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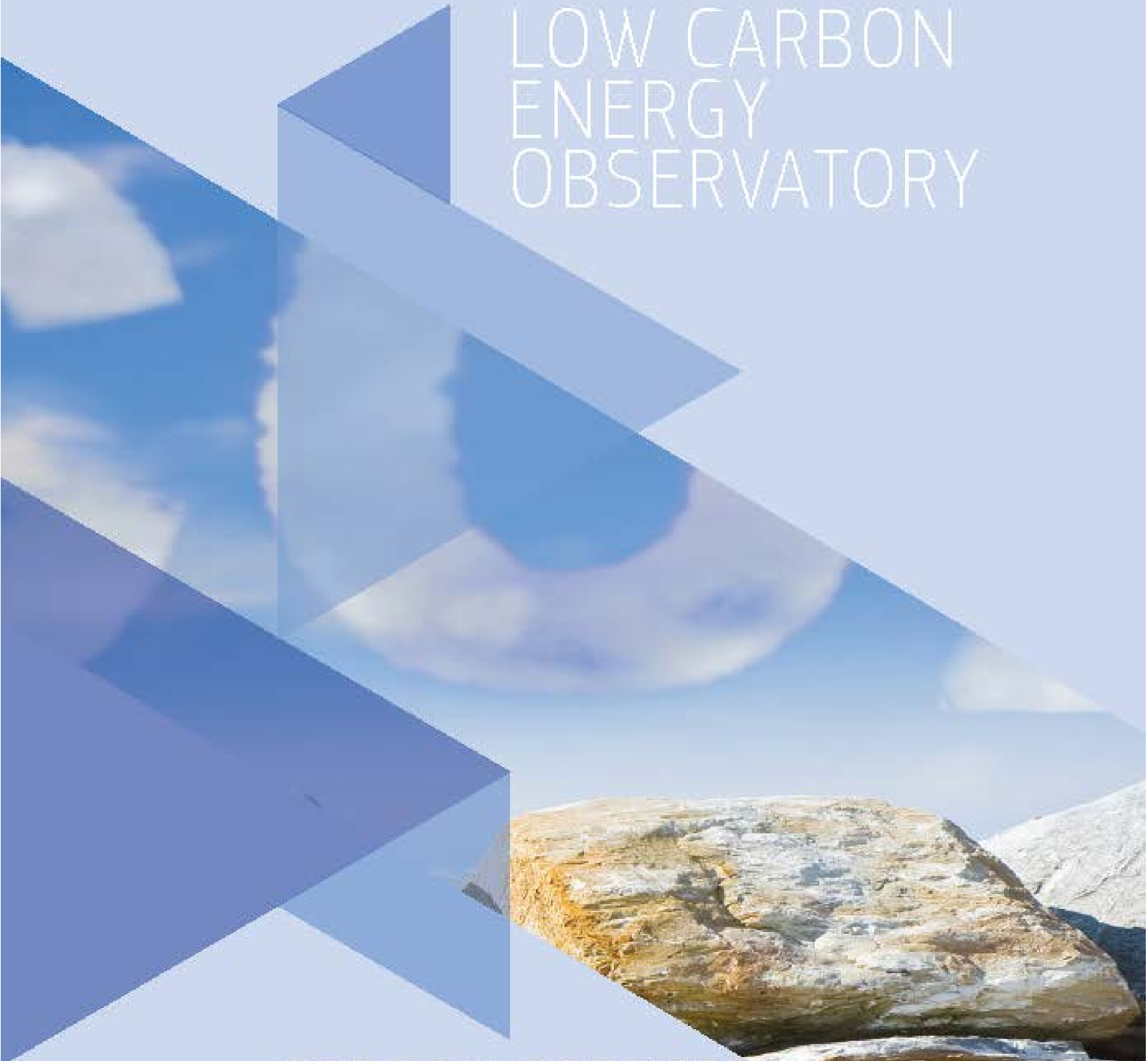
LOW CARBON ENERGY OBSERVATORY



CARBON CAPTURE UTILISATION AND STORAGE

Technology development report

Joint Research Centre

EUR 30506 EN

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Contents

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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.

1 Introduction

In December 2015 at the Climate conference (COP 21) in Paris, policy makers agreed on the ambition to keep the temperature bellow 2 ^{0}C aiming for 1.5 ^{0}C. According to the IEA, to reach the 2 ^{0}C scenario target [1][2], it will be necessary to store around 94 Giga tonnes of (cumulative) or 6 Giga tonnes (Gt) per year of CO_2 by 2050. So far, nearly 260 million tonnes (Mt) of CO_2 emissions have been captured and stored globally [3]. The Special Report on Global warming of 1.5°C (IPCC SR15) reinforced the important role of CCS in avoiding dangerous climate change [4]. More recently, the 1.5°C compliant scenarios in the European Commission's strategic long-term vision depend on CCS and CO_2 removal techniques to achieve climate neutrality.

In Europe, carbon capture and storage gained more political attention from 2005. The first CCS communication from the EU dates in 2006 [5]. In 2007, CCS was included in the European agenda as an important tool to keep climate change in control. In 2009, the first EU CCS directive was published and then several funding mechanisms for R&D, demonstration projects have been created via framework programmes and other EU funding schemes.

CCUS has been acknowledged in the context of the European Energy Union as a fundamental research and development priority to achieve 2050 climate objectives in a cost-effective way [6]. Most recently, the new European Green Deal included carbon capture, storage and utilisation in the technologies necessary toward a transition to climate neutrality [7]. CCUS is relevant to a number of areas including energy generation, industry, transport sector, and waste disposal.

CO_2 utilisation has attracted interest due to a potential for the replacement of non-sustainable fossil fuels by recycled CO_2 that could both prevent the use of fossil fuel and avoid net CO_2 emissions into the atmosphere [8], [9]. CO_2 utilisation has also emerged as a source of potential competitive advantage for the European industry in the production of fuels, chemicals and materials. A variety of CO_2 sources is available which can be classified as point CO_2 sources and atmospheric CO_2 sources. The predicted short-term market potential by [8] for CO_2 utilisation processes is around 200 $MtCO_2$/y (300 in the best case), compared to about 14 000 $MtCO_2$/y emitted from large point sources [10]. Thus, mapping the best points of CO_2 emission and matching with utilisation opportunities will be significantly important to justify the potential of CO_2 utilisation potential. Finally, potential uses of CO_2 would need to satisfy certain criteria such as emission reduction benefits, revenue to cover CO_2 feedstock costs and meaningful scale [11] to make sense as a climate change mitigation option.

Following the CO_2 capture and or its use, the CO_2 is transported via pipelines and/or shipped to the site of injection. It can then be stored in deep saline aquifers, deep coal bed methane (enhanced), combined or used in EOR, in depleted oil/gas reservoirs and most recently in basalts. The estimated quantity of CO_2 that can be stored permanently in the world, mainly by mineral trapping is 8 000 and 55 000 Gt [12]. However it's necessary to harmonize different methodologies to have more precise amount. CO_2 monitoring can be by accurate geochemical and geophysical techniques for safety reasons.

While CO_2 emissions from fuel combustion have been declining in Europe [13], process industries like cement, iron and steel, aluminium, pulp and paper, and refineries have inherent CO_2 emissions resulting from raw material conversion. In many of these, CCUS is the only option for deep emissions reduction. However, while many large-scale CCS projects are currently in operation worldwide, many others have been cancelled on the grounds of financial restrictions and/or regulation, political risks and also due to the lack of a robust business case.

This report updates the previous version of the Technology Development Report series, focusing on CCUS [14]. Since the previous version of this report, two more large scale CCUS projects (Gorgon Carbon Dioxide Injection, AU and CNPC Jilin Oil Field CO_2 EOR, CN) came online, bringing the number of operational CCUS projects worldwide to nineteen. In terms of research projects, twelve H2020 projects were completed and eleven new started under the latest calls. The respective chapters of this report have been updated to include this information. All projects are listed in the Appendix of this report together with information on technology and funding.

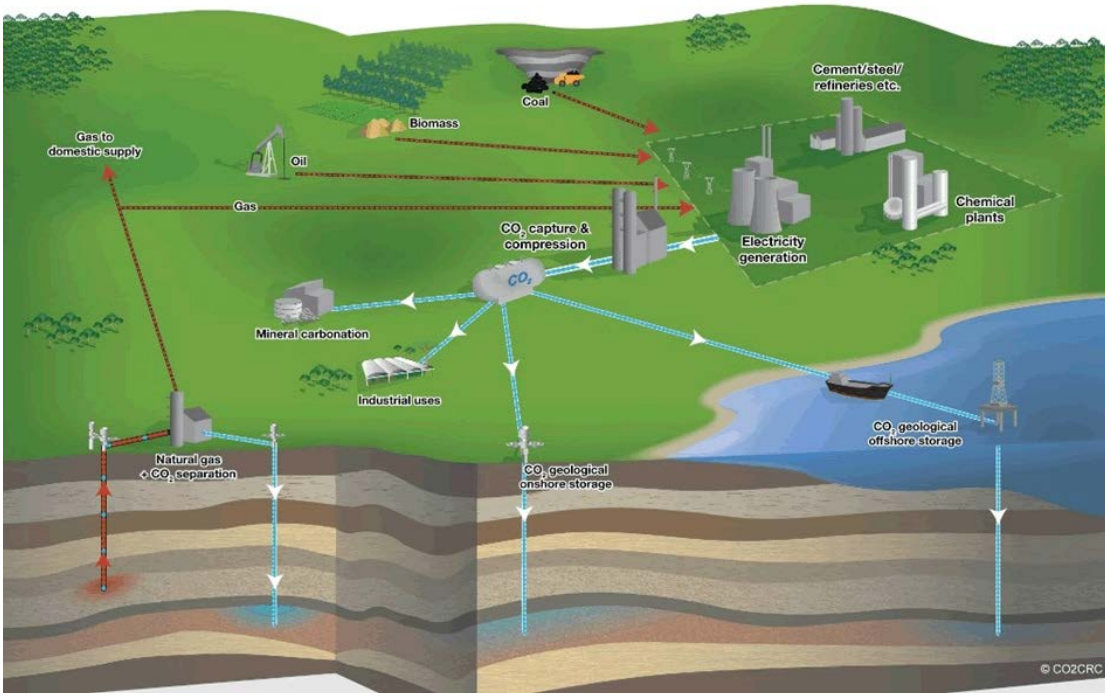
1.1 Methodology and data sources used

The objective of this report is to assess the maturity of the key technologies for carbon capture, utilisation and storage (CCUS) as well as to review the status of the technology with respect to the deployment targets and EU policy goals. The technologies covered include power generation and industry. Figure 1 is a scheme of the carbon capture, utilisation and storage (CCUS) chain. Note that the CO_2 needed by the CO_2 utilisation processes is orders of magnitude lower than the CO_2 that may be captured from power plants. CO_2 used in such processes may come from other sources, as by-product, or captured from industrial processes.

For the current analysis, given that industrial applications are also considered, the usual classification (pre-, post-, oxy- combustion) may not be applicable. In industrial processes, CO_2 may not come from fuel combustion but from the process itself such as for example, in calcination of calcium carbonate to give calcium oxide. As such, CO_2 capture is defined by the separation technology involved:

- Absorption
- Adsorption
- Membrane Technology
- High Temperature Looping

Figure 1. CCUS value chain facilities [15]



CO_2 utilisation processes include the chemical transformation of CO_2 into another product with commercial value. Enhanced oil recovery (EOR), and other uses, as in the food industry or as supercritical solvent, where CO_2 is subjected to physical and long-term chemical changes, have not been considered in this report. The overview covers all applications, related to the synthesis of fuels, chemicals and materials. Regarding CO_2 storage the focus is both on offshore and onshore aquifers, but also considering alternative ways such as basalts. On transport, it is about evaluating the combination between shipping and pipelines. Monitoring techniques necessary to guarantee the safety of CCS projects are also reviewed.

The review of each topic is organised following main blocks: (i) Literature review and technology analysis to depict the state-of-the-art of CCS and CO_2 use technologies. (ii) Technology assessment based upon technology readiness level (TRL) evolution according to European R & D projects.

Every effort has been made to use the most recent data at the time of drafting this report (early 2020). Some very recent developments may not be included. It is noted that the term "EU" may refer to the EU28 for data for the period up to 31/1/2020 when the UK was a member of the EU.

1.2 Literature review, data sources and analysis

The review of the state-of-the-art of the different parts of CCUS, namely capture, utilisation, storage, transport and monitoring is based on different relevant sources such as:

- Scientific articles published in peer-reviewed journals;
- the SET Implementation Plan (IP) 2017, SETIS webpage and associated SET Plan action;
- The Carbon Sequestration Leadership Forum (CSLF);
- Online information on the Innovation and Networks Executive Agency (INEA);
- Online information from the Global CCS Institute.
- The book "Carbon dioxide utilisation: Closing the carbon cycle" [9].
- The book 20 years of CCS - accelerating future development [1].
- The book "Carbon Capture" [16].
- The book "Carbon Capture and Storage - Energy and Environment Series" [17].
- The Global Status of CCS 2019 [18].

In the patenting activities section the data are sourced from the Joint Research Centre (JRC) based on data from the European Patent Office (EPO). Patent data are based on PATSTAT database 2019 autumn version (JRC update: December 2019). The methodology behind the indicators is provided in [19]–[21]. The current version of the report includes data for 2015 and 2016 in addition to data of up to 2014 in the previous report.

In the *R & D overview* chapter, the main sources are CORDIS and internal databases for identifying the EU co-funded projects.[1] Aside the straightforward technological routes, the projects' relevance also was determined based on their connection technologically to the SET Plan actions and Implementation Plan. The projects were further used as a cross reference to identify any additional, based on the call/funding scheme they were funded. It should be noted that the majority of H2020 projects are still ongoing, and whether they have achieved their aims and targets is still inconclusive. Projects that do not consider the separation of CO_2 directly or its immediate re use, such as for example specific catalyst development with chemical functionalisation, artificial photosynthesis and technologies aiming to advance CO_2 reduction have been excluded from the analysis. Also excluded are technologies that are focusing on the molecular level.

For the identification of the *technology trends, needs and barriers*, apart from the sources used for the state-of-the-art of the technology, we have used the technology roadmaps and reports from the International Energy Agency (IEA), the Zero Emissions Platform (ZEP), and CSLF.

1.3 Technology readiness assessment

The focus is on CCS and CO_2 utilisation projects granted H2020 (2014-2020) funding. Technologies that refer to standalone techniques, envisioned to be part of CO_2 capture or utilisation chain have not been considered (for example, the study of integrated plat-

[1] The keywords used were: carbon capture, carbon dioxide, CO_2 capture, carbon utilisation and use, carbon use, surplus, CO_2 storage, CO_2 transport, CO_2 monitoring and CCS.

forms for photocatalytic water splitting and CO_2 reduction). It should be noted that in most cases the technology readiness level achieved at the end of a project is not clearly indicated. In such cases expert judgement of results is applied.

The TRL assessment follows the definitions as described in the previous version of this report [14]. For CO_2 utilisation technologies, processes for the synthesis of fuels, chemicals or materials are also examined. TRL levels for CO_2 storage, transport and monitoring follow classification as given by [22] and [23]. Finally, to determine the TRL of a sub-technology we assume that there should exist at least one project at the specific TRL assigned.

1.4 Technology forecasts

The technology forecasts are based upon the JRC-EU-TIMES model. Different scenarios of this model determine possible deployment rates for CCS and CO_2 utilisation/reuse (based on fuels synthesis) technologies among the other conventional and renewable power plant technologies. Model results encompass the trade-offs for technology deployment, under different scenarios, i.e. under different assumptions and input data. In this version, we include the "zero carbon" scenario which reaches 100% emissions reduction by 2050. We also include the corresponding projections from the scenarios included in the in-depth analysis accompanying the Communication A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy [24].

2 Technology state-of-the-art

Carbon capture is already implemented in processes like natural gas (NG) processing and industrial hydrogen production. Demonstration of carbon capture in a full-scale power plant is pending. The first large-scale CCS 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 CCS project operational since January 2017. Both plants utilise CO_2 for EOR [18].

Commercial uses of CO_2 also exist and CO_2 utilisation can contribute in a number of sectors, such as synthesis of chemicals, organic and inorganic carbonates, fuels and olefins. Each product synthesis, and each synthesis pathway, are at different TRL level, spanning from TRL 1 to 5 [25] but also up to 7 [26].

From the source to the sink of CO_2 in both onshore and offshore, it is necessary to transport it and to have a deep knowledge of the geological structure of the site of injection. To create a safe storage, avoiding any leakage of CO_2 an advanced and accurate system of monitoring is required.

Table 1 summarises the main sub-technologies identified for CCUS.

Table 1. Sub-technologies

Sub-technology
Capture
Absorption
Adsorption
Membrane Technology
High Temperature Looping
Hybrid Approaches
Utilisation
Boosting commercial processes (e.g. urea)
CO_2 use without transformation: EOR, EGR, ECBM*[1] CO_2 use without transformation (as solvent): supercritical CO_2
Chemicals and polymeric materials
Fuels: alcohols, hydrocarbons and derivatives, hydrogen carriers (e.g. methanol, formic acid)
Mineralisation
Storage
Injection in geological sites
Definition and Characterisation of the storage site
CO_2 migration and improved storage management procedures
Monitoring; CO_2 leakage, CO_2 long-term behaviour, safety, cost and risk reduction
Transport
CO_2 compression
Ship transport
Pipeline transport and network design
Safety aspects of transport

Other research areas of a more trans-technological and cross-technological nature are included in Table 2.

Table 2. Other research areas

Area
Materials and corrosion
Storage (natural analogues)
CO_2 storage in other geological site, ex. Basalts
Synergy with renewables such as geothermal energy, biomass, CSP, wind/H_2
Integration among the overall CO_2 value chain (capture, transport, utilisation, storage): CO_2 emissions evaluation. Cost competitiveness of the overall project and new business models.

2.1 Carbon capture and utilisation technology

Until now, CO_2 capture configurations were described with definitions mainly applied in power generation.

First generation capture technologies correspond to (i) amine-based solvents (PostC), (ii) physical solvents like Selexol or Rectisol (PreC), and to (iii) cryogenic air separation (air separation unit – ASU) to obtain pure oxygen (OxyC). These technologies are currently available but research and development on necessary improvements is ongoing. Second generation technologies include those in R&D phase that will be ready for demonstration at a later stage, while third generation technologies are at an early stage of development, even at a conceptual stage. Different demonstration timeframes have been suggested over the years. However, some technologies have not evolved in their TRL in the last 10 years, perhaps indicating some fundamental challenge to further development (e.g., functional material reactivity and/or stability, need of extreme operating conditions, limitations in gas-liquid/solid contact area, etc.). These technologies may have fallen into the “valley of death” where further development may not be viable and specifying timeframes for demonstration may prove inconsistent.

Commercial CO_2 capture plants include the Boundary Dam project (TRL 8) in Estevan, Canada with a capacity of about 1 $MtCO_2$/yr. It uses an amine technology from CANSOLV, considered as a 2nd generation capture technology [27], [28]. Petra Nova uses the KM-CDR Process developed by Mitsubishi Heavy Industries (MHI) and the Kansai Electric Power Company (KEPCO) with a proprietary amine solvent called KS-1.

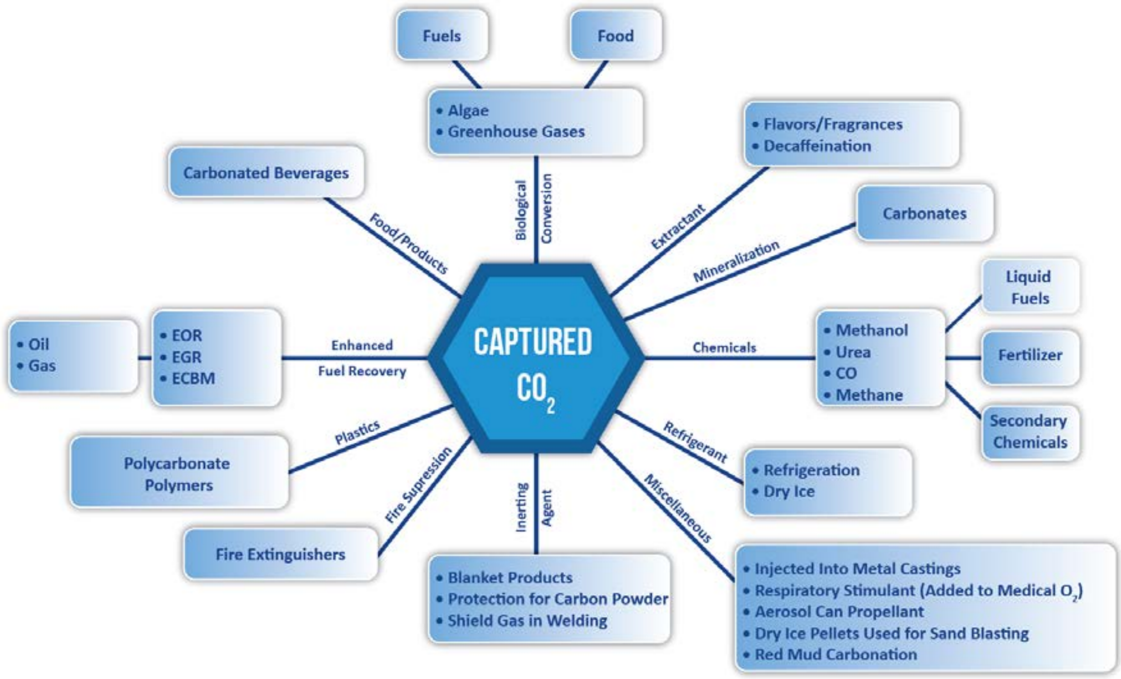
CO_2 capture with Chemical Looping (CLC) applied to coal and NG is at TRL 5. Boiler studies for coal and NG are at TRL 6. Up to the date, the European plants have driven capture projects with calcium carbonate looping up to TRL 5, amines and chilled ammonia up to TRL 6 similarly to the PreC concept studied now for industrial application (H2020 STEPWISE project) (Appendix B).

Regarding utilisation, synthesis of products from CO_2 is already taking place. So far, CO_2 has been a by-product of industrial processes such as in H_2 production by steam reforming of NG or ethanol production by fermentation, and not captured from flue or industrial gas streams. The value chain for captured CO_2 is similar to that of already existing CO_2 by-product: once the CO_2 is separated from other components, it is liquefied and transported to the end-users. Current uses are among others, for beverage and food industry, for medical applications, to produce rubber/plastics or mixed with gases/aerosols (as propellant or as blowing agent) [29]. Several studies [8], [30]–[34] highlight the wide range of possibilities for CO_2 use as a raw material, each one at different levels of development, different product scales and market prospects. Figure 2 below summarises the products that can be synthesised from CO_2.

Some technologies could be readily established in existing mature markets e.g. utilisation of CO_2 to boost urea production, whereas others are at prospective phases, or are at the pilot/demonstration phase, and need further development to reach commercial status. Certain technologies require a specific set of circumstances to be applied on a large and replicable scale [35]. Catalytic synthesis is the most developed conversion method for carbon recovery. Electrochemical and photochemical conversion while at a relatively low TRL, may be more efficient and emit less CO_2 because of the direct use of renewable sources. The production of chemicals and fuels from CO_2 is mostly at the development phase.

Algal synthesis is an example of an emerging technology for biofuel production, with a probable relevant contribution as a capture/utilisation technology [36], [37].

Figure 2. Classification of CO_2 utilisation options (US Department of Energy's National Energy Technology Laboratory)



2.2 CO_2 transport, storage and monitoring

CO_2 underground storage is currently possible in deep saline aquifers; deep coal bed methane (enhanced also called as ECBM); combined or in use in enhanced oil recovery (EOR) and in depleted oil/gas reservoirs. EOR is the preferred option used by industry but the majority of international projects (USA and China, for example) are developing as combined CO_2 storage and EOR. At least two projects for storage in porous basalts are being developed in US and in Iceland (CARBFIX 2, see Appendix). In Europe, the only 2 industrial projects are located in Norway, where since 20 years, more than 1 million CO_2 per year is injected in offshore.

The knowledge and the development of technologies linked to CO_2 storage, transport and monitoring are well known since they have been developed by the oil and gas industry mainly for EOR proposals, starting in the US in the 70s. However, for enlarging this use to permanent disposal of CO_2, it is firstly necessary to estimate the storage potential of each region. This is fundamental to initialise CO_2 storage projects. Currently, aproximately 260 million tonnes of CO_2 have been injected underground in the world, mostly in US and Canada for EOR; in Norway for dedicated CO_2 storage and Algeria, Brazil China, Saudi Arabia, UEA, Germany and France for both EOR and dedicated CO_2 storage [18].

After completing a CO_2 storage assessment and publishing the first CO_2 atlas in the african continent, South Africa, in the end of 2016 launched a CO_2 storage pilot project aiming to inject between 10 000 to 50 000 tonnes of CO_2. The total estimated CO storage capacity is 162 Gt of CO_2 [2]. In the Americas, Petrobras in Brazil has had two projects combining CO_2 to EOR (Miranga field, onshore project) and Lula Field in the pre-salt fields (offshore) where CO_2 should be injected to more than 4 000 m depth. Different provinces in Canada have different approaches and needs for CO_2 use depending on their energy and industry mix impacting CO_2 emissions. If a trend can be identified, this would be towards EOR and CO_2 conversion depending on the province. Activity is ongoing in Mexico since 2014 with the major focus on EOR.

China follows US tendency to create CCUS project combined with Enhanced Oil recovery with CO_2 transported only by pipelines. In Japan the estimated resource for CO_2 storage is 146 $GtCO_2$ (Takahashi et. al 2009; Consoli & Wildgust 2017]. South Korea has recently started to show interest for CCUS and plans to construct two projects in the next future, Korea-CCS 1&2 is under evaluation and should start in 2020, for a capacity of 1 Mtpa.

Regarding the Middle East**,** Uthmaniyah CO_2 EOR demonstration project started in 2015 with capacity of 0.8 Mtpa CO_2, transported via pipeline to the aquifers. Abu Dhabi CCS was launched in November 2016 where the captured CO_2 is transported via pipeline to Abu Dhabi National Oil Company (ADNOC) oil reservoirs for enhanced oil recovery.

After separation from other gases, CO_2 is compressed to above 8 MPa and in dense phase (supercritical state), it becomes cheaper to be transported for injection or for reuse. Depending on the volume CO_2 can be transported via ships or pipelines. These last ones are considered the most adapted method to be used for CO_2 transport onshore and/or offshore. The pipelines also show a long lifetime and are expected to be in use for many years.

CO_2 can also be transported in liquid phase via road or rail tankers but in this case tanks should be at a temperature below the ambient. This means of transport is already in use for small quantities of CO_2 used in the food industry. For large distances this way of transportation is not economically viable.

According to the IEA [38] the needs for pipelines in the world should be around 100 000 km for all kind of fuel, which can be transported. Adding the necessity to transport CO_2 and permantly store it offshore or onshore, this amount can be 10 times higher.

Concerning shipping transport, CO_2 is liquefied as other liquefied petroleum gases (around 0.7 MPa) and then transported to the site of injection. Commercial capacities for CCUS should still be demonstrated but in some locations this option may be more effective than transport via pipelines, at least for economical point of view.

South korean projects will use ships for CO_2 transport to the storage site and the first CCS full chain project in Norway will combine shipping and pipeline for the same proposal (see international projects chapter 2.1.1).

CCUS is feasible at commercial/industrial scale but analyses of safety or risks linked to possible leakage of CO_2 must be completed accurately. Moreover, the CO_2 should be monitored for long time in both subsurface and surface environment. The techniques to control the CO_2 movement in subsurface vary from geophysical to geochemical techniques. The first ones include 3D and 4D surface seismic, acoustic image, multicomponent (MC) seismic, microseismic monitoring, borehole-based seismic, 4D cross-hole seismic surveying, 4D vertical seismic profiling (VSP), acoustic sonar bathimetry techniques, electrical resistance tomography (ERT), ground penetrating radar, borehole radar, magnetotelluries. The second involves isotope methods, geochemical tracers, water chemistry.

In 2006, a pre-feasibility project has been submitted to Norwegian environmental agency for a construction of a CO_2 lab field (Miranda-Barbosa, *et al*. 2006) only to test some of these mentioned techniques. Later, the results have been published, proving that it is necessary to use both geophysical and geochemical techniques to have more accurate CO_2 monitoring underground. These studies have been later approved.

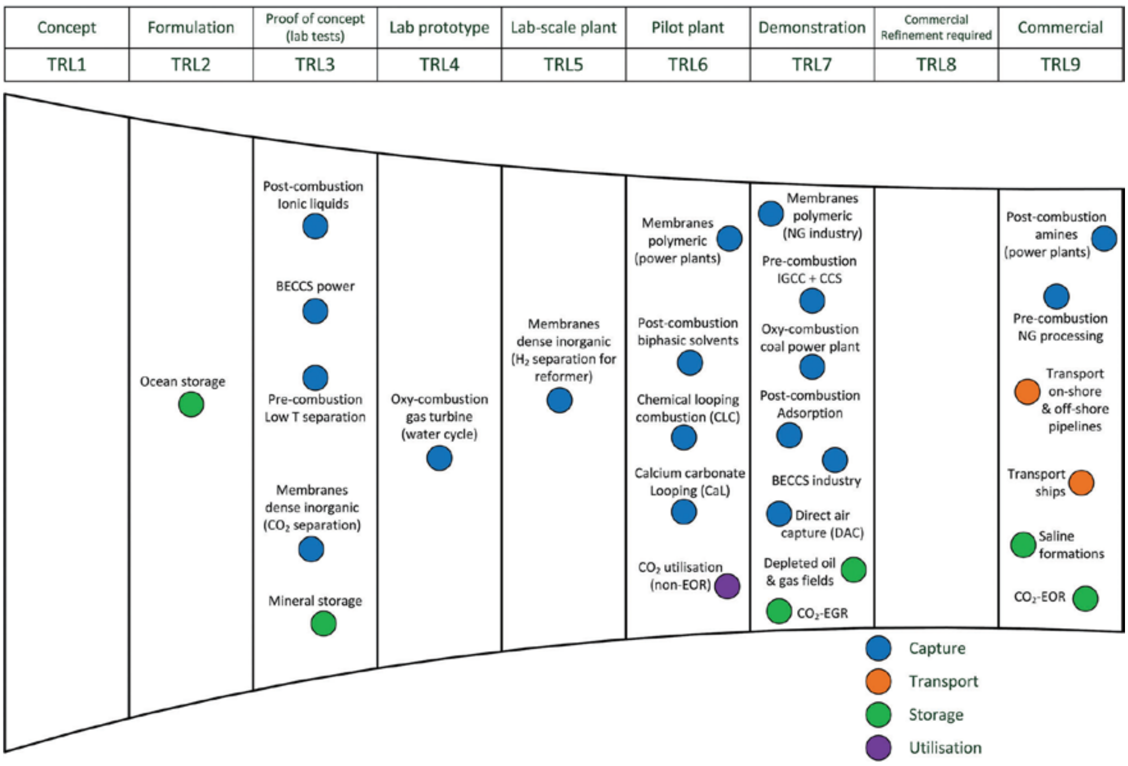
The monitoring techniques and their specific use for CO_2 storage are well described from many authors such as Gardner (2006), Pearce et al. (2014), Paxar (2015). Jenkins et al. [39] have elaborated a ten years state of the art about CO_2 monitoring. There was an intense and significant progress to minimize risks of CO_2 leakage. To guarantee the safety for using this technology it is necessary to plan for long term CO_2 monitoring to eliminate any leakage risks during or after CO_2 injection, as described in the CCS directive (EC, 2009). To control the CO_2 migration in the surface, soil gas techniques and remote sensing are complementary techniques.

(Ikeda et al. 2016) suggested the use of a continuous and well controlled system. This is an accurately controlled routinely operated signal system (ACROSS) which allows the detection of any modification of velocity phases associated to CO_2 leakage before that CO_2 reaches the surface.

2.3 Key performance indicators

Within H2020, certain indicators where proposed for assessing the results and impact of the programme. These include journal publications, patents applications, number of start-ups and spin-offs created etc. but primarily concern the performance of the projects funded and not the technologies they are studying. Literature sources as well as guidelines at the European level [42]–[44] focused on the evolution of the technology readiness level (TRL). Figure 3 gives a summary of the TRL for the different technologies and CCUS components.

Figure 3. Current development progress of carbon capture, storage and utilisation technologies in terms of technology readiness level (TRL). BECCS = bioenergy with CCS, IGCC = integrated gasification combined cycle, EGR = enhanced gas recovery, EOR = enhanced oil recovery, NG = natural gas.



Note: CO_2 utilisation (non-EOR) reflects a wide range of technologies, most of which have been demonstrated conceptually at the lab scale. The list of technologies is not intended to be exhaustive [45].

The SET Plan Action 9 and Implementation plan of 2017, have also specified certain targets for CCUS which are presented in section 3.2.2 of this report.

2.3.1 Carbon capture

For carbon capture technologies, the highest goals through the different funding programmes were set for Chemical Looping (CLC) and Calcium Looping (CaL) which were expected to reach TRL 6. For the rest of the CO_2 separation technologies as well as for systems introducing process improvements a TRL of 5 was expected.

In 2015, the US Department of Energy published a comprehensive overview of the CO_2 capture technologies for power generation funded. This included detailed objectives per technology and a generic target of 90 percent carbon capture at USD 40/tonne CO_2 [46]. In the 2018 edition of this document, these targets were revised to UDS 30/tonne CO_2 (sorbent technology) or even USD 15/tonne CO_2 for Mixed Matrix Membrane (MMM) technology [47].

Table 3 summarises several relevant quantitative research priorities identified by ZEP for CO_2 capture.

Table 3. Summary of relevant research priorites for CO_2 capture [48]

	Before 2020	2020-2030	After 2030
Efficiency loss	10 % points	< 10 % points	< 5 % points
Energy required for solvent regeneration	< 3 GJ/ tCO_2	< 2 GJ/ tCO_2	< 1.5 GJ/ tCO_2
Energy required for O_2 obtaining (ASU)	250-310 kWh/tO_2	210-270 kWh/tO_2	210-270 kWh/tO_2
Energy required for O_2 obtaining (OxyC)	140-170 kWh/tO_2	120-150 kWh/tO_2	90-120 kWh/tO_2

With these targets primarily referring to projects in power generation, key performance indicators for industrial projects appear scarce. Metrics that could be included in the process of setting key performance indicators include but are not limited to capture rate, CO_2 avoided, avoidance rate,[2] CO_2 captured per year, cost of CO_2 avoided, cost of CO_2 captured, levelised cost of product etc. Indicatively, for an oxy fired cement and a steel plant using a amine-based CO_2 capture process, relevant values are given on Table 4.

Table 4. Indicative performance metrics for cement and steel industries (adapted from [49], [50])

	Cement	Steel
Capture rate (%)	90	54-65
CO_2 avoided (tCO_2/tproduct)	0.548	1.05-1.26
Avoidance rate (%)	0.525	50-60
Total levelised cost (€/tCO_2)	72.4	487-506
CO_2 avoided cost (€/tCO_2)	40.9	55-60.5

A variety of technologies for carbon capture have also been considered for implementation in refinaries. With these being complex industrial sites that are highly integrated and characterised by diverse process configurations, a more detailed analysis would be required for acquiring even indicative values on metrics.

[2] The effective reduction of CO_2 emissions per unit of product.

2.3.2 CO_2 utilisation

The SET-Plan Integrated Roadmap [44], included the synthesis of olefins, fine chemicals (cyclic and linear carbonates, carboxylic acids, etc.), polymers and mineral carbonate within the essential CO_2 utilisation processes. The following goals and KPIs have been indicated for year 2020 [44].

Goals

- ✓ Develop and demonstrate (TRL 4 and above) routes to convert CO_2 into light olefins (mainly ethylene and propylene). These are (i) direct conversion of CO_2 with H_2 using modified Fischer–Tropsch (FT) catalysts; (ii) indirect conversion, after transformation of CO_2 into methanol, followed by a methanol-to-olefin conversion.
- ✓ Develop and demonstrate (TRL 6 or above) fine chemicals production. The following are fine chemicals that have been validated in lab-scale or pilot:
  - Cyclic and linear carbonates, carbamates
  - Carboxilic acids
  - Diols + CO_2
  - Alkenes + CO_2 + oxidant in one step reaction
  - Internal epoxides + CO_2
  - Insertion of CO_2 into CH bonds
- Develop and demonstrate (TRL 6 or above) polymers production. It encompasses new or existing polymeric structures based on CO_2, at pilot scale.
- Develop and demonstrate (TRL 6 or above) mineral carbonate production with CO_2 from flue gas and their usage as additives for cement. Estimation of the potential of (i) the penetration pathways of mineral carbonates into the market and for disposal, and of (ii) the raw materials that can be combined with CO_2.

KPIs

- Major industrially driven projects to produce olefins: 2-3 projects
- Demonstration on the synthesis of fine chemicals: 5 projects
- Pilot plants on polymers synthesis: 2-3 plants
- Small-scale industrial production plant for polymers synthesis: 1 plant
- Pilot plants to perform CO_2 conversion into mineral carbonate: 2-3 plants.
- Full demonstration about the use of the mineral carbonate (as new material): 1 project

A significant number of projects are ongoing in Europe for CO_2 utilisation solutions to be demonstrated at pre-commercial and/or industrial demonstration scale level (i.e. beyond the pilot level). These cover different technologies and CO_2-based products and many of the targets above are to be reached. Producing a detailed inventory of such projects is ongoing as part of Horizon 2020 project IMPACTS9.

2.3.3 CO_2 storage, transport and monitoring

The KPIs for storage and/or transport process are more related to the assessment and risks. A set of KPIs should be included during the operation and closure steps. These should serve as basis for the monitoring plan. Currently, results for some projects are more qualitative than quantitative which compromises the efficiency [37].

Storage and transport costs have been excluded from the calculations of overarching KPIs [38]. The main reason is that this cost is not originally dependent on technology development. Concerning targets and KPIs (excluding economic) for CO_2 storage, transport and monitoring, 4 points should be considered for the future:

1 - Costs and risk deduction. CO_2 atlases can be an important source of information which can contribute to reducing both costs and risks. An overview of the CO_2 storage capacities can be found in the Appendix.

2 - The characterisation of injection sites. Following the several R&D projects since 1993, a database for deep saline aquifers has been created, however for onshore there are still gaps. The monitoring of CO_2 is also a relevant topic and R&D currently focuses on it.

3 - The absence of multiple pilot storage sites is one of reason for slow movement towards to commercialisation of this technology. New demonstration projects should be created in Europe in the next years.

4 – Dissemination of information about CCUS is absolutely necessary to improve the public acceptance about this technology. This is urgent and an important barrier to the development of new projects.

KPIs toward 2030 and 2050 include expectations on the creation of supply chains, which will facilitate the implementation of CO_2 storage infrastructure, the reduction of costs of about 10-20 %, increasing of efficiency and safety knowledge. Better dissemination of the information of this technology will help to improve the public acceptance, which is needed to deploy CCUS projects in all Europe.

Analysis of transport costs in integrated CO_2 network of pipelines is necessary to complete the CO_2 storage process. The Feasibility study for Europe-Wide CO_2 infrastructures completed in 2010 and presented complete scenarios for 2050 for both storage and transport. In this study, researchers have simulated costs and infrastructure to successfully achieve CO_2 storage proposals.

Table 5. Entry costs CO_2 transport and storage for 2030 and 2050

Scenario		CO_2 volume (Mt/y)	Total Length (km)	Total Cost (EUR mil)
2030	Low	50	6 879	2 074
	Medium	120	9 719	4 011
	High	350	12 384	7 592
2050	Low	280	11 775	6 785
	Medium	600	14 334	10 901
	High	800	15 013	12 667

Considering only storage in offshore:

Table 6. Entry costs for CO_2 transport and storage (only in offshore)

Scenario		Total Length (km)	Total Cost (€m)
2030	Low	8 971	3 434
	Medium	10 829	5 747
	High	14 908	11 206
2050	Low	13 746	9 560
	Medium	18 635	16 439
	High	20 041	19 781

Norway has found a way to reduce transport costs, combining transport by shipping (500 km) and from east to west coast and then more 50 km of pipeline to the field of Smeaheia.

2.4 Technology trends

According to the Global CCS Institute, there are 19 CCUS projects in commercial operation, 4 under construction and 10 in advanced development. These facilities cover a wide range of industries and sectors including chemical and hydrogen production, iron and steel, natural gas processing, power generation, fertiliser and ethanol production.

In Europe, promising projects in advanced phases of development are shifting focus toward CO_2 infrastructure such as the PORTHOS project in the Netherlands. In Norway, the plan for a full-scale CCS project capturing emissions is confirming this further as well as the shift toward CO_2 capture from industrial sources. Hydrogen production from Steam Methane Reforming (SMR) with CCUS has received a lot of attention in the last years, and one project (Port Jérôme) is operational since 2015. There are three more projects (Hydrogen to Magnum, Northern Gas Network H21 North of England and HyNet North West) in Hydrogen production albeit in early development. It remains to be seen whether this trend will last and develop. Direct Air Capture (DAC) has also received a lot of attention besides the typical CO_2 separation technologies. The first commercial plant operating since 2017 is using porous granulates filter modified with amines but other technologies employing sorbents are also considered.

2.4.1 Carbon capture and utilisation

A number of trends and needs are identified for CO_2 capture technologies applicable to power generation and energy intensive industry. Some challenges apply generically throughout different sectors and include:

- ✓ Effective process integration of 1st, 2nd and 3rd generation capture technologies;
- ✓ A combined environmental control system (i.e. for amines emissions, for instance);
- ✓ Flexibility to work at full/partial load;
- ✓ The impact of CO_2 impurities on the CO_2 and overall system.

More specifically, for chemical/physical solvent-based absorption solvent costs are still considered to have a reduction potential as well as overall energy requirements. For solid sorbent adsorption costs associated with equipment size remain a challenge. Research on minimizing the cycle times could improve this area. For membranes, certain limitations exist regarding membrane separation performance such as the trade-off of gas permeance and selectivity of most polymeric membranes. Further, membrane stability and short lifetime when exposing to a gas stream containing impurities remain topics of study as high-performance membranes with low material cost and high stability should be developed. For high temperature looping systems (CLC and CaL), 2nd and 3rd generation CO_2 capture technologies are expected to improve the efficiency and reduce the cost of first generation but the most promising options have to be identified and stimulated.

Typically, system costs may be prohibitive especially for plant streams where CO_2 is at low partial pressure and large equipment volumes are required for separation. Research is already focusing on reducing equipment volumes by developing more effective contacting surfaces and faster cycles.

CO_2 utilisation has been viewed as an opportunity to make use of CO_2 as raw material and produce valuable products. Originally, it was perceived as a means to incentivise CCS by lowering the cost of capture [43]. Development of the CO_2 utilisation market will depend upon the available CO_2 (i.e. amount and quality of the CO_2 made available by power plants, industries and captured from the atmosphere) and the penetration of CO_2-based products. Research programmes are also crucial to increase the TRL of the different CO_2 utilisation options. Trends and needs in this field include [23], [51]:

- ✓ Design of processes and business models that allow CO_2-based products to be competitive in the market.
- ✓ Evaluation of the net amount of fossil fuels that can be avoided with the use of CO_2 utilisation technologies.
- ✓ Evaluation of the net emission reduction achieved by specific routes throught out the whole process chains.
- ✓ Evaluation of the CO_2 emitted/saved by the whole supply chain through a customised LCA with standardised tools.
- ✓ Optimisation of the processes through the design of heat integrated plants, well-developed environmental control systems and operation flexibility.
- ✓ Identification of synergies and integration with other sectors. For example, with renewable sources (as zero emitting sources) and smart grids (flexibility, full/partial load).
- ✓ Identification of the best CO_2 sources in Europe, according to concentration and impurity needs of the different CO_2 utilisation routes.
- ✓ Bridging ETS and non-ETS sectors avoiding CO_2 utilisation being used as an arbitrage to avoid surrendering allowances.
- ✓ Verifcation of efficiency of some CO_2 utilisation techniques for the mitigation of climate change.

2.4.2 CO_2 storage, transport and monitoring

CO_2 storage, transport and monitoring require safe techniques and the control of CO_2 migration. To avoid any CO_2 leakage risks some of the technical/infrastructural issues should also be improved. The main research topics have been storage efficiency, monitoring, geochemical properties, capillary trapping, interfaces between plumes and water. The biggest progress has been done for deep saline aquifers, due the investments from oil and gas industry [52]. The storage in coal beds or even in shales has also been studied, with the latter being one of the new topics.

Gaps in research still exist as, for example, the analysis of sealing capacity of caprocks situated over the injection site. These caprocks should stop any possible CO_2 migration due mainly to their low porosity and permeability of their lithology and clay minerals composition. The majority of current geological models do not take into account the sealing capacity since it is difficult to measure it. The recent use of molecular modelling can improve the knowledge on sealing rocks and their sealing capacity.

The oldest CO_2 storage project in Europe, Sleipner, in Norway has now over 20 years of continuous operation. Both Norwegian CO_2 storage projects, Sleipner and Snøhvit have been repermitted by Norwegian government under EC CCS directive in 2016 [53].

Concerning the CO_2 storage assessment in Europe, some progress has been done by some regions and countries such as the Norwegian Storage Atlas for both North and Barents sea in 2014. This has been followed in 2015 by a Nordic storage atlas including FI, SE, DK, NO and IS data. In 2016 UK published the Strategic UK CO_2 Storage Appraisal Project (CO_2 Stored).

Several projects were developed to answer questions linked to safety and analyse the risks and assessments. The majority of results confirm the safety of CO_2 storage operations [1] but lack of clarity in issues such as liabilities pose limitations. The dissemination of information about CO_2 storage has not been effective until now and it has become a barrier for CCUS demonstration projects.

Research and development projects have been concentrated on the injection of CO_2 in the saline aquifers. These seem to be the biggest reservoir for CO_2, therefore it is expected that this would be the most efficient way to store CO_2. However the concept of CO_2 efficiency in numerical values has been recently introduced in the technical literature [54]. This can be measured by several factors:

- ✓ Type of aquifer;
- ✓ Permeability and capillary entry pressure;
- ✓ Characteristics of CO_2 storage operation;

- ✓ Regulatory constraints such as the maximum bottom-hole injection pressure.

Improving databases of storage locations is fundamental to achieve to commercial and successful projects. Improvement on site characterization, integration of geological data are also an important issue to be developed. Research and development projects are going towards safety of CO_2 storage and then monitoring is an essential part of the next future projects. In summary, the detailed characterisation of the site of injection translated in numeral values can give a better estimation for CO_2 storage reserves to conclude about their efficiency.

Globally there is not yet a standard method to calculate CO_2 storage capacity, since different countries use different ways to calculate it. In this report when it is possible, the theoretical CO_2 storage capacity will be mentioned. This is the maximum amount of CO_2 that the system can store efficiently, i.e. the capacity limited by the physical and chemical characteristics of the system/reservoir.

2.4.3 Inventive activities

Activity on CCUS is identified by using the relevant Y code families (Y02C and Y02P)[3] 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

Y02P 20/142 - CO_2 utilisation

To identify trends, we analyse the "inventive activity" of EU companies in certain technologies, i.e. the family of patents relevant to the technologies. Figure 4, shows the inventive activity from 2006 to 2016. Capture by absorption peaked in 2009 surpassing all the other technologies considered. In 2011 it was surpassed by capture with chemical separation and capture by adsorption has been the major trend ever since. Activity in technologies using CO_2 as a feedstock, peaked in 2007 and after a drop in 2010 has been fairly stable. According to the data, patent families related to CO_2 storage peaked in 2009 and 2015 but have been generally stable.

The following graphs are indicating trends of inventive activity per year in different technologies as well as most active countries (hence no y-axis presented).

[3] 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 4. Inventive activity by technology from 2006-2016. Source: JRC, 2018 based on [55]

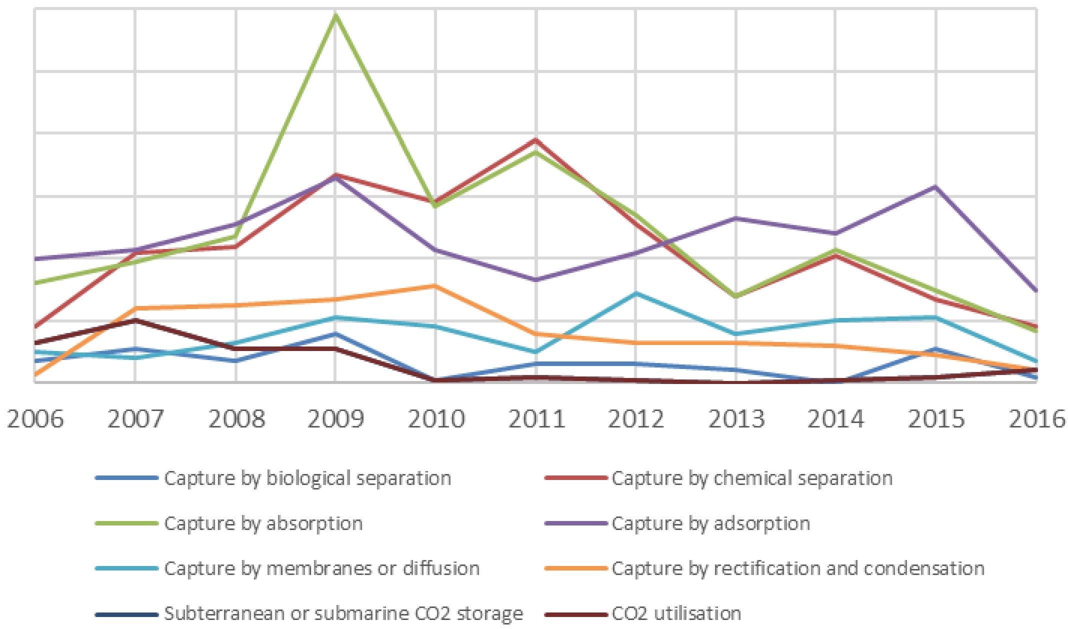


Figure 5, Figure 6 and Figure 7 show activity of companies of European Member States in each component of CCUS. Germany dominated activity in CO_2 capture technologies, followed by France and the Netherlands. The trend remains the same for CO_2 utilisation, while these countries were also among the four countries with interest in CO_2 storage, together with Austria.

Figure 5. Relative activity by EU MS companies in CO_2 capture. *Source:* JRC, 2018 based on [55]

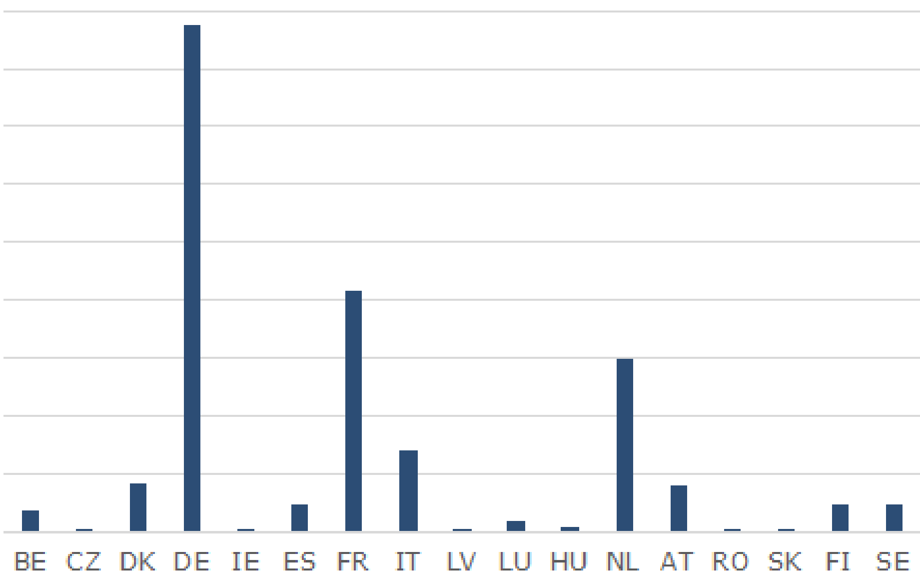


Figure 6. Relative activity by EU MS companies in CO_2 utilisation. *Source:* JRC, 2018 based on [55]

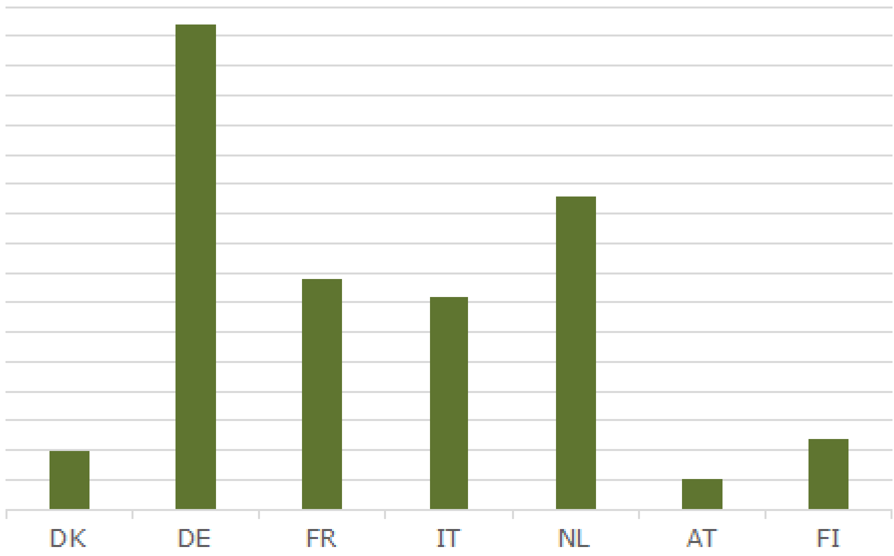
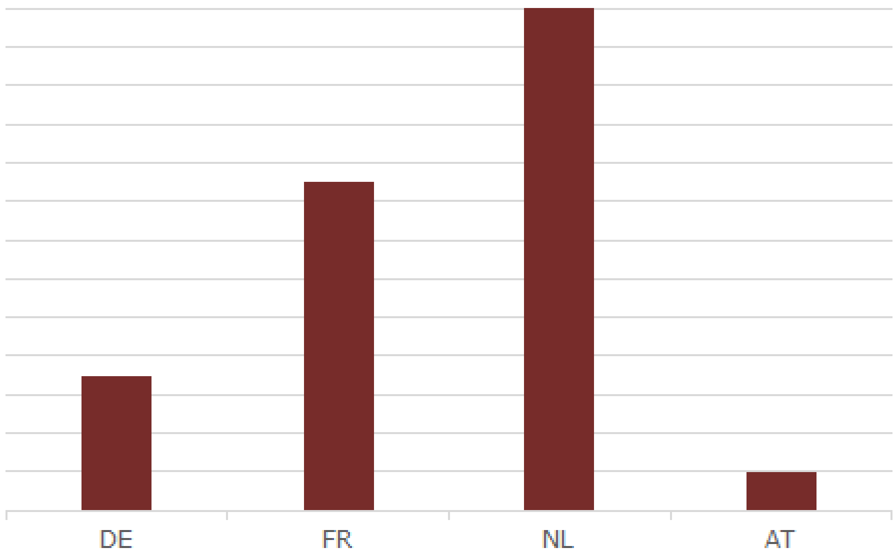


Figure 7. Relative activity by EU MS companies in CO_2 storage. *Source:* JRC, 2018 based on [55]



2.4.4 Hubs, clusters and infrastructure

Interest has been increasing for the creation of CO_2 hubs and clusters. FR, BE, NL and UK are currently developing relevant business plans for example at the Port of Rotterdam in the Netherlands and Foss-sur Mer in France.

In December 2019, the European Commission adopted the fourth list of Projects of Common Interest (PCI) for implementing cross-border energy infrastructure in the EU. In order to help the EU achieve their energy policy and climate objectives; affordable, secure and sustainable energy for all citizens, and the long-term decarbonization of the economy in accordance with the Paris Agreement. Five projects are included in the list of Cross-border carbon dioxide network (Table 7).

Table 7. Cross-border carbon dioxide network projects in the fourth PCI list

	Project	Countries/Regions
	CO_2-Sapling	United Kingdom, in further phases Netherlands, Norway
	CO_2 TransPorts	Rotterdam, Antwerp and the North Sea Port
	Northern lights	United Kingdom, Ireland, Belgium, the Netherlands, France, Sweden, Norway
	Athos	The Netherlands and open to receiving additional CO_2 from others, such as Ireland and Germany
	Ervia Cork	Ireland

Projects are considering CO_2 cross-border transport both using pipelines and shipping between UK, NL with storage site in NO. These 3 countries are also implementing CO_2 sampling transport and infrastructure across UK. A CO_2 hub is also being considered in UK, with further phases in NL, BE and DE.

3 R&D overview

In the previous version of this report [56], we extensively presented projects within the Framework Programs (FP) and H2020 projects that were ongoing. In this report we have identified 14 more projects that were funded in the meantime. Within H2020, technical aspects, creation of hubs and cross borders projects have been stimulated. For projects encompassing all or different aspects of CCUS including non technological, we estimated an EU contribution of approximately EUR 310 million within H2020 so far. These leveraged approximately EUR 130 million in funds from public/private organisations and industry. Horizon Europe, the successor of H2020, is the European Union’s seven-year research and innovation programme, which will run from 2021 to 2027. The programme’s general objective is to deliver scientific, technological, economic and societal impact from the Union’s investments in R&I, to strengthen the scientific and technological bases of the EU, and foster its competitiveness in all Member States. Horizon Europe is includes CCUS under cluster 5 – Climate, Energy and Mobility.

For carbon capture, 17 projects were identified in H2020, with the majority of them under the theme "Secure, clean and efficient energy". For CO_2 utilisation we have identified 33 relevant projects. Projects on CO_2 storage, monitoring, and transport were concentrated to develop more knowledge on safety and monitoring of CO_2.

An overview of the selected projects, ordered by programme, action, and classified according to (i) their research (fuels, materials and chemicals), and (ii) project focus, is found in the Appendix.

For carbon capture, H2020's STEPWISE (sorbents) remains at the top of the list with EU funding of around EUR 13 million. For CO_2 utilisation it is GECO (EUR 16 million) over passing FReSMe (EUR 11.4 million, methanol production) which was the highest financed project within H2020 program in the previous version of this report. In the previous report, funding for CO_2 capture and CO_2 utilisation projects was in a similar range (EUR 94 million and EUR 119 million, respectively). In this update, while absolute amounts are significantly smaller for both, CO_2 utilisation projects received more funding than CO_2 capture projects (EUR 47 million and EUR 29 million, respectively).

Overall, the most highly funded projects, count with an amount of partners in the range of 1 up to 18 per project. The organisations identified among H2020 projects' partners, are quite diverse compared to previous programmes.

With regard to Member States, the highest participation was identified for Germany and the United Kingdom, coordinating and/or participating in 29 and 28 projects for each. The Netherlands, Italy and Spain are following with 26, 25 and 22 project participations respectively. Norway's relevance in projects is maintained being the European Economic Area (EEA) country with the biggest coordination/participation in H2020 projects (14 projects).

The main partners for CCS projects focusing on storage, transport and monitoring are industrials, mainly from the oil and gas industry such as Statoil, Shell, BP, Total, EON. Geological surveys in Europe participating come from the Member States: Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, France, Germany, Greece, Hungary, Ireland, Italy, Lithuania, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and UK. Latvia is included in Estonian-Latvian border project and also non Member States: FYROM, Norway, Serbia, Switzerland have also participated mainly on the projects with ambition to create a network of data base, infrastructure or to disseminate CCS information.

3.1 Research focus and topics

The projects in the field of carbon capture are described according to the different sub-technologies identified in Chapters 1 and 2. The projects belonging to CO_2 utilisation are classified depending on the final product synthesised: fuels, materials and chemicals.

In some cases, one project explores more than one sub-technology or studies a sub-technology and any other initiative. These projects have been considered accordingly, distributing the funds between technologies. As such, the following graphs represent primarily trends.

Projects addressing carbon capture and utilisation have received nearly EUR 280 million EU funding in H2020 programme.

Within FP programmes, EU co-funded projects have reached TRL 7 in amine-based and physical solvents capture. Calcium looping, at TRL 6 was the next most developed capture technology. From TRL 5 in FP7, SEWGS reached TRL 6 within H2020 (. CLC is also targeting TRL 7 within H2020. The overview of the European co-funded projects show a noticeable shift in CO_2 sources, from fossil power plants towards "large point sources".

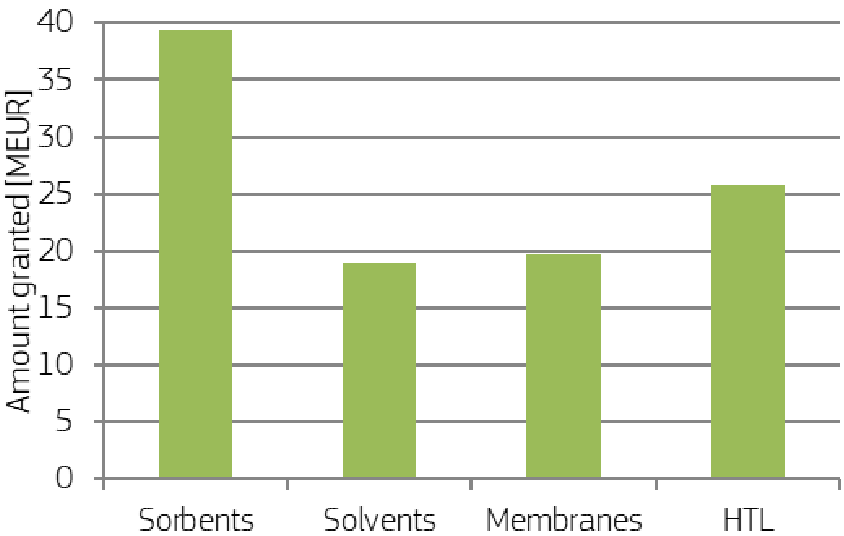
3.1.1 Carbon capture

17 technological projects identified in H2020 programme, have been classified according to their main subject(s) of research. Up to now, H2020 programme funds have been awarded mostly on CO_2 utilisation and less in capture and projects (EUR 162 million and EUR 108 million, respectively). It should however be noted that projects examining CO_2 utilisation are also addressing other aspects too. For example, HyMethShip is looking at combining a membrane reactor, a CO_2 capture system, a storage system for CO_2 and methanol, methanol reforming to hydrogen as well as a hydrogen-fueled combustion engine into one system.

Within FP programmes overall process development together with capture technologies in power generation were topics of the highest granted projects. In H2020 CO_2 separation via sorbents and membranes has also been highly funded with solvents receiving the least support.

In Figure 8 projects and amount granted per sub-technology and areas of research (according to the classification in Table 1) are presented.

Figure 8. Identified amounts granted in H2020 to the different carbon capture sub-technologies and areas of research.



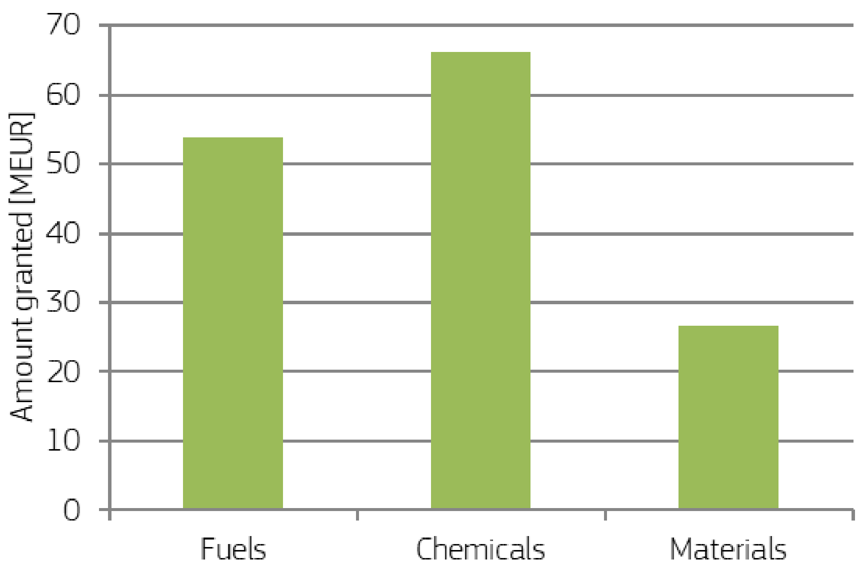
In overall, sorbent technologies represent the most supported research area (EUR 39 million).

3.1.2 CO_2 utilisation

Research on catalytic, photochemical and electrochemical pathways for CO_2-based products is ongoing at industrial and academic levels. Within H2020 the projects are targeting TRL up to 7.

Figure 9 takes into account projects awarded for studying CO_2 utilisation, classified according to their main research areas with projects within H2020 programme focusing on chemicals/chemicals for fuels.

Figure 9. Identified amounts granted in H2020 to the different CO_2 utilisation sub-technologies



3.1.3 CO_2 storage, transport and monitoring

7 projects were identified within H2020 in the CO_2 storage, transport and monitoring domain. It is sometimes difficult to separate transport and monitoring projects from storage, since many times they are connected and projects are looking at those aspects simultaneously. Here projects have been divided in CO_2 storage, transport and monitoring, but the majority of them has the CO_2 storage as final goal. EU funding for these projects has contributed with EUR 48 million.

The CCS R & D programs have been done in cooperation with all EU member states. The majority of CO_2 storage, transport and monitoring projects has been carried out mainly with research centers, European universities, particularly with the European Geological surveys (EGS) for CO_2 storage assessments. Many of these projects have been concentrated to characterise and define the sites of injections for CO_2 storage. Other projects correspond to all CCS chain. H2020 projects are more concentrated on new and more accurate techniques to monitor CO_2, avoiding any CO_2 leakage. Some transport projects have been developed to make possible a better intercommunication or shared gas/CO_2 transport in Europe.

3.2 Significant projects on national and international level

3.2.1 Project overview

According to the Global CCS Institute, there are 19 large-scale projects CCS operating worldwide [18], two more than the ones reported in the previous version of our report. In Europe, the two operating projects in Norway, are implemented in NG processing plants. Worldwide, being in the Americas, the majority of the operating projects employ EOR as final CO_2 disposal except for the Norwegian plants, which use dedicated geological storage. Overall, the projects in operation and construction have the capacity to capture and permanently store around 40 $MtCO_2$/yr.

Large scale, full chain CCS

The Petra Nova facility, a coal-fired power plant located near Houston, US, is one of only two operating power plants with carbon capture and storage (CCS) in the world, and it is the only such facility in the United States. The 110 megawatt (MW) Boundary Dam plant in Saskatchewan, Canada, near the border with North Dakota, is the other power sector facility using a CCS system.

In the Netherlands, the Port of Rotterdam has been leading the efforts to identify the path to collecting and transporting CO_2, which can then be stored in gas fields under the North Sea. These developments have been considered a valuable opportunity to unlock the potential of Rotterdam's industrial zones to become a key CCS cluster. A new businnes plan is currently being elaborated focusing on transport and storage.

Even if not a European Member State, Norway has contributed and collaborated in many EU projects. Norway has developed a strategy for CCS, which aims at identifying measures to promote technology development and to reduce the costs of CCS. A feasibility study report presented in July 2016 showed that realising a full-scale CCS chain in Norway by 2022 is possible and at lower costs than for projects examined earlier. Norway is now in the final study phase and are preparing the basis for investment decision on a full scale CCS project in the Norwegian Parliament in 2020/21.

The Oil and Gas Climate Initiative (OGCI) has also announced its intention to invest up to USD 1 billion for CO_2 reduction technologies and projects over the next ten years.

In the US, the CCUS agenda has been led by the oil and gas industry, which in the Enhanced oil recovery (CO_2-EOR) has found a way to develop and go further with CCS for industrial proposals [57], [58]. This has not been the case in Europe, where there are no new commercial–scale projects planning to or employing CO_2 EOR.

Global assessements and complete evaluation of geological CO_2 storage capacity are still difficult mainly due to inconsistent data with insufficient quality from some regions. Furthermore, the global CO_2 assessment has several shortages and also the method to calculate CO_2 storage capacity is not same in different regions. Despite of this and using the more detailed studies found in the literature, [12] developed a database for regional geologic CO_2 storage capacity wordwilde. They estimated the global CO_2 storage capacity betweeen 8 000 and 55 000 Gt (due the lack of harmonized methodology). The CO_2 storage capacity depends on the knowledge of the geological conditions to store CO_2 and studies about risks and assessments are still not concluded in many parts of the world.

Together with US, China and Middle East, the majority of projects are related to enhanced techniques, EOR (Enhanced oil recovery), ECBM (enhanced coal bed methane) [59]. According to IEAGHG the global capacity for CO_2 storage is 140 Gt CO_2 in more depleted oil fields. CO_2-EOR can play an important role to meet the global CO_2 reduction emissions. In Europe, CO_2-EOR has been analysed by Norway and UK. However, companies activities such as Shell and BP have showed that this technology is not economic in the North Sea. The transport of large CO_2 volumes offshore the infrastructure costs would be prohibitively high. Despite of this, the Danish company Maersk is currently examing the possibility of CO_2-EOR in Denmark. In the UK there is a task force to identify CO_2-EOR as potential cost saving element regarding future CCS projects.

3.2.2 Activities by region

Europe

In 2017, European stakeholders created a Temporary Working Group (TWG) to elaborate a SET PLAN for CCUS. This group was composed by 11 countries (the Czech Republic, France, Germany, Hungary, Italy, Norway, the Netherlands, Spain, Sweden, Turkey and UK), industrial stakeholders, non-governmental organizations 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 group has the task to advance the respective Implementation plan, reaching collectively the agreed technology targets.

SETIS[4] has created a reporting methodology to facilitate this process, which form the basis of the pilot "2019 SET Plan progress report". This publication presents the state of the implementation of the SET Plan based on the inputs from the SET Plan IWGs. For CCUS, the IWG suggests revision of its targets because of new policy directions [60].

SET Plan has indicated specific targets that may support further development of specific technologies:

- At least one commercial-scale, whole chain CCS project operating in the power sector.
- At least one commercial scale CCS project linked to an industrial CO_2 source, having completed a FEED study.
- 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, this could also involve cooperation across borders for transporting and storing CO_2 (at least 5 clusters in different regions of the EU).
- 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.
- An update inventory on CO_2 storage sites and capacity in Europe
- At least 3 new CO_2 stroage projects
- 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.
- 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.
- By 2020, Member States having delivered on their 2030 nationally determined contributions to the COP21 agreement. This entails MS 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 to make their energy systems compatible with the 2050 long-term emission targets.

The SET Implementation plan endorsed in September 2017, also includes targets for CCS and CCU under the SET Plan Action 9.[5] Table 8 lists the projects that, at that time, were indicated as SET Plan flagship projects.

Table 8. SET Plan flagship CO_2 capture/utilisation projects

Location	Project	TRL	Industry	Partners
FR	VALORCO	3-5	Steel	ArcelorMittal, CNRS, LRGP, Université de Lyon, IFPEN, Air liquide, IJL, ICSM,

[4] SETIS is the online Information System for the European Strategic Energy Technology (SET)-Plan.

[5] SET Plan Action 9: 'Renewing efforts to demonstrate carbon capture and storage (CCS) in the EU and developing sustainable solutions for carbon capture and use (CCU)'.

Location	Project	TRL	Industry	Partners
				ICF, IDEEL
UK	Carbon8	9	Fertiliser manufacturing	Carbon8 Systems/Carbon8 Aggregates
FR	CIMENTALGUE	5-7	Cement	HeidelbergCement, AlgoSource technologies, GEPEA (University of Nantes)
DE	Carbon2Chem		Steel	Various depending on process studied
FR	Cryocap	6-9/10	Hydrogen production	Air Liquide
SE	FreSMe	5-7	Iron and Steel	i-deals, ECN, SWEREA MEFOS, CRI, Kemiski Institut Slovenia, Univ. Babes Bolyai, SSAB EMEA, Stena Rederi, Kisuma Chemicals, Tata Steel, Array Industries, Politecnico di Milano
FR	JUPITER1000	7-8	Unidentified	GRTgaz, CEA, Atmostat, CNR, McPhy Energy, Leroux et Lotz, GPMM (Marseille Port Authority), TIGF
FR	VABHYOGAZ 3	9	Waste processing	Hera France, HP SYSTEMS, TRIFYL, EMTA (VEOLIA), Mines d'Albi
FR	VASCO2	7	Iron, waste processing	AM, Total, CEA, GPMM, IFREMER, COLDEP, HelioPurTechnologies, Solamat Merex, Kem One, INOVERTIS, Métropole Aix-Marseille Provence

France

France has two main sources of financing R&D in CCUS, the French National Research Agency (ANR) and ADEME. In 2005, the ANR started a research programme on CCS with 33 projects receiving more than EUR 27 million. In 2011, the ANR re-launched a call for proposals on CCUS. ANR has financed several research projects, among others evaluating the conversion of emitted CO_2 by heavy industry processes into methanol, syngas production and conversion into fuels and membranes integration.[6]

ADEME financed 26 R&D projects between 2001 and 2009. In 2010, within the framework of Future Investments, France started to cover CCUS, within demonstration and technology platforms for renewable, low-carbon energy and green chemistry (ADEME, EUR 1.35 billion) and centres of excellence on low-carbon energy (ANR, EUR 1 billion) [48]. In the innovation programmes from ADEME in the time frame of 2014 to 2020, different themes such as algae, power-to-gas, or chemical conversion of CO_2 are examined [61]. ADEME is managing a EUR 4 billion program for R&D support in the environment and renewable energy sectors, which consists of subsidies, refundable grants, and equity. This includes assistance for CCUS, which is a component in its "Sustainable Production and Renewable Energy" programme.

The French Energy ministry (DGEC) is a member of Mission Innovation (Challenge 3-CCUS) and the French Research Ministry (MESR) supports CCUS via participation at the new call of ERANET ACT (CCS and CCU) and PHOENIX, the CCU initiative between Germany, Netherlands, France and Flanders.

Germany

[6] http://www.agence-nationale-recherche.fr/projets-finances/?tx_lwmsuivibilan_pi1[Programme]=270

Germany has focused on research and R&D in CCS supporting specific schemes. Cooretec funding initiative supported by the Federal Ministry of Economics and Technology is followed up by the "Flexible Energieumwandlung". The specific research themes of this initiative will be incorporated into the 7th Energy Research Programme, which was adopted in 2018.[7] The Geotechnologien programme on CO_2 storage (2005-2011), funded by the Federal Ministry of Education and Research and the German Research Foundation, has financed around 20 projects in the field, including the storage catalogue of Germany finished in 2011 by BGR[8] [48], [62].

The Federal Ministry of Education and Research has a specific funding programme on "Technologies for sustainability and climate protection" that includes "Chemical processes and use of CO_2" as one of the supported lines of research. The CO_2 utilisation programme which started in 2009 and has been complemented by the Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF), includes the major research framework program "FONA[3]—research for sustainable development." Research themes that have been supported include the synthesis of polymers, dimethylether, aldehydes, acrylic acid; or research on catalytic processes, photocatalysts and electrocatalysis. In addition, the Ministry launched the "CO2Plus" programme, focused on CO_2 utilisation, and "r+Impuls", aimed at supporting the upscaling of technologies up to, at least, TRL 5 (BMBF, 2018; Mennicken, 2016). Other initiatives include the PHOENIX initiative (See above) and Carbon2Chem, running until 2020 with a budget of EUR 60 million.

Ireland

In its 2019 Climate Action Plan,[9] Ireland included CCS in Action 33. This refers to the "establishment of a Steering Group to examine and oversee the feasibility of the utilisation of CCS in Ireland, and report to the Standing Committee on Climate Action as appropriate". ERVIA-Gas Networks Ireland are considering the development of a CCS facility off the coast of Cork, Ireland. The EUR 1 billion project would involve capturing CO_2 from Whitegate and Aghada — two gas-fired power plants in the area — and storing it at the Kinsale gas field, which is expected to be exhausted within a few years.

Norway

The Norwegian government (Ministry of Petroleum and Energy) has initiated plans for a full-scale carbon capture and storage (CCS) project. The Norwegian Parliament is expected to make an investment decision for the project in 2020/2021. The project will then be able to commence operations in 2023/2024. The Norwegian government within its plans for a full-scale CCS project in Norway, does not overrule opportunities for CO_2 use for fuel production which can be parallel to the commercial scale of CO_2 storage, or for EOR and geothermal power applications [65], [66]. The Norwegian parliament has also specifically granted funds for research on captured CO_2 to feed aquaculture fish stocks. Operational since 2016, the pilot will undertake a five-year research programme with a view to establishing a commercial plant for the production of marine algae once testing is complete [67]. While CCUS projects in Norway focus on a permanent storage proposal, specific projects on a national level such as the Futurefeed project, led by Sintef explored CO_2 as a feedstock for chemicals, polymers, and fuels.

Spain

The CIUDEN CO_2 Storage and Technology Development site has been operational since 2015. Two projects were identified for CO_2 Utilisation, partly subsidised by the Ministry of Finance and Competitiveness within the "Local investment fund for employment – government of Spain": The BIOSOS project to develop technologies for designing integrated bio-refinery concepts, the SOST-CO_2 project, to address the whole lifecycle of CO_2 to-

[7] https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/7-energieforschungsprogramm-der-bundesregierung.html /

[8] http://www.geotechnologien.de/index.php/en/index.html

[9] https://www.dccae.gov.ie/en-ie/climate-action/publications/Documents/16/Climate_%20Action_Plan_2019_Annex_of_Actions.pdf

wards a sustainable alternative to geological storage, and the CO_2FUNNELS project, to demonstrate the possibility of capturing CO_2 by fertilisation of energy crops, obtaining biomass which may be used in turn to generate energy [68].

The Netherlands

Since 2004, NL has supported CCS through its programmes CATO-1 (2004-2008) and CATO-2 (2010-2014). The CATO-3 programme started in 2011 with eight differentiated sub-programmes including CO_2 use, transport and storage, capture, or public perception [69].

Current Dutch initiatives mainly focus on the industrial sector, specifically waste-to-energy plants, as well as fertilizers, ammonia and melamine plants. Other highlights include green hydrogen production, as well as CO_2 utilisation in a concept of waste-to-energy, where the CO_2 will be used in horticulture. The Port of Rotterdam continues to develop the CO_2 storage and transport parts of the formerly ROAD project after the capture component was cancelled in 2017.

In 2019, the Dutch government published its Climate Agreement where CCS in industry is "regarded by the sector and by the national government as a crucial activity to achieving the 2030 target".

Table 9 indicates a growing number of industrial projects including national initiatives. On the technology specifics, analysis shows that CO_2 capture technologies that projects are considering to be employed in industrial applications are generally mature. Additionally, industrial processes often yield exhaust streams containing higher CO_2 content than the flue exhausts from fossil-fuel fired electricity production such as coal and natural gas. As it is generally accepted that there is an inverse relationship between cost of CO_2 separation and initial feed stream, carbon capture from industrial processes may offer more economical abatement than what is projected in similar applications within the power sector [70].

The high levels of technology readiness that is indicated denotes that industry is technically ready for CO_2 capture realisation. Thus, it is demonstration projects that will be mostly needed in specific sectors or processes.

Table 9. Industrial CO_2 capture/utilisation laboratory/bench, pilot and demonstration plants in continental Europe

Location	Project	Status	Industry	Partners
BE	ArcellorMittal Steelanol Ghent	In construction	Iron & Steel	ArcelorMittal; Primetals Technologies; LanzaTech; E4tech
FR	DMX™ Demonstration in Dunkirk	Advanced development	Iron & Steel	ArcelorMittal; Axens, IFP energies nouvelles, Total
NL	HIsarna Pilot Plant	Planned	Steel	TATA Steel
BE	LEILAC	In construction	Cement	Calix (Europe) Limited; Heidelbergcement Ag; Cemex Research Group Ag; Tarmac Trading Limited; Lhoist Cherche Et Developpement Sa; Amec Foster Wheeler Energy Limited; Calix Ltd; Stichting Energieonderzoek Centrum Nederland; Imperial College Of Science Technology And Medicine; Process Systems Enterprise Limited; Quantis
NL	MAGNUM	Under evaluation	Hydrogen production	Statoil, Vattenfall and Gasunie
NO	Norway CCS	Planned	Cement, ammonia production, waste processing	Norcem AS, Yara Norge AS, Klemetsrudanlegget AS
FR	Port Jerome CO_2 capture Plant	Operational	Hydrogen production	Air Liquide
VL	Port of Rotterdam CCUS Backbone Initiative (PORTHOS)	Advanced development	Various	Port of Rotterdam, ebn, gasunie
NO	Sleipner	Operational	Oil and gas	Statoil
NO	Snohvit	Operational	Oil and gas	Statoil
SE	STEPWISE	Operational	Iron & Steel	Stichting Energieonderzoek Centrum Nederland; Swerea Mefos AB; Universitatea Babes Bolyai; Johnson Matthey PLC; SSAB EMEA AB; Politecnico Di Milano; Kisuma Chemicals BV; Amec Foster Wheeler Italiana SRL; TATA Steel UK Consulting Limited

Location	Project	Status	Industry	Partners
NL	Twence Waste-to-Energy CO_2 Capture and Utilisation	Operational	Waste incineration	Twence, Aker Solutions

4 Impact Assessment

Besides technology projects, funding has been channeled to initiatives that do not directly develop the technology but are crucial for its advance: professional networks, personal training, social opinion and policy advice.

The main projects related to all CCUS chain have been either as full chain or focusing on more than one components:

H2020 ACT – ACT aims to accelerate CCUS technologies in Europe. ACT started in June 2016 with a finishing time planned for 2021.

H2020 IMPACTS9 – Starting on May 2019, the project aims to support the realisation of the SET Plan Implementation Plan on CCS and CCU.

CCUS Knowledge Network - Building on the work of the European CCS Demonstration Project Network, which operated from 2009 to 2018, this EC funded project aims to support sharing knowledge and learning within project members toward the delivery and deployment of CCS and CCU.

The full list of projects is given in the Appendix.[10]

4.1 CO_2 capture

Levelised Cost of Electricity, LCOE (EUR/MWh), cost of capture (EUR/tCO_2), cost of CO_2 avoided (EUR/tCO_2), capture rate (%), energy for solvent regeneration or obtained O_2, operational hours (h) or efficiency penalty (%) have all been used as key performance indicators (KPIs) for projects.

Technology readiness level (TRL) is a common metric that has been widely used to indicate the maturity level of particular technologies. However, it is not always clearly indicated by project developers and research consortia. Making TRL reporting a prerequisite for future programmes could provide a uniform basis in analysing the results and impact of supported projects.

Ionic liquids (IL) were included in the studies within H2020 DIACAT. Contrary to previous programmes, sorbent facilitated capture via CO_2 adsorption has been a main focus of H2020 projects.

Projects focusing on CLC received important support in FP programmes. The decreased support identified within H2020 can be justified as the technology moved up to TRL 7. Calcium looping (CaL) focused projects were present within FP6 and FP7 achieving a TRL 6. CaL was studied within a range of technologies for the cement industry reaching TRL 6.

Completed H2020 projects aimed at TRL 6 for oxyfuel, chilled ammonia, membrane, sorbent and CaL in industrial processes. While there have not been breakthroughs with regards to increases in TRL, these projects have swift the approach of carbon capture to industry.

For ongoing projects, with regard to certain technological options and based on specific targets indicated by projects on their TRL evolution it is expected that:

- ✓ Calcium looping (CaL) and Chemical Looping Combustion (CLC) moves up to TRL 7 within H2020.
- ✓ Process improvements bring membrane application to TRL 8 and up to TRL 9 for ceramic and polymeric membranes.
- ✓ Adsorption process using solid sorbents move up to TRL 8.

[10] 2019/2020 projects for which grant agreements are in preparation have been excluded.

4.2 CO_2 utilisation

Fuel synthesis has been the dominant area of study for CO_2 utilisation both in FP 7 and H2020. For methanol as a fuel while in FP the aim was achieving TRL 4 while within H2020 projects the aim was to move methanol synthesis to TRL 6. While H2020 projects are ongoing, seven projects that can be classified in this category are currently completed. Two of the projects mark “successful testing”.

Regarding materials synthesis, the three FP 7 projects employing catalytic processes achieved TRL 4 and TRL 5 for cyclic carbonates and polypropylene carbonate respectively. In H2020, materials synthesis moved up to TRL 7 for polyols production.

CarbonNext project was to evaluate the potential use of CO_2/CO and non-conventional fossil natural resources as feedstock for the process industry in Europe. Results of the project included the identification of value chains within processes and where industrial symbiosis can be valuable (chemistry, cement, steel, etc.).

4.3 CO_2 storage

6 projects have been identified within H2020 with focus on CO_2 storage:

ECCSEL - European carbon dioxide capture and storage laboratory infrascture. ECCSEL finished in 2017 and became ECCSEL-ERIC, led by Norway and with participation of 5 other European countries. ECCESL-ERIC aimed to become an trans-national center and multi-facilities for CCS research. ECCSEL currently is inviting other countries in the world to become member of ECCSEL-ERIC, enlarging its ambition.

ECCSEL had some deviations and delays of its objectives but achieved the majority of tasks. The project had 3 publications and had participated in several conferences and workshops. There is also a webpage dedicated to this project [71].

The total costs of this project was EUR 3.25 million and EU has contributed with the complete amount.

CO2NOR – Carbon dioxide storage in nanomaterials based on ophiolitic rocks and utilisation of the end-product carbonates in the building industry. This project started in October 2017 and reached its objectives investigating a new method for safe CO_2 storage in low-cost ultramafic and mafic rocks in Cyprus. This method can be used for a faster mineral trapping of CO_2, making more efficient the CO_2 storage process.

Novel nanomaterials produced during the experiments can also be used in the building industry.

The total costs for this project was EUR 0.15 million and EU has contributed with the whole amount.

OMNICS – This project developed a toolset to investigate the microstructure evolution of geomaterials specifically for geological CO_2 storage.

The geochemical reactions involved in CO_2 storage processes were well analysed using combining Synchroton technique for the analysis of pore development. This has been coupled with a numerical programme which allows to predict the structural changes of porous media in a flow field.

The results have been disseminated in conferences and papers in technical journals.

The total costs for this project was EUR 0.2 million and EU has paid all costs.

STEMM-CCS – Strategies for environmental monitoring of marine carbon capture and storage. This project started in 2016 and should finish in 2020. Some preliminar results show that there are high costs associated to monitoring CO_2 but there are also some strategies to reduce these costs.

The total costs of this project is EUR 15.9 million. It will be covered completely by EU funds.

ENOS - Enabling onshore CO_2 Storage in Europe. 5 field sites have been selected across Europe (IT, UK, ES, CZ and NL) for CO_2 storage characterisation, monitoring, leakage simulations, dissemination, social acceptance and recently in the Q16-Maas field, there is consideration to combine CCS and geothermal energy.

This is an important project regarding CO_2 storage assessment trough 5 European countries. It is also an interesting verification of techniques for safe CO_2 storage. It is planned to finish in 2020. The total costs are EUR 12.4 million, and totally covered by EU funds.

CARBFIX 2 – Upscaling and optimizing subsurface, in situ carbon mineralisation as an economically viable industrial option.

This project is a continuation of CARBFIX from FP7. The project is known for the particularty to make possible and efficient the CO_2 storage in basalts. The ongoing project is expected to be finished in 2021.

The total costs for this project will be EUR 2.3 million covered completely by EU.

4.4 CO_2 transport

GATEWAY – Developing a pilot case aimed at establishing an European infrastructure project for CO_2 transport. This project finished in 2017 and aimed to achieve a paneuropean infrastructure to enable transport of CO_2 in a commercial and legal way.

The total costs for this project was EUR 0.78 million and EU covered all costs.

4.5 CO_2 monitoring

GEAGAM – Geophysical Exploration using advanced Galerkin methods. This project started in 2015 and finished in April 2018. The results obtained include the state-of-art of numerical methods which can better determing the material properties that compose the Earth's subsurface. A webpage built during this project where around 100 publications and 25 presentations can be found [72].

This project involved PhD students, post doc researchers and professors of 10 universities and research institutes across the world. Courses and lectures have also been organized for the dissemination of this project.

This project had total costs of EUR 0.5 million completely covered by EU.

STEMM-CCS – Strategies for environmental monitoring of marine carbon capture and storage. The objective of this project is to test the detection of CO_2 leakage by quantifying it. The results should serve as technical support for mitigation and remediation policies in and under North Sea. This project also aims to become a demonstration pilot taking in account geochemical and biological variability in the North Sea. It is a pan European project involving universities, and various industries. The costs are estimated to EUR 16 million and EU will cover all costs. The project is led by the National Oceanography Centre (NOC) in the UK.

CARBSENS – An ultracompact greenhouse gas remote sensing system for ranges between 500 and 2 000 m. This includes monitoring of CO_2 leakage from CO_2 storage sites. This project is finished in 2018 and the total costs are EUR 0.14 million fundedtotally by EU.

VIRTUALSEIS - Virtual seismology: monitoring the Earth's subsurface with underground virtual earthquakes and virtual seismometers. With this technique it is expected to monitor fluid flow in aquifers. This can be useful for CO_2 storage reservoirs. The project should be completed in 2022. The total costs for this project will be EUR 2.5 million, covered in total by EU funds.

5 Technology Development Outlook

The basic idea of capturing CO_2 and preventing it from being released into the atmosphere was first suggested in the late 1970's,[11] proposing to use existing technology in new ways. Since then, although not always a "smooth sail", several milestones can be highlighted for the technology:

- ✓ The first full scale demonstration plant, and therefore, the most advanced legal framework for storage has been developed in Canada.
- ✓ The US is where the second large scale demonstration plant, Petra Nova CCS project is located.
- ✓ The US is also the place with favourable business model integrating CO_2 capture with EOR but projects have taken off even with employing geological storage.
- ✓ Developments can be noted not only in power generation but also in industrial applications where an Ethanol Production plant (Illinois Industrial Carbon Capture and Storage) has been operating since 2017.
- ✓ Two more projects can now demonstrate CCUS viability for industrial applications: Abu Dhabi CCS for iron and steel and Uthmaniyah CO_2-EOR Demonstration in natural gas processing.
- ✓ Norway has pioneered deep saline aquifer storage and has been capturing CO_2 from flue gases in large scale sources for more than 20 years. 1 M tonnes per year is injected in the Norwegian offshore.
- ✓ The Netherlands decarbonisation plans include constructing a hub for CO_2 transport in Rotterdam from onshore to offshore, where CO_2 will be stored.
- ✓ The first "commercial ready" direct air capture (DAC) plant opened in Switzerland iin 2017. This technique is currently tested in Iceland, to be combined with CO_2 storage in basalts. The first results show faster storage.
- ✓ China's willingness to exploit coal resources brings potential to decreasing the costs of capture, also by combining CO_2-EOR in the storage process.

Nevertheless, for CCS/U to make the maximum contribution to emissions reductions, the pace of development and deployment needs to increase substantially.

5.1 Economic factors

Different production routes as well as capture technologies and configurations result in a broad range of CCUS costs. Different studies adopt different assumptions in estimating costs and may not be directly comparable. While the aforementioned values are only indicative, they reflect that many factors influence costs including plant location as well as potential technology deployment.

In 2011, the European Zero Emissions Technology & Innovation Platform (ZEP) presented CCS costs in power generation ranging from nearly EUR 30-60 per tonne CO_2 avoided [73]. The Global CCS Institute published a series of publications presenting CCS cost data but with the US Gulf Coast as a reference location [74], [75]. Rubin et al. presented costs information from various studies [76] indicating a mean range of EUR 35-67 (USD 46-87) for every tonne of CO_2 avoided in different coal fired power generation options.[12] A more recent study presents a range of EUR 50-75 per tonne of CO_2 avoided in supercritical power plants with CO_2 capture versus 65-95 €/t for the NGCC plants for the different locations [77].

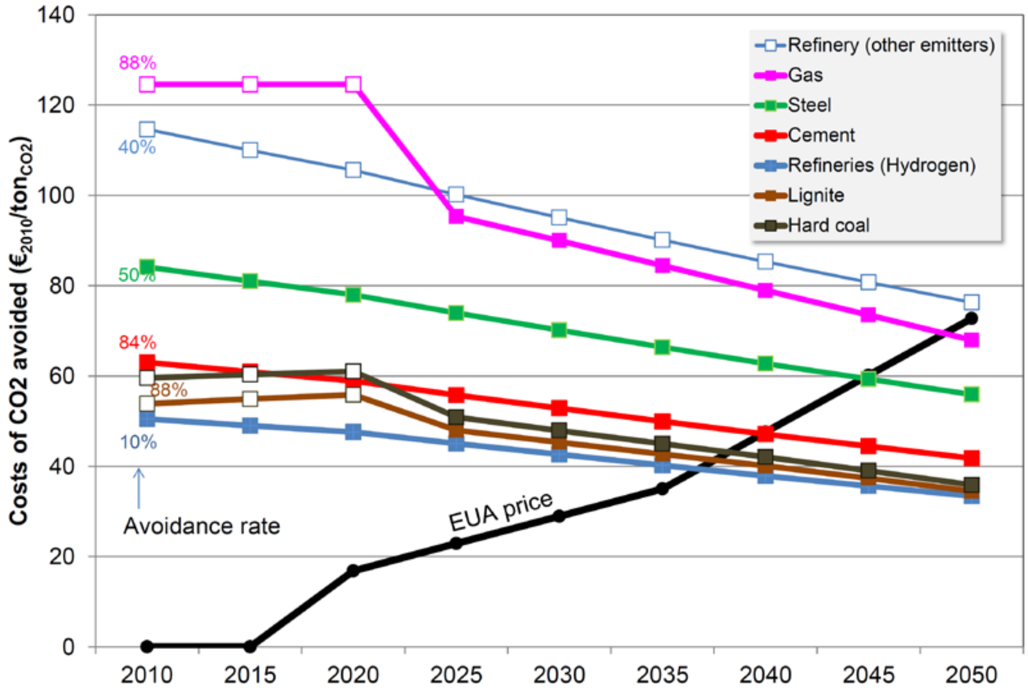
Regarding CCS in main industrial emitters, ZEP reported for oil refineries a cost[13] of EUR 30 per tonne of CO_2 to abate emissions from the gasifier and EUR 90-120 per tonne of CO_2 for the other emitters. For an integrated steel mill, the costs for avoiding 50/60% of CO_2 emissions are estimated to be EUR 55/61 per tonne of CO_2, respectively, while for cement they report nearly EUR 41 tonne of CO_2 avoided [78].

Regarding the cost development of low carbon power generation technologies, Tsiroupoulos [79] project capital cost reductions within the different decarbonisation scenarios considered of up to 30%. De Vita et al., for the data underpinning the European Commission's reference scenarios [80], project a reduction of 10-16% in overnight costs

[11] On Geoengineering and the CO_2 Problem. IIASA Research Memorandum. IIASA, Luxemburg.
[12] Original values in 2013 USD (1 EUR = 1.301 USD).
[13] Without transport and storage.

and up to 28% in operating costs toward 2050. ZEP expected cost reduction of CO_2 capture units by 2050 as shown in Figure 10 and included analysis also for industrial installations.

Figure 10. Costs of CO_2 avoided for different sectors [78]



In 2018, the International CCS Knowledge Centre (Knowledge Centre) released the feasibility study for implementing CCS in the Shand power station in Canada. One of the key findings of the report is the deep capital cost reductions for next projects reaching a 67% decrease per tonne of captured CO_2 in the case study provided in the report [81].

5.2 Deployment scenarios

The JRC-EU-TIMES modelling exercise [83] includes a scenario (Zero_Carbon) which reaches 100% emissions reduction by 2050. The reductions projected by this scenario are in the range of the EU long-term strategic vision scenarios. Underground CO_2 storage is limited to 300 Mt annually and nuclear expansion is allowed in those countries with no contradicting policies. The results show large amounts of RES, hydrogen and e-fuels driven by the GHG emissions reduction and the limitation on CO_2 storage.

According to the IEA, with only two large-scale CCUS power projects in operation, CCUS in power remains well off track to reach the 2030 Sustainable Development Scenario (SDS) level of 350 $MtCO_2$ per year. In the IPCC SR15 Report [4], three of the four pathways include CCS and bioenergy with CCS (BECCS) as necessary mitigation technologies. On the way to net-zero by 2050, CCS alongside other climate action solutions will be necessary. Net-zero will require a whole variety of measures: low-carbon and renewable energy, decarbonisation of industrial sectors, as well as carbon removal technologies, including carbon capture and storage (CCS).

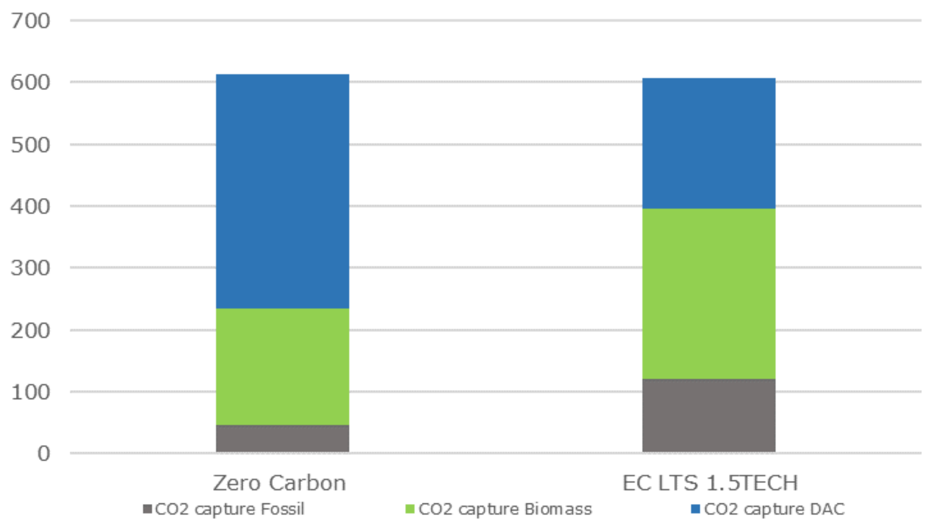
In the various scenarios put forward in the EU long-term strategic vision [82], carbon capture requirements reach 606 $MtCO_2$,[14] making a strong case that CCS has a role to play in supporting Europe's path to a climate neutral economy.

[14] 1.5TECH scenario.

CCS can significantly reduce emissions in energy-intensive industries including cement, petrochemicals and steel. In the cement sector, it is likely to be the only feasible route to eliminate process emissions. For the industrial sectors considered in the EU long-term strategic vision scenarios, one of the two reaching the highest emissions reduction by 2050, is that considering CCS.[15] Specifically, 97% reduction is projected for the iron and steel sector, 143% in the chemicals sector, 83% for lime and cement, 94% for pulp and paper and non ferrous metals and 90% for refineries.

In 2050, the JRC-EU-TIMES projects that the majority of CO_2 captured would come from DAC while the EU LTS scenario projects more CO_2 captured from BECCS (Figure 11).

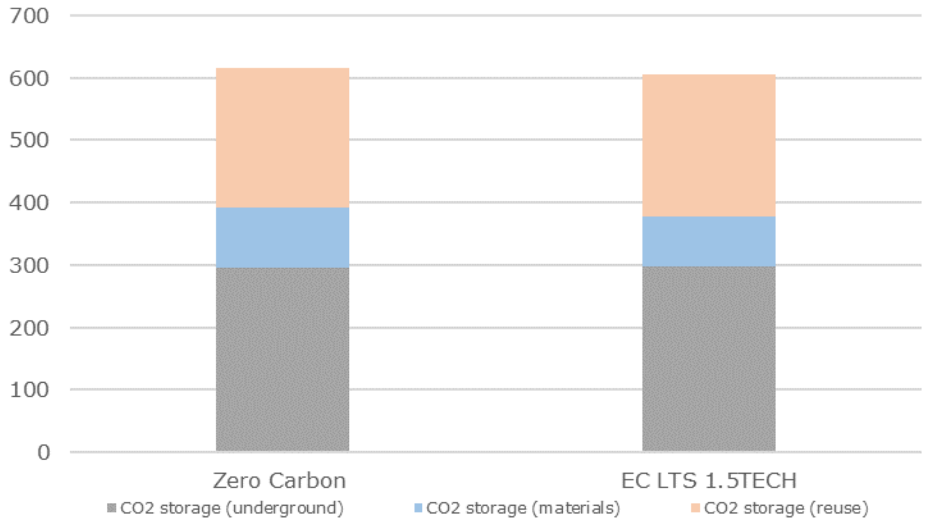
Figure 11. Mt/year of CO_2 captured toward 2050 carbon neutrality from the JRC-EU-TIMES and the EU long-term strategic (EU LTS) vision scenarios



Both scenarios project that significant amounts of CO_2 would need to be permanently stored underground or in materials (Figure 12). In the Zero Carbon scenario, CO_2 can be used as a feedstock in the petro-chemical industry, replacing oil and natural gas that are now used for non-energy purposes. CO_2 reuse for the production of fuels also plays an important role in both scenarios toward carbon neutrality.

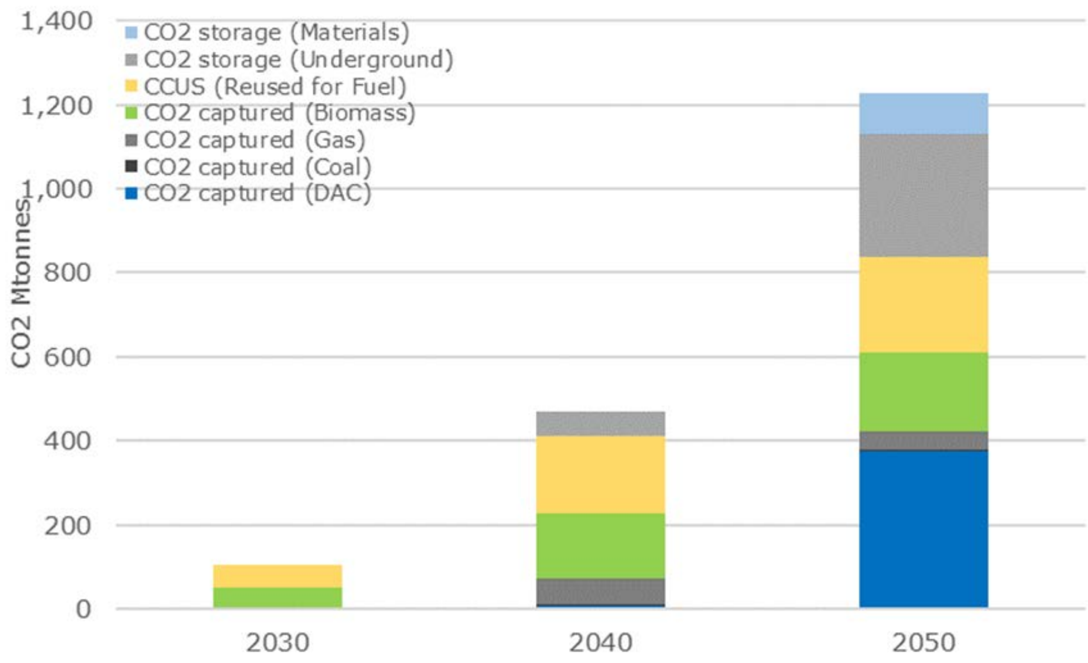
[15] The other scenario is the 1.5LIFE which relies less on the technology options of 1.5TECH, but assumes a drive by EU business and consumption patterns towards a more circular economy.

Figure 12. Mt/year of CO_2 stored and reused toward 2050 carbon neutrality from the JRC-EU-TIMES and the EU long-term strategic (EU LTS) vision scenarios



The JRC-EU-TIMES zero carbon scenario (Figure 13) projects that the minimal amounts of CO_2 captured by 2030 to be re used for fuel production. Toward 2040, direct air capture (DAC) appears even if with minimal CO_2 captured but takes off in 2050 for the capture of nearly 380 Mtonnes CO_2. Toward 2030, 2040 and 2050, CO_2 is collected mainly as a by-product from 2nd generation biofuel facilities ("Biomass" category) and reused for fuel production (CCUS category). Underground CO_2 storage appears in 2040 with CO_2 volumes increasing 6 times by 2050.

Figure 13. CO_2 captured, used and stored toward 2050 carbon neutrality from the JRC-EU-TIMES and the EU long-term strategic (EU LTS) vision scenarios



5.3 Technology barriers to large scale deployment

Different road-maps identify CCUS as part of the technologies necessary to facilitate the transition towards zero-emissions' industrial and energy sectors. However, CCUS has not yet completely met the expectations and requirements in terms of implementation rate. A list of main barriers to develop CCUS projects in the world has been given in the previous version of this report [56] and appear persisting. The most important barriers for the full CCUS chain are regulatory implementation, economics, risk and uncertainties associated with projects as well as social acceptance. The majority of people still appear unaware of CCS, at least in UK. Recent studies by Statista in UK [84] conducted between March 28 to April 6 2018 reveals that in face to face interviews with 2 102 people, 59 % had never heard about CCS and only 3 % responded that they really know about it.

For carbon capture, while technology is not expected to impede implementation, efficiency loss and cost remain the main barriers for carbon capture. Regarding CO_2 utilisation, besides the resolution of technological challenges needed to advance the TRL, other factors are also crucial to promote CO_2 utilisation processes. Specific incentives will be essential to set the basis of the roll-out of CO_2 as raw material. LCA analyses of the integrated approaches will be essential for this, by evaluating the CO_2 emissions savings of CO_2 utilisation plants vs. conventional. Technical aspects and infrastructure should be improved in certain areas especially concerning the transport and assessment level for CO_2 storage.

Listing the main barriers to the implementation of different CCUS is possible with different levels of difficulty, as showed in the table below according to [85].

Table 10. Main barriers to large-scale CCUS development

Barriers	Capture	Transport	Storage	Utilisation	Monitoring
Economic	High	High	High (but less than Policy)	High	Medium
Policy	Medium	Medium	High	Medium	Medium to high
Technology	Medium to low	Low to very low	Low	Medium to Low	Low

6 Conclusions & Recommendations

Carbon capture, utilisation and storage continues to be an important topic for research and innovation. Combining CCS and renewables is also promising mainly in terms of cost and energy savings and a dedicated report presents these synergies [86]. The currently ongoing H2020 projects are concentrating on developing or improving new techniques for CO_2 capture and utilisation and also to get more precise techniques for CO_2 monitoring.

The next step is to deploy this technology in Europe, involving different stakeholders. Many have already actively participated in the SET PLAN CCUS action 9 and are now putting effort to implement this. Action 9 has pointed out the gaps, necessary research and innovation actions for CCUS deployment. An Implementation Plan has been set (see Appendix D) since 2017.

According to this plan, there is the immediate necessity for at least one full chain CCS project and at least 3 pilot projects to be created in the next years for capture, utilisation and storage. The transport of CO_2 can be stimulated via Projects of Common Interest (PCI) funding. Clusters and hubs must be accelerated and CCU is to be a first step to industrial deployment. Dissemination and public acceptance studies must also be considered.

On a MS level, industrial interest is growing and business cases are currently being prepared by, for example, Norway (full chain CCS project) and the Netherlands (PORTHOS). Furthermore, the necessity to create hubs and clusters through Europe, as a way to accelerate this process and to share knowledge and costs, is becoming more and more evident.

Still, in terms of number and scale of projects Europe is behind other regions. The US is leading the way with the main reason for this being the link with enhanced oil recovery (EOR), which has made industrial investments more attractive (a trend also recently followed by China). In Europe, the two active industrial projects involve dedicated geological storage (Sleipner and Snøhvit, in Norway).

6.1 Carbon capture

The review of the state-of-the-art and of the EU co-funded projects shows that capture technologies are advancing towards higher TRLs. Specifically, high temperature looping technologies are targeting TRL 7 while sorbent technology is expected to reach up to TRL 8 and membrane systems a TRL 9. However, R&D efforts remain crucial with regards to technical challenges that in general concern:

- The parasitic loss caused in efficiency;
- Cost for solvent regeneration or capture;
- Materials optimisation for severe conditions, for increased availability and for reduced costs;
- Control of emissions other than CO_2, e.g. amine degradation;
- Flexibility for integration in flexible operation modes;
- Demonstration at full scale to increase the know-how and sufficient confidence in the technology.

In addition to CO_2 separation, understanding the potential of carbon capture in H_2 production will have to be pursued, i.e. H_2 production based on fossil (or biomass) fuels.

Significant research efforts have been undertaken in examining installation of carbon capture on coal power plants but there has not been progress in realising major pilot or demonstration projects in Europe. The demonstration of carbon capture technologies in natural gas (NG) plants will be necessary, if they become a dominant form of thermal plant capacity and as a consequence, a significant source of CO_2 emissions, even if lower than coal fired plants. The observed shift towards industrial carbon capture should also be taken into account.

In a more generic view, carbon capture technology could benefit from developing generally accepted cost and performance metrics such as a standard methodology, as well as relevant parameters and assumptions for the metrics' calculation.

Projects that have started in 2019, especially through H2020 ACT, are studying many of the issues that have been recommended in the previous version of this report. Further research on a larger scale and integrated with the CCUS chain should, thus, be the next step.

Costs relevant to CO_2 processes reported through the years differ significantly. Thus, the cost alone would not be an effective indicator for funding programmes. Rather, indicating specific cost reductions, in the context of a specific target (such as the US DOE target of USD 40/t CO_2) could be a good measure. Additionally, taking into account the changing setting in power generation will be particularly important. For example, NG plants may take a larger share of new installations for electricity production in the following years. Thus, it is important that issues such as flexibility are also studied together with the most suitable capture technologies for such plants.

Another important observation is the shift of interest to implementation of carbon capture in industry. However, deploying carbon capture in industry changes the boundary conditions for the capture operation. The composition and flow rates of flue or off-gases to be treated as well as the operationg conditions vary among different industries. As such, viewing technologies and their potential with regards to their applicability in specific industries will continue to be relevant.

Finally, Direct air capture (DAC) has gained interest mostly in popular media, because it appears to be an easy fix to the issue of climate change [45]. This technology is currently being demonstrated by the Swiss Climeworks and with a plant capacity of around 900 tonnes of CO_2 annually. The technology is also being tested for a combination of CO_2 capture and storage in basalts in Iceland. The Scientific Advice Mechanism High Level Group of Scientific Advisors (SAM HLG) in their opinion published in May 2018 indicate the climate change mitigation potential of CO_2 use technologies to be enhanced if the CO_2 used comes from DAC [87]. However, future endeavor will still need to examine barriers of this technology such as ability to be replicated in bigger scale, cost, land and energy requirement as well as its perspective role within the EU ETS.

6.2 CO_2 utilisation

CO_2 utilisation technologies are advancing regarding TRL levels, expected to reach TRL as high as 8 for synthetic fuels within H2020. The number of CO_2 utilisation projects funded through H2020 are significantly more than the projects previously identified within the FP programmes and commercial scale plants already exist.

Increasing the efficiency of CO_2 utilisation pathways will require intensified research on improved catalysts. Proposed, better processes including reactor designs, must target higher efficiency levels, and lowering costs.

Developing a standardised methodology for the evaluation of CO_2 emissions reduction would be necessary if CO_2 utilisation processes are evaluated based on their positive impact on climate change mitigation.

The debate on the duration of CO_2 mitigation through utilisation has been continuous in the scientific community and interested parties. This enhances the view that studies on developing robust methodologies and metrics to assess the time period in which it is likely that the captured CO_2 will be kept away from the atmosphere should be supported. As several efforts are ongoing to address this issue, the upcoming studies should avoid duplications. In parallel, studies to produce information and key data to be used to generate results based on the endorsed LCA methodology should also be supported.

Mineralisation implies permanent storage of CO_2. Thus, from the CO_2 emissions reduction standpoint, it is advisable to prioritise research in this technology. Except mineralisation, CO_2 utilisation processes where the used CO_2 is released back after the utilisation of the product, do not currently qualify to be considered within the EU ETS. However, the benefit of potentially reduced net CO_2 emissions as well as reduced use of fossil fuels should be examined. In this context, studies on materials and relevant properties to enable carbon storage in products should also be prioritised.

6.3 CO_2 storage, transport and monitoring

The research priorities for CO_2 storage, transport and monitoring are concentrated in safety and analysis of risks. Combining CO_2 storage and enhanced oil recovery can represent a good commercial opportunity as the EOR model has the dual objective to maximise oil output and to permanently store CO_2. However the use of the CO_2 EOR technology is concentrated in North America where it has been in commercial use for more than 40 years and more recently in China, where infrastructure is being built for such activities.

Further research should be supported in areas for:

Storage: the majority of storage sites considered for CO_2 injection are concentrated in sedimentary basins. Currently there are some studies testing the efficacy of CO_2 injection in basalt. Preliminary results show that trapping mineralisation can be faster in basalts. These can represent an alternative for CO_2 storage in the future.

It is currently difficult to accurately estimate the global CO_2 storage capacity and one reason is the use of different methodologies. Harmonization of these methodologies is necessary and this should be completed to include risk and liability assessments, techno-economic and geological assessment to reduce the residual uncertainties. Moreover, including dynamic properties of the geological reservoir will contribute to more accurate assessment. Knowledge and data sharing is also important to advance the technology.

Transport: hybrid systems to transport CO_2 involve pipeline and shipping. In some regions of the world, for instance in Asia, there are also some investigations of shipping CO_2 from onshore to offshore. However, some national regulations may need to be adapted to allow it.

Monitoring: Several new projects are concentrated to make CO_2 monitoring more accurate, for example by finding the best technique to measure the exact CO_2 plume size and to investigate better the interactions between fluid flow – rocks and CO_2. The characterisation of site, choice of the best method to transport the CO_2 and precise monitoring plan during and after injection are the key requirements to create a commercial project.

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Acronyms and abbreviations

CAPEX	Capital expenditure
CC	Combined cycle
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture, utilisation and storage
CDU	Carbon Dioxide Utilisation
CFB	Circulating fluidised bed
CLC	Chemical looping combustion
CHP	Combined Heat and Power
CSLF	Carbon Sequestration Leadership Forum
EBTF	European Benchmarking Task Force
EC	European Commission
ECCSEL	European Carbon Dioxide Capture and Storage Laboratory Infrastructure
EEA	European Economic Area
EGS	European Geological Surveys
EII	European Industrial Initiative
EOR	Enhanced oil recovery
ETS	Emissions Trading System
EU	European Union
FP	Framework Programme
FP5	5^{th} Framework Programme
FP6	6^{th} Framework Programme
FP7	7^{th} Framework Programme
FT	Fischer-Tropsch
GHG	Greenhouse Gas
H2020	Horizon 2020 Programme
HTL	High Temperature Looping
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
ITM	Ion transport membrane
KPI	Key performance indicator
LCA	Life cycle assessment
LCOE	Levelised cost of electricity
LHV	Lower Heating Value
MOF	Metal organic frameworks
MS	Member state
NG	Natural gas
NGCC	Natural gas combined cycle

OPEX	Operational expenditure
OTM	Oxygen transport membranes
OxyC	Oxy-combustion
PC	Pulverised coal
PostC	Post-combustion
PreC	Pre-combustion
RFCS	Research Fund for Coal and Steel
SETIS	Strategic Energy Technologies Information System
SET Plan	Strategic Energy Technology Plan
SEWGS	Sorption enhanced WGS
TRL	Technology Readiness Level
WGS	Water-gas shift
ZEP	Zero Emissions Platform

Countries abbreviation
(EU, EFTA and world countries 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
UK	United Kingdom
US	United States
ZA	South Africa

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Appendix A

List of projects identified

Table 11. Projects identified exploring different CCUS aspects

Project Acronym	Capture	Transport	Storage	Other	Status	EU contribution (EUR)	Total (EUR)
ACT	✓	✓	✓	✓	Ongoing	11 799 665	38 233 782
CarbonNext				✓	Completed	495 748	495 748
CHEERS	✓	✓	✓		Ongoing	9 727 105	16 818 668
ECCSEL	✓	✓	✓		Completed	3 252 279	3 252 279
ELCOREL				✓	Ongoing	3 616 665	3 616 665
IMPACTS9				✓	Ongoing	1 100 299	1 100 299
SESZEP				✓	Completed	464 047	464 047
SSFZEP				✓	Ongoing	997 672	997672
STRATEGY CCUS				✓	Ongoing	2 959 534	3 069 474

Table 12. Projects funded under the H2020 ACT

Project Acronym	Capture	Transport	Storage / Moniring	Use	Other*	Funding (EUR)
ALIGN	✓	✓	✓	1.	✓	14 000 000
ELEGANCY	✓	✓	✓	2.	✓	8 900 000
Pre-ACT			✓	3.	4.	4 500 000
ACORN	✓	✓	✓	✓	✓	2 000 000
ECOBASE			✓	5.	✓	1 200 000
DETECT			✓	6.	7.	2 000 000

Project Acronym	Capture	Transport	Storage / Moniring	Use	Other*	Funding (EUR)
GASTECH	✓			8.	✓	1 650 000
3D_CAPS	✓			9.	✓	1 500 000
AC2OCEM	✓			10.	11.	3 000 000
ACTOM			✓	12.	13.	1 500 000
ANICA	✓			14.	15.	2 400 000
DIGIMON				✓	16.	5 000 000
FUNMIN				✓	17.	700 000
LAUNCH	✓			18.	19.	5 100 000
MemCCSea	✓			20.	21.	1 700 000
NEWEST-CCUS	✓			22.	23.	2 200 000
PrISMa	✓			24.	25.	2 100 000
REX-CO2			✓	26.	27.	2 500 000
SENSE			✓	28.	29.	2 700 000
SUCCEED			✓	✓	30.	2 500 000

*Includes activities such as developing materials (for example sorbents, membranes) relevant to CCUS, developing business case, knowledge networks, dissemination, knowledge sharing, raising public awareness etc.

Table 13. H2020 projects identified in the field of carbon capture and utilisation with EU funding contribution >250 kEUR

Project acronym	CDU	Solv.	Sorb.	Memb.	HTL	Other	Process Improvements	Status	EU Contribution (EUR)	Total Cost (EUR)
BIOCONCO2	✓							Ongoing	6 999 886	6 999 886
BioRECO2VER	✓							Ongoing	6 812 188	6 990 938
C2Fuel	✓							Ongoing	3 999 840	4 130 291
Carbon4Pur	✓							Ongoing	7 765 359	7 765 359
CarbonNext	✓							Completed	495 748	495 748
CARMOF			✓					Ongoing	5 993 228	7 440 050
CELBICON	✓							Completed	5 429 202	6 211 040
CEMCAP				✓	✓			Completed	8 778 701	10 030 121
CHEERS					✓			Ongoing	9 727 105	16 818 668
Circlenergy	✓							Ongoing	1 827 381	2 610 544
CLEANKER					✓			Ongoing	8 972 201	9 237 851
CO2Catalyst	✓							Completed	2 490 767	3 558 239
CO2EXIDE	✓							Ongoing	5 420 113	5 420 113
CO2Fokus	✓							Ongoing	3 994 950	3 994 950
CO2LIFE	✓							Ongoing	1 302 710	1 302 710
CO2MPRISE	✓							Ongoing	702 000	702 000
COFleaf	✓							Ongoing	1 497 125	1 497 125
COSMOS			✓	✓				Ongoing	1 500 000	1 500 000
COZMOS	✓							Ongoing	3 997 164	4 752 387
DeCO-HVP	✓							Ongoing	1 499 994	1 499 994
DIACAT	✓							Completed	3 872 981	3 872 981
DMX Demonstration in Dunkirk		✓							14 739 370	19 239 369
eCOCO2	✓							Ongoing	3 949 979	4 447 979
ELCOREL	✓							Ongoing	3 616 665	3 616 665
ENGICOIN	✓							Ongoing	6 986 910	6 986 910

Project acronym	CDU	Solv.	Sorb.	Memb.	HTL	Other	Process Improve-ments	Status	EU Contribu-tion (EUR)	Total Cost (EUR)
FReSMe	✓						✓	Ongoing	11 406 725	11 406 725
GasFermTEC	✓							Ongoing	2 496 875	2 496 875
GECO	✓					✓		Ongoing	15 599 843	18 220 331
GENESIS				✓			✓	Ongoing	9 563 904	9 563 904
GRAMOFON			✓					Ongoing	4 188 254	4 273 289
HybridSolarFuels	✓	✓				✓		Ongoing	1 498 750	1 498 750
HyMethShip	✓							Ongoing	8 438 110	9 288 310
ICO2CHEM	✓							Ongoing	5 948 589	5 948 589
KEROGREEN	✓							Ongoing	4 951 959	4 951 959
LEILAC						✓		Ongoing	11 932 231	20 770 635
LOTER.CO2M						✓		Ongoing	4 264 453	4 264 453
MaGic			✓					Ongoing	2 486 720	2 486 720
MEMBER				✓				Ongoing	7 918 901	9 596 542
MefCO2	✓							Completed	8 622 293	11 041 538
MetaFuel	✓							Completed	2 297 925	3 282 750
MOF4AIR	✓							Ongoing	9 947 143	11 094 138
NanoMEMC2				✓				Completed	4 990 816	4 990 816
OCEAN	✓						✓	Ongoing	5 523 650	5 523 650
ProGeo	✓							Completed	2 443 875	3 493 750
RECODE	✓							Ongoing	7 904 415	7 904 415
ROLINCAP		✓					✓	Completed	3 089 845	3 212 588
sCO2-Flex	✓						✓	Ongoing	5 630 855	5 630 855
SOCRATCES					✓			Ongoing	4 975 403	4 975 403
STEELANOL	✓							Ongoing	10 192 516	14 560 737
STEPWISE			✓					Completed	12 968 371	12 968 371
UltimateMem-branes				✓				Ongoing	1 875 000	1 875 000

Project acronym	CDU	Solv.	Sorb.	Memb.	HTL	Other	Process Improve-ments	Status	EU Contribu-tion (EUR)	Total Cost (EUR)
Willpower	✓							Completed	1 709 750	2 442 500

Table 14. List of projects funded by EU and related to CO_2 storage, transport and monitoring

Projects Acronyms Or names	**Project focus**			**Status**	**Total Costs (EUR)**	**EU contribution (EUR)**
	Transport	**Storage**	**Monitoring**			
CarbFix2		✓		Ongoing	2 200 318	2 200 318
GEAGAM		✓		Completed	580 500	580 500
CO2NOR		✓		Completed	151 649	151 649
STEM-CCS			✓	Ongoing	15 968 369	15 968 369
GATEWAY	✓			Completed	787 700	787 700
ENOS		✓		Ongoing	12 485 259	12 485 259
SECURe		✓	✓	Ongoing	8 932 484	8 450 609
S4CE (Science for Clean Energy)		✓		Ongoing	9 785 730	9 785 730

Global resource assessment for CO_2 storage

Table 15. Global CO_2 storage resources – in Gt CO_2 (modified from [2])

Assessment Status COUNTRY	ASSESS-MENT STA-TUS	ESTIMATED RE-SOURCE (GTCO2)	RE-SOURCE LEVEL
EUROPE AND RUSSIA			
Norway, Denmark and Sweden	Full	134*	Effective
Iceland (basalts)	Full	21-400*	Theoretical
Russia	Very Limited	6.8	Theoretical
UK	Full	78	Theoretical
AMERICAS			
Brazil	Moderate	2 030	Theoretical
Canada	Full	198-671	Effective
Mexico	Moderate	100	Theoretical
USA	Full	2 367-21 200	Effective
ASIA-PACIFIC			
Australia	Full	227-702	Effective
Bangladesh	Limited	20	Theoretical
China	Full	1573	Effective
India	Moderate	47-143	Theoretical
Indonesia	Moderate	1.4-2	Effective
Japan	Full	146	Effective
Korea	Full	100	Theoretical
Malaysia	Moderate	28	Effective
New Zealand	Moderate	16	Theoretical
Pakistan	Moderate	32	Theoretical
Philippines	Limited	23	Theoretical
Sri Lanka	Limited	6	Theoretical
Thailand	Limited	10	Theoretical
Vietnam	Limited	12	Theoretical
MIDDLE EAST			
Jordan	Limited	9	Theoretical
Saudi Arabia	Very Limited	5-30	Theoretical
UAE	Very Limited	5-25	Theoretical
AFRICA			
Algeria	Very Limited	10	Theoretical
Morocco	Limited	0.6	Theoretical
Mozambique	Moderate	2.7-229	Theoretical
South Africa	Moderate	162	Theoretical

Global CO_2 storage assessment (modified from Consoli et al. 2017)

*Data from Nordic CO_2 storage atlas (NORDICCS 2015)

European SET Plan for CCUS – Action 9

Research & Innovation Activities under the SET-Plan Action 9

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[16] and within national R&D programmes in several Member States. Furthermore, R&D infrastructure is built and operated in the ESFRI project ECCSEL[17], 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. 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 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

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

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

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).

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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