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Carbon Capture and Storage (CCS): Technology, Projects and Monitoring Review

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Abstract

Carbon capture and storage (CCS) in terms of geological sequestration represents the process of capturing CO_2 from large point sources, its transportation to a storage site, and its deposition into deep geological layers. In addition to the ecological benefits, underground injection of CO_2 shows certain potential risks associated with unwanted migration of CO_2 to groundwater and the surface, so the possibility of carrying out such projects depends on the possibility of reducing the mentioned risks to an acceptable level. For this purpose, detailed risk assessment and analysis must be carried out, serving as the basis for a monitoring plan. A well designed and implemented monitoring plan and program provides important data on site integrity, well injectivity, and the entire storage complex performance. This paper gives an overview on a large scale and pilot projects of CO_2 capture and geological storage in operation, under construction and in the phase of development all over the world, technology basics and available monitoring techniques. An example of CCS project monitoring is given through the monitoring program of the Lacq pilot project in France.

Keywords:

Carbon dioxide, carbon capture and storage projects, CO_2 migration, monitoring

1. Introduction

Besides a high concentration of CO_2 in the Earth's atmosphere, a significant rise in its annual growth rate is also worrying. The CO_2 atmospheric concentration is instrumentally monitored as an integral part of the Global Greenhouse Gas Reference Network research program, which includes continuous measurements at observation stations, located in Alaska (Barrow); Hawaii (Mauna Loa); American Samoa (Cape Matatula); and South Pole, at a sufficient distance from the huge polluters. The measurements at the Mauna Loa observation station started back in 1957. The average monthly concentration of atmospheric CO_2 and its annual grow rate for the whole period of measurement are shown in **Figures 1 a)** and **b)**.

Although fossil fuels are considered to be largely responsible for climate changes, due to many obstacles in terms of infrastructure, technology and prices, they cannot be replaced with renewables in the near future. However, in order to reach the international climate change target, set in Paris in 2015, i.e. to limit the average temperature rise in the atmosphere under 2 °C compared to levels before industrialization, it is necessary to switch to a decarbonised economy (**Novak Mavar, 2016**). As per the Synthesis Report Summary for Policymakers published by the Intergovernmental Panel on Climate Change (abbr. IPCC), the Carbon Capture and Storage (abbr. CCS) has an irreplaceable role as a climate mitigation technology and now the governments are faced with finding appropriate mechanisms to shift its usage from the demonstration-phase to wide application (**IPCC, 2014**). However, an inevitable rise in carbon market prices will have a decisive influence. According to the International Energy Agency, to achieve the climate targets, about 4 000 million tonnes per year (Mt/y) of CO_2 has to be captured and stored by 2040; which is almost 100 times higher than the currently operated capture capacity (**IEA, 2016**). The Global Status of CCS, 2016 Summary Report published by the Global CCS Institute highlights key recommendations to help accelerate CCS deployment (**Global CCS Institute 2016**).

2. CCS technology overview

The CCS technology considers capturing carbon dioxide from the large stationary sources, its transportation and removal from the atmosphere by permanent disposal. There are 3 basic stages in the typical CCS pro-

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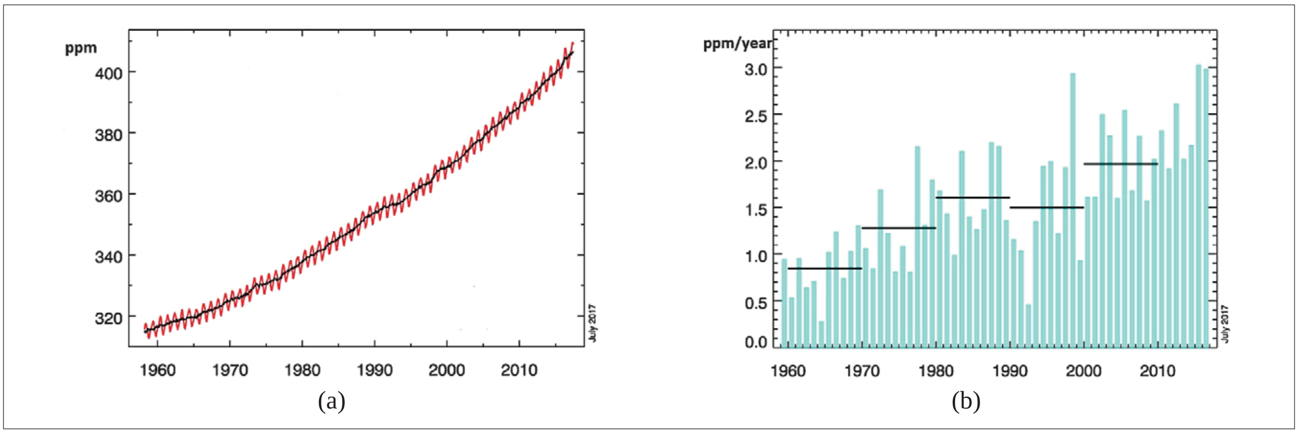

Note: CO_2 concentration measured at the Mauna Loa observation station

Figure 1: Average monthly atmospheric CO_2 concentration (a), and Annual grow rate of atmospheric CO_2 concentration (b) (modified according to https://www.esrl.noaa.gov/gmd/ccgg/trends/full.html)

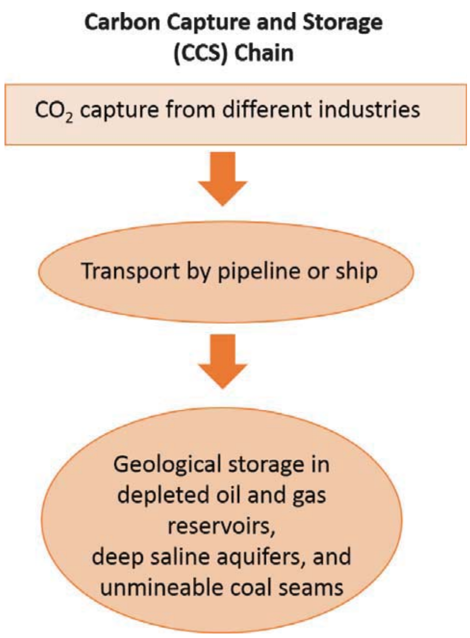

Figure 2: CCS Chain

cess: (1) ***Capture***, (2) ***Transport***, and (3) ***Storage*** (see **Figure 2**).

The CCS technology is applicable to different industries (natural gas processing, power generation, iron and steel production, cement manufacturing, etc.). Due to storage capacity, existing infrastructure and the acceptable risk of CO_2 migration, depleted hydrocarbon reservoirs are one of the most favourable storage options. The CCS term also includes EOR projects where, in case that the system is not closed, a part of the CO_2 ends up in the atmosphere (**Gaurina-Međimurec & Novak Mavar, 2017**).

2.1. CO_2 capture systems

Flue gas contains only a small quantity of CO_2 (3-15 %), while the rest of the volume percent is comprised of nitrogen, steam and smaller quantities of particulates and other pollutants. Therefore, pure CO_2 from the waste stream must be extracted and prepared for transportation (**IPCC, 2005; IEA 2013**).

Depending on the concentration of CO_2 in the gas stream, pressure and fuel type (solid or gas), one of four basic CO_2 capture systems can be applied: (a) ***Pre-combustion capture system***, (b) ***Post combustion capture system***, (c) ***Oxyfuel combustion system***, (d) ***Industrial separation*** (see **Figure 3**).

A ***Pre-combustion capture system*** considers decarbonisation of fossil fuels, using the processes of "steam reforming" (adding steam to primary fuel), "partial oxidation" (adding oxygen to liquid fuel) or "gasification" (adding oxygen to solid fuel). The first stage of the reaction produces synthesis gas (syngas - a mixture of hydrogen (H_2), and carbon monoxide (CO)). By further reaction of CO and steam in the shift reactor, a mixture of H_2 and CO_2 is produced, with a CO_2 concentration of 5 -15 % vol. The mixture is further separated into CO_2 and hydrogen. Physical or chemical adsorption represents an inherent part of the pre-combustion capture. Although the initial steps of fuel processing are more complex and expensive than in post-combustion capture systems, high concentrations of CO_2 in the second reactor and the high pressures applied are more suitable for separation and represent an advantage of this technology (**IPCC, 2005; IEA, 2013**).

A ***Post-combustion capture system*** implies CO_2 capturing from the flue gas by physical or chemical solvents, or its separation by adsorbents or membranes. After being separated, CO_2 is compressed for transportation, while the solvent is recycled. The advantage of the post-combustion capture process is in the possibility of its upgrading to existing coal or gas thermal power plants, industrial facilities, etc. (**IPCC, 2005; IEA, 2013**).

An ***"Oxyfuel" combustion capture system*** uses oxygen in the process of fossil fuel combustion, in order to

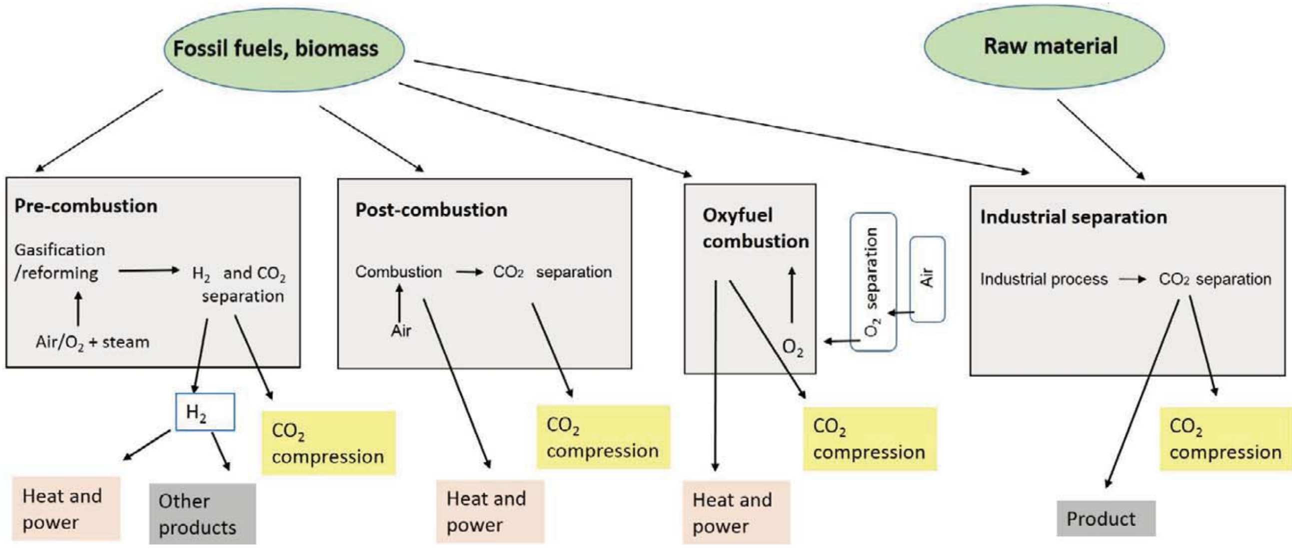

Figure 3: Schematic representation of capture systems (modified according to **IPCC, 2005**)

achieve a more concentrated CO_2 stream (more than 80 % vol.), convenient for easier separation. The removal of water steam is achieved by cooling and compressing the gas stream. In theory, this technology is simpler and cheaper than the more complex absorption process used in post-combustion systems, and it can achieve a high efficiency of CO_2 removal. However, the main barrier for its wide application are the high costs of gaining pure oxygen (**IPCC, 2005; IEA, 2013**).

Industrial separation is done by different methods for more than 40 years. Unwanted CO_2 is separated in different industry processes, such as natural gas sweetening, production of hydrogen and ammonia, etc. (**IPCC, 2005; IEA, 2013**).

2.2. CO_2 transport systems

Captured CO_2 can be transported in solid, gaseous or liquid phases or as a supercritical fluid. One of two main transport options can be selected: pipelines and ships. Transport by pipelines is considered to be the most practical solution in the case of CCS commercial use, due to huge disposal quantities which can reach millions of or even billions of tonnes of CO_2 per year.

2.3. CO_2 storage systems

CO_2 can be permanently disposed into: (a) ***depleted oil and gas reservoirs***, (b) ***deep-saline aquifers***, (c) ***unmineable coal layers***. Hydrocarbon reservoirs are well known thanks to the exploration and exploitation of hydrocarbons, deep-saline aquifers have a huge storage potential but generally they are still not sufficiently explored, while coal seals present a future option, after solving the problem of injecting huge volumes of CO_2 into low permeability layers.

CO_2 geological storage uses well known and proven technology developed by the oil and gas industry. CO_2 is stored through injection wells as a supercritical fluid, achieved by compression and heating above the critical conditions of 73.9 bar and 31.1 °C. Depths of over 800 m ensure a supercritical state, but for safety reasons, the injection is planned at a depth of more than 1 000 m. A depth of 2 500 m is considered to be the economic boundary since the amount of needed energy is increased with depth. Suitable layers dedicated for CO_2 storage must meet criteria in the sense of sufficient porosity (>20 %), permeability ($>500 \cdot 10^{-3}$ μm^2) and capacity (estimated effective capacity much larger than total volume to be stored), the presence of structural traps, the presence of impermeable caprock (thickness >100 m) with stratigraphically uniform lateral continuity, small or no existence of faults, and the absence of potable water (**Chadwick et al, 2008**).

3. Carbon capture and storage in today's and near future application

Large CCS research programs have been implemented in Europe, the United States, Canada, Australia and Japan for several decades. Many years of operation of huge demonstration projects, such as Sleipner in Norway, Weyburn in Canada, and In Salah in Algeria (injection suspended in 2011) have resulted in a significant database and important knowledge platform (**Bennaceur et al., 2004; Chadwick et al, 2008; White, 2009; Whittaker et al., 2011**). There are a number of online CCS project databases collected by different associations, providing data and information which can be used in further CCS project designing: Carbon Capture and Sequestration Technologies at Massachusetts Institute of Technology (abbr. MIT) (https://sequestration.mit.edu/tools/projects/index.html), Global CCS Institute (https://www.globalccsinstitute.com/projects), International Energy Agency (abbr. IEA) Greenhouse Gas Research and

Table 1: Asset lifecycle model (modified according to **Global CCS Institute, 2016**)

Early Development	Advanced Development	In Construction	Operating	Completion
Carrying out studies and comparisons of alternative concepts in terms of costs, benefits, risks and opportunities. Consideration of alternative solution from all relevant aspects (i.e. stakeholder management, regulatory approvals, infrastructure, etc.). Best option selection. Prefeasibility study. Project costs estimation (capital and operating). Site assessment studies.	Further development of a selected option through the feasibility and preliminary front-end engineering design (FEED). Determination of technology, project costs, permitting, and key risks to the development. Finding out finance or funding opportunities. Feasibility studies.	Asset construction. Commissioning.	Operation of the CCS facilities under regulatory framework. Maintenance of the facilities and modification in order to improve performance. Preparation for decommissioning.	Asset decommissioning. Implementation of a post-injection monitoring program.
	FINAL INVESTMENT DECISION		DECISION ON DECOMISSIONING	

Development Programme database (http://ieaghg.org/ccs-resources/rd-database), National Energy Technology Laboratory (abbr. NETL) Carbon Capture and Sequestration database (http://www.netl.doe.gov/research/coal/carbon-storage/strategic-program-support/database), Scottish Carbon Capture and Storage CCS database (http://www.sccs.org.uk/), Zero CO_2 (http://www.zeroco2.no/), Zero Emissions Platform database (http://www.zeroemissionsplatform.eu/), CO_2 Stored database (http://www.co2stored.co.uk/home/index), etc. Regarding the MIT database, it is important to note that it was done in the scope of work of the industrial consortium, the Carbon Sequestration Initiative. The collaboration finished in 2016 and since then the web data base has been kept online primarily as an archive. Therefore, some CCS initiatives that might have occurred in the meantime are not recognized and presented in this study.

Different stages of the CCS project (development, construction, operations, and closure) are given by the asset lifecycle model (see **Table 1**). Final investment decisions and decisions on decommissioning are the most important points in a project's lifetime.

Large-scale projects. The facility can be declared as a large-scale integrated CCS facility if it captures a minimum of 0.8 Mt of CO_2 annually from a coal–based power plant, or a minimum of 0.4 Mt of CO_2 annually from other industrial sources. The facilities at this scale dispose of anthropogenic CO_2 into a geological storage formation and/or inject it underground with the purpose of increasing hydrocarbon recovery (CO_2-Enhanced Oil Recovery, abbr. EOR; CO_2-Enhanced Gas Recovery, abbr. EGR) operations (**Global CCS Institute, 2016**).

The Sleipner CO_2 storage facility represents one of the best known large-scale projects injecting CO_2 into a dedicated geological storage. Since 1996, this Norwegian offshore facility has captured and injected over 16.5 Mt of CO_2 into an offshore sandstone reservoir at a depth of 800 –1 000 m. Another world-famous example, Great Plains Synfuels Plant and Weyburn-Midale Project, connects a coal gasification facility in North Dakota (USA) with the Weyburn Oil Field in Saskatchewan (Canada) through a 325 km long pipeline. After transportation, CO_2 is injected at a pressure of 149 bar into the Midale carbonate reservoir, at an average depth of 1 419 m, for the purpose of EOR. Within the project, approximately 35 Mt of CO_2 have been disposed to date.

Although the CCS technology is in operation for many years, significant progress in its usage is visible recently, especially in the United States, China, Japan, the Middle East and Europe. For instance, in 2016, two significant projects were launched: the large-scale Emirates Steel Industries (ESI) CCS Project (Phase 1) in Abu Dhabi (United Arab Emirates), and CCS Demonstration Project in Tomakomai (Japan). The Abu Dhabi project represents the first application of CCS to iron and steel industry. It considers the capturing of approximately 0.8 Mt/y of CO_2 from the direct reduced iron process for the purpose of EOR. With regards to the Tomakomai CCS Demonstration Project, it uses emissions from a hydrogen production process at the Tomakomai port. Within the project, 0.1 Mt/y of CO_2 is injected underground into sandstone layers of the Moebetsu formation, from 1 000 to 1 200 m under the seabed and into the reservoir (T1 Member of Takinoue Formation), from 2 400 to 3 000 m under the seabed (**Global CCS Institute, 2016**).

In 2017, some new large-scale projects are planned for operation: the Petra New Carbon Capture project in Texas, Illinois Industrial Carbon Capture and Storage in Illinois, and the Gorgon Carbon Dioxide Injection project in Australia (**Global CCS Institute, 2016**). Petra Nova Carbon Capture has been operating since January 2017. The project is of special importance due to the applied world's largest post-combustion CO_2 capture system. The capture facility, installed at the W. A. Parish

Table 2: A list of large-scale CCS facilities in the stage of operation (modified according to **Global CCS Institute, 2016**)

<table>
<tr><th>Project/ Facility name</th><th>Location</th><th>Capt. capacity (Mt/y)</th><th>Industry</th><th>Capture process</th><th>Transport type</th><th>Transport length (km)</th><th>Storage type</th><th>Operation date</th></tr>
<tr><td>Terrell Natural Gas Processing Plant (formerly Val Verde Natural Gas Plants)</td><td>TX, USA</td><td>0.4-0.5</td><td>Natural gas processing</td><td rowspan="11">Industrial separation</td><td rowspan="3">Pipeline</td><td>316</td><td rowspan="3">EOR</td><td>1972</td></tr>
<tr><td>Enid Fertilizer</td><td>OK, USA</td><td>0.7</td><td>Fertilizer production</td><td>225</td><td>1982</td></tr>
<tr><td>Shute Creek Gas Processing Plant</td><td>WY, USA</td><td>7.0</td><td rowspan="2">Natural gas processing</td><td>Multiple, maximum of 460 km</td><td>1986</td></tr>
<tr><td>Sleipner CO_2 Storage</td><td>North Sea, NOR</td><td>1.0</td><td>Not required (direct injection)</td><td>Not applicable</td><td>Saline aquifers</td><td>1996</td></tr>
<tr><td>Great Plains Synfuel Plant and Weyburn-Midale</td><td>SK, CAN</td><td>3.0</td><td>Synthetic natural gas</td><td rowspan="3">Pipeline</td><td>329</td><td>EOR</td><td>2000</td></tr>
<tr><td>Snøhvit CO_2 Storage</td><td>Barents Sea, NOR</td><td>0.7</td><td rowspan="3">Natural gas processing</td><td>153</td><td>Saline aquifers</td><td>2008</td></tr>
<tr><td>Century Plant</td><td>TX, USA</td><td>8.4</td><td>64 to 240</td><td rowspan="6">EOR</td><td>2010</td></tr>
<tr><td>Petrobras Santos Basin Pre-Salt Oil Field CCS</td><td>Santos Basin (off the coast of Rio de Janeiro), BRA</td><td>Approx. 1.0</td><td>Not required (direct injection)</td><td>Not applicable</td><td rowspan="4">2013</td></tr>
<tr><td>Air Products Steam Methane Reformer</td><td>TX, USA</td><td>1.0</td><td>Hydrogen production</td><td rowspan="9">Pipeline</td><td>158</td></tr>
<tr><td>Coffeyville Gasification Plant</td><td>KS, USA</td><td>1.0</td><td>Fertilizer production</td><td>112</td></tr>
<tr><td>Lost Cabin Gas Plant</td><td>WY, USA</td><td>0.9</td><td>Natural gas processing</td><td>374</td></tr>
<tr><td>Boundary Dam Carbon Capture and Storage</td><td>SK, CAN</td><td>1.0</td><td>Power generation</td><td>Post-combustion</td><td>66</td><td>2014</td></tr>
<tr><td>Quest</td><td>AB, CAN</td><td>Approx. 1.0</td><td>Hydrogen production</td><td rowspan="4">Industrial separation</td><td>64</td><td>Saline aquifers</td><td rowspan="2">2015</td></tr>
<tr><td>Uthmaniyah CO_2-EOR Demonstration</td><td>Eastern Province, SAU</td><td>0.8</td><td>Natural gas processing</td><td>85</td><td rowspan="2">EOR</td></tr>
<tr><td>Abu Dhabi CCS Project (Phase 1, Emirates Steel Industries)</td><td>Abu Dhabi, UAE</td><td>0.8</td><td>Iron and steel production</td><td>43</td><td>2016</td></tr>
<tr><td>Illinois Industrial Carbon Capture and Storage</td><td>IL, USA</td><td>1.0</td><td>Chemical production</td><td>1.6</td><td>Saline aquifers</td><td rowspan="2">2017</td></tr>
<tr><td>Petra Nova Carbon Capture</td><td>TX, USA</td><td>1.4</td><td>Power generation</td><td>Post-combustion</td><td>132</td><td>EOR</td></tr>
</table>

power plant near Houston, Texas, captures 1.4 Mt/y of CO_2, which is then transported via pipeline and injected into an oil field near Houston to enhance oil recovery. Illinois Industrial CCS started with an operation in April 2017. It captures CO_2 generated in ethanol production (corn-to-ethanol plant in Decatur, Illinois). Through the project, newly built compression and dehydration facilities are connected to an existing one, constructed under the Illinois Basin Decatur Project, achieving a total CO_2 injection capacity of approximately 1 Mt/y. The cap-

Table 3: A list of large-scale CCS facilities in the stage of construction (modified according to **Global CCS Institute, 2016**)

Project/Facility name	Location	Capt. capacity (Mt/y)	Industry	Capture process	Transport type	Transport length (km)	Storage type	Operation date
Kemper County Energy Facility	MS, USA	3.0	Power generation	Pre-combustion (gasification)	Pipeline	98	EOR	2017
Gorgon Carbon Dioxide Injection	WA, AUS	3.4 - 4.0	Natural gas processing	Industrial separation		7	Saline aquifers	
Alberta Carbon Trunk Line ("ACTL") with Agrium CO_2 Stream	AL, CAN	0.3 - 0.6	Fertilizer production			240	EOR	2018
Alberta Carbon Trunk Line ("ACTL") with North West Sturgeon Refinery CO_2 Stream	AL, CAN	1.2 - 1.4	Oil refining			240		
Yanchang Integrated Carbon Capture and Storage Demonstration	Shaanxi Province, CHN	0.4	Chemical production			150		

Table 4: A list of large-scale CCS facilities in the stage of advanced development (modified according to **Global CCS Institute, 2016**)

Project/Facility name	Location	Capt. capacity (Mt/y)	Industry	Capture process	Transport type	Transport length (km)	Storage type	Operation date
Sinopec Qilu Petrochemical CCS	Shandong Province, CHN	0.5	Chemical Production	Industrial separation	Pipeline	75	EOR	2019
Rotterdam Opslag en Afvang Demonstratieproject (ROAD)	Zuid-Holland, NLD	1.1	Power generation	Post-combustion		6	CCS - offshore depleted oil and/or gas reservoir	2019 - 2020
Sinopec Shengli Power Plant CCS	Shandong Province, CHN	1.0				80	EOR	2020
CarbonNet	VIC, AUS	1.0 - 5.0	Under evaluation	Under evaluation		130	Saline aquifers	
Lake Charles Methanol	LA, USA	4.2	Chemical production	Industrial separation		244	EOR	2021
Texas Clean Energy Project	TX, USA	1.5 - 2.0				Not specified		
Norway Full Chain CCS	Southern Norway, NOR	1.2	Various	Various	Shipping and pipeline	Not specified	Saline aquifers	2022

tured CO_2 is transported to a nearby injection well for dedicated geological storage.

Gorgon CO_2 Injection, as a part of the wider offshore Gorgon LNG project in Western Australia, uses reservoir CO_2. After separation and compression at facilities located on Barrow Island, it is planned to be transported via pipeline to CO_2 injection wells on the Island. The project's full operation considers a capture capacity of 3.4 – 4.0 Mt/y of CO_2.

As per the Global Carbon Capture and Storage Institute database, currently there are twenty two large-scale CCS facilities in operation or under construction (see **Tables 2** and **3**), with a CO_2 capture capacity of approximately 40 Mt/y, seven projects in the advanced planning phase (see **Table 4**) with an approximate CO_2 capture capacity of 9 Mt/y, as well as eleven projects in earlier stages of planning, having a CO_2 capture capacity of 21.1 Mt/y (see **Table 5**).

Table 5: A list of large-scale CCS facilities in the stage of early planning (modified according to **Global CCS Institute, 2016**)

Project/Facility name	Location	Capt. capacity (Mt/y)	Industry	Capture process	Transport type	Transport length (km)	Storage type	Operation date
Korea-CCS 1	Either Gangwon Province or Chungnam Province, KOR	1.0	Power generation	Post-combustion	Shipping	Not specified	Saline aquifers	2020
Korea-CCS 2	KOR	1.0		Pre-combustion or Oxyfuel combustion		Not specified		
Shenhua Ningxia CTL	Ningxia Hui Autonomous Region, CHN	2.0	Coal-to-liquids (CTL)	Industrial separation	Pipeline	200-250	Under evaluation	
Riley Ridge Gas Plant	WY, USA	2.5	Natural gas processing			Not specified	EOR	
Sinopec Eastern China CCS	Jiangsu Province, CHN	0.5	Fertilizer production			200		
China Resources Power (Haifeng) Integrated Carbon Capture and Sequestration Demonstration	Guangdong Province, CHN	1.0	Power generation	Post-combustion		150	Saline aquifers	
Huaneng GreenGen IGCC Project (Phase 3)	Tianjin, CHN	2.0		Pre-combustion (gasification)		50-100	EOR, geological storage options under review	
Shanxi International Energy Group CCUS	Shanxi Province, CHN	2.0		Oxyfuel combustion		Not specified	Under evaluation	
Teesside Collective	Tees Valley, UK	0.8	Various	Various		Not specified	Saline aquifers	
Caledonia Clean Energy	Scotland, UK	3.8	Power generation	Pre-combustion (gasification)		382	Saline aquifers with EOR potential	2022
South West Hub	WA, AUS	2.5	Fertilizer production and power generation	Industrial separation		80-110	Saline aquifers	2025

Project location. As per the data shown in **Tables 2 - 5**, it can be summarized that most of the temporary operating and under construction large-scale CCS projects (68 % of all projects) are located in North America: the USA and Canada. The European Union has regulated the geological storage of CO_2 within the EU Directive 2009/31/EC framework, but CCS project realization is still not at a satisfactory level due to several reasons. The very long project lifetime affects long-term certainty, which is crucial for the investment decision, while insufficient policy support and huge project costs connected with funding obstacles have resulted in the cancellation of a number of projects intended to reach a large scale demonstration level (e.g. Compostilla in Spain, and Peterhead in UK, which could store 1.6 Mt/y and 1.0 Mt/y CO_2 respectively, have been cancelled recently). So, currently in Europe, there are two large-scale CCS projects operating (Sleipner and Snøhvit). The projects are operating in Norway, which is not surprising due to high carbon taxes set by the Norwegian government. Future CCS activities in Europe are going to be expanded on two new offshore storage projects: the Norway full chain CCS, planned for 2022, and the Rotterdam Opslag en Afvang Demonstratie project (the ROAD project), planned for 2019/2020 (see **Table 4**).

Storage type. Considering the storage type, most of the projects currently in operation are connected with EOR activities (76 % of all operating large-scale projects), since residual oil production positively influences project economic viability. However, the EOR process produces additional fossil fuel, considered to be responsible for significant emission. Due to the emission reduction commitments, it can be expected that future investment incentives will be in the CO_2 storage projects rather than in the EOR. Large demonstration projects of storage technology in deep saline aquifers (CarboNet and Norway Full Chain CCS) and depleted hydrocarbon reservoirs (the ROAD project), planned for operation in the next decade, will serve as an important source of experience.

Industry type as a CO_2 source. Regarding the source of CO_2, it can clearly be seen that most of the large-scale projects in operation are connected with the natural gas processing (47 % of all large-scale projects in operation), since CO_2 separation belongs to the common process of natural gas purification. On the other hand, future applications are mostly related to electric power and chemical industry, which can be explained by stringent reduction obligations imposed on the industry. The very first large-scale CCS facility connected to a power generation facility at Boundary Dam, in Saskatchewan, Canada, has been in successful operation for three years, while recently, most of the CCS activities in the power sector have moved to Asia (nine projects in the phase of advanced development and early planning). In regards to other industries, such as iron and steel, or cement production, which are also recognized as huge CO_2 emitters, currently there are not many large-scale capture projects applied due to high capture costs.

Capture process. Although both the post-combustion and the oxyfuel combustion systems can be applied to power plants, only the post-combustion technology has been in large demonstration usage so far, due to high costs connected with the oxyfuel combustion process. In the early development phase, there is one large-scale project example related to oxyfuel combustion technology. It refers to construction of a new power plant with an installed oxyfuel combustion unit in Shanxi Province, China.

CO_2 transport. Pipeline transport, as the most convenient transportation option, is used in almost all the considered projects.

Small scale projects (demonstration and pilot projects). Some of the CCS projects do not meet the large-scale projects criteria regarding sufficient capture capacity or full integration, but still contribute to technology development through providing valuable information and performance data. Given that some of the projects are not integrated, they can be focused only on a specific part of the CCS chain development.

As per Carbon Capture and Sequestration Technologies at MIT database, a significant number of demonstration and pilot projects at a scale relevant to industry have been completed **(**see **Table 6)**, or are in operation **(**see **Table 7)**, aiming at the demonstration of the technical feasibility and achievement of operational experience and economic information.

Tables 6 and **7** show the available data and information on completed and operating pilot projects. Numerous companies from Europe (e.g., Total, Enel, Eni, E. ON, etc.), Australia (CS Energy, etc.) and the USA (Tampa Electric, Powerspan, etc.) were involved in operations. Pilot projects were carried out for 1 to 6 years. Although some of them were also connected to the EOR process (such as Pikes Peak in Saskatchewan, Canada, or Brindisi in Italy), a notable number of projects (more than 55 %) were performed only for the purpose of permanent CO_2 storage. The projects were mostly located in Europe (61 %), where about 90 % of them represent CCS technology application in the power sector. In three European pilot cases, the implementation of the oxyfuel combustion process was tested.

In regards to currently operating pilot projects, they are mostly carried out in Asia (China, Japan and South Korea), and to a lesser extent in North America and Europe. Only two projects are operating in Europe (Norway and Germany). Although there is visible progress in the application to other industries, the widest application is accomplished in the power generation industry.

However, besides those mentioned here as declared CCS projects, there are some cases of underground injection of CO_2 which are not formally considered to be geological storage, such as the recent Croatian example, the EOR project Ivanić and Žutica, performed by the INA-Oil and Gas Industry Plc. The project involves the dehydration, compression and transmitting of 600 000 m^3/day (approximately 0.4 Mt/y) by gas pipeline from the Gas Processing Facilities Molve to the Fractionation Facilities Ivanić Grad. After compression and liquefaction, CO_2 is furtherly sent by pipeline at high pressure (200 bar) for injection into the fields Ivanić and Žutica. The first phase of the project commenced in 2014, and during 25 years of the project, approximately $5 \cdot 10^9$ m^3 of CO_2 will be injected in the reservoirs for the EOR, out of which about 50 % will be produced together with associated gases. Although leakage of that closed system is possible only in the case of an incident, leakage is prevented through the selection of corrosion-resistant materials, while possible migration of CO_2 from the reservoirs is disabled by naturally occurring seals and by maintaining the mechanical integrity of the CO_2 injection wells. The environmental monitoring includes: air,

Table 6: A list of Pilot CCS Project - completed (modified according to **MIT, 2016**)

Project/Facility name	Location	Capt. capacity (Mt/y)	Industry	Capture Process	Storage type	Operation date
K12-B	NLD, EU	0.200	Natural gas processing	Industrial separation	Depleted gas reservoir	2004-2006
Pleasant Prairie	WI, USA	0.002	Power generation	Post-combustion	Vented	2008-2009
ECO_2 Burger	OH, USA	0.007				2008-2010
Karlshamn	SWE	0.015				2009-2010
Otway	AUS	0.065	CO_2 source - Natural deposit	Natural Deposit	Depleted gas reservoir	2008-2011
AEP Mountaineer	WV, USA	0.100	Power generation	Post-combustion	Saline aquifer	2009-2011
Puertollano	ESP, EU	0.037		Pre-combustion	CO_2 is recycled	2010-2011
Brindisi	ITA, EU	0.008		Post-combustion	Saline aquifer	Tested 2011
Compostilla	ESP, EU	0.020		Oxyfuel combustion		2009-2012
Ketzin	DEU, EU	0.060	Power generation Hydrogen production and oxyfuel pilot plant (Schwarze Pumpe)	Post-combustion		2008-2013
Lacq	FRA, EU	0.075	Power generation	Oxyfuel combustion	Depleted gas reservoir	2010-2013
Buggenum	NLD, EU	0.002		Pre-combustion	Vented	2011-2013
Ferrybridge CCSPilot100+	UK, EU	0.037		Post-combustion		2012-2013
Schwarze Pumpe	DEU, EU	0.075		Oxyfuel combustion	Depleted gas reservoir	2008-2014
Aberthaw	Wales, UK. EU	0.0004		Post-combustion	Not applicable	2013-2014
Polk	FL, USA,	0.300		Pre-combustion	Saline aquifer	Tested 2014
Callide-A Oxy Fuel	AUS	0.300		Oxyfuel combustion		2012-2015
Pikes Peak	SA, CAN	0.005		Post-combustion	EOR potential	2015

Table 7: A list of Pilot CCS Project - operating (modified according to **MIT, 2016**)

Name	Location	Capt. capacity (Mt/y)	Industry	Capture Process	Storage type	Operation date
Zama	AB, CAN	0.026	Natural gas processing	Industrial separation	EOR	2006
Shengli	CHN	0.040	Power generation	Post Combustion		2007
Shidongkou	CHN	0.100	Power generation		Commercial use	2009
Jilin	CHN	0.200	Natural gas processing		EOR	
Ordos	CHN	0.100	Coal liquefaction		EOR/Saline aquifer	2011
Plant Barry	AL, USA	0.150	Power generation		Saline aquifer	
Jingbian	CHN	0.040	Chemical production	Pre-combustion	EOR	2012
Wilhelmshaven	DE, EU	0.025	Power generation	Post Combustion	Vented	
Mongstad	NOR	0.100			Saline aquifer	
Boryeong Station	KOR	0.073			Vented	2013
Lula	BR	0.700	Gas processing	Industrial separation	EOR	
Shand	CAN	0.043	Power generation	Post Combustion	Vented	2015
Tomakomai	JP	0.100	Hydrogen production		Saline aquifer	2016
NET Power	TX, USA	-	Power generation	Oxyfuel combustion	EOR	Planning

Table 8: Measurement techniques and measurement parameters applicable to the CCS project (**IPCC, 2005**)

MEASUREMENT TECHNIQUE	MEASUREMENT PARAMETERS	EXAMPLE APPLICATIONS
Introduced and natural tracers	(1) Travel time; (2) Partitioning of CO_2 into brine or oil; (3) Identification of sources of CO_2.	(1) Tracing movement of CO_2 in the storage formation; (2) Quantifying solubility trapping; (3) Tracing leakage.
Water consumption	(1) CO_2, HCO_3^- , CO_3^{2-} ; (2) Major ions; (3) Trace elements; (4) Salinity.	(1) Quantifying solubility and mineral trapping; (2) Quantifying CO_2-water-rock interactions; (3) Detecting leakage into shallow groundwater aquifers.
Subsurface pressure	(1) Formation pressure; (2) Annulus pressure; (3) Groundwater aquifer pressure.	(1) Control of formation pressure below fracture gradient; (2) Wellbore and injection tubing condition; (3) Leakage out of the storage formation.
Well logs	(1) Brine salinity; (2) Sonic velocity; (3) CO_2 saturation.	(1) Tracing CO_2 movement in and above storage formation; (2) Tracking migration of brine into shallow aquifers; (3) Calibrating seismic velocities for 3D seismic surveys.
Time-lapse 3D seismic imaging	(1) P- and S-wave velocities; (2) Reflection horizons; (3) Seismic amplitude attenuation.	Tracing CO_2 movement in and above storage formation.
Vertical seismic profiling and crosswell seismic imaging	(1) P- and S-wave velocities; (2) Reflection horizons; (3) Seismic amplitude attenuation.	(1) Detecting detailed distribution of CO_2 in the storage formation; (2) Detecting leakage through faults and fractures.
Passive seismic monitoring	Location, magnitude and source characteristics of seismic events.	(1) Development of microfractures in formation or caprock; (2) CO_2 migration paths.
Electrical and electromagnetic techniques	(1) Formation conductivity; (2) Electromagnetic induction.	(1) Tracking movement of CO_2 in and above the storage formation; (2) Detecting migration of brine into shallow aquifers.
Time-lapse gravity measurements	Density changes caused by fluid displacements.	(1) Detect CO_2 movement in or above storage formation; (2) CO_2 mass balance in the subsurface.
Land surface deformation	(1) Tilt; (2) Vertical and horizontal displacements using interferometry and GPS.	(1) Detect geomechanical effects on storage formation and caprock; (2) Locate CO_2 migration pathways.
Visible and infrared imaging from satellite or planes	Hyperspectral imaging of land surface.	Detect vegetative stress.
CO_2 land surface flux monitoring using flux chambers or eddy covariance (EC)	CO_2 fluxes between the land surface and atmosphere.	Detect, locate and quantify CO_2 releases.
Soil gas sampling	(1) Soil gas composition; (2) Isotopic analysis of CO_2.	(1) Detect elevated levels of CO_2; (2) Identify source of elevated soil gas CO_2; (3) Evaluate ecosystems impacts.

soil, surface and underground water quality analysis, before the beginning of the project, during the project's operation and after its closure. Nevertheless, according to current legislation, the EU Directive 2009/31/EC on the geological storage of carbon dioxide and relevant national legislation, the project is considered not to be a CCS due to the usage of CO_2 which is not a fuel combustion product for EOR purposes. Transposition of the "CCS Directive" into national regulation has been done through the Mining Act "Official Gazette" No. 56/13 and 14/14, and the Ordinance on the permanent disposal of gases in geological structures "Official Gazette" No. 106/13.

4. CCS Monitoring as confirmation of proper CCS operation preserving the storage complex

Risk management is required in all stages of the storage lifetime, in order to ensure a safe process without harmful effects to human health or the environment, therefore it is very important to identify all potential risks and make a plan for their elimination or mitigation. The risks associated with underground CO_2 storage depend on many factors, including: the used infrastructure, the type of reservoir dedicated for storage, the geological characteristics of the selected layers, caprock and

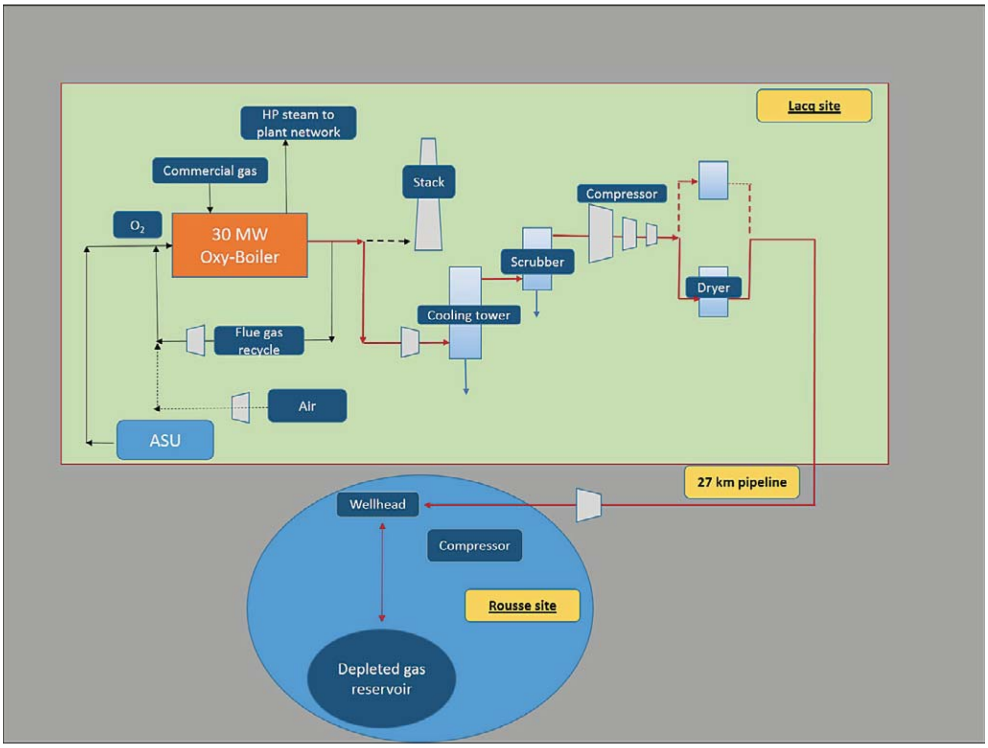

Figure 4: Surface facilities in the Lacq CCS pilot project (modified according to **Total, 2015**)

stratigraphic heterogeneity, geomechanical properties of rocks, the existence of other wells, the method of well abandonment experience, etc.

Before applying CCS, it is necessary to determine whether the identified risks are acceptable and comparable with the risks of other CO_2 reduction options. A comprehensive and properly prepared risk assessment serves as the basis for response plans and monitoring strategies for a given site (**Gaurina-Međimurec & Pašić, 2011; Gaurina-Međimurec & Novak Mavar, 2017**). The monitoring of certain parameters have to be done in compliance with the approved plan, and obtained data is compared with those predicted by modelling and risk assessment. Geological storage of carbon dioxide must be monitored for a long period due to slow geochemical reactions.

The monitoring has to be done due to several technical reasons (**IPCC, 2005; Manchao et al., 2011; Bauer et al., 2012**): (a) the determination of the injected CO_2 volume by injection rate monitoring and measuring wellhead pressure and reservoir pressure, (b) the determination of the CO_2 quantity stored by various mechanisms, (c) storage project optimization by real data on the storage volume, the most suitable pressures and the necessity of drilling new wells, (d) the demonstration of CO_2 retention in the storage formation, (e) leak detection in order to apply remedial measures; (f) the determination of well (in operation or abandoned) condition, (g) microseismic detection associated with storage processes.

Before the start of CO_2 injection, it is necessary to perform measurement of all parameters required for site control and characterization, serving as a basis for future measurements. Seasonal variability of some properties implies that some measurements have to be tested during different seasons.

The measurement of CO_2 injection parameters is a common practice in oil and gas exploitation. Surface and formation pressure measurements are generally carried out, which in combination with temperature measurements provide information on the state of CO_2 (supercritical, liquid or gaseous) and the precise amount of CO_2 injected.

For the monitoring of possible leakage of CO_2 from geological storage formation, direct measurement methods for CO_2 detection, geochemical methods and tracers, or indirect measurement methods for CO_2 plume tracking can be used. Measurements are done during and after the injection of CO_2 in order to verify the storage effectiveness. Measurement techniques and measurement parameters applicable to the CCS projects are shown in **Table 8**. Measured data and obtained information are used for the evaluation of numerical reservoir model prediction. If the predictions are not in line with real behaviour, the model is corrected to get a more precise estimation.

5. An example of monitoring – Lacq, France

The Lacq Pilot, performed by French multinational integrated oil and gas company - Total, is the first project which integrated a CO_2 capture system using oxyfuel

Table 9: Annual monitoring plan of the Lacq Pilot Project (modified according to **Monne, 2012; Total, 2015**)

Monitoring parameter				Monitoring period											
				Winter			Spring			Summer			Autumn		
				Month											
				XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Environment	Water quality	Surface water	Chemistry												
			Bioindicators												
		Phreatic aquifers (springs)	Chemistry												
		Groundwater	Chemistry												
	Ecosystems	Fauna													
		Flora													
	Soil gas														
Site	Reservoir and caprock	Microseismics + Pressure & temperature		Permanent											
	Injection well	CO_2 sensors		Permanent											
		Well annulus pressure		Permanent											
		Pressure & temperature		Permanent											
		Flow and composition		Permanent											
Additional for R&D	Soil gas	C isotopes, inert gas, Radon													
	Phreatic aquifers	Shallow well (6 m)		Permanent											
		Shallow well (80 m)		Permanent											
		Springs		Permanent											
	CO_2 concentration in atmosphere	Flux tower		Permanent											
		Infrared and LIDAR		Testing											

Note: Period of carrying out monitoring is grey coloured

combustion technology combined with onshore CO_2 injection into a depleted natural gas reservoir, located at a depth of 4 500 m below ground level, at Rousse (Pyrenees), 30 km from Lacq (**Monne, 2012**).

The project was operational in the period from January 2010 to March 2013, and during that time approximately 51 000 tonnes of CO_2 were injected. It included the conversion of an existing air-gas combustion boiler into an oxygen-gas combustion boiler in order to achieve a flue gas stream with a higher CO_2 concentration. Oxygen was delivered by an air separation unit (ASU). The 30 MW_{th} oxy-boiler delivered up to 38 t/h of steam (60 bar and 450 ºC) to the gas processing plant. At the outlet of the boiler the flue gas composition was about 33 % vol. of carbon dioxide, 66 % vol. of water, and 1 % vol. of nitrogen, argon and oxygen. Installation of a flue gas recycle line enabled partial recycling of the flue gas to the inlet of the oxy-burners in order to maintain the required combustion chamber temperature. The rest of the flue gas stream was provided for cleaning and conditioning. After washing out (in order to capture unburnt particles and protect the compressor), and cooling (in order to reduce the 90 % water content), the rich CO_2 stream was compressed using 3-stage parallel compressors from a near atmospheric pressure to a pressure of 27 bar, dried and transported in gaseous phase by pipeline to the injection site. At the well head, the CO_2 was furtherly compressed up to the injection pressure of 50 bar. The injection target was the Rousse field reservoir, located in the Mano formation of Upper Jurassic age. A simplified scheme of surface facilities in the Lacq CCS pilot project is shown in **Figure 4 (Monne, 2012; Total, 2015)**.

Comprehensive monitoring was done according to a prepared plan, during operation and in the three year period after injection.

The main project targets included: demonstration of the technical feasibility of an integrated CCS chain; gaining experience in order to upscale the technology from pilot (30 MW_{th}) to an industrial scale (200 MW_{th}), and to develop methodologies for geological storage qualification and monitoring methodologies (**Monne, 2012; Total, 2015**).

Based on prepared qualification studies and risk assessment, and in compliance with the legal requirements, a comprehensive monitoring plan was prepared. Although the risk of CO_2 leakage from the reservoir is very low due to reservoir depth, the existence of thick sealing, applied injection conditions (maximal injection pressure far below the initial reservoir pressure), and small quantities of injected CO_2 with regard to the reservoir storage capacity, some key information on site integrity (confirmation that there is no leakage from the reservoir through the well, the caprock or the faults), well injectivity (flow rate, injected gas composition, well performance), and storage performance (to check if CO_2 behaviour is in line with the reservoir simulation predictions) have to be provided through monitoring. Annual monitoring plan of the Lacq Pilot Project is shown in **Table 9**.

The environmental baseline study, which included soil gas, aquifers and ecosystems, as well as the microseismic baseline study were made to get baseline data before injection. The following parameters were monitored continuously: CO_2 stream composition, concentration and flow, CO_2 atmospheric concentrations at the injection well pad, well annulus pressure, pressure and temperature along the injection well, bottom-hole reservoir pressure and temperature, reservoir and caprock integrity (microseismic monitoring). Measurements of soil gas concentration and fluxes, as well as groundwater and surface water measuring were performed periodically, while biodiversity of the ecosystems was subject to annual research (annual inventory of representative ecosystems).

As per collected data, Total's Geoscience teams has qualified the Rousse site as an ideal location for storing the CO_2 captured from Lacq's industrial installations.

6. Conclusion

Globally, economic and population growth leads to higher CO_2 emissions derived from fossil fuel combustion and causes climate changes, which are recognized as one of the most important 21st century issues. The European Union took a firm attitude in combatting climate changes by setting the targets related to increasing energy efficiency, increasing the share of renewable energy consumption, and the reduction of greenhouse gas emissions. Currently, there are two large-scale CCS projects operating in Europe (the Sleipner project and the Snøhvit project in Norway). Future CCS activities in Europe include two new offshore storage projects (one in Norway planned for 2022 and one in the Netherlands planned for 2019/2020). Demanding emission reduction commitments, as well as the expected increase in CO_2 prices in the market, will likely lead to a wider commercial application of carbon capture and geological storage technology. However, CCS is an expensive technology and the CCS project costs are directly connected with the applied capture system.

Based on the analysis of the available data presented in this paper, it is possible to conclude the following:

- Most of the operating and future large-scale CCS projects (68 % of large-scale projects in operation and under construction) are located in North America: the USA and Canada.
- The CO_2 capture capacity of ongoing large-scale projects of approximately 40 Mt/y confirms a positive shift in CCS technology application.
- The number of the large-scale projects currently under construction (5 projects with a total capacity of 9 Mt/y of CO_2) and in advanced development (7 projects with approximately CO_2 capture capacity of 15 Mt/y**)** confirm a certain future for this technology.
- CCS pilot projects were carried out for 1 to 6 years. A notable number of pilot projects (above 50 %) were performed only for the purpose of permanent CO_2 storage.
- The small scale projects are mostly operating in Asia (China, Japan and South Korea), and to a lesser extent in North America and Europe.
- The widest application of CCS technology has been accomplished in the power generation sector (14 % of all large-scale projects in operation or under construction, as well as 75 % of the small scale projects completed and operating).
- The most cost-effective project solution can be realized in industries where CO_2 production takes a part of a normal operation (such as natural gas processing, production of fertilizers and bio-ethanol).
- Many of the CCS projects (large-scale and pilot) are connected to the oil and gas industry (even 47 % of all large-scale projects in operation use CO_2 generated in the gas sweetening process). Furthermore, if separated CO_2 is used for EOR/EGR purposes, the projects are justified by the additional production of hydrocarbons.
- In 76 % of the operating large-scale projects, CO_2 was injected into reservoirs for EOR purposes, and in 24 %, it was injected into saline aquifers.
- All the EOR projects operating worldwide are not labelled as CCS due to lack of comprehensive monitoring and verification plans.
- CO_2 has been transported by pipelines in 86 % projects, and in 14 % of projects, transport was not required (CO_2 was directly injected underground).
- Comprehensive risk assessment and properly designed monitoring plan are obligatory.
- CCS project realization depends on policy support and funding possibilities.
- Many years of operation of huge demonstration projects (Sleipner in Norway, Weyburn in Canada,

and In Salah in Algeria) have resulted in a significant database and important knowledge platform.

- The planned projects will result in additional knowledge that will enable their rapid implementation at a time when CCS projects become economically feasible.

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