Carbon capture and storage scenarios in Slavonia

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CARBON CAPTURE AND STORAGE SCENARIOS IN SLAVONIA

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Abstract

Carbon capture and storage is one of the key technologies for mitigating global climate change. This paper estimates the range of CO_2 capture, transport and storage costs for several companies in Slavonia and one from Hungary. The costs of capture, transport and storage are not always fixed and varies due to geological, geographical conditions, plant characteristics and technical factors. The calculations suggest that the costs of capture, transport and storage vary from \$ 80.98/tCO_2 to \$ 195.85/tCO_2 depending on the costs of capturing CO_2, the distance that CO_2 is transported and the amount of CO_2 that is transported and stored. Some scenarios are not profitable and would probably not be developed.

Keywords: CCS, costs of CCS process, climate change, emitters, CCS projects in Europe, CO_2 price

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SCENARIJI ZA HVATANJE i SKLADIŠTENJE CO_2 U SLAVONIJI

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Sažetak

Hvatanje i skladištenje ugljika (CCS) jedna je od ključnih tehnologija za ublažavanje globalnih klimatskih promjena. Ovaj rad procjenjuje raspon troškova hvatanja, transporta i skladištenja CO_2 za nekoliko tvrtki u Slavoniji i jedne u Mađarskoj. Cijena hvatanja, transporta i skladištenja nije uvijek fiksna i varira ovisno o geološkim i zemljopisnim uvijetima, karakteristikama postrojenja i tehničkim faktorima. Na temelju izračuna može se zaključiti da troškovi hvatanja, transporta i skladištenja variraju od \$80,98/tCO_2 do \$195,98/tCO_2 ovisno o troškovima hvatanja CO_2, udaljenosti na koju se CO_2 transportira i količinama CO_2 koje se transportiraju i skladište. Neki scenariji nisu profitabilni i vjerojatno ne bi bili razvijeni.

Ključne riječi: CCS, troškovi CCS procesa, klimatski promjene, emiteri, CCS projekti u Europi, cijena CO_2

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LIST OF ACRONYMS

GHG	Greenhouse gases
CO_2	Carbon dioxide
CCS	Carbon capture and storage
CCUS	Carbon capture utilization and storage
CCU	Carbon capture and utilization
BECCS	Bioenergy with CCS
DACCS	Direct air carbon capture and storage
IGCC	Integrated gasification combined cycle
CO	Carbon monoxide
WGS	Water gas shift reactor
PPC	Post-combustion capture
LCOE	Levelized cost of electricity
ASU	Air Separation Unit
Mtpa	Megatonnes per annum
GQCS	Gas Quality Control system
CPU	CO_2 Purification Unit
CAGR	Compound annual growth rate
PPI	Producer Price Index
IPPC	United Nations Intergovernmental Panel on Climate Change
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas

1 INTRODUCTION

The transition to a low-carbon economy in response to climate change is currently a major issue for the industrial sector. The challenge of a low carbon energy future has long seen CO_2 sequestration as an essential component given the current heavy reliance on fossil fuels. Carbon capture and storage technologies receive strong support through the Climate Target Plan, EU Climate Law and EU strategy on energy system integration. At the global level, climate change has become an important factor that affects decision-making in economically developed countries. The European Union has pledged that the economy will be climate neutral by 2050. In September 2020, the European Commission proposed reduction in greenhouse gases (GHG) emissions by 55 % by 2030. Carbon dioxide is an important greenhouse gas, whose concentration in the atmosphere has been rising since the Industrial Revolution due to emissions from anthropogenic activities (Santos et al., 2019). Total carbon dioxide emissions from fossil fuels and industry were 37.15 Gt CO_2 in 2022, which is about 60 % higher compared to 1990 (Statista, 2023). Also, carbon dioxide can be used in industries and globally, around 230 million tonnes (Mt) of carbon dioxide are used every year (IEA, 2019). The largest consumer is the fertilizer industry where 130 Mt CO_2 is used in urea manufacturing, followed by oil and gas industry with a consumption of 70 to 80 Mt CO_2 (IEA, 2019). CO_2 sequestration is recognized as an essential component of reducing CO_2 emissions, and delays in the deployment of this technology could significantly threaten the ability to achieve the aims of Paris agreement and to achieve the negative CO_2 emissions required for the 1.5 °C and 2 °C climate goals. Installing the required carbon capture and storage facilities is a huge engineering and financial challenge, but if the set goals are to be achieved and if CO_2 sequestration is to play a significant role, adequate transport and storage infrastructures are needed to support individual carbon capture projects.

CO_2 reduction includes a set of technologies, which can be divided into three groups: carbon capture and storage (CCS); carbon capture, utilization and storage (CCUS); and carbon capture and utilization (CCU). In literature, there are different definitions, in this regard, the classification by Tcvetkov may be used (Figure 1) (Tcvetkov et al., 2019).

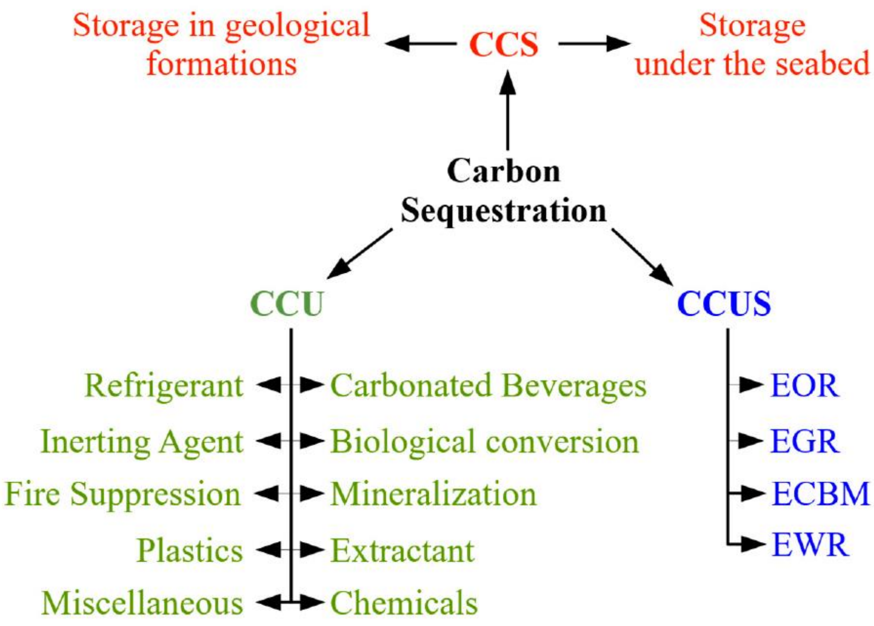

Figure 1-1 Cluster of carbon sequestration technologies (Tcvetkov et al., 2019)

According to Figure 1-1, CCS involves capture and disposal of CO_2 in any geological formation or method of offshore storage, with no other uses (van der Zwaan et al., 2016). CCS will be a key technology to achieve the goals of the Paris agreement. It is a technology that enables a deep reduction of emissions from industrial processes and from fossil fuel use in power sector. The world's leading climate and energy bodies – the United Nations' Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) agree that CCS will be particularly important for sectors that are large emitters of CO_2 emissions such as steel, cement and petrochemical industries (hard-to-abate sectors).

CCUS involves projects that use CO_2 to improve the efficiency of natural resource extraction processes (oil, natural gas, groundwater, geothermal energy etc.). It involves the capture of CO_2 from large point sources because large amounts of greenhouse gases are emitted at a geographical point. One of the most suitable point sources are industrial plants that use either fossil fuels or biomass as fuel and point sources from electricity generation. CO_2 can be compressed and transported by pipeline, ships, or trucks and can be injected into depleted oil and gas reservoirs or saline aquifers. After the extraction stage, CO_2 is stored under the ground. CCU projects involve capture and use of CO_2 in the manufacturing process as a raw material or chemical agent (Fantucci et al., 2019).

2 CARBON CAPTURE AND STORAGE (CCS)

CCS is a proven technology that has been used safely and effectively since the 1970s (Global CCS Institute, 2023). The dual role it plays in mitigation and removal of emissions is what makes CCS such an important and versatile technology. CCS involves three major steps: capturing CO_2 at the industrial facilities point sources or directly from the air, transporting the captured CO_2 by specially designed pipeline or by ship or road tanker to a suitable storage site and injecting CO_2 into a layer of rock, i.e., its interconnected pores. CO_2 becomes trapped within the pores and locked in many layers. Constant monitoring both above and below ground ensures that CO_2 stays safely and permanently in place. There is a high level of variability in transport and storage costs and much of the uncertainty in existing estimates is driven by a lack of extensive experience in building a cost database. CCS provides the foundation for technology-based carbon dioxide removal including bioenergy with CCS (BECCS) and direct air carbon capture and storage (DACCS) where CO_2 is captured and removed from ambient air. CO_2 can be captured by a variety of methods, which are: pre-combustion, post-combustion and oxy-combustion.

However, implementation of carbon capture and storage is accompanied by a number of barriers that need to be overcome (Budinis et al., 2018):

2.1 Technical, economic, public perception, legal and regulatory barriers

CCS consists of a number of complex processes, including CO_2 separation, compression, transport, injection into underground reservoirs, and long-term monitoring. The implementation of these processes can be accompanied by leaks, accidents, environmental pollution, danger to public health, and so on (Cherepovitsyn et al., 2020).

Because of its relative novelty, there is no specific legislation regulating such project in a number of countries where the implementation of CCS technology has significant potential. Prior to a CCS project's implementation, it is necessary to introduce clear legislation for CO_2 capture and storage. A lack of specific legislation causes a CCS project to be postponed or canceled (Romasheva et al., 2019). CCS projects are characterized as high capital costs and risks, making them currently less attractive compared to schemes involving CO_2 utilization.

Separate groups of stakeholders frequently oppose the implementation of carbon capture and storage technology (Dütschke et al., 2011). According to research conducted in

Germany, public perception is the second greatest barrier after economic factors to the implementation of CCS (Fischedick et al., 2009).

2.2 CO_2 capture technologies

2.2.1 Pre-combustion capture

Pre-combustion CO_2 capture system can be used for an integrated gasification combined cycle power plant (IGCC power plant) and in natural gas power plant. Pre-combustion capture involves inducing reaction of a fuel with oxygen or air and/or steam to obtain mainly a synthesis gas (syngas) or fuel gas composed of carbon monoxide (CO) and hydrogen (H_2) (Davidson, 2011). The amount of air or oxygen available inside the gasifier is carefully controlled so that only a portion of the fuel burns completely (National Energy Technology Laboratory, 2022). The next step in pre-combustion CO_2 capture process is the water gas shift reactor (WGS) where CO reacts with inlet steam, and the CO_2 and H_2 mole concentrations increase. This process occurs in a catalytic reactor, called a shift converter and occurs in two stages: a high temperature reactor (300 ºC – 500 ºC) and a low temperature reactor (180 ºC – 270 ºC). The syngas outlet from the shift reactor is rich in hydrogen and carbon dioxide and lean in carbon monoxide. At this point, CO_2 has a high partial pressure, which significantly improves the driving force for various types of separation and capture technologies (National Energy Technology Laboratory, 2022). This syngas outlet goes to the CO_2 adsorber. The syngas steam typically enters the separation stage at 20 – 70 bar of pressure with a CO_2 concentration in the range of 15-60 % by volume (Hospital-Benito et al., 2022). Physical absorbents such as Selexol, Purisol and Rectisol are most commonly used at relatively high pre-combustion CO_2 partial pressure because under proper operating conditions, they can entail less heating duty in comparison with chemical solvents since there is no any chemical reaction involved, but requiring a higher solvent flow rate and thus increasing the electricity consumption (Theo et al., 2016). The solvent is then sent to a regeneration step where CO_2 is released, which is then sent for compression, transport and storage. The CO_2-lean solvent is pumped back into the CO_2 absorber. The outlet syngas from this CO_2 absorber is very rich in hydrogen. This goes to the power block for power generation. In pre-combustion, the gasification process is at very high pressure and CO_2 is present in the syngas in high concentrations compared with post-combustion process. Figure 2-1. shows pre-combustion capture process.

Pre-combustion has the potential to be cheaper than post-combustion for the same amount of captured CO_2, because a smaller amount of gas needs to be treated which leads to lower capital costs.

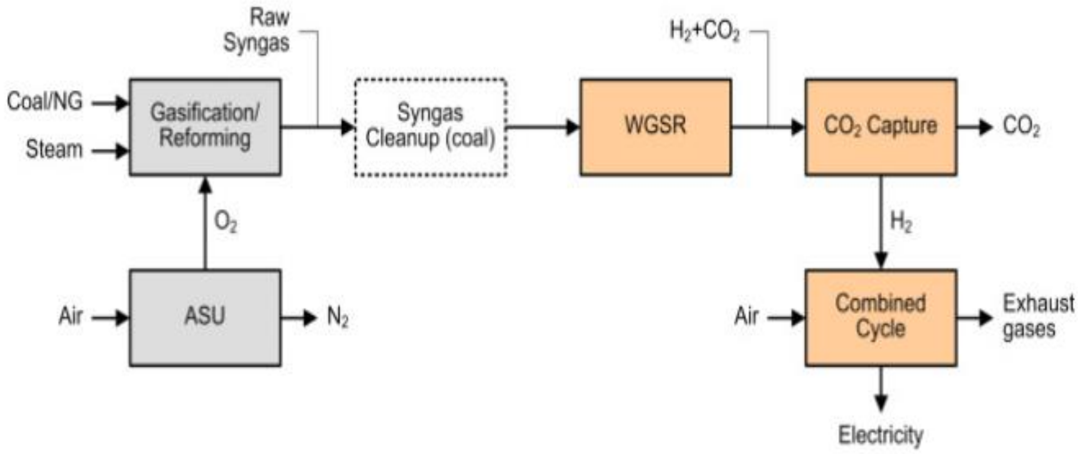

Figure 2-1 Pre-combustion capture (Cebrucean and Ionel, 2022)

2.2.2 *Post-combustion capture (PCC)*

Post-combustion capture is an energy intensive and expensive process that is used to reduce emissions in a variety of sectors where decarbonization would be possible but costly in the long term. In the cement industry, power generation, steel industry, as well as in chemical plants and conventional natural gas and pulverized coal-fired (PC) power generation retrofitting existing plants with post combustion capture units may be the only effective and economical way to reduce emissions at the stack without affecting the process upstream (Zanco et al., 2021).

Separating CO_2 is particularly challenging due to the low concentration of CO_2, large volume of flue gas to process and the high purity requirement of the resulting CO_2 stream (Zamarripa et al., 2018). The power plant flue gas from the SO_2 capture unit flows through a flue gas blower to overcome the pressure drop of the system. The flue gas consists mostly of nitrogen (N_2) and CO_2. It then passes through a direct contact cooler to further cool the gas. The flue gas then flows into an absorber, where CO_2 is captured using an amine solvent and the remaining gas is then released to the environment through the stack. The solvents for CO_2 captured can be physical, chemical or intermediate, but chemical solvents, known as amines, are most likely to be used for post-combustion process because chemical solvents are less dependent on partial pressure than physical solvents, and the partial pressure of CO_2 in the flue gas is low, typically 4-14 % by volume (Global CCS Institute, 2007). The solvent, which is now rich in CO_2, is pumped to a regenerator, where the CO_2 is released in a temperature swing process, in which the solvent is heated to release the CO_2. This heat is nominally supplied from the power plant steam cycle. That heat is transferred to the solvent via a heat exchanger, also known as a reboiler. A concentrated CO_2 stream then exits the regenerator and is dehumidified and compressed to a supercritical fluid for transport to the CO_2 regeneration site. The used solvent from the regenerator is then cooled in another heat exchanger and circulated back to the absorber.

The post-combustion capture approach is attractive in part because it can be retrofitted to existing chemical plants by being added at the back end (Adams et al., 2017). Although the cost of retrofitting an existing plant is relatively low, one study found that adding post-combustion solvent-based CO_2 capture to a classic pulverized coal power plant caused the average levelized cost of electricity (LCOE) to increase by 50-90% (Merkel et al., 2010). Figure 2-2. shows post-combustion process.

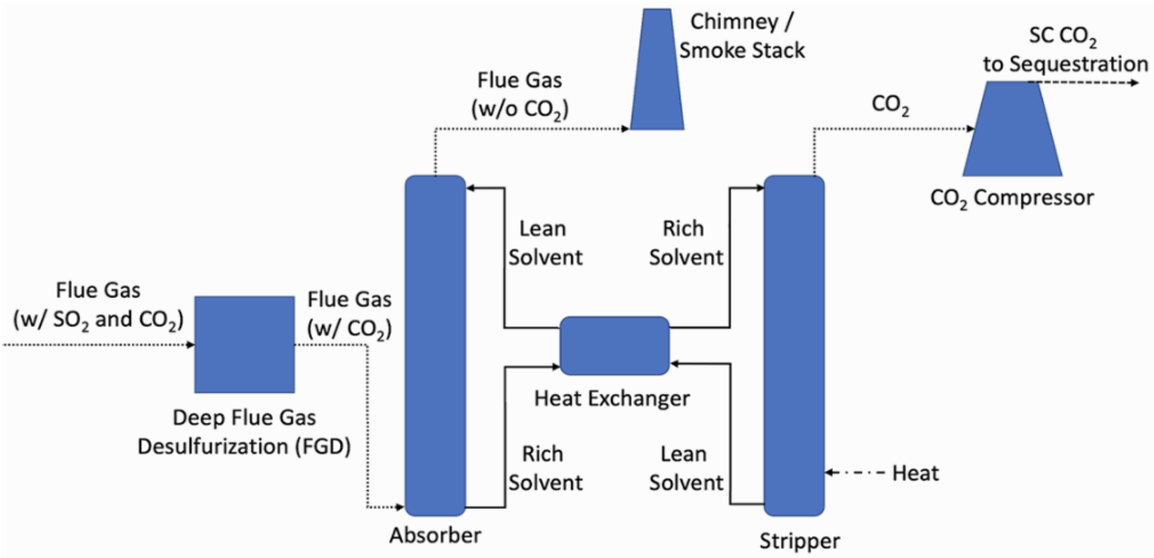

Figure 2-2 Post-combustion process (Long International, 2022)

2.2.3 *Oxy-combustion process*

Oxy-fuel refers to fossil fuel combustion with nearly pure oxygen and recycled flue gas or CO_2 and water/steam, and production of a flue gas consisting of CO_2 and water (Global CCS Institute, 2007) (Figure 2-3.). Oxy-fuel technology was proposed for the first time in 1982 for producing a high purity (so-called food grade) CO_2 stream for use in enhanced oil recovery (Horn and Steinberg, 1982).

Oxy-combustion plants will include the following major component systems (Global CCS Institute, 2012):

1. Air Separation Unit (ASU) – This system separates oxygen from air and supplies the oxygen for combustion.

2. Combustion/Heat transfer / Gas Quality Control system (GQCS) – The components of this system are nearly the same as components for a corresponding plant with combustion in air.

3. CO_2 Purification Unit (CPU) – the CPU will include a flue gas dehydration sub-system and compressors to deliver the obtained CO_2 to a receiving pipeline or geological storage site.

In the oxy-fuel process, a mixture of recycled flue gas and pure O_2 obtained from an air separation unit is introduced into the combustion chamber to replace air as oxidant gas (Duan and Li, 2023). Combustion in pure oxygen results in a high concentration of CO_2 in the exhaust gases that are composed of 80–85 % of CO_2 and water (Wall et al., 2009). Part of the gases will be recirculated into the reactor; the presence of water allows combustion temperature to be lowered (Zheng, 2011). Oxy-combustion reaction is more efficient than the traditional combustion reaction (Raho et al., 2022). The biggest advantage of this process is high concentration of CO_2 that can be obtained in flue gas, which enables its feasible compression, transport and storage. It also has other advantages, such as low NO_x emissions, easy scale-up, and applicability in existing power plants (Chen et al., 2012).

The oxy-fuel process has special characteristics that have beneficial effects on the efficiency of the reaction (Zheng, 2011; Yin and Yan, 2016; Dobó et al., 2019; Stanger et al., 2019):

High-pressure operation results in a higher temperature condensation of water steam in the exhaust gas, resulting in more efficient latent heat recovery. The energy required for CCS is reduced as the CO_2 is delivered at high pressure. The size of the heat exchanger can be reduced as the exhaust gases have a higher convective heat transfer coefficient.

The feasibility of the process can be improved by reducing the energy consumption in the process of separating oxygen from the air. High energy consumption results in higher operating costs. The cost is also affected by the type of fuel used in the combustion process. The use of lower quality fuels such as lignite can increase the cost of CO_2 capture due to the high ash content and low calorific value. The use of high-quality fuels such as natural gas can reduce the cost of CO_2 capture. Oxy-combustion is preferable because, being controlled combustion that takes place between fuel and pure oxygen, and contains less pollutants. In particular, at the end of the process, there will be a significant decrease in NO_x and SO_x, because the presence of nitrogen and sulfur, which are mostly in the air, decreases significantly when only oxygen is involved in the reaction (Raho et al., 2022). The amount of oxygen required in oxy-combustion is significantly greater than in pre-combustion applications, increasing CO_2 capture costs (National Energy Technology Laboratory, 2022). Oxygen is produced using low-temperature cryogenic separator. In cryogenic air separation plant, air is compressed to a pressure of 0.48 to 0.62 MPa and purified to remove H_2O, CO_2, N_2O and trace hydrocarbons. Two or more switching fixed bed adsorbents are used, which can be regenerated by either temperature or pressure swing, using in each case, a low-pressure waste N_2 stream. The air is cooled against returning products (O_2 and N_2) and separated into pure O_2 and N_2 fractions in a distillation column.

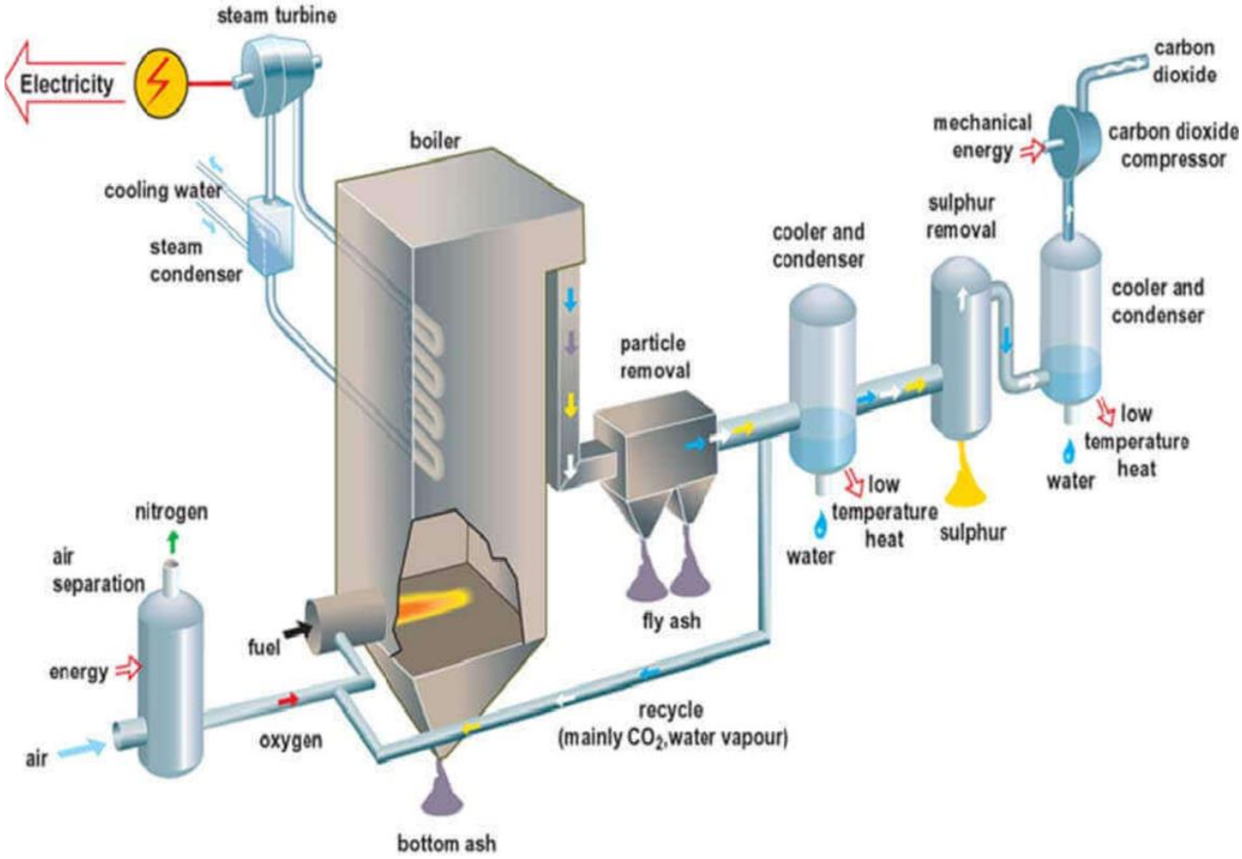

Figure 2-3 Oxy – combustion process (Duan and Li, 2023)

2.3 Transport of CO_2

The safe transport of CO_2 from CO_2 capturing plant to a storage site is the second stage of CCS. CO_2 can be transported using tanks, ships, railroads, and pipelines. Although transportation can be the least expensive part of the CCS process, it can be the most demanding when it comes to planning and directing fluids to their destination. CO_2 transport costs vary due to transport method, whether CO_2 is transported onshore or offshore, over various distances from emitters to CO_2 storage, featuring monitoring and regulatory requirements, specific cost structure, capital investment and labor costs. All of these methods vary from region to region due to different geological, geographical and legal condition.

With regard to transport method, CO_2 pipelines are still the main transport option modeled in the literature (IEA, 2020). Gas takes up less volume when it is compressed, and even less when it is liquefied, solidified, or hydrated. Therefore, captured CO_2 is often compressed and liquefied before transport. In the reservoir, CO_2 almost always becomes a supercritical fluid (Drax Global, 2022). Numerous studies have also explore ship transport, which can be a cost-effective option for offshore CO_2 storage depending on the distance and volume of CO_2 transported (Jakobsen et al., 2017). Several studies have investigated truck and rail transport (Sanchez et al., 2018; Psarras et al., 2020). Rail and truck transport typically involve small volumes of CO_2. However, most analyses indicate that deploying CCS on the scale required to achieve global climate goals is likely to require pipelines, ships, and project networks capable of transporting megatons of CO_2 (not to mention much lower cost of all components) (Friedmann et al., 2020). Carbon dioxide is much safer to transport than oil and gas because it does not form flammable or explosive mixtures with air. Moreover, CO_2 is not directly toxic to wildlife and humans when released into the air.

2.3.1 Transport by pipelines

When CO_2 is transported through pipelines, this is usually done in supercritical, dense or subcooled liquid state, so that the volumes to be transported are not large, unlike the gas phase in which the density is low. Transporting CO_2 as a subcooled liquid has advantages over transporting of CO_2 as a supercritical fluid due to its higher density, lower compressibility and lower pressure losses. Transporting liquid CO_2 requires thinner pipes compared to supercritical CO_2 when transported under the same pipeline pressure conditions. As the CO_2 flows along the pipeline, the pressure drops, the liquid expands resulting in velocity increase, which further increases the pressure loss with possibility of two-phase flow occurrence. CO_2 is commonly kept above its critical pressure throughout the pipeline to maintain the desired, stable and predictable fluid properties, such as density and low viscosity (McKaskle et al., 2022) (Figure 2-4.). Most CO_2 pipelines operate at pressures ranging from 8.3 MPa (83 bar) to 15.2 MPa (152 bar), and possibly up to 19.3 MPa (193 bar) (National Petroleum Council, 2021). It is extremely important to know the thermodynamic properties of the different CO_2-mixtures to be transported under these conditions and the interactions between the pure carbon dioxide and other components that may be present in the streams (i.e., N_2, O_2, Ar, CH_4, H_2) (Mazzoccoli et al., 2013). Definition of the Equations-of-State (EOS) that calculates the thermodynamics properties of various CO_2-rich mixtures could be of great benefit for CCS processes.

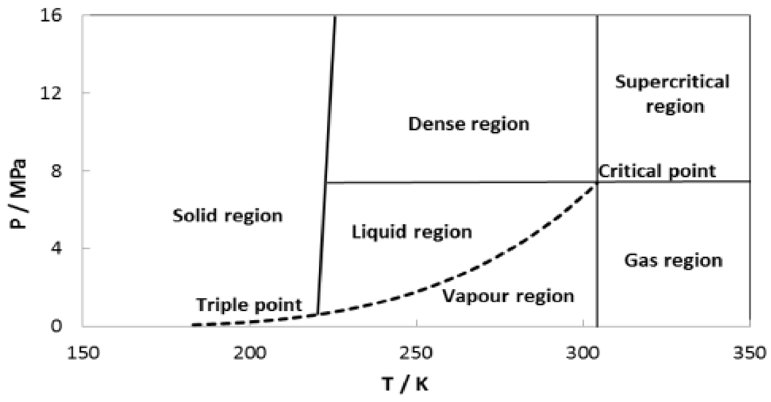

Figure 2-4 p-T diagram of pure CO_2

Large projects with significant capital investments in CO_2 transport and storage infrastructure should be based on a detailed assessment of the interaction between CO_2 quality and the planned equipment designs to ensure that the investment is well-founded. The cost of transporting CO_2 through pipelines depends on the diameter and length of the pipeline. A pipeline diameter that is too small would result in a high fluid velocity with a large pressure drop and erosion. The fluid flow rate determines the internal diameter of the pipeline (Figure 2-5.). Pipes of inadequate thickness and strength can burst or implode when exposed to high internal pressures. CO_2 pipelines have a greater pipe thickness than natural gas pipelines due to transport at higher pressure. Carbon steel pipes are used for transport, generally in grades X65 or X70 for high pressure operations. The feasibility of repurposing natural gas pipelines for CO_2 transport is not certain because it has been proven that the existing infrastructure is not suitable for transferring huge amounts of CO_2. (e.g., 20 Mtpa) over long distances (160 km or more). This is because CO_2 in liquid state requires a higher pressure than natural gas for pipeline transport (NPC, 2019). For efficient transport, CO_2 is compressed to above 7.38 MPa, which is higher than the critical pressure for pure CO_2. Offshore pipelines tend to be more expensive due to the more complicated offshore equipment required for construction on the seabed.

Impurities in the CO_2 stream can also contribute significantly to expenses since pipeline degradation might occur if not removed in time. The level and type of impurities depend on the CO_2 source and capture technology. Different impurity levels result in different critical points and phase diagram shape. Impurities create larger two-phase region where vapor and liquid coexist, and pipelines are usually designed to operate outside such a region to avoid flow assurance problems. CO_2 pipeline accidents are typically caused by the formation of CO_2 hydrates and corrosion (Kim et al., 2024). The root cause of CO_2 hydrate formation and corrosion is the presence of water in the pipelines. CO_2 hydrates are easily formed when the pressure in the pipeline exceeds 4.45 MPa and the temperature is below 10.2 ℃ (Pradier and Pradier, 2014). CO_2 hydrates can increase the pressure in pipelines. Corrosion is caused by CO_2 dissolved in water, which then forms carbonic acid (H_2CO_3) and reacts with the steel in the pipes (Kim et al., 2024).

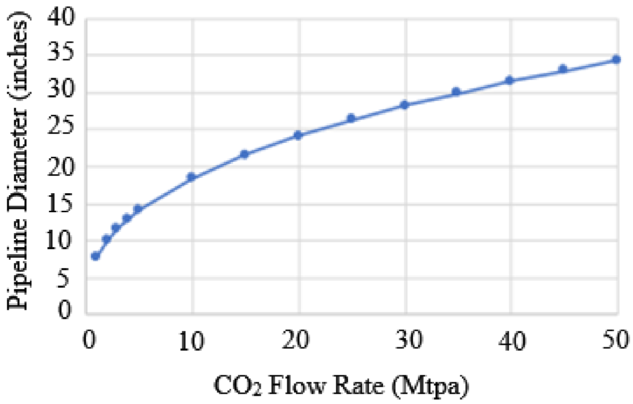

Figure 2-5 Pipeline diameters as a function of CO_2 flow rate (Smith et al., 2021)

2.3.2 *Transport by ships*

With the expansion of the CO_2 market in the future and with more and more CCS projects, transport of CO_2 by ships will be more significant. CO_2 ships are more similar to LPG tankers than LNG tankers because CO_2 is transported under high pressure, while LNG is transported at atmospheric pressure. CO_2 is transported as a liquid at a pressure around 1.5 MPa and a low temperature of -28 °C. This requires dehydration followed by cooling, CO_2 condensation (liquefaction), pumping processes and distillation to remove impurities. LPG tankers can be repurposed for CO_2 or dual-purpose transport, but in general, tankers specifically designed for CO_2 transport can be better optimized for maximum capacity and investment cost (IEAGHG, 2020). Factors that affect the cost of transporting CO_2 by ship are the distance, the size and type of ship used, the condition of the ports and terminals involved, and local regulations. The advantage of ship transport is the safe and reliable transport of smaller volumes of CO_2 over longer distances and transport from remote areas. Ship transport is also more flexible than pipeline transport because (a) routes can be changed and (b) injection can be easily switched to another storage site (e.g., if more injection capacity is required) (Weihs et al., 2014).

2.3.3 *Transport of CO_2 by rails*

The transport of CO_2 by rail could have an important impact on the implementation of the CCS projects in Europe. The transport small to medium quantities of CO_2 over medium to long distances is very attractive and could be essential to implementation of CCS by small and scattered CO_2 emitters. Europe can take advantage of a strong railway infrastructure and be a flexible option for transport of CO_2 inland. Given that the rail industry has historically transported coal, using rail for CO_2 transport is a way to maintain work and employment (Ho et al., 2024). Rail-based transport of CO_2 could solve many of the problems which pipelines and trucks are faced with. While pipeline projects seeking permits in large industrial regions or populated areas face a gauntlet of permitting, rigorous regulation, and negative public perception, rail infrastructure already exist, often already directly connected to capture sites such as power plants or production facilities with rail tracks (Ho et al., 2024). Several studies have shown that rail-based transport could be cheaper than pipeline at lower volume (Metz et al., 2005; Roussanaly et al., 2014).

2.3.4 *Transport of CO_2 by trucks*

Trucks are a flexible method for small to medium distances. The CO_2 liquid is transported at 1.8 MPa and -23 °C and trucks can be used to assist by delivering small volumes of CO_2 between ports and industrial sites. The limitations of transportation by trucks are cost-effectiveness, added emissions and volume. Given the large quantities of CO_2 that would be captured via CCS in long-term, it is unlikely that truck transport will be significant (Global CCS Institute, 2018).

2.4 CO_2 storage

CO_2 geological storage is the final step in CCS chain. It should isolate CO_2 permanently from the atmosphere for hundreds of years. The cost of CO_2 storage varies as it is depends on geological sites, capital, drilling and other costs. What makes a suitable, safe and permanent site for storing CO_2 is an optimal combination of the storage depth, location and capacity. The efficiency of CO_2 storage in geological media, defined as the amount of CO_2 stored per unit volume, increases with increasing CO_2 density (Brennan and Burruss, 2003).

The depth should in general be over one kilometer. The primary reason for this is the behavior of the CO_2 and the fact that favorable storage conditions presume supercritical state, because of liquid-like density, but lower viscosity and surface tension. The pressure and flow regimes of formation waters in a sedimentary basin are important factors in selecting sites for CO_2 storage (Bachu et al., 1994).

The second key element is a suitable location. The best option for CO_2 storage is when it is contained within a structural closure and most commonly this is ensured by an anticline with an impermeable cap rock. Criteria for basin suitability for CO_2 storage include also: basic characteristic (sediment type, geothermal and hydrodynamic regimes, tectonic activity), industry maturity and infrastructure, level of development, economy, public education and attitudes (Bradshaw et al., 2002).

The third element is capacity and there must be sufficient space to permanently contain all the CO_2 injected, which is defined by the volume of a structural trap, the porosity and the compressibility of the system (CO_2, brine and pore compressibility).

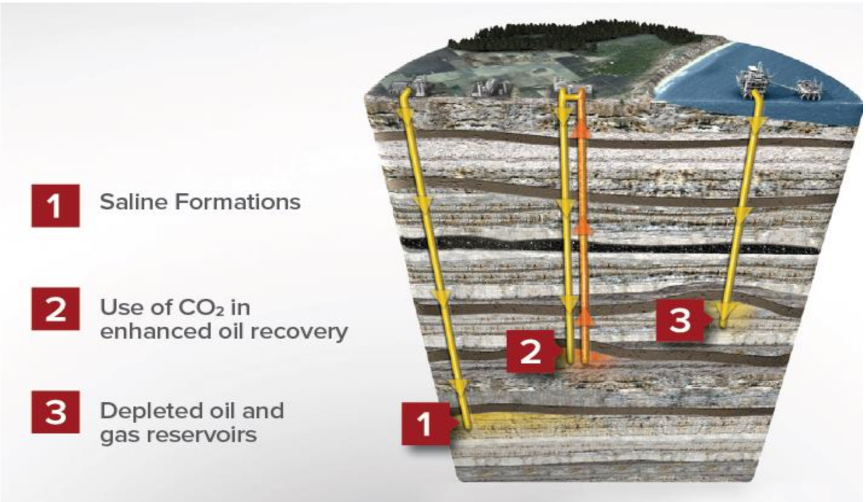

Figure 2-6 Storage overview (Global CCS Institute, 2018)

CO_2 can be stored in saline formations, depleted oil and gas reservoirs, or used for enhanced oil recovery (Figure 2-6.). Saline formations are large reservoirs with containment mechanism, typically a cap rock, and represent the most common and largest target for the CCS industry. Some studies report cost projections for other types of storage reservoirs such as shale, offshore sedimentary, and basalt formations, but most of these sites are at an early stage of research and development and are not considered technically mature (Gunnarsson et al., 2018; Snćbjörnsdóttir & Gislason 2016). With regard to saline aquifers, many studies do not consider pressure management which presents a trade-off between CO_2 storage capacity and cost (Anderson et al., 2017). The advantage of abandoned oil and gas fields is that the geological structure and physical properties have already been studied and are known from the past. There are already simulation models that predict the movement and behavior of the injected fluid. Injection of fluids into deep geological formations is achieved by pumping fluids down into a well. The flow rate of fluid depends on the number and properties of the fluid phases present in the formation. The presence of several different phases may decrease the permeability and slow down the migration rate (Intergovernmental Panel on Climate Change [IPCC], 2005). Low-permeability layers within the storage formation have the effect of slowing the upward migration of CO_2, which would otherwise cause CO_2 to bypass deeper parts of the storage formation (Doughty et al., 2001). As CO_2 migrates through the formation, some of it dissolves into the formation water. In systems with slow flowing water, numerical simulations show a that considerable proportion, up to 30 % of the injected CO_2,dissolves in the formation water over the course of ten year (Doughty et al., 2001). If the injected CO_2 is contained in a closed structure (no flow of formation water), it takes much longer for the CO_2 to dissolve completely, as there is less contact with unsaturated formation water (IPCC, 2005.). Water saturated with CO_2 is slightly denser (approximately 1 %) than the original formation water (Bachu and Adams, 2003).

Many analyses have attempted to quantify the potential cost savings of re-using legacy infrastructure, but there is still a fair amount of uncertainty about whether the time and cost of verifying infrastructure integrity would reduce or increase CO_2 storage costs relative to saline aquifers (Pale Blue Dot Energy, 2016; NPC, 2019).

The reservoir geological properties, primarily fluid saturations, pressure and (relative) permeability determine the CO_2 injection rate (injectivity). For reservoirs with geological properties (low reservoir permeability thickness product) that significantly limit the injection rate, additional wells are required. However, the number of wells, and hence maximum rate in a given area, is not limited by the performance of a single well but by pressure interference between them, such that there is a diminishing return (incremental injection rate) for additional wells (Global CCS Institute, 2011). The storage formation should be capped by extensive confining units (such as shale, salt or anhydrite layers) to ensure that CO_2 does not escape into overlying, shallower rock units (IPCC, 2005). Adequate CO_2 density is also an important parameter. Density increases significantly with depth while CO_2 is in gaseous phase, it increases only slightly or levels off after passing from the gaseous phase into the dense phase and may even decrease with the further increase in depth, depending on temperature gradient (Ennis-King and Paterson, 2001).

There are four phases of storage are: free phase, residual trapping, dissolution trapping and mineral trapping.

The free phase is the phase in which CO_2 moves to the caprock and gets tracked. In the second phase, residual trapping, molecules of CO_2 are trapped in pores of the sand and cannot move even under pressure, but they start to dissolve in the saline water. CO_2 rich water is heavier than the surrounding fluid and migrates downwards where it may react to form minerals such as those found in limestone. Mineral trapping may be relatively fast or very slow, but it effectively and permanently locks the CO_2 into a solid mineral (Global CCS Institute, 2018). Differences in regulatory regimes and institutional settings can affect the cost of CO_2 storage. In some regions, there is public resistance to onshore CO_2 storage due to concerns about induced seismicity or concerns about the permanence of geologic CO_2 storage due to leakage. Regions differ in how they address these concerns through policy and by extension, studies differ in how they capture the costs or savings associated with a constantly shifting policy landscape. Some regions have a favorable regulatory environment that reduce the cost of CO_2 storage, for example through tax credits and exemptions, access to loans or capital, the ability to access, reuse, or share nearby oil and gas infrastructure, and other policy mechanisms.

2.5 Use of CO_2

The global carbon dioxide market size was estimated at USD 10.94 billion in 2023 and is expected to grow at a compound annual growth rate (CAGR) of 5.0 $ from 2024 to 2030 (Grand View Research, 2024). The big reason for that is the growing use of CO_2 in enhanced oil recovery (EOR) process due to the depleted oil reservoirs and heavy dependence on oil imports of Pacific countries.

The growing demand for carbon capture and storage (CCS) technologies contributes to developing the CO_2 market (Figure 2-7). With the increasing focus on reducing CO_2 emissions, the demand for CCS technologies rises (Polaris Market research, 2023). In EOR, CO_2 is injected into oil reservoirs to recover additional oil that cannot be recovered through primary or secondary methods. If designed properly, most of CO_2 can be retained in the oil reservoir after CO_2-EOR. CO_2 can be used in acidizing and fracturing operations. In acidizing, CO_2 is injected into the formation to dissolve minerals and improve permeability, facilitating the flow of oil and gas to the wellbore. In hydraulic fracturing, CO_2 can be used as an alternative to water in the fracturing fluid, reducing water consumption and environmental impacts.

The medical and food and beverages industries contribute to the growth of the CO_2 industry and its expansion in coming years. In the medical segment CO_2 is used in surgeries to inflate and stabilize the cavities in the human body, thereby ensuring better visibility of the surgical area. In construction, some companies are researching possibility of use of CO_2 to strengthen concrete, reducing the carbon footprint of the building industry. In the food and beverage industry CO_2 is used for cryogenic freezing, which offers great flexibility in terms of temperature compared to mechanical cooling. Cryogenic cooling and freezing with CO_2 offers increased production capacity, better preservation of aromas and nutrients, and efficient conservation of natural taste, color and food quality (Grand View Research, 2024). Carbon dioxide can be used also as a natural preservative to inhibit the development of bacteria and other microbes (Allied Market Research, 2023). It should be highlighted that emissions from all of the above uses of CO_2 are negligible in comparison to the cement, fertilizer, steel, and iron industries, power plants, and other major point sources.

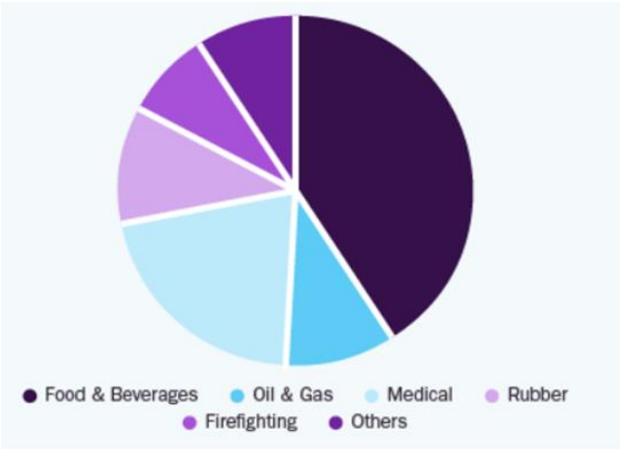

Figure 2-7 Global carbon dioxide market (Grand View Research, 2024)

Carbon dioxide can be obtained as a by-product in the production of ethyl alcohol through alcohol fermentation, as a by-product during the production process of hydrogen and from a number of other sources. The carbon dioxide process is influenced by demand, supply, production cost, emission regulations, transportation and competition.

2.6 CO_2 price analysis

The CO_2 price market is dynamic and diverse, and its development is significantly influenced by political and economic conditions. The prices of carbon dioxide (CO_2)

emissions has changed significantly over time, reflecting changes in regulatory frameworks, market dynamics and political decisions (Figure 2-8.). The European Union Emissions Trading System (EU ETS) is launched in 2005 and it is the largest carbon market in the world (Climate Trade, 2021). Initially, prices were low, often below € 10 per tonne of CO_2. However, prices began to rise significantly in the late 2010s due to tighter regulations and market reforms aimed at reducing the surplus of allowances. In the period between 2005 and 2020 prices ranged between €5 and €20 per tonne because of economic downturns and oversupply of allowances. From 2019 the prices started to rise and by 2022 they went up to €40 per tonne. Due to more ambitioned in EU climate policy and the tightening of the emission cap, prices rose to around €90 per tonne in 2022. From mid-2024, the EU carbon price has stabilized at around €70 per tonne. In 2023 EU ETS carbon price surpassed the €100 per tonne for the first time in February (Statista, 2024). The price fluctuation is attributed to varying demand for allowances and the recovery in natural gas price. The European Union's carbon prices are expected to continue their downward trend as the predicted decline in emissions in the dominant power sector, tepid gas prices and oversupply issues persist, according to market sources (S&P Global, 2023). Germany has increased its fixed national CO_2 price for transport and heating fuels from €30 to €45 per tonne as of January 2024. The higher CO_2 price aims to accelerate the country's decarbonization efforts while transitioning to a marked-based pricing system by 2026 (Clean Energy Wire, 2023). Regulatory changes such as tightening caps or reducing the number of allowances can drive up the price. An economic downturns can reduce emissions and demand for allowances and can lower the price. Higher fossil fuel price can make alternative, low-carbon energy sources more competitive, reducing emissions and the demand for CO_2 allowances. Carbon pricing mechanisms such as cap-and-trade system and carbon taxes, are being increasingly adopted worldwide, driven by the need to meet international climate commitments and mitigate greenhouse gas emissions. Changes in CO_2 prices highlight the importance of strong carbon pricing strategies for transition to a low-carbon economy.

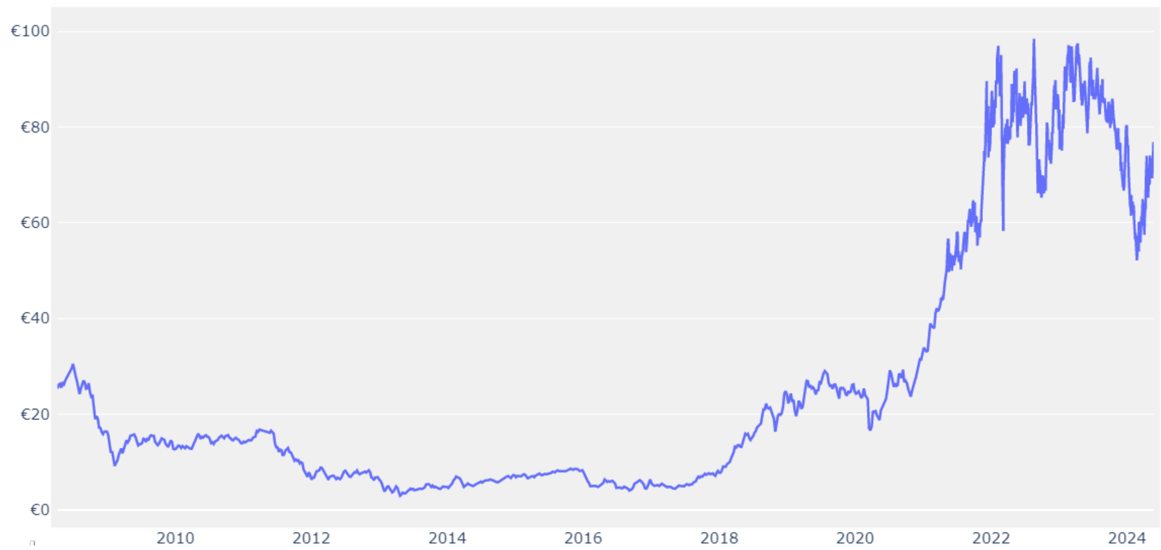

Figure 2-8 Carbon prices (Sandbag, 2024)

2.7 CO_2 emitters

Emissions of CO_2 have increased mainly due to Industrial Revolution and exponential growth in manufacturing activities around the world (Figure 2-9). Deforestation, agriculture and fossil fuels use are the primary anthropogenic sources of CO_2 (Investopedia, 2023). In 1950, the world emitted 6 billion tonnes of CO_2, and now it is over 35 billion tonnes each year (Our World in Data, 2024).

Figure 2-9 Annual CO_2 emissions (Our World in Data, 2023)

In 2022, the largest emitters were China, the United States, India, Russia and Japan (Statista, 2023) (Figure 2-10). The primary source of CO_2 emissions in China is fossil fuels, as China has extensive industrial activity and relies on coal for energy generation. Coal is rich in carbon, and its combustion in China's power plants and industrial facilities and boilers results in releasing large amounts of CO_2 into the atmosphere (U.S. Energy Information Administration, 2023). Although China currently emits the highest amounts of CO_2 annually, it has emitted far less than the United States over the past three centuries. Since 1750, the United States has produced more than 400 billion metric tonnes of cumulative carbon dioxide emissions (Statista, 2023). Emissions from coal-fired power plants increased by around 3 %, partly due to the ramp up of coal power plants during heat waves, as well as to increasing reliance on coal-fired electricity or district heating (IEA, 2023). Apart from China, other countries in the Asia-Pacific region also rely heavily on coal for energy production.

The United States is the second largest emitter of CO_2 in 2022 accounting for 13.6 % in global emissions. Even though the U.S. government undertook significant efforts to reduce the reliance on coal for electricity generation, the country remains a major producer of crude oil (U.S. Energy Information Administration, 2023). The largest sources of CO_2 come from transportation and electric power generation. US emission grew by 0.8 % or 36 Mt in 2022 compared to 2021. While many other countries reduced their natural gas use, the United States saw an 89 Mt increase in CO_2 emissions from gas, as it was called upon to meet peak electricity demand during summer heat waves (IEA, 2023).

India is the third largest CO_2 emitter. Coal is the dominant energy source in India. A rising population, a rapidly growing economy, and increased fossil energy consumption have all contributed to emissions in India soaring in recent decades (Statista, 2024). India's CO_2 emissions come from various sectors such as energy sector, industrial sector and transportation.

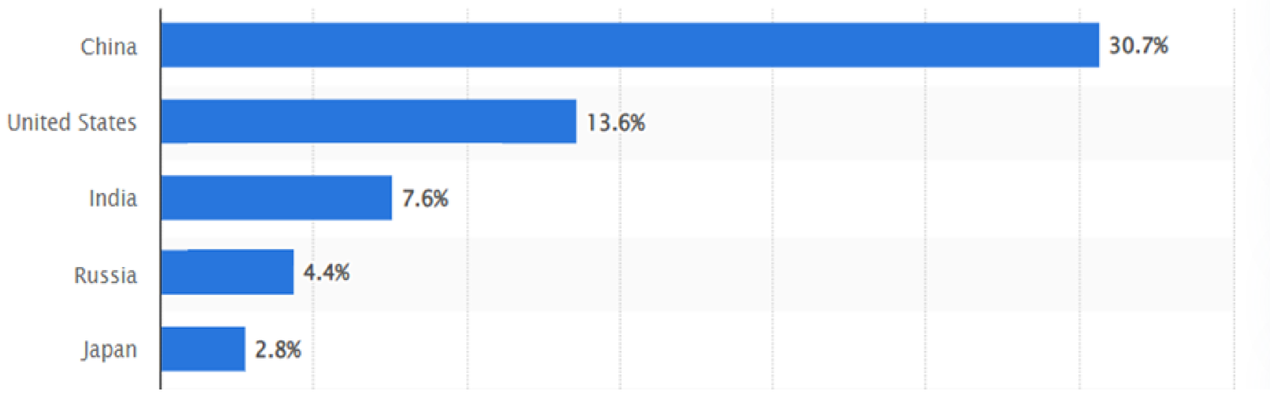

Figure 2-10 Share of global CO_2 emissions in 2022 (Statista, 2023)

According to the latest available data, Croatia emitted 17.53 million tonnes of CO_2 in 2022 which corresponds to 0.05 % of global CO_2 emissions (Our World in Data, 2023), which is significantly less than in 2007, when the peak value was 24.86 million tonnes (Figure 2-11.). Figure 2-12. represents CO_2 emissions by fuel or industry in Croatia, showing that oil industry is the larger emitter of CO_2. A look at the Environmental Pollution Register shows that the emitters in Slavonia (eastern part of Croatia) are as follows: Uni Viridas with 105 581.56 t/y, TE-TO Osijek with 76 042.41 t/y and NEXE with 715 592.63 t/y, while Hungarian cement company Beremend that is discussed in this paper emitted 513,790 t/y in 2017 according to the latest available data.

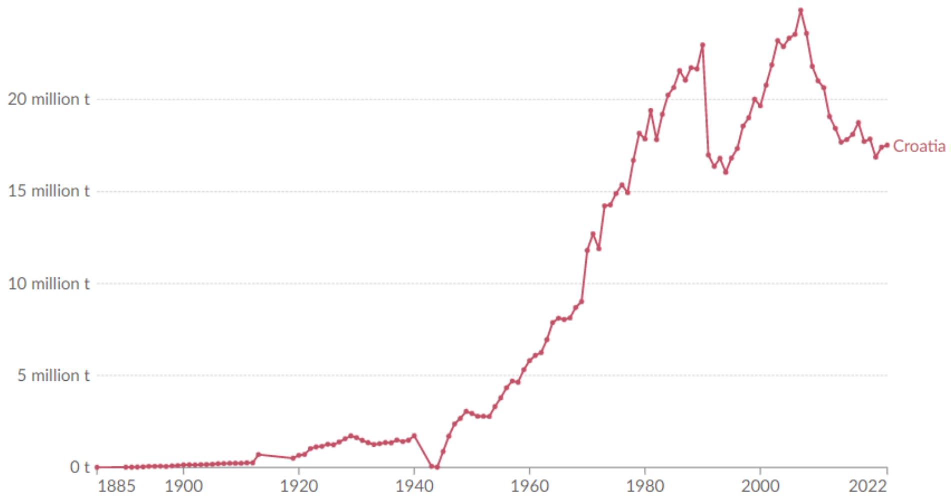

Figure 2-11 Annual CO_2 emissions in Croatia (Our World in Data, 2023)

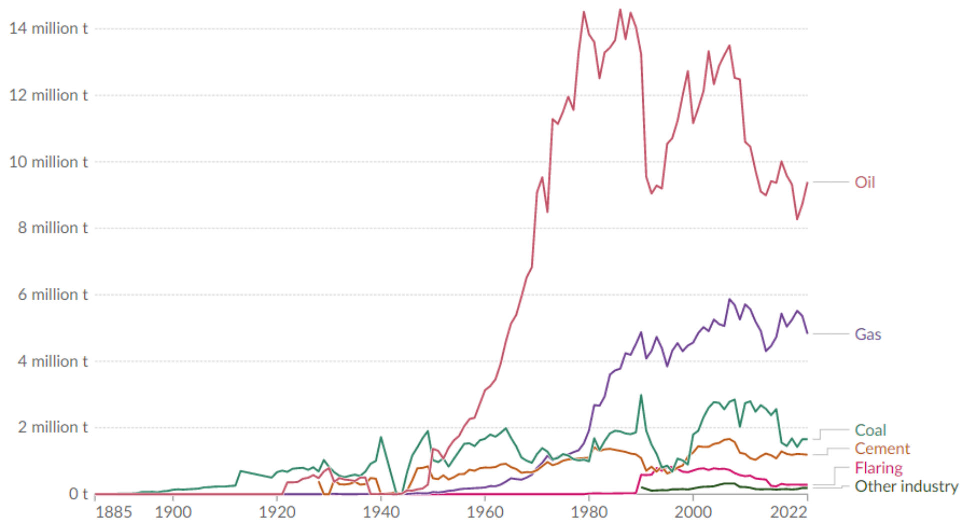

Figure 2-12 CO_2 emissions by fuel or industry in Croatia (Our World in Data, 2023)

2.8 CCS projects in Europe

Supportive policies and clearer goals and deadlines have led to an increase in the number of CCS projects in Europe. The European Commission's *Vision for an European Union 2050 Long-term Strategy* listed carbon capture and storage as one of seven strategic building blocks, multiple carbon capture projects were selected in the EU's Innovation Fund, and carbon capture was put at the center of the European Commission's Net Zero Industry Act (NZIA) proposal (Clean Air Task Force, 2023a). This landmark act proposes an annual CO_2 storage injection capacity target of 50 Mt CO_2/y by 2030, an obligation on oil and gas producers, as well as provisions for accelerating permitting, expanding member state coordination and enabling data sharing on CO_2 storage sites (Clean Air Task Force, 2023a).

There are currently 119 commercial CCS facilities in different stages of construction in Europe (Figure 2-13., Global CCS Institute, 2023). The North Sea is preferred location for CO_2 storage in Europe but Bulgaria, Croatia and Greece are developing CCS projects in south-eastern Europe, Italy has got a pilot storage license in the Adriatic Sea (Ravenna Hub) and Denmark and Poland are considering onshore storage. Denmark and the United Kingdom recently launched their first tenders for CO_2 storage licenses in the North Sea, including in both saline aquifers and depleted oil and gas fields (Danish Energy Agency, 2022; North Sea Transition Authority, 2022). The depleted Nini West oil field in the Danish North Sea will serve as a storage site for the CO_2 for the project Greensand and in its final phase it is planned to store up to 8 million tonnes of CO_2 each year (Wintershall Dea AG, 2023). The world's first open-source CO_2 transport and storage infrastructure, Northern Lights, is scheduled to be operational by 2025 and will be built in such way that it can be expanded to meet increasing storage demand (Northen Lights, 2022). The project is a partnership between Equinor, Shell and TotalEnergies, and aims to store up to 1.5 million tonnes of CO_2 per year (DNV, 2024). In the Netherlands, the Porthos project is aimed to develop the first large-scale CO_2 transport and storage system. Porthos is expected to be operational by 2026 and aims to store 2.5 million tonnes of CO_2 per year for 15 years. Porthos is designed to capture CO_2 from industries in the port area and store it in empty gas fields beneath the North Sea. Another large-scale Dutch project, the Aramis project, will allow several CO_2 storage sites to connect to its offshore transport backbone (Aramis, 2021).

Several German companies are looking at the prospects of shipping CO_2 captured at industrial plants to offshore storage sites developed by others in the North Sea, but the government still needs to modify the legislation to eliminate legal barriers (Reuters, 2023).

On the other hand, several European countries offer policy support for CCS through the development of CCS strategies or inclusion of CCS in their national decarbonisation strategies. The British government has pledged to invest $25.5 billion over the next 20 years in projects to capture, utilize and store carbon dioxide, as part of its plan to meet climate goals. By 2030, it aims to capture and store 20-30 Mtpa of CO_2 (Reuters, 2023).

In the last few years, Croatia has made significant steps in the development of CCS projects. One of the significant projects in Croatia named KOdeCO net zero is the company Holcim in Koromačno, which plans to become carbon neutral by 2030. Its goal is to capture more than 5 million tonnes of CO_2 annually (Holcim Croatia, 2023). Another large CCS project is called CO_2NTESSA by NEXE group, which plans to achieve carbon neutral cement production and thus take a step towards more environmental friendly and energy-efficient operations. The CO_2NTESSA project is worth €400 million, and is expected to capture about 700 Mt of CO_2 per year. The second-generation oxyfuel technology will be used at the cement plant in Našice. The captured CO_2 will be transported and stored in a saline aquifer at the Bockovci-1 site, potentially making this the first onshore CO_2 storage facility in Europe (Balkan Green Energy News, 2023). The project is being carried out in collaboration with Thyssenkrupp Industrial Solutions for engineering and modification of the clinker production. Another important CCS project in Croatia is the project of Petrokemija Kutina. Petrokemija, a company that produces ammonia, is currently implementing a full chain CCS pilot project in which natural gas is used as the main feedstock. Captured CO_2 will be transported through pipelines to be stored in depleted oil and gas fields near Ivanić Grad, 41 km from Zagreb. The project intends to capture, transport and store 190,000 tonnes of CO_2 per year.

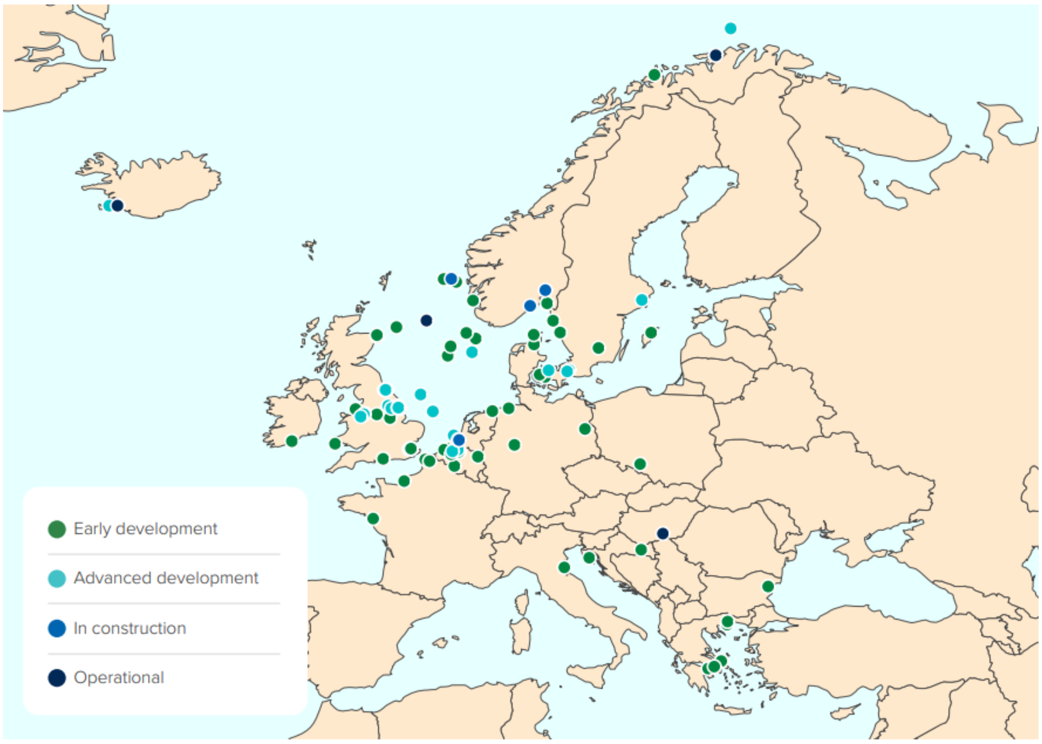

Figure 2-13 Map of CCS projects (Global CCS Institute, 2023)

3 ECONOMIC PARAMETERS FOR CCS

3.1 Carbon emissions trading

The carbon market is a fast growing sector in the global economy. Carbon emissions trading refers to a system in which permits to emit carbon dioxide are traded. This market operates under the cap-and-trade principle, where a cap, or limit is set on the total amount of emissions allowed by participating entities such as companies or countries. The aim of the CO_2 market is to provide economic incentives for entities to effectively reduce their emissions. Companies that can reduce their emissions at a lower cost than buying permits have a financial incentive to do. The governments distribute a predefined number of CO_2 credits to companies. Companies can emit as much CO_2 as they are credited with. The government reduces the number of permits each year, thereby reducing the total emission cap resulting in permits price increasing. Over time, companies have an incentive to reduce their emissions more efficiently and invest in clean technology as it becomes cheaper than buying permits (Investopedia, 2020). Those who have an excessive number of credits can sell them to companies that exceed their limit (Capital). Companies are taxed if they emit more than their permits allow.

Carbon emission trading offers several potential benefits:

- Emission reductions can be achieved at the lowest possible costs, as companies can choose to reduce emissions internally or to buy allowances from others.
- Trading allows companies to adopt their emissions reduction strategies to market conditions and cost considerations.
- Carbon pricing provides an incentive for companies to invest in cleaner technologies and practices to reduce emissions.

Emission trading can be an effective way for reducing emissions, but it also faces challenges such as setting appropriate emission caps, preventing market manipulation, and ensuring environmental integrity.

3.2 CO_2 capture costs

The cost of capturing carbon dioxide makes up the bulk of the cost of deploying CCS technology (Congressional budget office, 2023). Published estimates for CO_2 capture costs vary widely, mainly due to different assumptions about technical factors related to plant design and operation (e.g., plant size, net efficiency, fuel properties and load factor) as well as key economic and financial factors such as fuel costs, interest rates and plant lifetime. The costs depend on the choice of CO_2 capture technology and the choice of power system or industrial process that generates the CO_2 emissions. For CO_2 capture systems, it is generally assumed that the capital cost (CAPEX represent the total expenditure required to design, purchase and install the system of interest. It may also include the additional costs of other plant components, such as the costs of an upstream gas purification system to protect the capture system. Capital costs also include the cost of capture technology (adsorption, absorption), material required for installation and fees for planning and installation. Operational costs (OPEX) include the energy required for the capture process, repairs, staff salaries, the cost of materials used in capture process, utilities (water, compressed air), etc. Interest rate, the discount rate is estimated in the analysis of the discounted cash flow to determine the time value of income and outcome. If, at the same time, inflation is considered, some parts of cash-flow analysis should not be discounted. An important factor in the cost of CO_2 capture is the partial pressure, which affects the size of the process equipment and the technology that can be used for capture. A higher partial pressure means that the CO_2 will pass more quickly from the source gas to the solvent or adsorbent used to capture the CO_2. A faster transition results in lower costs as less energy is used. In its 2019 Report, the IEA estimates the costs of CO_2 capture by sector. It is clear that prices range from \$ 15-25/tCO_2 in some sectors to \$ 40-120/tCO_2 in cement production (Figure 3-1.). The lower the CO_2 concentration in the gas, the higher the energy demand to capture the CO_2, resulting in higher costs. Industrial applications such as natural gas processing and ammonia production already have a high degree of CO_2 concentration, leading to lower CCS costs (International Institute for Sustainable Development [IISD], 2023). Thus, the total incremental cost of CO_2 capture for a given plant design is best determined as the difference in total cost between plants with and without CO_2 capture, producing the same amounts of useful (primary) product, such as electricity (Intergovernmental Panel on Climate Change, 2005).

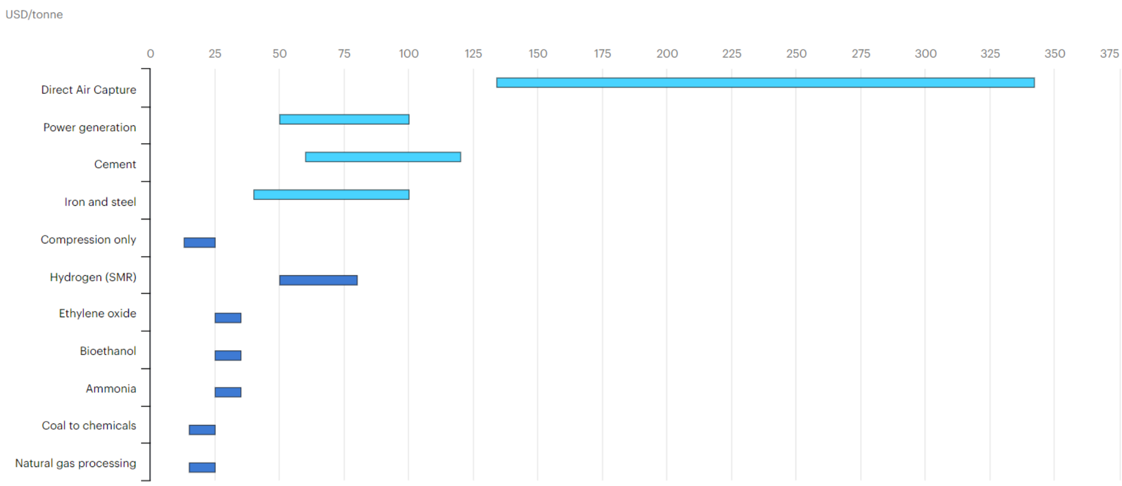

Figure 3-1 Cost of CO_2 capture by sector (IEA, 2019)

The IPCC (2005) has provided a range of costs for CO_2 capture based on assumptions about economic, operational and technical costs. These costs cannot be assumed for all situations and the main factors influencing the variation in costs are plant size, location, efficiency, fuel type, capacity factor and cost of capital. For power plants current CO_2 capture systems reduce CO_2 emissions per kilowatt-hour by approximately 85 % to 90 % compared to a similar plant without capture. The cost of electricity production attributed to CO_2 capture increases by 35 % to 70 % for a natural gas combined cycle plant, by 40 % to 85 % for a new pulverized coal plant and by 20 % to 55 % for an integrated gasification combined cycle plant. Comparing the costs of CO_2 capture by individual technology, the costs of post-combustion capture are in the range of $40-80 per tonne of captured CO_2. This technology is applied to capture CO_2 from the flue gases of fossil fuelled power plants. Pre-combustion process are used in gasification plants and costs range from $20 to $60 per tonne of captured CO_2. For oxy-fuel combustion, the costs are from $30 to $70 per tonne of CO_2 captured. The most expensive technology is Direct Air Capture (DAC), which is still in the early stages of commercial development, and the cost of capture is between $100 and $600 per tonne of captured CO_2.

In this thesis, costs based on the IEA (2019) were taken and converted into current values using an inflation calculator. The assumed capture prices were determined for companies whose initial costs of the CCS process are calculated in this paper. The companies NEXE and Beramend belong to the cement industry sector and the CO_2 capture costs were taken in the range of $72-145 per tonne. For TETO Osijek and Delta Energy and Uni Viridas the costs were $61-122 per tonne.

3.3 CO_2 transport and storage costs

Data for the costs of transporting different amounts of CO_2 via pipelines are limited, but natural gas pipelines are a useful analogy for understanding the cost components and variability that underpin CO_2 pipeline. Both depend largely on pipeline diameter and distance and differ little in land construction costs, though CO_2 pipelines may cost slightly more due to greater pipe thickness needed to transport CO_2 at higher pressure (Heddle et al., 2003). Pipelines are generally the most cost-effective option for transporting CO_2, although shipping can be cost-effective for transporting CO_2 over long distances. Shared CO_2 transport networks offer significant potential for cost reduction through economies of scale (Friedmann et al., 2020). The costs and feasibility of CO_2 transport networks depend on the distance between the CO_2 source and the storage hub. There are several promising locations around the world for CCS clusters and hubs that could enable a commom transport infrastructure, particularly in the United States, Europe, and China (IEA, 2020).

The three most importatnt factors in determining transport costs:

1) distance,
2) the amount of CO_2 transported,
3) the capital costs of the pipeline.

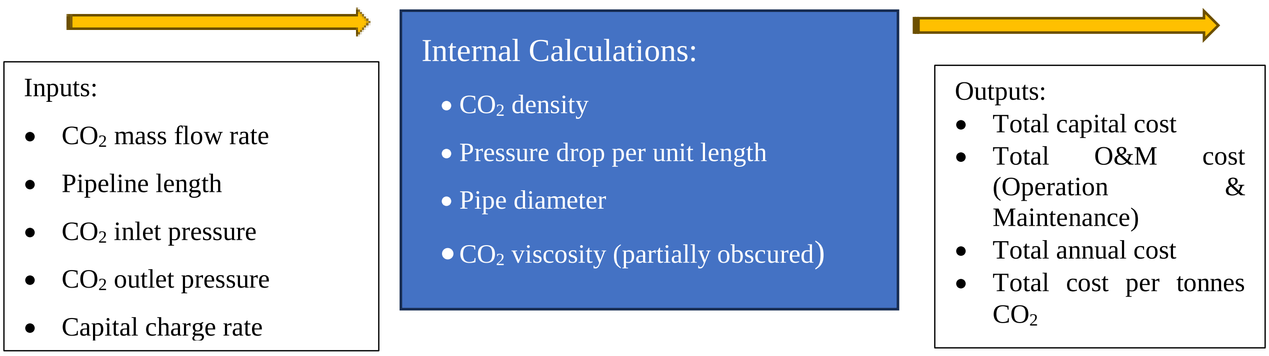

Figure 3-2 Pipeline transport cost model overview diagram (Heddle et al., 2003)

More detailed parameters required for the calculation of transport costs are shown in Figure 3-2. According to the Global CCS Institute (2011) transport of large quantities of CO_2 needs to be performed in dense or liquid phase as the volume in the gaseous phase requires unrealistic pipeline dimensions that increase costs. The minimum operating pressure for onshore summer temperatures should be in the range of 7 MPa for buried pipelines. At temperatures of up to 31 °C, CO_2 may exist in gaseous phase down to 7.3 MPa. Thus, to avoid numerous compressor stations along the pipeline, the inlet pressure – also for onshore pipelines – probably needs to be higher than the existing maximum requirements for gas pipelines. Investments are higher when compressor stations are required to compensate for pressure losses along the pipeline, or for longer pipelines or for hilly terrain. Compressor stations may also be also by increasing the pipeline diameter and reducing the flow velocity (IPPC, 2005). Operating temperature of CO_2 pipelines is generally determined by the temperature of the surrounding soil. In northern latitudes, the soil temperature varies between a few degrees below zero in the winter and 6–8 °C in summer, while in tropical areas it can reach up to 20 °C (Skovholt, 1993). The maximum allowable pressure drop per unit length ($\Delta P/\Delta L$) is found as the difference between the pipeline inlet and outlet CO_2 pressures divided by the pipeline length (Heddle et al., 2003). Transport at lower densities (i.e., gaseous CO_2) is inefficient because of the low density of the CO_2 and relatively high pressure drop per unit length. The pipeline diameter is calculated using the equations for pressure drop and head loss due to frictional resistance in a pipe, assuming turbulent flow (Heddle et al., 2003). McCoy and Rubin (2008) in their research (Figure 3-3.) show that the compressibility of CO_2 is non-linear in the pressure range commonly used for pipeline transport and that it is very sensitive to impurities. The difference between compressed pure CO_2 and CO_2 with 10 % H_2S is also shown.

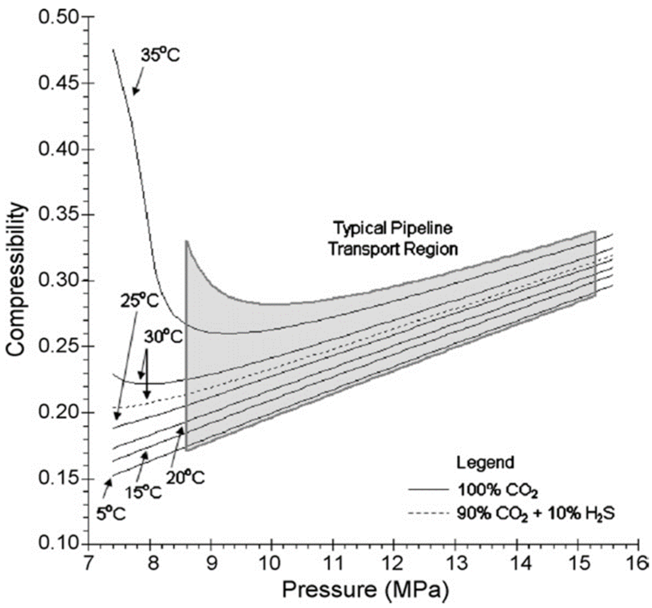

Figure 3-3 The compressibility of CO_2 based on the Peng–Robinson equation of state (McCoy and Rubin, 2008)

Heddle et al. (2003) employ a pipeline capital cost factor in dollars per inch per mile and provide an Excel-based model for users to calculate the cost to transport CO_2 under different criteria. Pipeline construction costs include materials, labor, rights of way, and other miscellaneous costs (e.g. surveying, engineering, supervision, contingencies, etc.). Heddle et al. (2003) based on natural gas pipeline data from 1989 to 1998, showed the relationship between average CO_2 pipeline construction costs ($/mile) as a function of flow. The costs obtained from Heddle et al. (2003) to 2024 dollar values according to the Producer Price Index (PPI) (Figure 3-4.).

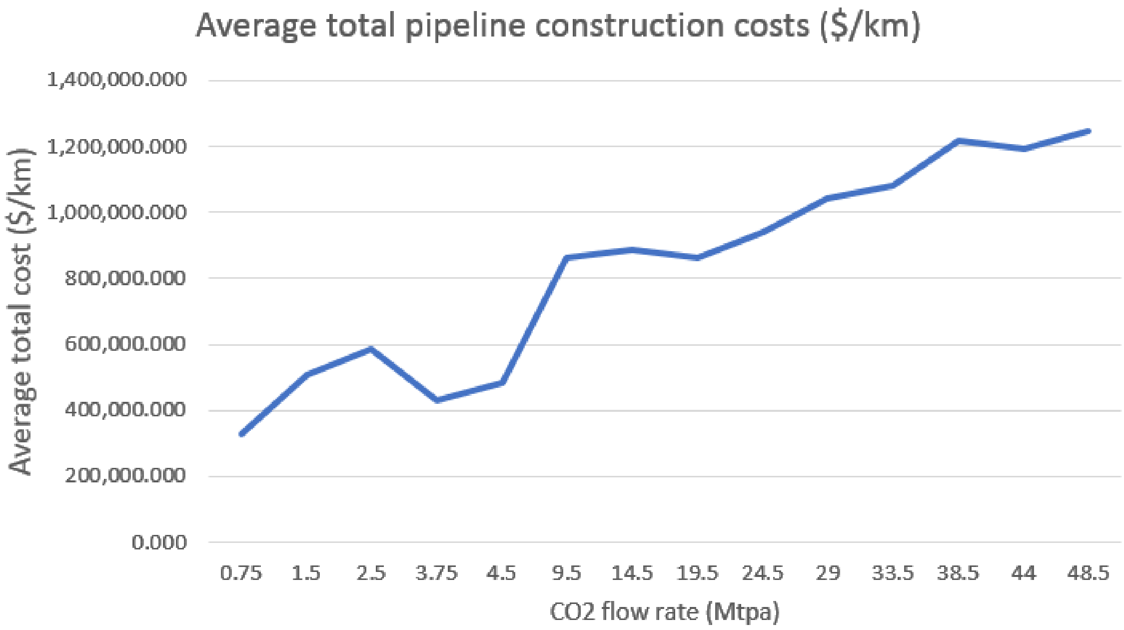

Figure 3-4 Average pipeline construction costs

After determining the costs, following the example of Smith (2021), the total cost of transporting CO_2 per kilometer was determined. The value of the dollar into values from the year 2024 was converted using the inflation calculator (Figure 3-5.).

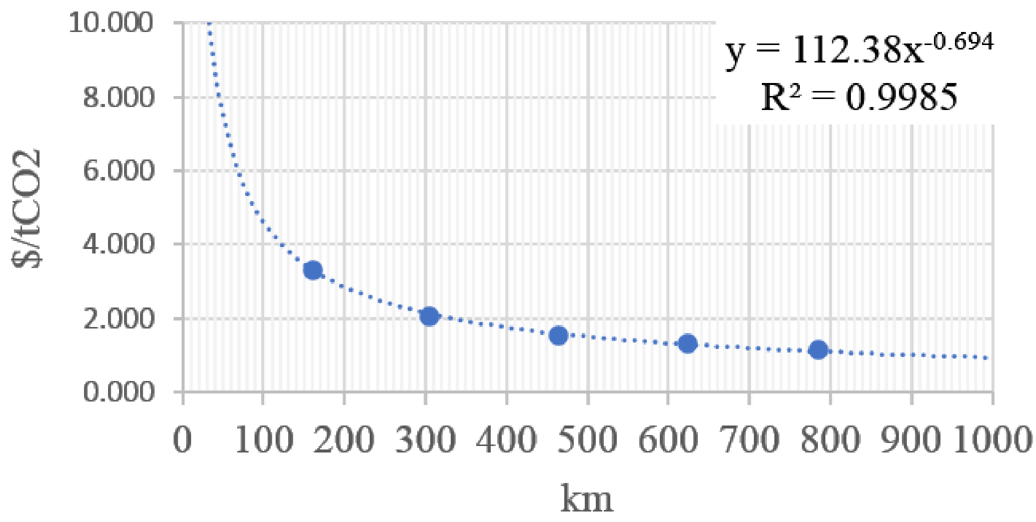

Figure 3-5 Total CO_2 transport costs per kilometer

McCoy and Rubin (2008) analyze pipeline transportation costs in six US regions. When calculating the total cost of construction, they took into account: materials, labor, right-of-way (ROW) and miscellaneous charges. The material category includes the cost of piping, pipe coating and cathodic protection. Labor is the cost of pipeline construction labor. ROW covers the cost of obtaining right-of-way for the pipeline and allowance for damages to landowners' property during construction. Miscellaneous include the cost of surveying, engineering, surveillance, unforeseen situations, telecommunications equipment, taxes, fees for funds used during construction, administrations, overheads and regulatory archive fees. Based on the input data, they conclude that a doubling of the length and diameter of the pipeline results in a 6-fold increase in material cost and doubling the length results in a doubling of the ROW cost. The operating and maintenance costs are not very high compared to the annual capital costs of the pipeline of transport. Pipeline costs consist mainly (usually over 90 %) of CAPEX (Global CCS Institute, 2019). Bock et al. (2003) report that the O&M costs of operating a 480 km CO_2 pipeline are between $65,000 and $100,000 per month. On an annual basis, this amounts to approximately $5,500 per kilometer of pipeline. McCoy and Rubin (2008) estimate the total levelized cost and $1.90 per tonne of CO_2 transported. They assumed that the annual mass transported is equal to the designed capacity of the pipeline. The cost of transportation increases with distance and decreases with the increase of the calculated capacity for a fixed distance. For a typical 500 MW power plant (emissions of approximately 2-3 million tonnes per year), transportation costs can range from $0.25 per tonne for a 10 km pipeline to $6.74 per tonne for a 200 km pipeline based on a 100% capacity factor. Figure 3-6. shows how transport costs vary in Europe with darker colors indicating higher costs. The estimated transport costs are a combination of the distance to the nearest suitable CO_2 storage site and the most accessible CO_2 transport mode to the emitter, which could be rail, pipeline, river barge or sea-going ship. However, Europe is blessed with large areas of suitable geology for CO_2 storage. Selecting the 'long term' scenario reveals how transport costs could be dramatically reduced if storage sites can be developed in areas where the geology and current regulations allow, with costs below €60 per tonne in almost the entire region (even at the highest estimate). The construction of a new pipeline reduces costs for most sites and eliminates any remaining zones of excessive cost. This could be an important option for areas that do not manage or choose to develop storage sites nearby (Clean Air Task Force, 2023b).

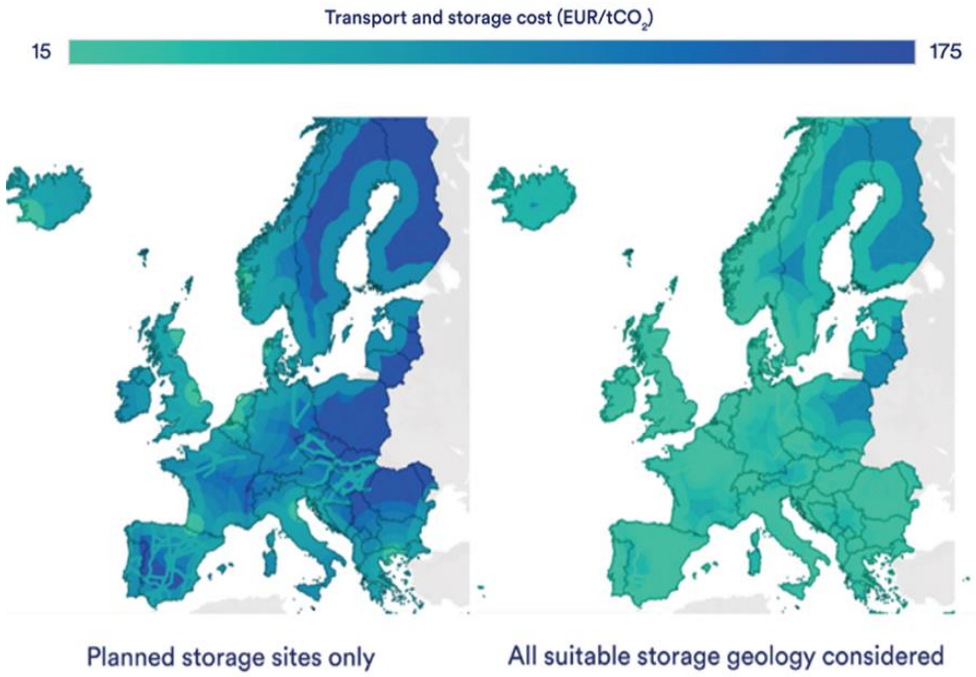

Figure 3-6 CO_2 transport costs (Clean Air Task Force, 2023b)

If all areas with suitable geology can store CO_2, and new pipelines are possible, 98% of facilities have a total cost below €120 per tonne (low estimate). At the high estimate, 60% of facilities come in below €150 per tonne (Clean Air Task Force, 2023b).CO_2 storage costs are highly site dependent as geological characteristic vary from site to site, and injection, labor, drilling, capital and other costs vary regionally. A handful of geological parameters primary determinate whether a reservoir is favorable for CO_2 storage: permeability, thickness, depth, porosity, and lateral continuity (USDOE, 2017). These parameters determine the total volume of CO_2 that can be injected into a reservoir as well as the maximum rate of CO_2 injection per well. Reservoirs with the lowest storage costs are permeable and thick, while reservoir depth can impact the cost of drilling injection and monitoring wells (Smith et al., 2021). Thick, permeable formations are optimal because they can store more total CO_2 and require fewer injection wells. CO_2 storage costs typically decrease as the scale of the storage project increases. As CCS development increases, CCS hubs using shared CO_2 transport and storage infrastructure - are expected to develop and reduce CO_2 transport and storage costs through economies of scale.

Grant (2019) used the NETL CO_2 Saline Storage Cost Model to report CO_2 storage costs for 4 U.S. formations with a range of geologic properties. The model assumes a flat cap on the CO_2 injection rate per well and rigorous monitoring requirements. NPC (2019) uses a modified version of USDOE (2017) that reduces the ration of monitoring wells per injection well, reduces the number of 3D seismic surveys and focuses on formations with the lowest cost (<$15-20/t depending on region). The study calculated CO_2 storage costs using volume-weighted averages across several U.S. regions, with a national average value for of $8/t$CO_2CO_2$ storage cost. The only flaw of the USDOE (2017) model is that it capped cumulative CO_2 injected into each reservoir at levels significantly below 15 Mtpa CO_2.

In order to store CO_2 in saline aquifers, different types of wells (exploration, injection, and monitoring) must be drilled, which account for a large share of the total storage costs. In addition, many published CO_2 storage cost estimates of saline aquifers do not consider the cost of extracting, processing, and disposing of formation fluid to make way for injected CO_2, which is particularly an issue in closed onshore saline formations (Anderson et al., 2019). Regulatory regimes and financial assumptions also impact the cost of CO_2 storage. In the United States, the 45Q tax credit is intended to incentivize investment in carbon capture and sequestration. Previous studies have suggested the cost of CO_2 storage in depleted oil and gas fields is lower than in saline aquifers because the oil and gas fields have already been explored and offer the potential to reuse existing infrastructure (Platform, Z.E., 2011). Other geological formations have potential to store CO_2. Formations that are in the early stage of study include shale formations, basalt formations where CO_2 crystallizes into solid carbonate minerals and shallow offshore sedimentary formations (Gunnarsson et al., 2018).

In 2011, the Zero Emission Platform (ZEP) published an analysis of the technical costs of CCS storage. The cost of storage was estimated to lie in the range of €2-20 /t. The costs of onshore storage sites are typically at the lower end of this range, while offshore storage, which is generally more expensive is at the upper end of the range (Platform, Z.E., 2011). According to (IEA, 2021), onshore storage costs in the USA show that more than half on onshore storage capacity is estimated to be available below €9.21 t/CO_2. Figure 3-7. shows that field capacity has either the largest or second largest effect and the selection of storage reservoirs with respect to their capacity is a key element in reducing the cost of CO_2 storage.

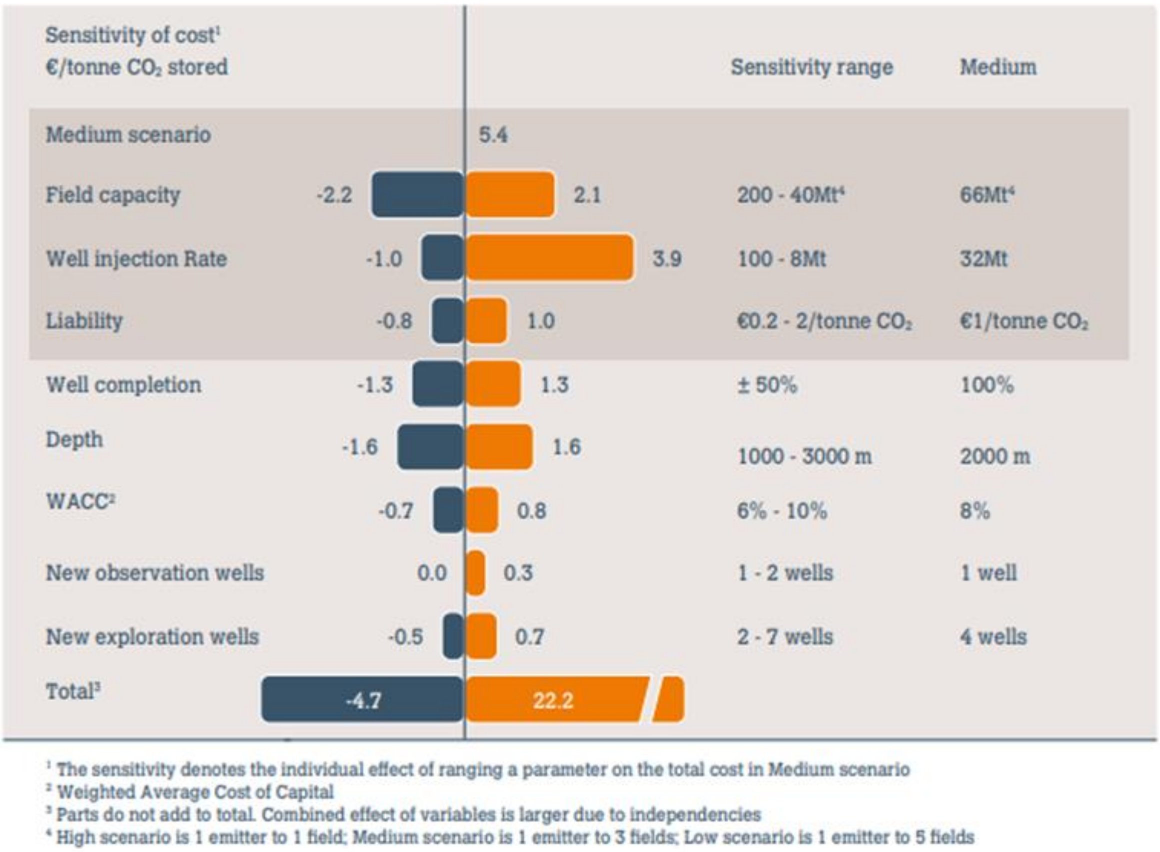

Figure 3-7 Illustration of sensitivities in the storage cost calculations for one storage case (Global CCS Institute, 2019)

In order to calculate CO_2 storage costs by volume in my thesis, the Smith's model based on the assumptions of NPC (2019) and USDOE (2021) was adopted. Three scenarios are shown (low, mean and high) and prices are converted according to current values (Table 3-1).

Table 3-1 CO_2 storage cost range

Mtpa CO_2	Low ($)	Mean ($)	High ($)
1	11.9	20.12	28.34
3.2	6.41	9.77	13.13
6	5.33	8.22	11.11
15	4.95	7.62	10.31

Based on Table 3-1, the curve equations for all of the three scenarios were calculated for the purpose of this thesis. (Figure 3-8.).

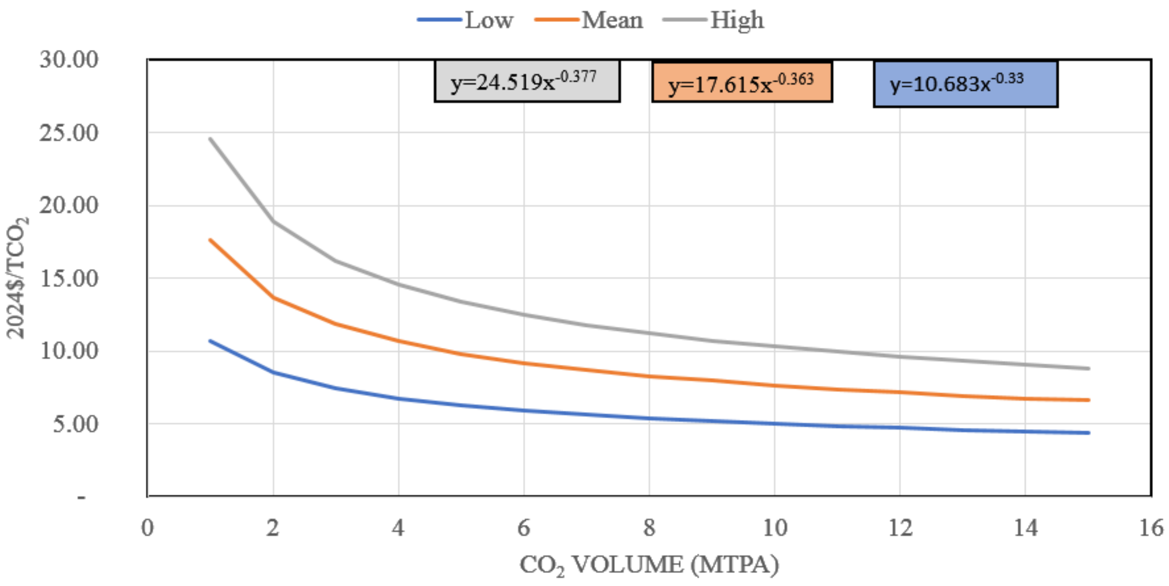

Figure 3-8 CO_2 cost storage range $/tCO2

3.4 Combined CO_2 capture, transport and storage range

After calculating the costs of CO_2 capture, transport and storage, several scenarios were created where the costs of capture, transport and storage were combined and the total costs for a certain scenario were obtained.

Table 3-2. shows the combined transportation and storage costs for different scenarios. The scenarios vary depending on the distance of transport and the cost estimation of low, mean or high storage costs. Costs range from a low value of $4.37/t$CO_2$ to a high value of $35.13t/$CO_2$. Some of the scenarios are not profitable and such projects would probably not be developed.

Table 3-2 Combined CO_2 transport and storage costs for various combinations

CO_2 scale and distance	**Low ($)**	**Mean ($)**	**High ($)**
1 Mtpa, 0 km	10.68	17.62	24.52
1 Mtpa, 30 km	21.28	28.23	35.13
1 Mtpa, 60 km	17.23	24.17	31.07
1 Mtpa, 90 km	15.63	22.57	29.47
4 Mtpa, 0 km	6.76	10.65	14.54
4 Mtpa, 30 km	17.37	21.26	25.15
4 Mtpa, 60 km	13.31	17.20	21.09
4 Mtpa, 90 km	11.71	15.60	19.49
6 Mtpa, 0 km	5.91	9.19	12.48
6 Mtpa, 30 km	16.52	19.80	23.09
6 Mtpa, 60 km	12.46	15.74	19.03
6 Mtpa, 90 km	10.86	14.14	17.43
12 Mtpa, 0 km	4.71	7.15	9.61
12 Mtpa, 30 km	15.32	17.76	20.22
12 Mtpa, 60 km	11.26	13.70	16.16
12 Mtpa, 90 km	9.66	12.10	14.56
15 Mtpa, 0 km	4.37	6.59	8.83
15 Mtpa, 30 km	14.98	17.20	19.44
15 Mtpa, 60 km	10.92	13.14	15.38
15 Mtpa, 90 km	9.32	11.54	13.78

3.5 Total costs of scenarios for each company

Given that the work is based on the calculation of capture, transport and storage costs for individual companies in Slavonia (Croatia) (NEXE, TETO Osijek, Uni Viridas and Delta Energy) and a company from Hungary (Beremend) that would transport CO_2 Bockovci and store it there, the air distance between the two places was taken and the prices were taken from the chapter where transport prices were calculated. Distances were measured using a geoportal.hr (Figure 3-9.).

Figure 3-9 Locations of Croatian companies and distance from Bockovci

Given that the company Beremend is not located in Croatia, but in Hungary, the distance to the storage location was obtained using Google maps (Figure 3-10.).

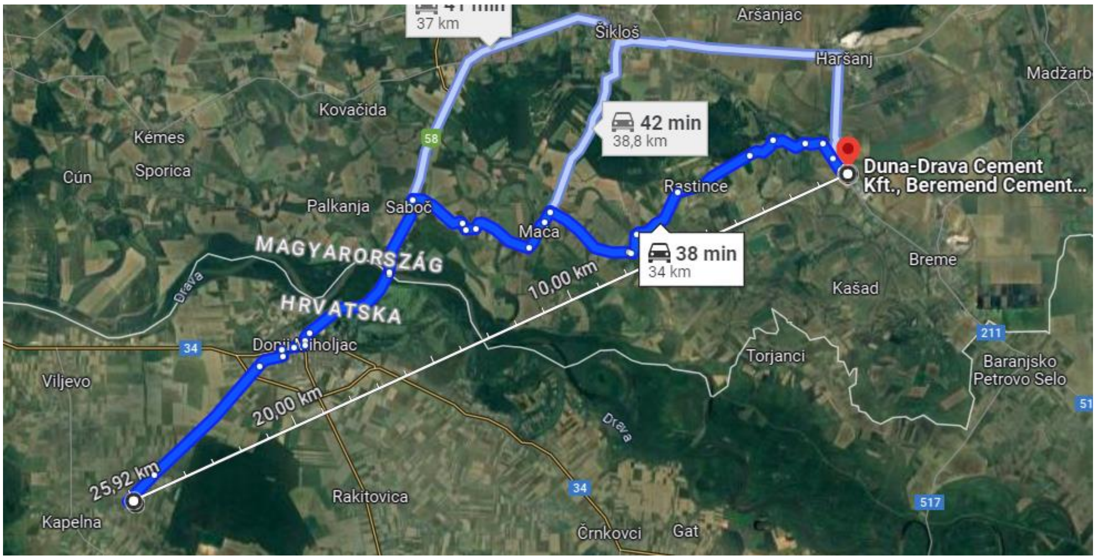

Figure 3-10 Distance from Beremend to Bockovci

Based on the calculations that obtained the predicted costs of capture, transport and storage, costs were created for a particular part of the CCS process, where the costs of individual companies are shown in $/t$CO_2$ (Table 3-3., Table 3-4., Table 3-5.). With the previous assumptions, two scenarios for capture are shown, one for transport and three for storage and with their combinations six different scenarios for each company are shown (Table 3-6.).

Table 3-3 Total CO_2 transport costs

Transport			
	Distance to Bockovac (km)	**Amount of CO_2 (Mtpa)**	**$/t$CO_2$**
NEXE	28.42	0.71	11.01
Uni Viridas	74.43	0.11	5.64
TETO Osijek	54.05	0.07	7.05
Beremend	25.92	0.51	11.73
Delta Energy	60.01	0.50	6.55

Table 3-4 Total CO_2 storage costs

Storage			
	Low ($/t$CO_2$)	**Mean ($/t$CO_2$)**	**High ($/t$CO_2$)**
NEXE	11.96	19.94	27.89
Uni Viridas	22.13	39.25	56.35
TETO Osijek	25.69	46.25	66.80
Beremend	13.34	22.49	31.60
Delta Energy	13.43	22.65	31.84

Table 3-5 Total CO_2 capture costs

Capture		
	Low ($/t$CO_2$)	**High ($/t$CO_2$)**
NEXE	72	145
Uni Viridas	61	122
TETO Osijek	61	122
Beremend	72	145
Delta Energy	61	122

Table 3-6 Total costs for various combinations for each company

	NEXE ($/t$CO_2$)	**Uni Viridas ($/t$CO_2$)**	**TETO Osijek ($/t$CO_2$)**	**Beremend ($/t$CO_2$)**	**Delta Energy ($/t$CO_2$)**
T+LS+LC	94.97	88.77	93.74	97.07	80.98
T+LS+HC	167.97	149.77	154.74	170.07	141.98
T+MS+LC	102.95	105.89	114.30	106.22	90.22
T+MS+HC	175.95	166.89	175.30	179.22	151.20
T+HS+LC	110.90	122.99	134.85	115.33	99.39
T+HS+HC	183.90	183.99	195.85	188.33	160.39

T-transport scenario, LS- low storage, MS-mean storage, HS-high storage, LC-low capture, HC-high capture

4 CONCLUSION

Based on the calculated values, the CCS process costs for five companies were determined, which range from \$80.94 t/CO_2 to \$195.95 t/CO_2. Pipelines are expected to remain the main way of transporting CO_2 in the future, and transport costs can increase or decrease depending on the configuration of the area, the conditions, and whether the pipeline transport is onshore or offshore. The expansion of transport network in Europe would reduce the costs. An opportunity to reduce the costs of CO_2 transport lies in increasing the CO_2 flow through the pipeline, by combining the captured CO_2 from multiple sources through a larger pipeline to a common storage site. The available data on the costs of the CCS process, and the individual segments, are still limited and mostly based on assumptions. If the EU goal of achieving net zero emissions is to be achieved, it will be necessary to build infrastructure for the transport and storage of CO_2 in much larger quantities. The aim is to create several hubs and build a transport network so that the costs of CCS processes are lower in less developed areas. CO_2 capture still represents the greatest contribution to the cost of CCS. Despite the fact that the costs of CCS are high compared to traditional electricity generation, electricity producers are currently emitting large amounts of CO_2 into the atmosphere. In view of the current policies in the EU and the world and the emission limits, they will no longer be able to work the way they used to.

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IZJAVA

Izjavljujem da sam ovaj rad izradio samostalno na temelju znanja stečenih na Rudarsko-geološko-naftnom fakultetu služeći se navedenom literaturom.

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STATUTORY DECLARATION

I declare that I wrote this Thesis and performed the associated research myself, using the knowledge gained at the Faculty of Mining, Geology and Petroleum Engineering and the literature cited in this work.

Domagoj Mrnjavčić

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KLASA: 602-01/24-01/83
URBROJ: 251-70-12-24-2
U Zagrebu, 28. 6. 2024.

Domagoj Mrnjavčić, student

RJEŠENJE O ODOBRENJU TEME

Na temelju vašeg zahtjeva primljenog pod KLASOM 602-01/24-01/83, URBROJ: 251-70-12-24-1 od 29.05.2024. priopćujemo vam temu diplomskog rada koja glasi:

CARBON CAPTURE AND STORAGE SCENARIOS IN SLAVONIA

Za mentora ovog diplomskog rada imenuje se u smislu Pravilnika o izradi i obrani diplomskog rada Prof. dr. sc. Domagoj Vulin nastavnik Rudarsko-geološko-naftnog-fakulteta Sveučilišta u Zagrebu i komentoricu Dr. sc. Lucija Jukić.

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