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CO_2 Capture and Storage from Fossil Fuel Power Plants

Dumitru Cebrucean[a,]*, Viorica Cebrucean[b], Ioana Ionel[b]

[a]*Institute for Energy Systems, Technical University of Munich, Boltzmannstrasse 15, 85748 Garching, Germany*
[b]*Department of Mechanical Machines, Equipments and Transportation, Politehnica University of Timisoara, M. Viteazu 1, 300222 Timisoara, Romania*

Abstract

Fossil fuel power plants generate significant amounts of CO_2 emissions into the atmosphere, which are believed to be the main cause of climate change. Among CO_2 mitigation options, carbon capture and storage is considered the only technology that can significantly reduce the emissions of CO_2 from fossil fuel combustion sources. There are mainly three technological routes for CO_2 capture from power plants: post-combustion, pre-combustion and oxy-fuel combustion. Unfortunately, their application may reduce the net efficiency of a plant by up to 14% points and increase the cost of electricity by 30-70%. This paper briefly reviews the performance of power plants with carbon capture, and presents current research and development, and demonstration activities on CCS.

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Keywords: CO_2 capture; CO_2 storage; fossil fuel; power plant.

1. Introduction

Currently existing fleet of fossil fuel combustion power plants generate significant amounts of carbon dioxide emissions into the atmosphere (more than 12 billion tonnes of CO_2 per year [1]), which are believed to be the main cause of climate change [2]. According to the International Energy Agency [3], the electricity production from fossil fuels will increase by about 30%, by 2035, which will inevitably lead to more CO_2.

The emissions of CO_2 from fossil fuel-fired power plants can be reduced by [4]: (i) increasing the efficiency of the plants (1% increase in efficiency reduces CO_2 by 2-3%); (ii) switching, partially or totally, to low carbon content

* Corresponding author. Tel.: +49-89-289-16284; fax: +49-89-289-16271.
E-mail address: d.cebrucean@tum.de

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fuels or to "carbon neutral" fuels; (iii) capturing CO_2 and storing it, for example, in geological formations. CO_2 capture and storage is considered the only technology that can significantly reduce the emissions of CO_2 from power generation sector.

There are three main technology options to capture CO_2 from fossil fuel power generation plants [3], namely: (i) post-combustion (CO_2 is separated from the flue gas); (ii) oxy-fuel combustion (uses nearly pure oxygen for the combustion of fuel, then CO_2 is removed from the generated gases, formed principally from water vapor and CO_2); and (iii) pre-combustion (CO_2 is removed from the fuel before combustion). Unfortunately, application of CO_2 capture technologies may reduce the net efficiency of a plant by up to 14% points [5]. In addition, the cost of electricity would increase by 30-70% [2,6] (depending on fuel used, plant type and capture technology).

The main advantage of post-combustion capture is that it can be integrated into existing power plants without altering the combustion process. However, for example, in the case of amine-based absorption/desorption post-combustion systems large amounts of low pressure steam would be needed to be extracted from the turbine and this will cause high energy penalty, reducing the electricity output of a power plant by about 20-30%. To reduce the energy penalty, a number of alternative post-combustion capture technologies have been proposed. The process based on the absorption of CO_2 into ammonia appears promising and would offer some advantages over amines (e.g., lower energy requirement for solvent regeneration, higher absorption capacity). But, due to its high volatility, the ammonia slip into the flue gas stream after absorption would present one of the major technical issues. A very promising alternative to conventional absorption/desorption capture systems is the calcium looping process, also known as a "hot" post-combustion process because the separation of CO_2 from the flue gas occurs at high temperatures (>650°C). Other capture technologies are being developed, such as CO_2 capture processes based on amino-acid salts, ionic liquids or membranes.

This paper briefly reviews the performance of power plants with carbon capture, and presents current research and development, and demonstration projects on CCS.

2. CO_2 emissions from fossil fuel power plants

The amount of CO_2 emissions generated from a fossil fuel power plant will mainly depend on the type of fuel used, the type of power generation technology, the size of the plant, and the efficiency. For example, using IPCC default emission factors [7], a lignite-fired power plant with a capacity of 500 MW, having a thermal efficiency of 40%, would generate approximately 455 tonnes of CO_2 per hour (~910 $kgCO_2/MWh$), while the plant with the same capacity and efficiency, but fuelled with bituminous coal would generate 426 tonnes of CO_2 per hour (~850 $kgCO_2/MWh$), which is 6.4% less CO_2 emitted. If, for example, the efficiency of coal-fired power plants can be increased to 50% (the target for advanced USC-PC plants) it will result in even higher CO_2 reduction.

The effect of efficiency improvement on the emissions of CO_2 from a coal-fired plant is shown in Fig. 1. At 50% efficiency, a power plant will emit up to 40% less CO_2 than the plant with a thermal efficiency of 30%. It should be noted here that the average global efficiency of coal-fired plants is currently 33% [8]. The addition of CCS will further reduce the emissions of CO_2 by more than 85% in comparison with the reference plant, without CCS. But, to achieve this reduction the CO_2 capture unit will consume up to 30% of the energy produced by the plant, which means more fuel must be burnt in order to generate the same amount of energy as the plant without CCS.

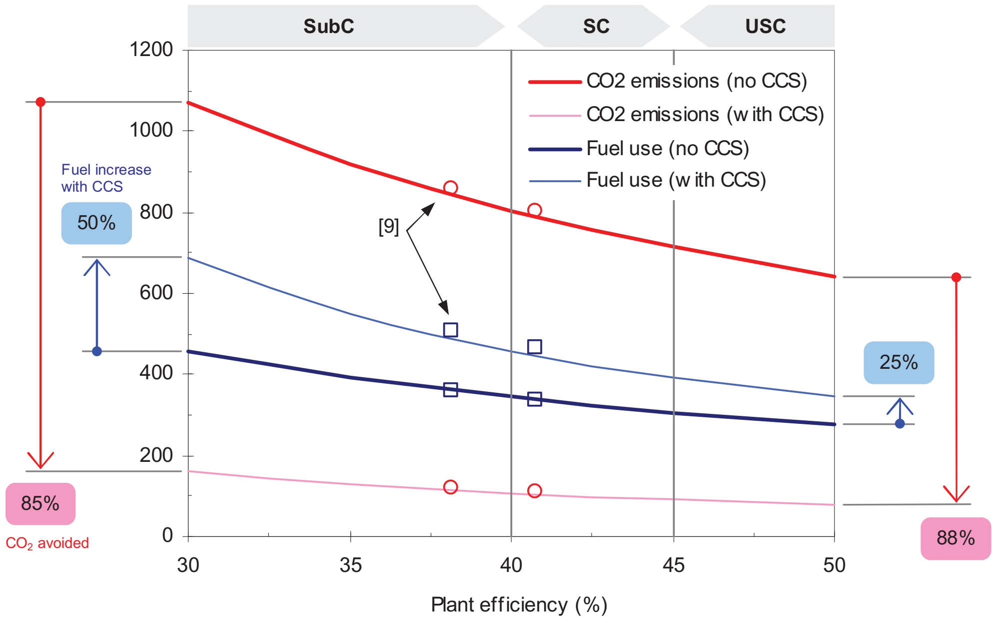

Fig. 1. CO_2 emissions vs efficiency (y-axis: specific CO_2 emissions and fuel consumption in kg/MWh). Calculation was made for a PC plant firing bituminous coal with a LHV of ~26.2 MJ/kg and carbon content of 0.64. CO_2 capture rate of 90% and efficiency penalty of 10% points were assumed when CCS is added.

Examples of the most efficient coal-fired power plants, with efficiencies greater than 41%, are given in Table 1.

Table 1. Examples of some most efficient coal-based power plants currently operated in the world [10,11].

Plant name (country)	**Plant type (fuel used and LHV)**	**Net output (MW)**	**Net efficiency (% LHV)**	**Steam parameters (MPa/°C/°C)**
Nordjylland 3 (Denmark)[a]	USC-PC (bituminous coal, 25.2 MJ/kg)	384	47	29/582/580/580
Niederaussem K (Germany)	USC-PC (lignite, 10.5 MJ/kg)	965	43.2	27.5/580/600
Isogo 1 (Japan)	USC-PC (bituminous coal, ~25 MJ/kg)	568	>42	25/600/610
Genesee 3 (Canada)	SC-PC (sub-bituminous coal, 17.3 MJ/kg)	450	41.4	25/570/568
Younghung (Korea)	SC-PC (bituminous coal, ~25 MJ/kg)	1548[b]	43.4	24.7/566/566
Wangqu 1,2 (China)	SC-PC (coal, 23.6 MJ/kg)	1200[b]	41.4	24.2/566/566
Lagisza (Poland)	SC-CFB (hard coal, ~20 MJ/kg)	439	43.3	27.5/560/580

Notes: USC, power plant with ultra-supercritical steam parameters; SC, power plant with supercritical steam parameters, PC, pulverized coal combustion technology; CFB, circulating fluidized bed combustion technology.
[a] Power plant with double reheat.
[b] Total power output (Younhung and Wahgqu power plants have two power generating units each).

Unlike coal-based power plants, natural gas combined cycle power plants emit significantly less CO_2 per unit of energy produced, around 350 kg/MWh, which is on average 45% of the CO_2 emitted from coal-fired plants.

3. Efficiency penalty due to CO_2 capture

Fig. 2 compares the efficiency of different power plants, coal-based (PC and IGCC) and natural gas-based (NGCC) plants, with and without CO_2 capture. For post-combustion capture there were considered processes only based on MEA [5,9,12-17], for pre-combustion capture – Selexol [9,15,17,18], and for oxy-combustion the oxygen was produced using cryogenic processes [17,19].

As can be seen in Fig. 2, the efficiency penalty of PC and NGCC plants with MEA-based post-combustion CO_2 capture system is around 10% points (and may vary between 6 and 14% points) and 8% points, respectively. The use of MDEA as solvent for post-combustion capture leads to an efficiency reduction of 8.5% points for PC plants [18] and about 6% points for NGCC plants [18]. The efficiency reduction for PC plants with sodium- and potassium-based capture systems is 9-9.5% points [20,21], with ammonia-based systems is in the range of 8-16% points [22,23], while the use of a calcium looping process will reduce the net efficiency of the plant by 6-9% points [24-27].

The efficiency loss due to CO_2 capture for IGCC plants is estimated to be in the range of 5-11% points using the Selexol process [9,15,17,18,28], 4% points using pressure swing adsorption [28], 7-10% points using calcium looping [29,30] (integrating the plant with a novel air separation system based on membranes and coupling with calcium looping for CO_2 capture may lead to only 2.4% points loss in efficiency [29]), and less than 3% points if an iron-based chemical looping combustion process is applied [28,31].

For PC and NGCC power plants with oxy-combustion the efficiency loss is almost 10% points [17,19]. The energy consumption for oxygen production using cryogenic air separation accounts for about 50% of the total efficiency reduction. To reduce the energy penalty associated oxygen production, more efficient air separation technologies should be used (e.g., membrane- or solid-based).

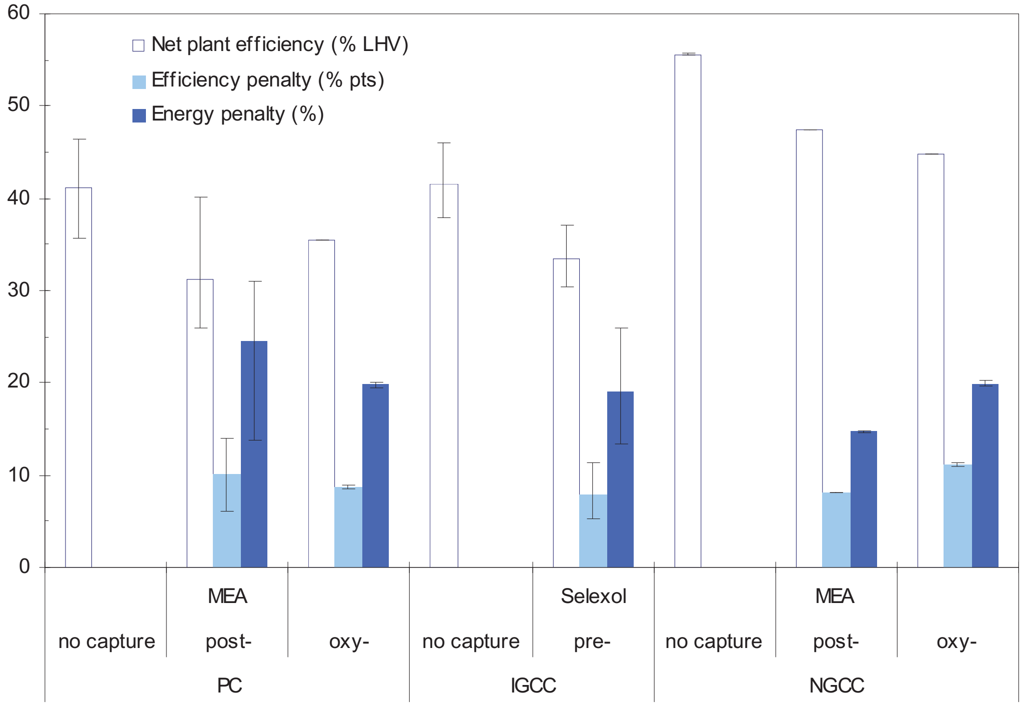

Fig. 2. Efficiency of power plants with and without CO_2 capture (y-axis: percentage values) [5,9,12-19].

4. Pilot plants and CCS demo projects

The capture technologies used in post-, oxy- or pre-combustion have been tested in pilot plants with CO_2 capture capacities of <1000 tCO_2 captured per day. For instance, about 24 tCO_2/day were captured at the Esbjerg pilot plant using an amine-based post-combustion capture system, >7 tCO_2/day at the La Pereda pilot plant with calcium looping process, >90 tCO_2/day at Elcogas with amine-based pre-combustion capture, and around 200 tCO_2/day at Schwarze Pumpe with oxy-fuel combustion.

Large scale CO_2 capture demo projects are also planned [32,33]. In Europe there are plans for six CCS demo projects: two of them will use post-combustion capture ROAD (The Netherlands) with a capture capacity of 1.1 $MtCO_2$/yr and Peterhead (UK) with a capture capacity of 1.0 $MtCO_2$/yr; one project demonstrating oxy-fuel combustion White Rose (UK) with a capture capacity of 2.0 $MtCO_2$/yr; and three projects with pre-combustion capture Don Valley, C.GEN North Killingholme and Captain Clean Energy, all in the UK, with capture capacities of 5.0, 2.5 and 3.8 $MtCO_2$/yr, respectively. None of these projects will be operational until 2017, although some of them were previously announced to begin operation earlier.

Table 2 presents the current list of planned large scale CCS demonstration projects. As can be seen, amine-based capture systems will be used in most projects with post-combustion capture while commercial processes Rectisol and Selexol will be used for pre-combustion CO_2 capture.

Table 2. List of large scale CCS demonstration projects [32,33].

Project name (country)	Capture technology	CO_2 capture capacity (Mt/yr)	Storage option	Operation year
Boundary Dam (Canada)	post-combustion: amine-based (Cansolv)	1.0	EOR (onshore)	2014
Petra Nova (USA)	post-combustion: amine-based (KM-CDR)	1.4	EOR (onshore)	2016
ROAD (The Netherlands)	post-combustion: amine-based	1.1	DGR (offshore)	2017
Sinopec (China)	post-combustion: amine-based	1.0	EOR (onshore)	2017
Sargas (USA)	post-combustion: hot potassium carbonate	0.8	EOR (onshore)	2017
Korea-CCS 1 (Korea)	post-combustion: amine or solid sorbents[a]	1.0	SA (offshore)	2018
China Resources Power (China)	post-combustion: amine-based	1.0	SA (offshore)	2018
Peterhead (UK)	post-combustion: amine-based	1.0	DGR (offshore)	2019
Bow City (Canada)	post-combustion: amine-based (Cansolv)	1.0	EOR (onshore)	2019
FutureGen 2.0 (USA)	oxy-fuel	1.1	SA (onshore)	2017
White Rose (UK)	oxy-fuel	2.0	SA (offshore)	2018-2019
Datang Daqing (China)	oxy-fuel	1.0-1.2	SA (onshore)	2020
Shanxi (China)	oxy-fuel	2.0	nd	2020
Kemper County (USA)	pre-combustion: Selexol process[b]	3.0	EOR (onshore)	2015
Quintana South (USA)	pre-combustion	2.1	EOR (onshore)	2018
Don Valley (UK)	pre-combustion: Rectisol process[c]	~5.0	SA (offshore)	2019
HECA (USA)	pre-combustion: Rectisol process	~2.7	EOR (onshore)	2019
TCEP (USA)	pre-combustion: Rectisol process	2.7	EOR (onshore)	2019
Dongguan (China)	pre-combustion	1.0-1.2	DGR (offshore)	2019
C.GEN North Killingholme (UK)	pre-combustion: physical solvent	2.5	nd	2019
Huaneng GreenGen (China)	pre-combustion: amine-based	2.0	EOR (onshore)	2020
Captain Clean Energy (UK)	pre-combustion: Rectisol process	3.8	SA (offshore)	2021

Notes: ROAD, Rotterdam Capture and Storage Demonstration Project; HECA, Hydrogen Energy California Project; TCEP, Texas Clean Energy Project; KM-CDR, Kansai Mitsubishi Carbon Dioxide Recovery Process; EOR, Enhanced Oil Recovery; DGR, Depleted Gas Reservoir; SA, Saline Aquifers, nd, not yet defined.

[a] The post-combustion capture system for the Korea-CCS 1 demo project will use a process based either on advanced amine solvents (e.g., KoSol-4) or dry regenerable sorbents (e.g., KEP-CO2P2). Both processes are currently under development and testing at the two KEPCO's CO_2 capture pilot plants Boryeong (amine-based) and Hadong (solid sorbents).
[b] Selexol process uses a mixture of dimethyl ethers of polyethylene glycol.
[c] Rectisol process uses methanol as a solvent.

5. EU research activities on CCS

5.1. EU research projects on CO_2 capture

In post-combustion capture there could be mentioned the following recently completed projects: CAOLING aimed to test and demonstrate the calcium looping process, which is considered one of the most promising concepts for CO_2 capture from coal-fired power plants; ICAP intended to develop new CO_2 capture technologies, aiming principally to reducing the energy penalty to less than 5% points, decreasing the heat requirement for solvent regeneration down to 2.3 MJ/kgCO_2 captured, and achieving a cost of CO_2 avoided of around 15 €/tCO_2. Currently ongoing projects are, for example: CAPSOL, IOLICAP, OCTAVIUS or HIPERCAP. Within the OCTAVIUS research project, first generation post-combustion capture processes based on amine solvents are further developed and investigated. There are three different amine-based CO_2 capture pilot plants where the experiments will be carried out (i.e., the Cato pilot plant in Maasvlakte, The Netharlands, with a capacity of 6 tCO_2/day, the EnBW pilot plant in Heilbronn, Germany, with a designed capture capacity of 7.2 tCO_2/day, and the Enel pilot plant in Brindisi, Italy, with a capture capacity of about 60 tCO_2/day). In addition, the so-called DMX process with the energy consumption of around 2.3 MJ/kgCO_2 captured will be demonstrated at pilot scale. The HIPERCAP project aims to investigate and compare novel absorption, adsorption and membrane-based processes for CO_2 capture from flue gas with existing post-combustion capture technologies.

The CO_2 capture projects related to oxy-fuel combustion are, for example: FLEXI BURN CFB aimed to develop and demonstrate an advanced oxy-based CFB reactor power plant in which different types of fuels could be (co-)fired; INNOCUOUS had the objective to create new reactive oxygen carriers other than those based on nickel; HETMOC has proposed to develop efficient oxygen transport membranes in order to reduce the energy penalties associated with oxygen production; the issues concerning the fuel combustion, heat transfer, flame stability, corrosion during oxy-fuel combustion are currently experimentally and numerically investigated within the RELCOM project; while the O2GEN project aims to demonstrate the so-called second generation oxy-fuel CFB concept. The main target of which is to reduce the overall efficiency penalty of the plants with carbon capture from around 12% to 6% points.

Pre-combustion CO_2 capture technologies have been researched in: DECARBIT aimed to develop and improve the CO_2 separation technologies based on membranes, sorbents or solvents as well as oxygen separation technologies using new advanced cryogenic and non-cryogenic techniques; CACHET II was mainly focused on testing new palladium-alloy membranes for efficient hydrogen separation in pre-combustion applications; HY2SEPS2 investigated hybrid systems, combining pressure swing adsorption processes with membrane separation, for efficient hydrogen separation and purification; DEMOCLOCK aims to demonstrate the chemical looping combustion concept for power generation with carbon capture.

Table 3 lists some of the EU research projects on CO_2 capture.

Table 3. List of some completed/ongoing EU research and development projects on CO_2 capture.

Project name	Project title	Period	Web
Post-combustion capture:			
CESAR	CO_2 enhanced separation and recovery	2008-2011	www.co2cesar.eu
CAOLING	Development of post-combustion CO_2 capture with CaO in a large testing facility	2009-2012	www.caoling.eu
CAL-MOD	Modeling and experimental validation of calcium looping CO_2-capture process for near zero CO_2 emission power plants	2010-2013	http://cal-mod.eu-projects.de

ICAP	Innovative CO_2 capture	2010-2013	http://icapco2.org
CAPSOL	Design technologies for multi-scale innovation and integration in post-combustion CO_2 capture: From molecules to unit operations and integrated plants	2011-2014	www.capsol-project.eu
IOLICAP	Novel ionic liquid and supported ionic liquid solvents for reversible capture of CO_2	2011-2014	www.iolicap.eu
OCTAVIUS	Optimization of CO_2 capture technology allowing verification and implementation at utility scale	2012-2017	www.octavius-co2.eu
ECO-SCRUB	Enhanced capture with oxygen for scrubbing of CO_2	2007-2017	
HIPERCAP	High performance capture	2014-2017	www.sintef.no/Projectweb/HiPerCap
Oxy-fuel combustion:			
FLEXI BURN CFB	Development of high efficiency CFB technology to provide flexible air/oxy operation for power plant with CCS	2009-2012	www.vtt.fi/sites/flexiburncfb
INNOCUOUS	Innovative oxygen carriers uplifting chemical-looping combustion	2010-2013	www.clc-innocuous.eu
HETMOC	Highly efficient tubular membranes for oxy-combustion	2011-2015	
RELCOM	Reliable and efficient combustion of oxygen/coal/recycled flue gas mixtures	2011-2015	www.relcomeu.com
O2GEN	Optimization of oxygen-based CFBC technology with CO_2 capture	2012-2015	www.o2genproject.eu
Pre-combustion capture:			
CAESAR	Carbon-free electricity by SEWGS: Advanced materials, reactor and process design	2008-2011	http://caesar.ecn.nl
DECARBIT	Enabling advanced pre-combustion capture techniques and plants	2008-2012	www.sintef.no/Projectweb/DECARBit
CACHET II	Carbon dioxide capture and hydrogen production with membranes	2010-2012	www.cachet2.eu
HY2SEPS-2	Hybrid membrane – Pressure Swing Adsorption (PSA) hydrogen purification systems	2011-2013	http://hy2seps2.iceht.forth.gr
DEMOCLOCK	Demonstration of a cost effective medium size Chemical Looping Combustion through packed beds using solid hydrocarbons as fuel for power production with CO_2 capture	2011-2015	www.sintef.no/Projectweb/DemoClock

5.2. EU research projects on CO_2 transport and storage

Technical and operational challenges/issues, current infrastructure and regulations associated with CO_2 transportation have been researched within the following project initiatives: CO2EUROPIPE analyzed the existing/required infrastructure in Europe that can be (re-)used for the transport of large quantities of CO_2; while, for example, in the COMET project, the transport infrastructure and possible CO_2 storage locations were evaluated for the West Mediterranean area; CO2PIPEHAZ assessed quantitatively potential failure, consequences and hazards for next generation pipelines.

Storage of CO_2 is currently researched within: ECO2 is mainly focused on investigating the impact of CO_2 leakage on marine ecosystem, studying sub-seabed storage sites that are currently in operation (i.e., Sleipner), recently opened (i.e., Snohvit) or planned (i.e., Baltic Sea); SITECHAR provides the key steps required to achieve readiness for large-scale implementation of CO_2 storage in Europe; potential risks associated with CO_2 storage into deep geological formations is investigated within the RISKS project while the impact of impurities in the CO_2 stream on transport and storage is currently under investigation within the IMPACTS project; the aim of the PANACEA project is to develop methods and tools in order to accurately predict the behavior of the injected CO_2 in a geological field.

A list of research projects on transport and storage of CO_2 is given in Table 4.

Table 4. List of some completed/ongoing EU research and development projects on CO_2 transportation and storage.

Project name	Project title	Period	Web
Transportation:			
ECCO	European value chain for CO_2	2008-2011	www.sintef.no/Projectweb/ecco
CO2EUROPIPE	Towards a transport infrastructure for large-scale CCS in Europe	2009-2011	www.co2europipe.eu
CO2PIPEHAZ	Quantitative failure consequence hazard assessment for next generation CO_2 pipelines	2009-2013	www.co2pipehaz.eu
COCATE	Large-scale CCS transportation infrastructure in Europe	2010-2012	http://projet.ifpen.fr/Projet/jcms/c_7861/cocate
COMET	Integrated infrastructure for CO_2 transport and storage in the west Mediterranean	2010-2012	http://comet.lneg.pt
CO_2 Storage:			
MUSTANG	A multiple space and time scale approach for the quantification of deep saline formations for CO_2 storage	2009-2013	www.co2mustang.eu
RISKS	Research into impacts and safety in CO_2 storage	2010-2013	www.riscs-co2.eu
CGS EUROPE	Pan-European coordination action on CO_2 geological storage	2010-2013	www.cgseurope.net
SITECHAR	Characterization of European CO_2 storage	2011-2013	www.sitechar-co2.eu
CO2CARE	CO_2 site closure assessment research	2011-2013	www.co2care.org
ECO2	Sub-seabed CO_2 storage: Impact on marine ecosystems	2011-2015	www.eco2-project.eu
ULTIMATECO2	Understanding the long-term fate of geologically stored CO_2	2011-2015	www.ultimateco2.eu
PANACEA	Predicting and monitoring the long term behavior of CO_2 injected in deep geological formations	2012-2014	http://panacea-co2.org
IMPACTS	The impact of the quality of CO_2 on transport and storage behaviour	2013-2015	www.sintef.no/Projectweb/IMPACTS
CO2QUEST	Techno-economic assessment of CO_2 quality effect on its storage and transport	2013-2016	www.co2quest.eu

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