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Economic and Practical Feasibility of Co_2 Sequestration

Millicent Agyeiwaa Opoku* and Mohan Kelkar

McDougall School of Petroleum Engineering, The University of Tulsa

***Corresponding author:** Millicent Agyeiwaa Opoku, McDougall School of Petroleum Engineering, The University of Tulsa.

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Abstract
This study examines the economic and practical feasibility of CO_2 sequestration, which includes the costs of capture, transport, and storage. Particular attention is paid to the impact of the concentration of CO2 in the effluent stream, which can significantly impact the cost of separation. We collected data from across the world for 2024 to calculate the cost of sequestration. We assume that it is logical to first sequester relatively pure sources of CO_2 before choosing lower concentration CO_2 sources. Results show a clear inverse relationship: high-purity industrial streams from ethanol (~99%), ammonia (~95%), and ethylene oxide (~90%) plants achieve a total sequestration cost of about \$5-\$21 billion depending on the scenario. Medium-concentration industries such as cement (~30%) and steel (~23.5%) require a total CO_2 sequestration cost of about \$209-\$256 billion, adding up to tens of billions of dollars. Removing CO2 from coal-fired power (~14%) approaches \$1.5 trillion in total sequestration costs, while direct air capture of CO_2 sequestration is about 7 trillion. Removing CO_2 from all the sources will require an annual cost between \$9 and \$12 trillion. These costs are prohibitively expensive and impractical. Projects such as Sleipner (~\$17 per ton) and Decatur, Illinois, confirm that long-term CO_2 storage can be achieved securely. The cumulative cost analysis shows that while high-purity sources are limited in scale, they represent the most practical near-term opportunities. Low-concentration and diffuse sources remain very expensive without major advances in technology and stronger policy support.

Keywords: CO_2 Sequestration, Carbon Capture and Storage (CCS), Capture Cost Analysis, Cost of Separation Cost of Removal, Geological Sequestration, Techno-Economic Analysis.

Introduction

United Nations considers climate change to be a global emergency. One important aspect of climate change is the rising temperature of the earth. Compared to pre-industrial levels, the temperature of earth has risen by 1.2 degrees Celsius. To combat climate change, United Nations recommends that the global emissions of greenhouse gases need to be substantially reduced to limit the temperature rise of earth to no more than 2 degrees Celsius (and preferably 1.5 degrees Celsius) above pre-industrial levels. United Nations estimates that to maintain the global warming less than 1.5 degrees, emissions of greenhouse gases need to be reduced by 45 % by 2030 and be eliminated by 2050 [1,2].

There are several ways in which CO_2 can be emitted and released into the atmosphere; it can be either through point sources or dispersed (diffused) sources. Some of the sources include fossil fuel–based power plants, industrial facilities, waste management facilities, large-scale agricultural operations, aviation and shipping hubs, and land use and deforestation. Figure 1 represents the global greenhouse gas emission by the different sectors [3].

There are many pathways by which greenhouse gas emissions can be reduced. One of the easiest solutions is to simply stop using fossil fuels for energy sources; however, that solution is not practical and almost impossible to achieve based on historical data. Another solution is to capture CO_2 in the atmosphere and remove it from the atmosphere so that it can be permanently stored in a form so that it does not impact climate. The world has emitted over 1.5 trillion tonnes of CO_2 cumulatively since 1751. Figure 2 shows the evolution of CO_2 emissions since pre-industrial times [4-6].

Even though there are multiple ways by which CO_2 can be sequestered, including terrestrial sequestration, this paper concentrates on the feasibility of CO_2 storage underground. The paper does not delve into technical feasibility and challenges associated with injecting CO_2 underground. Instead, based on the existing technologies, it assesses the economic feasibility and associated costs for sequestering (storing) CO_2underground [7].

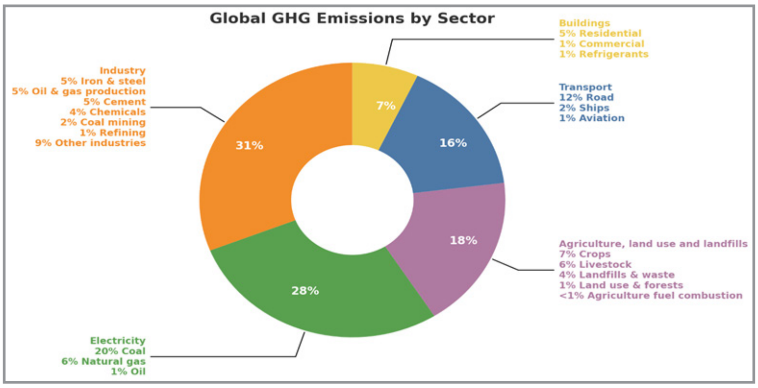

Figure 1: The Global Greenhouse Gas Emission by Sector, Indicating that the Industry Sector is the Dominant Contributor. Data Source: [8].

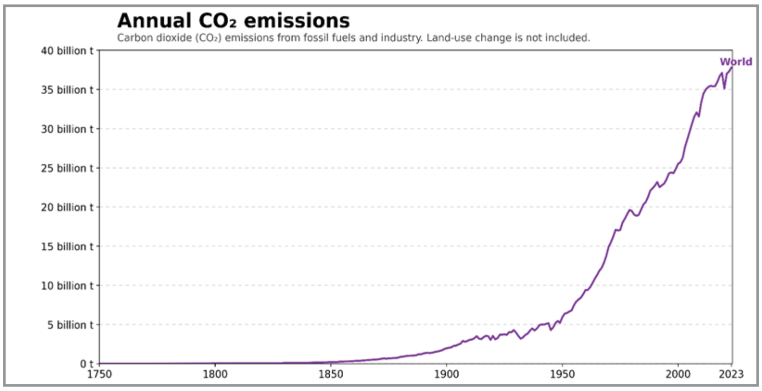

Figure 2: The Annual CO2 Emissions from Fossil Fuel and Industry from 1750 to 2023, land-use Change is not Included. Data Source [9].

Steps Involved in CO_2 Sequestration

CO^2 sequestration requires four steps: separation, transportation/compression, injection and storage, and monitoring. The cost of separation is sensitive to concentration of CO^2 in the effluent stream. When considering CO^2 sequestration, we will need to add all the costs to calculate the overall costs of sequestration. We consider each of those four costs separately.

Methods Involved in CO_2 Separation

Carbon capture and separation technologies that extract CO_2 from industrial emissions are vital components of strategies to mitigate climate change. There are several CO_2 extraction methods for gas stream function that use different physical or chemical principles at various technological development phases. This section talks about fundamental CO_2 separation methods, such as absorption and adsorption, along with membrane separation, cryogenic separation, and calcium looping.

Absorption is the process where a liquid absorbent within an absorption column interacts with a gas stream rich in CO_2 from power plants. Adsorption is the process by which CO_2 molecules adhere to the interior regions of a solid surface. This process is primarily by physical forces but also possibly by chemisorption. Membranes are used to separate CO^2 by a selective process in which molecules of CO_2 pass through a narrow barrier while other gases remain behind. Cryogenic CO_2 separation works by cooling CO_2 to liquid or solid states, which enables simple separation from lighter gases. The calcium looping (CaL) process operates as a high-temperature cyclic system that traps CO_2 via a reversible reaction between calcium oxide (CaO) and carbon dioxide. Significant literature exists in each of these processes. However, for our work, we summarize in Table 1 each of those processes in brief. We provide information on advantages and disadvantages of each method, the limits of CO_2 concentration each method can tolerate, the scale of operation over which each method has worked in the field and the approximate cost of each method [10-11].

Table 1: Comparison of CO2 Capture Processes by Operational and Economic Characteristics

Process Used	Advantages	Disadvantages	Min & Max CO_2 Concentration Processed	Maximum Scale of Operation	Cost Range ($/t$CO_2$)	CO_2 Purity at Outlet

Absorption (Solvent Scrubbing)	Mature and widely used; high capture efficiency (90%+); outlet CO_2 >99%; proven at coal power plants & ammonia facilities	High energy demand (3.5–4 GJ/tCO_2); solvent degradation; 20–30% efficiency penalty for coal plants	Works at low CO_2 partial pressure (~10–15% in flue gas)	Large commercial scale – Boundary Dam captures ~1 MtCO2/year	$40–100	>99%
Adsorption (Solid Sorbents)	Flexible cyclic operation; can reach >95% purity; scalable to $MtCO_2$/year (e.g., Port Arthur plant)	Sorbent degradation and replacement costs; lower performance with dilute flue gas; water vapor interference	Post-combustion ~15% CO2; high-pressure streams up to ~45% CO_2	Port Arthur plant: ~1 Mt CO_2/year	$50–150	95%+ (depending on cycle)
Membrane Separation	No chemical solvents needed; modular/compact; effective at high pressure; can be hybridized with cryogenics	Limited selectivity (permeability–selectivity trade-off); requires compression for dilute streams; fouling by SOx/NOx	Works well at 8–10% CO2 (natural gas) to ~30–60 bar; post-combustion ~14% CO_2 requires compression	Large natural gas processing plants (pipeline-scale)	$15–55 (high-pressure), $40–100+ (flue gas)	40–60% (1st stage); 90% possible with multistage
Cryogenic Separation	Very high purity (>99%); proven in LNG & food-grade CO_2; large production scale possible	High refrigeration cost; limited to high CO_2 concentration streams; still at pilot stage for dilute flue gas	Best for high CO_2 (>50%); not economical for ~15% flue gas	Hundreds of thousands of tons/year (industrial)	$55–130	>99%
Calcium Looping	Uses cheap, abundant limestone; high capture rate (85–90%); >95% CO_2 purity in calciner output; lower energy penalty than amines	High temperature needed (650–950 °C); sorbent sintering/reduced reactivity; still not commercial	Flue gas ~10–15% CO2	Pilot: HECLOT plant (Taiwan) ~1 tCO_2/hour; projected 50 MWe demo	<$30 (optimistic); $58–80 typical	>95%

Methods of Transportation Involved in CO_2 Sequestration

The operation of carbon capture utilization and storage (CCUS) technologies depends on effective CO_2 transportation systems that link locations for capturing carbon dioxide and storage facilities. The transportation methods include pipelines, which remain the dominant choice for large-scale CO_2 movement; trucks or rails, which use pressurized tankers for transportation; and marine shipping. Challenges and considerations in CO_2 transportation include safety and risk management; CO_2 quality materials; cost and economic viability; and regulatory and public acceptance [12-14].

CO_2 needs to be compressed at high pressures for it to remain in a dense phase during the transportation of CO_2 through pipelines. Operating conditions are around 10-15 MPa and 15-30°C for onshore CO_2 pipelines. The minimum pressure is kept above the CO_2 critical pressure of 7.38 MPa to maintain a supercritical or liquid state along the pipeline. Water (H_2O), oxygen (O_2), hydrogen sulfide (H_2S), and nitrogen oxides (NOx) are some of the impurities present in the CO_2 stream that negatively affect the pipeline performance. Water forms carbonic acid, which leads to internal corrosion, and sulfur or oxygen impurities further intensify this degradation. As a result, CO2 transported for CCS applications must meet tight gas-quality specifications to maintain system safety and durability [15,16].

Pipelines are more economical for transporting large volumes of CO_2 over long distances because the gas is kept in a dense phase, typically at 8.5-15 MPa and 13-44°C, which improves flow efficiency. Where pipelines are not feasible, such as offshore storage sites, CO_2 can be transported by ship in a liquefied form. To achieve this, the temperature needs to be lowered to about -50°C, and the pressure needs to be kept at a moderate level (0.7 MPa in low-pressure designs or 1.5 MPa and -30°C in medium-pressure designs). Transporting CO_2 through shipping is more flexible but requires additional liquefaction and storage infrastructure, making it expensive than pipelines [17].

Geological Storage of CO_2

Injecting CO_2 at depths beyond 800 meters into suitable geological formations transforms CO_2 into a supercritical fluid and initiates several trapping mechanisms that guarantee the long-term sequestration of CO_2. Several mechanisms, operating through multiple time intervals, support geological storage security. The primary mechanisms for trapping CO_2 include structural and stratigraphic trapping, as well as residual (capillary) trapping, solubility trapping, and mineral trapping. Structural and stratigraphic trapping is when CO_2 is injected into an aquifer, displaces brine and forms a plume of less dense supercritical CO_2, which is contained by caprock. Residual trapping is when the brine returns to fill smaller pores in the rock, trapping CO_2 bubbles through the capillary forces. Solubility trapping refers to the slow dissolution of trapped CO_2 in the surrounding brine, forming carbonic acid. Over time mineral trapping happens when low-pH brine weathering silicate minerals release divalent metals (Ca, Mg, Fe) that combine with CO_2, forming stable carbonate minerals like limestone ($CaCO^3$) [18-20].

As shown in Figure 3, CO_2 storage security increases over time as trapping mechanisms evolve. Structural and residual trapping dominate for few years after injection, while solubility and mineral trapping strengthen the storage over hundreds to thousands of years [21].

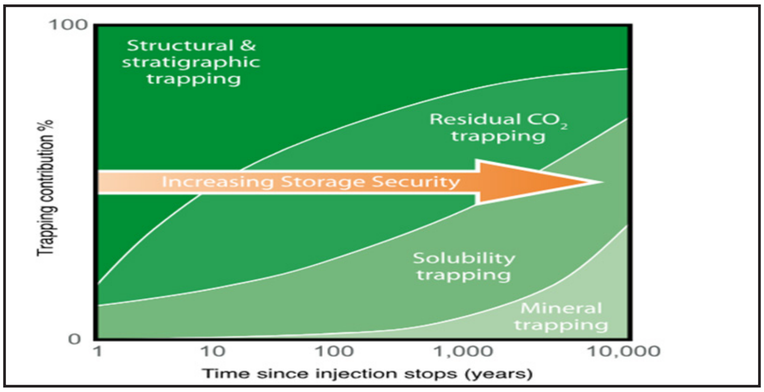

Figure 3: Evolution of CO_2 trapping mechanisms and storage security over time

Saline aquifers, especially deep brine-filled formations, hold significant global capacity for carbon capture and storage (CCS) projects. Depleted oil and gas reservoirs also serve as excellent storage sites due to their proven seals and existing infrastructure. Additionally, while unmineable coal seams and organic-rich shales can store CO_2 via adsorption, their capacity is limited compared to saline aquifers. Basalt formations have potential for reactive capacity but are less common geographically [22, 23].

Some of the challenges and risks involved in the geological storage of CO_2 are making sure it stays in place, stopping it from leaking, causing earthquakes, getting people to accept it, and figuring out how it affects the environment [24].

Monitoring of CO_2 After Sequestration

Monitoring CO_2 storage projects is essential to ensuring the injected CO_2 remains contained in the reservoir and free from leaking. Some of the techniques involved in ensuring proper monitoring are time-lapse seismic surveys (4D seismic); vertical seismic profiling (VSP) and micro-seismic monitoring; and satellite and remote sensing techniques (InSAR) [25].

The benefits of continuous monitoring of CO2 storage projects include safety and environmental protection; regulatory compliance and liability management; gaining the public's trust; improved reservoir management and learning; and knowledge sharing and research value [26].

Cost of CO^2 Separation

In this paper, we have conducted scoping study to calculate the actual costs of CO_2 sequestration based on certain assumptions. These assumptions may not hold true and variations in our estimations will be required. Our assumptions are as follows:

- It is more efficient to remove CO_2 from highly concentrated sources before dealing with low concentration sources. Ammonia plants and fertilizer plants are examples of sources where effluent stream contains highly concentrated CO_2, and it is cheaper and easier to remove CO_2.
- It is more efficient to remove CO_2 from single point source – such as refinery, power plants, etc. – compared to CO_2 from diffused sources (e.g., from atmosphere)
- The cost of CO_2 sequestration is independent of the location of the source. It is possible that depending on the infrastructure, different countries will have different degrees of difficulty in CO_2 sequestration processes. For the purposes of scoping study, we considered CO_2 evolved in the globe and assumed that reduction in CO_2 concentrations needs to be accomplished across the globe.
- We only considered yearly cost of storage (using 2024 as a sample year) to show the scale of expenses. Obviously, depending on a particular year and the emitted amount of CO_2, the costs will vary.
- We did not consider government policies which can impact the incentives to remove CO_2.

We begin our calculations by first projecting the total emissions of CO_2 from various sources as shown in Figure 4. In 2024, cumulative emissions from various sources exceeded 37 Gtons of CO_2. Every year the amount of CO_2 emitted will exceed in the future but let us only consider 2024 a snapshot of emission and estimate the cost of sequestering CO_2. The graph starts with lowest concentration of CO_2 and progressively increases concentration of CO_2. It is very clear from the graph that more than 35 Gtons of CO2 come from sources where the CO2 concentration in the effluent is less than 25 %. This information is relevant since the cost of CO_2 separation is directly related to the concentration of CO_2 in the effluent stream.

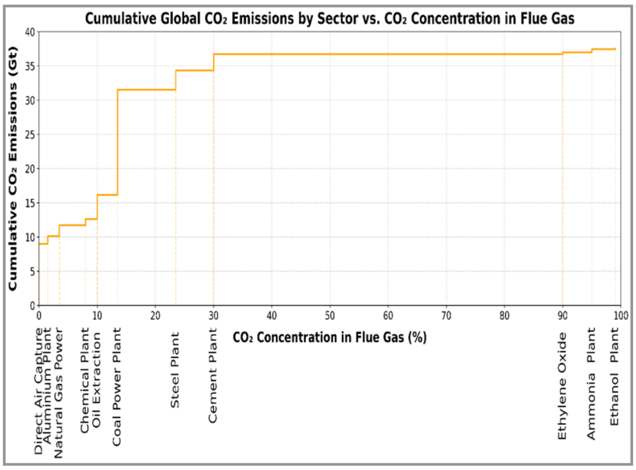

Figure 4: Cumulative global CO_2 emissions by sector plotted against CO_2 concentration in flue gas [29-35].

Thermodynamically, lower is the concentration of CO_2 in the effluent stream, higher is the cost to separate CO_2 into purified form. Figure 5 shows the work required to achieve CO_2 purity from impure stream in kJ/mol. The energy requirement for CO_2 separation is approximately equivalent to the cost of CO_2 separation. As the concentration of CO_2 gets smaller in the effluent stream, the energy requirement increases exponentially. Different lines on this graph indicate different levels of purity achieved as well as what % of CO_2 is captured. We can generalize to state that higher purity levels are achieved at higher costs, and higher % of CO_2 is captured at higher cost.

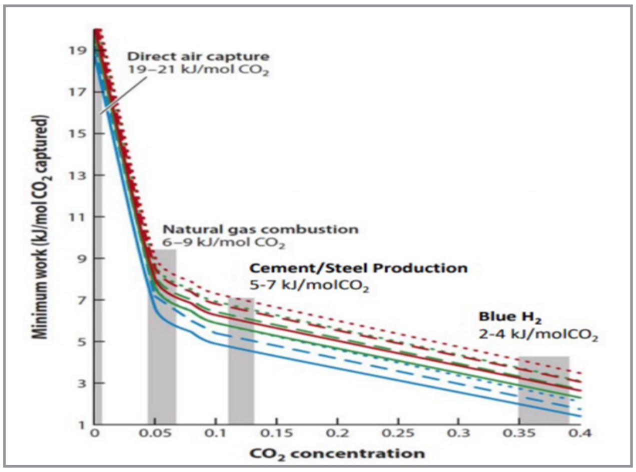

Figure 5: Minimum work for CO_2 capture versus concentration in flue gas at different capture fractions and purities.

Shaded regions show typical ranges for direct air capture, natural gas combustion, cement/steel, and blue hydrogen sources.

Figure 6 is consistent with Figure 5 which shows the cost of CO_2 separation for different sources. The insert in the figure shows limited scale on x axis so that costs can be easily visualized. The low concentration sources such as direct air capture can range from \$500 to \$1,000 per ton, although high purity streams from ammonia or ethanol facilities are frequently below \$50 per ton. The variations between low, middle, and high-cost estimates indicate uncertainties caused by technology selection, energy use, and plant size. The difference explains why high concentration point sources are regarded as cost-efficient and the dilute sources continue to pose economic challenges [36-37].

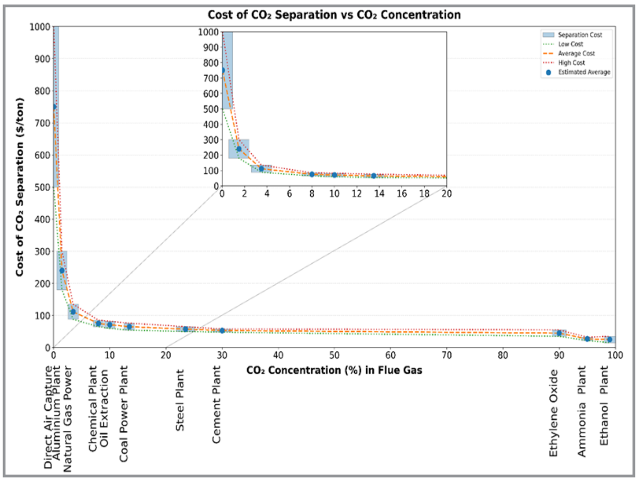

Figure 6: Capture costs as a function of CO_2 Concentration.

Our methodology of calculating the cost of CO_2 separation can be explained as follows:

- We first estimated the total amount of CO_2 emitted in 2024 from various sources. We categorized them as point source or diffused source. We plotted the CO_2 emitted from each source starting with the highest concentration and progressively going to 0.4 % concentration for all the diffused sources.
- We then assumed that the separation of the highest concentration source will happen first followed by progressively lower concentration of CO_2 since it is most efficient to remove the high concentration CO_2 source first.
- We multiplied the cost of separation of CO2 per ton by the total tonnage that can be removed for each source (starting with the highest concentration source) and then cumulatively added the costs as each source is added to the previous source. The last source of CO_2 will be the CO_2 in the atmosphere.

Figure 7 shows the yearly emissions of CO_2 from various sources in 2024. Each source is listed below and the cumulative amount of CO_2 in Gtons is shown on y axis as each source is added. The plot on x axis begins at 100 % CO_2 concentration and slowly reduces to 0.4 % so that one can clearly see how much CO_2 is added by each source. The graph is plotted in reverse so that we can visualize how removing CO_2 from successive sources will result in less CO_2 remaining in the atmosphere [38-40].

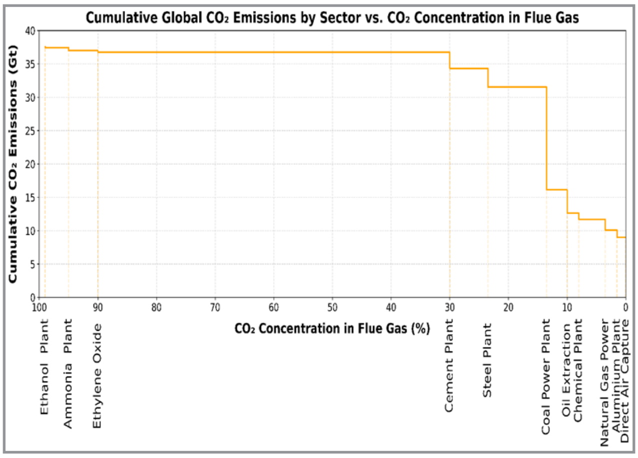

Figure 7: Cumulative global CO_2 emissions by sector plotted against CO_2 concentration in flue gas.

By combining the data from figure 7 with the average cost of separation from Figure 6, we created Figure 8 which shows the costs in billions of dollars as high purity CO_2 streams are first separated followed by lower purity separation. The costs of separating high purity CO_2 streams approach just few billion dollars but the amount of CO_2 removed is fairly small. As we add coal fired power plant, the costs approach 1.32 trillion (1320 billion dollars). If we include direct air capture, the cost will reach 9 trillion dollars (9000 billion dollars).

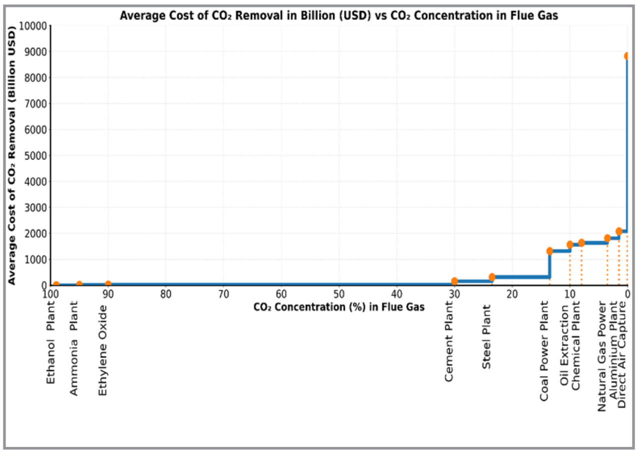

Figure 8: Costs of separation as a function of CO_2 concentration in effluent stream.

Figure 9 takes a closer look at the CO_2 sources up to cement and steel plants. The cost of removing CO_2 with up to concentration of 23 % of CO_2 in effluent stream is about 315 billion dollars per year. These numbers are hard to read in Figure 8.

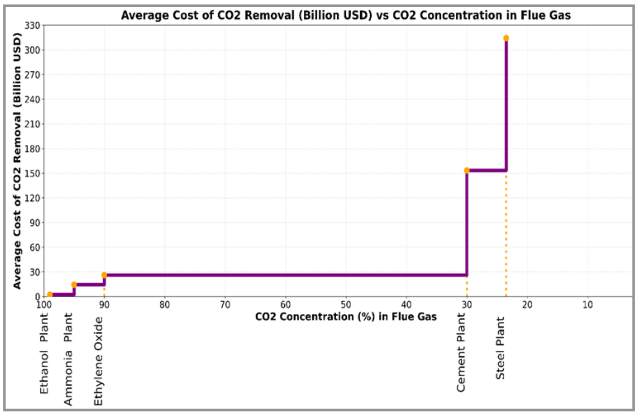

Figure 9: Cost of Removal of CO_2 with higher concentrations of CO_2 in effluent streams.

Ethanol plant, which produces an almost pure stream of CO_2 (~99%), has the lowest removal cost at only about $2.3 billion. Ammonia (~95%) and ethylene oxide (~90%) plants are a bit higher, with cumulative costs of about $26 billion. By contrast, cement (~30%) and steel (~23.5%) plants show a much steeper cost, cumulatively making the cost of $315 billion. The figure clearly shows how capturing from nearly pure CO_2 streams is far more affordable than from medium-purity sources like cement and steel, making these high-concentration industries attractive starting points for sequestration .

Figure 10 shows the cumulative cost of removal of CO_2 as a function of % of CO_2 removed from the atmosphere. These numbers are calculated based on average of cost of CO_2 removal.

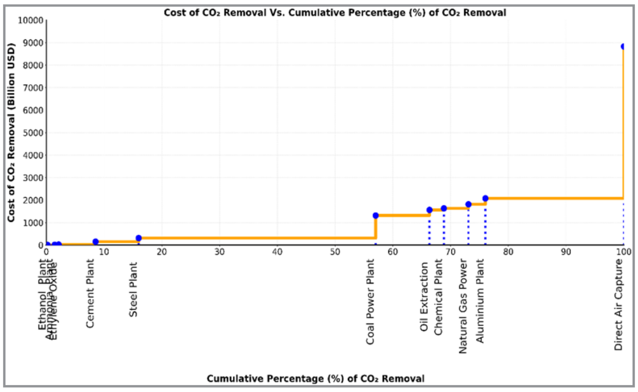

Figure 10: Cumulative cost of CO_2 separation as a function of cumulative amount of CO_2 that will be removed from the atmosphere.

The cost of removing about 9 % of CO_2 (about 3.2 Gtons) from the atmosphere is quite small. Removing 57 % of CO_2 (about 21.4 Gtons) becomes quite expensive, totaling about 1.32 trillion dollars. After that costs increase very rapidly. The cheapest sources come from ethanol, ammonia, and ethylene oxide plants, which cost only a few billion dollars to capture but make up a very small share of emissions. Costs rise steadily when cement and steel are added (with cumulative amount of about 15 % of the total CO_2 emitted) and grow much larger with coal power and other medium-concentration industries, passing \$1.32 trillion. The biggest increase comes from direct air capture, which alone pushes costs around \$9 trillion. The figure shows that high-purity sources are affordable, but they only cover a fraction of the challenge, leaving the more dilute sources as the real economic problem.

Figure 11 below shows the minimum cost of removing CO_2 based on minimum costs of separation. To remove all the CO_2 from the atmosphere, the cost will approach 6.3 trillion dollars.

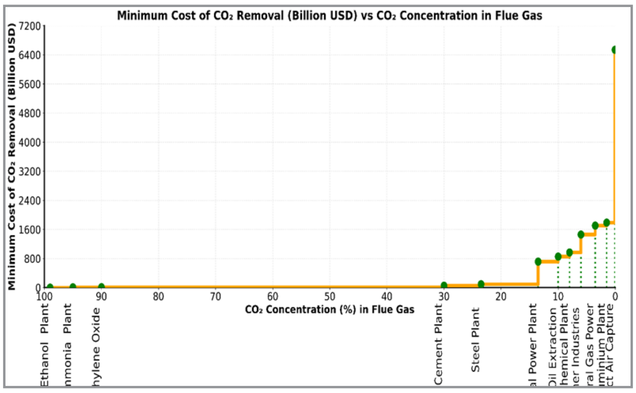

Figure 11: Minimum Costs of Removing CO_2 from Different sources.

At the high end of concentration, ethanol (~99%), ammonia (~95%), and ethylene oxide (~90%) plants remain very affordable, with cumulative removal costs of only \$20 billion. Medium-concentration industries like cement (~30%) and steel (~23.5%) are much higher, making cumulative costs of about \$276 billion. Coal power plants, with about 14% CO_2 in their flue gas, already push the cumulative cost to about \$1107 billion, while direct air capture stands out as the most expensive option, even at its minimum, about \$6.3 trillion in total.

Figure 12 below shows the cost of CO_2 separation based on maximum costs of CO_2 separation.

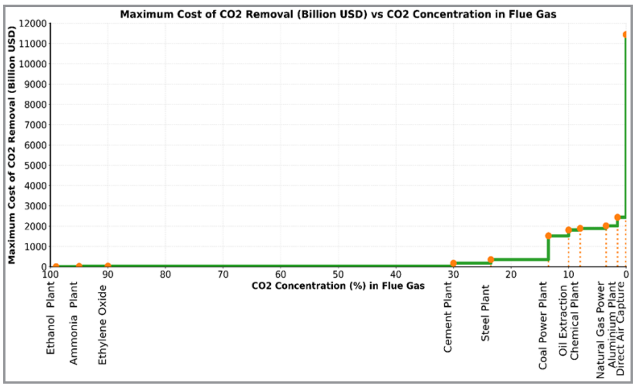

Figure 12: Maximum cost of CO_2 separation

Even at their upper limits, high-purity sources such as ethanol (~99%), ammonia (~95%), and ethylene oxide (~90%) remain relatively cheap, with a cumulative cost of about \$32 billion. The picture changes for medium-concentration industries: cement (~30%) and steel (~23.5%) plants CO_2 removal increases cumulative costs of 353 billion. Coal power plants emit approximately 14% CO_2 and incur cumulative cost of about \$1.53 trillion. Direct air capture is the most expensive option, with cumulative costs exceeding \$11.4 trillion.

Total Cost of CO_2 Sequestration

The cost of CO_2 separation is one of the most important costs which depends on the CO_2 concentration in the effluent stream. However, that is not the only cost in sequestering CO_2 in the ground. Other costs include cost of transportation/compression, costs of storage and costs of monitoring. We assumed the costs of transportation to be \$ 17/ton (the details of how we arrived at this number are in the Appendix), we assumed the average cost of storage to be \$ 15/ton (the details are in the Appendix), and we assumed the cost of monitoring to be \$ 2/ton. That is, total cost of compression/transportation, storage and monitoring is approximately \$ 34/ton. If we include these costs on top of separation costs, we can generate Figure 13 which includes the average cost of sequestration. Figure 13 shows the total cost of sequestration as a function of % of CO_2 present in the effluent stream. Figure 14 shows the total cost of sequestration as a function of % of CO_2 removed from the atmosphere.

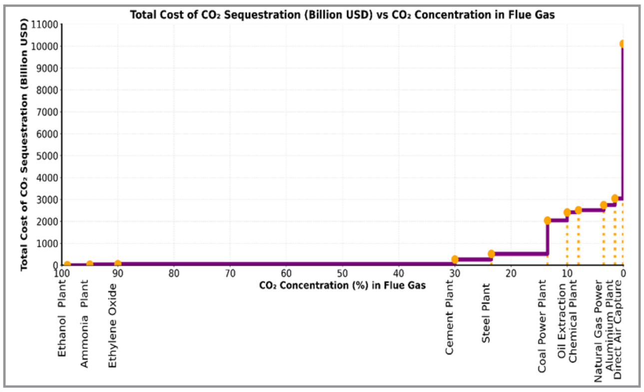

Figure 13: Total cost of sequestration as a function of % of CO_2 present in the effluent stream.

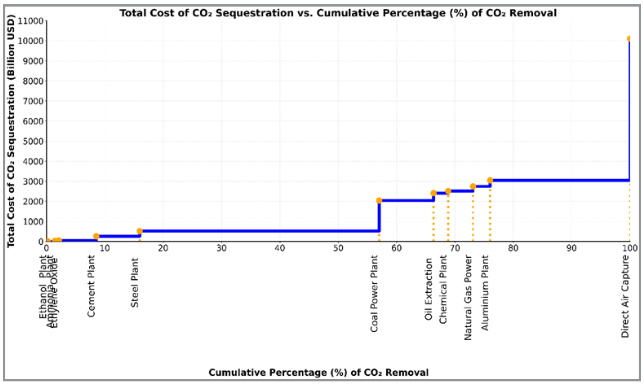

Figure 14: Total cost of sequestration as a function of % of CO_2 removed from the atmosphere.

Examining the numbers in Figure 14, removing about 9% of CO_2 in the atmosphere (about 3.2 Gtons) is approximately 262 billion dollars. Removing about 57% of CO_2 is little over 2 trillion dollars. Beyond that point, the costs of sequestering CO_2can be very expensive.

Figure 15 takes a closer look at the CO_2 sequestration with lower percentage (%) of CO_2 removed from the atmosphere from ethanol plant to steel plant. The cost of removing CO_2 with up to about 9% of CO_2 removed from the atmosphere is about 262 billion dollars per year. These numbers are hard to read in Figure 14. After including the costs of transportation, storage and monitoring, the costs of sequestration for high concentration CO_2 have almost doubled. These costs show serious economic challenges even for removing about 9% of CO_2 from the atmosphere. Without significant government support, it would be very difficult to achieve this sequestration. Recall these costs are annual costs and will have to be incurred every year.

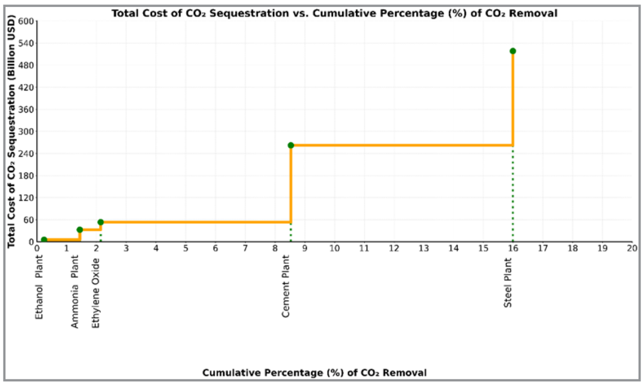

Figure 15: Total cost of CO_2 sequestration with lower percentage (%) of CO_2 removed from the atmosphere.

We realize that the numbers presented in the above graphs represent only scoping study and the actual costs may vary depending on individual government incentives. We also realize that there has been significant effort in trying to improve the separation technologies to reduce the cost which may have significant impact of the costs of CO_2 sequestration. However, many of these technologies have not been applied on a large scale projects so they remain experimental at this juncture. The impact picture that emerges from this scoping study is that CO_2 sequestraion is an immensely challenging project. Even if the technologies are available and can be successfully deployed, the infrastructure requirements are tremendous and very challenging. To frame this problem in proper context, the overall investment in oil and gas industry today approaches 10 trillion dollars. This investment is made over more than 150 years and it is motivated by desire to produce profitable products such as oil and gas. Oil and gas industry on an average invests about 500 billion dollars each year. If our goal is to sequester even 8 to 9 % of CO_2 from the atmosphere every year, the costs will approach about 260 billion dollars which is half of the annual investment made by oil industry. These are significant costs and for oil and gas industry to have the incentive to invest (the industry which has the best experience in executing such type of project) will require strong government incentive. Where would this money come from is a big challenge which needs to be addressed.

Conclusions

Carbon dioxide sequestration is a critical pathway for achieving climate goals, but its feasibility depends on both technical performance, economic costs and significant government support. Our scoping study reveals that even separation of small amounts of CO_2 (about 9 % per year) will incur significant costs close to $262 billion dollars. To gain a perspective on this number, oil and gas industry, which makes significant money by selling its products, invests about $ 500 billion each year in capital costs. If a significant dent must be made to remove CO_2 from the atmosphere (e.g., 30 % per year), the annual costs will far exceed what oil and gas industry invests in every year. The costs for removing 30 % of CO_2 will exceed 1 trillion dollars. The infrastructure required to sequester 30 % of CO_2 will far exceed what oil and gas industry has built over 150 years of oil and gas production. Without significant government support, acceptance by the societies and incentives across the globe, this is indeed a very challenging and difficult task.

References

1. United Nations. (2023). Climate change. https://www.un.United Nations. (2023). Climate change. https://www.un.org/en/global-issues/climate-change
2. United Nations Framework Convention on Climate Change. (2015). The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement
3. Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C., Hauck, J., ... & Zheng, B. (2023). Global carbon budget 2023. Earth System Science Data, 15(12), 5301–5369. doi.org
4. Turkamani, H. S. (2025). The challenge of phasing out fossil fuels for highly fossil fuel-dependent countries in international law. Leiden Journal of International Law. Advance online publication. https://doi.org/10.1017/S0922156525100319
5. Kazlou, T., Cherp, A., & Jewell, J. (2024). Feasible deployment of carbon capture and storage: Historical growth constraints and implications for 1.5 °C pathways. Nature Climate Change, 14(10), 1047–1055. https://doi.org/10.1038/s41558-024-02104-0
6. Our World in Data. (2024). Cumulative CO2 emissions (1751–2023) [Dataset]. https://ourworldindata.org/grapher/cumulative-co-emissions
7. International Energy Agency. (2023a). Carbon capture, utilisation & storage – Energy system. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage
8. Rhodium Group. (2024, November 26). Global greenhouse-gas emissions: 1990–2022 and preliminary 2023 estimates. https://rhg.com/research/global-greenhouse-gas-emissions-1990-2022-and-preliminary-2023-estimates/
9. Our World in Data. (2024). Cumulative CO2 emissions (1751–2023) [Dataset]. https://ourworldindata.org/grapher/cumulative-co-emissions
10. Rath, G. K., Pandey, G., Singh, S., Molokitina, N., Kumar, A., Joshi, S., & Chauhan, G. (2023). Carbon dioxide separation technologies: Applicable to net zero. Energies, 16(10), Article 4100. https://doi.org/10.3390/en16104100
11. Kammerer, S., Borho, I., Jung, J., & Schmidt, M. S. (2023). Review: CO2 capturing methods of the last two decades. International Journal of Environmental Science and Technology, 20(7), 8087–8104. https://doi.org/10.1007/s13762-022-04680-0
12. Brunetti, A., Scura, F., Barbieri, G., & Drioli, E. (2010). Membrane technologies for CO2 separation. Journal of Membrane Science, 359(1-2), 115–125. https://doi.org/10.1016/j.memsci.2009.11.040
13. Erans, M., Manovic, V., & Anthony, E. J. (2016). Calcium looping sorbents for CO2 capture. Applied Energy, 180, 722–742.
14. Global CCS Institute. (2023). Global status of CCS 2023: Executive summary. https://www.globalccsinstitute.com/resources/publications-reports-research/global-status-of-ccs-2023-executive-summary/
15. International Energy Agency. (2024). CO2 transport and storage. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/co2-transport-and-storage
16. Simonsen, K. R., Hansen, D. S., & Pedersen, S. (2024). Challenges in CO2 transportation: Trends and perspectives. Renewable and Sustainable Energy Reviews, 191, Article 114149. https://doi.org/10.1016/j.rser.2023.114149
17. Peletiri, S. P., Rahmanian, N., & Mujtaba, I. M. (2018). CO2 pipeline design: A review. Energies, 11(9), Article 2184. https://doi.org/10.3390/en11092184
18. Barker, R. J., Hua, Y., & Neville, A. (2016). Internal corrosion of carbon steel pipelines for dense phase CO2 transport in carbon capture and storage (CCS) – a review. International Materials Reviews, 62(1), 1–31. https://doi.org/10.1080/09506608.2016.1176306
19. Zero Emissions Platform & Carbon Capture and Storage Association. (2022). Network technology guidance for CO2 transport by ship [Report]. https://zeroemissionsplatform.eu/wp-content/uploads/ZEP-CCSA-Report-on-CO2-transport-by-ship-March-2022.pdf
20. Worden, R. H. (2024). Carbon dioxide capture and storage (CCS) in saline aquifers. Geosciences, 14(6), Article 146. https://doi.org/10.3390/geosciences14060146
21. Li, N., Feng, W., Yu, J., Wang, S., Li, Z., Wang, Z., & Chen, Y. (2023). Recent advances in geological storage: Trapping mechanisms, storage sites, projects, and application of machine learning. Energy & Fuels, 37(14), 10087–10111. https://doi.org/10.1021/acs.energyfuels.3c01433
22. Xu, T., Apps, J. A., Pruess, K., & Yamamoto, H. (2007). Numerical modeling of injection and mineral trapping of CO2 with H2S and SO2 in a sandstone formation. Chemical Geology, 242(3–4), 319–346. https://doi.org/10.1016/j.chemgeo.2007.03.022
23. Krevor, S., Blunt, M. J., Benson, S. M., Pentland, C. H., Reynolds, C., Al-Menhali, A., & Ni, B. (2015). Capillary trapping for geologic carbon dioxide storage: From pore-scale physics to field-scale implications. International Journal of Greenhouse Gas Control, 40, 221–237. https://doi.org/10.1016/j.ijggc.2015.04.006

24. Kelemen, P. B., Benson, S. M., Pilorgé, H., Psarras, P., & Wilcox, J. (2019). An overview of the status and challenges of CO2 storage in minerals and geological formations. Frontiers in Climate, 1, Article 9. https://doi.org/10.3389/fclim.2019.00009
25. Callas, C., Saltzer, S. D., Davis, J. S., Hashemi, S. S., Kovscek, A. R., Okoroafor, E. R., ... & Zoback, M. D. (2022). Criteria and workflow for selecting depleted hydrocarbon reservoirs for CO2 storage. Applied Energy, 324, Article 119668. https://doi.org/10.1016/j.apenergy.2022.119668
26. Xiao, T., Chen, T., Ma, Z., Tian, H., Meguerdijian, S., Chen, B., ... & Li, L. (2024). A review of risk and uncertainty assessment for geological CO2 storage. Renewable and Sustainable Energy Reviews, 189, Article 113945. https://doi.org/10.1016/j.rser.2023.113945
27. Li, C., & Zhang, X. (2024). Geophysical monitoring technologies for the entire life cycle of CO2 geological sequestration. Processes, 12(10), Article 2258. https://doi.org/10.3390/pr12102258
28. Kaven, J. O., Hickman, S. H., McGarr, A. F., Walter, S., & Ellsworth, W. L. (2015). Surface monitoring of microseismicity at the Decatur, Illinois CO2 sequestration demonstration site. Seismological Research Letters, 86(4), 1234–1242. https://doi.org/10.1785/0220150062
29. Global CCS Institute. (2025). Advancements in CCS technologies and cost. https://www.globalccsinstitute.com/resources/publications-reports-research
30. International Energy Agency. (2023b). Emissions from oil and gas operations in net zero transitions. https://www.iea.org/reports/emissions-from-oil-and-gas-operations-in-net-zero-transitions
31. International Energy Agency. (2023c). Emissions measurement and data collection for a net zero steel industry. https://www.iea.org/reports/emissions-measurement-and-data-collection-for-a-net-zero-steel-industry
32. Tiseo, I. (2025a, July 7). Cement industry emissions worldwide – statistics & facts. Statista. https://www.statista.com/topics/11056/cement-industry-emissions-worldwide/
33. Tiseo, I. (2025b, July 10). Global carbon dioxide emissions from coal combustion, 2023, by selected country. Statista. https://www.statista.com/statistics/1014423/co2-emissions-from-coal-combustion-in-selected-countries/
34. Tullo, A. H. (2021). The search for greener ethylene. Chemical & Engineering News, 99(9), 20–22. https://doi.org/10.1021/cen-09909-feature3
35. World Bioenergy Association. (2024). Global bioenergy statistics report 2024: Summary (11th ed.).
36. CarbonChain. (2022). Understand your aluminum emissions. https://www.carbonchain.com/blog/understand-your-aluminum-emissions
37. Global CCS Institute. (2025). Advancements in CCS technologies and cost. https://www.globalccsinstitute.com/resources/publications-reports-research
38. Intergovernmental Panel on Climate Change. (2022). Transport. In Climate change 2022: Mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-10/
39. International Energy Agency. (2021, February 17). Is carbon capture too expensive? https://www.iea.org/commentaries/is-carbon-capture-too-expensive
40. International Energy Agency. (2025). Global energy review 2025. https://www.iea.org/reports/global-energy-review-2025