# State of the art report

# Carbon Capture & Storage

FÉDÉRATION EUROPÉENNE DES GÉOLOGUES
EUROPEAN FEDERATION OF GEOLOGISTS
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# 1. INTRODUCTION

Considerable changes are impacting our society due to the rapid socioeconomic development that has taken place in the last few decades. The number of people with access to electricity has increased by 1.7 billion since the 1990s while the global demand for energy is expected to increase 30% by 2040, which will dramatically affect $CO_2$ emissions. As long-term effects, climate change will maintain societal inequalities in specific areas, bringing floods, failed crops, displacement, and famine to entire populations. Dealing with those issues diverts investments and actions from other priorities, e.g. the current COVID-19 pandemic. Effective investment in CCS is strategically important, actively acting now on $CO_2$ emissions and mitigating their effects instead of doing more expensive remediation afterward.

The EU communication and roadmap "Green Deal" aims to make Europe a greenhouse gas-free region by 2050 [1]. It also aims to promote neutral capital and health protection in the EU by mitigating environmental risks. The Green Deal is in line with the United Nations' targets of 2030 for sustainable development. Binding targets to be met by Green Deal include [1]: a) increasing the EU's climate ambition by 2030 and 2050, b) supplying clean affordable and secure energy, c) mobilising the industrial sector towards clean and secure technology, d) building and renovating in an energy and resource efficient way, and e) a zero pollution-ambition, among others.

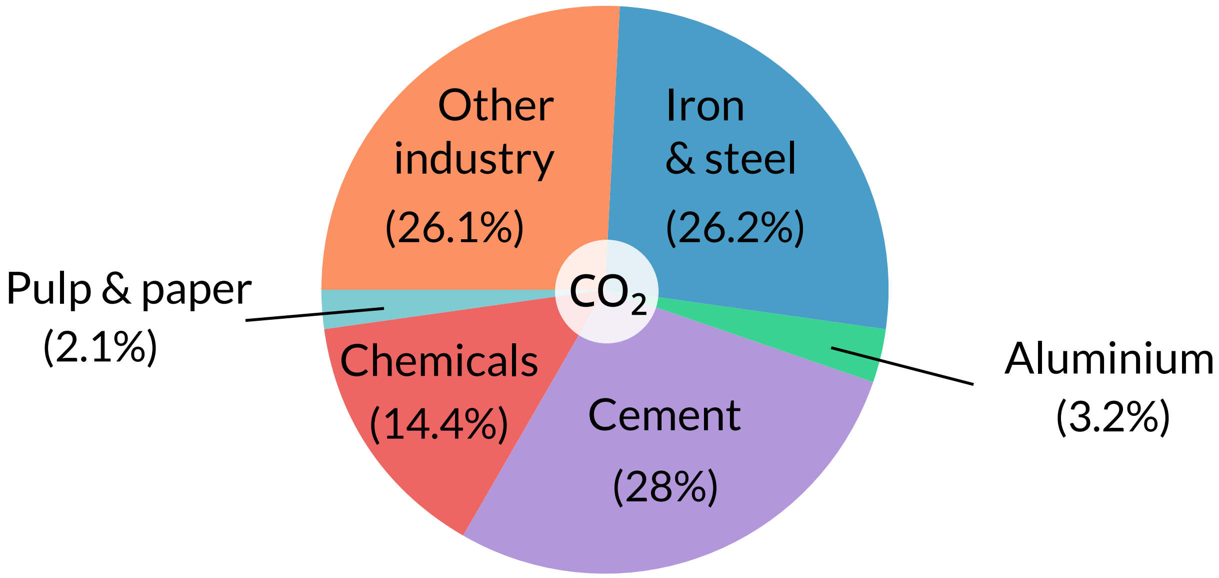


**Figure 1.** Industrial worldwide emissions originating from different sectors (2017 [2])

Reducing the amount of carbon dioxide ($CO_2$) released to the atmosphere is a vital step in meeting these goals. Naturally it is important to find ways to cut down on emissions produced, which vary depending on the industry generating these emissions (Fig. 1). Other approaches involve capturing $CO_2$ before release and then either fixing it or using it for another purpose. Various measures will be needed to achieve substantial gains in reducing the amount of $CO_2$ released into the atmosphere and sustainable energy use.

This report offers a brief introduction to carbon capture technologies in use or being investigated, particularly in the energy industry, which emits a considerable amount of $CO_2$ (~7.5% in 2017) [2] in the course of producing the materials, fuel and power that make our lifestyles possible. The earth sciences are very important in many of these technologies, meaning that geologists, geoscientists and geoengineers have an essential role in sustainable progress.


# 2. CARBON CAPTURE AND STORAGE TECHNOLOGIES

To achieve the target of using clean energy, several $CO_2$-capturing methods and technologies are currently implemented [3]. Carbon capture and storage (CCS) technologies aim to capture $CO_2$ emissions from point sources such as thermal power plants using fossils fuels and industrial processes, thus contributing to the mitigation measures related to the reduction of greenhouse gas (GHG) emissions. $CO_2$ is captured and transferred to a selected site for long-term geological storage or is used to produce products with the objective of an economic benefit.

## 2.1 CARBON CAPTURE

$CO_2$ capture technologies are available nowadays but still remain costly; in fact, they make up 70–80% of the total cost of a full capture, transport and storage system [4]. Consequently, significant efforts are being focused on the reduction of operating costs and energy consumption. There are three main capture technologies.

### 2.1.1 Pre-combustion capture

The pre-combustion capture process is mainly applied in power production systems and chemical industries. In the power sector, it typically works with solid fuels such as in Integrated Coal Gasification Combined Cycle (IGCC) Power Plants. The coal is gasified to produce a synthetic gas (syngas) and reacts with water to produce $CO_2$, and hydrogen. With regard to the chemical production, pre-combustion is mainly applied in ammonia manufacturing. Prior to ammonia synthesis, the $CO_2$ that is co-produced with hydrogen is removed and sometimes used to react with ammonia to produce urea. For $CO_2$

pre-combustion capture applications, trends in materials technology development principally include amine-based solvents, physical solvents, membranes and solid sorbents. High construction costs and decreased short-term flexibility are identified as the most important disadvantages of the technology.

### 2.1.2 Post-combustion capture

Post-combustion technologies are the preferred option for retrofitting existing power plants. In this process, $CO_2$ is separated from flue gas after fuels have completely burned. The main challenge for post-combustion $CO_2$ capture is the large parasitic load associated with the low $CO_2$ levels in post-combustion flue gas (i.e., 7%–14% for coal-fired and as low as 4% for gas-fired). The term parasitic load refers to the energy consumption during post-combustion capture (PCC). This energy is associated mainly with the regeneration processes of the solvent [5]. Reduction of parasitic load is one of the most important priorities that must be considered in PCC. Thus, research efforts are focused mainly on the design of new chemical processes and novel power plants that will require lower energy consumption for the capture compared to the compression energy [5]. Accordingly, the energy consumption and the associated costs for the capture unit to reach the concentration level of $CO_2$ needed for transport and storage are estimated to be high. However, post-combustion processes exhibit lower fuel costs and capital (€/ MWh) than those of oxy-fuel [6].

### 2.1.3 Oxy-fuel combustion capture

Oxy-fuel combustion can be applied in power generation related to fossil-fuelled plants, cement production and the iron and steel industry [7]. In contrast to standard combustion using air, fuel combustion occurs in an oxygen-enriched (i.e. nitrogen-depleted) environment, burning fuel with nearly pure oxygen (>95%) mixed with recycled flue gas, consisting mainly of $CO_2$ and $H_2O$. The substitution of $N_2$ by $CO_2$ and $H_2O$ leads to the reduction of the flame speed, resulting in poor combustion performance. High-temperature materials are thus required. The residual gases contain a $CO_2$ concentration of 80%–98%, depending on the fuel used [8]. The main attraction of oxy-fuel combustion is that there is no need for chemicals for $CO_2$ separation and thus no environmental costs related to their use. Further developments are required in oxygen separation from air; to decrease the energy costs and the amounts of pure oxygen that are needed. In addition, the environmental impacts related to production are high due to the high energy consumption required, whereas the costs are further increased compared with a plant without CCS [9,10].

## 2.2 $CO_2$ UTILISATION

The term $CO_2$ utilisation describes the conversion of $CO_2$ into new marketable products. CCU technologies are primarily assessed on their potential to contribute to the goals of Paris Agreement [11]. Carbon capture and utilisation (CCU) can supply products (such as polymers, fuels and methanol) that sequester $CO_2$, perhaps for a few seasons or maybe for only some weeks or days [12]. This process combines industrial development (production of industrial products) with mitigation of climate change (reduction of $CO_2$ emissions in the atmosphere). $CO_2$ is used as a carbon source in the industrial sector, providing the potential for both mitigation of climate change and for industrial development.

$CO_2$ capture and utilisation (CCU) is an old concept, which was initially implemented to produce urea. At the current stage, there are many available CCU methods, including catalytic reduction and direct addition [12]. These products can be commercially utilised, either directly or after conversion [13]. Examples of direct utilisation include use in the food and drink industry, as well as conversion of $CO_2$ into chemicals or fuels. Although $CO_2$ can serve as a petrochemical alternative in the production of chemicals and fuels, it presents significant drawbacks associated with the high energy consumption required for its conversion [3]. The two most important concerns regarding $CO_2$ utilisation are: (1) limited duration of storage and (2) the current scale and immaturity of the technology.

## 2.3 $CO_2$ GEOLOGICAL STORAGE

Geological storage (Fig. 2) is the most viable method for storing large quantities (up to several tens of millions of tonnes) of trapped $CO_2$ [14]. It has been estimated that the $CO_2$ storage potential can reach 400–10,000 Gt for deep saline aquifers [15]. Geological parameters that must be taken into consideration before the implementation of $CO_2$ storage methods include the porosity-permeability and the thickness and depth of the reservoir formation, as well as the presence of a cap rock with good sealing properties [14]. Additional factors that substantially affect the implementation of geological storage methods include safety issues ($CO_2$ leakage) and socio-economic conditions such as social acceptance and cost parameters [14].

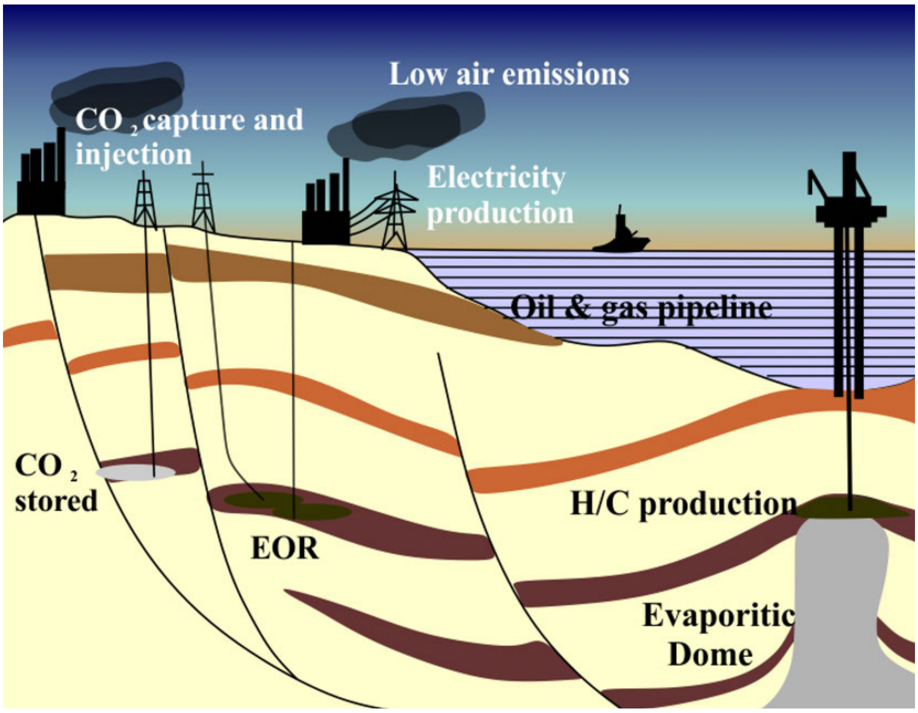


**Figure 2.** Overview of geological storage and enhanced oil and gas recovery cases (Adapted from [16])

## 2.3.1 Deep saline formations

Saline formations are deep water-saturated sedimentary rocks with high concentrations of dissolved salts [3]. Although they are abundant in water, these formations are considered unsuitable for human health and agricultural activities [3,17,18]. $CO_2$ can be injected and dissolved into the formation water providing the potential for long-term carbon storage through mineralisation. Potential risks and problems are well known and manageable [18]. The most common issue that must be considered prior to $CO_2$ storage concerns the possibility of $CO_2$ and/or brine migration into groundwater aquifers or into the atmosphere. These problems can be caused by the acidic water pH (due to dissolution of the injected $CO_2$), with significant impacts on water quality, rock stability and well-cement properties [18]. In addition, hydrated $CO_2$ (due to high $H_2O$ fractionation) is more corrosive to metal piping than dry $CO_2$ [17]. Thermo-mechanical effects can be caused by temperature differences between the injected $CO_2$

and water, as well as by thermal stress processes [18]. However, risks can be substantially mitigated by the following measures: a) conducting detailed geological studies for identification of potential fault zones in the well domain, b) keeping the injection pressure below critical values and c) conducting numerical simulations with all available data on geological features and leakage risks [18].

### 2.3.2 Abandoned coal mines and salt caverns

$CO_2$ storage in abandoned coal mines is a sustainable option due to the higher permeability and injectivity of already mined coal seams in comparison to unmineable ones. $CO_2$ storage in abandoned coal mines is accomplished through the following physical mechanisms [19]: a) adsorption on the remaining coal, b) solution in the mine water and c) compression in the empty space of the mine. Key factors that must be considered prior to the implementation of $CO_2$ storage include [20,21] a) the absence of lateral communication with other mines (to avoid gas migration) and/or between the mine reservoir and the surface (to avoid gas leakage), b) low water influx to prevent potential gas leakage and c) a minimum depth of 500 m for the mine top. However, sequestration of $CO_2$ in abandoned coal mines presents significant difficulties associated with structural defects such as faults or effects associated with the mining activity, as well as water influx problems. To prevent water influx the reservoir pressure must be 30% greater than the hydrostatic pressure [21]. Thus, risk factor assessments must be conducted prior to the implementation of $CO_2$ injection into abandoned coal mines [22].

The term salt cavern refers to artificial underground cavities resulting from drilling processes. Drilling wells pump water to the salt formation, creating a controlled dissolution process of the salt-rock. The dissolved salt returns to the surface in the form of brine. In some cases, the geometrical volume of a salt cavern reaches up to 1,000,000 $m^3$ or more [23]. Salt caverns exhibit significant advantages for implementation of $CO_2$ storage such as their high sequestration efficiency and high filling rate. Concerns regarding the storage of $CO_2$ in salt caverns are associated with their depth and their low capacity [24], as well as $CO_2$ containment. Hence, parameters that must be considered for long-term $CO_2$ storage in salt caverns are [25] a) salt creep, b) compressibility of $CO_2$, c) $CO_2$ leakage from caverns and d) $CO_2$ leakage along the wells.

### 2.3.3 Depleted hydrocarbon fields

In depleted hydrocarbon fields, it is possible to increase reservoir pressure again by replacing formation water by $CO_2$. Depleted hydrocarbon fields provide the potential for long-term and cost-effective (low operational cost) $CO_2$ storage. These structures have well known physical parameters such as porosity, permeability and storage capacity. In addition, significant existing equipment is already in place and can be re-used for $CO_2$ storage. The potential additional recovery of oil and gas (EOR-EGR) can further balance the operational costs. The documented history of hydrocarbon fields proves that they have stored hydrocarbon for a long geological period, which remarkably reduces uncertainties regarding $CO_2$ containment and storage capacity [26]. However, many research studies point out that there is a leakage risk due to seal penetration by legacy wells, casing vent flow, tubing failures, cement degradation and wellbore properties [27].

#### 2.3.3.1 Enhanced oil recovery (EOR)

$CO_2$-enhanced oil recovery ($CO_2$-EOR; Fig. 3) has emerged as a major option for productively utilising $CO_2$ emissions captured from industrial plants. Oil fields can provide secure, well characterised sites for storing $CO_2$, while at the same time providing revenues to offset the costs of capturing $CO_2$. Economic benefits associated with $CO_2$ –EOR methods include the extension of the function of significant oil fields for long periods, even over a decade [28]. However, this technology is less relevant in Europe than in the US or Middle East.

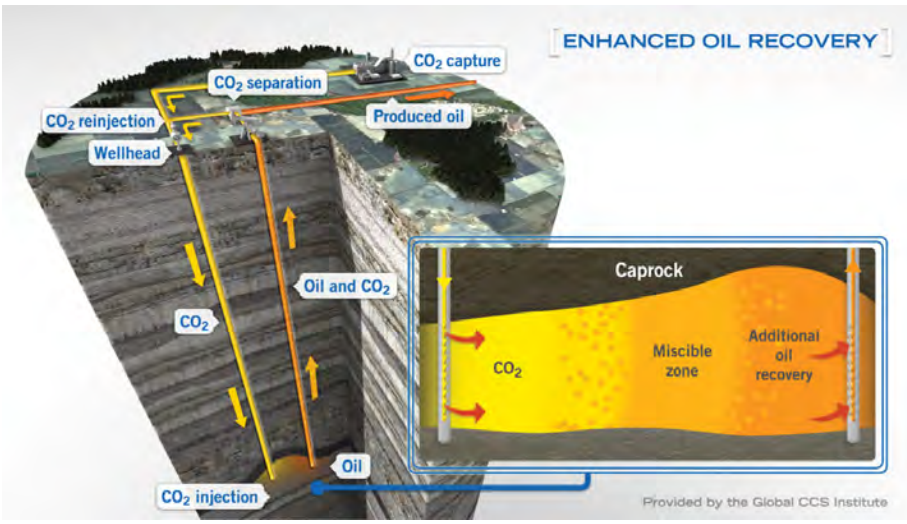


**Figure 3.** Schematic illustration of enhanced oil recovery and $CO_2$ storage [29]

### 2.3.3.2 Enhanced gas recovery (EGR)

The term enhanced gas recovery (EGR) describes the recovery process of natural gas from hydrocarbon reservoirs. This gas can be contained within sands, shales and coal seams [30]. EGR provides the potential for storage of injected $CO_2$, which further accelerates gas recovery by keeping a constant reservoir pressure and increasing the sweep efficiency [31]. Recent studies indicate that EGR will potentially favour countries with limited oil fields but large gas reservoirs [32]. The major risk concerning the implementation of EGR techniques is associated with the potential mixing of $CO_2$ with natural gas. This can significantly affect the gas quality and cause natural gas contamination. $CO_2$ presents high dissolution in formation water, density and injectivity to methane. These features potentially affect the efficiency of $CO_2$-EGR [32]. In general, the efficiency of $CO_2$-EGR depends on the operating conditions, reservoir properties, the type and length of the injection wells (horizontal vs. vertical), as well as the physicochemical interactions that take place between different phases [33].

## 2.3.4 Coal Seams

In most cases, coal seams suitable for $CO_2$ storage occur at depths greater than 800 m, corresponding to temperature and pressure (critical) conditions that exceed 31°C and 7.4 MPa, respectively [34]. Issues that must be considered prior to injection of $CO_2$ into coal seams concern the upward and/or lateral migration of $CO_2$ into adjacent aquifers. In general risks tend to reduce with the increasing depth of the coal seam [35]. Additional concerns are associated with the swelling effects of the coal seam during $CO_2$ injection. Swelling is substantially reduced by temperature increase (reduced sorption capacity of coal), whereas it is increased by high injection pressures that significantly affect the coal stress and pore space [35]. Physical parameters of coal seams, including coal structure (intact and tectonic coals), significantly affect their porosity, which determines the amounts of gas desorption in long-term storage [34,36].

### 2.3.5 Mineralisation

Mineralisation is an accelerated form of weathering of naturally occurring silicate rocks and has been proposed as an alternative approach for $CO_2$ sequestration. The procedure involves the dissolution of the captured $CO_2$ into water during the injection into the rock via an injection well. In this process the injected $CO_2$ bubbles are dissolved in water, avoiding the $CO_2$-buoyancy and mitigating risks associated with $CO_2$ migration into adjacent permeable formations [37]. In mineral carbonation, acidic water derived from the dissolved $CO_2$ reacts with the metal oxides (such as MgO or CaO) of the reservoir rock to form carbonates in a chemical process. Magnesium and calcium are normally found in nature in the form of silicate minerals such as serpentine, olivine and wollastonite. Rock types suitable for implementation of $CO_2$ mineralisation include basalts, ultramafic rocks and sandstones. Basaltic rocks present the appropriate physicochemical properties for $CO_2$-mineralisation due to their abundance of Ca-FeMg-bearing minerals [38]. In basalt, low alteration grade, silica undersaturated composition, abundance of Ca-bearing minerals and high porosity are among the most important parameters for implementing long-term and safe $CO_2$ storage scenarios [38]. Regarding sandstones, their widespread distribution, physicochemical properties (permeability and pH buffer capacity [39], coupled with their mineralogical composition (plagioclase, alkali-feldspars, calcite, quartz, clay minerals) favour their implementation in $CO_2$-mineralisation. In the case of serpentinites, the reaction of $CO_2$ with the abundant Mg-bearing silicate minerals of the ultramafic rock provides the potential to produce large amounts of Mg-carbonate minerals such as magnesite [40,41].

Carbon mineralisation also provides the potential for long-term storage of large $CO_2$ volumes of $CO_2$ [37,42]. Risks associated with carbon storage through mineralisation mostly concern potential contamination of underground water due to the dissolution of toxic metals (such as Al and Cr) from the reservoir rocks [37]. Thus modelling simulations and monitoring methods are measures that have to be implemented in order to mitigate risks.

# 3. CCS PROJECTS

There is a growing presence of CCS on the global scale. Based on the Global Status of CCS report, 51 large scale projects were active in 2019 [43]. Of these projects, 19 were in operation, 4 under construction, 10 in advanced development, and 18 in early development [43]. The facilities in operation and construction have the capacity to capture and permanently store around 40 million tonnes of $CO_2$ every year [43].

North America has taken the lead in CCS technologies, possessing 13 of the world's large-scale operating CCS facilities. The Great Plains Synfuels plant in North Dakota captures $CO_2$ from the coal (lignite) gasification process, producing syngas (hydrogen and carbon monoxide) for energy use and chemical production. It has delivered around 38 million tonnes of $CO_2$ for EOR in the Weyburn and Midale fields in Canada since 2000. The Shute Creek gas processing plant in Wyoming, with a $CO_2$ capture capacity of 7 Mtpa (million tonnes per annum), has cumulatively captured more than 100 million tonnes of $CO_2$ from natural gas processing operations for use in enhanced oil recovery. The Alberta Carbon Trunk Line (ACTL), a 240-kilometre $CO_2$ pipeline that began operation in June 2020 and offers $CO_2$ transport services to industry in Alberta, Canada. The North West Redwater Partnership's Sturgeon refinery and an oil refinery and fertiliser plant jointly supply around 1.6 Mtpa of $CO_2$ via the pipeline to EOR operations in central Alberta.

The off-shore $CO_2$-EOR facility of Petrobas is located in Brazil. In 2019 Petrobas managed to capture 10 million tonnes of $CO_2$, aiming to reach the target of storing more than 40 million tonnes of $CO_2$ until 2025 [43].

There are two large-scale CCS facilities that are currently operating in Norway, capturing and storing 1.7 million tons of $CO_2$ per annum. The Sleipner project was the first commercial-scale project for off-shore geological $CO_2$ storage, operating since 1996 and storing around 1 Mpta of $CO_2$ per year [43]. More recently in Norway the Snohvit gas project, provided offshore injection into the Tubaen formation and now into the Sto formation [43]. CarbFix is a large-scale CCS project that was initialised in Iceland during 2007. Its concept includes the implementation of $CO_2$-$H_2S$ injection (produced by an adjacent geothermal power plant) into basaltic rocks. Estimates indicate that during 2017 10,000 tonnes of $CO_2$ were injected into basalts. Other injection operations include the In Salah injection in Algeria, which was operational from 2004 to 2011 and injected approximately 0.5 Mt $CO_2$ a year.

China leads CCS activity in Asia with one large-scale facility in operation, two in construction and five in early development [43]. Japan has currently five pilot and demonstration CCS facilities in operation. In the United Arab Emirates, the Abu Dhabi National Oil Company (ADNOC) is developing its second CCUS facility aiming to capture 1.9 to 2.3 Mtpa of $CO_2$ using EOR [43].

$CO_2$ injection commenced at the Gorgon natural gas processing plant on Barrow Island off the coast of Western Australia in August 2019. This will be the world's largest dedicated geological $CO_2$ storage in terms of full capacity, storing up to 4.0 Mtpa $CO_2$ [44].

# 4. GEOLOGY AND CCS

The role of geology in the implementation of CCS activities is crucial. Different disciplines of geology contribute to CCS and to $CO_2$ storage in general. Geological mapping, field geology, structural geology, geophysics, geochemistry, mineralogy, oil and gas drilling and geological modelling are some of the disciplines required for CCS. The exploitation of the geological site for potential storage of $CO_2$ starts with an examination of the geological background of the suggested area by geologists. In case of existing information, such as for oil and gas fields, further examination of the storage site and further data are required.

Prior to $CO_2$ injection, a series of baselines should be observed to identify the dynamic nature of the local environment and subsurface parameters. The data acquisition programme should be tailored to make best use of the wellbore construction phase and consider the proposed injection profile of the sequestration project. Consideration should be given to installation of fibre optic and electroresistivity tomography cables behind the casing during wellbore construction for stress/strain and acoustic measurements [45] and imaging sub-surface structures and localised matrix fluid changes. A programme of environmental monitoring including soil gas, water sampling, wellbore sampling and passive seismic should be designed specifically for the injection area and wellbores with periodic reviews [46]. The data obtained will be used to pattern match against the predictive models and provide correction where needed.

In particular, geological scientific fields that significantly contribute to the development and implementation of CCS are the following: a) geological mapping, which is requested for new areas or areas with a low degree of geological information, b) petrological, mineralogical and geochemical studies that investigate the physicochemical features (mineralogical-chemical composition, porosity and permeability) of the potential storage formations, c) geophysics and seismic data, when available, d) deep drilling data to gain accurate information on the $CO_2$ potential storage site, and e) geological modelling, which is an essential part of the assessment of the area.

The role of geologists is not restricted to the assessment of a potential region to serve as a CCS site. This contribution should be integrated with the rest of the techniques involved in this industry, such as the engineering and economic sides of building CCS projects, to ensure optimal development. A key aspect here is communicating to other disciplines, which needs to be implemented from the planning phase. Geologists also contribute with their knowledge on the monitoring of $CO_2$, in order to ensure the safety of the storage complex. Safety and risk assessments are always necessary to evaluate potential sources of $CO_2$ leakage or seepage away from the storage complex, in order to plan remediation options. $CO_2$ is likely to remain stored for millions of years. Therefore, the safety of subsurface storage can be supported by the several known natural accumulations of $CO_2$, which can be used to gather further knowledge on containment conditions.

# REFERENCES


1. European Commission, 2019. COM/2019/640 final. Communication from the Commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions. The European Green Deal.
2. International Energy Agency, 2019. Tracking Clean Energy Progress, accessed from https://www.iea.org/topics/tracking-clean-energy-progress
3. Chiotis, E., 2018. Climate Changes in the Holocene: Impacts and Human Adaptation. Boca Raton: CRC Press, Taylor & Francis Group.
4. Blomen, E.; Hendriks, C.; Neele, F. 2009. Capture technologies: Improvements and promising developments. Energy Procedia, 1, 1505-1512. https://doi.org/10.1016/j.egypro.2009.01.197.
5. Global Carbon Capture and Storage Institute. 2012. $CO_2$ Capture Technologies. Canberra, Australia.
6. ZEP. 2011. The costs of $CO_2$ capture, transport and storage: Post-demonstration CCS in the EU. European Technology Platform for Zero Emission Fossil Fuel Power Plants. Zero Emissions Platform. 50 pages. Available at: https://www.globalccsinstitute.com/archive/hub/publications/17011/costs-co2-capture-transport-and-storage.pdf
7. Cuellar-Franca, R.M.; Azapagic, A. 2015. Carbon capture, storage and utilization technologies: A critical analysis and comparison of their life cycle environmental impacts. Journal of $CO_2$ Utilization, 9, 82-102. https://doi.org/10.1016/j.jcou.2014.12.001
8. Zero Emissions Resource Organization. http://www.zeroCO2.no
9. Low, T.B.; Zhao, L.; Merkel, T.; Weber, M.; Stolten, D. 2013. A parametric study of the impact of membrane materials and process operating conditions on carbon capture from humidified flue gas. Journal of Membrane Science, 431, 139-155. https://doi.org/10.1016/j.memsci.2012.12.014
10. Powell, C.E.; Qiao, G.G. Polymeric. 2006. $CO_2/N_2$ gas separation membranes for the capture of carbon dioxide from power plant flue gases. Journal of Membrane Science, 279, 1-49. https://doi.org/10.1016/j.memsci.2005.12.062
11. Bujnicki, J.; Dykstra, P.; Fortunato, E.; Heuer, R.-D.; Keskitalo, C.; Nurse, P. 2018. Novel Carbon Capture and Utilisation Technologies, Scientific Advice Mechanism (SAM), European Commission.
12. Armstrong, K.; Styring, P. 2015. Assessing the potential of utilization and storage strategies for post-combustion CO2 emissions reduction. Frontiers in Energy Research, 3, Article 8, 9 pages. https://doi.org/10.3389/fenrg.2015.00008
13. European Commission. Carbon Capture and Utilization. Website, Smart Specialisation Platform. https://s3platform.jrc.ec.europa.eu/carbon-capture-and-utilization (last accessed: July 2020).

14. Leung, D.Y.C., G. Caramanna, and Maroto-Valer, M. 2014. An overview of current status of carbon dioxide capture and storage technologies. Renewable and Sustainable Energy Reviews, 39: 426-443. https://doi.org/10.1016/j.rser.2014.07.093

15. IEA. 2004. Improvements in power generation with post-combustion capture of $CO_2$. International Energy Agency Report – IEA Greenhouse Gas R&D Programmes, PH4/33.

16. Koukouzas, N.; Gemeni, V.; Tsoukalas, N. 2018. Perspectives of clean energy and carbon dioxide capture, storage and utilization: Impacts and human adaptation. In Chiotis, E. (Ed.), Climate Changes in the Holocene: Impacts and Human Adaptation. pp. 373-386. Boca Raton: CRC Press.

17. Eke, P.E.; Naylor, M.; Haszeldine, S.; Curtis, A. 2011. $CO_2$-Brine Surface Dissolution and Injection: $CO_2$ Storage Enhancement. Society of Petroleum Engineers, 6, 1. SPE-124711-PA. https://doi.org/10.2118/124711-PA

18. Celia, M.A.; Bachu, S.; Nordbotten, J.M.; Bandilla, K.W. 2015. Status of $CO_2$ storage in deep saline aquifers with emphasis on modeling approaches and practical simulations. Water Resources Research, 51, 6846-6892. https://doi.org/10.1002/2015WR017609

19. Jalili, P.; Saydam, S.; Cinar, Y. 2011. $CO_2$ Storage in Abandoned Coal Mines, 11th Underground Coal Operators' Conference, University of Wollongong & the Australasian Institute of Mining and Metallurgy, pp. 355-360.

20. Houtrelle, S., 1999. Stockage de gaz naturel en mine de charbon abandonnée. Approche géologique du site d'Anderlues. Master thesis, Faculté Polytechnique de Mons.

21. Piessens, K.; Dusar, M. 2003. $CO_2$-sequestration in abandoned coal mines. In: Proceedings of the 2003 International Coalbed Methane Symposium, University of Alabama, Tuscaloosa, Alabama, Paper No. 0346, 11 p.

22. Busch, A.; Krooss, B.M.; Kempka, T.; Waschbüsch, M.; Fernández-Steeger, T.; Schlüter, R. 2009. Carbon dioxide storage in abandoned coal mines. In M. Grobe, J. C. Pashin, and R. L. Dodge, (eds.), Carbon Dioxide Sequestration in Geological Media: State of the Science. AAPG Studies in Geology vol. 59, pp. 643–653. Tulsa, OK: American Association of Petroleum Geologists.

23. Letcher, T.M. 2016. (ed.). Storing Energy: With Special Reference to Renewable Energy Sources. Amsterdam and New York: Elsevier.

24. Bennaceur, K. 2014. $CO_2$ Capture and Sequestration, In T.M. Letcher (ed.), Future Energy: Improved, Sustainable and Clean Options for our Planet (2nd edn.). Amsterdam: Elsevier Science. pp. 583-611.

25. Xie, L.Z.; Zhou, H.; Xie, H. 2009. Research advance of $CO_2$ storage in rock salt caverns. Yantu Lixue /Rock and Soil Mechanics, 30(11), 3324-3330

26. Hannis, S.; Lu, J.; Chadwick, A.; Hovorka, S.; Kirk, K.; Romanak, K.; Pearce, J. 2017. $CO_2$ storage in depleted or depleting oil and gas fields: What can we learn from existing projects? Energy Procedia 114, 5680-5690. https://doi.org/10.1016/j.egypro.2017.03.1707

27. Raza, A.; Gholami, R.; Rezaee, R.; Bing, C.H.; Nagarajan, R.; Hamid, M.A. 2017. Well selection in depleted oil and gas fields for a safe $CO_2$ storage practice: A case study from Malaysia. Petroleum, 3(1), 167-177. https://doi.org/10.1016/j.petlm.2016.10.003

28. CEPAC 2014. Brazilian Atlas of $CO_2$ Capture and Geological Storage. Center of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage.

29. Global CCS Institute. Storing carbon dioxide. https://www.globalccsinstitute.com/why-ccs/what-is-ccs/storage (last accessed Apr. 2020)

30. Fanchi, R.J. 2018 Principles of Applied Reservoir Simulation. Houston, TX: Gulf Professional Publishing.

31. Goodwin, A.R.H.; Pirolli, L.; May, E.E.; Marsh, K.N. 2014. Conventional oil and gas, fossil fuels (energy resources). In T.M. Letcher (ed.), Future Energy: Improved Sustainable and Clean Options for our Planet, 2nd ed. Amsterdam: Elsevier. pp. 19-52.

32. Moghadasi, R.; Rostami, A.; Hemmati-Sarapardeh, A. 2018. Enhanced oil recovery using $CO_2$. In: A. Bahador (ed.), Fundamentals of Enhanced Oil and Gas Recovery from Conventional and Unconventional Reservoirs. Amsterdam: Elsevier. pp. 61-99. https://doi.org/10.1016/B978-0-12-813027-8.00003-5

33. Jikich, S.; Sams, W.; Bromhal, G.; Smith. D.; Pope, G.; Gupta, N. 2003. Carbon dioxide injectivity in brine reservoirs using horizontal wells. Proceedings, Second Annual Conference on $CO_2$ Sequestration, May 5-9, Alexandria, VA.

34. Su, E.; Liang, Y.; Li, L.; Zou, Q.; Niu, F. 2018. Laboratory study on changes in the pore structures and gas desorption properties of intact and tectonic coals after supercritical CO2 treatment: Implications for coalbed methane recovery. Energies, 11(12), 3419. https://doi.org/10.3390/en11123419

35. Ranathunga, A.S.; Ranjith, P.G.; Perera, M.S.A. 2017. Challenges and issues for $CO_2$ storage in deep coal seams. In X-T. Feng (Ed.), Rock Mechanics and Engineering, 4: Excavation, Support and Monitoring (pp. 87-119). Rock Mechanics and Engineering Series, Vol. 4). Boca Raton: CRC Press. https://doi.org/10.1201/b20406

36. Pan, J.; Zhao, Y.; Hou, Q.; Jin, Y. 2015. Nanoscale pores in coal related to coal rank and deformation structures. Transport in Porous Media, 107, 543-554. https://doi.org/10.1007/s11242-015-0453-5

37. Snæbjörnsdóttir, S.Ó.; Wiese, F.; Fridriksson, T.; Ármansson, H.; Einarsson, G.M.; Gislason, S.R. 2014. CO2 storage potential of basaltic rocks in Iceland and the oceanic ridges. Energy Procedia 63, 4585–4600. https://doi.org/10.1016/j.egypro.2014.11.491

38. Koukouzas, N.; Koutsovitis, P.; Tyrologou, P.; Karkalis, C.; Arvanitis, A. 2019. Potential for Mineral Carbonation of $CO_2$ in Pleistocene Basaltic Rocks in Volos Region (Central Greece). Minerals, 9, 627. https://doi.org/10.3390/min9100627

39. Koukouzas, N.; Kypritidou, Z.; Purser, G.; Rochelle, C.A.; Vasilatos, C.; Tsoukalas, N. 2018. Assessment of the impact of $CO_2$ storage in sandstone formations by experimental studies and geochemical modeling: The case of the Mesohellenic Trough, NW Greece. International Journal of Greenhouse Gas Control, 71, 116-132. https://doi.org/10.1016/j.ijggc.2018.01.016

40. Zevenhoven, R.; Eloneva, S.; Teir, S. 2006. Chemical fixation of $CO_2$ in carbonates: Routes to valuable products and long-term storage. Catalysis Today, 115, 73-79. https://doi.org/10.1016/j.cattod.2006.02.020

41. Boschi, C.; Dini, A.; Dallai, L.; Ruggieri, G.; Gianelli, G. 2009. Enhanced $CO_2$-mineral sequestration by cyclic hydraulic fracturing and Si-rich fluid infiltration into serpentinites at Malentrata (Tuscany, Italy). Chemical Geology, 265, 209-226. https://doi.org/10.1016/j.chemgeo.2009.03.016

42. Gislason, S.R.; Oelkers, E.H. 2014. Carbon Storage in Basalt. Science, 344, 373−374. https://doi.org/10.1126/science.1250828

43. Page, B.; Turan, G.; Zapantis, A.; Beck, L.; Consoli, C.; Havercroft, I.; Liu, H.; Loria, P.; Schneider, A.; Tamme, E.; Townsend, A.; Temple-Smith, L.; Rassool, D.; Zhang, T. 2019. Global Status of CCS. Targeting Climate Change. Global CCS Institute.

44. Global CCS Institute. 2018. The Global Status of CCS Report 2018, Melbourne, Australia. Available from: https://www.globalccsinstitute.com/resources/global-status-report/

45. Bergmann, P.; Schmidt-Hattenberger, C.; Kiessling, D.; Rücker, C.; Labitzke, T.; Henninges, J.; Baumann, G.; Schütt, H. 2012. Surface-downhole electrical resistivity tomography applied to monitoring of CO2 storage at Ketzin, Germany. Geophysics, 77(6), 253-B267.

46. Rütters, H.; Möller, I.; May, F.; Flornes, K.; Hladik, V.; Arvanitis, A.; Gülec, N.; Bakiler, C.; Dudu, A.; Kucharic, L.; Juhojuntti, N.; Shogenova, A.; Georgiev, G. 2013. State of the Art of Monitoring Methods to evaluate CO2 Storage Site Performance. CGS Europe Report No D3.3, Korre, A.; Stead, R.; Jensen, N.B. (Eds.) 2013, p. 109.

**About EFG:** The European Federation of Geologists is a non-governmental organisation that was established in 1980 and includes today 27 national association members. EFG is a professional organisation whose main aims are to contribute to a safer and more sustainable use of the natural environment, to protect and inform the public and to promote a more responsible exploitation of natural resources. EFG's members are national associations whose principal objectives are based in similar aims. The guidelines to achieve these aims are the promotion of excellence in the application of geology and the creation of public awareness of the importance of geoscience for the society.

**About the EFG Panel of Experts on $CO_2$ Geological Storage:** This panel of experts has been created in October 2008. Before it was part of the Panel of Experts on Geothermal Energy and $CO_2$ Sequestration. The PE on $CO_2$ Geological Storage supports the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP).

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