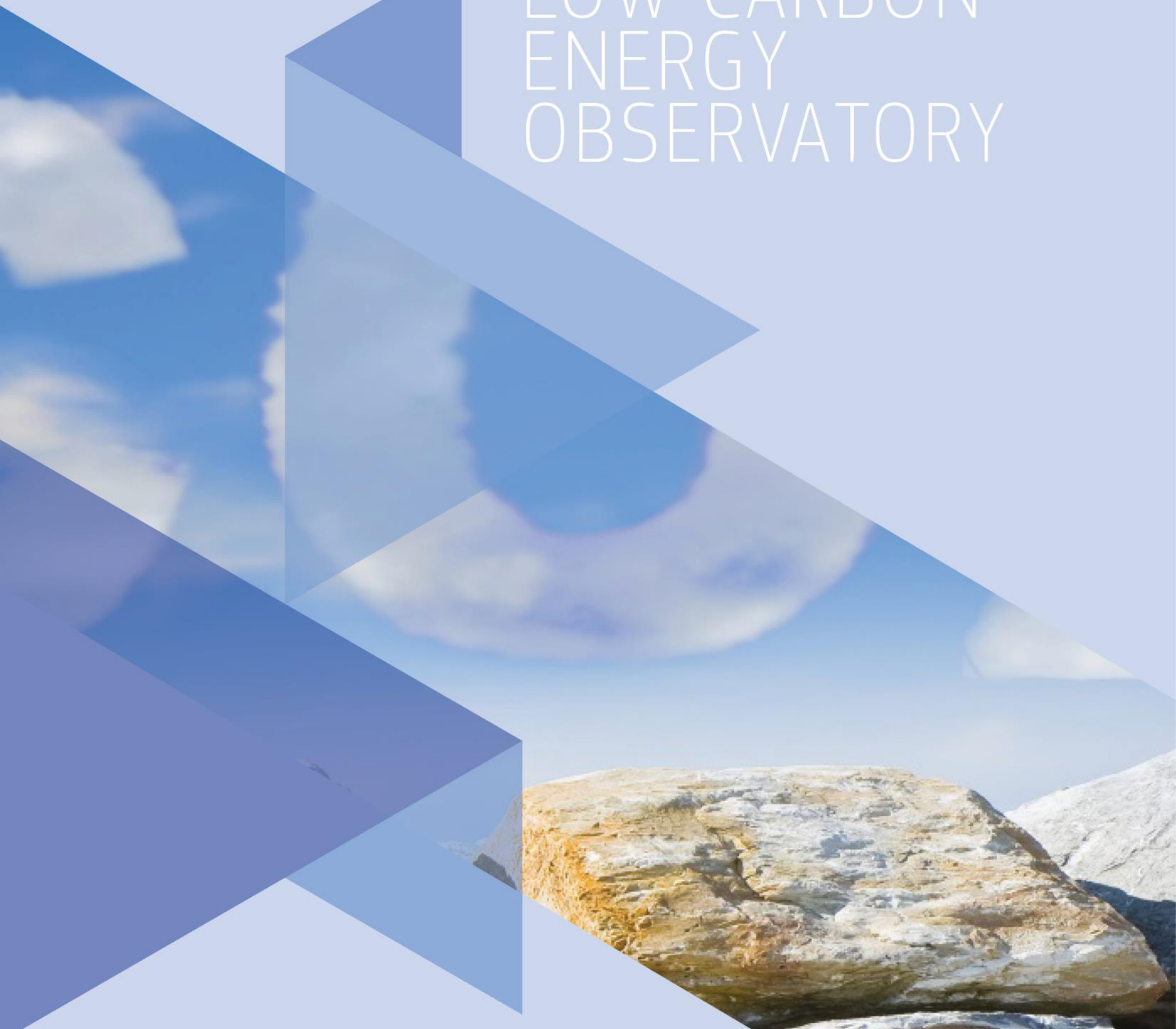
European Commission

LOW CARBON ENERGY OBSERVATORY



CARBON CAPTURE UTILISATION AND STORAGE

Technology development report

Joint Research Centre

EUR 29909 EN

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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	5th Framework Programme
FP6	6th Framework Programme
FP7	7th 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

COUNTRY NAME ABBREVIATIONS

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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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 about the ambition to keep the temperature bellow 2 ^{0}C aiming for 1.5 ^{0}C. It has been followed during the next COPs 22 and 23. Recent analysis indicates that in absolute values, the largest carbon dioxide (CO_2) emitters are China, the United States, and the European Union, followed by India, the Russian Federation, and Japan [1]

Several organizations and institutions such as IPCC, IEA, NETL, and European Commission argue that without Carbon Capture, Utilisation and Storage (CCUS) it is difficult to keep the temperature levels indicated in the Paris agreement. In fact, it will be necessary to store (cumulative) around 94 Giga tonnes of CO_2 in the world by 2050 to reach the target of 12 % of emissions reductions via CCS in the IEA's 2 ^{0}C scenario [2][3] or a need of 6 Giga tonnes per year.

Globally, until 2017 over 200 million tonnes CO_2 has been injected underground [4].

While CO_2 emissions from fuel combustion have been declining in Europe [5], process industries like cement, iron and steel, aluminium, pulp and paper, and refineries have inherent CO_2 emissions resulting from raw material conversion. From an economical point of view it has been estimated that the total costs without deploying CCUS in the world can be 138 % higher, if this technology is not taken in account [6].

In Europe, Carbon capture and storage gained more political attention from 2005. The first CCS communication from the EU dates in 2006 [7]. In 2007 CCS was included in the European agenda as an important tool to keep in control the climate change. In 2009, the first CCS EU directive was published and then several funding mechanisms for R&D, demonstration projects have been created via framework programmes and other EU fundings.

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 [8]. CCUS is not only relevant to the energy generation or to the heavy industry sectors, but also in a number of other areas: transport sector, waste disposal, chemical industry and technological development. Large-scale CCS projects are currently in operation worldwide. However some projects have also been cancelled. The majority of these projects is plagued by financial restrictions and or regulation, political risks and also due to the lack of a robust business case.

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 instance.

CO_2 capture technologies include the main separation nethods such as:

- Absorption
- Adsorption
- Membrane Technology
- High Temperature Looping

Hybrid configurations and combinations have also been studied through the years. This classification is zooming in to the categories traditionally used when referring to carbon capture in power generation, namely post-, pre- and oxy- combustion. For this report, given that industrial applications are also considered, the usual classification 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.

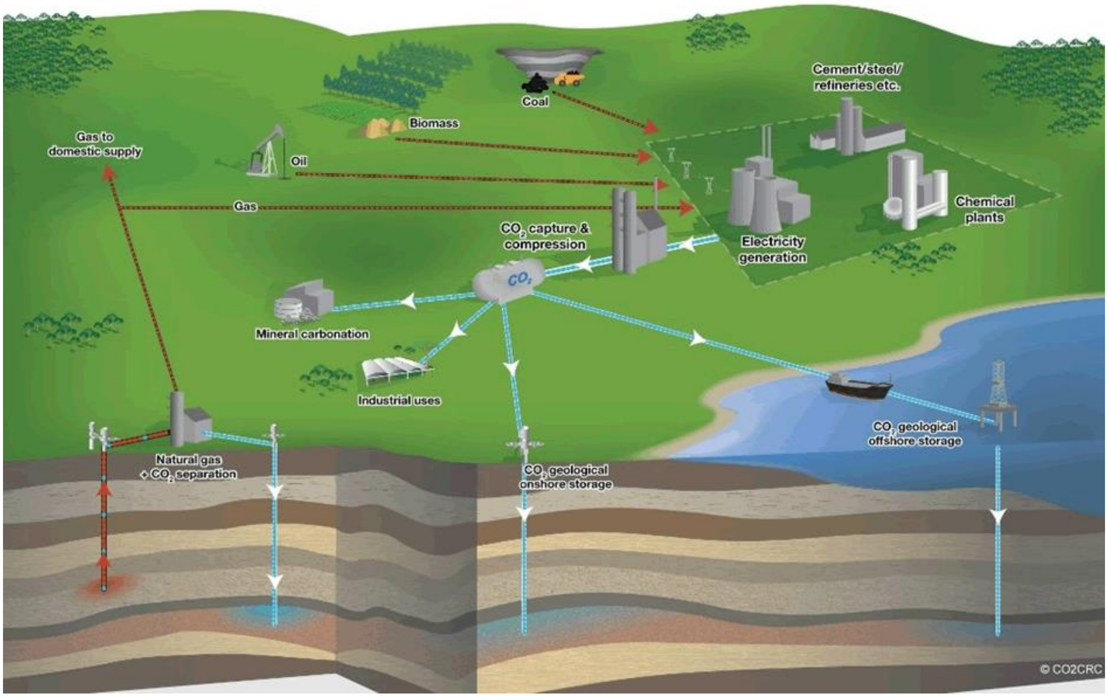

Figure 1 CCUS value chain facilities [9]

To be transported, captured CO_2 is compressed to supercritical state, injected and/or used. The compression step is usually included at the capture system.

<u>CO_2 utilisation processes</u> often 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. 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 [10], [11]. 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 [10] 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 [12]. 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 [13] to make sense as a climate change mitigation option.

Following the CO_2 capture and or its use, the CO_2 is <u>transported</u> via pipelines and/or shipped to the site of injection. It is then <u>stored</u> in deep saline aquifers, deep coal bed methane (enhanced), combined or used in EOR, in depleted oil/gas reservoirs and most recently in basalts. CO_2 is then monitored by accurate geochemical and geophysical techniques for safety reasons.

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 [14]. However it's necessary to harmonize different methodologies to have more precise amount.

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), 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. Concerning the CO_2 utilisation technologies, 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's currently evaluating the combination between shipping and pipelins, therefore it has been considered both in this report. More accurate monitoring techniques are necessary to guarantee the safety of CCS projects and these are detailed and new tedances are also reviewed.

The review of each topic is organised following three main blocks: (i) Literature review and technology analysis to depict the state-of-the-art of CCS and CDU technologies. (ii) Technology assessment based upon two main indicators: technology readiness level (TRL) evolution according to European R & D projects, and patents trend as an indicator of the technology evolution; and (iii) technology forecast, provided by the JRC-EU-TIMES model to estimate the future impact of CCS and CDU in the European industry and energy sectors.

The main key performance indicators (KPIs) aim at quantifying the development of the technology, and the JRC-EU-TIMES model forecasts aim at identifying the role of CCUS in the near and long term future scenarios.

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;
- Future CCS technologies, ZEP [15];
- the SET Implementation Plan (IP) 2017, SETIS webpage and associated SET Plan action;
- Carbon Sequestration Leadership Forum (CSLF);
- SCOT project database;
- Online information on the Innovation and Networks Executive Agency (INEA);
- Online information from the European Carbon Dioxide Capture and Storage Laboratory Infrastructure (ECCSEL) and the Global CCS Institute.
- The book "Carbon dioxide utilisation: Closing the carbon cycle" [11].
- The book 20 years of CCS - accelerating future development [2]

In the *R & D initiatives* chapter, the main sources are CORDIS and other relevant databases for identifying the EU co-funded projects.[1] Aside the straightforward techlogocial 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 as the majority of H2020 are still ongoing, 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.

[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.

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.

Future priorities section provides guidelines for future research of relevance for the upcoming calls.

1.3. Technology readiness assessment

The focus is on CCS and CDU projects granted H2020 (2014-2020) funding but also within FP6 (2002-2006), FP7 (2007-2013) frameworks. It should be noted that 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 platforms for photocatalytic water splitting and CO_2 reduction). Specifically for CO_2 storage, transport and monitoring, FP3 (1993-1995), FP4 (1998-1999) and FP5 (1999-2002) are also added to FP6, FP7 and H2020, since some of these projects follow a progressing line and they are connected.

The TRL assessment follows the definitions as described in D2.1.9. The projects rated at TRL 1-3 in Chapter 4, are considered as future and emergent technologies (FET) and will be further discussed under Work Package 3. TRL 9 is the last step of the technology development. Sub-technologies rated between TRL 4 to 8 are discussed in Chapter 4.

For CDU technologies, processes for the synthesis of fuels, chemicals or materials are also examined. Therefore, the TRL scale is defined in a qualitative way.

TRL levels for CO_2 storage, transport and monitoring follow classification as given by [16] and [17]

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, that determine under different scenarios possible deployment rates for CCS and CDU (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.

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][19][19][19][19].

Commercial uses of CO_2 also exist and CDU 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 [20] but also up to 7 [21].

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 geological structure of the site of injection. To create a safe storage, avoiding any leakage of CO_2 is required an advanced and accurate system of monitoring. The state of the art of main technologies linked to storage, transport and monitoring of CO_2 is described further.

Table 1 summarises the main sub-technologies identified for CCUS. Other research areas of a more trans-technological and cross-technological nature are included in Table 2.

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

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 asgeothermal energy, biomass, CSP, wind/H2
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. Overview

2.1.1. National and International projects

According to the Global CCS Institute, there are 17 large-scale projects CCS worldwide operating [4]. In Europe, the two operating projects in Norway, are implemented in NG processing plants. Worldwide, there are 13 operating demonstration projects, using EOR as final CO_2 disposal except for the Norwegian plants, which use dedicated geological storage. Overall, the capture capacity of these projects is approximately 31 $MtCO_2$/yr. Almost 70 % of this capacity is located in the USA with only 6 % in Europe.

2.1.1.1. 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.

Kemper County, Mississippi, was expected to be fully operational and capable of using CCS by mid-2014. However, Kemper has operated primarily on natural gas, essentially as a combined-cycle plant, since August 2014. In June 2017, Mississippi Power made the decision to suspend operations activities relating to the coal gasification process, electing to operate Kemper strictly as a natural gas-fired combined-cycle plant. Kemper has also abandoned plans to use technology to capture its greenhouse gas emissions.

In Europe, six CO_2 capture and storage (CCS) projects located in Germany, Italy, the Netherlands, Poland, Spain and the UK were selected for funding under the European Energy Program for Recovery (EEPR). Established in 2009, this program was the largest support scheme for CCS demonstration projects. The initial plan was for the projects to be operational by the mid 2010's. By 2013, three out of six projects were suspended with the Dutch ROAD project being the last one within this scheme.

In June 2017, the Dutch Government announced that the ENGIE Group and Uniper Energy will withdraw from the ROAD Carbon Capture and Storage (CCS) project in Rotterdam. Since then, 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 focusin on transport and storage.

The Dutch government has clearly expressed its continued dedication to CCS deployment. The technology has been identified as key to achieving national climate change targets in the Dutch Energy and Climate Plan. The Netherlands are also already in the process of developing a roadmap designed to identify the path to large-scale CCS deployment.

Even if not a European Member State, Norway has contributed and collaborated in many EU projects, being the leader on CCS 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. Three projects were considered: The first one, Klemestrud (nearby Oslo) pilot project has started in 2016 and is financed by Oslo municipality. The ambition is to capture 300 000 CO_2 from waste incineration. The other projects include, Norcem in Brevik (cement industry) and Yara Porsgrunn (fertilizers industry). In may 2018, Norway decide to support only Norcem project (FEED phase). Klemestrud project will be reviewed by a comittee since they provided new data and information to the gorvnement. The third project, Yara is not anymore considered for full chain CCS.

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 [22], [23]. 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, [14] 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).

US has already done the 5th version of their CO_2 atlas which is fundamental for a geological assessment. It has been estimated that 1.6 Gt of CO_2 can be stored in mainly saline aquifers only. 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.

It is also important to include dynamic properties to precise better the measurement of the CO_2 storage capacity.

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) [24]. In the way to reduce costs of CCS 136 projects in Canada and USA, are planning to inject 3.4 Mt CO_2 combined with EOR in the next 4 years.

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 but the Norwegian oil directorate is still working about this possibility.

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.

2.1.1.2. Activities by region

2.1.1.2.1. Europe

Set Plan

In 2017, european stakeholders created a Termporary 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 organisations and research institutions. The SET Implementation PLAN has been approved and finally endorsed by the European Commission in November 2017. The same group constitutes now the Implementation Working Group (TWG).

The SET PLAN set out the main 10 targets for the deployment of CCUS and determined 8 research and innovation actions to achieve these targets (see Appendix F), enphasizing on the following 5 as flagships: englobing all aspects of CCUS, selecting hubs and clusters and projects in advanced development (see Appendix F for more details).

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.

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) [25].

In 2017, ADEME created a temporary work group to review the French CCUS national strategy. This is currently being finalised by this group wich includes government, industrials, universities and research institutes.

Germany

Germany has focused on research and R&D in CCS via supported 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 is currently under preparation and is expected to be available in summer 2018.[2] 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 [3] [25], [26].

Italy

The Sulcis Fault laboratory (SFL) is one of the field sites selected in H2020 project ENOS (Enabling onshore CO_2 geological storage in Europe. Despite not being focused on storage, this laboratory can help in the idenfication of the best sites for storage. The undertaken research addresses the leakage risks, the impact in the local environment and ground water. It's also part of the work to test different monitoring techniques to follow CO_2 migration. This laboratory can serve running pre-feasibility tests for other sites. ENOS sites and technologies are classified at TRL 4 to 6 with plans to be finished in 2020.

Ireland

ERVIA- Gas Networks Ireland are considering the development of a carbon capture and storage facility off the coast of Cork, Ireland. The EUR 1 billion project would involve capturing CO_2 from Whitegate and

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[2] http://kraftwerkforschung.info/quickinfo/organisation-der-forschung/struktur-flexible-energieumwandlung/

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

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. It could be the first CCS facility in the EU, as several other schemes have been cancelled or postponed in recent years [27]. ERVIA. Is now, preparing a business plan for full chain CCS.

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. It has eight differentiated sub-programmes including CO_2 use, transport and storage, capture, or public perception. CATO projects work together, demonstrating coherence and continuity along the different projects financed [28].

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. A new business plan is being elaborated and other industrial actors are expected to joing the Port of Rotterdam in this year.

Another CO_2 storage option in the Netherlands is the gas field Q16 with onshore instalations. This is field site in the project ENOS supported by EC and after depletion can receive 2 Mt CO_2. A future possibility to combine geothermal energy with CO_2 storage in this field has also been identified [29].

UK

In October 2017, the UK Government released its Clean Growth Strategy, stating its ambition to show international leadership in carbon capture usage and storage (CCUS), with up to GBP 100 million of investment for innovation and the setting up of a new CCUS council. As part of the government's re-commitment to CCS, they have set out an ambition to deploy CCS at scale during the 2030s [30].

2.1.1.2.2. Africa

In 2009, the world bank group created a trust fund for CCS, to develop this technology in developing countries . 9 countries have been selected, the majority in Africa: Botswana, Egypt, Maghreb region and South Africa, where progress has been done.

South Africa

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 [3].

In Salah project in Algeria, it has been planned to inject 1.2 million CO_2 tonnnes by year, but the project has been suspended in 2012. However the particurlarty of this project was successufully to use satelites as part of monitoring program

2.1.1.2.3. Americas

The US created collaboration with China, developing CO_2 storage mainly linked to EOR. In the US the new regulation about underground injection (Underground Injection Control - UIC) approved, develops specific criteria on characterisation requirements, standards for well construction, comprehensive CO_2 monitoring plan and wells financial responsibility requirements [31]. The US tendency is to install more shale gas power plants, whose penetration is limited in the Clean Power Plan [32]. CCS efforts in the US have, so far been led by the goal of reaching advanced energy systems with CO_2 capture at less than USD 40/tCO_2 by 2020 [17].

Petrobras in Brazil has 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. The last project is in starting phase and it is expected to capture 0.7 Mtpa CO_2 without transport being required.

A CO_2 atlas of possibilities to store CO_2 in Brazil was published in 2015 relating that for Campos Basin (south east Brazil) alone, the most important oil/gas field in Brazil, the CO_2 capacity is 950 $MtCO_2$. However the lack of pipelines is a potential problem for commercial projects.

2.1.1.2.4. Asia

China has accelerated the development of CCS., there are currently 18 projects ongoing (Figure 2)

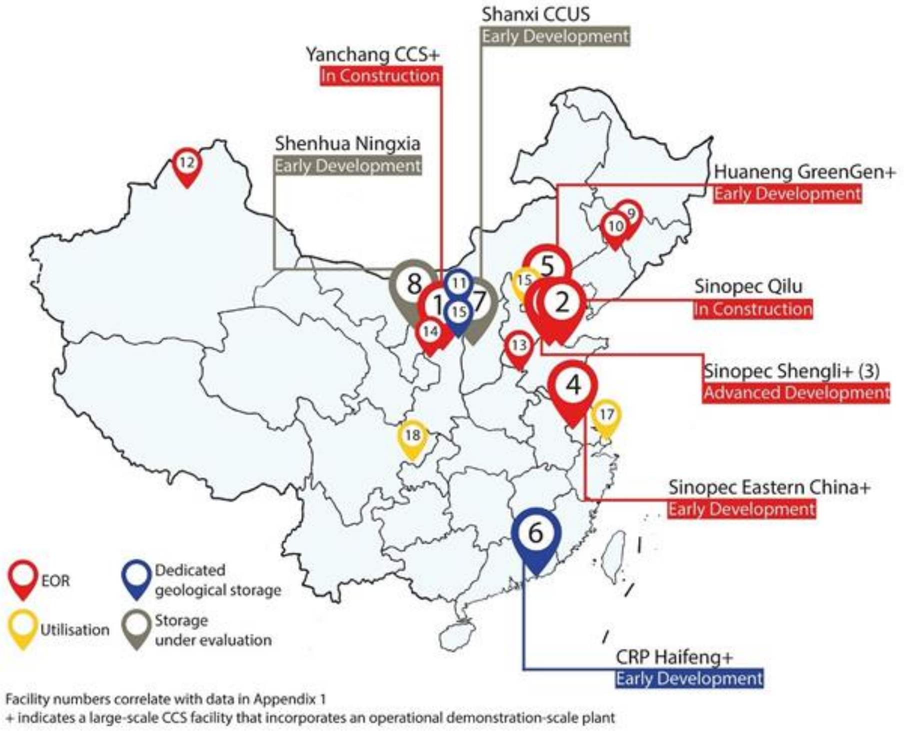

Figure 2 Current status of CCS projects in China ([33].

The main projects are in different phases of development:

a)Two projects under construction are intended for industrial separate:

- Sinopec Qilu Petrochemical CCS project, to be started in 2019, with capture capacity of 0.4 Mtpa CO_2, this will be transported via pipeline to be stored in the oil fields for EOR proposal.
- Yanchang CCS + (Integrated carbon capture and storage), this project was launched in march 2017 and it should be the first large-scale CCS facility in Asia.

b) One is in advanced phase of development

- Sinopec Shengli Power Plant CCS project planned for 2020 with capture capacity of 1 Mtpa. Captured CO_2 will be transported by pipeline and injected at 3 000 m depth into Shengli oil field, at the Yellow river delta. The proposal is to combine CCS and EOR**.**

c) And the others are in early development:

- Shenhua Ningxia CTL Project, also for 2020 with capacity of 2 Mtpa; the site of injection is still under evaluation.
- Shanxi International Energy group CCUS project for 2020 with capture capacity of 2 Mtpa; CO_2 will be transport by pipeline and site of injection is currently under evaluation.
- The Huaneg GreenGen, planned for 2020 with capture capacity of 2 Mtpa; the storage location is currently under evaluation and will serve for EOR proposal.
- Sinopec Eastern China aims to capture 0.5 MtPa of CO_2 from ammonia facility and a coal to

hydrogen facility. It is planned for 2020 and will be used in EOR.

- Haifeng expects starting operations of a 1 Mtpa capacity CCS project combined with EOR in the 2020s. CO_2 is to be transported by pipeline to deep saline aquifer in the south China sea.

China follows US tendency to create CCUS project combined with Enhanced Oil recovery. The CO_2 is transported only by pipelines. China expects to lead CCUS in Asia.

Activities are also undertaken in Japan, where the "Cool Earth 50" initiative launched in 2007 is currently in its second step through the COURSE 50 project.[4]

In Japan the estimated resource for CO_2 storage is 146 $GtCO_2$ (Takahashi et. al 2009; Consoli & Wildgust 2017]. However the individual basin resources are not yet published. A demosnstration project is ongoing in Tomakomai, co-funded by the local municipalities. This project is unique in that CO_2 injection can take place both on sedimentar basins and also basalt (started in march 2018).

South Korea has recently started to show interest for CCUS and plans to construct two projects in the next future, Korea-CCS 2 is under evaluation and should start in 2020, for a capacity of 1 Mtpa.

In the southeast Asia (mainly Indonesia, Philippines, Malysia, Thailand and Vietnam) a storage assessment study has been done in 2013 and the estimation is between 74.4 to 80 G tonnes CO_2 [34].

2.1.1.2.5. Australia

Australia has started new projects in the last years, via a cooperation between industry, government and research institutes to accelerate R&D and the creation of pilot projects. Currently, the Gordon project (capture capacity of 3.4-4.0 Mtpa) is under construction and expected to be operational in 2018. CarbonNet project with a capture capacity of 3-4 Mtpa CO_2 is under development and expected to be online in 2020. The South West Hub, also under development is expected to be operational in 2025. All the projects are intending to use pipelines to transport CO_2 and then to store it in aquifers without any link to EOR.

There is not yet a national atlas, for the whole country, but an assesement for potential zones for CO_2 storage has been elaborated in the last years by [35] and englobes:

- Gunnedah Basin in NSW Australia
- Sydney Basin, also in NSW Australia
- Galilee Basin in Queensland and
- Otaway Basin in Victoria

The estimated CO_2 storage capacity of Australia is between 227 to 702 Gt CO_2 [3].

2.1.1.2.6. 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 is the world's first fully commercial CCS facility in the iron and steel industry. CO_2 is captured via a new build CO_2 compression facility using high purity CO_2. This is produced as a by-product of the direct reduced iron-making process at the Emirates Steel Industries factory in Mussafah. Launched in November 2016, the compression facility has a capture capacity of 0.8 Mtpa. The captured CO_2 is transported via pipeline to Abu Dhabi National Oil Company (ADNOC) oil reservoirs for enhanced oil recovery.

2.1.1.3. CO_2 utilisation

Several MS, specific international initiatives, research centres and industries that have invested and are interested in carbon capture, are also involved on CDU. Countries like France, Germany or UK have a strategic interest on CDU projects [36].

[4] http://www.jisf.or.jp/course50/outline/index_en.html

CO_2 utilisation processes are at different stages of maturity: options like CO_2 to boost urea production can rapidly enter the existing mature markets. Other technological processes are at theoretical and research phases, or are at pilot/demonstration phases. The main KPI for the utilisation sector is a lower carbon footprint than the one from the benchmark fossil fuel route.

Canada

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. Plans to put pricing on carbon currently under discussion are expected to further advance the already numerous CCUS activities in Canada.

France

In 2014 ADEME published a document that identified and analysed the most feasible pathways for CO_2 utilisation in France: methanol synthesis, synthesis of formic acid and production of sodium carbonate was among them. The report calculated how much CO_2 can be effectively avoided and acknowledged difficult economic competitiveness. Several projects have been financed by the Agence Nationale de la Recherche (ANR), at research level among others evaluating the conversion of emitted CO_2 by heavy industry processes into methanol, syngas production and convertion into fuels and membranes integration.[5] In the innovation programmes from ADEME in the timeframe of 2014 to 2020, different themes such as algae, power-to-gas, or chemical conversion of CO_2 are examined [37].

Germany

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 CDU programme which started in 2009 and has been complemented by the Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF), has announced 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 CDU, and "r+Impuls", whose aim is to support the upscaling of technologies up to, at least, TRL 5 (BMBF, 2018; Mennicken, 2016). Other initiatives include the Kopernikus project running from 2016 until 2019 with a budget of EUR 32 million and Carbon2Chem, running until 2020 with a budget of EUR 60 million.

Mexico

Activity is ongoing in Mexico since 2014 and a national roadmap is currently under preparation. A major development has been the launch of the Mexican CCUS Centre a couple of months ago. This centre will coordinate federal government activities with various actors involved. As involvement in Mexico has taken off only recently, there is little activity on a research level with the major focus on EOR.

Norway

The Norwegian government (Ministry of Petroleum and Energy) 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 [40], [41]. 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 [42]. While CCUS projects in Norway focus on permanent storage proposal, projects exist on a national level such as the Futurefeed project, led by Sintef and exploring CO_2 as a feedstock for chemicals, polymers, and fuels, the FinnFjord project intending to create a National Council for CCU funded by the Norwegian government.

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

Spain

Two projects were identified in CDU, 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 towards 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 [43].

UK

The UK government (Department for Business, Energy and Industrial Strategy) announced support on CO_2 utilisation under its Clean Growth Strategy Innovation Program [30]. A previous study, "Demonstrating CO_2 capture in the UK cement, chemicals, iron and steel and oil refining sectors by 2025: a techno-economic study", analysed different CDU plants potential integrated with heavy industries [44]. The UK holds important entities in the CDU field like the UK Centre for carbon dioxide utilisation (CDUUK). The Engineering and Physical Sciences Research Council (EPSRC) funded the "CO2Chem Grand Challenge Network" in 2010. The 4CU programme, has been funded over 4.5 years (EUR 6.3 million), and dealt with CO_2 capture, reduction and the study of process viability [45].

2.1.2. Fossil fuel power plants

Fossil fuel consumption for electricity production in Europe is mainly from coal and NG power plants [46]. Fossil fuel plants can be retrofitted to increase their efficiency and/or to include the CCS technologies, and new fossil fuel plants should integrate the latest technology and be carbon capture ready [47].

The types of coal power plants include subcritical, supercritical and ultra-supercritical PC, or integrated gasification combined cycle (IGCC) plants. 17 % of the European fleet are ultra-supercritical plants [48] following the majority of the plants running on a subcritical mode. IGCC plants using coal as raw material has been demonstrated in two large facilities in Europe [47]. NG power plants can be conventional, only using a gas turbine, or based upon a combined cycle (NGCC) plants.

The most common power plant is the subcritical coal power plant, followed by NGCC and NG conventional, with supercritical coal power plants being the less common. The plants commissioned after year 2000 are mainly advanced fossil fuel plants and principally fuelled by NG.

The carbon capture configurations that can be implemented in power plants are:

- Post-combustion (PostC) CO_2 capture at supercritical and ultra-supercritical PC and NGCC power plants;
- Pre-combustion (PreC) CO_2 capture at coal-based IGCC power plants and in NG reforming for energy purposes;[6]
- Oxy-combustion (OxyC) at supercritical or ultra-supercritical PC power plants and in NGCC.

Carbon capture can also be retrofitted in power plants but this may further reduce the efficiency of the already lower-efficient, old plants. Moreover, retrofitting corresponds to almost the cost of new plants [49].

[6] Hydrogen production is also achieved. However, hydrogen has been widely produced by NG steam reforming (Bolat & Thiel, 2014), where usually H_2 is separated from CO_2 with a pressure swing adsorber (PSA).

2.1.3. Industry

A number of industries such as the steel, cement and chemical industries require fossil fuels as an input to their production process. In these industries, fossil fuels are utilised directly and not as a primary energy source to generate electricity.

Unlike power generation, in industrial processes it is not always possible to reduce associated emissions by substituting fossil fuels deriving energy with renewable. In these cases, large emissions reductions are attainable by implementing CCUS technologies.

Industrial processes vary and the CO_2 content of streams to be treated differ considerably in different industrial processes.

Adapted from IEA [50], carbon capture in industry can be generically classified as:

Separation from diluted streams The low-pressure associated makes this similar to post-combustion capture in power generation. One example could be application in Iron and Steel.

Separation from oxy-fired streams, similar to oxy combustion in power generation, one example could be processes in the cement industry.

Pre-process separation, similar to pre-combustion CO_2 capture in power generation applications. Possible applications include for example the refinaries sector.

In Europe, the iron and steel sector operates a relatively small number of sites that are very large point sources of CO_2. The European cement industry, on the other hand, is much more spread out between more, smaller sites.

Table 3 indicates a growing number of industrial projects including national initiatives but also projects funded on the European level that could be identified. In addition Europe could further lead the way with promising projects such as the Leeds and Manchester-Liverpool Hydrogen projects in the UK, and the Magnum project in the Netherlands. In Leeds, work is ongoing to determine the feasability of converting the existing gas infrastructure into one for hydrogen. In Manchester and Liverpool, hydrogen resulting mainly by the conversion of natural gas through Steam Methane Reforming and storage of the CO_2 in the Irish Sea, would be supplied to car manufacturers and refineries, as well as households. For the dutch project, the plan is to convert one of the three Magnum gas power plant units into hydrogen fuelled combined to CCS.

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 [51]

Technology readiness is particularly addressed within the SET Plan flagship projects indicated (Appendix D). The SET Plan includes specific targets relevant to industrial applications and flagship projects are included in the implementation plan. These concern primarily the utilisation of captured CO_2 from industrial sources (Table 4).[7] 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.

[7] Included in the table are only projects that explicitly indicate use of CO_2 captured from industrial sources and not all SET Plan flagship projects.

Table 3 Industrial CO_2 capture/utilisation laboratory/bench, pilot and demonstration plants in Europe

Location	Project	Technology	Status	TRL	Industry	Partners
NL	HIsarna Pilot Plant	Sorbents and cryogenic	Planned	8 (estimate)	Steel	TATA Steel
NL	MAGNUM	To be decided	Under evaluation	8 (estimate)	Hydrogen production	Statoil, Vattenfall and Gasunie
NO	Norway CCS	Chemical solvent, membrane, CaL	Planned	8 (estimate)	Cement, ammonia production, waste processing	Norcem AS, Yara Norge AS, Klemetsrudanlegget AS
NO	Sleipner	Chemical solvent	Ongoing	9	Oil and gas	Statoil
NO	Snohvit	Chemical solvent	Ongoing	9	Oil and gas	Statoil
UK	TEESIDE Collective	To be decided	Planned	8 (estimate)	Chemicals, fertilisers and plastics	Department for Business, Energy and Industrial Strategy, NEPIC, BOC, CF Fertilisers, Lotte Chemical UK, Tees Valley Combined Authority, Sembcorp Utilities UK , SABIC
H2020						
DE, NO	CEMCAP	Oxyfuel, chilled ammonia, membranes, calcium looping	Ongoing	6	Cement	Sintef Energi AS; European Cement Research Academy GMBH; GE carbon capture GMBH; GE Power Sweden AB; Nederlandse Organisatie Voor Toegepast Natuurwetenschappelijk Onderzoek TNO; c.t.g. spa; Norcem AS; IKN GMBH Ingenieurburo-Kuhlerbau-Neustadt; Thyssenkrupp Industrial Solutions AG; Eidgenoessische Technische Hochschule Zuerich; Universitaet Stuttgart; Politecnico Di Milano; Agencia Estatal Consejo Superior Deinvestigaciones Cientificas; VDZ GMBH; Heidelbergcement AG
UK, DE, CH, BE, NL, AU	LEILAC	Direct separation	Ongoing	6	Lime, 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
ES, NL, NO, CH, UK, FR, IL, LV, BE	GENESIS	Sorbents, membranes	Ongoining	6 (estimate)	Cement, Steel	Acondicionamiento Tarrasense Associacion; Technische Universiteit Delft; Stiftelsen Sintef; Universiteit Twente; Stichting Energieonderzoek Centrum Nederland; Fundacio Institut Catala De Nanociencia I Nanotecnologia; Ecole Polytechnique Federale De Lausanne; MOF Technologies Limited; Funzionano AS; Ceramiques Techniques et Industrielles SA; Orelis Environnement SAS; Yodfat Engineers (1994) LTD; Cemex SIA;

						Arcelormittal Belgium NV

Table 3 Industrial CO_2 capture/utilisation laboratory/bench, pilot and demonstration plants in Europe (continued).

NO, FR, CN_X_HK, PL, BE	CHEERS	CLC	Ongoing	7	Oil refinery	Sintef Energi as; Ifp Energies Nouvelles; stiftelsen sintef;total raffinage chimie sa;dongfang boiler group co ltd;zhejiang university;politechnika slaska
IT, ES, DE, FI, CH, EE, CN_X_HK	CLEANKER	CaL	Ongoing	7	Cement	Buzzi Unicem SPA; Agencia Estatal Consejo Superior Deinvestigaciones Cientificas; Italcementi Fabbriche Riunite Cemento SPA; IKN GMBH Ingenieurburo-Kuhlerbau-Neustadt; Lappeenrannan Teknillinen Yliopisto; Politecnico Di Milano; QUANTIS; Tallinna Tehnikaulikool; Tsinghua University; Universitaet Stuttgart; VDZ gGmbH; Amici Della Terra Onlus
NL, SE, RO, UK, IT	STEPWISE	SEWGS	Ongoing	6	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

Table 4 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, 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

2.2. 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 developmets 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.

2.2.1. Carbon capture

Given that industrial applications have gained significant ground in carbon capture considerations, the usual classification post-, pre-, oxy- combustion used in power sector may not be applicable as used in the previous report version 2016. In industrial processes, CO_2 may not come from fuel combustion but from the process itself. Figure 3 outlines the main areas of research and focuses primarily on the separation technology.

Technologies for CO_2 capture from a mixture of gases are commercially available in three segments: (i) NG treatment, (ii) production of hydrogen, ammonia or other chemicals, and (iii) capture of CO_2 from gas streams. The most well-known method for CO_2 capture is by chemical absorption with an aqueous MEA (monoethanolamine) solution, a 1st generation capture technology. However, different problems remain unsolved, including corrosion and volatility, solvent losses, amine degradation and air emissions. The degradation of nitrosamines (that result from the combination of the amine with nitrogen) can be toxic. The emission of amines to the air, for a 400 MW pulverised coal (PC) plant, ranges between 40-160 t/yr. Degraded amine can reach up to 690 t/yr for the same plant [FP7 IOLICAP].(Appendix B) As a result, R&D for the development of 2nd and 3rd generation capture methods is focused on more efficient, cheaper and environmentally friendly capture methods.

The key performance indicators (KPIs) for the CO_2 capture sector indicate that, (i) a cost of capture below EUR 15/tCO_2, (ii) an efficiency loss of less than 5 % points, (ii) a capture rate of 90 % by 2050, and (iv) a minimum energy required for solvent regeneration and/or O_2 obtaining are needed for commercialisation of CO_2 capture. Moreover, capture techniques will have to provide sufficient flexibility if they are to be applied in the context of variable electricity production.

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2.2.1.1. Solvent-based capture

In a typical plant, the product gas goes to the capture process possibly after a conventional pollutants control step, such as nitrogen and sulphur oxides and particulate matter removal. Different CO_2 concentrations apply for product streams of different processes. The benchmark amine-based solvent requires additional energy to (i) release the captured CO_2 and to (ii) regenerate the solvent. As a result, plants with carbon capture bear an inventable energy requirement.

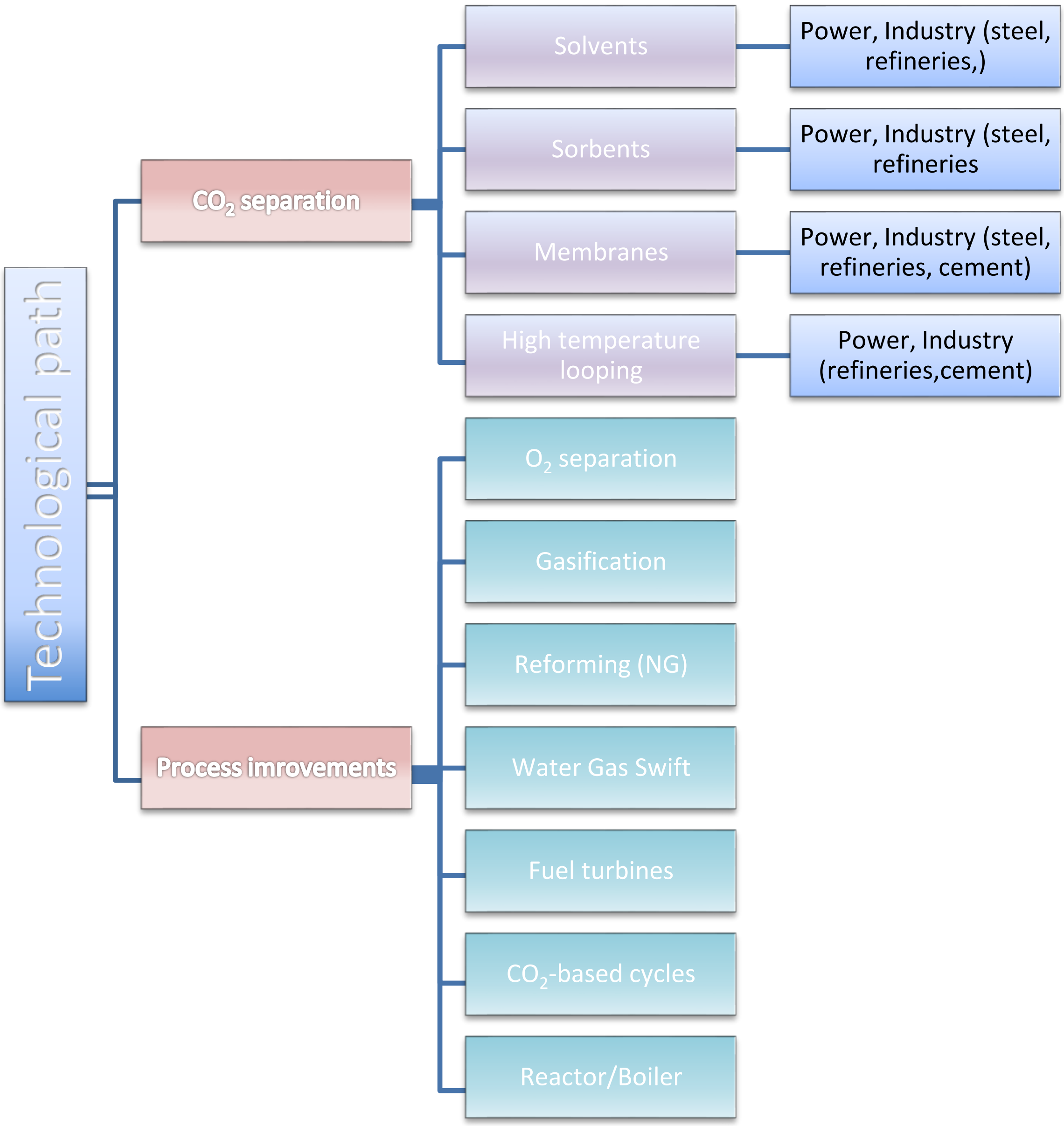

Figure 3 Key technological paths for CO_2 capture and process improvements.

Solvent-based capture involves chemical or physical absorption of CO_2 into a liquid carrier. Important properties of solvents CO_2 capture are: (i) CO_2 solubility, (ii) kinetics and (iii) speciation distribution [52]. The benchmark is the MEA solvent (30 wt % aqueous MEA). For the 1st generation amines (chemical absorption) (TRL 7-8), the aim is to [17], [53]:

- develop low-cost and non-corrosive solvents;
- high CO_2 loading capacity;
- improved reaction kinetics;
- resistance to degradation or decrease of off-gas emissions;
- lower regeneration energy.

Heat duty for solvent regeneration has been decreased from 5 to 1.8 GJ per tonne of CO_2 produced [53], or to 2.6 GJ per tonne of CO_2 captured [52]. However, the possibility of further improvement is still under testing in pilot and demonstration plants, via solvent optimisation and process integration.

Absorption processes separating H_2 and CO_2 also scrub the syngas with a liquid solvent that selectively removes acid compounds (CO_2 and H_2S). In this case, physical solvents (TRL 8) are more common than chemical solvents, as physical solvents provide better results at high partial pressures. At low CO_2 partial pressures, MDEA (Methyl diethanolamine) is the preferred amine-based solution. Typical physical solvents for such processes are: Rectisol©, Purisol© and Selexol© processes [54]. Research on 1st generation methods is focused on [17]:

- improving CO_2 carrying capacity at high temperature;
- reducing heat of absorption;
- modifying regeneration conditions to recover the CO_2 at a higher pressure.

2.2.1.2. Sorbent-based capture

For solid sorbents, pressure or temperature swing (PSA, TSA) adsorption is used for sorbent regeneration. The contact between the gas for separation and the sorbent occurs in a fixed, moving or fluidised bed. In NG plants specifically, the rationale is mainly the production of H_2 rather than electricity.

CO_2 capture techniques can also aim at obtaining a high purity H_2 stream. In these cases, CO_2 is separated using typically a physical solvent. To obtain high purity grade H_2, sorbents in a PSA configuration using activated carbon (TRL 8) are commonly used after a previous PreC separation step. This layout is applicable to plants that produce syngas (a mixture of mainly H_2 and CO), i.e. gasification (for example IGCC plants) and NG reforming plants.

2.2.1.3. Membranes

Capture using membranes technology is based upon a permeable or semi-permeable material to selectively separate CO_2 from the flue gas. Gas separation involves a physical or chemical interaction and/or surface reaction and selective transport. Usually, the membrane system consists of multiple stages and recycled streams.

2.2.1.4. High temperature looping systems

O_2 is obtained inside the own boiler using metal or other solid O_2 carriers that oxidise fast at high temperature. This technology is at TRL 4-5.

In such process, membranes and sorbents are designed to separate O_2 from the air:

- OTM integrate O_2 separation and combustion in one device. These membranes are usually ceramic tubes (made of mixed-ionic and electronic conducting materials; composite materials can also achieve these two functions) (TRL 2-3).
- Ion transport membranes (ITM) base O_2 separation on ionic transport and on ion-electron conducting membrane (TRL 3-6).
- Perovskite ceramic oxide adsorbent at high temperature (as a particular ceramic type) (TRL 3-6).

2.2.1.5. Hybrid systems

These systems correspond to the combination of any of the above technologies: for instance, supported amines, or membranes integrated with absorption. These are also called membrane contactors.

2.2.1.6. Existing projects

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 [19], [53]. 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.

Table 5 summarises the projects identified in Europe, with TRL between 4 and 6. The "entity" column refers to research centres, technology providers and/or electricity providers linked to the project. The list is not exhaustive and contains only information that could be clearly derived from public information. It should be noted that such information is difficult to verify, especially when it comes to the operational status of projects/facilities.

The main observations also reflecting on information presented in Table 3 and Table 4 are that:

- high temperature looping technologies remain of high interest for study;
- one pilot (STEPWISE) profits from learning in pre combustion projects previously undertaken continuing work but for industrial application;
- a general swift towards industrial applications is emerging;
- for existing facilities coal as well as natural gas are studied as a feedstock;
- for high temperature looping, the projects are distributed among Chemical Looping Combustion (CLC) projects (TRL up to 5) and boiler and burners adaptation projects (TRL up to 6).

CO_2 capture with 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).

2.2.1.7. CO_2 compression

The degree of purity, the temperature and the pressure of the CO_2 stream depend upon the separation method. If the specifications for storage or utilisation are not fulfilled, further purification and/or conditioning is required. Depending on the fate of CO_2, the stream will need to either meet the pressure and temperature requirements from the CO_2 utilisation plant, which often differ from those required by transport, or CO_2 will need to be compressed and then transported. Storage sites need high pressure CO_2. The CO_2 is firstly compressed slightly above its critical pressure (centrifugal compressors with intercooled stages, usually between 4 and 7), and afterwards, is cooled-down to the liquid state. It is finally pumped up to 110-150 bar, after CO_2 dehydration to avoid acid formation and transport limitations [17], [54]. Compression and pumping are well known processes and do not have specific drawbacks, besides investment and operation costs.

2.2.2. CO_2 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) [63]. Several studies [10], [64]–[68] 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. The figure 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 [69]. 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 [70], [71].Numerous reports [72], [73], [74], [75] highlight the potential of existing and future CDU options, their limited but feasible scale contribution, and their competitive advantage. Figure 5 presents different CDU technologies at different TRLs.

Table 5 CO_2 capture laboratory/bench, pilot and demonstration plants in Europe.

Entity	Location	Project	Technology	Links and current status	Scale (MW)	Capacity (tCO_2/d)	Application	TRL	Further info
AKER Solutions	Mobile, NO		Amine	Ongoing (commercial-ised)		5	Coal, NG, industry	5	[55]
ENEL/IFRF	IT		Boiler	FP7 DEBCO, FP7 RELCOM, FP7 BRISK. Plant (assumed) ongoing	0.05; 3 (th)		Coal, mixtures	4-5	[56]
SINTEF	NO	OxyFUN	High pressure OxyC, Boiler and burners	FP6 ENGAS RI, HIPROX. Ongoing	0.125-0.25 (th)		NG	4	[57]
Gassnova, Statoil, Total, and Shell	NO	Technology centre Mongstad	(i) Chilled ammonia, (ii) amine	Ongoing	(i) 12, (ii) 7	(i) 215, (ii) 55	NG	6	[58]
Technische Universitaet Wien	AT	FP5 GRACE, FP6 CLC GAS POWER, RFCS CCC, ViennaGreenCO2	CLC	FP6 CACHET, G-volution (Austrian Climate and Energy fund), FP7 INNOCUOUS. Ongoing	0.12 (th)		NG	5	[59]
Technische Universität Darmstadt	DE	LISA and LISA II, (COORETEC pro-gramme)	Calcium looping	FP7 SCARLET. RFCS CARINA (Assummed) ongoing	0.3; 1 (th)		Coal	5	[60]
TU Darmstadt	DE	FP7 SUCCESS, RFCS ECLAIR	CLC	RFCS ACCLAIM. Ongoing	1 (th)		Coal	5	[60]
UK Carbon Capture and Storage Research Centre	UK		CLC	Ongoing	0.05 (th)		Coal, co-firing, NG	4	[61]
University of Stuttgart	DE		Boiler, burners, gas cleaning	FP6 ENCAP. National and industrial: ADECOS, KW21, Oxyval. RFCS OxyCorr, Oxyburner. RFCS OXYMOD, RFCS ASSOCOGS. Ongoing	0.5 (th)		Coal, blends	5	[62]
University of Stuttgart	DE		Calcium looping	Ongoing	0.2 (th)		Solids (e.g. coal, wood)	4	[62]
University of Stuttgart	DE		SER	Ongoing	0.2 (th)		Coal, biomass	5	[62]

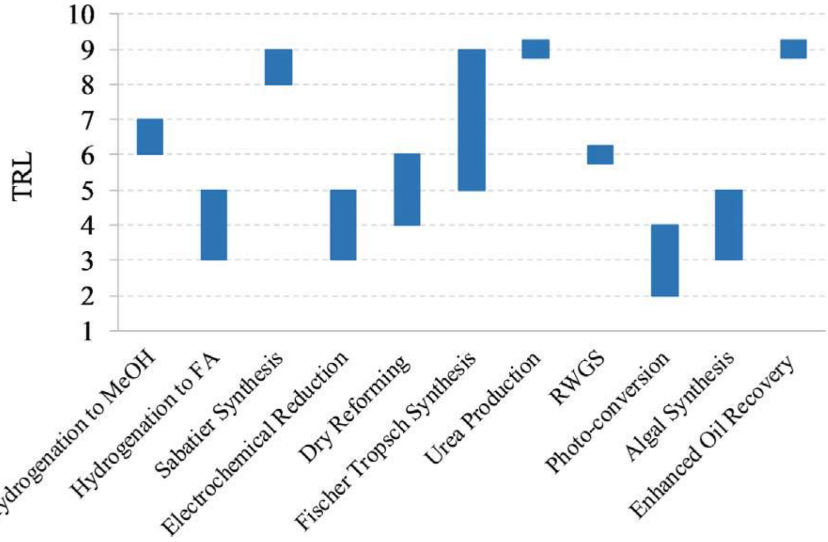

Figure 4 Technology Readiness Level (TRL) ranges of the considered CO_2 utilisation (Jarvis & Samsatli, 2018).

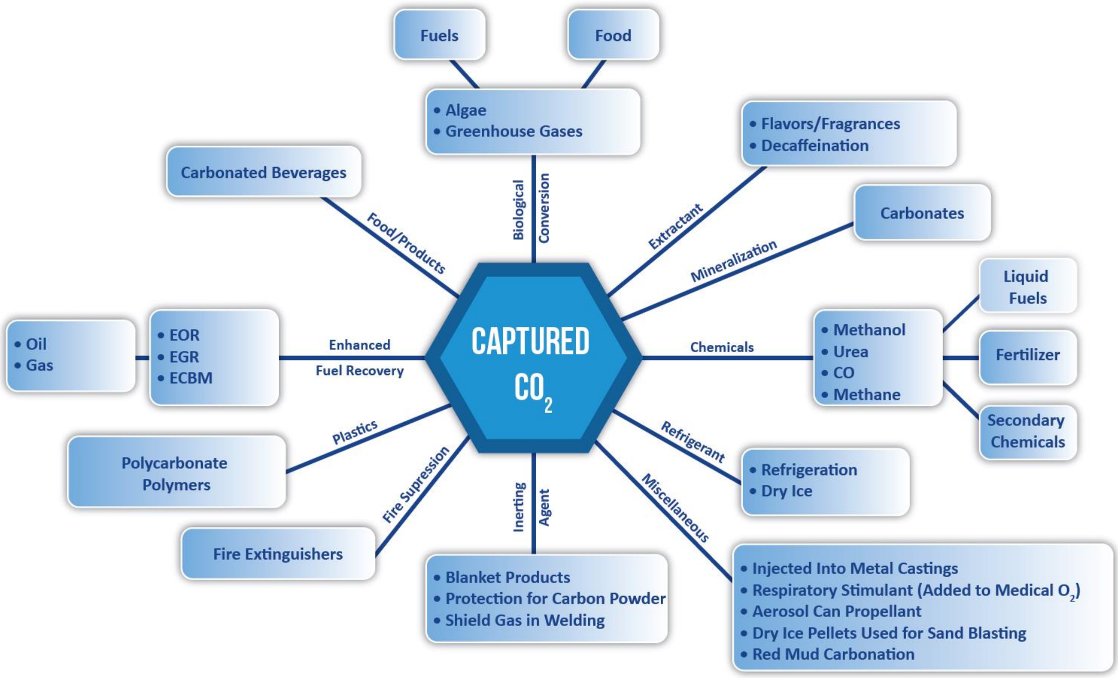

Figure 5 Classification of CO_2 utilisation options (US Department of Energy's National Energy Technology Laboratory).

2.3. CO_2 transport, storage and monitoring

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 70's in US. 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 220 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 (Figure 6).

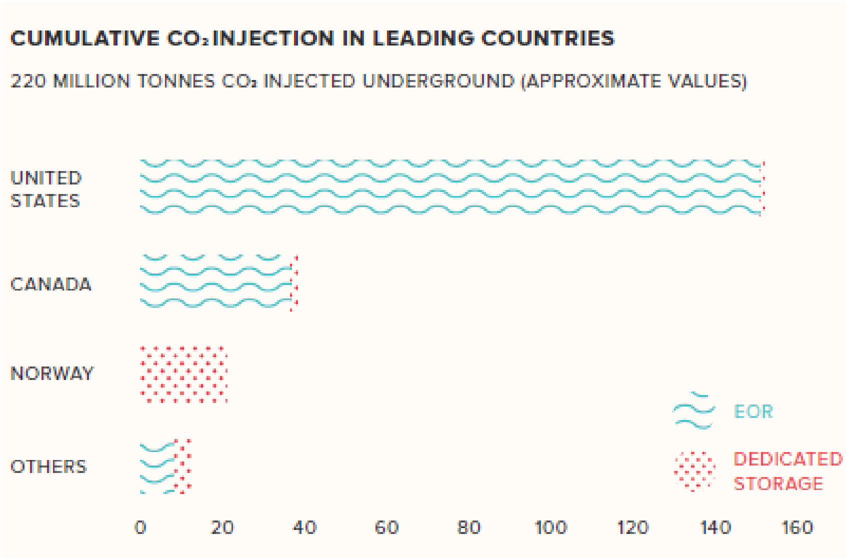

Figure 6 Global injection of CO_2 in the world [4].

Focusing on Europe, it is evident that the lack of geological assessment and complete data represent a barrier for new project developments. The published and theoretical storage estimated resource in Europe is currently 72 $GtCO_2$ (excluding Norway, UK and Russia). In terms of theoretical resource estimation, in Norway alone it is 82 $GtCO_2$ (effective resource), 78 for the UK and 6.8 for Russia [3]. However these data are outdated for Europe.

Nordic countries (except FI where no geological conditions have been found) have an estimated CO_2 storage capacity of 134 Giga tonnes(NO, DK and SE). In Iceland, the possibility to store CO_2 in order of 21-400 Giga tonnes.

Most recently, some regions in Europe have also re-calculated and made new versions of their assessment on CO_2 storage capacity. It's the case their estimations for the nordic countries, UK and ES.

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 [76]

Storage and transport costs have been excluded from the calculations of overarching KPIs [77] The main reason is that this cost is not originally dependent on technology development. There is no cost data for both storage and transport.

The necessity to include KPIs or other future indicators is important for the design of a project and can be fundamental to the site permitting process since it will enable a consideration about safety and mitigation options.

2.3.1. CO_2 storage

Putting CO_2 in the geological formations is still a promising remediation to reduce the CO_2 emissions and it is currently the most efficient way to permanently store CO_2. The technology to use has been progressing in the last 20 years due a large research program supported by EU. The main developed topics ar storage efficiency, monitoring, geochemical properties, capillary trapping, interfaces between plumes and water. Surely, the most progress has been done for deep saline aquifers, due the investments from oil and gas industry [78]. The storage in coal beds or even in shales has also been studied, with the latter being one of the new topics. Synergy with geothermal energy is also a new issue which can even reduce the costs linked to CO_2 storage.

From a research point of view, 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 [2].

Despite of this, there are limitations due to the lack of regulation and not clear liabilities. The dissemination of information about this subject has not been effective until now and it has become a barrier for CCUS demonstration projects. Resistance from local governments and population have posed barriers, as in the case of Barendrecht, the Netherlands [79]. The Dutch government took the decision to store CO_2 only offshore with the CO_2 to be transported mainly via pipelines.

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. The majority of international projects (USA and China, for example) are developing as combined CO_2 storage and EOR.

Most recently at least two projects for storage in porous basalts are being developed in US and in Iceland (CARBFIX 2, see Appendix A).

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 the expectation to 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 [80]. 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.

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 CO_2 storage capacity in the <u>theoretical</u> way will be mentioned. This is the maximum amount of CO_2 that the system can store <u>efficiently</u>, i.e. the capacity limited by the physical and chemical characteristics of the system/reservoir.
In Europe, the only 2 industrial CO_2 projects are located in Norway, where since 20 years, more than 1 million CO_2 per year is injected in offshore.

2.3.2. CO_2 transport

After CO_2 separation from other gases, it is compressed to above 8 MPa and in dense phase (supercritical state), CO_2 becomes cheaper to be transported to the site for injection or for reuse. Depending on the CO_2 volume to be transported this can be made 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 (Figure 7).

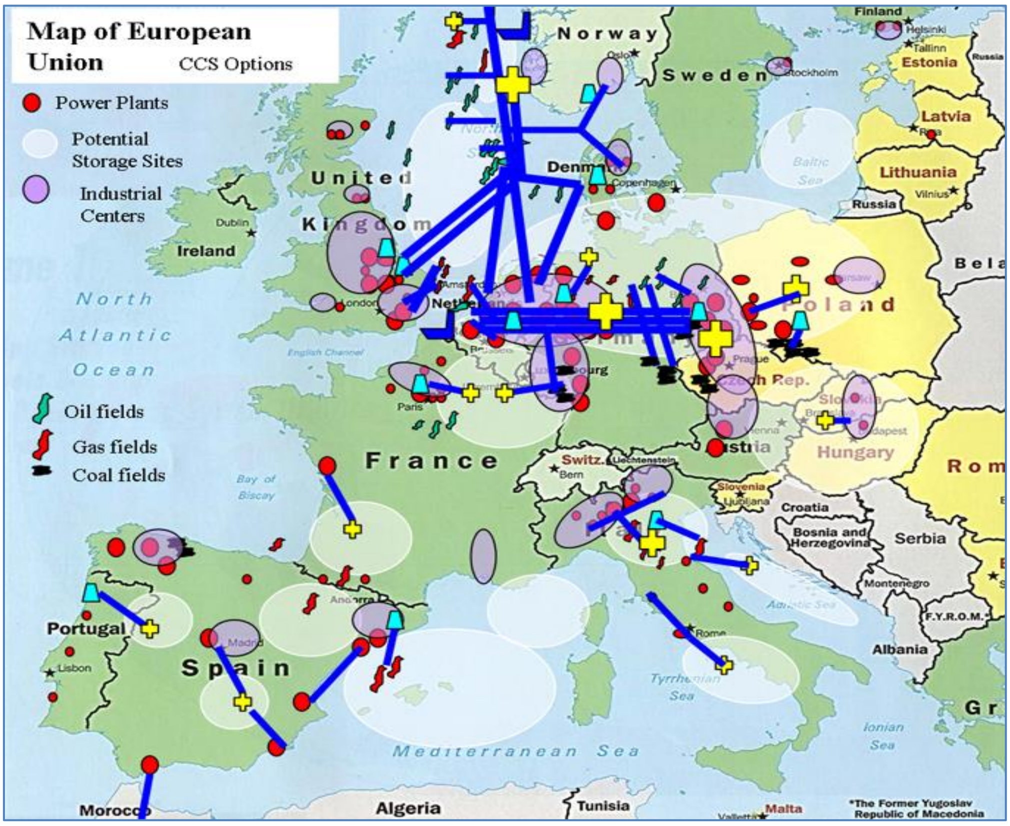

Figure 7 Options to transport CO_2 in Europe, via pipelines or and or shipping (CO2 EUROPIPE project, courtesy by Shell, 2011).CO_2 monitoring

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 one. 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 report [81] 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 use combining shipping and pipeline for the same proposal (see international projects chapter 2.1.1).

2.3.3. CO_2 monitoring

CCUS is feasible at commercial/industrial scale. However, 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's 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. [82] 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 of use for this technology it is necessary to plan for long term CO_2 monitoring is a *sine qua non* condition 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.

Figure 8 shows a summary of main monitoring techniques proposed by British Geological Service (BGS).

(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.

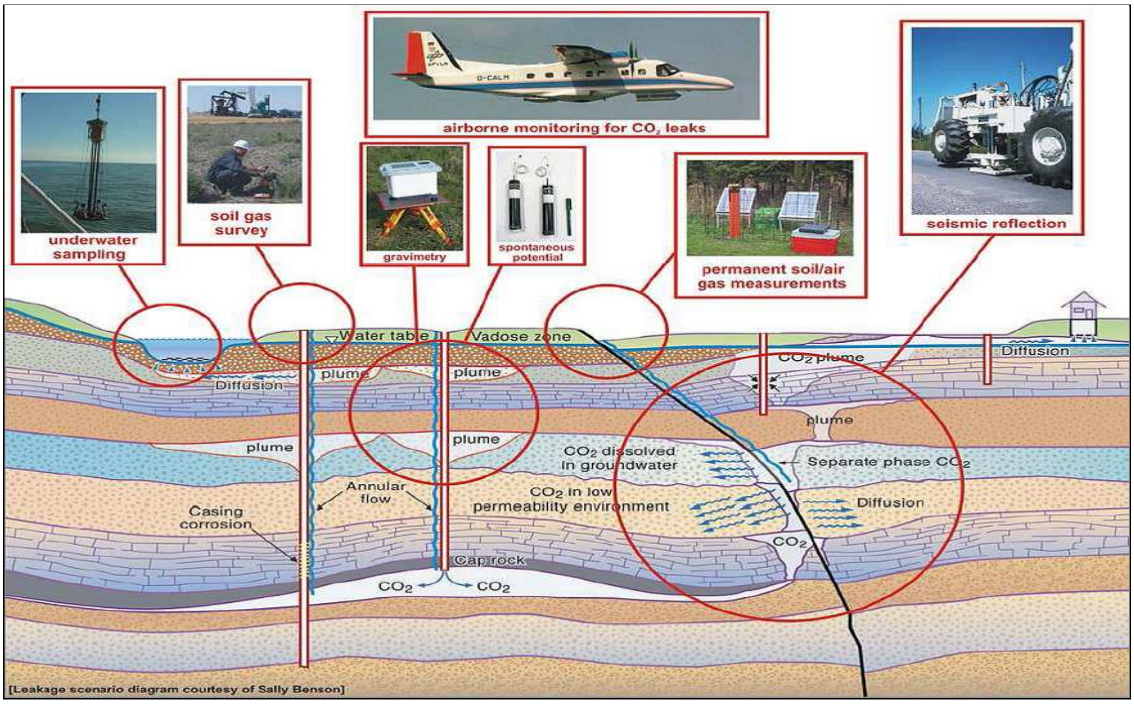

Figure 8 Summary of monitoring techniques (courtesy by BGS, 2006).

2.4. Targets and KPIs

2.4.1. Limitations

Limitations can be identified when attempting to quantify targets and performance of certain technological routes. One example is the Levelised Cost of Electricity (LCOE) metric that has been used over the years to assess power plants with CCUS. The formula for the calculation of the LCOE and the amount of CO_2 avoided, are rarely explained making the comparison of the different options challenging. Furthermore, as the focus swifts away form projects in power generation, this metric is expected to be used less and less even if the need for standardised metrics remains.

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. The SET-Plan Integrated Roadmap [85] does not mention which is the reference scenario or the evaluation formula for each parameter. On the contrary, the EIICCS stated in the EII KPIs section, the calculation formula for each one of the selected KPIs. However, it is unclear whether this evaluation methodology has been used or if the different upcoming projects will do so.

SET Plan has nevertheless indicated specific targets that may support further development of specific technologies. The ones relevant to CCS/U are to realise:

- 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.

2.4.2. Carbon capture

Literature sources as well as guidelines at the European level [85]–[87] focused on the evolution of the technology readiness level up to 2020. The highest goals were set for CLC and 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. According toTable 11 these goals are in the line with project achievements.

ADEME published in 2011 a CCUS roadmap towards year 2030. Table 6 summarises several relevant quantitative research priorities identified by ZEP (consulted as a panel of experts in the ADEME report).

Table 6 Summary of relevant research priorites for CO_2 capture [25].

	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,[8] 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 7.

Table 7 Indicative performance metrics for cement and steel industries (adapted from [88], [89]

	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.

2.4.3. CO_2 utilisation

The SET-Plan Integrated Roadmap [85], 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 [85].

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 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

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

        - 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. First pilot finished by 2018
- Full demonstration about the use of the mineral carbonate (as new material): 1 project

Table 8 Summary of 2020 technological KPIs identified for specific CO_2 utilisation processes [85].

	2020
Fine chemicals	
Carbon footprint reduction if compared to the established fossil route	20 %
Polymers	
Carbon footprint reduction if compared to the established fossil route	20 %

The SET Implementation plan endorsed in September 2017, also includes targets for CCS and CCU under the SET Plan Action 9.[9] Regarding CO_2 utilisation, these refer to the delivery of regional CCU clusters, as well as a dedicated CCU action. Specific targets include:

- 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;
- Several large scale commercial plants in place in Europe for each of the main CO_2 valorisation routes, i.e. carbonation, transformation into methanol, fuels and chemicals, and production of polymers on the way to 2030.

Table 4 indicated that SET Plan flagship projects are relevant in realising these goals, especially with regards to chemicals, polymers and mineral carbonate within the essential CO_2 utilisation processes aiming to reach TRLs up to 9.

2.4.4. CO_2 storage, transport and monitoring

It has been demonstrated in the previous SET plans and EU reports the importance of CCUS in the transition for a decarbonising Europe.

[9] 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)'.

As mentioned before, transport and storage costs are not taken in account for the overarching KPIs calculations due the fact that these costs are not depending on technology development. New indicators should be created to measure this part of the CCUS chain.

Concerning the new targets and KPIs (excluding economic) for CO_2 storage, transport and monitoring, 4 points should be considered:

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

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

3 - The absence of 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. At least, 3 new pilot storage sites have been defined in the SET PLAN action 9 (Appendix E)

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. H2020 project should create their webpages which reveals a good tool for dissemination.

KPIs are shown in the table, based on CCUS stakeholders and probable future commercial targets in 2030 and 2050. The expectations include the creation of supply chain, 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, important topic to install CCUS projects in all Europe.

Table 9 KPIS and targets (2030 and 2050)

1- CO_2 storage capacity, site characterisation and safety (including monitoring)

	Costs (MEUR)	Duration of project (years)	2030 KPI	2050 KPI	Costs reductions Targets
Storage capacity (Gt)	20	3 (2015-2018)	1.8	12.2	10-20%
CO_2 storage characterisation – improved methods)	60	3 (2015-2018			10%
CO_2 monitoring	100	5 (2015-2018			20%
Safety	100	4 (2016-2020)			Reduction by store tonne of CO_2

2 – Demonstration projects

	Costs (MEUR)	Number of CO_2 storage pilots/patents	Duration of projects (years)
Industrial and Research program	270	6/10	6 (2015-2020)
Safe storage exploitation	100	3	4 (2016-2020

3 – CO_2 transport

	Costs (MEUR)	Number of CO2 storage pilots	Duration of projects (years)	Linked project
R & D	67.5		6+	ECCSEL
Industrial research and pilots	54		6 (2020)	Pan-European transport of CO_2
Integration and cross-cuting issues	36		6	

3. R&D OVERVIEW

The EU has supported CCS technologies since FP3. FP5 projects were mainly focused on CO_2 storage and monitoring, while FP6 and FP7 projects have also addressed the capture part. Other research areas of relevance in FP7 projects are process improvements, public acceptance, engineering studies for CCS demonstration plants and CO_2 value chains. In 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, the EU has contributed approximately EUR 17 million within FP6, around EUR 18 million within FP7 and almost EUR 30 million within H2020 so far. An ongoing call focused on CO_2 storage and transport has deadline in September 2018 and the second call will serve to stimulate CCUS industrial projects is forthcoming in 2019.

For carbon capture projects identified in the FP programs, 15 also explored issues other than technological (cross-cutting and regulatory issues), i.e. cooperation, training and networking initiatives, information/advice initiatives for social acceptance or for policy support. Concerning technological projects, 7 were identified in FP6 and 19 in FP7. The main financing themes have been Sustdev-Energy in FP6 programme and Energy in FP7 programme. FP7 programme has supported CCS mainly through two energy themes or activities: CCS and clean coal technologies (CCT). In H2020, 14 projects were identified with the majority of them under the theme "Secure, clean and efficient energy".

For capture projects identified along the FP6, FP7 programmes, correspond to a total of EUR 137 million granted by the EU. This amount levereged EUR 175 million from the participants. With a focus in power generation applications, FP6 and FP7 programs projects focused mainly in Pulverised Coal (PC, hard coal and/or lignite combustion plants), followed by NGCC, as the first and second main fossil fuel technologies in Europe. An overview of the selected projects, ordered by programme, action, and classified according to (i) their research and (ii) project focus, is given in the Appendix. Please note that for most projects funded within H2020 results are not yet available due to their early project stage.

Between 2003-2014, 11 RFCS funded projects have been identified and one for the period 2015-2016. The total amount granted to these projects over the years is EUR 16 million. All belong to the action "TGC3: Coal combustion, clean and efficient coal technologies, CO_2 capture".

The first CO_2 utilisation project found is an FP6 project, under the FP6-Policies action with a TRL of 3. For CO_2 utilisation, 8 projects have been awarded within FP6 and FP7 programmes, mostly focusing on technologies above TRL 5. In FP7, 7 projects were identified while H2020 has so far awarded 23 CO_2 utilisation projects. Within the FP6 and FP7 programmes, a total of EUR 18 million was granted to projects by the EU.

The MS that have focused more on CO_2 utilisation are Germany and France. These countries have their own programmes to support CO_2 utilisation processes. In Germany, the Federal Ministry of Education and Research started to finance CO_2 utilisation in 2009, along different financing tools. Its novel funding instrument, focused on projects with a TRL higher than 4 [39].

In France, CO_2 utilisation is supported as a part of the decarbonised energy programme of the French National Research Agency, and part of the innovation programmes of the French Agency of Environment and Management of Energy [90].

UK has funded, through the Engineering and Physical Sciences Research Council, the CO2Chem Network and the 4CU programme [45].

On the EU level, the FP7 SCOT (Smart CO2 Transformations) project run until 2016 aiming at paving the way for CO_2 utilisation in Europe. H2020's CarbonNext will build on the findinds of the SCOT project. Other projects include the BMBF funded coordination project CO2Net as well as the CO2Chem network.

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 Appendix B.

At least 59 projects have been developed focusing on CO_2 storage, monitoring, and transport. All of them are at least TRL 3 while other projects concern all CCS chain. Following a chronological order from the oldest program FP3 to the newest H2020, EEPR and NER300, it is possible to detect the continuation of some projects, especially for characterisation of the CO_2 injection site. New projects were concentrated to develop more knowledge on safety and monitoring of CO_2.
The total costs of all storage, transport and monitoring projects (excluding CCS projects from EEPR, NER 300) is around EUR 513 million and EU has contributed with EUR 328 million. Note that some projects can be focuses in all aspects of CCS.

For carbon capture, projects with the highest funding are ENCAP (EUR 10.4 million, process development) for FP6, H2-IGCC (EUR 11.3 million, gas turbine) for FP7 and H2020's STEPWISE (sorbents) at the top of the list with funding of around EUR 13 million. For CO_2 utilisation it is the CYCLICCO2R (EUR 3.85 million, carbonates) within FP7 and FReSMe (EUR 11.4 million, methanol production) as financed by the H2020 program so far.

Overall, these most funded projects, count with an amount of partners in the range of 1 (H2020, "Innovation in SMEs") to 30 (FP6-SUSTDEV), including universities, research centres and private companies. In FP6 and FP7 programmes a high connection among the different projects was identified, i.e. project participants tend to be involved in more than one project. A large number of (shared) partners was also identified for H2020 reaching up to 18 per project. The organisations identified among H2020 projects' partners, are quite diverse compared to previous programmes. Organisations with major participation in previous programmes is noticeably lower in H2020. Indicatively, Stiftelsen Sintef and Sintef Energi (NO) are each present in 3 and 2 H2020 projects, down from 10 and 6 respectively in the framework programs. IFP Energies Nouvelles (FR) is present in one, down from 9, and both TNO (NL) and NTNU (NO) in one, down from 7 each. Nevertheless, Norway's relevance in projects is maintained, being after Switzerland, the European Economic Area (EEA) country with the biggest participation in H2020 projects.

With regard to Member States, the highest participation was identified for Germany and Italy, with 21 projects for each. The Netherlands, the UK and Belgium are following with 19, 18 and 15 project participations respectively.

The main partners for CCS projects focusing on storage transport and monitoring are industrials, mainly for oil and gas industry such as Statoil, Shell, BP, Total, EON. All geological surveys in Europe 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 Figure 3. 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. As such, they have been considered accordingly and the following graphs represent primarily trends.

Carbon capture and utilisation EU co-funded projects have received nearly EUR 360 million taking into account FP6, FP7, H2020 programmes.

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 are aiming for TRL 7 within H2020. CLC is also targeting TRL 7 within H2020 (CHEERS project).

The overview of the European co-funded projects show a noticeable hshift in CO_2 sources, from fossil power plants towards "large point sources".

3.1.1. Carbon capture

24 technological projects identified among FP6, FP7 and H2020, have been classified according to their main subject(s) of research. Up to now, FP7 is the programme that invested the largest amount in carbon capture (EUR 112 million). Within H2020 programme funds have been awarded mostly on CO_2 utilisation and less in capture and projects (EUR 117 million and EUR 87 million, respectively).

Within FP programmes overall process development together with capture technologies in power generation were topics of the highest granted projects. Solvents, Membranes and High Temperature Looping (HTL) were the technologies of the projects that attracted the highest funding in FP7 programme. In H2020 CO_2 separation via membranes has also been highly funded with solvents receiving the least support.

In Figure 9 projects and amount granted per sub-technology and areas of research (according to the classification in Figure 3) are presented. FP6 funded projects focused on process improvements while this trend has been decreasing.

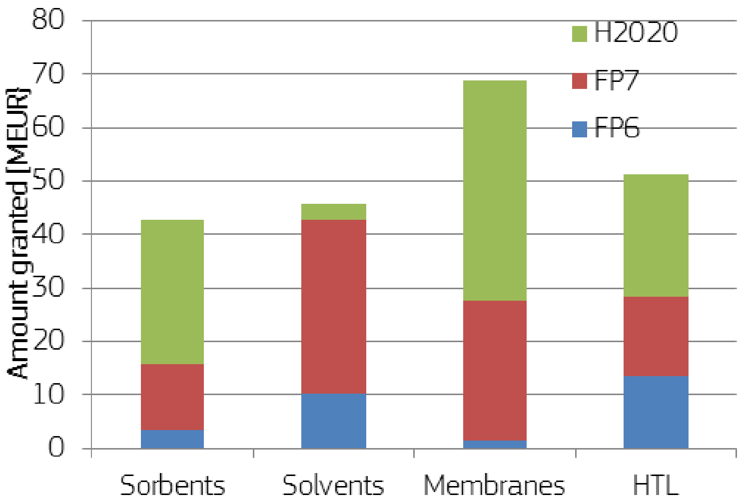

Figure 9 Amount granted by programme to the different carbon capture sub-technologies (Figure 3) and areas of research.

Among the RFCS projects examined, projects investigating multiple technological paths (solvents, sorbents, membranes, solid looping) were the ones that received the highest amounts of funding.
In overall, membrane technologies represent the most supported research area with liquid solvents following. Considering that initiatives examining process improvements can be broadly classified, this area received significant support too within the different programmes.

3.1.2. CO_2 utilisation

Research on catalytic, photochemical and electrochemical pathways for CDU-based products is ongoing at industrial and academic levels. Within FP7, the largest share of identified projects has been at TRL up to 4. Within H2020 the projects are targeting TRL up to 7. Within the FP programs, five projects have been identified in the field of fuels synthesis with some also proposing to study specific technologies both for fuels and chemicals. Two projects aimed to examine the synthesis of materials targeting to advance the proposed route up to TRL 7.

Figure 10 takes into account projects awarded for studying CO_2 utilisation, classified according to their main research areas. Fuels production is the sub-technology granted funds in all FP6, FP7 and H2020 programmes. It is noted that CDU projects increased significantly during FP7 programme. H2020 programme focuses on chemicals/chemicals for fuels.

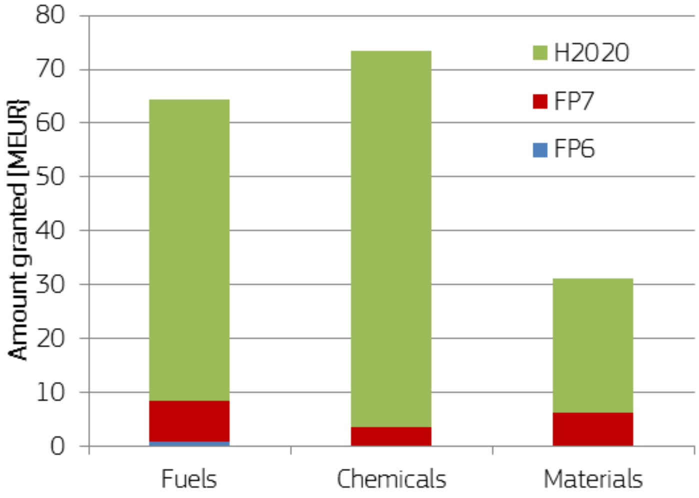

Figure 10 Amount granted to the different CO_2 utilisation sub-technologies (Figure 3), by programme.

3.1.3. CO_2 storage, transport and monitoring

The evolution of the EU projects since 1993 from FP3 program until H2020 is showed below. It is followed by the description of the main results of the most important projects developed between 1993 to 2015 and comments, as well as objectives of the new projects initialized or finalized in the program H2020, until 2018. A complete list of all projects can be found in the Appendix B. Thre was continuity in several over thse programmes to try to progressively solve gaps or improve knowledge.

FP3 (1993-1995) – 1 project (costs not available)

FP4 (1998-1999) – 1 project (costs not available)

FP5 (1999-2002) – 5 projects with a total cost of EUR 14.6 million. EU has contributed with EUR 7.0 million.

FP6 (2002-2006) – 8 projects with a total costs of EUR 64 million. Not available cost information for the project ASAP. EU has contributed with EUR 32.8 million.

FP7 (2007-2013) – 31 projects. The total cost of these projects was EUR 128 million and EU has contributed with EUR 94 million.

H2020 (2014-2020) – 11 projects and 2 projects in the reserve list (MINEFIX and STREAM). The total cost of these projects was around EUR 76.5 million and EU has contributed with EUR 50 million.

Finally 3 contract projects, not linked to any programs have been found.

INTAS (2007-2009). The total cost of the projects was EUR 112 100 with 100% EU contribution.

Feasibility study for Europe-Wide CO_2 infrastructures. (2010) – Extended feasibility project elaborated by ARUP, Scottish Carbon Capture and Storage in cooperation with DG Energy and Transport. The objective was the quantification of capture, storage and transport infrastructure in Europe. Important simulation scenario mainly on transport has been demonstrated.

CO2StoP (2012-2014). The total cost of the project was EUR 238 581 with 100% EU contribution.

The CCS R & D programs have been done in cooperation with all EU member states. The same as for capture, the EU programme with more investments was FP7. 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. From FP7, projects linked to the risks and assessments especially on monitoring, have been developed. 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. Below there is a short description about EU funding organized by technology and by chronological order (storage, transport and monitoring,) and projects related to all CCS chain. It is sometimes difficult to separate transport and monitoring projects from storage, since they are absolutely connected. Here it has been divided in CO_2 storage, transport and monitoring, and CCS projects according to their focus, but the majority of them has the CO_2 storage as final goal.

Table 10 summarizes the projects on CO_2 storage, transport and monitoring, including TRL and duration of the projects.

Table 10 CCS projects focus on storage, monitoring and transport., CCS all chain projects, including EEPR and NER300 (European projects).

	Number of projects/technology	**Total Costs (EUR)**	**EU contribution (EUR)**	**Duration of project (years)**
FP3	1 Storage	N/A	N/A	2
FP4	1 storage	N/A	7 02 M	1
FP5	5 storage	14.6 M	14.6 M	3
FP6	8	64.3 M	32 8 M	4
FP7	31	128. M	93 8 M	6
H2020	11	76.5 M	50 M	1-6
Contract projects	3	350,861 (EUR)	350,861 (EUR)	

3.1.4. Synergies between CCS and renewables

Combining CCS and renewables is promising and it has progressed in the last years, mainly for economical reasons. The advantage to use the same infrastructure and to get more efficiency using CO_2 as working fluid, for example in the case of CCS-Geothermal [91] has also been explored. Other possibilities include the use of biomass (Bio-CCS), CCS and concentrated solar power (CSP). Another option that is gaining a lot of interest though CO_2 utilisation is the wind energy which is used to produce H_2which can then be combined with captured CO_2 to produced added value products [92].

Currently some pilots are in construction mainly on CCS and geothermal (IS, FR), Bio-CCS (SE, FI), CCS and H_2 (NL, NO).

4. IMPACT ASSESSMENT

4.1.1. Projects employing different CCUS aspects

Besides technology projects, funding has been channelled 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:

Projects FP6 INCA-CO_2, FP6 ACCSEPT, FP6 FENCO-ERA, FP7 NEARCO2, FP7 STRACO2 and FP7 CO2TRIP focused on cooperation, communication and networking among stakeholders and public-social acceptance of CCS.

FP6 ZEST, FP7 ZEPPORT, FP7 ZEPPOS and H2020 SESZEP supported the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) secretariat. ZEP aims to provide information, support and assistance to management, administration, information and communication bodies about CCUS.

FP7 ECCSEL, FP7 ECCSEL PP2 and H2020 ECCSEL support the European Carbon Dioxide Capture and Storage Laboratory Infrastructure. The purpose of ECCSEL is to prepare and manage a European coherent research infrastructure for CCS. In a similar line of research, FP7 CCS-PNS aimed at sharing the generated knowledge among the large-scale European demonstration projects in CCS.

FP7 ECCO studied and provided advice for decision making in the field of CCS for EOR and enhanced gas recovery.

FP7 ELCAT aimed to train electro-catalysis experts for CDU processes. FP7 SCOT was an initiative to facilitate the transition towards the use of CO_2 as raw material.

FP6 DYNAMIS – Towards Hydrogen and Electricity Productions with Carbon Dioxide Capture and Storage. The production of hydrogen and electricity from fossil fuel can generate CO_2 and then it should be stored or in parallel to be used as enhanced oil recovery. EUR 4 million were used by EU in this project which lasted 36 months.

FP6 CASTOR – from Capture to Storage – All CCS chain was analysed here, with intention to create pilots to validate the knowledge acquired in this project. The ambition was to capture and store 10 % of European CO_2 in aquifers and in depleted hydrocarbon reservoirs. This projected is linked to GESTCO project initialized in FP5 regarding the CO_2 storage locations in Europe. Techniques and developments on safety have been improved in this project.

FP7 GHG2E – Greenhouse gas recovery from coalmines and unmineable coalbeds and conversion to energy. Storage in coal bed methane. The most important result from this project was the knowledge on the quality of gas and consequently how to store CO_2..

FP7 CO2QUEST – Techno-economic assessment of CO_2 quality effect on its storage and transport. Large CCS project focusing on fluid properties and phase behaviour, CO_2 transport, reservoir integrity (site of injection), techno-economic assessment, impacts and risks, dissemination plan, exploitation and management.

FP7 TOPS – Technology options for coupled underground coal gasification and CO_2 capture and storage. Research and technical knowledge have been improved to allow the use of combined technologies as CCS and coal gasification. This project solved some gaps on topics as geomechanical, risks of ground water contamination and subsidence impacts, process engineer linked to CO_2 storage.

H2020 CO2NOR – Carbon dioxide storage in nanomaterials based on ophiolitic rocks and utilization of the end-product carbonates in the building industry. This project started in 2015 and finished in 2017.

H2020 ACT – One of the most recent European CCUS project with a goal is to accelerate CCUS technologies in Europe. ACT started in June 2016 with a finishing time planned for 2021.

EEPR - Starting in 2009, the European Commission via Energy Programme for Recovery (EEPR) selected six CCUS projects in Europe. Jänschwalde in Germany, Porto Tolle in Italy , Belchatow in Poland, ROAD in the Netherlands, Compostilla in Spain and Don Valley in UK. The promoters came from both private and public undertakings and the EU was to contribute with maximum 80 %. The EEPR only covered projects concentrated in the entire CCS chain. i.e. CO_2 capture, storage and transport. All of the EEPR projects are now cancelled.

NER300 – White Rose project. A full chain, capture and storage project based on coal power-plant. The ambition was to create a commercial scale project, capturing two million tonnes CO_2/year via oxy-fuel combustion from Drax Power Station, in North Yorkshire, UK. Then CO_2 should be transported via pipeline to the offshore storage in the UK North Sea. However in November 2015, UK government decided to stop financial support to this project.

The full list of projects is given in the Appendix.

4.1.2. Carbon 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 been previously identified as key performance indicators (KPIs) for projects of past programmes.

Projects within FP 7, reported a cost of CO_2 avoided for solvent-based capture at EUR 36/tCO_2 and a value for amine regeneration of maximum 3.5 GJ/tCO_2. For CO_2 separation technologies via solids sorbents, solvent and membranes and low temperature (also known as cryogenic), results reported a LCOE of EUR 77.8-90.6/MWh, a cost of capture between EUR 19.5-29/tCO_2, a cost of CO_2 avoided of EUR 25.1-40.4/tCO_2, and a capture rate between 76.5-91 %. For SEWGS technology the denoted values are in the range of EUR 77.8-90.6/MWh for LCOE, as well as a EUR 23/tCO_2 as a cost of capture. For the cost of CO_2 avoided values have been in the range of EUR 36-53/tCO_2 while for CLC a cost of CO_2 avoided has been denoted between EUR 12-32/tCO_2. For calcium looping a LCOE between EUR 85-110/MWh, a cost of capture of EUR 20-25/tCO_2, a cost of CO_2 avoided of EUR 29/tCO_2 were reported. H2020 projects such as STEPWISE and CACHET II are aiming to lower the cost of CO_2 avoided for the respective technologies examined.

Most projects of past programs adopted the perspective of power sector applications. Thus, it could be expected that respective KPIs estimated from an industrial application perspective may differ.

Given the noticeably different approach of projects between FP and Horizon 2020 programmes, detaching from the power sector inevitably lessened specific indicators' relevance (for example LCOE). Thus, suggesting specific indicators as a prerequisite for future programmes could provide a uniform basis in analysing the results and impact of supported projects.

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

- Capture through improved amine reaches TRL 7, setting the basis for the implementation of a full-scale plant.
- Calcium looping moves up to TRL 7 within H2020.
- CLC is at TRL 6 with FP7 SUCCESS. It set the basis for a pilot plant at relevant environment.
- SEWGS and H_2 turbines (process improvements) are at TRL 6.
- Hybrids for CO_2 capture involving membrane and cryogenic separation, are towards TRL 6.
- Solvents, sorbents, CLC and CaL can be implemented in a full scale plant after reaching TRL 7 within H2020.

Regarding specific technological paths of carbon capture with solvents, FP6 and FP7 projects focused on advanced amines and amine blends as well as new solvents. Establishing detailed guidelines for operational issues and providing specific information about amines emissions and degradation was also a topic of project focus within FP6 and FP7 but no records could be found within H2020. Synthesis of novel ionic liquids (IL) was studied within FP7 (IOLICAP) and H2020 DIACAT is also including ILs in their workplan.

Contrary to FP6 and FP7 programmes, sorbent facilitated capture via CO_2 adsorption has been within the focus of H2020 projects. Projects studying hybrid configurations spun throughout FP projects, RFCS as well as H2020 with the latter indicating a TRL 6. This is significantly higher from the previous programmes where a TRL 4 was indicated.

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 focused projects were present within FP6 and FP7 achieving a TRL 6. Within H2020 this is expected to move up to TRL 7. Other specific topics studied have been sorbent performance as well as O_2 use in the gasifier and in the reformer. Tests for obtaining O_2 with advanced cryogenic methods were also conducted within FP 7.

4.1.3. CO_2 utilisation

Within the FP programmes, seven projects can be identified at TRL > 3. Lower TRL projects aimed at using sunlight (i.e. photocatalytic and electrophotocatalytic approaches) to provide the needed energy for CO_2 reduction.

Fuel synthesis has been the dominant area of study 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 is to move methanol synthesis to TRL 6. For methanol as a precursor of fine chemicals the objective within FP 7 was to attain TRL 4. While the majority of H2020 projects are ongoing, MetaFuel, a project that can be classified in this category was completed in the end of 2017. The project has achieved most of its objectives and milestones which marks a success for H2020 project.

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 is expected to reach TRL 7 for polyols production.

H2020 CarbonNext project is 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 will include the identification of value chains within processes and where industrial symbiosis can be valuable (chemistry, cement, steel, etc.).

4.1.4. CO_2 storage

The main projects with focus on CO_2 storage are described below:

FP3 – The underground disposal of carbon dioxide was one of the first projects in Europe carried between 1993 and 1995 to analyse both technical and economic aspects of CCS. It was the starting point to quantify the CO_2 to be stored and also the costs involved on it. Technically, the viability to store CO_2 in Europe has been proved, mainly under the North Sea, but the costs involved were very high. However it also has been noted that if the CO_2 storage is combined with enhanced oil recovery, the cost credits from the sale of this oil can reduce the CCS operational costs.

The total costs of this project was not published but reported a TRL 3-4.

FP4 – In the period 1998 to 1999, EU funded one project, SACS – Saline aquifer CO_2 storage – an offshore demonstration at the Sleipner field. This was the first demonstration industrial project and the main objective was the characterisation of offshore deep aquifer to store 1 milliontonnes CO_2 per year. This was the most successful project until now in Europe and it has been used as best practice manual for further projects. An accurate CO_2 monitoring has been done in systematic way since the first injection of CO_2. There are no data about the costs of this project which indicated a TRL between 7-8.

FP5 – Between 1999 and 2002 at least 5 projects received funding from the European Commission. Universities, research institutes and industries joined effort to improve the knowledge on CCS technologies. Some projects were more focused on geological storage, in general looking for a better overview of where and how to store CO_2 in Europe. These projects are listed below:

GESTCO – European potential for geological storage of CO_2 from fossil fuel combustion, analysing storage both onshore and offshore possibilities and all CCS chain, from an economic point of view. A series of case studies have been evaluated in this project verifying the potential for CO_2 storage in saline aquifers, geothermal reservoirs, coal seams and oil/gas reservoirs. These studies also took into account the economic feasibility and environmental acceptance.

The total costs for this project was EUR 3.8 million and EU has contributed with EUR 1.9 million.

The results show a TRL 4.

SACS 2 – Saline aquifer CO_2 storage, the continuation of the demonstration project in the Sleipner field, North Sea, Norway, initialised during the period 1998-1999 (SACS project – FP4, mentioned earlier). It has improved some data about characterisation of reservoir and modelling.

The total costs for SACS 2 was EUR 3.03 million and EU has participated with EUR 1.2 M

The results of this project show a TRL 7-9.

RECOPOL – Reduction of CO_2 emission by means of CO_2 storage in coal seams in the Silesian coal basin of Poland (management of GHG emissions) – This was a feasibility study on storing CO_2 in subsurface coal seams. A pilot site, Silesian Coal Basin, in Poland has been chosen.

The total costs of RECOPOL was EUR 3.7 million and EU has contributed with EUR 1.7 M.

TRL between 3-4.

CO2STORE – On-land long-term saline aquifer CO_2-storage. In this project the focus was to simulate conditions of reservoirs to store CO_2 onshore. Geochemical reactions and geophysical techniques were analysed to improve the knowledge on CO_2 monitoring. This project is connected with SACS 2 project (despite of offshore characteristic of this last one).

CO2STORE total costs was EUR 2.5 million and EU has participated with EUR 1.2M. TRL 5 for this project.

FP 6 – In the period between 2006 to 2009, 8 projects received funding in order to know better the technology involving CO_2 storage. The majority of them has been related to the characterisation of injection sites, as well to monitor the CO_2 and then to determine the safest way to store CO_2. Research on more sustainable source of energy was also a focus of this period and other utilisation or re-utilisation of $CO_{2.}$

Below is the description of the main projects:

CO2 SINK – In situ R & D laboratory for Geological Storage of CO_2. This was a pilot project to understand better the CO_2 storage in onshore, in the city of Ketzin, near Berlin, DE. To avoid any leakages is fundamental to know the site of injection and mainly to monitor the CO_2 migration. In this laboratory several geophysical and geochemical monitoring techniques have been tested to provide the most advanced CO_2 monitoring in subsurface. This was an international project with a duration of 60 months. EU contributed with EUR 8.7 million. TRL from 4 to 5.

CO2GEONET – Network of Excellence on Geological Sequestration of CO_2. The focus was on safety of CO_2 storage and developing a network to share knowledge about this technique. The project had high costs EUR 9.18 and has received EUR 6 million from EU and lasted for 60 months. The obtained results show TRL 4-5.

EU Geocapacity – Assessing European capacity for Geological Storage of Carbon Dioxide. This project was the first project to integrate different and more complete data from several kinds of aquifers, possible sites of CO_2 injection in Europe using techniques as Geographical Information System (GIS) and Decision Support SystemDSS. This project is related to the previous GESTCO initialized in FP5. The development of methods to measure the capacity of CO_2 storage and as well economic modelling and site selections have been elaborated. Data from 26 European countries were analysed and the goal was to elaborate a source to sink matching across Europe. The total costs was EUR 3.4 million and EU has ontributed with EUR 1.9 million for this project, which lasted for 26 months.

A TRL from 4-5 has been obtained.

FP7 - SITECHAR – Characterisation of European CO_2 storage sites. Improving on data base and quantification of CO_2 storage capacity in Europe. This project is linked to CASTOR from FP6 and ECCO (FP7).

This project costed around EUR 5 million and EU has participated with EUR 3.7 M. TRL was 6.

ECCO – European value chains for CO_2. The main goal was to create a model to measure the storage capacity of CO_2, the costs involved and recommendations for the elaboration of safe CCS projects in Europe.

The total costs for this project was EUR 5.4 million and EU has contributed with EUR 3.8 M. The TRL obtained was 4-5.

MIRECOL – Remediation and mitigation of CO_2 leakage – The objective of Mirecol is to provide and improve knowledge about mainly safety in CO_2 storage operation. The results from this project are also useful for mitigation and remediation alternatives.

The total costs for this project was EUR 5.2 million and EU has contributed with 3.7, to achieve a TRL 5-6.

CARBFIX – Creating the technology for safe, long-term carbon storage in the subsurface. The first European project to verify the possibility to store CO_2 in basalts. Some results show that interactions between gas, fluids and minerals from these rocks can be faster, increasing the efficacity and diminish costs linked to CO_2 storage.

The total costs for this project was EUR 2.2 million and EU has participated with EUR 1.5 M. The TRL obtained was 4-5.

H2020 – 6 projects and 2 in the reserve list.

ECCSEL - European carbon dioxide capture and storage laboratory infrascture. ECCSEL finished in 2017 and became now ECCSEL-ERIC, led by Norway and with participation of 5 other European countries. ECCESL-ERIC aims to become an trans-national center and multi-facilities for CCS research. ECCSEL currently is inviting other countries of 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 of several conferences and workshop. There is also a webpage dedicated to this project [93].

The total costs of this project was EUR 3.25 million and EU has contributed with the complete amount. TRL 5.

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 nanoterials 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 will all amount. TRL obtained was 5.

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 process were well analysed using combining Synchrot-on 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. The TRL obtained was 5.

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 associ-ated to monitoring CO_2 but there are also some strategies to reduce these costs.

The total costs of this project EUR 15.9 million 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 ac-ceptance 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 M, totally cover 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 the previous and completed CARBFIX from FP7. The project is known for the particularty to make possible and efficient the CO_2 storage in basalts. The ongoing project expected to be finished in 2021.

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

2 others projects have been evaluated and due the limits of budget, they are now in the reserve list .

MINEFIX – The energy potential of hard coal mine: the integration of CO_2 storage with the production of heat and methane.

STREAM – Development and demonstration of safe and environmmentaly sound best pratices for CO_2 storage cycle with mature technologies.

Contract projects

Feasibility study for Europe - Wide CO_2 infrastructures. This project carried in 2010 represents a significant contribution to measure the needs to establish CCS projects in Europe in terms of capture, storage and transport. Simulations for the 2030 and 2050 horizons have been made on infrastructure as well as for the costs for each of these parts of CCS. The data obtained has been used for the following program for localisation of CO_2 storage sites, such as CO2StoP.

CO2StoP This project elaborated by JRC and several geological European surveys, coordinated by GEUS between 2012 and 2014. With the calculations made in the CO_2 StoP project it is possible to have a picture of CO_2 storage locations in Europe. However, gaps exist on, for example, quality of some data bases, geological studies and seismic surveys.Other data should be completed and information about drilling should be delivered by European geological surveys.

Table 11 CO_2 storage projects funded by diverse EU programs since 1993. Some projects have a continuation as showed below

CO_2 storage – EU projects with TRL (technology readiness levels)*									
Programs/period	FP3	FP4	FP5	FP6	FP7	H2020	EEPR	NER300	Contracts
Projects	**The underground disposal of carbon dioxide *3-4**	**SACS* 7-8**	**GESTCO*4**	**CO2 SINK*4-5**	**SITECHAR*5-6**	**ECCSEL 5**			**Intas*3**
			SACS2*7-9	**CO2GEONET*4-5**	**CGSEurope* 4-5**	**CO2NOR 5**			**Feasibility study…5**
			ICBM*4-5	**Geocapacity*4-5**	**UltimateCO2*5**				**CO2StoP*5**
			RECOPOL* 3-4		**ECCO*4-5**	**OMNICS *4**			
			CO2STORE *5		**Mirecol*5-6**	**ENOS**			
					Co2-react*4				
					CARBFIX*4-5	**CARBFIX 2**			

4.1.5. CO_2 transport

FP7 From the period 2007 to 2013, at least five projects have been developed for CO_2 transport. The main project are:

<u>CO2Europipe</u> – Focus on transport infrastructure for large-Scale CCS in Europe, mainly via pipeline.

<u>COCATE</u> – Large-scale CCS transportation infrastructure in Europe. The purpose of this project was the implementation of shared transport for gases and CO_2 from the industries in Europe. Important data on network and costs linked to transport were demonstrated.

The total costs for this project was EUR 4.5 million and EU has contributed with EUR 2.9 million. TRL is 7-8.

<u>CO2PIPEHAZ</u>– Quantitative failure consequence hazard assessment for next generation CO_2 pipelines).

<u>IMPACTS</u> – The impacts of the quality of CO_2 on transport and storage behaviour. Detailed studies about CO_2 behaviour and techniques. Also on variable costs to transport the CO_2.

CO2-MATE – CO_2 multiphase reactive transport modelling which has improved the knowledge about the CO_2 flow and transport of CO_2 in saline aquifers. Emphasis was given on chemical reactions.

H2020 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 pan-european 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. It has reached a TRL 7.

Table 12 Projects with focus on CO_2 transport during the program FP7

CO_2 transport - EU projects with TRL (technology readiness levels)*									
Programs/ period	FP3	FP4	FP5	FP6	FP7	H2020	EEPR	NER300	Con-tracts
Projects					**CO2Europipe*7-8** → **COMET*4-5** **COCATE*7-8** **CO2PIPEHAZ*6** **IMPACTS*5** **CO2-MATE*4-5**	**GATEWAY*7**			

4.1.6. CO_2 monitoring

FP6 - MOVECBM – Monitoring and verification of CO_2 storage and ECBM in Poland. Focus on monitoring of CO_2 after injection in coal bed. They also analysed the behaviour of methane migration. The goal was to create an Enhanced coal bed methane project (ECBM).

This project had the total costs of EUR 2.6 million and EU has contributed with EUR 1.3 M. TRL is 5.

ASAP – Advanced seismic acquisition and processing. The aim of the project was to spread the knowledge on CO_2 storage and monitoring in all Europe. The focus was on countries with fewer resources for such activities.

The total costs for this project was EUR 0.9 M, covered by EU. TRL obtained was 5.

CO2REMOVE – CO_2 geological storage: research into monitoring and verification, started in 2006 and finished in 2012. A consortium between industry, research and universities has been created, joining European and international institutes. This was initially planned to be used in onshore and offshore. The best results have been obtained in onshore saline aquifers, Ketzin, Germany. The main technique used was the seismic which has been the preferred for structural imaging. To check the modification of CO_2 in the pore fluid, geoeletric methods revealed to be the most efficient.

This project costs were EUR 15.4 million and has received EUR 8.2 million from EU. The TRL obtained was 6-7.

FP7 MUSTANG – A multiple space and time scale approach for the quantification of deep saline formations for CO_2 storage. A large project analysing in detail all CCS chain, with a characterisation of deep saline aquifers with focus on risk and assessment.

The toal costs for this project was EUR 10.5 million and EU has contributed with EUR 7.9 million.The TRL is 7-8.

PANACEA – Predicting and monitoring the long-term behaviour of CO_2 injected in deep geological formations. Monitoring and simulation techniques to control CO_2 movement and predict environmental or risks impacts.

The total costs for this project was EUR 5.2 million and EU has participated with EUR 3.6 M. The TRL obtained was 6.

TRUST – The results obtained helped to get a high resolution monitoring, real time visualization and reliable modelling of highly controlled, intermediate and up-scalable size pilot injection tests of underground storage of CO_2. Also included were development and tests on new, updated techniques for CO_2 monitoring.

The total costs for this project was EUR 11.4 million and EU has participated with EUR 8.6 M. The TRL obtained is 5-6.

H2020 GEAGAM – Geophysical Exploration using advanced Galerkin methods. It isa project initialized in 2015 and finished in April 2018. The results obtained include the state-of-art of numerical methods which can use to better estimate the material properties that compose the Earth's subsurface. A webpage has been build during this project where around 100 publications and 25 presentations can be found [94].

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 a total costs of EUR 0.5 million completed covered by EU. The TRL obtained was 5.

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 coverall 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 expected to be finished in June 2018 and the total costs are EUR 0.14 million fundedtotally by EU. The TRL is 5.

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.

Table 13 Projects with focus on CO_2 monitoring during the programs FP6 and 7

CO2 monitoring - EU projects with TRL (technology readiness levels)*									
Programs/ period	FP3	FP4	FP5	FP6	FP7	H2020	EEPR	NER300	Contracts
Projects				**MOVECBM*5**	**MUSTANG*7-8**	**GEAGAM 5**			
				CO2REMOVE*6-7					
				ASAP*4-5	**PANACEA*6**	**STEMM-CCS**			
					TRUST*5-6	**CarbSens 5**			
						Virtualseis			

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,[10] proposing to use existing technology in new ways. Since then, although not always a "smooth sailing", several milestones can be highlighted for the technology:

- The first full scale demonstration plant and the most advanced legal framework for storage has been developed in Canada.
- The US has a second large scale demonstration plant, Petra Nova CCS project is located.
- The US has developed a favourable business model integrating CO_2 capture with EOR but projects have taken off even with employing geological storage.
- Developments 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 captured CO_2 from flue gases from large scale sources for more than 20 years. 1 M tonnes per year is injected in the Norwegian offshore.
- The Netherlands decarbonisation plan includes 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 be 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. Table 14 presents a summary of identified needs to be addressed for CCUS large scale deployment.

Table 14. CCUS needs for deployment.

Nature of needs	Needs
Political	A robust regulation framework needs to be addressed (transport). To become feasible, financial incentives are crucial. In the long term, a stable carbon pricing mechanism (or carbon market) could enable commercial CCS deployment.
Economic	Achieving significant cost reductions will require a sustained amount of R & D projects and an important level of commercial deployment. CO_2 monitoring cost must also be taken in account due to the long time during and after injection. A robust business case needs to be developed.
Technical/Infrastructure	The CO_2 infrastructure (transport and storage), as well as the whole CO_2 capture and storage supply chain, has to be developed to ensure the disposal of the CO_2 and risk management for possible CCS investors. Assessment and identification of suitable storage sites. Harmonization of methodology to measure the CO_2 storage capacity.
Social/ Environmental	The projects that are currently in development, must be completed in order to contribute to the acquisition of knowledge and to the posterior formation of the CCS infrastructure. Awareness campaigns and training are required to increase overall. These should be carried in cooperation between researchers, technical staff and politicians.

[10] On Geoengineering and the CO_2 Problem. IIASA Research Memorandum. IIASA, Luxemburg.

5.1. Technology trends and needs

5.1.1. Carbon capture

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 each technology the following trends and needs can be identified.

Chemical/Physical solvent-based absorption

- Chemical absorption (e.g., using aqueous amine solutions) has been used to remove CO_2 from natural gas for decades.
- Optimisation of solvent management, demonstration of flexibility and operability, and understanding of solvent degradation are major issues.
- Solvent costs are still considered to have a reduction potential as well as overall energy requirements.
- 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 could focus on reducing equipment volumes by developing more effective contacting surfaces and faster cycles.

Solid sorbent adsorption

- Novel adsorbent materials to improve properties continue to require investigation, especial with regards to stability in water and impurities.
- Standardized testing procedures of new materials will also be required on this front.
- Costs associated with equipment size remain a challenge. Research on minimizing the cycle times could improve this area.

Membranes

- Developments in polymeric membranes have enabled the technology to successfully achieve demonstration scale.
- Membrane separation can be associated with callenges such as competitive adsorption, permeation and contamination between H_2 and CO_2.
- Membrane systems are linked to large areas for effective separation where specific membrane properties play an important role.
- Stream conditions such as low CO_2 concentration and pressure can pose notable hurdles at this separation.
- Sealing, stability, mechanical stress, fouling, water condensation and durability are some persisting challenges for membrane technology.

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.
- Optimising fuel conversion in solid fuel reactors is considered a priority.
- Materials with reasonable reactivity and mechanical stability will be required to address chemical reactivity.

Process and system improvements

- Oxygen separation efficiency and cost is a challenge for systems that employ relevant systems.
- Materials to be used with supercritical CO_2 require the design of high temperature and pressure

combustion systems to be directly connected into supercritical CO_2 systems.

- Materials for severe thermal conditions have to be optimised. For example, for H_2/CO_2 separation at high pressure and high temperature (adapted to the optimum gasification conditions).
- Gasifiers performance at optimum operating conditions for low rank coals remain an issue.
- High firing temperatures and cooling exhibit the need for designs and advanced components in H_2-rich fuel turbines.

5.1.2. CO_2 utilisation

CO_2 utilisation has been viewed as an opportunity for the industrial sector 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 [87]. 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 [17], [95]:

- 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 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 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.

5.1.3. 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. From a research point of view there are some gaps, 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 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. 16 Mt CO_2 have been stored and monitored until 2017. Both Norwegian CO_2 storage projects, Sleipner and Snøhvit have been repermitted by Norwegian government under EC CCS directive in 2016 [96].

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).

5.1.4. New projects

At least 16 MS are developing research projects linked to geological storage of CO_2 trough altenative like CO_2 utilisation.

Networks for transport and storage have also received attention in this last years in Europe. There are currently two CCUS regional networks:

1 – North Sea Basin task force, composed by UK, NL, NO, DK and BE.

2 – Baltic Sea Region with ET, DK, FI, NO and SE. Note that some countries such as FI has no adequate geological conditions for storage but is working on CO_2 transport.

Interest is also increasing for the creation of 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.

Using the scheme of Project of Common Interest (PCI), new hubs/clusters are now in development as shown in Figure 11.

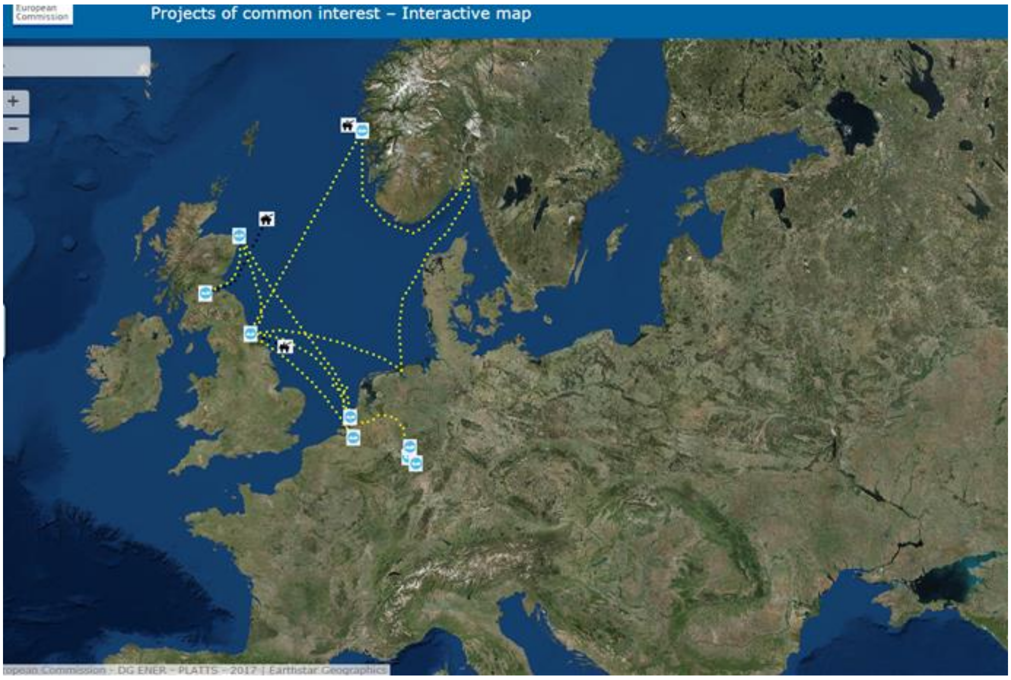

Figure 11 Interactive map with all projects with CCUS recently funded via PCI – European Commison [97].

In implementation phase, there are 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.

Financing requirements proposed for CCUS deployment in Europe [98] have been elaborated and updated during the SET PLAN, action 9 [99]. These include:

- Development of the National Low Carbon Roadmaps, out to 2050, by the MS;
- Updated integration of CCS in EC 2030 framework;
- Support from the Innovation Fund: identification of transnational pilot and demonstration projects;
- Identification of projects of common interest that would enable the development of clusters;
- Selection of 10 targets to be reached using 8 research and innovation actions englobing all aspects of CCS and CCU.
- Definition of 5 flagships which are expected to contribute to accelerate CCS and CCU deployment.

- Monitoring the progress of these actions towards 2020 and beyond.

Social acceptance

From the social point of view, the majority of people still appear unaware of CCS, at least in UK. Recent studies by Statista in UK [100] conducted between march 28 to april 6 2018 reveals that in face to face interviews with 2,102 people, 59 % never heard about CCS and only 3 % responded that they really know about it.

5.2. Deployment trends

5.2.1. Modelling Carbon Capture Use and Storage

According to the JRC-EU-TIMES model results, CCUS plays a major role in almost all the decarbonised scenarios, in coherence with IPPC [6]. The model assumes that CCUS technologies enter the market in 2030 and that there is no limitation for CCS penetration. The following figures summarise a number of key trade-offs identified among different scenarios. Further description about the JRC-EU-TIMES model is available in the dedicated report [101].

The core scenarios are:

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

In addition, further 13 sensitivity cases are considered but in this part, only results from scenarios relevant to CCUS will be presented.

Figure 12 depicts results of the JRC-EU-TIMES when it comes to modelling CO_2 emissions. In a scenario where carbon capture is deployed for 2050 targets to be achieved:

- Around 50% of the CO_2 produced is captured with the majority coming from power production and CHP.
- The majority of CO_2 is captured from new installations for power plants or CHP, large-scale hydrogen production, 2nd generation biofuels and Direct Air Capture (DAC). Cement is the largest industrial source, as no hydrogen alternative was included in the model.
- At least 100 Mton is captured from DAC per year.

Without the option to permanently store CO_2 under the ground (RES 1 scenario), more than 400 Mton/year CO_2 is still captured and reused. The main use of this CO_2 is the production of diesel/kerosene by combining hydrogen and CO_2 .

Two sensitivities to the Diversified scenario (Div1) are shown in Figure 13. With cheaper Direct Air Capture technology the model predicts that a vast amount of CO_2 is captured directly from the air (up to 500 Mton/yr) over the option of CO_2 captured from industrial processes.

Nevertheless, taking into account the swift of interest to deploy carbon capture in industries other than the power sector, a second sensitivity was examined. Results indicate increased scales in carbon capture in industrial applications in the case that carbon capture is not deployed in the power sector. Significant emission reduction comes from hydrogen production from fossil sources, i.e. coal gasification and steam methane reforming.

Preliminary results regarding CO_2 sinks show that complementarity with CO_2 storage remains crucial for deep CO_2 emissions reduction.

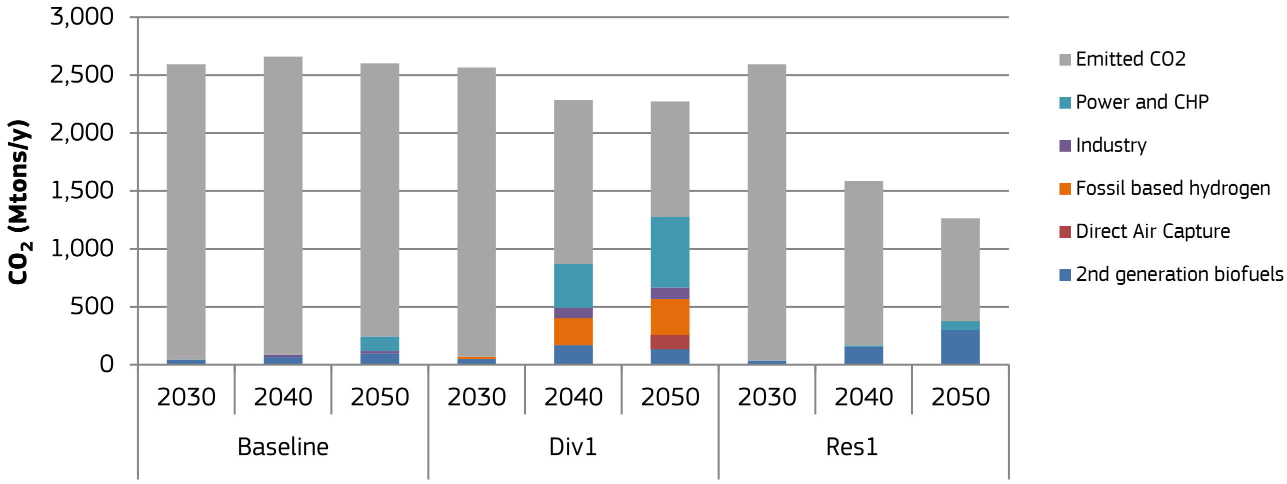

Figure 12 CO_2 emitted and captured in different scenarios up to 2050.

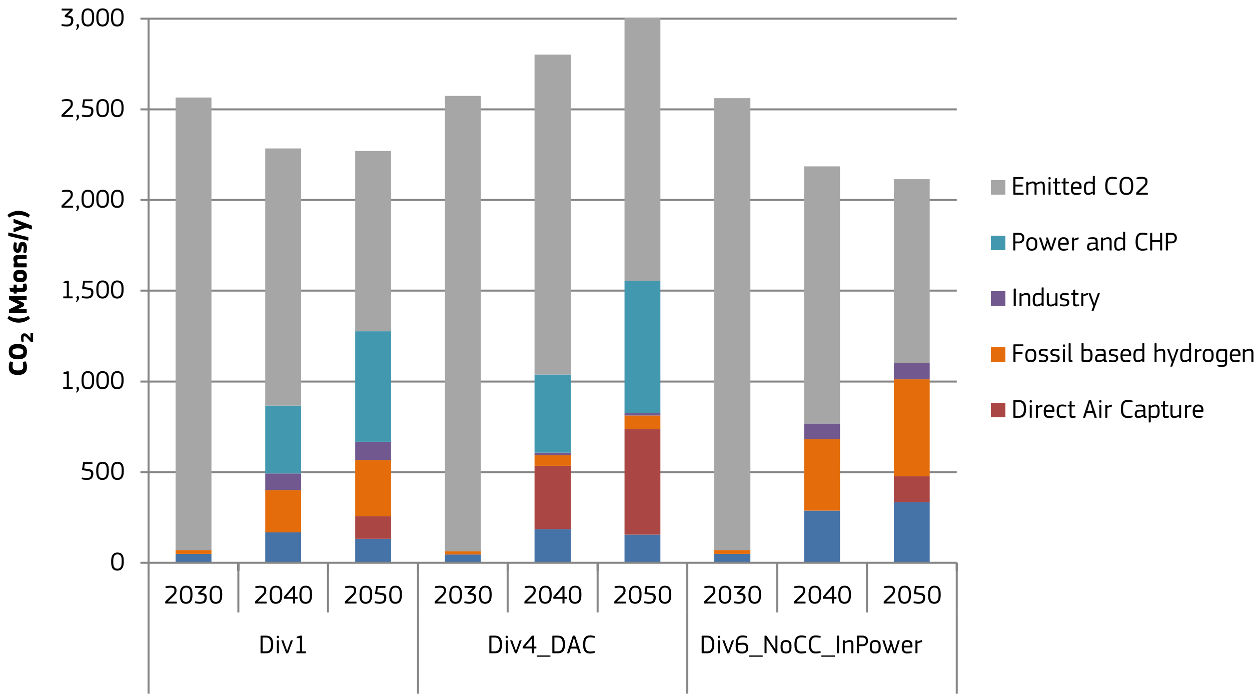

Figure 13 CO_2 emitted and captured up to 2050 considering DAC but no implementation of carbon capture in the power sector.

5.2.2. CO_2 storage, transport and monitoring

Regarding CO_2 storage, transport and mornitoring, to improve the database 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.

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 was completed in 2010. It is still the most complete study on scenarios for 2050 for both storage and transport:

Entry cost in 2030, 2050

In the Feasibility study for Europe - Wide CO_2 infrastructures. (2010)–project, researchers have simulated costs and infrastructure to successfully achieve CO_2 storage proposals. This is also important to include transport in these calculations. It is clear that by prioritising only offshore storage, costs, mainly on transport, will be higher if the onshore possibilities could also been taken in account. In any case more extensive pipeline network should be implemented until 2050 to facilitate the storage of higher volume of CO_2.

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. Currently the full chain CCS project is in FEED phase.

Table 15 Entry costs CO_2 transport and storage for 2030 and 2050.

SCENARIO	TOTAL LENGTH (KM)	TOTAL COST (€M)
2030 LOW	6 879	2 074
2030 MEDIUM	9 719	4 011
2030 HIGH	12 384	7 592
2050 LOW	11 775	6 785
2050 MEDIUM	14 334	10 901
2050 HIGH	15 013	12 667

Considering only storage in offshore:

Table 16 Entry costs for CO_2 transport and storage (only in offshore).

SCENARIO	TOTAL LENGTH (KM)	TOTAL COST (€M)
2030 LOW	8 971	3 434
2030 MEDIUM	10 829	5 747
2030 HIGH	14 908	11 206
2050 LOW	13 746	9 560
2050 MEDIUM	18 635	16 439
2050 HIGH	20 041	19 781

5.3. Technology barriers to large scale deployment

Different roadmaps 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. The main general technological and non-technological barriers to the deployment of CCS and CO_2 utilisation are summarised in the following sections.

5.3.1. Carbon capture

The main challenges for the development of carbon capture options include:

- Improvement of the parasitic loss caused in efficiency;
- Cost reduction for solvent regeneration or capture;
- Materials optimisation for severe conditions, for increased availability and reduced costs;
- Control of emissions other than CO_2, e.g. amine degradation;
- Identification of the optimum operating conditions for boilers and gasifiers for employing CO_2 capture;
- Flexibility for integration in flexible operation modes;
- Improved power cycles;
- Demonstration at full scale to increase the know-how and sufficient confidence of potential future investors and of the general public.

While technology is not expected to impede implementation, efficiency loss and cost remain the main barriers for carbon capture.

5.3.2. CO_2 utilisation

The penetration rates of CO_2 based products in Europe generally depend on (i) the roll-out of CO_2 capture, (ii) the maturity progression of the technology, (iii) the demand for the product, and the (iv) cost competitiveness of CO_2 utilisation compared to the benchmark technology.

The contribution of CO_2 utilisation to the current climate change mitigation actions is still debated. While in principal CO_2 utilisation could lead to the reduction of net CO_2 emissions as well as use of fossil resources, robust LCAs will need to confirm this expectation.

The main influencing variables to determine the competitiveness of CO_2 utilisation plants include the availability and quality of feedstock CO_2, the availability and quality of feedstock H2 (if needed) and/or the source of electricity used to provide this H2. Literature studies indicate that CO_2 utilisation processes using hydrogen as raw material should have access to renewable hydrogen. The amount of electricity required, and the prices of electricity and product are important as well. The available renewable electricity that can be directed to cover the CO_2 utilisation plant power needs will be determining for the plant's dimensions.

Some CO_2 utilisation processes such as the fuel synthesis from Sunfire, or Audi and the calcium carbonate production from Carbon 8 are technically feasible and deployed. However, other technologies remain at lower TRLs. CO_2 labelling as an "environmentally-friendly" raw material can impact the deployment of CO_2 utilisation processes. Further difficulties to overcome concern the whether CO_2 based products will be competitive compared to their fossil fuel counterparts and customer confidence that is yet to be established.

Therefore, 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. The EU funded SCOT project, suggest that at the moment it is not advisable accrediting CO_2 displaced or avoided to be included in the actual scheme of EU-ETS. Prior to the 2025 mid-term review of the EU-ETS, an analysis of the potential of accrediting avoided emissions under the EU-ETS should be undertaken. 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.

Some issues that indirectly can impact the roll out of CO_2 utilisation processes include but are not limited to:

- The cost of CO_2 capture (the "price" of CO_2);
- Cost reductions promoted by the capability to use CO_2 as impure as possible;
- Flexible CO_2 utilisation plants integrated with renewable sources of energy;

- Renewable energy players interest on being integrated with CO_2 utilisation plants, effecting technology scalability.

5.3.3. CO_2 storage, transport, and monitoring

The main barriers continue to be political, economic and social. The lack of specific framework such as legality, liability of storage as well the storage monitoring responsibility after CO_2 injections, absence of large-scale monitoring test sites. There is not a transport regulation specific for CO_2, despite that there are many pipelines which are used for natural gas. However the main barrier linked to transport is the costs linked to the infrastructure of a project. This is different for each region.

There has also been an economic gap about how to fund the demonstration projects since the carbon price has been low. On the monitoring side, costs related to mainly seismic techniques and low precision represent a barrier for CCUS implementation. Another important barrier for CO_2 storage is the public acceptance especially about injection onshore as well for CO_2 transport approval in onshore.

Different methodologies to measure the storage capacity worldwide makes it difficult to have an overview of total CO_2 storage capacity. The coverage and quality of the CO_2 storage assessment is dependent on available and completeness ofof data. This is an important barrier in Europe since the geological surveys of all MS were not completed in 2018.

The implementation working group in the SET PLAN has created a task force to improve it and the plan is to make an inventory of European CO_2 storage sites until 2020. Knowledeg/data sharing is fundamental for the success of this task.

5.3.4. CCUS full chain

The most important barriers for the full CCUS chain are regulatory implementation, economics, risk and uncertainties associated with projects as well as social acceptance. 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 [102].

Table 17 Main barriers to large-scale CCUS development

Barriers	Capture	Transport	Storage	Utilisation	Monitoring
Economic	High	High	Higher 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

The EU CCS Directive was adopted in April 2009 and reviewed in 2017. It establishes the legal framework to safely store CO_2, covering all the CO_2 storage formations in the EU and the lifetime of the storage sites. By 2013, all the MS notified transposing measures, with conformity check ongoing. The CCS Directive has been evaluated by consultants and stakeholders and a report was published in 2015.[11] The view among stakeholders noted in the report was that the lack of progress in CCUS has been driven by the lack of a commercial case, largely because of the global economic downturn and low carbon prices (via the European Union Emissions Trading System (EU-ETS)). The evaluators cocluded that this lack of practical experience makes it not possible to identify specific effects induced by the CCS Directive. The report also

[11] Support to the review of Directive 2009/31/EC on the geological storage of carbon dioxide

exhibited the clear stakeholder concern that "reopening the Directive would bring a period of further uncertainty for CCS, which would not be helpful in a sector where investor confidence is already low".

A list of main barriers to develop CCUS projects in the world is given in Table **18**. Public acceptance can be decisive for a CCUS project progress. In Europe the diversity of public acceptance is an important challenge, both in the Netherlands and Germany the lack of technology dissemination and information stopped CO_2 storage projects onshore.

Table 18 Overview of barriers identified for CCS**.**

Nature of barriers	**Barriers**
Political	Lack of political commitment to CCS by some Member States, exacerbated by regulatory prescriptive procedures
Economic	High investment and operational costs and therefore lack of competitiveness compared to other low-carbon technologies.
	There is often no financial compensation for the additional capital and operational costs associated with CCS
	A market for CO_2 capture/utilisation technologies is not fully developed.
Technical, Infrastructure	Lack of CO_2 infrastructure (transport and storage) development. Update CO_2 asssement, data sharing
	Projects that do not reach the final levels of implementation.
Social	CCS still remains unknown for the overall public.
	Resistance to CO_2 storage concept operations
	Environmental risks concerning health, water pollution are perceived negatively by public opinion.

6. CONCLUSIONS & RECOMMENDATIONS

Carbon capture, utilisation and storage continues to be an important topic for research and innovation. The currently ongoing H2020 projects are concentrating to 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 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 businness cases are currently being prepared by, for example, Norway (full chain CCS project) and the Netherlands (former ROAD project focusing on CO_2 storage and transport). 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. To achieve this the following are also needed:

- A standard methodology, as well as relevant parameters and assumptions for the metrics' calculation;
- Common boundaries for their evaluation;
- Regular reviews for indicators and metrics to check relevance, validity, applicability and rate of realisation.

In a more specific view, CO_2 capture technologies could benefit from further research on, but not limited to:

- Specific properties in **solvent based** technologies; tailoring chemical structures for improved absorption performance and stability, also with respect to different feed stream compositions.
- Testing and screening materials performance and CO_2 loading capacity under simulated and ideally real flue gas streams. Also, work on process design and integration targeting performance and economics improvements, for **sorbent based** technologies.
- Validation of **membrane** selectivity in various gas environments. Problems associated with membrane sealing and failure also need to be studied.
- Studying combinations of **high temperature looping** technologies to be used for hydrogen production or thermal storage.

Until now the focus has been on applying carbon capture in the power generation sector. As such, KPIs, goals and targets have usually been reported for these applications. 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 [103]. 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 [104]. However, future endeavours 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 containment 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, for example within the European Technology Platform for Zero Emissions Plants (ZEP) [105], 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

According to the storage readiness assessment elaborated by the Global CCS Institute [107] only Norway is prepared for large-scale storage in Europe. Germany, Netherlands and the United Kingdom, are in a very advanced level with France and Spain making progress .

Comparing with the rest of the world, only Brazil, Canada and USA are prepared for large-scale CO_2 storage projects with Australia, China being in advanced level. Japan, South Korea, South Africa, Thailand are making progress [107][3].

In order develop and implement projects in Europe it is fundamental to work in international cooperation with leading countries such as Canada, US, Brazil in Americas, as well as China, South Korea and Japan in Asia and Australia.

The future 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, 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 been built for such activities.

Further reseach should be supported in areas for:

Storage: the majority of storage sites considered for CO_2 injection are concentrated on 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 a best practice can be adopted following recent suggestions for CO_2 storage resource management, from the Society of Petroleum Engineers [106]. This should be completed including risk and liability assessments, also techno-economic and geological assesement, reducing the residual incertainities. Moreover to include dynamic properties of the geological reservoir will contribute to more accurate assessment.

Knowledge and data sharing is also important, as demonstrated with the proposal of the CO_2 storage data consortium initiated between US and NO in 2017 to build an international data sharing platform.

Transport: hybrid systems to transport CO_2 involve pipeline and shipping. Pipelines are the more common CO_2 transport means used. 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.

The first European full scale CCS system (planned to be constructed in Norway) will use a combination of shipping (500 km) and a pipeline (50 km) to the site of injection in Smeaheai, west of Norway.

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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APPENDIX A
LIST OF PROJECTS IDENTIFIED

Table 19 Projects identified exploring different CCUS aspects.

Call for proposal/funding scheme	Project Acronym	CDU	Capture	Transport	Storage	Monitoring	Other*	EU contribution (MEUR)	Total (MEUR)
FP6-SUSTDEV-ENERGY	INCA-CO2						✓	444 900	708 536
	ZEST						✓	521 213	1 042 425
	DYNAMIS		✓		✓			4 000,000	7 461 000
	CASTOR		✓		✓			8 499 920	15 840 387
FP6-POLICIES	ACCSEPT						✓	399 000	399 000
FP6 COORDINATION - ERA-NET	FENCO-ERA						✓	2 998 296	2 998 296
FP7 - ENERGY	CCS-PNS						✓	2 994 389	3 670 745
	ECCO		✓		✓		✓	3 886 575	5 426 360
	NEARCO2						✓	994 256	1 246 738
	STRACO2						✓	859 135	1 040 830
	ZEPPORT						✓	500 000	1 143 828
	ZEPPOS						✓	500 000	1 137 996
FP7 - INFRASTRUCTURE	ECCSEL		✓	✓	✓		✓	1 499 961	2 580 497
	ECCSEL PP2		✓	✓	✓		✓	1 199 912	1 905 597
FP7 – Peo-ple	CO2TRIP						✓	300 300	300 300

FP7 – Regions	SCOT	✓					✓	2 373 854	2 140 400
H2020-LCE-2015-3 ERA-NET Cofund	ACT		✓	✓	✓		✓	11 799 665	38 233 782
SPIRE-05-2016	CarbonNext						✓	495 748	495 748
H2020-LCE-2017-RES-CCS-RIA	CHEERS		✓	✓	✓			9 727 105	16 818 668
H2020-INFRADEV-1-2015-1 RIA	ECCSEL		✓	✓	✓			3 252 279	3 252 279
H2020-MSCA-ITN-2016	ELCOREL	✓					✓	3 616 665	3 616 665
H2020-LCE-2016-ETP CSA	SESZEP						●	464 047	464 047
EEPR	Janschwalde		✓	✓	✓		✓	180 000 000	
EEPR	Porto Tolle		●	●	●		✓	100 000 000	
EEPR	Rotterdam		✓	✓	✓		●	180 000 000	
EEPR	Belchatow		✓	✓	✓		●	180 000 000	
EEPR	Compostilla		✓	✓	✓		●	180 000 000	
EEPR	Don Valley		●	●	●		✓	180 000 000	
NER300	UK CCSoxy White Rose		✓	✓	✓		●	300 000 000	

Table 20 FP6 projects identified in the field of carbon capture and utilisation. Projects that are non-technological are marked in blue. Projects that have a focus on setting the basis of the technology at TRL higher than 4 or that use and validate existing technology are marked in grey. All projects are completed.

		CDU	**Sol**	**Sor**	**Mem**	**HTL**	**Process Improvements**	**EU contribution (MEUR)**	**Total (MEUR)**
FP6-SUSTDEV-ENERGY	C3-CAPTURE			✓				1 799 787	2 723 945
	CACHET						✓	7 500 000	13 447 999
	CAPRICE		✓					383 000	1 241 000
	CASTOR		✓					8 499 920	15 840 387
	CLC GAS POWER					✓		1 700 000	2 127 000
	COACH		✓			✓		1 500 000	2 620 200
	ENCAP					✓	✓	10 455 000	21 564 000
	HY2SEPS			✓	✓			1 559 400	2 528 800
	ELCAT	✓						875 246	875 246

Note:
Sol: Solvent based CO_2 separation
Sor: Sorbent based CO_2 separation
Mem: Membrane based CO_2 separation
HTL: High temperature looping (CLC and CaL)

Table 21 FP7 projects identified in the field of carbon capture and utilisation. Non-technological projects marked in blue. Projects that have a focus on setting the basis of the technology at TRL higher than 4 or that use and validate existing technology are marked in grey.

		CDU	**Sol**	**Sor**	**Mem**	**HTL**	**Process Improvements**	**EU contribution (MEUR)**	**Total (MEUR)**
FP7 – ENERGY	CACHET II				✓			3 899 944	5 235 328
	CAESAR							2 263 515	3 143 422
	CAOLING		✓					3 733 542	6 601 096
	CAPSOL		✓					2 337 282	3 255 110
	CESAR		✓					3 999 995	6 700 530
	DECARBIT		✓		✓		✓	10 215 750	15 535 004
	DEMOCLOCK					✓		5 304 509	8 193 828
	FLEXI BURN CFB						✓	6 413 869	10 851 767
	H2-IGCC						✓	11 279 697	17 191 878
	IOLICAP		✓		✓			3 978 128	5 770 719
	M4CO2				✓			7 932 375	10 497 585
	MACPLUS						✓	10 704 675	19 651 044
	O2GEN						✓	6 604 702	11 856 915
	OCTAVIUS		✓					7 963 738	13 563 943
	OPTIMASH						✓	3 430 036	5 303 906
	SCARLET			✓				4 731 259	7 344 129

	SUCCESS					✓		7 089 325	9 920 376
FP7 - ERC	NOCO2					✓		2 500 000	2 500 000
	SUNFUELS	✓						2 187 650	2 187 650
FP7 - TIFCH	ELECTRA	✓						2 240 552	4 007 085
FP7-NMP	CYCLICCO2R	✓						3 851 934	5 254 691
	ECO2CO2	✓						3 424 438	4 711 872
	MACADEMIA			✓				7 599 998	11 624 431
	HOMCAT	✓						231 283	231 283
FP7-Transport	SOLAR-JET	✓						3 120 030	2 173 548
FP7 - Environ-ment	ECO-CEMENT	✓						2 138 511	1 598 296

Note:
Sol: Solvent based CO_2 separation
Sor: Sorbent based CO_2 separation
Mem: Membrane based CO_2 separation
HTL: High temperature looping (CLC and CaL)

Table 22 H2020 projects identified in the field of carbon capture and utilisation with EU funding contribution >250 kEUR.

Call for proposal/funding scheme	Project acronym	**CDU**	**Sol**	**Sor**	**Mem**	**HTL**	**Other**	**Process Improvements**	**EU Contibution (MEUR)**	**Total Cost (MEUR)**
H2020-NMBP-BIO-2017 RIA	BIOCONCO2	✓							6 999 886	6 999 886
H2020-NMBP-BIO-2017 RIA	BioRECO2VER	✓							6 812 188	6 990 938
H2020-SPIRE-2017 RIA	Carbon4Pure	✓							7 765 359	7 765 359
H2020-SPIRE-2016 CSA	CarbonNext	✓							495 748	495 748
H2020-NMBP-2017-two-stage IA	CARMOF			✓					5 993 228	7 440 050
H2020-ISIB-2015-2 RIA	CELBICON	✓							5 429 202	6 211 040
H2020-LCE-2014-1 RIA	CEMCAP				✓	✓			8 778 701	10 030 121
H2020-LCE-2017-RES-CCS-RIA	CLEANKER					✓			8 972 201	9 237 851
H2020-SMEINST-2-2016-2017 SME-2	CO2Catalyst	✓							2 490 767	3 558 239
H2020-SPIRE-2017 RIA	CO2EXIDE	✓							5 420 113	5 420 113
ERC-2017-STG	CO2LIFE	✓							1 302 710	1 302 710
H2020-MSCA-RISE-2016	CO2MPRISE	✓							702 000	702 000
ERC-2014-STG	COFleaf	✓							1 497 125	1 497 125
ERC-2017-STG	COSMOS			✓	✓				1 500 000	1 500 000
H2020-FETOPEN-2014-2015-RIA	DIACAT	✓							3 872 981	3 872 981
H2020-MSCA-ITN-2016	ELCOREL	✓							3 616 665	3 616 665
H2020-NMBP-BIO-2017 RIA	ENGICOIN	✓							6 986 910	6 986 910
H2020-LCE-2016-RES-CCS-RIA	FReSMe	✓						✓	11 406 725	11 406 725
H2020-NMBP-2017-two-stage IA	GENESIS				✓			✓	9 563 904	9 563 904
H2020-LCE-2016-RES-CCS-RIA	GRAMOFON			✓					4 188 254	4 273 289

ERC-2016-STG	HybridSolarFuels	✓							1 498 750	1 498 750
H2020-SPIRE-2017 RIA	ICO2CHEM	✓							5 948 589	5 948 589
H2020-LCE-2015-1-two-stage RIA	LEILAC						✓		11 932 231	20 770 635
H2020-NMBP-2017-two-stage RIA	LOTER.CO2M						✓		4 264 453	4 264 453
ERC-2014-ADG	MaGic			✓					2 486 720	2 486 720
H2020-NMBP-2017-two-stage IA	MEMBER				✓				7 918 901	9 596 542
H2020-SPIRE-2014 IA	MefCO2				✓				8 622 293	11 041 538
H2020-SMEINST-2-2014 SME-2	MetaFuel	✓							2 297 925	3 282 750
H2020-LCE-2016-RES-CCS-RIA	NanoMEMC2				✓				4 990 816	4 990 816
H2020-SPIRE-2017 RIA	OCEAN	✓						✓	5 523 650	5 523 650
H2020-SMEINST-2-2015	ProGeo	✓							2 443 875	3 493 750
H2020-SPIRE-2017 RIA	RECODE	✓							7 904 415	7 904 415
H2020-LCE-2016-RES-CCS-RIA	ROLINCAP		●					✓	3 089 845	3 212 588
H2020-LCE-2017-RES-CCS-RIA	sCO2-Flex	✓						✓	5 630 855	5 630 855
H2020-LCE-2016-RES-CCS-RIA	SOCRATCES					✓			4 975 403	4 975 403
H2020-LCE-2014-2 IA	STEELANOL	✓							10 192 516	14 560 737
H2020-SMEINST-1-2016-2017	STEPWISE			✓					12 968 371	12 968 371
H2020-SMEINST-2-2016-2017 SME-2	Willpower	✓							1 709 750	2 442 500

Table 23 Summary of the RFCS projects identified in the field of carbon capture. All projects are completed.

		CDU	Sol	Sor	Mem	HTL	Process Improvements	EU contribution (MEUR)	Total (MEUR)
TGC3: Coal combustion, clean and efficient coal technologies, CO_2 capture	ASSOCOGS						✓	2 941 793	1 765 076
	OXYMOD					✓	✓	1 294 011	2 156 685
	ECO-Scrub		✓				✓	1 555 064	2 591 775
	ECLAIR					✓		2 270 770	6 421 724
	CARINA			✓				1 475 050	2 458 416
	ACCLAIM					✓		1 591 434	3 200 765
	RECaL			✓		✓		1 618 765	2 697 943
	ASC2		✓	✓				1 546 630	3 093 261
	CaO2			✓		✓		1 583 054	3 166 109

Table 24 List of projects funded by EU and related to CO_2 storage, transport and monitoring.

Program	**Projects Acronyms Or names**	**Research technology**							**Project focus**						**Notes:**	**Total Costs (EUR)**	**EU contribution (EUR)**
		Transport		**Storage**				**Moni-toring**	**CCS**	**Trans port**	**Storage**	**Moni-toring**	**CCS**	**Training/ trans-fer of know-eledge**			
		Pipeline	ship-ping	off-shore	on-shore	coal (ECBM)	bas-alts									not available	not available
FP3	The underground disposal of carbon dioxide			x	x						X					not available	not available
FP4	SACS			x							x						
FP5	GESTCO			x	x						x					3 799 868	1 899 934
FP5	SACS2			x							X				Con-tinua-tion of SACS project (FP4)	3 033 600	1 200 000
FP5	ICBM					x					x					1 553 052	1 000 000.
FP5	RECOPOL					X					X					3 739 507	1 711 146
FP5	CO2STORE			x							X				Direct link with SACS 2 project (FP5)	2 497 062	1 210 085
FP6	COACH					x			X			X				2 620 200	1 500 000
FP6	MOVECBM					x		X			X	X				2 670 737	1 250 000
FP6	ASAP							X				X		X		not available	969 390
FP6	CO2SINK				x			x			x	x				23 159 401	8 700 000

FP6	CO2GEONET			x	x						X			x		9 180 000	6 000 000
FP6	EUGeocapacity			x	x	x					X					3 464 349	1 900 000
FP6	CO2REMOVE							x								15 465 663	8 299 852
FP7	CO2SOLSTOCK										X (bio)					2 963 464	2 283 345
FP7	CO2EUROPIPE	x								X						2 419 000	1 099 560
FP7	MUSTANG								X				X			10 555 790	7 995 154
FP7	RISCS								X				X			5 258 119	3 958 530
FP7	COCATE	x								X						4 555 430	2 994 968
FP7	COMET	x								X						3 125 087	2 343 129
FP7	CO2PIPEHAZ	x								X						2 725 645	2 067 377
FP7	MUIGECCOS										X					127 117	127 117
FP7	CO2-MATE	x								X						223 537	223 537
FP7	CO2CARE								X				X			5 313 492	3 966 574
FP7	SITECHAR										X					5 072 670	3 720 575
FP7	CGS EUROPE										X					2 619 559	2 236 837
FP7	ECO2										X (env.)					13 978 174	10 500 000
FP7	GHG2E								X				X			2 447 811	1 635 775
FP7	CO2SHALESTORE										X					45 000	45 000
FP7	ULTIMATECO2										X					5 331 268	4 026 120
FP7	PANACEA							X				X				5 207 496	3 685 771
FP7	CARBFIX						X				X (basalt)				Storage in basalts	2 257 008	1 570 813
FP7	IMPACTS	x							X	X			X		Focus on transport	5 573 556	4 000 765
FP7	TRUST							X			X	X				12 296 626	8 677 241
FP7	CO2QUEST								X				X			3 985 399	2 922 477
FP7	CO2-REACT										X					3 900 802	3 900 802
FP7	MIRECOL										X					5 199 967	3 756 249

FP7	TOPS										X (coal)				Focus on coal bed me-thane stor-age	4 096 732	2 996 239
H2020	GEAGAM										X					580 500	580 500
H2020	CO2NOR										X (basalt)					151 649	151 649
H2020	STEM-CCS							x								15 968 369	15 968 369
H2020	GATEWAY	x	x													787 700	787 700
H2020	OMMNICS				x	x										200 195	200 195
H2020	ENOS															12 485 259	12 485 259
	Contract Projects															N/A	N/A
	Feasibility study for Europe -Wide CO2 infrastruc-tures															N/A	N/A
EN-ER/C1/154-2011-SI2.611598	CO2StoP				x	x										238 581	238 581
INTAS 2006-1000025-9220	INTAS					x										112 100	112 100

APPENDIX B
GLOBAL RESSOURCE ASSESSMENT FOR CO_2 STORAGE

Table 25 Global CO2 storage resources – in Gt CO2 (modified from [3])

Assessment Status COUNTRY	ASSESSMENT STATUS	ESTIMATED RESOURCE (GTCO2)	RESOURCE 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)

APPENDIX C
EUROPEAN SET PLAN FOR CCUS – ACTION 9

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

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

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

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

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

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

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

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

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

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

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

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

Research & Innovation Activities

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

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

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

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

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

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

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

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

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

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

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

Flagship activities

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

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

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

Flagship project: Fos-Berre/Marseille CCU cluster

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

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.

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

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

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