European Commission

LOW CARBON ENERGY OBSERVATORY

CARBON CAPTURE UTILISATION AND STORAGE

Market development report

Joint Research Centre

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Foreword on the Low Carbon Energy Observatory

The LCEO is an internal European Commission Administrative Arrangement being executed by the Joint Research Centre for Directorate General Research and Innovation. It aims to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

Which technologies are covered?

- Wind energy
- Photovoltaics
- Solar thermal electricity
- Solar thermal heating and cooling
- Ocean energy
- Geothermal energy
- Hydropower
- Heat and power from biomass
- Carbon capture, utilisation and storage
- Sustainable advanced biofuels
- Battery storage
- Advanced alternative fuels

How is the analysis done?

JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patents filings. External experts may also be contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

What are the main outputs?

The project produces the following report series:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Future and Emerging Technology Reports (as well as the FET Database).

How to access the reports

Commission staff can access all the internal LCEO reports on the Connected LCEO page. Public reports are available from the Publications Office, the EU Science Hub and the SETIS website.

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Abstract

The CCUS Technology Market report is produced within the LCEO project by the JRC for DG RTD. The analysis was conducted in 2018 and data primarily refer to 2017 and before. The aim of the report is to give an impartial assessment on the state of the art, identification of development trends and market barriers, as well as to present the status of private and public funds and policy measures. It provides a description of the market status and trends in CO_2 capture, transport and monitoring, as well as storage (CCUS) and carbon dioxide utilisation (CDU) processes. The main actors involved in CCUS and their role in the value chain are identified, based on completed and on-going projects. While the focus is on the European market, but important international developments are also considered. For CDU, the focus is primarily on Europe.

1 Introduction

The climate conference in Paris (COP21, November 2015) and the following conferences COP22 and 23 reaffirmed the consensus that we cannot achieve the CO_2 reductions required to maintain the global temperature rise below 2 ^{0}C, without CCUS. Similarly, ambitions in the European Union (EU) for decarbonisation by 2050 are unlikely to be reached without this technology. To achieve 2 ^{0}C scenarios in 2050, almost 6 billion tonnes of CO_2 should be captured and stored each year across all sectors. The European Commission's newly released Strategy for long-term greenhouse gas emission reductions sets the tone for Europe’s climate ambition and presents carbon capture and storage (CCS) as part of the solution in the efforts to decarbonise Europe’s economy and energy system (European Commission, 2018).

Figure 1 summarises the main parts of the CCUS chain. CO_2 utilisation processes can exploit CO_2 captured from different sources such as from power plants and industrial activity. CO_2 can also be captured from the air or occur naturally such as from natural gas extraction. Various stakeholders related to the CCUS business are identified in the current report. CCUS activities have been undertaken in sectors such as the oil and gas, the chemical industry and enhanced oil recovery (EOR) but not necessarily for CO_2 mitigation. The main incentive so far for companies involved in CCUS has been economic, i.e. to obtain revenue by selling/using CO_2 for EOR, or minimising obligations for carbon taxes. In the current report, we identify the main companies from (i) existing plants, (ii) EU R&D co-funded projects and (iii) patents registration.

As a large number of projects have been cancelled at the planning stage, CCUS is progressing slower than expected. The establishment of a CCUS market requires long-term and strict carbon policies and incentives. The development of an enabling infrastructure such as pan-European CO_2 transport network and storage sites (European CCS Demonstration Project Network, 2015) still remains relevant.

Around the world, eighteen large scale CCUS projects are now in operation bringing the existing capture potential globally to around 32 million tonnes CO_2 per year (Global CCS Institute, 2018b).

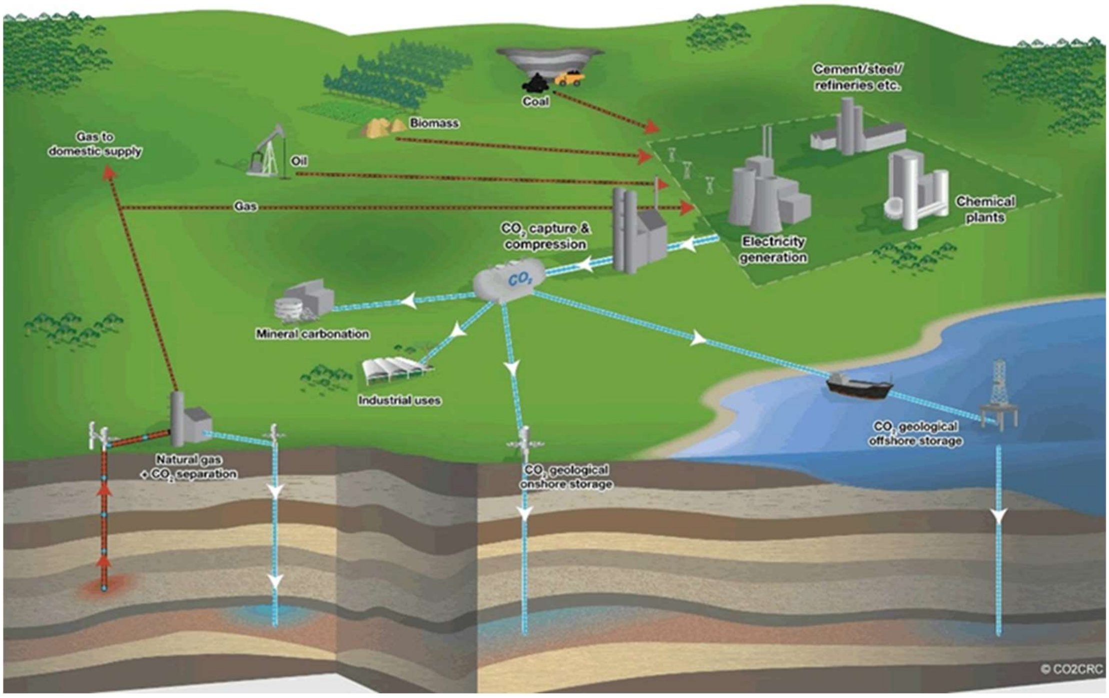
The individual elements of the CCUS chain have proven their technical feasibility. However, integrated projects at large scale are still not sufficiently cost competitive. While the operating costs are considerable, the associated capital costs remain high (Rubin *et al.*, 2012; Rubin, E. S., Davison, J. E., & Herzog, 2015). However, the recently published study with results from developing a real project indicates cost reductions as high as 67% for a next project to come online (International CCS Knowldege Centre, 2018).

CO_2 capture technologies have been primarily promoted for their application to power generation. Nevertheless, many of them can also be applied for CO_2 separation in industrial sites. CO_2 capture based on amine solvents has been considered intensively by the power sector for short-term implementation, and has been demonstrated commercially. Industrial separation applications involve in their majority natural gas processing where physical solvents are primarily employed.

Regarding CO_2 utilisation, research on catalytic, photochemical and electrochemical pathways for CO_2-based products is ongoing at industrial and academic levels. It is important to note that many companies already commercialise products made with CO_2, even if at the small scale (see the LCEO CCUS Technology Development Report and Chapter 3 below).

In Europe, CCUS R&D has been supported since 1993 through the Framework Programs (FP3, FP4, FP5, FP6, FP7 programs) as well as H2020. NER300 and EEPR (for more details see LCEO CCUS Technology Development Report) programs aimed at helping to accelerate CCUS commercialisation. However, similarly to other low-carbon technologies, CCUS is capital-intensive and as such impedes industrial developers in investing on this technology. Sufficient incentives to invest in infrastructure over the full CCUS chain will be key in significantly reducing the associated costs and incentivising private activities toward a market.

Figure 1. CCUS value chain facilities



Source: CO2CRC, 2017.

Note: "CCUS" used as an umbrella term for all projects where CO_2 is permanently stored, either geologically or by enhanced oil recovery. The term "CDU" or just "CO_2 utilisation" is used for projects where the captured CO_2 is used downstream but not necessarily permanently abated.

2 Technology trends and prospects

2.1 Deployment trends

The IPCC, both in the report of 2014 as well as the most recent one published in 2018 assign significant emission reductions potential over the course of this century to CCUS (IPCC, 2014, 2018).

Most of the technological components for CCUS are well known, the technology is well developed, and in some cases, it is mature. However the most difficult aspect is to set-up large-scale demonstration projects. There are still economic, political and social barriers, resulting in delays and the slowdown of CCUS deployment.

In contrast to Europe, the CCUS agenda in North America has always been led by the oil and gas industry, for which EOR provides a driver for developing the technology. The first large-scale CCUS project, launched in 2014, is Boundary Dam in Canada (coal power plant, PostC, 110 MW). Petra Nova in Texas (coal power plant, PostC, 240 MW) is another full scale CCUS project operational since January 2017. Both plants utilise CO_2 for EOR (Global CCS Institute, 2018a).

Figure 2 shows the development of CCUS globally. 18 large-scale facilities are currently operational, with an additional five expected to come on stream by 2020 (Global CCS Institute, 2017). The majority of the projects currently in operation are located in the USA. The projects operating around the world have a capture capacity of around 32 $MtCO_2$/yr in total, but this capacity must increase by a factor of 100 by 2040 to reach the Paris targets (Global CCS Institute, 2017).

Figure 2. CCUS projects in operation and under construction

Source: Global CCS Institute, 2017.

While initially the focus for CCUS development has been primarily on power generation, the switch towards its potential implementation in industry is reaffirming that it is particularly important in that sector. The production of industrial materials such as steel, cement and petrochemicals are interlinked with high levels of CO_2 and limited options exist to achieve deep emissions reduction. Carbon capture and storage is one of the few options available.

Rapid development can be achieved in industry sectors such as fertiliser production and natural-gas processing where CO_2 is already separated as part of the production processes and could be the "sweetspots" for market development.

Steel production, cement and chemical plants will need to be equipped with CCUS by 2050 to reach the globally agreed climate targets (IEA, 2011) and the recently published EU long term strategy (European Commission, 2018) further highlights this role in industry.

Currently operating projects concern mainly (i) natural gas (NG) processing plants and (ii) industrial plants that produce CO_2 as by-product (i.e. hydrogen production, the fertiliser industry).

Policies to stimulate CCUS projects with either direct government funding, fiscal incentives for industry (tax credits) or including requirements for CCUS in regulations are being implemented, especially in US, Canada, Asia (Japan, South Korea and most recently China), Australia and in Europe (Norway, UK, Germany) (Global CCS Institute, 2015).

2.1.1 CO_2 capture and utilisation

Regarding CO_2 capture, the most developed and mature technology is absorption with amines. Physical solvents which are commercially available have been used in industrial processes, with CO_2 separation as by-product, and in integrated gasification combined cycle (IGCC) power plants. Out of the 18 large scale CCUS projects operating worldwide (Global CCS Institute, 2018b), 15 employ solvents for CO_2 separation. For high temperature looping, another method achieving CO_2 capture, efforts are currently focused on solving issues related to the design of boilers (also see D2.2.9 CCUS Technology Development Report (2018)).

The trends in the market are focusing towards developing and optimising technologies that can be retrofitted in existing plants. Industry is also involved in projects for the testing and demonstrating the viability of the developed technology. CO_2 separation with solvents has dominated the market share and this trend is expected to continue toward 2030 (Accuray Research, 2018).

CO_2 utilisation uses this CO_2 as a feedstock for further downstream use. CO_2 has been used in the beverage and food industries, for medical applications, for rubber/plastics or to mix gases/aerosols among others. The sizes of the individual markets for specific CDU applications vary widely. With regards to concrete and carbonate materials from CO_2, there might be a large potential. Given technical and market readiness, this represents an opportunity for near term deployment (3-10 years) (Sandalow, David; Aines, Roger; Friedmann, Julio; Colin, McCormick; McCoy, 2017).

For CO_2 based chemicals the technology is fairly mature. Given technical and market readiness, this represents an opportunity for near to medium term deployment (5-20 years) (Sandalow, David; Aines, Roger; Friedmann, Julio; Colin, McCormick; McCoy, 2017).

Durable carbon materials are at a very early stage of development. Even if potentially the market for these materials may be quite large, they represent a long-term market opportunity.

Conversion of CO_2 to fuels has also been receiving interest towards a market of processes often known as power-to-liquid and power-to-gas or, collectively called power-to-X. This is often linked to the possibility that fuels can offer for indirect electricity storage, i.e. the use of electricity to create a fuel that can be stored. Methanol production from CO_2 is performed at industrial scale, for example at the Carbon Recycling International site[1]. Another example of a power-to-X is Sunfire, which aims at synthesising different gas and liquid fuels using water and CO_2 co-electrolysis[2] as well as Audi,[3] with its own power-to-gas facility in Werlte, in northern Germany, for producing synthetic methane from CO_2.

According to the latest report from the JRC, if a fuel can save GHG emissions, compared to the regular predominant fuels, it would worth including them in future analyses of advanced alternative fuels. However, any resulting emission reduction must be estimated with a verifiable manner such as via a robust life cycle analysis which takes into account the existing uses of feedstock materials.

2.1.2 CO_2 transport and storage and monitoring

CO_2 transport via pipelines is a mature technology and transport by ship is an option also considered in recent years to reduce costs. In all cases, to achieve large-scale CCUS project development, associated infrastructure at global level should be 100 times larger than that existing today (IEA, 2015b).

Certainty on CO_2 storage capacity can be a factor impacting "investor confidence" and consequently, the creation of a CCUS market. CO_2 storage has been already technically demonstrated but monitoring of the injected CO_2 will also be required. Such monitoring accounts for a considerable part of CCUS costs since it has to be planned for the long term, both during as well as after CO_2 injection.

CO_2 storage capacity is mainly based on estimates for saline aquifers which should be the largest injection sites by storage volume. These estimates are based on current knowledge of the geological conditions to store CO_2 but the necessary risk assessment studies are still pending in many parts of the world. Data from UK, NL and NO have been published via their national CO_2 storage atlases.

Research is ongoing to address both uncertainties associated with monitoring as well as costs. Alternative approaches, under research, are exploring ways to reduce costs and increase storage efficiency. These include synergies with geothermal energy, for example, using CO_2 as heat transfer fluid, sharing injection wells (Li *et al.*, 2016)(Ganjdanesh *et al.*, 2013)(Nielsen, Frykman and Dalhoff, 2013); combining CO_2 and H_2 storage (pilot project in Austria); and/or injecting CO_2 in basalts (faster mineral CO_2 trapping) (Matter *et al.*, 2011)(Gislason *et al.*, 2014)(Gislason *et al.*, 2010). These alternatives can reduce the costs and increase the storage efficiency (Li *et al.*, 2016).

[1] http://carbonrecycling.is/
[2] http://www.sunfire.de/en/
[3] https://www.audi-technology-portal.de/en/mobility-for-the-future/audi-future-lab-mobility_en/audi-future-energies_en/audi-e-gas_en

2.2 Targets

In 2007, the European Council agreed to an EU goal of having up to 12 large-scale demonstration projects by 2015 (Council of the European Union, 2007). This has not been realised and the most important step for CCUS still remains to create demonstration or pilot plants. Also for CO_2 transport and storage, sites where CO_2 is injected need to be monitored and evaluated under commercial conditions.

Linking CO_2 sources to clusters of sinks by creating CO_2 networks can be an option to overcome associated barriers and to promote large scale CCUS deployment. The latest global storage portfolio (Global CCS Institute, 2016) shows that the North Sea is the most suitably structured location in the world. Projects such the creation of CO_2 hub in Rotterdam, in the Netherlands, the Teesside Collective in the UK or the Scottish CO_2 hub can contribute in exploiting this potential.

In 2017, European stakeholders created a Temporary Working Group (TWG) through the EC's Strategic Energy Technology Plan initiative to elaborate a proposal for CCUS. This group is composed by 11 countries (the Czech Republic, France, Germany, Hungary, Italy, Norway, the Netherlands, Spain, Sweden, Turkey and UK), industrial stakeholders, non-governmental organisations and research institutions. The SET Implementation Plan has been approved and finally endorsed by the European Commission in November 2017. The same group constitutes now the Implementation Working Group (IWG).

The SET Plan set out the main 10 targets for the deployment of CCUS and determined 8 research and innovation actions to achieve these targets (see also D2.2.9 LCEO Technology Development Report 2018). It also sets targets of completed FEED studies for least one commercial-scale, full chain project operating in the power sector and at least one commercial scale project linked to an industrial CO_2 source, to further incentivise market development .

2.3 Regulatory framework and incentives

Regulations encompassing CCUS activities remain an important factor for project development and only a limited number of countries have legislation in place to facilitate the deployment of demonstration projects.

Storage

In 2009, the 2009/31/EC Directive (European Parliament and Council of the European Union, 2009c), established a legal framework to safely store CO_2. All Member States have notified transposition measures relative to the Directive (also known as the CCS Directive).

CO_2 utilisation

The consultation of the CCS Directive (Triple-e, Ricardo-AEA and TNO, 2015) highlighted awareness of CDU processes. CDU represents an innovative set of processes that could contribute to the rejuvenation of European industry and strengthen the European circular economy. The (ILUC) amendment (European Parliament and Council of the European Union, 2015) to the Renewable Energy Directive (European Parliament and Council of the European Union, 2009a) and the Fuel Quality Directive (European Parliament and Council of the European Union, 2009b) considered CO_2 utilisation for the production of fuels for transport such as renewable fuels of non-biological origin. The Renewable Energy Directive (RED II) revision specifically, opened possibilities for CO_2-based fuels to be counted towards national renewable energy targets and to be supported by the fuel blending quotas if they are recognised as renewable. The final compromise text of the EU Institutions specifies that the greenhouse gas emission savings from the use of renewable liquid and gaseous transport fuels of non-biological origin excluding recycled carbon fuels shall be at least 70% as of 1 January 2021 (General Secretariat of the Council of the European Union, 2018). Each Member State will define the detailed trajectory to reach these targets in their Integrated National Energy and Climate Plans.

In June 2018, the EC's Scientific Advice Mechanism (SAM) High Level Group (HLG) (SAM HLG, 2018) reaffirmed that renewable energy is a prerequisite in CDU for contributing to climate change mitigation. SAM HLG called for defining a life cycle assessment method to quantify the environmental impacts of these technologies. This Regardless of a market pull from the private sector itself, what is clear for CDU processes to be supported by public sources is that: (i) their net CO_2 emissions are less than the established routes', (ii) they decrease the consumption of fossil fuel as raw material, iii) they are cost competitive with products of the benchmark process.

Incentives

Challenge 4 of the SETIS Integrated Roadmap (European Commission, 2014), mentioned that CO_2-based products should be recognised as renewable products and benefit from appropriate support. However, an explicit policy framework, with an ad-hoc environmental assessment, is needed to promote CDU processes. So far, the only clear link of European policies with CO_2 use technologies is through the upcoming Innovation Fund. As there is no specific policy support for CO_2 utilisation processes, considering CO_2 as raw material and specifying how their emissions/characteristics should be evaluated may delay market development.

On the EU level, the Directive 2003/87/EC (European Parliament and European Council, 2003) established the scheme for emission allowance trading and the European Union Emissions Trading System (EU ETS)[4] was launched in 2005. Its amendments (Directives 2004/101/EC, 2008/101/EC, 2009/29/EC and most recently (EU) 2018/410) indicate that the sectors covered by the EU ETS will have to decrease their emissions by 43 % by 2030, compared to the emissions in 2005. For some of these industries CCUS may be the only available option to achieve such deep emissions cuts.

To help the industry and the power sectors overcome the innovation and investment challenges towards meeting the climate and energy targets set, the European Commission proposal for revision of the EU Emission Trading System (EU ETS) post-2020 put forward an Innovation Fund. This will support innovative demonstration projects in energy intensive industries, renewable energy and carbon capture and storage. The EU Emissions Trading System (EU ETS) will be providing the revenues for the Innovation Fund from the auctioning of 450 million

[4] http://ec.europa.eu/clima/policies/ets/index_en.htm

allowances from 2020 to 2030, as well as any unspent funds from the NER300 programme.

Beyond the EU

In the US, specific frameworks such as the 45Q tax incentives support for CCUS technology, making the US a leader in operating CCUS. However, while Japan and Norway do not yet have specific CCUS regulations, significant investment and development efforts (IEA, 2014) are noted. Regulatory framework and incentives are important but not determining.

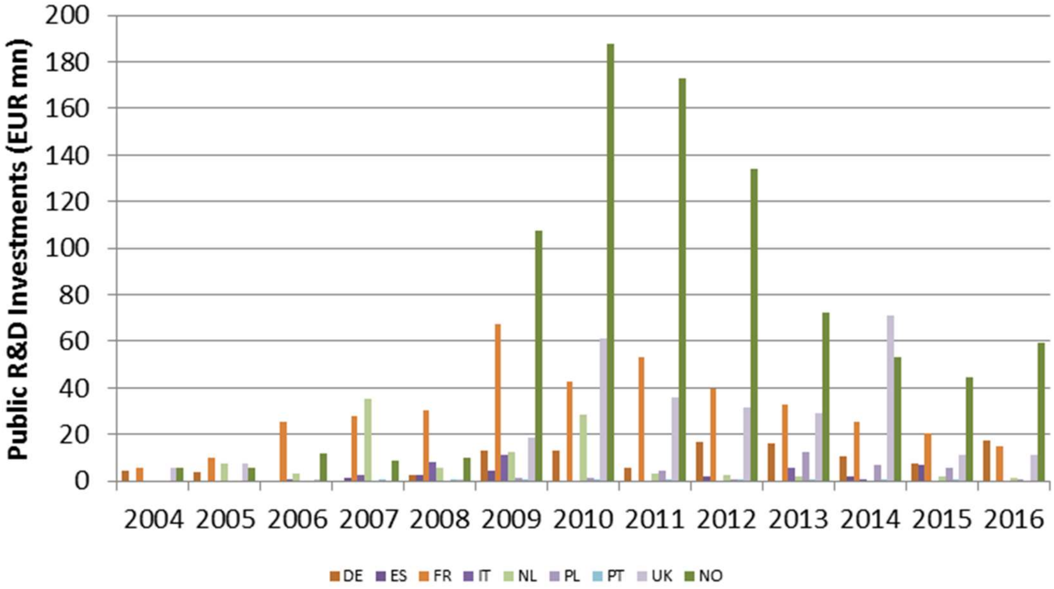
2.4 R&D Investment and patenting activity

Government, or public, R&D investment can have a significant positive effect on the development and deployment of the technology, creates a positive environment for private initiatives, and affects among others the number of relevant publications and patent applications. As such, both public and private R&D investments as well as patents activity are important indicators of the level of development and competitiveness in a given technological area. The analysis presented in the following is based on the JRC in-house methodology (Fiorini *et al.*, 2017; Pasimeni, Fiorini and Georgakaki, 2018), monitoring Research Innovation and Competitiveness in the Energy Union R&I priorities.

Public R&D investment from 2004 to 2016 in the European Economic Area (EEA), is shown in Figure **3**. Since 2009, Norway is the largest investor in CCUS R&D in terms of public funds, except from 2014 when it was overtaken by the UK. However, this is not the case with regards to private investments (**Figure 4**).

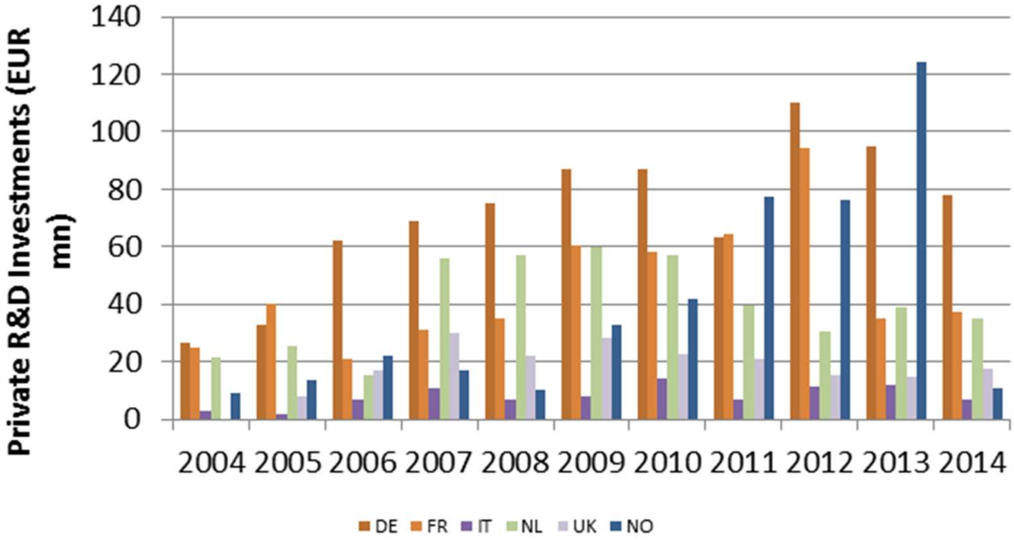
Amongst the countries most highly investing in CCUS, public to private R&D investments were mostly leveraged in Germany, followed by the Netherlands and France (**Figure 5**, **Figure 6**, **Figure 7**). This means that these countries noted significantly higher private investments compared to the public ones. N.B. Years showing no public investment indicates either zero investments or that data is unavailable.

Figure 3. Public R&D investments in CCUS for the EEA (top countries).



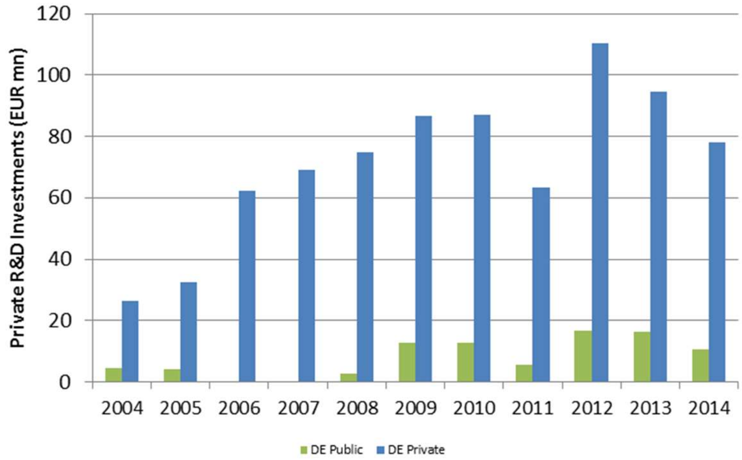
Source: JRC (JRC SETIS, 2018) based on IEA (IEA, 2018).

Figure 4. Private R&D investments in CCUS for the EEA (top countries, based on available data).



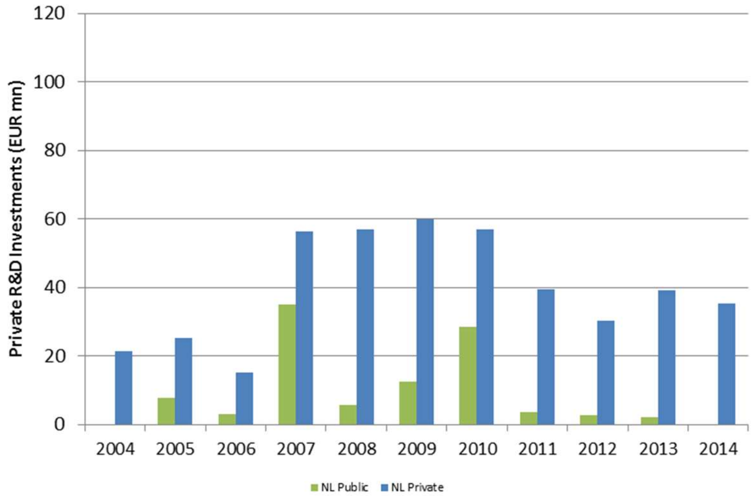
Source: (JRC SETIS, 2018).

Figure 5. Public and private R&D investments for CCUS in Germany.



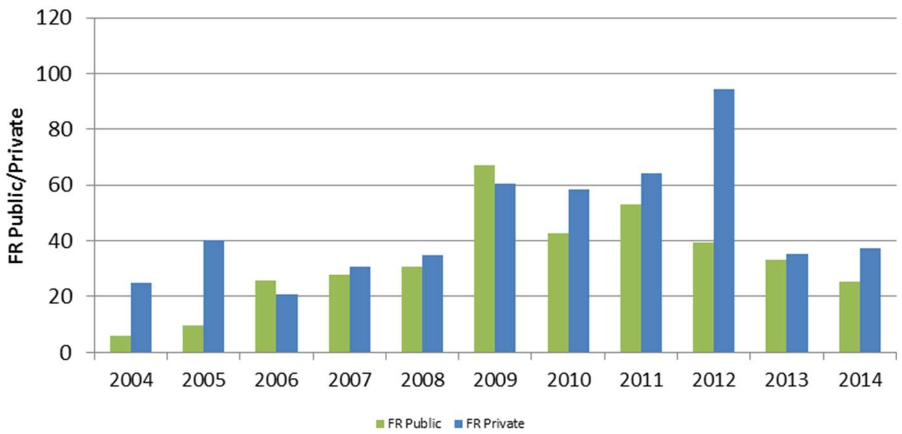
Source: (JRC SETIS, 2018).

Figure 6. Public and private R&D investments for CCUS in the Netherlands.



Source: (JRC SETIS, 2018).

Figure 7. Public and private R&D investments for CCUS in France.



Source: (JRC SETIS, 2018).

Patents on CCUS are identified by using the relevant Y code families (Y02C and Y02P)[5] of the Coordinated Patent Classification (CPC) for climate change. The following sub-classes on CCUS patents are relevant in this context:

Y02C 10/02 – Capture by biological separation

Y02C 10/04 – Capture by chemical separation

Y02C 10/06 – Capture by absorption

Y02C 10/08 - Capture by adsorption

Y02C 10/10 - Capture by membranes or diffusion

Y02C 10/12 - Capture by rectification and condensation

Y02C 10/14 - Subterranean or submarine CO_2 storage

In addition to the previous version of this LCEO report in 2016, this update includes the following sub-class:

Y02P 20/142 - CO_2 utilisation

Analysing the patenting activity per priority year, from 2004 to 2014, the larger number of cumulative patents is found in the categories of capture by adsorption and capture by rectification and condensation. The third sub-class with more patenting is capture by chemical separation. Despite the current interest on membranes, patenting is still far from the three leading technologies. Big multinational companies such as Shell, Air Liquide, Siemens, BASF and Linde are amongst the companies with the highest activity in patenting.

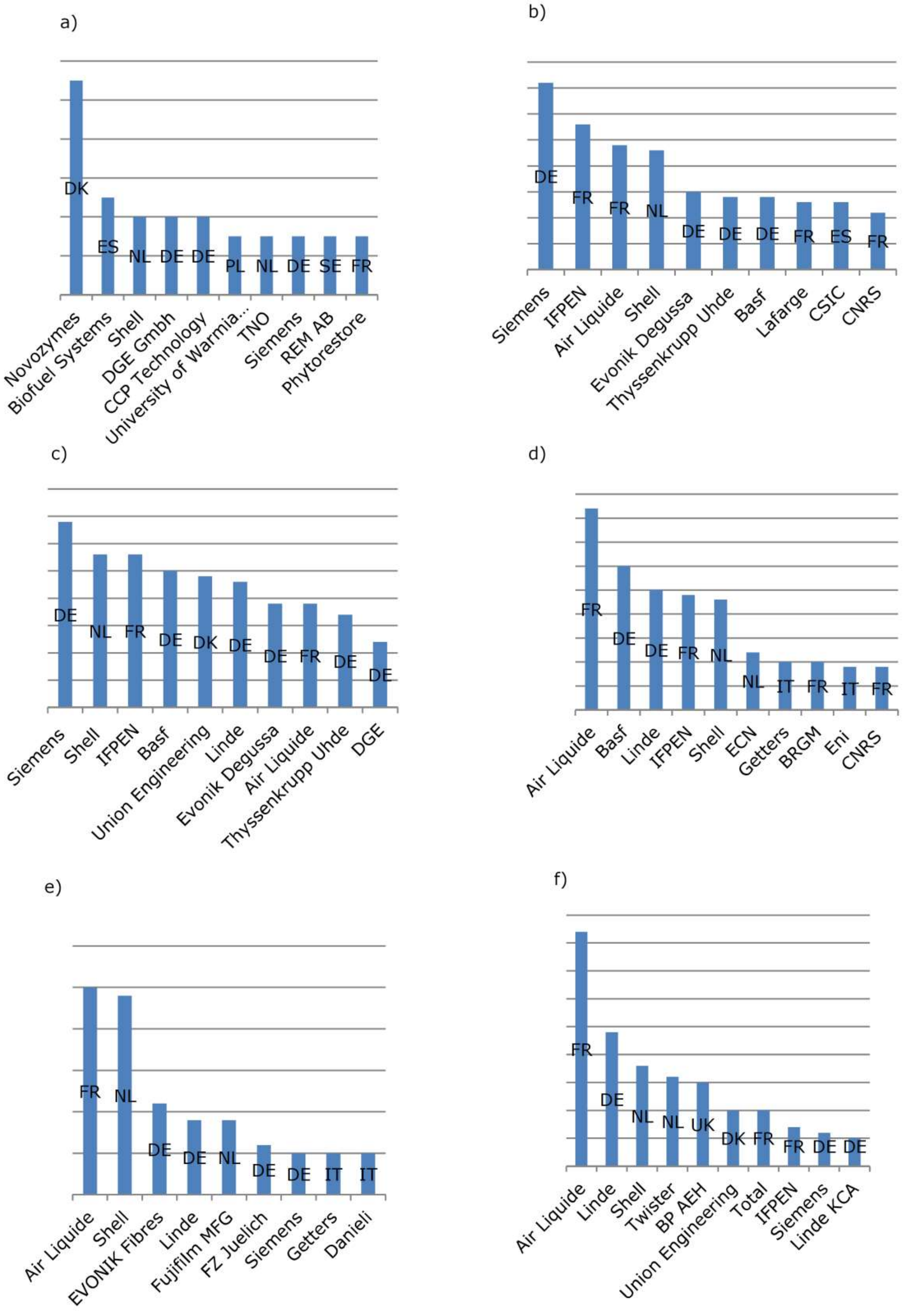
With regards to activity in technologies using CO_2 as a feedstock (**Figure 9**), big companies are amongst the top regarding patenting activity, as well as companies with multinational activities such as for example, SAIPEM which together with Stamicarbon are in the top 5. Interestingly, the two European countries that have relatively low public to private R&D investment ratios, namely Italy (~1 to 3) and the Netherlands (~1 to 4) are where these two companies are based. This could be attributed to that CO_2 utilisation technologies are interlinked with making a profit which is the primary driver in private activities.

Figure 8, **Figure 9** and **Figure 10** provide a qualitative ranking of entities most active in patenting in CO_2 capture, utilisation and storage technologies.

Since important investments on CCUS have been dependent on the oil and gas industry, the number of patents varies as a function of their interests for innovation or technology improvements (Figure 10). According to the data, patent families related to CO_2 storage peaked in 2007 and have decreased ever since.

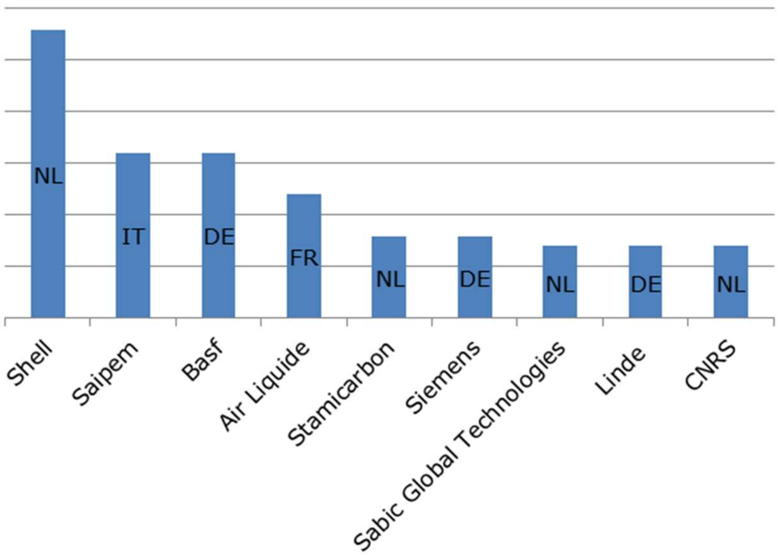
[5] Y02A 50 also refers to "Technologies for Adaptation to Climate Change" with CO_2 emission reduction but there are no details to further classify patents of this family.

Figure 8. Top companies and organisations patenting in CO_2 capture technologies according to CPC classes from 2004 to 2014 in Europe. a) capture by biological separation, b) capture by chemical separation, c) capture by absorption, d) capture by adsorption, e) capture by membranes, f) capture by rectification and condensation.



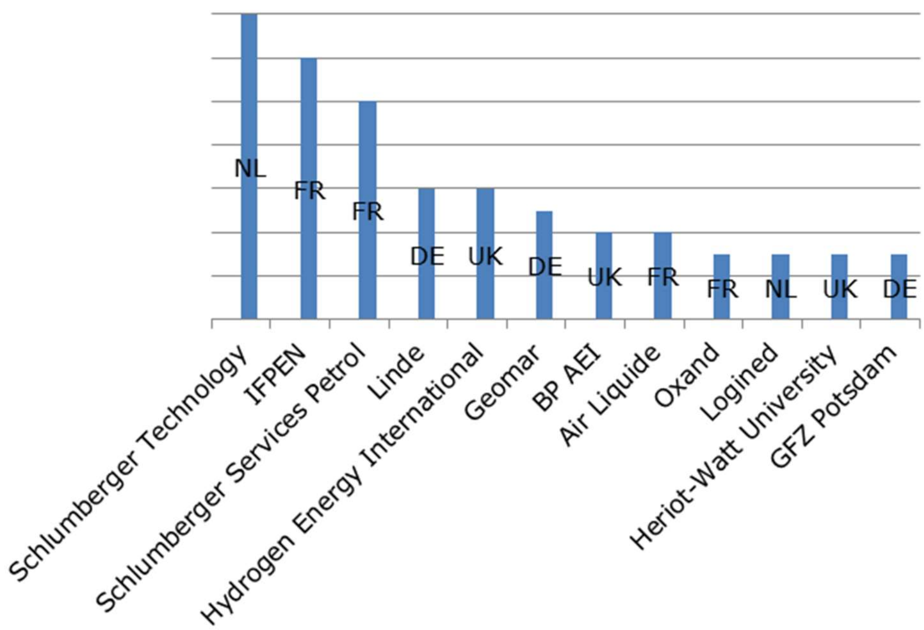
Source: JRC, 2018 based on (European Patent Office, 2018).

Figure 9. Top companies and organisations patenting in technologies using CO_2 as a feedstock from 2004 to 2014 in Europe.



Source: JRC, 2018 based on (European Patent Office, 2018).

Figure 10. Top companies and institutions patenting in subterranean or submarine CO_2 storage technologies in Europe from 2004 to 2014

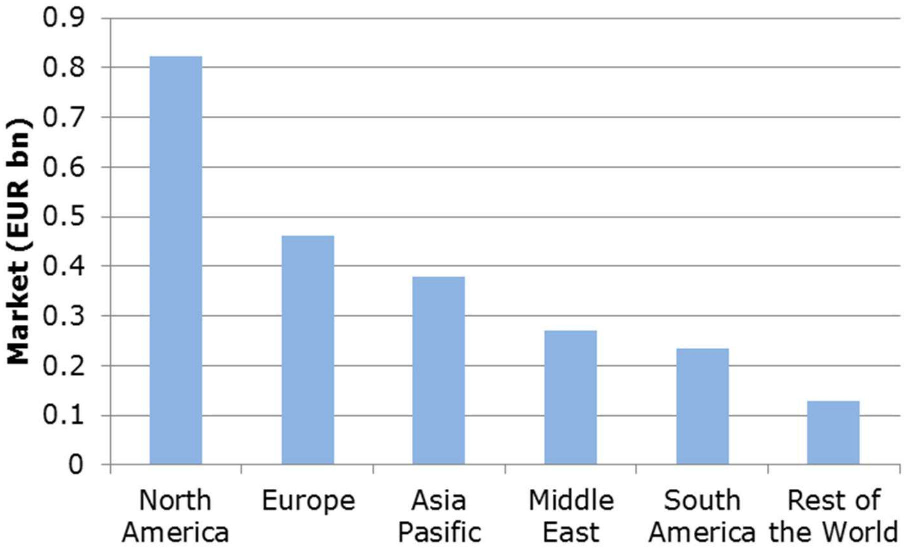


Source: JRC, 2018 based on (European Patent Office, 2018).

3 Market overview

Market analysis of the full CCUS value chain, i.e. capture, transportation with pipelines and storage, indicates that Europe holds the second highest market share in all CCUS elements following North America (**Figure 11**). Asia Pacific, Middle East and South America are following. Asia Pacific and Middle East can be seen as emerging since it is these regions which count the most projects in planning (Global CCS Institute, 2018b).

Figure 11. CCUS technologies market by region (2017)



Source: JRC, 2018 with data from (Accuray Research, 2018)

In Europe, the technology market did not progress as expected due to various (including economic) barriers, as well as issues of acceptance from the public (see also LCEO CCUS Technology Development Report (2018)). However, a study published recently (International CCS Knowldege Centre, 2018) indicates that, at least with regards to cost, significant reductions should be expected in CCUS projects. This claim is important as it comes from real life experience and lessons learned from an operational CCUS project.

Development can also be noted in small projects such as the activity at the municipality of Oslo to support to the Klemestrud project.[6] Adding carbon capture and storage in this district heating and waste management plant could permanently remove the associated GHG emissions.

The technology itself is considered mature for elements of capture, transport and storage, but apparently not yet ready move to a free market. The lack of clear incentives for implementing CCUS is one factor preventing the development of large-scale projects.

Half of the 18 CCUS projects in operation are linked with NG processing and 6 more are involved in chemical processes such as fertilizers or hydrogen production. As such, the majority of the CCUS projects operating worldwide contemplate EOR as

[6] https://www.fortum.no/fakta-om-prosjekt-ccs-pa-klemetsrud

final CO_2 destination. Having a "product", i.e. a revenue stream is particularly important in developing economic viability.

In the US, growing demand for clean technology together with supportive government initiatives are contributing to business growth. In the UAE, Masdar and ADNOC jointly supported a CCUS project in the steel industry that came into operation in 2016 (Global CCS Institute, 2017). The project has transformed a previously unwanted by-product of the industrial process into a valuable resource. Instead of using natural gas, captured CO_2 is used to support ADNOC's enhanced oil recovery plans.

In China, increasing deployment of fossil fuel fired power plants to cover electricity demand, along with growing awareness of the need to reduce carbon emissions, places carbon capture and storage in a prominent place regarding market potential.

In the UK growing demand for cost efficient technologies to achieve decarbonisation targets to reduce CO_2 emission in 2050 by 80% from 1990 level, as well as the recently launched Clean Growth Strategy (CCUS Cost Challenge Taskforce, 2018) could propel a CCUS market. At the end of 2018, the UK government pledged to spend an additional GBP 20 million (or EUR 22.5 million)[7] on Carbon Capture, Usage and Storage (CCUS) under its Clean Growth Action Plan, including the construction of the first CCUS emissions storage facility.

The majority of CCUS projects with well-developed business models are located in North America. In Europe, the biggest collective effort in creating a market was through the European Energy Programme for Recovery (EEPR). Six projects in different member states, located in Germany, Italy, the Netherlands, Poland, Spain and the UK were selected for funding. By 2017, and after the ROAD project announced it was abandoning plans for developing a full scale project, all EEPR projects are now cancelled.

Analysis on the most advanced projects at the time in Europe (Don Valley Power Project, Peterhead CCS Project and Rotterdam Opslag en Afvang Demonstratieproject (ROAD)) and in the US (Boundary Dam Carbon Capture and Storage Project, Illinois Industrial Carbon Capture and Storage (ICCS) Project, Petra Nova Carbon Capture Project and Texas Clean Energy Project) provided a useful overview of commercial developments (Kapetaki and Scowcroft, 2017): Carbon capture combined with enhanced oil recovery (EOR) as well as government support for example through 45Q incentives prescribed by US law to support CCUS projects, significantly promote market potential.

Contrary to North America, where there is a strong focus on revenues from CO_2 sales, European developers consider CCUS from a climate mitigation perspective. As such, projects have partly based their business cases on the CO_2 price. Within the EU, due to the insufficient price of the EU ETS allowances to generate enough savings for developers, the EU ETS has not succeeded yet to create a CCUS market. The recently revised EU ETS directive may be more efficient in supporting low carbon innovation, including CCUS initiatives.

[7] 1 GBP = 1.12515 EUR [Source: https://www.oanda.com/currency/converter/, accessed November 2019)

A previous CO_2 storage assessment (Global CCS Institute, 2016) concluded that the best site for CO_2 storage worldwide is the North Sea. This is mainly due to the wealth of geological data for the region as well as the existing oil and gas industry infrastructure.

CO_2 utilisation processes involve a number of products to be synthesised and the status of the associated technology varies. CDU can evolve towards a mature market if CO_2 is available, i.e. as by-product, or captured from sources such as industrial plants or from the atmosphere.

Despite the fact that ongoing initiatives have employed mature CCUS and CDU technologies, markets are still to be established. The market components follow the capture, transport, storage and utilisation elements and also consider the whole CCUS chain. Stakeholders can be clustered into the following groups:

- Fuel extractor
- Fuel transporter
- Plant owner and/or operator (industry, oil and gas companies or electricity and utilities companies)
- Capture plant owner and/or operator (industry, oil and gas companies or electricity and utilities companies)
- Technology supplier (equipment manufacturers, industrial gas companies or chemical companies)
- Pipeline/transport owner and/or operator
- Storage operator and monitoring
- Storage service provider
- Long term liability for the storage site (government)
- Start-ups and spin-offs for CDU business.

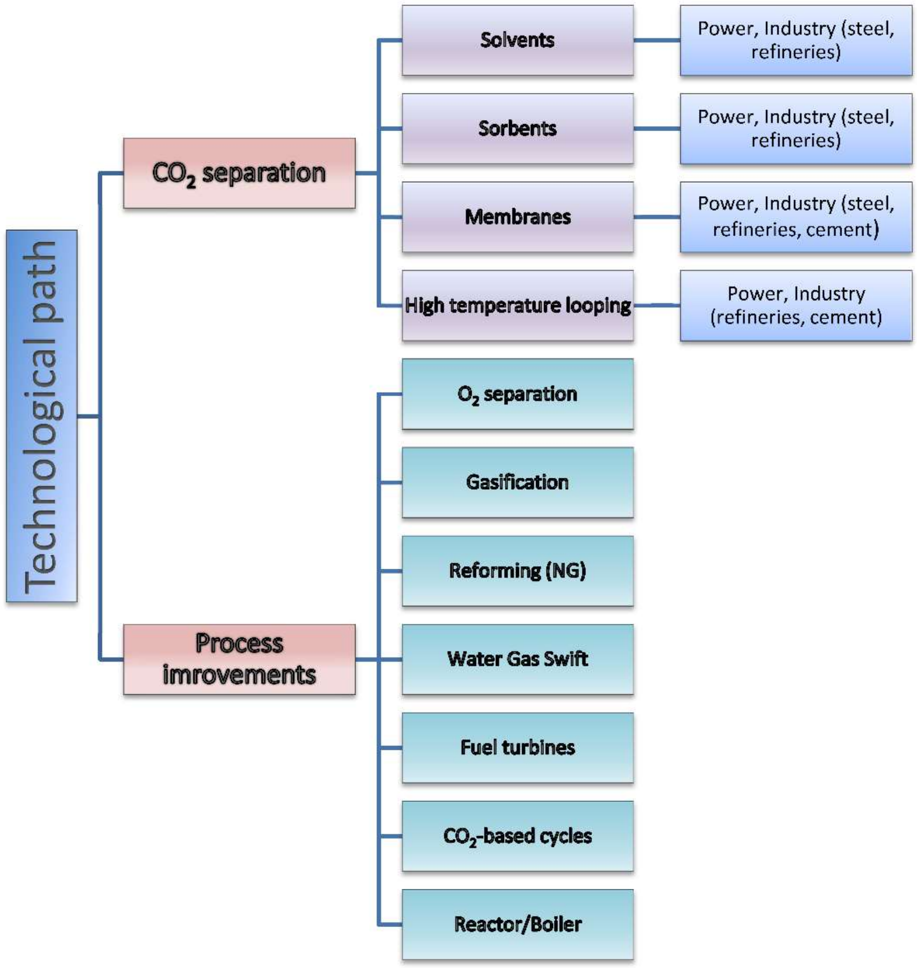
3.1 Carbon capture

The main company types involved are:

- Plant owner and/or operator
- Capture plant owner and/or operator
- Technology supplier
- Start-ups and spin-offs

Capture technologies and process improvements are mainly provided by equipment manufacturers, industrial gas and chemical companies. The key technological pathways are shown in Figure 12.

Figure 12. Key technological paths for CO_2 capture and improvements of upstream/downstream plant processes.



Source: JRC, 2018.

The following lists of technology providers are mainly based on the different research areas and focus, as described in the 2018 LCEO Technology Development Report (see **Figure 12**). While companies are also involved in prominent process improvements concerning gasifiers, H_2-rich fuel turbines and oxygen separation, this section will focus on the CO_2 separation technologies.

Table 1 presents relevant oil and gas companies and Table 2 lists the electricity and utilities companies, which have been involved in CO_2 capture even if briefly. Regarding oil and gas companies, Equinor (formerly Statoil), Shell and ExxonMobil have been the ones mostly active. Large oil and gas companies have mostly been involved in CCUS for commercial reasons, i.e. for obtaining a product (such as natural gas) that meets commercial specifications. Further interest is essentially related to the avoidance of their own CO_2 emissions. In 2016, the Oil and Gas Climate Initiative (OGI), made up of ten oil and gas companies, launched the OGCI Climate Investments.

Table 1 Main oil and gas companies associated with CO_2 capture (online information and (SBC Energy Institute and Schlumberger Business Consulting, 2012; Markets and Markets, 2013; VISIONGAIN, 2013; RESEARCHANDMARKETS, 2014; Accuray Research, 2018)).

EUROPE	COMMENTS	AMERICAS	COMMENTS
Shell (NL)	Commercialises and invests in solvents, sorbents and mineralisation.	ExxonMobil (US)	R&D activities on CCUS and in a new gas separation technology (the Controlled Freeze Zone)
BP (UK)	Involved in In-Salah and has collaborated in many R & D projects for capture.	Occidental Petroleum (US)	Feasibility study for a carbon capture project from ethanol to be used for EOR.
Equinor (Formerly Statoil) (NO)	It is particularly leading in capture from NG (for its own projects, like in NO and in DZ) using MEA solvent)	ConocoPhillips (US)	Mainly focused on gasifiers (E-Gas™) and integrated gasification projects.
		Petrobas (BR)	Developing the Lula project in BR, incorporating CO_2 separation from the oil fields.
		Honeywell's UOP (US)	Licencing Selexol™ process for carbon and sulphur capture (SeparALL process).

Table 2 Main electricity and utilities companies, that have been associated with power generation and CO_2 capture (online information and (SBC Energy Institute and Schlumberger Business Consulting, 2012; Markets and Markets, 2013; VISIONGAIN, 2013; RESEARCHANDMARKETS, 2014; Accuray Research, 2018)).

Europe	Americas	China	Others
Drax Group (UK)	Capital Power (US)	China Datang Corp	KEPCO (KR)
ENGIE (formerly GDF Suez, NL)	Chaparral Energy (US)	China Resources Power	CS Energy (AU)
Endesa (ES)	Chevron (US)	Dongguan Power	Tokyo Electric Power (JP)
Uniper (formerly E.ON, DE)	NRG Energy (US)	GreenGen	Tohoku Electric Power (JP)
Polish Energy Group (PGE) (PL)	SCS Energy (US)	Huaneng Power Group	Hokuriko Electric Power (JP)
SSE (UK)	Southern Company (US)	Shanxi International Energy Group (SIEG)	
Enel S.p.A. (IT)	Summit Power (US)	Sinopec	
RWE AG (DE)	SaskPower (CA)		
Scottish Power (UK)	Tenaska (US)		
Summit Power (UK)	TransAlta (CA)		
Vattenfall (SE)			

Beside CO_2 capture from point sources, start-ups and big companies alike are working to make CO_2 capture from air (direct air capture) both viable and profitable. These include: Global Thermostat (US), Carbon Engineering (CA), Climeworks, (CH), Skytree (NL), Infinitree (US).

In the long run, direct air capture has a real potential for technological development and could become a predominant technological option to remove CO_2 from the atmosphere (European Commission, 2018).

3.1.1 Chemical and physical absorption

Regarding carbon capture, amines have been widely used in the chemical industry with the first commercial scale plant in power generation being Boundary Dam in Canada operating since 2014. Secondary and tertiary amines may have lower efficiency penalty and costs, but they are classified as a following generation of commercial deployment in CO_2 capture methods. So far, oil and gas companies, utilities and equipment manufacturers have been the major players in the CO_2 capture industry but with smaller companies surfacing this landscape might change.

The following tables summarise the main suppliers of chemical absorption technologies. **Table 3** presents companies commercialising amine-based technologies. Suppliers limited to pilot plants have not been included.

Table 3. CO_2 capture with chemical absorption – (based on company webpages and (Duke *et al.*, 2010; EPRI, 2011; GCCSI, 2012; Rubin *et al.*, 2012; Markets and Markets, 2013; VISIONGAIN, 2013; RESEARCHANDMARKETS, 2014; Idem *et al.*, 2015; Stanger *et al.*, 2015)).

Company	**Technology**
Shell (NL)	Cansolv (aqueous amine solution)
Siemens (DE)	Second generation PostCap™ amino acid salt process
Hitachi (JP)	Amine-based H3-1 solvent
ABB (SE-CH)	Amine-based ABB Lummus Global Process
Mitsubishi Heavy Industries (MHI) (JP)	Amine-based MHI KM-CDR process that use KS-1™ amine
General Electric (GE) (US) with Dow Chemical (US)	Advanced amine process (AAP)
GE (US)	Chilled ammonia process (CAP)
Alstom (FR) and Dow Chemical (US)	Advanced amines (together with Dow Chemical) and chilled ammonia processes
Industrial gas companies	
Aker Solutions (NO)	Amine-based technology
Linde AG (DE)	Integrated capture of acid gases in pressure swing adsorption (PSA) technology
Chemical companies	
Fluor (US)	Fluor Econamine FG Plus™ and other MEA processes
Dow Chemical (US) and Alstom (FR)	Amine-based DOW UCARSOL™ FGC 3000
BASF (DE)	PuraTreat™ (amino acid based solvent/customisable)

The most common commercial physical solvents are Rectisol™, Purisol™ and Selexol™ (EPRI, 2011). Selexol™ solvent (licensed by Honeywell UOP (UOP, 2009)) is a mixture of dimethyl ethers of polyethylene glycol, and the Rectisol process (from Linde AG (Linde, 2016b)) uses methanol as solvent. The Purisol process is based on pyrrolidone and is licensed by Lurgi AG (Bryan Research & Engineering, 2009). Furthermore, companies such as Air Liquide offer more than one capture technology (Air Liquide, 2016).

Table 4. CO_2 capture with physical absorption – equipment manufacturers, industrial gas companies and chemical companies (online information and (EPRI, 2011; GSTC, 2014, 2016)).

COMPANY	TECHNOLOGY
Linde AG (DE)	Rectisol™
Air Liquide (FR)	Rectisol™ (Lurgi AG)
Lurgi AG (DE)	Purisol™
Honeywell UOP (US)	Selexol™
Sasol (ZA)	Fixed bed gasifiers

Note: Note that Air Liquide absorbed its subsidiary Lurgi AG in 2014, being Air Liquide Global E&C Solution.

3.1.2 Membranes

Membrane technologies for CO_2 capture are at various development stages and different companies are involved in relevant activities **Table 5**. Membranes for CO_2 separation have been applied to natural gas sweetening and numerous commercial membrane technologies have been available for this application. However, this does not necessarily ensure the feasibility of membranes for flue gas treatment because of several key differences between the two applications (Khalilpour *et al.*, 2015). While CO_2 separation with membrane can be considered a proven technology, the trade-off between its separation properties has been making it difficult to apply membrane technology commercially in large scale.

Table 5. CO_2 capture with membranes – equipment manufacturers, industrial gas companies and chemical companies (online information and (EPRI, 2011; GSTC, 2014, 2016), (Svec and Blinova, 2013)).

Company	Technology
Air Liquide (FR)	Membrane separation including methane
Air Products (US)	Ion transport ceramic membrane to electrochemically separate O_2
Eltron (US)	Membrane separation of H_2
Honeywell UOP (Various)	CO_2 separation (Separex)
MTR (US)	Membrane separation of H_2 and/or CO_2
Whitefox Technologies (UK, CA)	CO_2 separation

Note: Note that Air Liquide absorbed its subsidiary Lurgi AG in 2014, being Air Liquide Global E&C Solution.

3.1.3 High temperature looping

Activity in this technology features mainly, chemical and calcium looping combustion. O_2 separation processes with membranes and sorbents, and oxy-combustion process improvements, such as boiler design and CO_2 and water cycles, can be also included.

Table 6 provides the list of main actors. Currently air separation units (ASU) can be supplied by various companies, including Air Products (Air Products, 2016), Air Liquide and Linde AG (Linde, 2016a).

Table 6. CO_2 capture with high temperature looping and oxy-combustion – equipment manufacturers and industrial gas companies (online information and (EPRI, 2011; Stanger *et al.*, 2015)).

Company	**Technology**
Alstom (FR)	CLC – 3 MW_{th} prototype in Connecticut Boilers Gas cleaning units and integrated approaches
GE (US)	Boilers and gas cleaning units
Linde AG (DE)	Boilers
Babcock & Wilcox (BW) (US)	Boilers
Air Liquide (FR)	Boilers and CO_2 cryogenic purification units
Praxair (US) / Foster Wheeler (CH)	Boiler
NetPower (UK)	CO_2-based cycle
Clean Energy System (CES) Ltd (US)	Water-based CES cycle

3.2 CO_2 utilisation

CO_2 utilisation is emerging as a quite important sector in Europe, following North America. CO_2 use in agriculture, mainly in greenhouses, accounts for the majority of current activities. This is followed by CO_2 use as a feedstock for chemicals and polymers and for the production of secondary construction materials (Accuray Research, 2018).

Companies involved in CO_2 production for commercial purposes are Linde AG, Airgas, Praxair and Air Liquid. Additionally, CO_2 can result in from processes such as ammonia production, SNG production, ethyl alcohol production as well as from industrial activities as a by-product.

The CO_2 utilisation market may have different actors and business models. CO_2 may come from different sources, i.e. captured from a fixed source, captured from the atmosphere it can be naturally occurring CO_2, or CO_2 generated as by-product. Additionally, the synthesis of a CO_2-based product can be part of a renewable power plant as a means of using electricity production when demand or prices are low (I. González-Aparicio, Z. Kapetaki, 2018).

A number of companies consider using CO_2 as a way to reduce their overall CO_2 emissions and/or to reduce costs or increasing revenues. Examples of European companies active in this domain are given in **Table 7**. Companies such as Carbon Recycling International or Sunfire rely directly on CO_2 as a raw material.

Table 7. European companies that use or that are moving towards the use of captured CO_2 as raw material (source: Web pages of the companies, proceedings from (Bøwadt, Petrov and Marzano, 2015) and (SBC Energy Institute and Schlumberger Business Consulting, 2012; Bøwadt, Petrov and Marzano, 2015; Accuray Research, 2018)).

Company	**Country**	**Product**
Air Fuel Synthesis	UK	CO_2 capture from air and fuel synthesis
Arcelor Mittal	LU	Fuels and chemicals
Antecy	NL	CO_2 capture from air and fuels synthesis
Audi	DE	Methane
BASF	DE	Formic acid, methane
Bayer	DE	Polymers
Cambridge Carbon Capture	UK	Inorganic carbonates
Carbon 8	UK	Inorganic carbonates
Carbon Cycle	UK	Calcium Based Minerals, Gypsum, Chalk
Carbon Recycling International	IS	Methanol
Clariant	DE	Catalysts for methane and methanol synthesis
COVAL Energy	NL	Formic acid, carbon monoxide, methanol
Dioxide Materials	US	Fuels and chemicals
DNV GL	NO	Formic acid
E3Tec Service	US	Alkyl carbonates, dimethyl carbonate (DMC), mono-ethylene glycol.
Econic	UK	Polymers
Empower Materials	US	QPAC®25 poly(ethylene carbonate), QPAC®40 poly(propylene carbonate), QPAC®100poly(propylene/cyclohexene carbonate), QPAC®130 poly(cyclohexene carbonate), QPAC®60 poly(butylene carbonate)
EnPro	NO	Inorganic carbonates
GRTGaz	FR	Methane

Company	**Country**	**Product**
Haldor Topsoe	DK	Methanol
Integrated Carbon Sequestration Pty	AU	Ammonia-rich ammonium carbonate solution, carbonate rocks
Joule Unlimited	US	Hydrocarbon-based fuel, ethanol, jet fuel, gasoline, Sunflow-E, Sunflow-D
Lafarge	FR	Construction materials, CO_2 binder
Lanzatech	US	Fuel Ethanol, isopropanol, chemicals
Liquid light	US	Ethylene glycol, propylene, isopropanol, acetic acid
Linde	DE	Methanol, DME and urea
MBD Energy	AU	Water bioremediation, fertiliser and biochar, algal feed and food
Novacem	UK	Mineralisation
Novomer	US	Acrylic acid, polypropiolactone, polyhydroxylsx isocyanates,succinic anhydride and succinic acid, butanediol
Oakbio	US	Bioplastics, animal and aquafeed
Perlemax	UK	Microalgae
Repsol	ES	Fuels and chemicals, and artificial photosynthesis
Saipem	IT	Urea
Siemens	DE	Chemicals and fuels
Skyonic	US	Solid carbonate materials (sodium bicarbonate - baking soda), hydrochloric acid, and household bleach
Solidia	US	Solidia Concrete™, Solidia Cement
Solvay	BE	Fuels
Stamicarbon	NL	Urea
Sunfire	DE	Fuels
Synthomer	UK	Polymers
Thyssenkrupp	GE	Hydrocarbons, alcohols and chemicals
Total	FR	Fuels and chemicals
Viessman Group	DE	Methane

For CO_2 utilisation market, interest can be identified into power-to-X processes, producing gas or liquid fuels. However, penetration pathways of chemicals and materials are also ongoing and further analysis can be found in the CCUS Technology Development Report of the 2018 LCEO series (Kapetaki and Miranda-Barbosa, 2018).

One impediment to business development can be that CO_2 derived products and industries will have to compete in the market with already existing products synthesised from fossil fuels. Some issues relevant to taking up such activities may be:

- Profits might oscillate as a larger availability could decrease the price for currently commercially "valuable" products such as formic acid if it is substituted by a CO_2 derived product.
- CO_2 as a "raw material" requires setting a price but this may be different from what is needed to drive commercial profit or compensation within a CO_2 market.
- For the hydrogen required in some CO_2 utilisation processes low cost renewable electricity available in periods of over-supply will be necessary.
- Engaging consumers toward CO_2-based products will be a challenge. Consumers will not only have to embrace product changes but also be ready to take up the cost associated with "greener" products.
-

3.3 CO_2 storage, transport and monitoring

Currently, there are two CO_2 storage projects in Europe, both in Norway: the Sleipner Field, in the North Sea and Snøhvit, in the Barents Sea. In Salah project in Algeria led by European companies is currently closed for injection (Table 8).

Companies primarily involved in this sector are linked to the oil and gas industry but research organisations developing new CCUS technologies are in close collaboration with the industry. In Europe leading companies in the field include the Norwegian Equinor (formerly Statoil), followed by British-Dutch Shell, British BP, French Total. These companies are operating mainly in the North Sea where an enormous potential for CO_2 storage has been indicated (IEA, 2015a). The main criteria impacting the costs of CO_2 storage include location and type of storage sites, reservoir conditions and capacity as well as the size of the reservoir. Storing CO_2 onshore, in spaces with high level of injectivity or in depleted oil and gas fields can reduce the costs associated with CO_2 storage (ZEP, 2011).

CO_2 transport infrastructure will also be critical for large-scale CCUS project development. Combining CO_2 sources in close proximity, sharing CO_2 transport and storage infrastructure can facilitate development and business.

Table 8. European companies with CO_2 storage projects in Europe and Africa (Global CCS Institute, 2018b).

Project	**Companies**	**Country**	**CO_2 storage capacity (Mtpa)**	**Transport via**	**Storage type**
Sleipner	Statoil,Exxon Mobil and Total Norge	NO	0.85	Direct injection, no transport	Geological storage/offshore
Snøhvit	Statoil, Petoro, Total Norge GDF, RDW DEA Norge	NO	0.70	Pipeline	Geological Storage/Onshore to offshore
In Salah	Statoil BP, Sonatrach and Statoil	DZ	3.8 (from 2004-2011)	Pipeline	Geological Storage/Onshore

3.4 Emerging players and markets

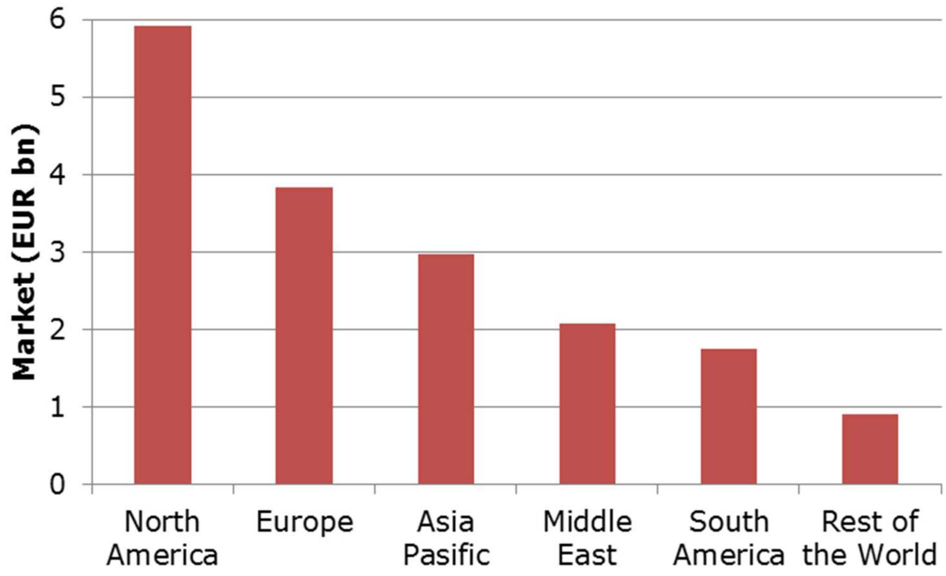
The CCUS project developers so far have mainly been companies that are large CO_2 emitters. Oil and gas companies were the first to enter CO_2 storage and have the longest history in CCUS projects. They have pioneered capture in gas processing plants, with the subsequent use of CO_2 for EOR (SBC Energy Institute and Schlumberger Business Consulting, 2012).

With regards to players and markets, Figure **13** indicates the current trend continuing toward the end of the 2020s on a regional level. North America is expected to continue leading on CCUS. The analysis assumes that the stringent US government regulation to curb greenhouse gas emission along with growing demand for clean energy will stimulate the carbon capture and storage market share. Specifically for the power generation sector, in 2015, under section 111 of clean air act, the U.S. Environmental Protection Agency introduced the New Source Performance Standards to limit carbon dioxide emission from natural gas-fired and coal-fired power plant. According to this standard, the new coal power plant cannot emit over 635 kg CO_2/MWh. Ability to reduce 85% to 90% of carbon emission is expected to make the adoption of CCUS preferable over other alternates (Accuray Research, 2018).

On specific countries, beside the Netherlands and Norway which are already established in CCUS, the UK, Germany and Italy are expected to become important players. Outside the EU, besides Canada and the US as well as Saudi Arabia and UAE and China which are already active in CCUS, emerging players are expected to be Japan, Brazil, South Africa as well as Argentina, India and Mexico (**Figure 14**).

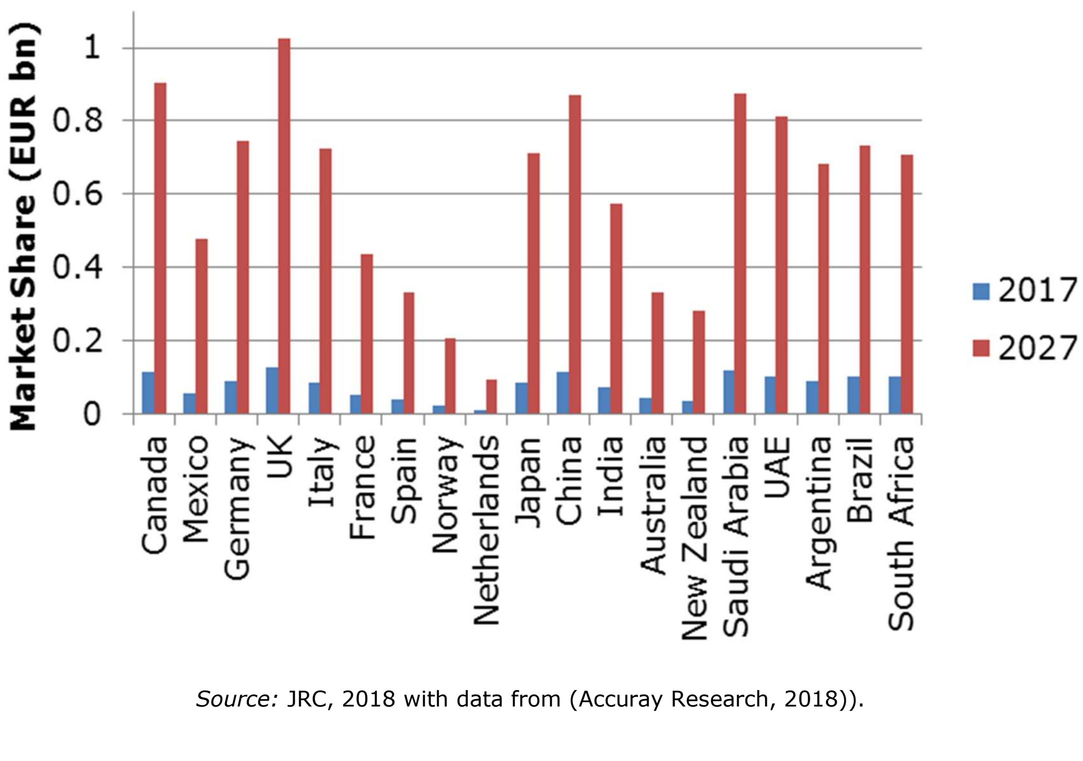
While Europe should not work in isolation from the leading countries in CCUS, such as Canada, USA, China, South Korea and Japan, the development of large scale projects in the region will be key to avoid disadvantaging EU industries in the short and medium term

Figure 13. CCUS technologies forecast by region toward 2027



Source: JRC, 2018 with data from (Accuray Research, 2018)).

Figure 14. CCUS technologies market and forecast by country (analysis with data from (Accuray Research, 2018))



Source: JRC, 2018 with data from (Accuray Research, 2018)).

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3.5 Industrial strategies and business models for CCUS projects

CCUS projects use a range of business models to address the needs the different actors present in the value chain. With the exception of large oil and gas companies, few plant owners have the capacity to manage storage, due to the need for detailed geological data.

In 2014, ZEP identified three distinct business models for the three stages of market development, i.e. demonstration, pre-commercial and mature industry (ZEP (Zero emissions Platform), 2014):

1. 'Contractor to the State' is effective before an established incentive mechanism exists and when market failure requires state support. Public funding is divided into smaller, project-size pieces, determined on a case-by-case basis.

2. An 'Enabled Market' comprises public support in some parts of the market, managed competition in others. It consists of a regulated entity (the 'Market Maker') which removes counterparty risk by a) Managing the development of primary infrastructure on behalf of the state (trunk pipeline + backup storage site) and b) Having a duty to take all captured CO_2 and ensure corresponding storage is available.

3. Private companies develop and manage pipelines, hubs and storage sites without specific state intervention in a 'Liberalised Market'.

Nevertheless, only the first model has been successfully implemented for the North Sea region. Uncertainty on access to financing, supply chain, as well as acceptance from the public has delayed progress of CCUS projects and consequently, a CCUS market creation.

For companies developing capture technologies, along with industrial expansion, contract agreements and merger and acquisitions (RESEARCHANDMARKETS, 2014), the creation of a new CO_2 commodity industry for use in enhanced oil recovery (EOR), bio-refining, and other products can be an additional driver in the major strategies.

Analysis presenting "real" life experiences in business models indicated that in developing CCUS (Kapetaki and Scowcroft, 2017) some lessons learnt include that:

- public funding support and alignment of government and industry (short-term) objectives are crucial;
- Developing hubs and clusters and exploiting economies of scale is very important;
- Maintaining simultaneous progress throughout the CCUS chain is challenging;
- It is particularly important to secure options to support OPEX while CAPEX could be funded by public sources;
- Combining activities with CO_2 utilisation, such as in greenhouse networks (NL) or EOR (US) can be beneficial;

- Extra revenues (for example from co-generation or polygeneration when using a gasification plant) and selling of by-products other than CO_2, e.g. sulphuric acid and fly ash can also be an advantage toward project development.

In November 2018, OGCI Climate Investments announced that it is entering into a strategic partnership with BP, ENI, Equinor, Occidental Petroleum, Shell and Total to progress the Clean Gas Project, the UK's first commercial full-chain CCUS project in Teesside. The Clean Gas Project, expected to be operational by mid-2020s will use natural gas to generate power, with the CO_2 captured and transported by pipeline for storage in the Southern North Sea.

This is the first step of creating a market in regions such as in Teesside where the infrastructure created would enable developing industrial clusters to capture and store CO_2 by sharing risks and costs. With CO_2 readily available, CO_2 utilisation companies could also be incentivised to join such clusters, revitalizing the hosting regions with new technologies and investment.

4 Market outlook

4.1 Outlook for future developments

The cost associated with CCUS remains a main barrier to large scale deployment. Collected information for associated costs from various studies (Rubin, E. S., Davison, J. E., & Herzog, 2015) indicate a mean range of EUR 35-67 (USD 46-87) for every tonne of CO_2 avoided in different power generation options.[8] For different industrial installations, the range is indicated at EUR 24-72 per tonne of CO_2 avoided (ZEP, 2015). In a more recent report the cost of CO_2 avoided presented for cement ranges from EUR 34-317 (USD 38-348) per tonne and EUR 31-122 (USD 34-135) for iron and steel industries (IEAGHG, 2018).[9] Different production routes as well as capture technologies and configurations result in a broad range of CO_2 avoided costs.

CCUS is also often interlinked with the continuation of coal use, stemming from the perception that CCUS is only applicable to power generation. Lack of public acceptance has been another factor causing delays or preventing CCUS developments.

Even if CCUS development did not proceed as anticipated, currently there are eighteen operational large scale CCUS projects in the world, three more than the last report LCEO Technology Market in 2016 (Global CCS Institute, 2018b). The main countries developing these technologies are US, Canada and Norway. China has six projects in the planning pipeline and with two in construction, expects to have its first demonstration project as early as 2019.

Within IEA 2DS scenario including data for ~600 Mtpa of “negative emissions” from BECCS, the IEA estimates that 3,800 Mtpa of CO_2 will need to be captured by 2040. Even though 20 projects are planned in total, which could amount to a capture capacity of nearly 34 million tons per year, this is still far lower than that necessary to achieve our climate goals (Global CCS Institute, 2017).

Modelling results published supporting the European Commission's Communication on a European strategic long-term vision, indicate that CCUS will be indispensable in the scenarios that target to the highest GHG reductions scenarios. These are to contribute to Paris Agreement goal of pursuing efforts to limit to a 1.5°C temperature change, translated to a target of around -100% GHG (including sinks), i.e. net zero GHG emissions in 2050 (European Commission, 2018).

In Europe some projects that have already started or are in their initial phases, could be accelerated by a clear business opportunity besides addressing climate change. Developing CCUS through infrastructure such as hubs and clusters with the active involvement of MS could further promote the market.

To examine the technology under different scenarios, the JRC-EU-TIMES results include CCUS in the model.[10]

[8] Original values in 2013 USD (1 EUR = 1.301 USD).

[9] Original values in 2016 USD (1 EUR = 1.108 USD, Source: Oanda.com).

[10] Further description about the JRC-EU-TIMES model is available in the dedicated report produced under the LCEO project deliverable 4.7 (Nijs *et al.*, 2018).

The core scenarios are:

- Baseline: Continuation of current trends; no ambitious carbon policy outside of Europe; only 48 % CO_2 reduction by 2050.
- Diversified (Div): Usage of all known supply, efficiency and mitigation options (including CCUS and new nuclear plants); 2050 CO_2 reduction target is achieved.
- ProRES (RES): 80 % CO_2 reduction by 2050; no new nuclear; no CCUS.

Outlook up to 2030

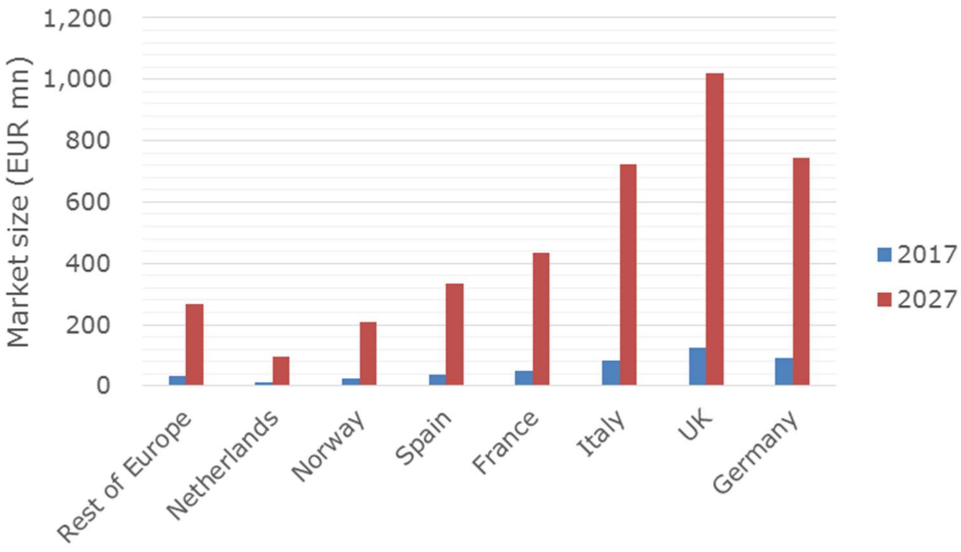
According the JRC-EU-TIMES modelling results, assuming that the goal is to achieve emission reductions of 80% compared to 1990 levels with fossil fuels and nuclear energy participating in the technology mix (Diversified scenario (Div1), CCUS is expected to start taking up in the power and industry sectors by 2030. In this context, EUR 15 billion of total investments in these different sectors will be needed by 2030. For CCUS in industry, JRC-EU-TIMES projects investments in the range of market forecasts (Accuray Research, 2018), i.e. ~EUR 2 billion (JRC-EU-TIMES) and ~EUR 2.5 billion (Accuray Reseach) respectively. When it comes to power generation, the Accuray market forecast predicts more than 3 times more investments by 2030 than JRC-EU-TIMES. This can be attributed to the fact that that JRC-EU-TIMES is looking at options to achieve specific targets for climate change mitigation cost effectively with renewable resources whereas market analysis assumes that the power sector will opt for carbon capture and offshore CO_2 storage in the North Sea. In JRC-EU-TIMES there is still a strongly increasing CCUS market however not in the "expected" markets of power and industry. More than 60 Mton of CO_2 is captured from the production of biofuels and hydrogen.

Zooming in specific regions and countries, market forecasts indicate an expectation for the CCUS technologies market to grow by a factor of up to 8 by 2027 (**Figure 15**). 12% of this growth is expected in industrial applications. In 2017, the UK noted the largest market revenue. By 2027 the CCUS market is expected to grow in Italy, Germany France and Spain (Accuray Research, 2018). The JRC-EU-TIMES also foresees CCUS developments in France and Spain by 2030, where the CO_2 is captured from biofuel and hydrogen production. In the Diversified scenario this CO_2 is being stored permanently, in the ProRES scenario this CO_2 is reused.

Outlook beyond 2030

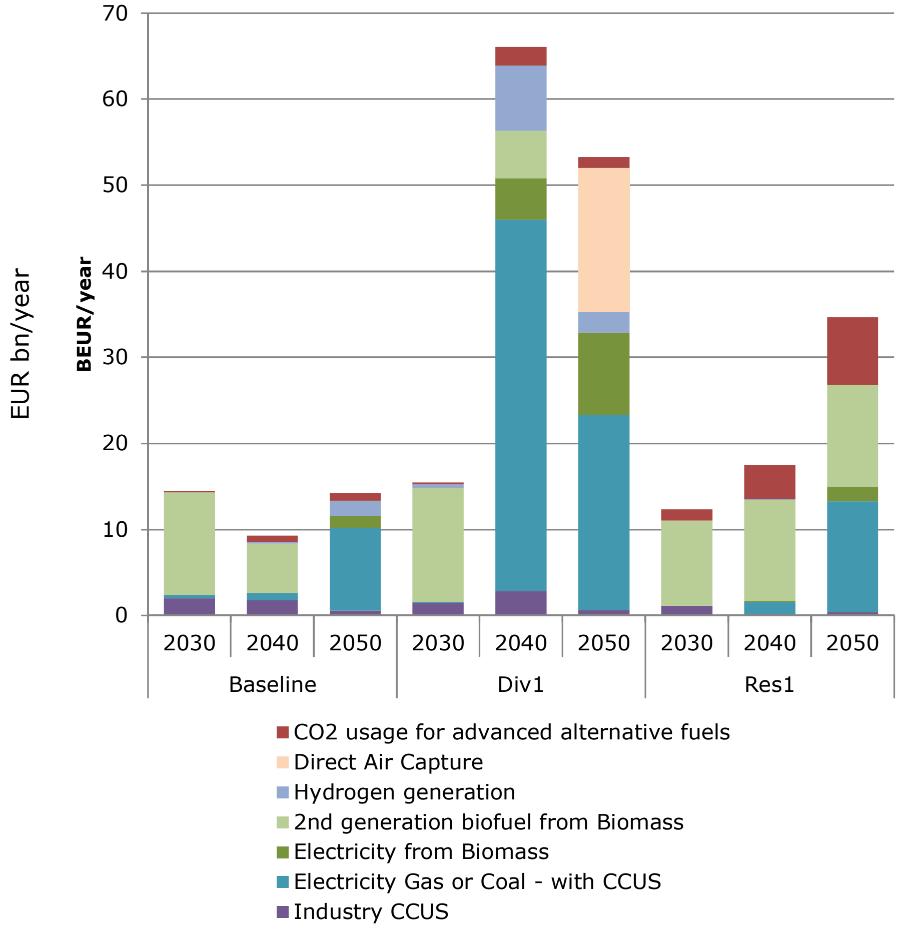
After 2030, the power and industry sectors provide a large market in the results of the diversified scenario of JRC-EU-TIMES. Including all forms of CCUS, the market goes up to almost EUR 65 billion by 2040. By 2050, almost 60% of the total CO_2 is captured in the diversified scenario (more than 1 000 Mton per year). CCUS markets scale up rapidly within the production of power and the production of 2nd generation biofuels, for example ethanol via fermentation or diesel via gasification and CO_2 removal. In a pro renewables world (Res1) with no option to permanently store CO_2, it is still captured (mainly from 2nd generation biofuel production) and reused for kerosene production.

Figure 15. CCUS technologies market and forecast by European country



Source: JRC, 2018 adapted from (Accuray Research, 2018).

Figure 16. Annual investments for CCUS related activities in different sectors according to JRC-EU-TIMES



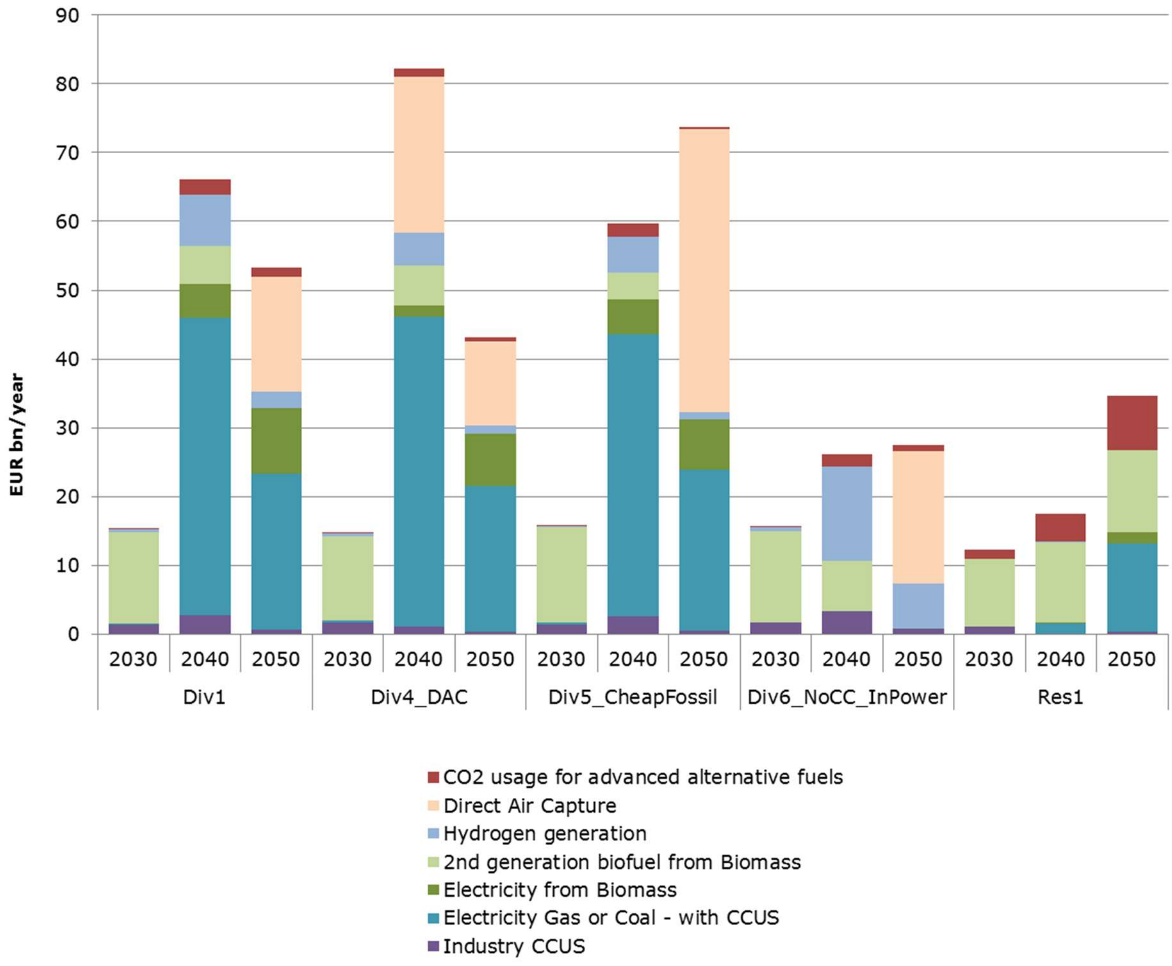
Source: JRC, 2018 (Nijs *et al.*, 2018).

4.2 Deployment under different scenarios

Within the JRC-EU-TIMES modelling activity sensitivities have been designed on three levels: technology cost learning rates, resources and policies. While in Res scenarios, no CCUS is included in the mix, in the Diversified scenarios (Div), CCUS is considered. The Div4 sensitivity scenario puts Direct Air Capture (DAC) earlier in the mix, while Div5 assumes that fossil fuels prices drop radically by 2050 and in Div6 CCUS is not used in the power industry (**Figure 17**).

For 2030 the projected investment needs follow a similar trend. Differences become evident by 2040 with particularly high projected investments needs in the scenario where DAC is considered (Div4). Capturing approximately 338 Mton/year of CO_2 corresponds to an investment of nearly EUR 23 billion. This changes by 2050, when for capturing 580 Mtons of CO_2 investments of nearly EUR 12 billion are needed, reflecting cost reductions from technology deployment and capacity deployment.

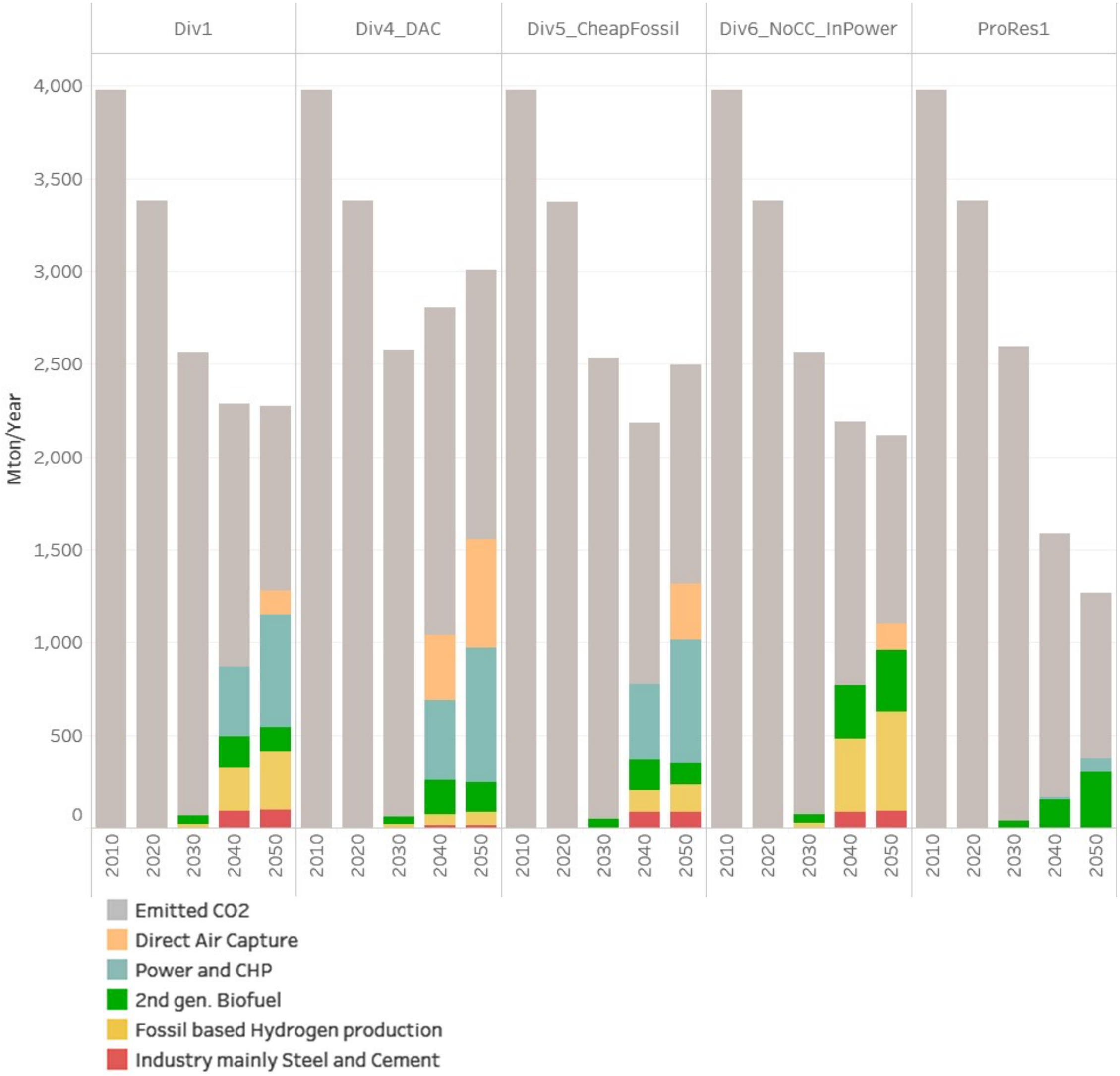
Figure 17. Sensitivities for CCUS according to JRC-EU-TIMES



Source: JRC, 2018 (Nijs *et al.*, 2018).

In a scenario where fossil fuel prices drop significantly (Div5), the majority of investments by 2040 emerge in the electricity sector (gas or coal) with around EUR 30 billion projected for capturing nearly 300 Mtons of CO_2. Assuming that carbon capture is not deployed in the power sector (Div6), more CO_2 will need to be captured from fossil based hydrogen production, i.e. coal gasification and steam methane reforming, and 2nd generation biofuel production. Without CCUS in the mix (ProRES), the CO_2 captured is notably smaller (**Figure 18**). However, in the scenario where there is no option to permanently store CO_2 under the ground (Res1), more than 400 Mton/year CO_2 is still captured and reused. The main use of this CO_2 is the production of diesel/kerosene by combining hydrogen and CO_2. Based on this result, deployment on these areas (fuel and hydrogen production) can be expected.

Figure 18. Emitted and captured CO_2 emissions according to JRC-EU-TIMES



Source: JRC, 2018 (Nijs *et al.*, 2018).

4.3 Key sensitivities and barriers to market expansion

In more than 20 years of experience with CCUS projects, technologies have improved and numerous projects have come online. However, the progress has been too slow for large scale CCUS deployment required to support the emissions reductions necessary to limit global temperature increase according to globally agreed targets.

The role of CCUS has been highlighted by international organisations and fora such as the Intergovernmental Panel of Climate Change (IPCC), the Carbon Sequestration Leadership Forum (CSLF), the International Energy Agency (IEA), and Mission Innovation etc. Yet, these calls have not been accompanied by commensurate support for the technology (Lipponen *et al.*, 2017). Often referred to as "lack of investor confidence", private sector companies appear either unwilling to or unsure of pursuing CCUS projects.

The impact of commitment on a political and policy level can be illustrated with a CCUS flashback through the years. Between 2007 and 2010, major funding programmes for large-scale projects had been announced in Australia, Canada, Europe (the United Kingdom in particular) and the United States (Lipponen *et al.*, 2017). By 2010, the total of announced global support for CCUS projects had exceeded USD 31 billion or approximately EUR 27 billion[11] (Global CCS Institute, 2010). This funding was expected to support up to 35 large-scale projects (IEA, 2016). However, commitment and financial support were not sustained at the initial level. In the period between 2009-2014, less than USD 3 billion or EUR 2.65 billion was actually invested in projects (Lipponen *et al.*, 2017). Such lack of commitment not only slows down technological progress but also delays the creation of an actual market discouraging any players that would potentially opt in.

With regards to full chain large scale CCUS projects, getting into a race for implementation in the power sector inevitably resulted in comparisons with alternative low emission solutions. Significant penetration and cost reductions achieved in alternative low emission solutions, including renewables and energy efficiency, have fuelled a perception that "CCUS is expensive, not required, or will only be needed in the long term" (Lipponen *et al.*, 2017).

Deploying large-scale CCUS projects has proven to be more challenging, expensive, and time demanding than anticipated. As such, companies originally involved with the technology have since withdrawn from pursuing CCUS projects, condensing even more the already small market, while others did not even enter the race. The number of large-scale projects globally which have been proposed but have failed to progress to operation outnumbers the successful projects by a factor of two to one (IEA, 2016).

First-of-a-kind CCUS projects have been complex and expensive, particularly when capital investment in new CO_2 transport and storage infrastructure is required. Early CCUS projects also have higher operating costs. For projects in the power sector, this can have implications also on the electricity prices.

[11] 1 USD = 0.88492 EUR (Source: https://www.oanda.com/currency/converter/). Please note that conversions from USD to EUR throughout the document are only indicative and do not consider inflation and currency exchange trends.

The following tables provide a SWOT analysis (strengths, weaknesses, opportunities, threats) for each segment, including CO_2 utilisation.

For CO_2 utilisation processes, uncertainties such as the associated cost, the ability to compete with established products and processes, consumers' perceptions as well as the lack of specific funding and policy incentives have not been able to support a relevant market which has been primarily driven by private initiatives.

Table 9. CO_2 capture SWOT analysis.

Strengths	**Weaknesses**
• It is proven with two long-running capture projects in Norway. • Many European oil and gas companies, electricity providers, equipment manufacturers, industrial gas and chemical companies with project experience. • R&D in progress for first, second and third generation capture methods.	• CO_2 capture through amines (the commercially advanced technology) penalises power plant efficiency and needs significant investment. • Most expensive stage of the CCUS value chain. • Lack of a clear business case (for the overall management of the whole CCUS chain). • Project risks for CO_2 capture combined with transport and storage.
Opportunities	**Threats**
• Fossil fuel power plants and industrial facilities with CCUS can decrease CO_2 emissions at an affordable cost according to many modelling results. • Fossil fuel power plants may be operated as "load-following" plants, addressing the needs of an electricity grid with a large share of renewables. • Carbon price resulting from the revised EU ETS (becoming sufficiently high may promote business and technology developments). • NG plants in the European electricity generation sector; commissioned after year 2000 may be appropriate candidates to use this advanced technology.	• Uncertainty in funding, which companies see as a risk regarding possible investment. • Competition from other potential zero emission sources such as renewables. • With many countries planning to phase out coal, implementation in the power sector is becoming more and more challenging. • Additional costs and complexity may bring up issues of carbon leakage, particularly in the most sensitive industry sectors.

Table 10. CO_2 utilisation SWOT analysis.

Strengths	**Weaknesses**
• Use of anthropogenic CO_2 as a raw material supporting the concept of a circular economy. • Potentially lower CO_2 emissions than the conventional fossil fuel-based process.* • Possible decreased dependency on fossil fuels.* • Several companies already active in commercialisation of CO_2-based products; • European companies are fairly advanced in terms of the use of CO_2 as raw material.	• Lack of a harmonised and generally agreed methodology to estimate environmental benefits. • Questionable CO_2 retention potential (except for mineralisation). • Need a source of captured CO_2 (either from fixed sources or from the atmosphere). • Some processes need H_2 as raw material; as a result low carbon electricity needs may be high. • R&D still needed to develop more efficient processes and to achieve cheaper configurations. Many current CDU processes have low TRLs.
Opportunities	**Threats**
• Can support European industrial rejuvenation. • CDU processes can promote a circular economy. • The need of renewables for alternative means of "storing" energy. • H_2 storage through a liquid carrier.	• Currently inadequate carbon price and other policy strategies to incentivise the development of CDU processes. • Lack of CO_2 transport infrastructure. • Public acceptance.

* Life cycle analyses will be required to support this argument.

Table 11. CO_2 storage, transport and monitoring SWOT analysis.

Strengths	**Weaknesses**
• Technology in place developed for large-scale demonstration. • Infrastructure from oil and gas industry. • Existing geological knowledge and assessment methods. • Well-developed transport infrastructure in Europe, via pipelines.	• Lack of knowledge dissemination. • European CO_2 storage atlas not yet developed. • Non-harmonised calculation methods for CO_2 storage capacity across different regions. • Lack of specific CO_2 transport regulations. • Monitoring requires several techniques, with associated increased costs. • Accuracy of new monitoring techniques to be verified. • Low level of public acceptance for onshore operations.
Opportunities	**Threats**
• Large CO_2 storage capacity in Europe, especially in the North Sea. • Possibilities to store CO_2 in basalts can be an alternative in certain geological conditions. • Captured CO_2 needs to be stored in order to reduce emissions. • Combined CO_2 and EOR can attract investments from industry • Hybrid system of CO_2 transport involving pipeline and ship can reduce costs (currently in the testing phase). • Synergy with other renewables, such as geothermal energy, can reduce costs and increase the efficiency.	• Current low investment. • Carbon tax does not stimulate new funding. • Low public acceptance, in particular for onshore storage. • Lack of specific regulations on CO_2 storage and transport.

5 Final remarks

In Europe, demonstrating the feasibility of the complete CCUS chain on a large scale remains a challenge and a CCUS market has not materialised so far. The main instrument to incentivise CCUS development has been through the EU ETS but prior to its reform and the EUA price was particularly low for a long time. Since then, it has seen a considerable increase which may give the necessary incentive for CCUS development. Alternatively, new business models may consider selling captured CO_2 in markets outside the EU ETS, as well as trading of by-products, such as fly ashes, for further use.

Oil and gas companies' interest on CCUS, indicated also by their patenting activity, is maintained, not least to manage their own CO_2 emissions. In the power sector, interest is not expected to increase, for various reasons, including many plants reaching retirement age, planned and announced phase outs from coal for many MSs as well as carbon allowance prices, so far inadequate to justify investment in carbon capture. Modelling results and market forecasts foresee growth for CCUS in industry even by 2030.

Developing more efficient and cheaper capture methods will increase the economic feasibility of the technology and its implementation. In this context, there might be a business opportunity, even niche, for the European CO_2 capture providers. The patenting activity showing on-going R&D effort is possibly an indication of the interest to address this issue for capture technologies.

CO_2 utilisation processes becoming mainstream may provide a motive to create a CO_2 trading market, incentivising CO_2 capture, with captured CO_2 becoming a revenue opportunity. A market for CO_2-synthesised products can, in turn, incentivise CO_2 capture as a technological pathway. The specific business models will depend on the synthesis processes, market value, marketing strategies etc. From a climate perspective, synergies with renewable sources of electricity are crucial and necessary particularly for processes that use H_2 as feedstock. On the business side though, the renewable energy producers will need to have a sufficient incentive to decide directing power for CO_2 utilisation rather than the electricity market.

Combining CO_2 and EOR has facilitated projects globally to progress faster and create a viable business case. Due to large scale CO_2 EOR applications North America has been a pioneer and is expected to continue leading on CCUS. The focus in Europe has been primarily in geological CO_2 storage but the various different methods used complicate the estimation of total capacity. The associated uncertainty impedes businesses to opt for getting involved in CO_2 storage activities and accurate estimations are needed to tackle this impediment. Linking CO_2 sources to clusters of sinks by creating CO_2 networks will be an option for risk and cost sharing taking advantage of economies of scale and overcome associated barriers holding back large scale CCUS deployment.

Rapid development can be achieved in industry sectors where CO_2 is already separated as part of the production processes becoming the "low hanging fruit" for market development.

Experiences gained in more than 20 years of CCUS development indicate that having a tangible, quantifiable incentive (revenue stream, profit, tax relief etc.) is necessary for creating a market that would support further development and vice versa.

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Abbreviations and definitions

AAP	Advanced amine process
CAPEX	Capital expenditure
CAP	Chilled ammonia process
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
CDU	Carbon dioxide utilisation
CLC	Calcium looping combustion
COP21	Conference on climate change Paris, 2015
EOR	Enhanced oil recovery
EC	European Commission
EU	European Union
FID	Final investment decision
FP	Framework Programme
GE	General Electric
GHG	Greenhouse Gas
H2020	Horizon 2020 Programme
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
MEA	Monoethanolamine
MHI	Mitsubishi Heavy Industries
MS	Member State
NG	Natural gas
NGCC	Natural gas combined cycle
OPEX	Operating expenditure
PSA	Pressure swing adsorption
ROAD	Rotterdam Opslag en Afvang Demonstratieproject
R&D	Research and Development
SEWGS	Sorption enhanced water gas shift process
TRL	Technology Readiness Level
ZEP	Zero emissions platform

Country abbreviations used in this report

AT	Austria
AU	Australia
BE	Belgium
BG	Bulgaria
CA	Canada
CH	Switzerland
CN	China
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
DZ	Algeria
EE	Estonia
EL	Greece
ES	Spain
FI	Finland
FR	France
HR	Croatia
HU	Hungary
IE	Ireland
IS	Iceland
IT	Italy
JP	Japan
KR	South Korea
LI	Liechtenstein
LT	Lithuania
LU	Luxembourg
LV	Latvia
MT	Malta
NO	Norway
NL	Netherlands
PL	Poland
PT	Portugal
RO	Romania

SE	Sweden
SI	Slovenia
SK	Slovakia
UAE	United Arab Emirates
UK	United Kingdom
US	United States
ZA	South Africa

Annexes

Annex 1. European SET plan for CCUS – Action 9

Targets for CCS and CCU under the SET-Plan Action 9

The agreed specific targets addressed in this Implementation Plan have been defined in the Declaration of Intent under SET Plan Action 9:

Target 1: At least one commercial-scale, whole chain CCS project operating in the power sector

Target 2: At least one commercial scale CCS project linked to an industrial CO_2 source, having completed a FEED study

Target 3: SET Plan countries having completed, if appropriate in regional cooperation with other MS, feasibility studies on applying CCS to a set of clusters of major industrial and other CO_2 sources by 2025-2030, if applicable involving cooperation across borders for transporting and storing CO_2 (at least 5 clusters in different regions of the EU)

Target 4: At least 1 active EU Project of Common Interest (PCI) for CO_2 transport infrastructure, for example related to storage in the North Sea

Target 5: An up-to-date and detailed inventory of the most suitable and cost-effective geological storage capacity (based on agreed methodology), identified and accepted by various national authorities in Europe

Target 6: At least 3 pilots on promising new capture technologies, and at least one to test the potential of sustainable Bio-CCS at TRL 6-7 study

Target 7: At least 3 new CO_2 storage pilots in preparation or operating in different settings

Target 8: At least 3 new pilots on promising new technologies for the production of fuels, value added chemicals and/or other products from captured CO_2

Target 9: Setup of 1 Important Project of Common European Interest (IPCEI) for demonstration of different aspects of industrial CCU, possibly in the form of Industrial Symbiosis

Target 10: By 2020, Member States having delivered as part of the Energy Union Governance their integrated national energy and climate plans for after 2020, and having identified the needs to modernise their energy system including, if applicable, the need to apply CCS to fossil fuel power plants and/or energy and carbon intensive industries in order to make their energy systems compatible with the 2050 long-term emission targets

Research & Innovation Activities

The SET-PLAN TWG9 has identified 8 Research and Innovation 'R&I' Activities required to deliver the 10 agreed targets listed under the Declaration of Intent on strategic targets in the context of Action 9 'Renewing efforts to demonstrate carbon capture and storage (CCS) in the EU and developing sustainable solutions for carbon capture and use (CCU)'. The actions contained under each of the R&I activities comprise of ongoing projects, in addition to proposals for additional actions required to meet targets.

R&I activities outlined in detail within this paper, and summarised below:

R&I Activity 1: Delivery of a whole chain CCS project operating in the power sector (target 1)

R&I Activity 2: Delivery of regional CCS and CCU clusters, including feasibility for a European hydrogen infrastructure (targets 2 & 3 and 10)

R&I Activity 3: EU Projects of Common Interest for CO_2 transport infrastructure (target 4)

R&I Activity 4: Establish a European CO_2 Storage Atlas (target 5)

R&I Activity 5: Unlocking European Storage capacity (target 7)

R&I Activity 6: Developing next-generation CO_2 capture technologies (target 6)

R&I Activity 7: CCU Action (targets 8 & 9)

R&I Activity 8: Understanding and communicating the role of CCS and CCU in meeting European and national energy and climate change goals (target 10)

These R&I activities outline the actions required to meet the 2020 targets. However, further CCUS development post-2020 is also required. Comprehensive R&I activities need to take place now in order to reach the Key Performance Indicators for 2030 listed in the Declaration of Intent under SET Plan Action 9. Ambitious R&D activities are already taking place under Horizon 2020, the ERA NET Co-fund ACT[12] and within national R&D programmes in several Member States. Furthermore, R&D infrastructure is built and operated in the ESFRI project ECCSEL[13], which has now proceeded to become a European Research Infrastructure Consortium (ERIC). All these activities should be strengthened onwards to 2020 in order to reach long-term CCUS ambitions.

Flagship activities

A number of Flagship Activities have been proposed, defined under the SET Plan Common Principles as a best example of how an R&I activity may deliver targets. 5 Flagship activities have been identified:

Flagship activity: Establish a CCS hub/cluster (including projects in the Netherlands, Norway and/or the UK)

A number of CCS clusters are currently being progressed in SET-Plan countries, linking a range of CO_2 emissions-intensive industries. These clusters may also be supported by the development of pan-European CO_2 infrastructure through the establishment of a Project of Common Interest (PCI).

Flagship project: Fos-Berre/Marseille CCU cluster

The Fos-Berre/Marseille CCU cluster aims to offer a supporting scheme for high-emitting industries in the region to reduce their CO_2 emissions, developing a wide range of CCU technologies, including chemicals, material and fuel production, and supported through industrial and public funding partnerships. A feasibility study was completed in 2013 with the aim of finding synergies between industrial emitters and potential CCU pathways, sustaining the industries in the area by reducing their CO_2 emissions. At present, the cluster will focuses solely on CCU aspects; however, there are also plans to evaluate the potential opportunities for offshore storage in the future. The initial study was based on a collection of emission data and an analysis of the evolution scenarios of the various industrial sectors in the Fos-Berre-Beaucaire-Gardanne area and the infrastructure required (pipeline collecting CO_2 from different sources and feeding different applications).

[12] ACT – Accelerating CCS Technologies, www.act-ccs.eu

[13] ECCSEL – European Carbon Dioxide Capture and Storage Laboratories Infrastructure, www.eccsel.org

Flagship activity: Progress Projects of Common Interest (PCIs)

The establishment of a Projects of Common Interest (PCI) under the 2017 European Commission call may act as a starting point for a European CO_2 transport infrastructure network, also supporting the development of regional CCS and CCU clusters.

Flagship activity: Establish a European CO_2 Storage Atlas

The establishment of a European CO_2 Storage Atlas will assist project developers and relevant permitting authorities to prioritise the most prospective areas for both onshore and offshore CO_2 storage, and will enable the design and development of transport infrastructure to be optimised.

Flagship Activity: Storage appraisal

Storage appraisal activities will build on the prospecting opportunities identified in the European CO_2 Storage Atlas, with the aim of expanding European experience of CO_2 storage, considering geographical balance, in addition to a range of storage options and injection volumes.

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