

*Review paper*

## **CRITERIA FOR CO<sub>2</sub> STORAGE IN GEOLOGICAL FORMATIONS**

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**Abstract:** CO<sub>2</sub> storage in geological formations represents today one of the main new technological solutions for CO<sub>2</sub> emission mitigation. Carbon capture and storage technology (CCS) includes capture of anthropogenic CO<sub>2</sub> from various emitters, its transportation and injection in different types of geological formations such as: depleted oil and gas reservoirs, saline formations, unmined coal beds, partially depleted oil reservoirs for enhanced oil recovery (EOR–CO<sub>2</sub> method) and others. The analysis of numerous criteria that are determining the success of process implementation from a technical, safety, ecological and economic point of view is necessary for considering the optimal CO<sub>2</sub> geological storage option.

In this paper, an overview of CO<sub>2</sub> geological storage types is presented, with an emphasis on criteria for selection of most adequate CO<sub>2</sub> storage option. They include geological, physical, thermodynamic, hydrodynamic, techno economic, social criteria, as well as the regulatory issues that are key factors for CCS technology development and further deployment.

**Keywords:** CO<sub>2</sub>, emission mitigation, geological storage, criteria

### **1 INTRODUCTION**

Since the beginning of industrial revolution in 18th century until to date, the concentration of greenhouse gases in the atmosphere has a trend of continuous growth. It is known that the largest impact on the climate change has a CO<sub>2</sub> emission, with a share of 80% in the total emission of greenhouse gases (EPA, 2018). CO<sub>2</sub> is the fossil fuel combustion product during the process of electricity generation, industrial activities and transport.

One of the recent solutions for CO<sub>2</sub> emission mitigation is CO<sub>2</sub> geological storage. This option includes capture of anthropogenic CO<sub>2</sub>, its transportation and injection in different types of geological formations such as: depleted oil and gas reservoirs, saline formations, unmined coal beds, injection in partially depleted oil reservoirs for enhanced oil recovery (EOR–CO<sub>2</sub> method), and others (salt caverns, basalt formations, shales). It is considered that CO<sub>2</sub> emission by implementation of CCS technology could be decreased by 2050 for 20% (Aminu et al, 2017). Besides that, main factors that affect lowering global CO<sub>2</sub> emission are: increasing energy efficiency (less emission for 36%), use of renewable

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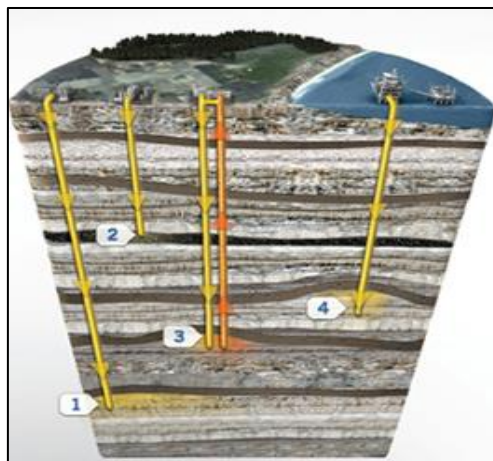
resource (less emission for 21%), nuclear energy (less emission for 6%) and using the natural gas instead coal would reduce emission by 18% (IEA, 2008).

In comparison with other types of geological formations, it is considered that the most suitable formation for storage CO<sub>2</sub> are depleted oil and gas reservoirs or partially depleted oil reservoirs where CO<sub>2</sub> is injected for enhanced oil recovery (EOR–CO<sub>2</sub> method). Main reasons for that are: structure of oil and gas reservoirs as an oil or gas-bearing accumulation is safe for CO<sub>2</sub> storage, a long-term exploitation period implies availability of sufficient reservoir data, i.e. well knowing of the future storage characteristics, and presence of needed infrastructure (Aminu et al, 2017).

In this paper are presented types of CO<sub>2</sub> geological storage with emphasis on criteria for selection of optimal CO<sub>2</sub> storage option. They include geological, thermodynamic, hydrodynamic, techno-economic, social criteria as well as regulatory issues that are the key factors for CCS technology development and further deployment.

## 2 GEOLOGICAL STORAGE OF CARBON DIOXIDE

CO<sub>2</sub> storage in geological formations in relation to other storage options (oceanic storage and carbonation) is an optimal solution from an economic, safety and environmental protection aspect. Geological formations that ensure a safe storage of CO<sub>2</sub> over a long period of time are primarily: depleted oil and gas reservoirs, unmined coal beds and saline formations. A certain amount of CO<sub>2</sub> can be stored during the CO<sub>2</sub> injection process for increasing oil recovery (EOR-CO<sub>2</sub>). Also, the potential storages of CO<sub>2</sub> are: salt caverns, basalt formations, and oil or gas rich shale. The possibilities of their application for these purposes are in the research phase for now. Figure 1. shows the types of CO<sub>2</sub> geological storages.



**Figure 1** CO<sub>2</sub> geological storage options: 1. Saline formations, 2. Unmined coal seams  
3.EOR projects 4. Depleted oil and gas reservoirs (Global CCS Institute, 2015)

Current worldwide CO<sub>2</sub> storage projects in geological formations are given in figure 2. In Europe, the first demonstration project of CO<sub>2</sub> injection into offshore saline formation, Sleipner in Norway, started 1996, and more than 17 Mt CO<sub>2</sub> has been injected (IEA, 2017). In addition, the largest ongoing projects are In Salah, Algeria, where 1 Mt CO<sub>2</sub> is injected per year into onshore saline aquifer, as well as Weyburn in Canada, that is combination of CO<sub>2</sub> storage and enhanced oil recovery. In this oil field, 1,8 Mt CO<sub>2</sub> is injected per year and CO<sub>2</sub> source is coal gasification facility in North Dakota over 300 km away (Franklin, 2009).



**Figure 2** Current worldwide CO<sub>2</sub> geological storage projects (Franklin, 2009)

### *Depleted oil and gas reservoirs*

Comparing to the other types of geological formations, CO<sub>2</sub> storage in depleted hydrocarbon reservoirs is considered as the most suitable option.

The main reason for this is the presence of least risk and uncertainty for possible leakage of CO<sub>2</sub> due to a high degree of reservoir exploration, long period of production that means large number of reservoir data is collected, as well as an available production history that enables correct storage capacity estimate.

The presence of infrastructure is very important, i.e. injection wells and surface facilities, since that significantly reduces storage costs. Possible CO<sub>2</sub> migration paths to the surface at this type of storage could be many existing wells. The estimated storage capacity varies between 675 and 900 Gt CO<sub>2</sub> (Global CCS Institute, 2014),

### *Unmined coal seams*

The possibility of storage in unmined coal seams is functioning at the principle of CO<sub>2</sub> adsorption at the coal surface and in fractures, where the methane is recovered because of CO<sub>2</sub> higher adsorption capacity compared to methane (IEAGHG, 2007). Besides storage, this method is at the same time an enhanced coalbed methane recovery (ECBM).

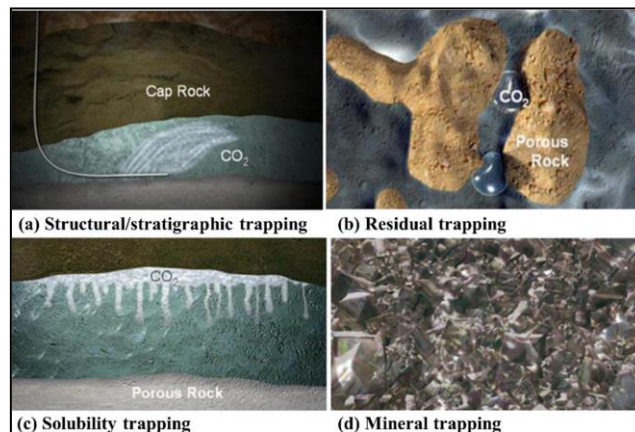
The estimated storage capacity range is 3-200 Gt CO<sub>2</sub> (Cook, 2012).

### *Saline aquifers*

Saline aquifers in comparison with other types of geological formations have the largest potential storage capacity, and for this reason they are considered very important. The lack of CO<sub>2</sub> storage in aquifers is that they have not been explored in detail, and there are no built infrastructure (injection wells and pipelines). Storage in these formations requires large investments to minimize the possible risks of CO<sub>2</sub> leakage.

The trapping mechanisms such as structural trapping, residual trapping solubility and mineral trapping occur in different periods of time and increase storage safety, figure 3 (Aminu et al,2017; CGS Europe, n.d.).

The estimated storage capacity varies between 1 000 and 10 000 Gt CO<sub>2</sub> (Cook, 2012).



**Figure 3** Trapping mechanisms in saline aquifers for safe CO<sub>2</sub> storage (Aminu et al, 2017)

***Enhanced oil recovery (EOR–CO<sub>2</sub> method)***

CO<sub>2</sub> injection method has been used in petroleum industry for over 40 years as an enhanced oil recovery method, but recently it represents a promising technology for mitigating greenhouse gas emission as a carbon storage method (Karović Maričić et al, 2015).

As in the case of depleted oil and gas reservoirs, knowing the reservoir and fluid characteristics, production history and presence of infrastructure, provides safe and relatively economical storage.

In comparison with depleted oil and gas reservoirs, storage capacity is significantly lower, because 30–40% of injected CO<sub>2</sub> is stored in pore space by dissolution in oil, while the rest of CO<sub>2</sub> is produced along with oil, separated from it on the surface and re-injected into the reservoir for enhancing oil recovery (IPCC, 2005).

In 2011, IEAGHG conducted a study on the assessment of CO<sub>2</sub> storage capacity and concluded that possible storage capacity during EOR–CO<sub>2</sub> process is around 370 billion tons (Kuuskraa et al, 2013).

***Salt caverns, basalts and oil or gas shale***

These types of formations have not been explored sufficiently yet, but it is considered that they have no significant storage potential. Basalts are interesting because the injected CO<sub>2</sub> could react with silicate minerals and become minerally accumulated. Salt caverns are more explored than basalts. The main problem for storing CO<sub>2</sub> in them is closing the caverns. Oil and gas shales are found around the world, but CO<sub>2</sub> storage options in these formations have not been developed yet, and it is considered that storage capacity may be significant (IPCC, 2005). At the present, there are no data on storage capacity in oil and gas shales.

**3 CRITERIA FOR CO<sub>2</sub> GEOLOGICAL STORAGE**

Before making a decision on geological storage of CO<sub>2</sub>, it is necessary to carry out an analysis of numerous criteria that are determining the success of process implementation from a technical, safety, ecological and economic point of view.

The criteria for CO<sub>2</sub> geological storage can be divided into the following groups (Bach, 2000; Llamas, 2014):

1. Geological
2. Physical (thermobaric conditions), thermodynamic and hydrodynamic
3. Techno-economic, social and regulatory

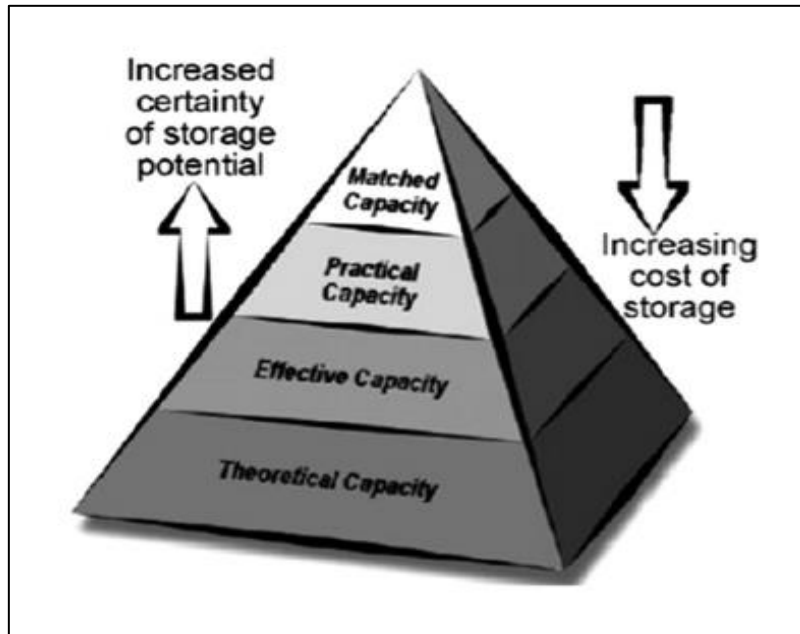
### 3.1 Geological criteria

The basic geological parameters that affect selection of potential formation-candidate for CO<sub>2</sub> storage are: type of basins i.e. reservoir, reservoir volume, porosity, permeability, depth, thickness, permeability of cap rocks, seismogenic potential of faults and stressed state of rock. The degree of basin exploration and hydrocarbon potential (if storage is considered in partially or fully depleted hydrocarbon reservoir) are also of great importance (Aminu et al, 2017).

The most appropriate types of basins for CO<sub>2</sub> storage are sedimentary ones where the most geological formations (hydrocarbons reservoirs, coal beds and saline aquifers-permeable rocks with pores filled with salt water) as the potential storage sites are located. As far as safety is concerned, CO<sub>2</sub> geological storage requires tectonically stable areas.

The pore space volume primarily determines the size of the storage capacity. Many methods have been developed for storage capacity estimate based on different parameters depending on the type of storage. For CO<sub>2</sub> storing in depleted oil or gas reservoirs or during EOR-CO<sub>2</sub> process, the following parameters are considered: values of original oil in place or gas in place (OOIP or OGIP) recoverable oil or gas reserves, reservoir pressure and temperature, reservoir rock volume, porosity, water saturation, potential water inflow, phase behavior of CO<sub>2</sub>, CO<sub>2</sub> solubility in water and possible spill point. For deep saline aquifers, besides aquifer characteristics, the significant parameters are water salinity, CO<sub>2</sub> solubility in water, as well as the presence of cap rocks' continuity. The most important parameters for coal beds are thickness and gas sorption capacity, and for estimating the storage capacity in the salt cavern are fracture threshold, stress state and the size of the cavern (Hsu, 2012; Bach, 2002).

Storage capacity is a complex parameter that depends on the above-mentioned parameters and on technical and economic factors. Taking account all these factors, the method for techno-economic estimate of hydrocarbon reservoirs and aquifers' capacity is defined by Carbon Sequestration Leadership Forum (CSLF, n.d.) that uses resource and reserve approach (Bach, 2007; CSLF, n.d.). The Carbon Sequestration Leadership Forum (CSLF, n.d.) is the international association of 24 countries and the European Commission that is engaged in the development and deployment of CCS technologies. In figure 4 is presented CSLF pyramidal classification that includes: theoretical, effective, practical and matched capacity.



**Figure 4** Techno-economic pyramid for CO<sub>2</sub> storage capacity (Zhao, 2014)

The theoretical capacity represents the total volume of the pore space where it is possible to inject CO<sub>2</sub> and this is the highest estimated value of the potential storage capacity. Its value corresponds to the OOIP or OGIP in case of storage in depleted oil and gas reservoirs. The effective capacity is part of the theoretical capacity, and it refers to a pore space that can be swept by injected CO<sub>2</sub>.

Its value corresponds to the recoverable oil and gas reserves for storage in depleted oil and gas reservoirs. For aquifers, effective capacity depends on the pore volume, CO<sub>2</sub> density and the aquifer characteristics.

Practical capacity estimate is based on the effective capacity value and certain economic and technical factors. The matched capacity, shown at the top of pyramid, has highest probability of estimate accuracy because it is determined on the basis of the largest number of data used in complex studies that include preliminary multicriterial analysis, laboratory analysis, integrated reservoir numerical modeling and implementation of CO<sub>2</sub> injection pilot test.

Optimal values of reservoir and fluid parameters for preliminary screening of possible CO<sub>2</sub> storing during the EOR- CO<sub>2</sub> process and in aquifers are given in Table 1 and 2. The reservoir parameters of the depleted hydrocarbon reservoirs as the potential storage, do not differ from the reservoir parameters of EOR- CO<sub>2</sub> process. In dependence whether

the oil displacement by injected CO<sub>2</sub> is realized in miscible or immiscible conditions in EOR-CO<sub>2</sub> process, favorable depth and temperature values are differentiated. Miscible CO<sub>2</sub>-oil process requires higher pressure values than minimum miscibility pressure, so that requires greater reservoir depth.

**Table 1** Optimal reservoir and fluid parameters for EOR -CO<sub>2</sub> (Terry, 2001)

	Value
Density, °API	>25
Viscosity, mPas	<12
Oil saturation, %	>30
Formation type	sandstone or carbonate
Net thickness, m	5-7,5
Permeability, 10 <sup>-15</sup> m <sup>2</sup>	non-critical
Depth, m	>600

**Table 2** Optimum reservoir and water parameters (Chadwick et al, 2008)

Reservoir and fluid parameters	
Depth, m	1000-2500
Thickness, m	>50
Porosity, %	>20
Permeability, mD	>300
Salinity, mg/l	>100 000

The properties of the aquifer cap rocks should provide "hermetic storage" that implies their lateral continuity, thickness greater than 100 m and the capillary entry pressure has to be significantly higher than the buoyancy force of the underlying CO<sub>2</sub> column (Chadwick et al, 2008).

According to IEA-GHG (2005), favorable qualitative parameters for CO<sub>2</sub> option storage in CBM include: laterally continuous thick, few seams, no faulting and folding, depth less than 1500 m, high gas saturation and ability to dewater the formation. Favorable quantitative parameters according to numerical simulation study results of (Pratama et al, 2017) are given in Table 3.



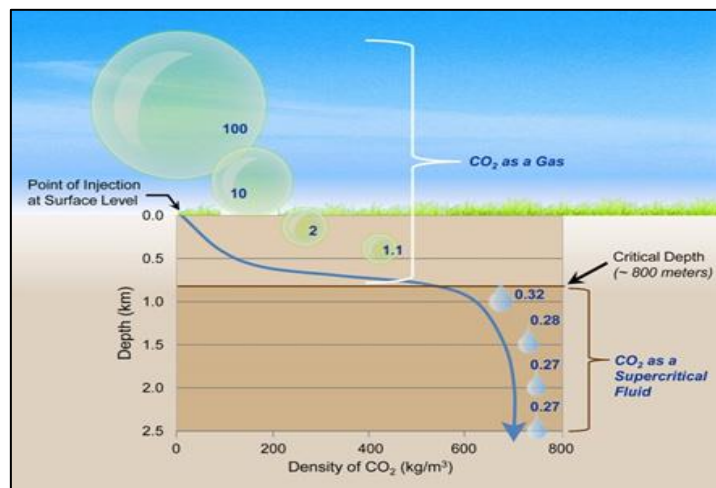
**Table 3** Optimum reservoir parameters (Pratama et al, 2017)

Reservoir parameters	
Depth, m	>500
Reservoir temperature, °C	<100
Fracture permeability, mD	>2
Matrix porosity %	>0,5

When the criterion of basin exploration degree is considered, it is obvious that the best choice is CO<sub>2</sub> storing in mature basins with known resource potential (estimated hydrocarbon potential-OOIP, OGIP and recoverable reserves) since this implies the availability of sufficient data for feasibility studies and ensures better storage safety.

### 3.2 Thermodynamic and hydrodynamic criteria

Thermodynamic criteria include temperature gradient and pressure gradient. CO<sub>2</sub> is injected into the reservoir in supercritical state achieved by compression and heating it above the critical point, i.e. pressure above 7.38 MPa and temperature above 31.1 °C. In these conditions, CO<sub>2</sub> has properties of gas and liquid, that is density of liquid and viscosity of gas. For conditions of hydrostatic gradient in the formation and geothermal gradient of the Earth (25-30 °C /km), the minimum depth for CO<sub>2</sub> injection in supercritical state is about 800 m. With depth increase, the volume of injected CO<sub>2</sub> is significantly reduced (Aminu et al, 2017). Figure 5 shows change in CO<sub>2</sub> volume at surface and reservoir conditions in supercritical state.



**Figure 5** CO<sub>2</sub> volume change at surface and reservoir conditions in supercritical state (NETL, 2018)

For increasing storage safety, CO<sub>2</sub> is injected at the depths greater than 1000 m. The maximum depth for injection is about 2500 m, because the increase in depth increases the injection costs (Kolenović, 2014).

Hydrodynamic criteria refer to the influence of formation water on CO<sub>2</sub> injection and storage. Formation water is very often present in active or depleted hydrocarbon reservoirs. Flow regime, salinity and pressure of formation water may have negative effect on CO<sub>2</sub> storing in terms of providing flow path for CO<sub>2</sub> leakage. By choosing the geological storage strategy in accordance with hydrodynamic regime, leakage of CO<sub>2</sub> can be avoided.

### **3.3 Techno-economic, social and regulatory criteria**

Techno-economic criteria include pre-storage costs, costs related to storage site and storage monitoring costs. Pre-storage costs include costs for capture, transportation, as well as for licensing and conduction of prefeasibility and feasibility studies for characterization and selection of an adequate CO<sub>2</sub> storage site. Capital costs refer to infrastructure for CO<sub>2</sub> capture, transportation, and costs of injection wells and field facilities depending on storage option. Injection strategy determines optimal injection well pattern and needed surface facilities. Operation costs are also part of overall costs. Storage monitoring costs depend on duration and regulatory requirement, and they are excluded in storage cost estimates. Many CO<sub>2</sub> storage costs estimates are made, and it is shown that the range of costs is very variable, depending of storage option. Besides that, costs within one storage option depend on many above-mentioned criteria.

So, according to Hendriks et al. (2002) and Bock et al. (2003) the onshore most probable storage costs estimated by probabilistic assessment for saline formations in Europe (depths of 1000–3000 m) are 2.8 US\$/t CO<sub>2</sub> stored, and for onshore depleted oil and gas fields the most probable value at the same depths is 1.7 US\$/t CO<sub>2</sub> stored. These estimates didn't include capture and transportation costs. EOR- CO<sub>2</sub> storage option requires less costs than saline aquifers and depleted hydrocarbon reservoirs. This is understandable since EOR- CO<sub>2</sub> projects are not primarily intended to be used as a CO<sub>2</sub> storage and its application provides additional oil production, and therefore a significant revenue.

Social criteria refer to increasing the public understanding of CO<sub>2</sub> geological storage benefits for CO<sub>2</sub> emissions mitigation. Also, it involves influence of CO<sub>2</sub> storage into the geological formations on surrounding population and environment.

The significant factors are regulatory issues, i.e. development and adoption of appropriate acts and regulations for CO<sub>2</sub> storage as the CSS legal framework and effects of political factors on commitments made through international agreements related to this issue.

In its “Roadmap for moving to a competitive low carbon economy in 2050” European Commission has pointed out that CCS technology has a leading role for CO<sub>2</sub> emission mitigation (European Commission, 2011). The main regulation for CCS in Europe is the Directive on Geological Storage of Carbon Dioxide (Directive 2009/31/EC, 2009) brought by the European Parliament and the Council. It contains provision on CO<sub>2</sub> capture, transportation and detailed requirements for storage sites from CO<sub>2</sub> injection to monitoring.

#### **4 CONCLUSION**

The criteria that need to be considered for the implementation of CO<sub>2</sub> geological storage include: geological factors, physical, thermodynamic and hydrodynamic parameters, as well as the techno-economic, social and regulatory issues. According to many studies on CO<sub>2</sub> geological storage types, it is concluded that CO<sub>2</sub> storing in depleted hydrocarbon reservoirs is the most appropriate option from the aspect of storage safety.

Saline aquifers have largest storage capacity, but the storage in this type of geological formation is accompanied by a high risk of CO<sub>2</sub> migration and leakage due to a low degree of exploration and small number of relevant data.

From the techno-economic point of view, underground CO<sub>2</sub> storage during EOR- CO<sub>2</sub> process is less expensive than other types of storages, since in this case the primary purpose is enhanced oil recovery and the achieved revenue from additional oil production compensates CO<sub>2</sub> cost. CO<sub>2</sub> storage in unmined coal beds enables simultaneously additional coalbed methane production, but that storage type provides small capacity.

Main concern in implementing CO<sub>2</sub> geological storage is long term isolation of CO<sub>2</sub>, reasonable cost and minimized environmental impact, as well as development and adoption of regulations that are necessary for CSS technology deployment.

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