of oil refining and petrochemicals, overall enabling technologies and metal processing (although this is declining). We also see a slight increase in specialisation in the chemicals industry and in production processes.

Asian economies have the lead in terms of absolute numbers of patent filings. However, EU and US companies protect a larger share of their inventions outside their home IPO territories and markets.

Due to its different patenting procedures[73,74], China is the dominant actor when patent families protected in only one country are included in the analysis, with an exponential increase of patenting activity in clean energy technologies (predominantly protected in the Chinese market). To eliminate this effect, we look at 'high-value' patents[75] as an alternative indicator of activity in the main economies.

The EU is in the lead, along with Japan, on high-value inventions. EU companies have a good presence in patenting activity relating to low-carbon technologies, with companies such as BASF, Siemens, ThyssenKrupp, Shell and L'Air Liquide prominent in more than one area. This shows the determination of major EU companies to develop relevant technology and demonstrates that their R&I activity reaches beyond the boundaries of their sector and is relevant across a number of energy-intensive industries. This is especially apparent in the chemicals and petrochemicals sectors, both of which feature major oil and gas companies, due perhaps to the proximity of technologies and processes.

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69 Papers on JRC SETIS methodology; https://setis.ec.europa.eu/publications/setis-research-innovation-data (JRC105642) *Monitoring R&I in low-carbon energy technologies* ;
Pasimeni F., *et al.*, *Assessing private R&D spending in Europe for climate change mitigation technologies via patent data* (WPI, 2019);
Pasimeni F., *SQL query to increase data accuracy and completeness in PatStat* (WPI, 2019).

70 Patent families are used as proxy of inventions. Patent applicants are considered, being the owners of the patent and thus those directly investing and financing R&D activities. The data source is PatStat, processed to increase accuracy and completeness of the dataset. The analysis concentrates on CCMTs identified through the Y02 and Y04 schemes of the cooperative patent classification (CPC). Applications to all offices are retrieved and fractional counting is used to assign an equal share to all combinations of CPC codes and patent applications protecting the invention, thus preventing multiple counting.

71 CPC Y02P section (CCMTs in goods production or processing).

72 Expressed as the share of this topic in total activity in the area of CCMTs in goods production or processing.

73 Preziosi, N., *et al.* (2019), *China — challenges and prospects from an industrial and innovation powerhouse* (EUR 29737 EN, Publications Office, Luxembourg, 2019, ISBN 978-92-76-02997-7, doi:10.2760/445820, JRC116516).

74 China Power Team, *Are patents indicative of Chinese innovation?* (15 February 2016; updated 26 August 2020; accessed 11 September 2020); https://chinapower.csis.org/patents/

75 High-value patent families (inventions) are those containing applications to more than one IPO, i.e. seeking protection in more than one country/market. This entails longer processes and higher costs and thus indicates a higher expectation of prospects in international markets.
Dechezleprêtre, A., *et al*. (2011), 'Invention and transfer of climate change–mitigation technologies: a global analysis', *Review of environmental economics and policy 5*, pp. 109-130;
Dechezleprêtre, A., *et al.* (2015), 'Invention and international diffusion of water conservation and availability technologies', *OECD Environment Working Papers*, No 82 (OECD Publishing, Paris).

EU Industrial R&D Investment Scoreboard companies and their subsidiaries account for around a third of the patenting entities in the EU. Major actors account for up to three quarters of inventions, depending on the technological area. The EU top 10 account for up to half the patenting activity.

In order to gauge relevant activity on the low-carbon industrial technologies set out in Section A, our analysis focuses on patent classification for technologies relating to the metal processing, chemical, petrochemicals and cement industries.

3.6 Patents for climate change mitigation technologies in metal processing[76]

EU companies lead in several sub-areas of patenting activity that are directly relevant to the development of the low carbon technologies as set out in Section 1.

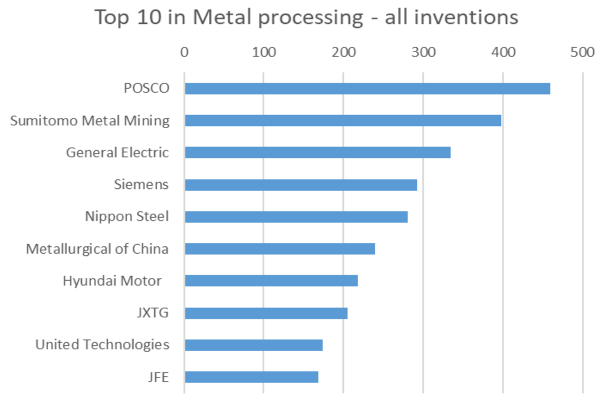
Error! Reference source not found. shows the top 10 entities in patent filings[77] for CCMTs relating to metal processing, by total and high-value patents. The list is dominated by EU and US firms, which tend to have an outward focus, protecting a larger share of their inventions in foreign markets and targeting each other's markets for protection. The top 3 (General Electric (US), Siemens (EU) and United Technologies (US)) have seen constant growth in their high-value patent portfolio since 2012 and are much more active than the rest.

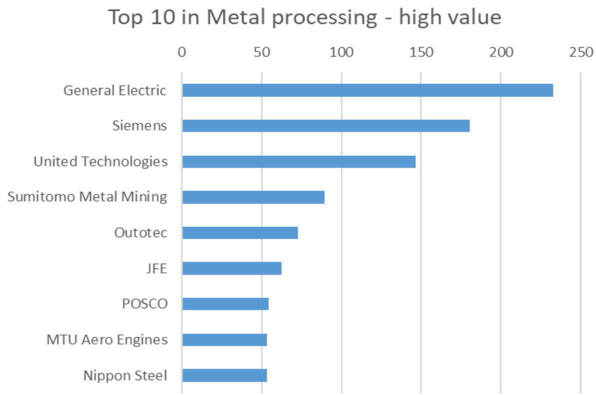
The differences suggest that Asian companies have a strong inward focus in their patenting strategies, protecting a number of inventions only in one (their own) market. Metallurgical of China ranks 101st in high-value patents, while the top-ranked Chinese firm is BOE Technology Group (52nd). The same trend is clear (to a much lesser extent) for Japan and South Korea.

In the EU, around 740 distinct entities filed for at least one patent in 2010-2016. Just over a third of these were Scoreboard companies and subsidiaries, but the latter account for three quarters of the patenting activity. The top 10 account for almost half of the inventive activity. There are three EU companies in the top 10 for high-value patents (Figure), but only Siemens has a portfolio comparable with that of the leading actor, General Electric.

Relevant patents are much more prominent in Asian companies' overall patent portfolios than in EU firms' portfolios.

Figure 11: Top 10 patenting entities in CCMTs in metal processing – cumulative inventions grouped by parent company (2010-2016)

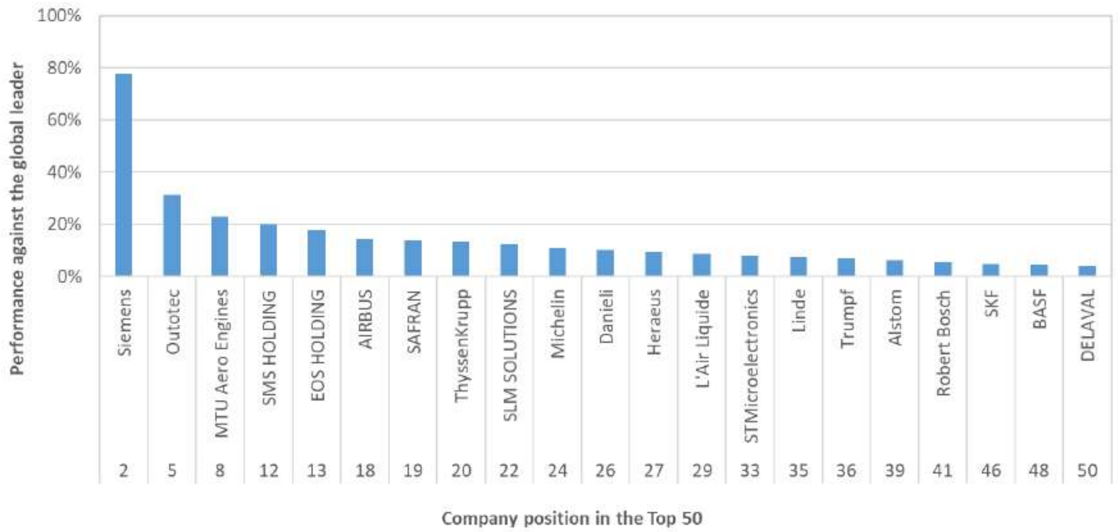




Source: JRC SETIS data

[76] Y02P 10 Technologies relating to metal processing.
[77] PatStat data, JRC.

Figure 12: EU companies in top 50 of patenting corporations in technologies in metal processing (high-value patents grouped by parent company), 2010-2016 – position and performance compared to the global leader General Electric (US)



Source JRC SETIS data.

Going into more detail, EU companies lead when it comes to increasing process efficiency by **reducing waste and recovering material streams**. The top EU firms are Outotec, Siemens, SMS Holdings and Heraeus. Japan is close behind, with firms such as JXTG, JFE, Hitachi and Nippon Steel.

Siemens leads on cumulative inventions relating to **carbon capture, utilisation and storage (CCUS) technologies** for metal processing, followed by Kobe Steel, Mitsubishi Heavy Industries, Danieli and Linde. The EU has a strong position in this area, although Siemens submitted most of its patent filings between 2010 and 2013 (Linde and Danieli have made more recent filings). Filings from Japanese companies in this area continue to increase.

As regards the horizontally important development of hydrogen technologies, POSCO and Kobe Steel are the clear leaders in the area of **CO_2 avoidance by using hydrogen**. Siemens and Danieli are the only EU companies that feature in that area.

Patenting activity on **electrolysis** is very low globally. The main actor is Hitachi, but of the EU companies, Salzgitter, Voest-Alpine and Outotec have submitted filings.

The EU, again followed by Japan, leads in patenting to increase the efficiency of **electric conversion processes**. ThyssenKrupp, Siemens and Skf are prominent for the EU. Nippon Steel, Ntn and Jfe lead for Japan, while Hyundai (KR) and General Electric (US) are also in the top 10.

General Electric, Mitsubishi, Linde, L'Air Liquide, Siemens and POSCO are the only groups patenting technologies for **renewable energy sources or cogeneration with other industries**.

3.7 Patents for climate change mitigation technologies in cement production[78]

EU firms[79] are the global leaders in CCMT patenting in cement production. However, there is little relevant patenting activity in the sector, suggesting that technology

[78] Y02P 40 Technologies relating to the processing of minerals, excluding Y02P 40/50 Glass production and Y02P 40/60. Production of ceramic materials or ceramic elements.

[79] N.b.: production takes place mostly outside the EU.

development plays a minor role in its low-carbon strategy. The technological areas receiving most attention are **geopolymers**, **belite cements** and **CCS**, the latter being the area with the most high-value patents.

In the EU, ThyssenKrupp, HeidelbergCement and Fives are the most active companies in **energy efficiency measures**, but their portfolios are smaller than those of the leading Japanese companies. The same actors, joined by Areva and Lafarge, feature in terms of **integrated production plants**, an area dominated by EU interests.

ThyssenKrupp, Lafarge and Linde are also looking into **fuels from biomass and waste**, but activity levels are very low compared to other areas.

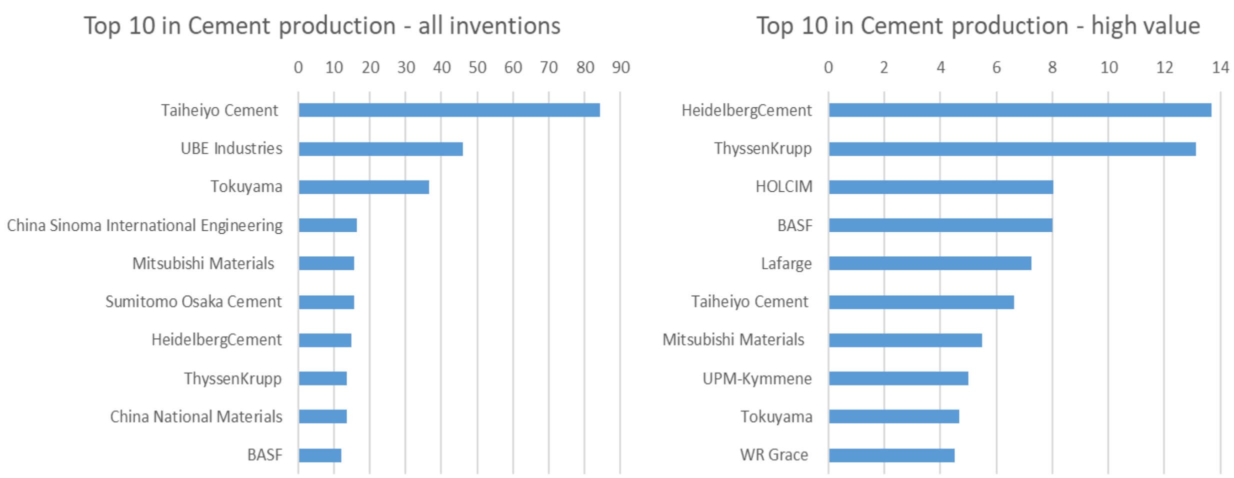
With regard to **CCS**, the EU leaders are ThyssenKrupp, Vinci, Lafarge, L'Air Liquide, BASF, Stora Enso and HeidelbergCement, with the EU having a very strong position overall.

Error! Reference source not found. shows the top 10 in patent filings for technologies relating to cement production. As in the case of metal processing, there is a clear difference of focus, in terms of the protection of inventions, between Asian firms on the one hand and EU and US companies on the other. In addition, a smaller share of inventions in these technologies seems to be protected in more than one IPO. The Swiss company HOLCIM features, along with those from the major economies. The best-ranking Chinese companies for high-value inventions are BAOSHAN Iron & Steel (59th) and BOE Technology Group (61st), both with very small counts. The top 3 from both EU and Japan display sustained patenting activity in these technologies, albeit at fairly low levels.

Error! Reference source not found. shows other prominent EU companies. Around 150 distinct EU entities filed for at least one patent in 2010-2016, almost 30% of which were Scoreboard companies and subsidiaries. However, the latter accounted for just over 60% of the patenting activity. The top 10 accounted for 50% of the inventive activity.

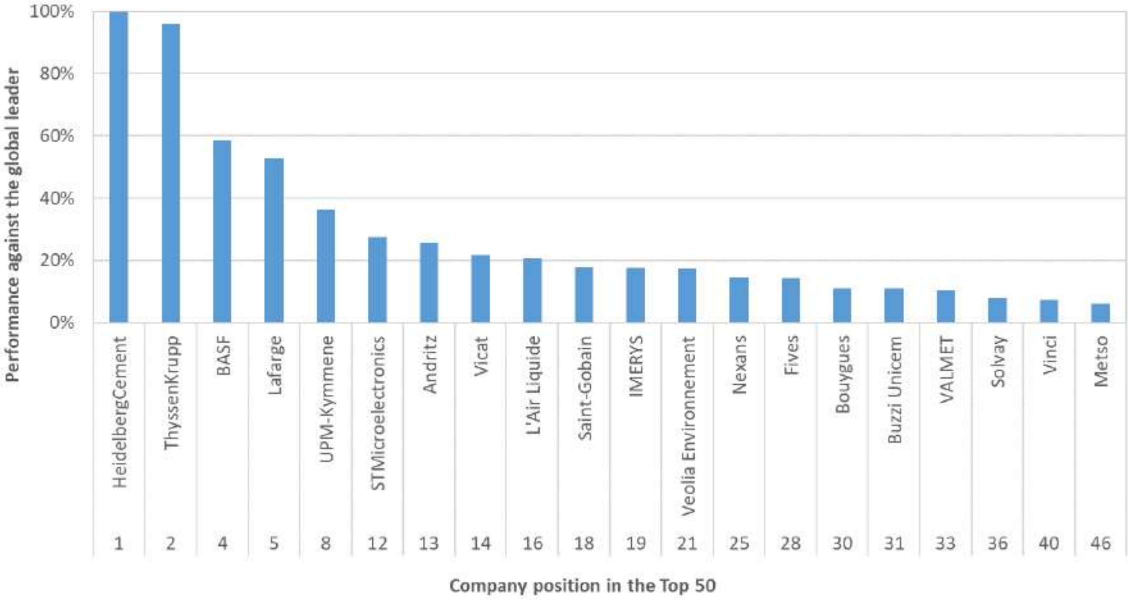
As the focus is on the cement sector, the above analysis has excluded other areas of minerals processing, such as glass and ceramics production. Of these, glass production is the most prominent area, with higher activity levels than cement. It is dominated by Japanese companies, with the exception of Corning (US), which is at the top of high-value inventions along with Asahi Glass (JP). EU companies Saint Gobain (9th) and L'Air Liquide (10th) make the top 10, but their portfolio is 10 times smaller than the two leaders'.

Figure 13: Top 10 patenting entities in CCMTs for cement production; cumulative inventions grouped by parent company (2010-2016)



Source: JRC SETIS data

Figure 14: EU companies in top 50 of patenting corporations in technologies in cement (high-value patents grouped by parent company), 2010-2016 – position and performance compared to global leader Heidelberg Cement



Source: JRC SETIS data.

3.8 *Patents for climate change mitigation technologies in the chemicals industry*[80]

The EU and USA are in the lead in terms of cumulative high-value filings for CCMTs in the chemicals industry. Since 2014, the EU has overtaken the USA in annual high-value filings, but numbers for both are decreasing. British BP and Saudi Basic Industries also feature in the top 10. Activity is more even across the top actors in these technologies and sustained throughout recent years.

In the EU, around 930 distinct entities filed for at least one patent in 2010-2016. About 30% of these are Scoreboard companies and subsidiaries, with the latter accounting for 70% of patenting activity. The top 10 account for almost half of the inventive activity. Relevant patents by EU companies represent a rather insignificant part of their patent portfolios, putting into question the extent to which their low-carbon business strategies involve technology development.
Figure 15 shows a good example of the effect of IP policies and practices in China. China Petroleum & Chemicals is ranked 21st in terms of high-value inventions, as it seeks protection outside China for only a very small share (1.5%) of its patent portfolio. Petro China and ZTE are outside the top 150.

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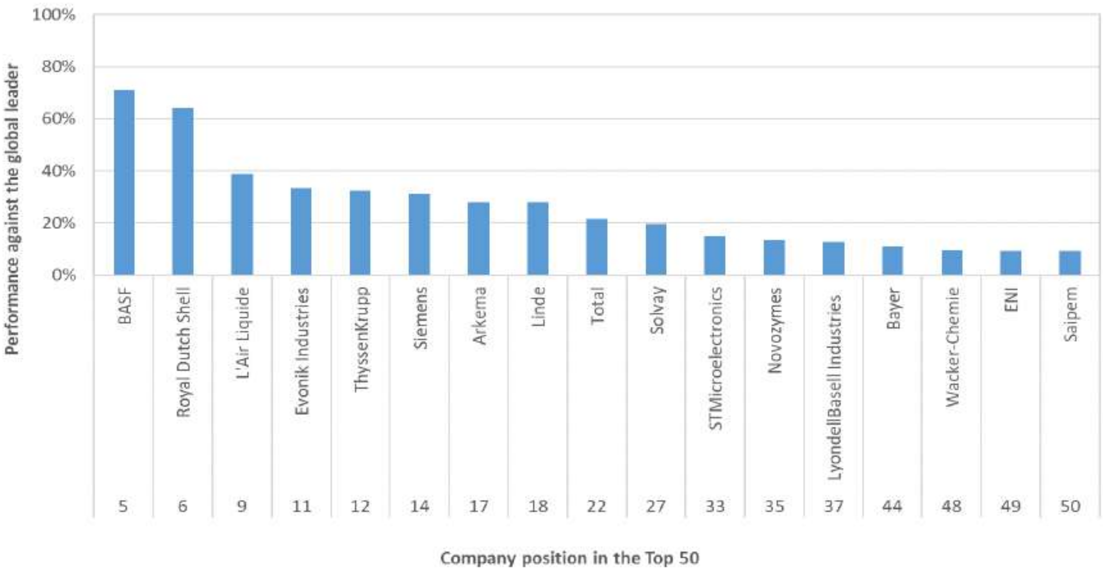
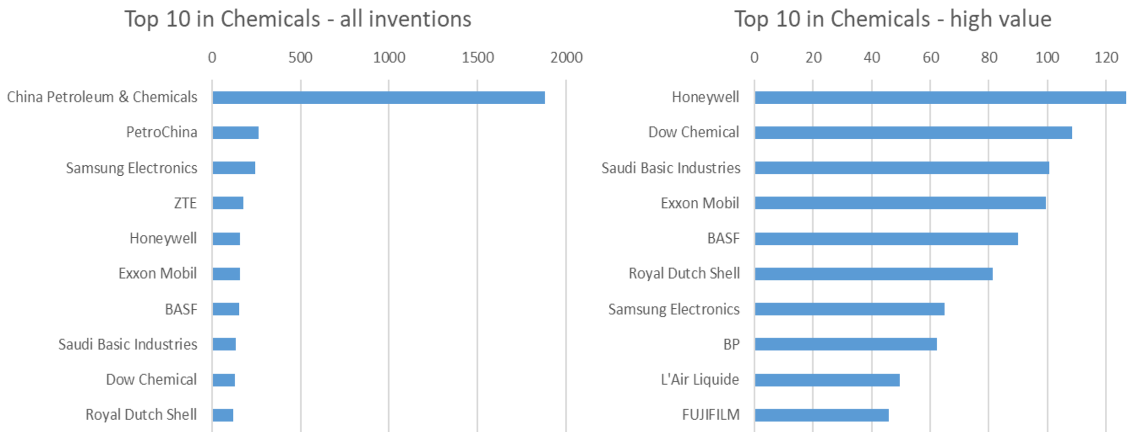
[80] Y02P 20 Technologies relating to the chemicals industry.

Figure 15: Top 10 patenting entities in CCMTs for the chemicals industry; cumulative inventions grouped by parent company (2010-2016)



Source JRC SETIS data.

Figure 16: EU companies in top 50 of patenting corporations in technologies in chemicals (high-value patents grouped by parent company), 2010-2016 – position and performance compared to Honeywell (US)



Source JRC SETIS data

In a further breakdown of activities:

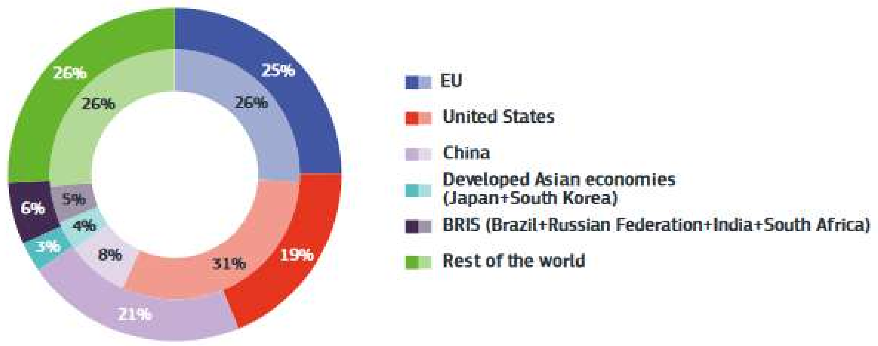
- Shell, Dupont and BASF are the EU companies prominent in **energy efficiency** measures;
- Siemens, L'Air Liquide, ThyssenKrupp, STMicroelectronics and Linde all feature with patents addressing technologies for **energy recovery** (another key area of position and interest for the EU);
- Siemens is the strongest EU firm in patent developments on **renewable energy sources**, along with Toshiba (JP); its portfolio in high-value patents is three times the size of the other EU top 10 companies'; and
- Linde is the top EU company (along with Mitsubishi and Fujifilm (JP)) in patenting activity concerning the **reduction of GHG emissions**, with L'Air Liquide and Shell also featuring in the top 10.

4 Maturity of innovation ecosystems for low-carbon technologies

4.1 R&I base - scientific publications

The EU and China are the global leaders in terms of scientific output, while the United States retains its lead in terms of scientific quality. Output from Chinese researchers has risen exponentially in the last two decades to almost match the EU's. In the EU, research intensity varies and there is a positive correlation between scientific quality and investment in most countries. More than 70% of European Research Council projects assessed in an independent study made scientific breakthroughs or major advances, while around 25% made incremental contributions[81].

Figure 17: Shares (%) of top 10 % of scientific publications on climate and environment, 2006 (interior) and 2016 (exterior)



Source: European Commission, *Science, research and innovation performance of the EU 2020.* Note: (1)Data produced by Science-Metrix based on Scopus database. Stat.link: https://ec.europa.eu/info/sites/info/files/srip/2020/parti/chapter61/figure-61-17.xlsx

In terms of high-quality scientific publications, China increased its shares exponentially across all societal challenges[82] between 2006 and 2016, while the USA lost its leadership across the board[83]. Against its major competitors (the USA, China and Japan), the EU leads in scientific publications relating to **food & bioeconomy** and **climate & environment**. Its overall share remained stable, except on energy, where it dropped from 24% to 18%. China took second place in climate & environment (22% in 2016), behind the EU (25%). Many of the lagging regions (mostly in eastern and southern Europe) performed better on scientific output, which indicates improved returns on R&D investment[84].

The EU contributed only 17% of the scientific articles relating to the **low-carbon energy** sector[85] that were published in 2019. The leading countries in this more specific field of science were China, the USA and India. In 2015-2019, there were 25 507 publications addressing energy efficiency in industry, which represents 3.4% of all low-carbon energy sector publications. EU publications per GDP increased only marginally, in contrast to the global 6% annual increase driven by countries such as China, Brazil and India. However, the EU was still above the global average in this respect (0.07 vs 0.04 per USD billion); the only other major economy above the median was South Korea.

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[81] *SRIP report 2020*, Section 6.1.

[82] The concept of "Grand Challenges" was suggested by the ERA Expert Group (European Commission (2008) *Challenging Europe's Research: Rationales for the European Research Area (ERA)-Report of the ERA Expert Group*) as a rationale upon which to build the European Research Area.

[83] *SRIP report 2020*, p. 381.

[84] *Ibid.*, p. 233.

[85] European Commission (2020), Publications as a measure of innovation performance: Selection and assessment of publication indicators. Report in progress under tendered study 2018/RTD/g1/OP/PP-07481-2018 authored by Provencal, S; Khayat, P., and Campbell, D., Science Metrix.The study focused on SET Plan key actions: No 1 in Renewables, Smart Solutions for Consumers, Smart, Resilient and Secure Energy System, Energy Efficiency in Buildings, Energy Efficiency in Industry, Batteries and e-Mobility, Renewable Fuels and Bioenergy, Carbon Capture Utilisation and Storage, Nuclear Safety.

The EU's specialisation score for clean energy fell between 2015 and 2019 to 0.85[86]. The EU specialises in fields such as psychology and cognitive sciences, economics and business, and clinical medicine, at the expense of other fields, such as information and communication technologies, and engineering, which are the focus of much of the clean energy research. However, the EU did show specialisation in the areas of new materials & technologies for buildings, and in energy efficiency in industry. Other major economies, such as the USA, Japan and China, were below the median.

The EU's share of international co-publications in low-carbon energy is above the world average and this also holds for publications in energy efficiency in industry. The best-performing EU countries were Estonia, the Netherlands and Belgium. The EU also has more open-access publications, both overall and on this specific topic, than the world average. Other major economies scored below the median on both indicators.

The number and share of public/private co-publications in energy efficiency in industry also increased, in line with the EU's strong performance in all low-carbon energy publications. The best-performing EU countries were Austria, Germany, Sweden, Denmark and Finland. The best performers from the rest of the world were Japan and the United States. China and South Korea were below the median.

The EU's collective impact was slightly below the world average, as measured by share of highly cited publications (among the 10% most cited). However, the EU scored slightly above the world average in energy efficiency in industry, with the best-performing EU countries being Denmark, Italy and Belgium. China and the USA also performed well, while Japan and South Korea were below the median.

R&I partnerships such as **SPIRE** play a crucial role in the dissemination of knowledge on low-carbon industry technological development. In 2019, 53% of surveyed projects reported plans to publish results, 75% reported that their results were broadly transferable to other sectors and 39% were contributing to European standards, with 16 contributing to standardisation documents, 10 making proposals for standards to an existing group and 3 setting up a new standardisation group.

4.2 Innovation ecosystems for low-carbon industries

The EU landscape of relevant actors and activity in R&I on low-carbon technologies is rather fragmented. A number of regions make considerable efforts and investments to cooperate with other parts of the EU in making industry more sustainable, digital and resilient[87], and the Commission is monitoring relevant progress[88]. Relevant action by Member States and regions will increase considerably with the implementation of NextGenerationEU, guided by cross-cutting principles and national recovery and resilience plans. Horizon Europe will bring targeted monitoring and assessment of R&I development in Member States and regions to the next level, facilitating the development of EU technology roadmaps through action in the relevant EU industrial ecosystems[89].

Current support for R&I on low-carbon technologies largely depends on the available green funding opportunities. This analysis therefore looks at the green funding and green

[86] Scores below 1 indicate lack of specialisation, i.e. the share of publications in the field is lower than that observed globally.

[87] The Smart Specialisation Platform, including on industrial transformation (https://s3platform.jrc.ec.europa.eu/) and the R&I strategies for smart specialisation are central elements of this work.

[88] The Horizon2020 Policy Support Facility (PSF) offered practical support to national and regional administrations to design, implement and evaluate reforms that enhance the quality of their R&I investments, policies and systems.

[89] DG R&I and the JRC aim to further improve the PSF under Horizon Europe to help Member States and regions play their role in developing industrial R&I. As part of Horizon Europe (Pillar III), the EIC is developing analytical capacities to monitor and assess relevant developments in EU innovation ecosystems.

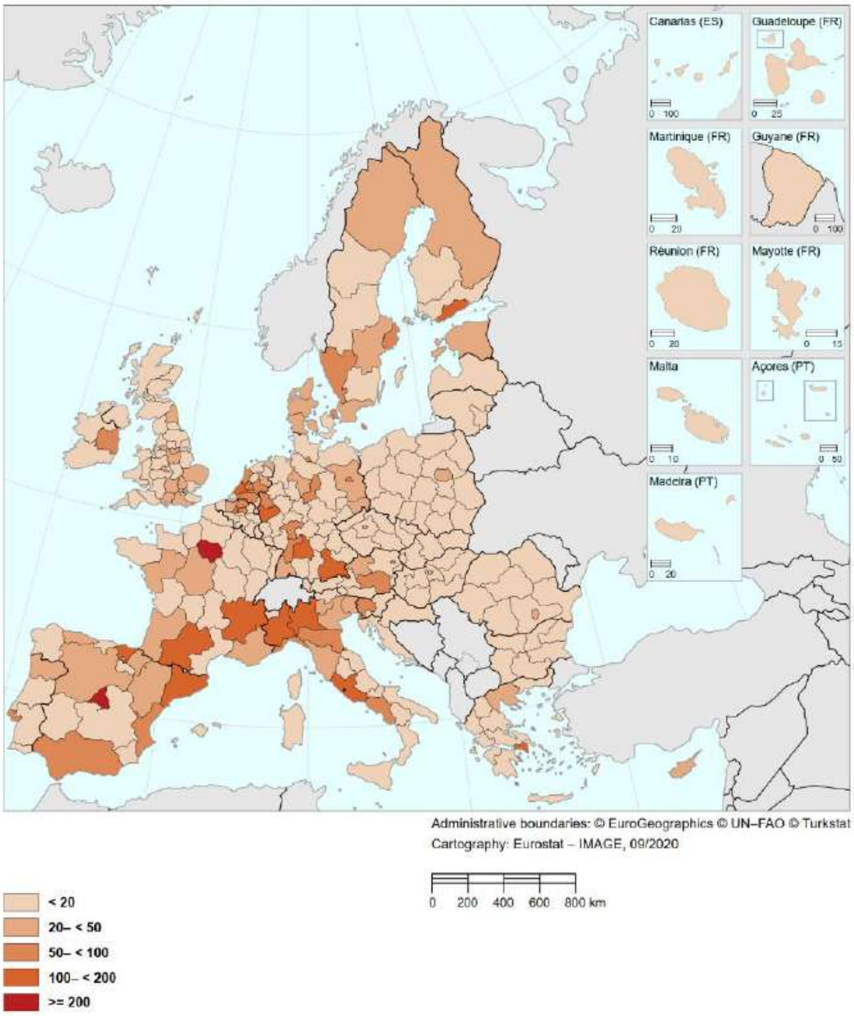
patent landscapes, and sets out a way forward to maximise efficiency and the impact of investments; this is based on:

- a better mapping of actors, places and networks; and
- a better understanding of models for coordination, governance and increased collaboration between them.

4.3 The funding landscape for low carbon technologies and the role of places

The **EU industrial strategy** highlights the importance of a renewed partnership, including regions, to drive the green and digital transitions with industry. In this context, it also suggests encouraging 'place-based' innovation and experimentation[90].

Figure 18: EU regions investing in Horizon 2020 low-carbon R&I projects (October 2019)



Source: Horizon 2020 Cordis dataset, DG R&I (October 2019)

Under **Horizon 2020**, the take-up of funding under the three 'grand societal challenges' relating to low-carbon technologies (energy, transport and climate) is unevenly distributed geographically. Figure 18 shows strong differences at regional level (based on aggregation of project-level data) and a significant imbalance between east and west, but less so between north and south. As of October 2019, €6.7 billion of a total of

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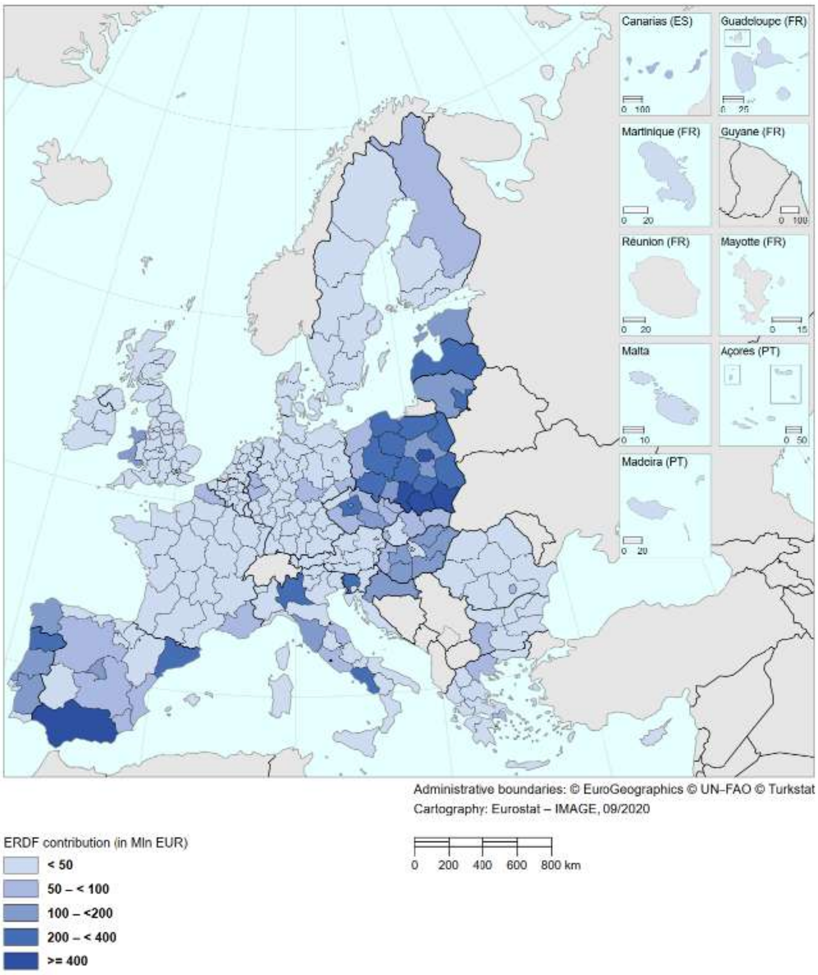
[90] *EU industrial strategy*, p. 10.

€47.14 billion had been allocated to collaborative R&I projects in the areas of energy, transport and climate. Figure 18 also shows that the disparities are much greater at regional level than at national level. This is also the case when considering overall Horizon 2020 funding for all technologies.

This imbalance is partially compensated by the geographical spread of similar investments under the **European Regional Development Fund** (ERDF), estimates of which are shown in Figure 18 (based on aggregation of project-level data selected through text analysis[91]).

Figure 19: EU regions investing in ERDF low-carbon R&I projects (June 2020)



Source: ERDF grants dataset (JRC 2020). Projects identified as covering multiple low-carbon domains (energy, transport and climate) are duplicated. The total amount per region may not correspond to the actual ERDF amount allocated.

Under regional innovation and smart specialisation strategies (RIS3s), the EU's current **cohesion policy** encourages regions and Member States to join forces in interregional partnerships, aiming to develop coalitions supporting the creation of new European value chains in areas associated with strategic growth. The RIS3 partnerships are grouped around three thematic smart specialisation platforms (industrial modernisation, energy and agri-food). The partnerships relevant for low-carbon technologies in steel, cement and chemicals include partnerships on chemicals, sustainable buildings, advanced manufacturing for energy applications, advanced materials for batteries, efficient and

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[91] Operations relating to low-carbon technologies co-funded by the ERDF have been identified through text analysis among the projects funded under European Structural and Investment Fund (ESIF) thematic objective 1 (R&I). The source of the information is a dataset gathering all ERDF operations at EU level as of June 2020. The text analysis gives only a rough estimate and a comparison with H2020 figures would require further work.

sustainable manufacturing, European hydrogen valleys, mining industry, bio-energy, solar energy, smart grids and geo-thermal energy.

Other relevant **EU R&I networks** in this context include:

- EIT knowledge and innovation communities (EIT Climate KIC, EIT Raw Materials KIC, EIT Innoenergy and EIT Manufacturing); and
- Horizon R&I partnerships (SPIRE, Factories of the Future and Energy-Efficient Buildings) with strategic innovation agendas providing important direction for R&I action at EU level.

Figure 20: Regions involved in the RIS3 partnership on chemicals

For the time being, a more detailed overview of networks, places and actors along specific value chains is still lacking. This makes it harder to align regional and national R&I agendas as part of EU technology roadmaps and increase the impact of relevant investments.

Box 4: Connecting actors and places in the area of smart energy systems

The JRC has been supporting the efforts of national/regional authorities and key stakeholders across the EU to plan the allocation of their EU funds to support investment in smart-grid R&I and deployment in the 2021-2027 programming period, so as to align their regional strategies with those of major EU R&I networks on smart energy systems. The JRC organised an initial meeting and the PAN European Technology Energy Research Approach (PANTERA) is working on further networking to connect public authorities involved in R&I strategies with relevant EU-level R&I networks[92].

[92] e.g. BRIDGE — Cooperation group of Smart Grids and Energy Storage H2020 projects; www.h2020-bridge.eu
European Innovation Partnership on Smart Cities and Communities (EIP-SCC); https://eu-smartcities.eu
Joint Programming Platform (JPP) ERA-Net Smart Energy Systems (ERA-Net SES); https://www.eranet-smartenergysystems.eu/

4.4 Landscape of technological capacity hotspots

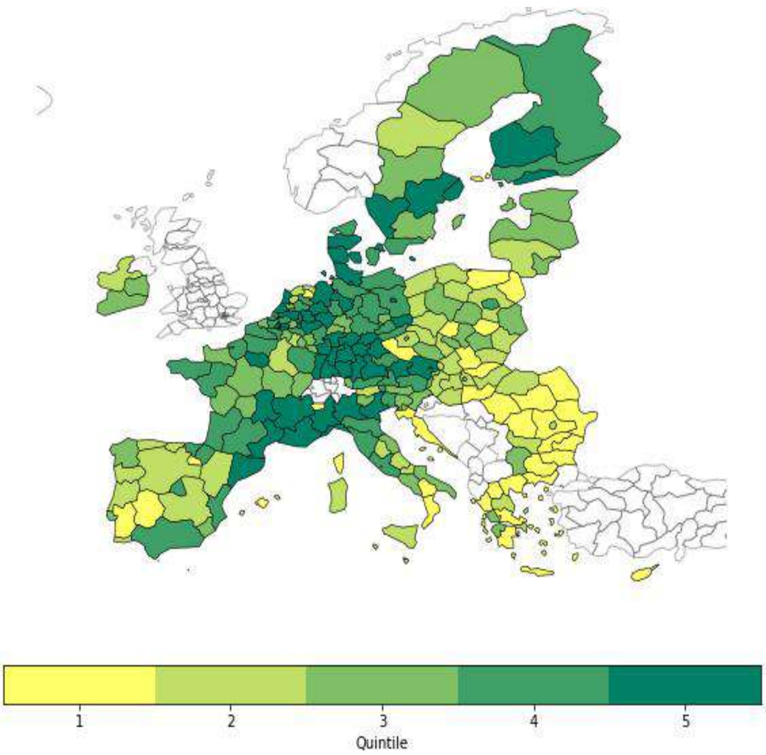
Figure 21 shows the geographical spread of green patents by NUTS2 region. As with Figure 18 (low-carbon H2020 funding), the 'centre of gravity' is in western Europe. Again, regional differences are also quite prominent.

Combining funding maps with the territorial spread of patents and future spending intentions can provide a good illustration of current and potential places of involvement in low-carbon R&I.

A mapping of the updated RIS3 priorities will be very helpful in providing an updated picture of R&I development in low-carbon and other industrial technologies, including national and regional priorities in the implementation of NextGenerationEU.

Updated data on spending intentions at regional level will become available when the RIS3s have been updated and the operational programmes to implement them have been approved.

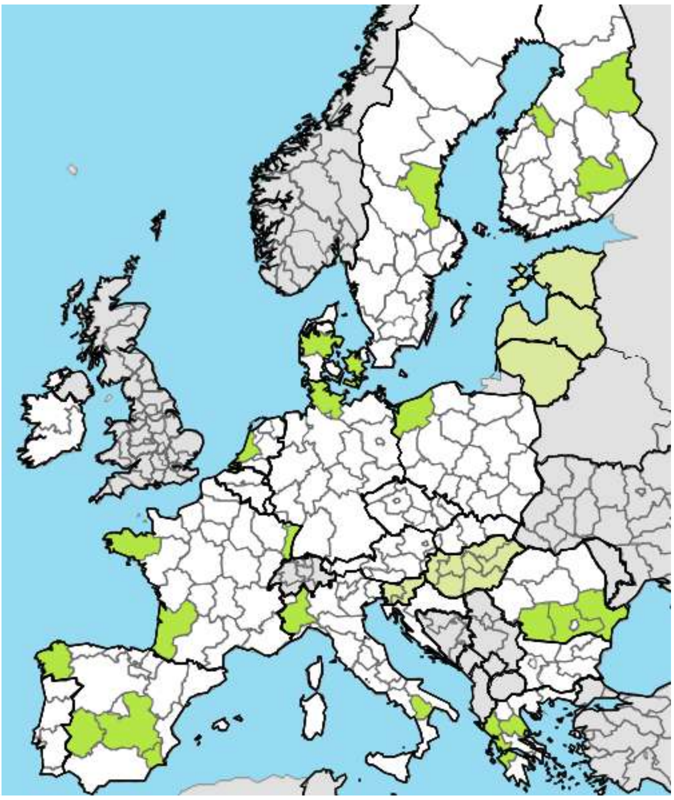
Figure 21: Number of green patents by EU region, NUTS2 level (based on inventor residence)



As an example, Figure 22 shows the regions that considered a focus in one of their RIS3 priorities on biomass for the 2014-2020 programming period.

Electronic Components and Systems for European Leadership (ECSEL); https://www.ecsel.eu/
InnoEnergy KIC; www.innoenergy.com

Figure 22: Regions with an RIS3 priority that includes biomass, 2014-2020 programming period



Source: Eye@RIS3

4.5 Capacity-building and place-based governance for the green economy

In line with the call in the EU industrial strategy for a renewed partnership between Member States, regions and industry to drive industrial innovation, the potential for a successful Green Deal and decarbonisation will depend on the EU's ability to build on its territorial and cultural diversity and to involve local stakeholders and communities. Experimentation with place-based solutions, in order to diffuse knowledge and align incentives, is important for successful implementation. This requires collaboration between actors and governance levels.

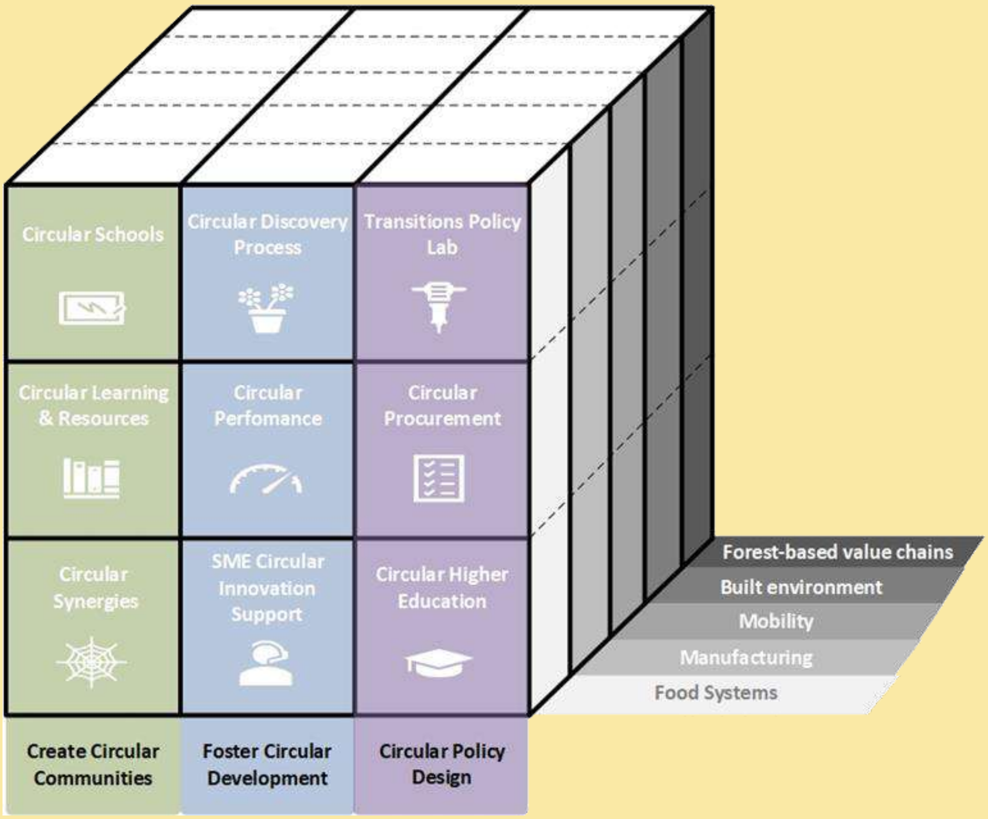
Regions face challenges with regard to quality of governance, skills and administrative capacities, coordination and involvement of stakeholders to better develop or use relevant industrial technologies. By understanding these better, EU policy recommendations and support mechanisms can have greater impact in strengthening innovation ecosystems. This capacity-building is particularly relevant in countries with more moderate innovation performance[93].

As an illustration, Box 5 describes the governance model applied for decarbonising Slovenia, building on five strategic priorities, including manufacturing and the built environment. We need a better understanding of the strengths and weaknesses of such collaborative models, in order to optimise the role of R&I in industrial transformation towards more sustainability.

[93] https://ec.europa.eu/growth/industry/policy/innovation/scoreboards_en

Box 5: Decarbonising Slovenia – a governance model for a circular, regenerative and low-carbon economy

The JRC, two EIT KICs and the Slovenian government are working together on the country's transition towards a circular economy for sustainable, competitive and green economic growth. Nine government ministries are involved. Smart specialisation has a central role in aligning different strategies and allocating the requisite resources, accessing global value chains and establishing collaborative government with all actors (national authorities, EU institutions, universities, NGOs, business, etc.). The collaboration involves a massive financial commitment and a huge coordination exercise to align all investments to achieve a common goal.



Comprehensive approach with nine groups of activities in five key sectors with emphasis on three pillars addressing different socio-economic and policy domains

5 Conclusions

- A significant number of low-carbon technologies under development in the EU have high potential to reduce greenhouse gas emissions in energy-intensive industries. These technologies are at very different levels of technological maturity. EU projects and partnerships have invested considerable resources to help them mature further, but it is difficult to gauge the broader impact of this investment.

- Many production pathways in energy-intensive industries are already highly streamlined and the incremental energy-efficiency improvements that are currently possible will not allow industry to meet the EU’s climate and energy targets. Fully decarbonised solutions are expensive and R&I results show projected cost increases of around 20% for some breakthrough technologies compared to current production in steel and chemicals (while world market prices are strongly influenced by non-EU competitors often subsidising non-decarbonised solutions).

- Public investment in R&I on energy-efficiency technologies (average €360 million/year) is higher in the EU than in other major economies, such as Japan (€290 million/year) and the United States (€165 million). However, Member States have recently reduced their funding for R&I on clean energy.

- In the private sector, only a small (and shrinking) share of revenues is being spent on R&I in sectors in which low-carbon technologies need to be adopted on a large scale. Relevant percentages of overall business investment in the EU are higher than those in the USA and comparable to those in Japan, but lower than those in China and South Korea.

- The EU and Japan are ahead of their international competitors in high-value patents in clean energy technologies. The EU is host to a quarter of the top 100 companies in this area.

- However, only EU companies in energy-related sectors lead (with Japan) on patents on climate change mitigation technologies. EU chemicals companies are trailing their Chinese counterparts and EU metals and related companies are still lagging behind the USA and China.

- EU patenting activity in relevant categories is dominated by a handful of companies in each sector.

- EU companies can be regarded as world leaders in particular sub-categories of technologies that help climate mitigation, such as process efficiency through reducing waste and recovering material streams, carbon capture, utilisation and storage (CCUS) technologies, electric conversion processes, energy recovery and renewable energy sources.

- The main EU companies’ R&D intensity is solid but decreasing in the chemicals and energy-related sectors, and low but stable in the metals and related sector. In the chemicals sector, the R&D performance of just one company (BASF: -11.6% in the 2018 financial year) has had a major impact.

- Value in metals and related start-ups is created mainly in China (followed by the USA), in chemicals in the USA (followed by the EU) and in energy-related start-ups in the USA (followed by China).

- More mature, well-known technologies (e.g. hydrogen-based steelmaking, carbon capture technologies and novel cements) often require significant investment for large-scale demonstration projects.

- Against a background of moderate public R&I investment and ailing private investment, an investment gap may open up in the EU for large-scale innovation projects.

- Past and current investment has led to ‘business as usual’ incremental improvements, but determined support for new technologies and massive investment in the large-scale demonstration of breakthrough technologies will be required if the EU is to achieve its climate and energy objectives.

- Connections between actors in value chains around breakthrough technologies are often weak and innovation ecosystems under-developed.

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The updated Industrial Strategy[94] announces the co-creation of transition pathways for industrial ecosystems with industry, public authorities and other stakeholders to accompany the twin transition. Such pathways shall lead to an actionable plan which will take into account inputs from Industrial technology roadmaps launched by New European Research Area[95]. Research and innovation results for new green and digital technologies are often scattered and not sufficiently transferred into the economy. Industrial technology prospect reports pull together valuable evidence for ERA Industrial technology roadmaps to underpin coordinated investment agendas from basic research to deployment. Building upon Horizon Europe partnerships with the private sector and considering breakthrough technologies supported by the European Innovation Council and other schemes at European and national level, they pave the first mile of pathways to strengthen EU industrial ecosystems.

Research and Innovation policy

94 COM(2021)350.
95 COM(2020)628, action 5.

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