Systems Engineering for Carbon Capture and Storage

by

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Submitted to the System Design & Management Program
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING AND MANAGEMENT

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2024

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August 9, 2024

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ABSTRACT

Carbon Capture and Storage (CCS) is a crucial technology in the mission to achieve NetZero carbon emissions by midcentury. By capturing and storing CO_2 from large industrial sources and power plants, CCS mitigates the impact of existing industrial activities while maintaining energy security and economic stability. The study underscores the necessity of a systematic approach to CCS system design and development to meet stakeholder requirements. It highlights the versatility of CCS in addressing emissions across various sectors, its ability to be retrofitted to existing infrastructure, and its potential for immediate emissions reduction compared to the longer timelines required for integrating renewable energy sources.

This study analyzes CCS systems holistically, identifying primary components and alternative options for capture, transport, storage, and utilization. It reveals that the transport type significantly impacts system utility, with pipelines being the most effective. The analysis also indicates that CCS systems capturing CO_2 from power plants, ammonia, and chemical production facilities and utilizing onshore pipelines and saline aquifers offer high utility and low cost. The Gulf Coast and Permian & Midcontinent regions show better performance due to existing infrastructure and storage capacity. The study emphasizes the benefits of staged CCS development for broader deployment, technology maturation, and cost recovery. Sensitivity analyses suggest that future technology advances could further improve CCS system performance and economic viability.

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Acknowledgments

I am deeply grateful to all who have supported and contributed to the completion of this thesis.

First, I am incredibly thankful to my thesis advisor, Eric Rebentisch, for his invaluable guidance and feedback on this study. His deep understanding of systems engineering and energy transition has been pivotal in shaping this work.

I also want to express my heartfelt gratitude to my family, particularly my husband Junhao and son Ningbo, for their constant encouragement and understanding. I could not have made it through this journey without their love and sacrifice. Their support has been a source of inspiration and strength.

In addition, I extend my sincere appreciation to my company, Chevron, for providing me the opportunity to undertake this Master's program in System Design & Management at MIT. I want to thank my department general manager, David Meinert, my managers, Daniel Emery and Johannes Visser, and my mentor, Yan Pan, for their unwavering support and encouragement both before and during my educational endeavor.

I want to acknowledge all the Cohort 5 members for their company and moral support during my time at MIT. It has been a great pleasure to be classmates with such a group of talented individuals with diverse personal and professional backgrounds. I will forever cherish the time we spent together inside and outside classrooms.

Lastly, I want to thank all the unnamed individuals at Chevron, the System Design & Management program at MIT, and elsewhere who have provided support and assistance during this research process.

Thank you all for your invaluable contributions to this thesis.

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August 2024

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Chapter 1 Introduction

Greenhouse gas emissions, particularly carbon dioxide emissions from fossil fuel consumption by humans, have been the major contributor to climate change, which results in extreme weather conditions and threatens Earth's ecosystems. To combat climate change, nearly 200 countries committed to limiting global warming to 2°C above pre-industrial levels by 2100, according to the 2015 Paris Agreement[1]. Achieving that goal requires a comprehensive strategy that not only reduces CO_2 emissions from fossil fuel consumption but also actively manages the CO_2 already present in the atmosphere.

There are multiple approaches to reducing carbon emissions and transitioning away from fossil fuels, including (1) replacing fossil fuels with renewable energy resources, such as solar and wind, (2) capturing CO_2 from emission sources and storing CO_2 permanently, and (3) reducing energy use and improving energy efficiencies. Due to the supply instability and slow pace of renewable energy adoption, it’s challenging to achieve net zero emissions solely with renewable energies in the near term. Therefore, carbon capture and storage (CCS) is often viewed as a bridging technology towards a decarbonized future energy economy[2].

The carbon capture and storage (CCS) process typically involves capturing carbon dioxide (CO_2) from power plants, industry processes, or directly from the air. The captured CO_2 is then transported via pipelines or ships and stored permanently in geological formations or utilized in industry processes. CCS plays a critical role in achieving net-zero emissions. It can be implemented in existing power plants to reduce their high carbon emissions. It also addresses emissions in industry sectors that have limited alternatives to fossil fuels for heat and power generation, such as cement, steel, iron, and chemical production. In addition, CCS can potentially reduce the excess CO_2 in the atmosphere, mitigating harmful climate impacts and helping achieve and sustain net-negative emissions in the long term. Moreover, the captured CO_2 can be utilized for enhanced oil recovery, chemical and fuel production, and carbonation in the food and beverage industry to help them achieve carbon-neutral goals.

Due to its pivotal role in combatting climate change, CCS has received increasing attention from policymakers, academia, and industries. Governments and companies are increasingly investing in CCS technologies. Extensive research has been conducted on carbon capture and storage technologies to improve efficiency and reduce cost. For example, novel solvents have been developed for carbon capture to achieve high cyclic capacity and low production cost[3]. Meanwhile, researchers have been exploring various utilization pathways of captured CO_2 to reduce the lifecycle cost of CCS. Baena-Moreno et al. provided a comprehensive review of the recent progress on CO_2 utilization, including CO_2 application as a solvent for different industry processes and as a feedstock for chemicals and fuel production, etc.[4]

Progress has also been made in the past few decades regarding CCS deployment. Most existing CCS projects are in the oil and gas sectors and reduce CO_2 emissions associated with fuel production and power generation. The captured CO_2 is transported via pipelines and injected into oil reservoirs for enhanced oil recovery or used in fertilizer production. The CCS deployment depends on many factors, such as system cost, technology maturity, location, and competitiveness among decarbonization options. Based on a 2023 Global CCS Institute report[5], the CO_2 capture capacity of all CCS facilities under development has had a steady annual growth of over 40% in the past few years. Almost 200 new facilities were added to the development pipeline in 2022 worldwide. However, the current capacity of CCS is still limited, even with tremendous growth. In 2020, the global CO_2 capture capacity was a little over 40 Million tons per year, constituting 0.1% of the total annual global emission of 37 Billion tons[5]. With the CCS project under development, the annual CO_2 capture capacity will reach about 280 million tons by 2030, accounting for 0.6% of global emissions. The global CCS capacity must reach 5 billion tons per year by the mid-century to reach the NetZero target[6], where emissions of greenhouse gases due to human activities and removal of these gases are in balance over a given period.

CCS cost is a significant consideration for CCS development and deployment. The current CCS cost ranges between \$30 and \$300+ per ton of CO_2, depending on the CO_2 source, location, capture technology, etc.[6] Among the segments, carbon capture cost is the highest, representing about three-quarters of the total cost. Even with government incentives like 45Q, most CCS capacity needed in the next few decades is still uneconomical based on current cost and infrastructure availability.

Despite its promise and several decades of development, CCS adoption faces high initial costs, regulatory uncertainties, public perception issues, and infrastructure needs. Over the past decades, many CCS projects announced in the power and industry sectors were canceled or postponed due to a lack of financial support or an unstable government policy environment. CCS project scaling requires local and state infrastructure for transportation and storage. Cost estimates are vital for CCS development and deployment, underscoring the importance of ongoing research to reduce costs and promote widespread adoption in the global fight against climate change. Despite increasingly focusing on the utilization of captured CO_2, which might improve the economics of CCS, most CO_2 conversion and utilization pathways are still at a nascent stage. The execution of large-scale commercial CCS projects necessitates the resolution of several design and operation challenges, especially those pertaining to the interaction of various system components under varying operating conditions, making CCS a complex techno-economic system.

A CCS system involves several components across multiple industries: carbon emission, capture, transport, utilization, and storage. Each component includes various architectural design options. Effective CCS system design and implementation require a good understanding and estimation of system performance, including technology readiness, capacity, and cost, for different CCS design options. Multiple government policies have been implemented in the past few years to provide financial levers for large-scale CCS projects. Given the large-scale, multidisciplinary nature and complexity of CCS, there is a strong need for comprehensive and holistic research in this field. A system model is necessary to simulate and benchmark possible CCS systems for their performance.

Some process engineering and optimization of CCS systems have been conducted to maximize the carbon capture process performance or minimize the cost of CCS projects[7]. The typical approach enables a comparative techno-economic analysis of viable pathways and tradeoffs between competing objects. Mathematical programming with mixed-integer non-linear programming or multi-objective optimization is often used for the CCS value chain optimization [8–13].

Given that CCS cost is the biggest hurdle for deployment, previous research has mainly focused on minimizing cost with the current emission status in a particular area of interest. Preselected CCS architecture was often assumed in those studies, such as pipelines for CO_2 transport and saline aquifers for CO2 sequestration. However, the emissions will change over time as renewable energy replaces fossil fuels in industry applications. Additionally, the long-term strategy of CCS development and deployment requires the system to be compatible with varied CO_2 sources and CCS technologies and be easily scaled up to a large capacity.

With more government policies on carbon taxes and incentives for emission reduction, along with increasing pathways for carbon utilization and value-added product development, it is now feasible to maximize the performance and profitability of the entire CCS value chain from a system perspective. It requires a holistic analysis of CCS system design, considering all possible options, and a detailed evaluation and comparison of system performance across various aspects.

The key research question to be answered in this study is how to design a CCS project from a system perspective and identify preferred CCS design options based on system requirements and stakeholders' preferences using systems engineering tools. The research approach includes CCS value chain decomposition, identification of alternative architectural designs and performance metrics, analysis and evaluation of the CCS system performance with system modeling, and recommendation of preferred CCS system design to meet system requirements and stakeholders' needs. The results will serve as guidance for policy-makers, investors, and operators who are interested in and responsible for CCS development and deployment strategies.

The main objective of this work is to conduct a holistic and comprehensive evaluation and optimization of the CCS value chain using a systems approach. It entails collecting possible architecture design options, modeling and accessing various CCS system performances from multiple aspects, and identifying best-performing CCS concepts via trade-space analysis. The research aims to advance the CCS field by reducing costs, enhancing efficiency, and facilitating the widespread deployment of CCS technologies.

The thesis comprises seven chapters. It begins with a literature review of the current status of CCS and its design challenges in Chapter 2. Chapter 3 introduces the CCS system components and associated technologies, including their performance measures and costs. Chapter 4 delves into CCS system architecture design options, considerations, and performance metrics. Chapter 5 builds system models and evaluates various CCS system performances in terms of cost and utility, including a sensitivity analysis with varying performance parameters. Chapter 6 discusses specific cases involving regional CCS systems. Finally, Chapter 7 concludes the study with key findings and recommendations for future work.

Chapter 2 Literature Review

2.1 CCS Development Worldwide

The Paris Climate Accord committed the world to keep the global average temperature below 2°C higher than preindustrial levels, aiming ideally for a 1.5°C limit[1]. To achieve a 90% chance of staying below 2°C and a 50% chance of limiting warming to 1.5°C, the world must reduce CO_2 and other greenhouse gases net emissions to around zero by mid-century, with a reduction of CO_2 emissions of around 40% achieved by 2030[14].

CCS plays a vital role in achieving net-zero emissions by (1) decarbonizing industry sectors where alternative energy sources to fossil fuels are technically limited, (2) delivering net carbon removal in addition to rapid decarbonization in energy supply, and (3) providing a low-cost decarbonization solution in some sectors and geographies where CCS is economically advantaged relative to other decarbonization vectors locally. It's estimated that between 7 and 10 Billion tons of CO_2 need to be captured annually by 2050, of which 65% relates to carbon capture from non-fossil fuel sources, e.g., bioenergy and ambient air, then stored or used[15].

Carbon capture and storage have gained significant momentum worldwide in recent years to achieve climate goals and reduce greenhouse gas emissions. Thirty commercial-scale CCS facilities were in operation globally in 2022, with an additional 11 CCS facilities under construction and 153 CCS projects in various stages of development[5]. The United States is at the forefront of operational and planned CCS projects regarding project count and CO_2 capture capacity. As of October 2022, the United States has 10 operating CCS projects and 100 projects in development. The existing carbon capture capacity worldwide was about 46 million metric tons per year in 2022, and the United States shares almost half of that, which was 20 Mtpa.

Figure 1 shows the CO_2 capture capacities of CCS plants in operation, construction, and development in different regions worldwide[5]. The United States has the highest total CO_2 capture and storage capacity, followed by Europe and Asia. Asia, particularly China, has the highest CCS capacity in construction.

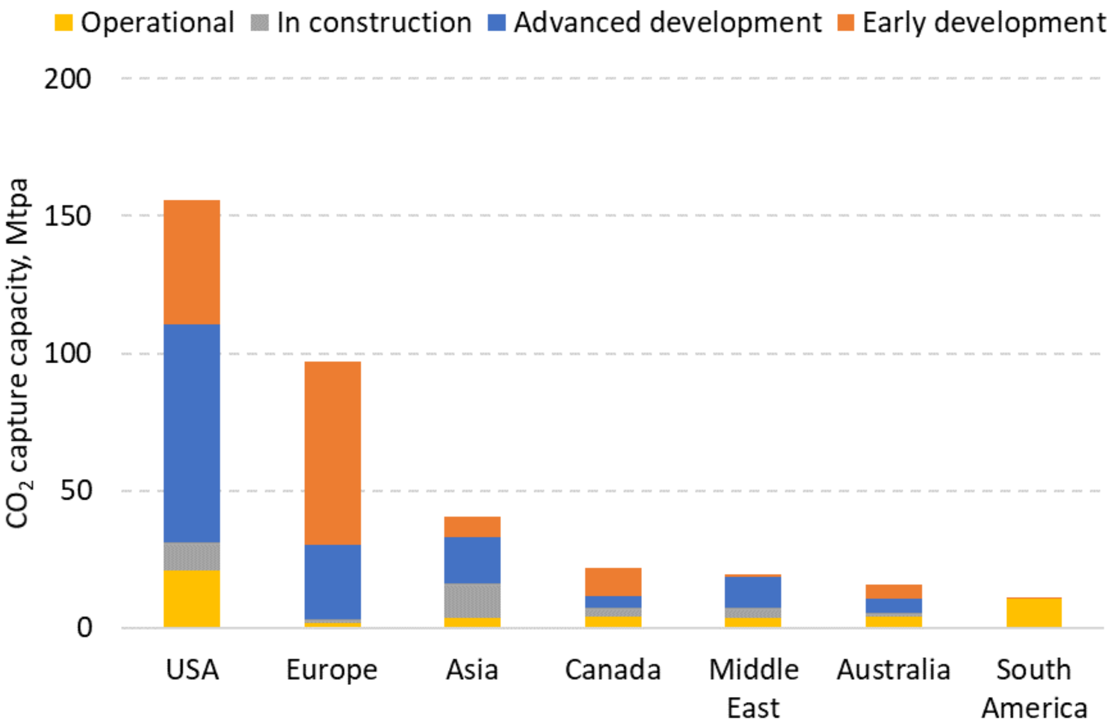


Figure 1 Capacity of carbon capture and storage facilities by region worldwide as of 2023

Figure 2 shows the carbon capture capacity by industry sector as of 2023. Most operational CCS projects exist in the natural gas (NG) processing facilities, where capturing CO_2 is relatively less expensive than in other subsectors. CCS projects in the development pipeline increasingly focus on blue hydrogen production and industries producing bioenergy, fertilizer/H_2/ammonia, cement, and ethanol. Regarding the destiny of captured CO_2, most existing CCS projects inject CO_2 into oil reservoirs for enhanced oil recovery (EOR), which generates positive cash flow for the operators. However, it is interesting to note that very few CCS projects in development are planned for EOR. The shift in focus of CCS to geologic storage rather than EOR is partly due to the oil price variability and uncertainty in the potential revenue streams associated with CO_2 capture.

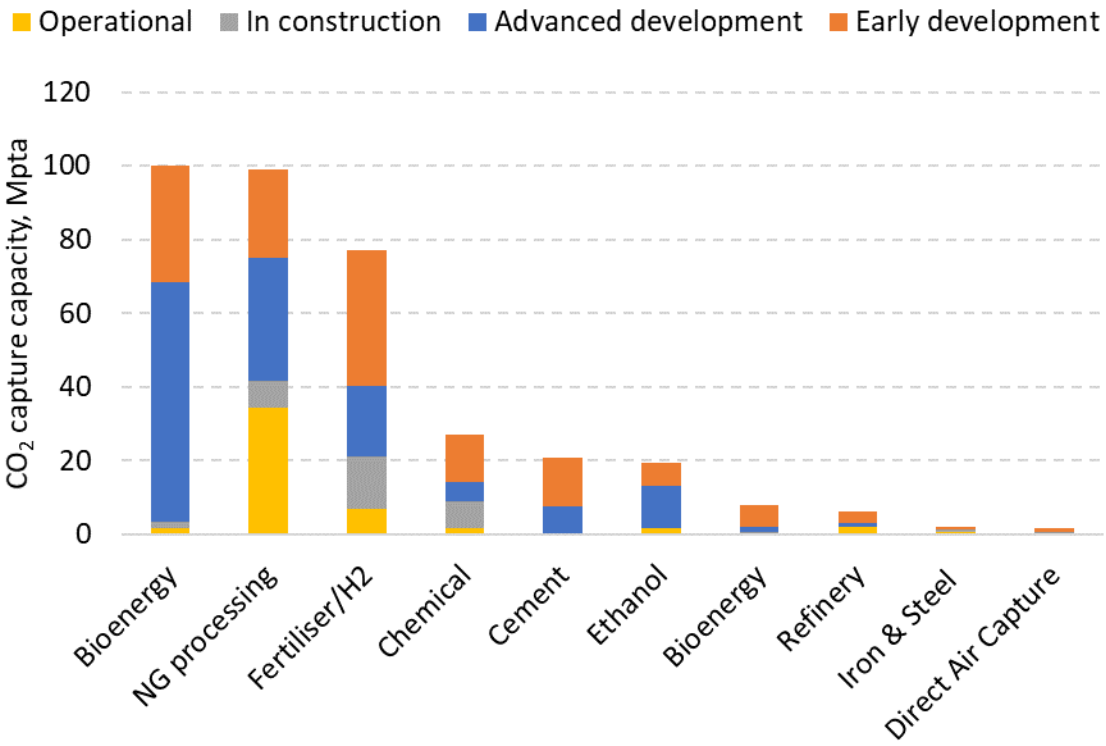


Figure 2 Capacity of carbon capture facilities by industry sector worldwide as of 2023

As shown in Figure 1 and Figure 2, the future CCS capacity under development is much higher than the existing capacity. Many new CCS projects have been initiated worldwide to expand CCS's capacity and reach the net-zero emission target. One example of recent CCS development is the project the Summit Carbon Solution company announced in 2021. The company partners with 57 ethanol plants across a five-state region in the United States to capture carbon dioxide before it is emitted into the atmosphere. It then compresses and transports the captured CO_2 through an extensive onshore pipeline network to geological storage locations in North Dakota[16]. $8 billion infrastructure with a 2,000-mile pipeline network has been proposed to capture more than 16 Mt of biogenic CO_2 emissions annually.

2.2 CCS System Components and Design Approaches

The CCS system consists of three main steps: CO_2 capture, CO_2 transport, and CO_2 utilization or storage. Figure 3 shows the CCS system components and boundary.

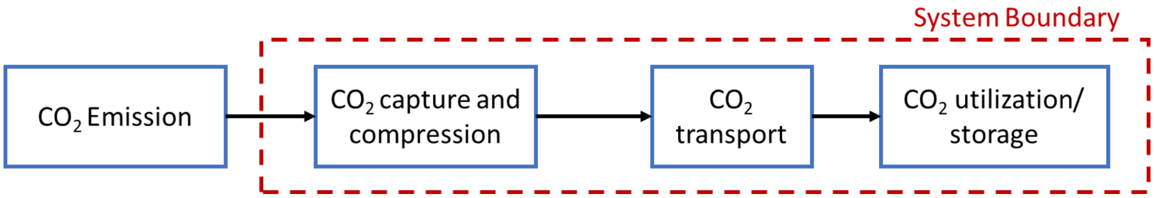


Figure 3 CCS system components and boundary

CO_2 emission is generally considered out of the system boundary for CCS, but it dramatically impacts what options are feasible for carbon capture and the capture cost. Each CO_2 emission source has a different emission rate, gas composition, and total volume. Power plants and industrial facilities producing emission-intensive products emit CO_2 in high concentrations and large quantities and are considered significant point sources of CO_2.

CO_2 capture involves separating CO_2 from other gases in the exhaust of industrial processes or in the ambient air. Post-combustion, pre-combustion, and oxy-fuel combustion are the three major processes extracting CO_2 from industrial emissions. Post-combustion capture is the most mature process, and it uses solvents to adsorb CO_2 from flue gases. Pre-combustion capture, mainly used in gasification processes, converts fuels into a mixture of hydrogen and CO_2 before combustion. Oxy-fuel combustion burns fuel in pure oxygen and produces a flue gas composed primarily of water vapor and CO_2, making the latter easier to capture.

If not utilized on-site, the captured CO_2 is compressed and transported to locations for geological formation sequestration or use in industry processes. Pipelines are the most cost-effective and efficient method for large-scale CO_2 transport, primarily used onshore. Ships can transport CO_2 in offshore environments. Compared to pipelines, ships offer more flexibility to transport CO_2 to offshore storage locations. Trucks and railcars are viable options for small quantities of CO_2 transport onshore, and they haven't been used widely due to the high operational cost.

The last step is CO_2 storage, which includes CO_2 sequestration in geological formation and CO_2 utilization in industry processes. Captured CO_2 can be injected into deep geological formations, such as depleted oil and gas fields, saline aquifers, and unmineable coal seams for permanent storage. These storage sites are selected based on their capacity to contain CO2 for hundreds or even thousands of years securely. CO_2 storage in subsurface formations requires periodic monitoring to evaluate and ensure the effectiveness of CO_2 sequestration. The captured CO2 can also be utilized for industrial purposes to generate revenue. For example, it can be injected into oil reservoirs for enhanced oil recovery (EOR). Additionally, CO2 can be converted into synthetic fuels or used in biomass processes to produce bioenergy.

The multiple components in the CCS system determine the multi-disciplinary nature and complexity of CCS projects. Correspondingly, the CCS system design and engineering will be a complex process that integrates all those components into a cohesive and efficient value chain. The implementation of CCS projects also requires that all value chain stages be technologically developed concurrently to ensure a smooth transition from one step to the next.

There are multiple approaches for CCS design and optimization. One is looking into specific CO_2 capture and utilization technology, such as high-performing materials for CO_2 separation from other gas molecules during carbon capture to improve efficiency and reduce cost, and novel CO_2 applications in industry processes to generate revenues[17]. Multiple papers have reviewed the recent progress of CO_2 capture and utilization technologies[3,4,18]. Those technologies vary in maturity, capacity, and cost. Some are suitable for specific industries or environments, whereas others have a wide range of applications but high costs. Lifecycle assessment was sometimes conducted to evaluate a particular CO_2 capture technology with process optimization to improve the technology's maturity and competitiveness among all alternative technologies, such as direct air capture of CO_2[19–22] and carbon capture from bioenergy generation[23–26]. Process optimization has also been used for CO_2 capture analysis in specific industry sectors, such as power plants, iron and steel, and cement production[27–29]. Another approach is the network design of the CCS system to incorporate multiple CO_2 emission sources, transport infrastructures, and storage sites to maximize CCS capacity and minimize cost[8–10,12,13,30,31]. The area of interest can be local, regional (i.e., across states), national, or international[32]. Each approach covers one or multiple aspects of CCS system design and optimization, providing valuable insights into the available carbon capture and utilization options and their current status for specific players in the CCS domain.

High cost and low infrastructure availability are the main challenges in adopting and scaling CCS systems. Many researchers have focused on cost modeling for CCS systems[33-38], while others have examined the supply chain and infrastructure needs[39–44]. Currently, operational CCS projects are limited to individual plant scales. Most CCS technologies under development are still prohibitively expensive for widespread deployment. The lack of adequate infrastructure for CO_2 transport and storage also impedes the large-scale adoption of CCS systems. To address these issues, the development of CCS hubs—industrial centers with shared CO_2 transport and storage infrastructure—is necessary. These hubs can support economies of scale and reduce CCS unit costs by minimizing duplication in infrastructure planning and development.

Additionally, CCS hubs enable the capture of CO_2 at smaller industrial facilities, where dedicated transport and storage infrastructure may be impractical and uneconomical. The early development of CCS hubs requires government leadership and coordination to underwrite investments in new CO_2 transport and storage infrastructure. It necessitates holistic CCS system design and implementation by considering all possible technological and supply options and including all performance aspects important to stakeholders.

2.3 CCS Challenges and Proposed Work

Despite the progress in the past few decades, CCS technologies are currently costly and energy-intensive, which pose significant barriers to their large-scale deployment. Even with a long history, CCS systems cannot be mass-produced because most CCS technologies are specifically designed to match a given type of CO_2 emission process and facility. CCS projects are also complex to coordinate because each step – capture, transport, and storage – is often owned and operated by different companies or industries. Additionally, CCS systems require high upfront capital investment and have a riskier revenue structure than other clean technologies, which can be prohibitive for project developers. There are also environmental risks associated with CCS, such as pipeline or storage leaks of CO_2, which negatively impact public acceptance. To overcome these challenges and enable large-scale CCS systems, it is essential to have CO2 transport infrastructure, a supportive regulatory framework and policies, ongoing research, development and demonstration, and successful execution of CCS projects.

The 2023 International Energy Agency (IEA) NetZero Emission (NZE) Roadmap[45] estimates that to reach net zero emissions in the energy sector by 2050, CCS will contribute about 8% of the total CO_2 mitigation of energy sector emissions. It includes around one gigaton of CO_2 ($GtCO_2$) to be captured and stored by 2030 and 5 $GtCO_2$ to be captured and stored in 2050 globally. In 2020, the global carbon capture capacity was about 50 $MtCO_2$ per year. The CCS projects under development are projected to capture 220 $MtCO_2$ per year by 2030, which is only a quarter of the IEA's sustainable development scenario (SDS) target. It requires almost 50% more CCS deployments to meet the SDS target to achieve net-zero carbon emissions by 2050.

Most operational CCS systems capture CO_2 from single plants and transport it to nearby reservoirs for CO_2-EOR or permanent storage. Expanding the CCS system to industrial scales requires clustering CO_2 emitters across multiple plants or industries to support the massive infrastructure development and geological storage at a distance. Extra interfaces will be introduced, and value chain integration must be considered when designing and implementing such CCS projects.

There are numerous architectural options for designing a CCS system, including the technology used for carbon capture, transport, and storage, the location of project implementation, and technical conditions such as CO2 flow rate during transport and injection for storage. At a detailed level, decisions must be made regarding the material for CO2 separation, the output condition of CO2 from capture plants, the number of boosting stations along the transport path, and the injection well design. Each option has specific requirements and operates under certain conditions. Given the multiple scales and complexities of a CCS system, typical design and modeling approaches often limit the study to a certain level and constrain available options to a specific region or technology to simplify the work[9,10]. Optimization of CCS system design traditionally focuses on maximizing capacity or minimizing cost, providing a unique solution applicable to particular cases[46]. However, CCS system performance encompasses various aspects, including capture capacity, technology maturity, system scalability, competitiveness with alternative solutions, and cost. Different stakeholders have different preferences when making design decisions for CCS systems. For example, CCS operators prioritize cost and revenue streams, while government agencies prefer designs that can be easily scaled to meet NetZero targets. Existing approaches in the literature cannot address all potential CCS system design solutions under different scenarios. Therefore, it is necessary to expand the scope to incorporate all possible options and model performance uncertainties over decade-long time horizons using a systems approach.

With the need for broad and deep deployment of CCS worldwide over the next few decades, a holistic CCS system model is needed to identify the different CCS design options and evaluate their performances, including the technology maturity, capacity, scalability, and cost to meet the stakeholders’ requirements. The CCS system's capacity and scalability depend heavily on the technology implemented for carbon capture, transport, and storage. CCS costs vary widely depending on the technology, application, location, and scale. Besides the technical parameters, the political environment, business models, and social acceptance strongly influence CCS system design decisions.

Systems engineering is crucial for carbon capture and storage because it ensures the integration of various components and processes to work effectively. First, CCS involves a complex interplay of technologies, from capturing CO_2 to transporting and storing it safely.

Systems engineering helps manage this complexity by designing and coordinating each component to function together seamlessly. Secondly, systems engineering principles can guide the efficiency improvement and optimization of each stage of CCS to reduce cost and increase the amount of CCS that can be captured and stored. Thirdly, systems engineering can ensure the safety and reliability of CCS projects and make them comply with environmental regulations and standards, thus minimizing risks and improving public acceptance.

In the next chapter, CCS system components and associated technologies are reviewed, and their performances are examined in terms of technology readiness, capacity, compatibility, scalability, and cost. Based on stakeholders' needs, several performance metrics are proposed for system evaluation. Systems engineering models are then built to assess the performance of various CCS systems with different architectural decision options. Through tradespace analysis, different CCS system designs are compared based on competing performance measures. Recommendations are made for CCS system designs to suit various development scenarios, with particular system concepts discussed for specific applications.

Chapter 3 CCS System Background

CCS is a suite of interconnected technologies for capturing CO_2 and storing it so that it is not reemitted into the atmosphere[47]. The CCS system generally involves three main steps: carbon capture, transport, and storage or utilization.

3.1 CO_2 Emissions

Table 1 shows the global CO_2 emissions and capture status by industry sector. Those emitters provide the main CO_2 supply for CCS.

Table 1 Global CO_2 emission and capture status by industry

Industries	Subsectors	2019 Global CO_2 emission, Mtpa[47,48]	Current capture capacity, Mtpa[5]	2050 capture target, Mtpa[2,49]	Typical CO_2 conc. in flue gas[50]	CO_2 emission level per plant, Mtpa[50]
Heavy industry	Cement	2400	0	1174	14-33%	0.7-1
	Iron & Steel	2600	1	391	4-27%	2-14
Oil & Gas refining	Chemical, Ammonia, Methanol	1400	2.5	461	95%	Varies
	H_2 production	800	6	1265	15-60%	0.2-1.3
	Fuel refinery	1600	2	338	95%	0.7-2.4
	Natural gas processing		27.5		95%	0.5-9
Power generation	Coal	9900	2	895	13%	
	Natural gas	3800		605	4%	
	Bioenergy	100	0.2	377	13%	
Transportation	Car, truck, aviation, ship, rail	7400				
Agriculture	Agriculture	12700				
Residential	Building	3400				
Others		5000				
Total		51000	42.2	6327		

Most existing CO_2 emissions come from power generation, agriculture, transportation, and heavy industries producing cement, iron, and steel. However, over 60% of existing CO_2 capture capacity is for natural gas processing, separating naturally occurring CO_2 from natural gas-producing wells. Some small-scale CO_2 capture is from chemical and fuel transformation and coal-fired power plants. To achieve the net-zero emission goal, IEA estimated the target capacity for CO_2 capture from each industry[49], which is also listed in Table 1. The total target capacity is two orders of magnitude higher than the current level. Notably, the industries involving point sources of CO_2 emission, such as heavy industry, oil and gas refining, and power generation, must expand their CO_2 capture capacity by a hundred to a thousand times by 2050 to meet the NetZero emission target. The following sections introduce the main industry sectors targeted for large amounts of CO_2 capture and their current statuses.

3.1.1 Power Generation

The power sector is the largest CO_2 stationary emitter among all industries. It emits about 14 $GtCO_2$ every year globally, about 40% of the total energy-related CO_2 emission. Two-thirds of that are coal-fired power plants, and the other one-third is natural gas-based. The emitted CO_2 is generated during the combustion process at a relatively low concentration (<15 Vol%). Carbon capture has been piloted in some power plants and is projected to contribute about 20% to the cumulative decarbonization efforts.

3.1.2 Natural Gas Processing

Till the 2000s, almost all the CO_2 captured globally at large-scale facilities was from gas processing plants, but CO_2 captured from natural gas processing now makes up about two-thirds of the total amount. It is a relatively mature process where CO_2 can be captured at a relatively low cost and high concentration. Captured CO_2 is generally reinjected into geological formations or used for EOR application. The process has a significant location dependency, i.e., a large-scale gas processing plant with nearby gas fields and CO_2 transport infrastructure. Physical separation using propriety solvents is currently the primary carbon capture method in natural gas processing. Membrane separation is still at the demonstration stage [47].

3.1.3 Cement Industry

Because of its size and the inherent characteristics of its production process, the cement sector is one of the primary sources of anthropogenic CO_2, accounting for 8% of global emissions. Process emission results from the conversion of limestone to calcium oxide $CaCO3 \rightarrow CaO + CO_2$, accounting for about 65% of the direct CO_2 emission. CO_2 capture can be accomplished in the cement industry using post- and oxyfuel combustion. Reducing CO_2 emissions from the cement industry faces challenges such as high reliance on coal for high-temperature heat and low margins of cement production [47].

3.1.4 Iron and Steel

Globally, the iron and steel sector's direct CO_2 emissions amount to 2.6 Gt in 2019, or 7% of total energy sector emissions and 28% of industrial emissions[35]. When indirect CO_2 emissions from electricity and heat generation during iron and steel production are included, the total emissions are around 3.6 Gt. The CO_2 intensity of steel production is high, with about 1.4 tons of direct CO_2 emissions per ton of crude steel, or 2 tons when including indirect emissions from electricity and heat generation. CO_2 is emitted by coal consumption and natural gas that acts as a reducing agent in the direct reduced iron (DRI) necessary to process iron ore. This sector relies heavily on coal for high temperatures and iron reduction, and has low margins.

3.1.5 Chemical Production

The chemical production sector is the third-largest industrial source of CO_2 emissions. Oil and natural gas are primary feedstocks for producing chemicals, with coal being used to a lesser extent. The share of hydrocarbon in the overall sector's energy use is very high at 85%[29]. It is particularly energy-intensive to produce primary chemicals, accounting for two-thirds of the chemicals sector's energy consumption. The large share of process emissions makes it difficult to decarbonize. Fossil fuels used as feedstock are difficult to fully substitute with bioenergy or electrolytic hydrogen.

3.1.6 Hydrogen Production

Current hydrogen production (~75 Mt H_2 annually, chiefly from fossil fuels) produces 800 MtCO_2. Unabated hydrogen production from fossil fuels results in emissions of 9 tCO_2/tH_2 in the case of natural gas (76% share of H_2 production) and 20 tCO_2/tH_2 in the case of coal (23% share of H_2 production)[47]. Pre-combustion carbon capture technologies can be applied to capture CO_2 before combustion occurs to produce blue hydrogen. The main challenge is that blue hydrogen with CCS might seem more expensive with additional capital, energy, and operating cost requirements. However, the cost is expected to come down substantially due to declining prices of renewable electricity and the scaling up of electrolyzers.

3.2 Carbon Capture

CO_2 can be captured from a facility emitting CO_2 (point source capture) or directly from the atmosphere (i.e., direct air capture) by separating CO_2 molecules from other gas molecules.

3.2.1 Carbon Capture Process

There are three main processes to capture CO_2 from a point source (mostly power plants) at different stages of combustion: post-combustion, pre-combustion, and oxyfuel combustion. Figure 4 shows the schematics of those three processes [10].

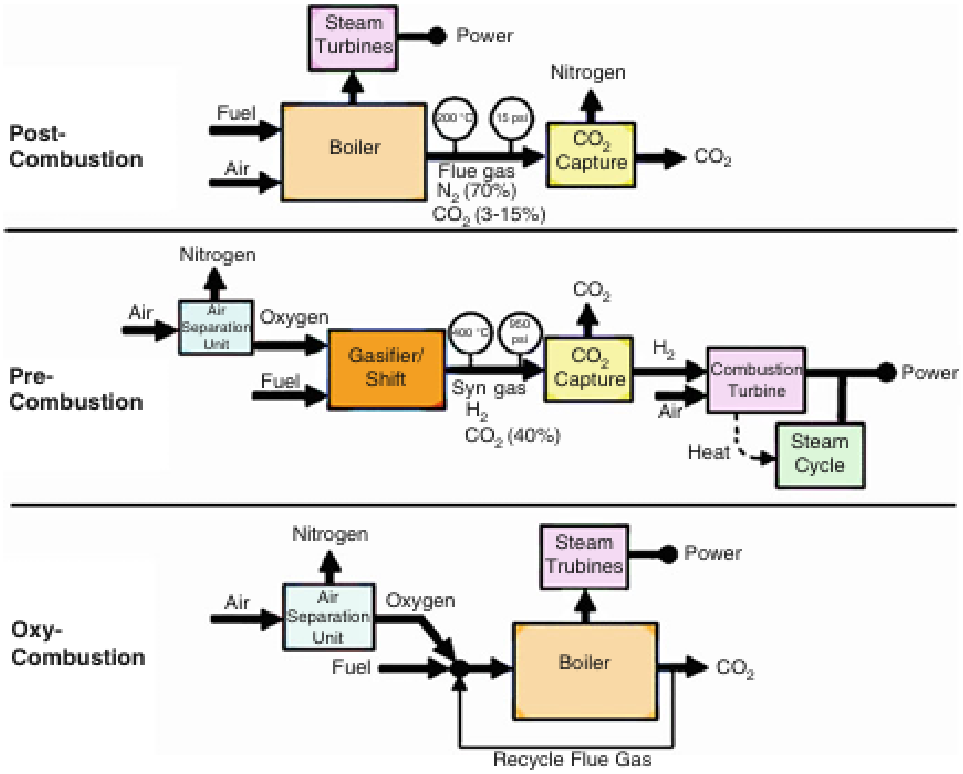


Figure 4 Carbon capture processes of post-combustion, pre-combustion, and oxyfuel-combustion[10]

Post-combustion

The post-combustion process of CO_2 capture separates CO_2 from combustion exhaust gases. The combustion flue gases are sent to a tank where most CO_2 binds chemically to amines, forming a CO_2-rich amine blend. The CO_2 is then separated from the amine blend through heating to create a high-purity CO_2 stream for transport and storage. One advantage of post-combustion capture is that it can be fitted relatively easily on existing emission sources. It works on any large stationary source, including industrial emissions. It has relatively high costs and energy penalties and is mainly used outside the oil and gas industry [13,47].

The flue gas during post-combustion generally consists of 80% N_2, 10% CO_2, some oxygen, vapor, and other pollutants. Additional drying, purification, and compression are required before transportation. Post-combustion is very mature technology and at the late demonstration stage and can be retrofitted to thermal power plants with supercritical pulverized coal (SCPC) and natural gas combined cycle (NGCC). The main applications of the post-combustion process are for paper and cement industry sectors. Due to the relatively low partial pressure of CO_2 in the flue gas, the post-combustion process is highly inefficient[47].

Pre-combustion

The pre-combustion process separates CO_2 from the fuel before the combustion takes place. The hydrocarbon fuel source, e.g., coal, natural gas, or biomass, is gasified into shifted syngas (H_2/CO_2 mix), from which the CO_2 is separated from hydrogen. The method is especially relevant in plants producing electrical energy and hydrogen. In power generation, the pre-combustion process is more energy efficient than post-combustion. However, it is generally only practical for new plants, as retrofitting existing emission sources would require heavy and expensive plant modification[13,47]. The main industry sectors for pre-combustion process applications are power and industrial hydrogen.

The shifted syngas comprises hydrogen and CO_2, with concentrations of 17% to 38%. With that, CO_2 can be easily separated from H_2. The pre-combustion process is usually applied to integrated gasification combined cycle (IGCC) plants with relatively high capital costs [47].

Oxyfuel-combustion

The oxyfuel combustion process uses oxygen instead of air for fuel combustion. The exhaust gas consists mainly of water vapor and CO_2, with between 80% and 98% CO_2, which can be easily separated to create a high-purity CO_2 steam. It has a high capture efficiency of nearly 100% but requires additional purification with low-quality fuels. Dehydration and compression are also needed before transportation. Oxyfuel combustion can be retrofitted to some existing power plants with significant redesign. It is usually applied in glass, metallurgical, and thermal energy engineering. The main industry sectors for pre-combustion process application are power and steel production[13,47].

Natural Gas Sweetening

Another process to capture naturally contained CO_2 from point sources, such as natural gas reservoirs, is called natural gas sweetening. In this process, CO_2 is separated from raw natural gas from production wells at a gas processing plant through amine absorption using methyl-diethanolamine (MDEA) as a solvent. It has a lower-cost opportunity to create a large flow of CO_2 with about 98% concentration CO_2 stream ready to be transported and stored[47]. Figure 5 shows the process diagram of natural gas sweetening [47]. Many existing CCS projects use this process to capture CO_2 from produced natural gas, such as the Gorgon CO_2 capture and injection project in Australia and Century Plant in Texas, United States. Globally, the most prominent commercial CCS plants are in the natural gas processing sector.

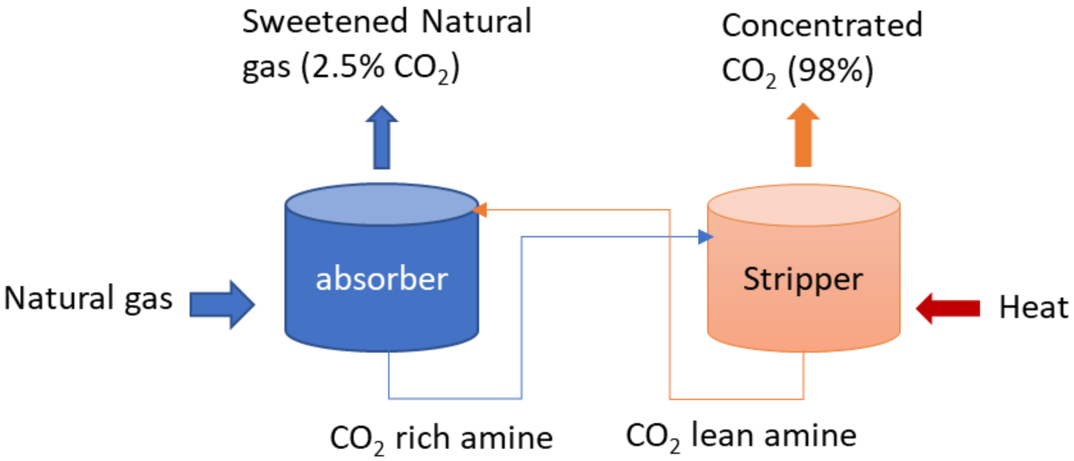


Figure 5 Process diagram of natural gas sweetening[47]

Direct Air Capture (DAC)

CO_2 can also be captured from ambient air besides stationary point sources of industry emissions. Two technologies can be used to capture CO_2 directly from air: liquid and solid DAC. Liquid DAC passes air through chemical solutions to remove CO_2. Solid DAC uses solid sorbent filters that can bind chemically with CO_2. When the filters are heated and placed under a vacuum, they release the concentrated CO_2, which is then captured for storage or use. However, the capacity of DAC usually is small, less than 1 Mtpa[13]. Figure 6 shows the process chemistry and thermodynamics of DAC[19].

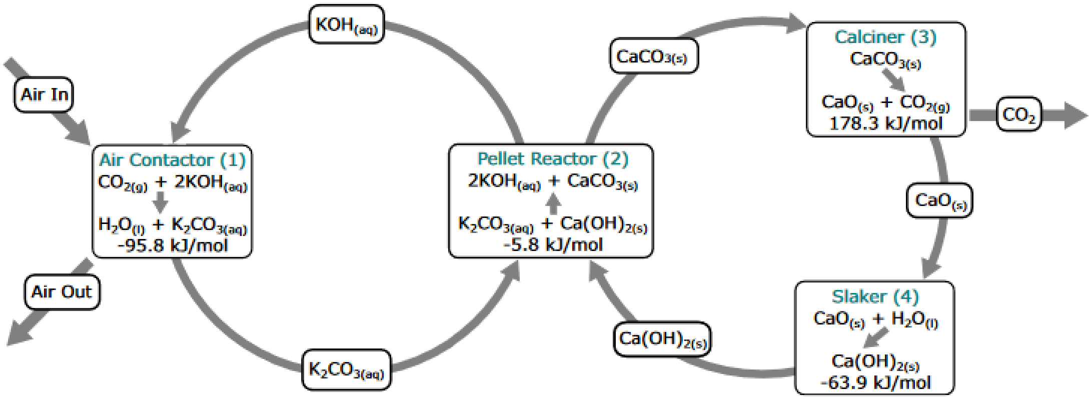


Figure 6 DAC chemistry and thermodynamics process[19]

The IEA NetZero Emission by 2050 Scenario requires DAC technologies to capture more than 980 $MtCO_2$ by 2050[20]. Among that, 350 Mt of air-captured CO_2 will be used to produce synthetic fuels like aviation fuels. It requires a significant and accelerated scale-up, given the current capacity of DAC of about 0.01 $MtCO_2$. The first large-scale DAC plant of up to 1 $MtCO_2$/year is in development in the United States and is expected to be operating by the mid-2020s.

Besides CO_2 capture from ambient air, a new method is being developed to remove CO_2 from the ocean. It could be far more efficient than air-capture systems due to the higher CO_2 concentration in seawater than in air. Removing CO_2 from seawater can be done through membranes or electrochemical cells, but it is still in early research and development[51].

3.2.2 Carbon Capture Technology

There are three main types of technologies used to separate CO_2 from flue gases or air:

(1) absorption and adsorption of the CO_2 by a liquid carrier (solvent) or solid carrier (sorbent) and regeneration of the liquid or solid carrier by increasing the temperature or reducing the pressure, (2) membranes (metallic, polymeric, or ceramic material) for gas separation, most suitable for high pressure and high CO_2 concentration, and (3) cryogenic method using low temperature to liquify and separate CO_2 from other gases. Among those technologies, adsorption and absorption are more dominant, but membranes and cryogenic have great potential[47].

The chemical absorption using amine-based solvents is the most advanced CO_2 separation technique with a technical readiness level (TRL) of 9. It has been applied in small- and large-scale carbon capture projects worldwide, such as power generation, fuel transformation, and steel and fertilizer production. The physical separation is mainly used in natural gas processing and fuel production, including ethanol, methanol, and hydrogen, with a TRL of 8 [2]. Currently, commercially viable capture systems can achieve 90% capture efficiency, and newer systems are approaching 100%[52]. Some of the technologies are mature and are used in the market, but some are still under development. Figure 7 shows the technology maturity curve of different CO_2 separation and capture technologies[47].

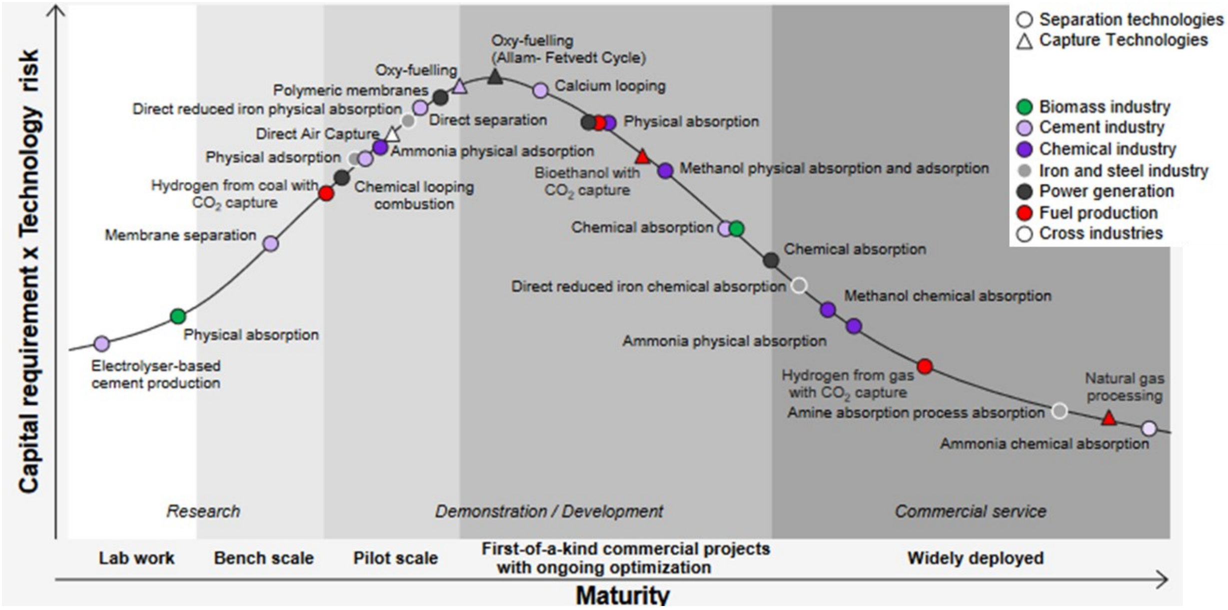


Figure 7 Maturity curve of different CO_2 separation and capture technologies[47]

3.2.3 Carbon Capture Target

IEA reported the global CO_2 capture capacity needs to increase from 40 million tons per year in 2020 to 5.6 billion tons per year by 2050 to meet energy-related sustainable development goals[52]. Figure 8 shows the IEA estimated global CO_2 capture capacity by source to reach the NetZero Emission (NZE) goal [53]. It's expected that most CO_2 capture will be from industry emissions, fuel production, and power generation. Direct air capture capacity will also grow significantly over time.

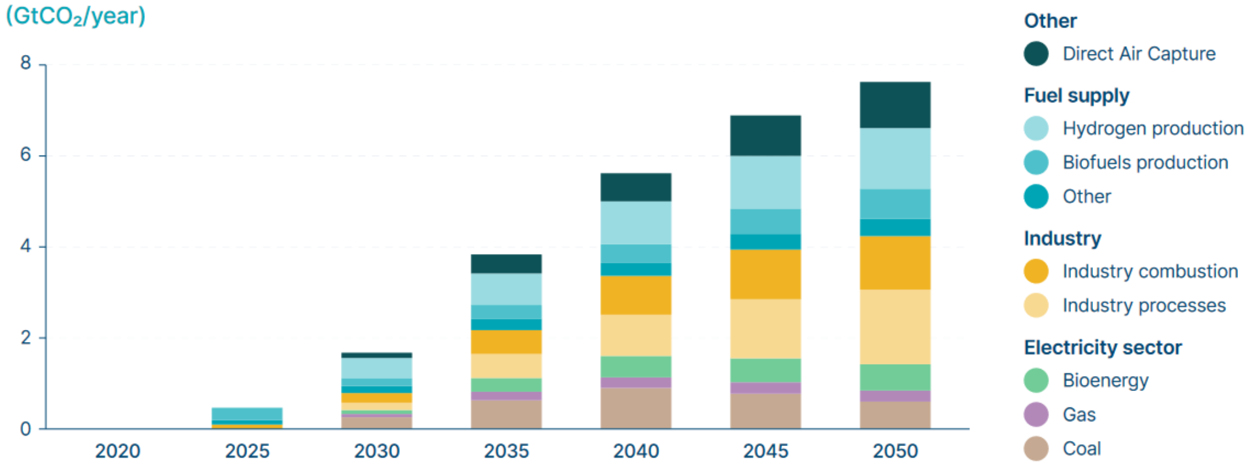


Figure 8 IEA NZE global CO_2 capture by source, 2020–2050[53]

3.2.4 Carbon Processing

The captured CO_2 must be dehydrated and compressed before being transported to its storage location. Without dehydration, the comingled water and CO_2 will damage mild steel over time by forming corrosive hydrides and acids. During the process, captured CO_2 is transported to purification and dehydration tanks via small anti-corrosion steel pipes and purified to above 99% CO_2 concentration. Triethylene glycol (TEG) is commonly used for CO_2 dehydration due to its high effectiveness and has been applied in the natural gas industry. In the process, wet CO_2 enters the bottom of a glycol contactor and comes into contact with liquid TEG. CO_2 dehydration units can also be combined with impurity removal units to remove other gases before CO_2 liquefication.

The treated, gaseous CO_2 is then liquified using compressors and chillers. The liquefaction process is necessary to reduce the CO_2 volume during the transportation[52]. The selection of a compressor is based on several variables, including ambient temperature, required flow rate, power requirement, etc.

3.3 Carbon Transport

Once processed, CO_2 can be transported to target locations for utilization or storage. The most common approach to transporting CO_2 is through pipelines, ships, trucks, and railcars.

3.3.1 Transport via Pipelines

Pipelines are primarily used for onshore transportation of large volumes of CO_2. The processed CO_2 is compressed into a supercritical fluid and moved through pipelines at high pressures. Pipelines are cost-effective for transporting large volumes of CO_2 over short distances due to low operational costs, providing economies of scale. Compared to other transport approaches, such as ships, pipelines also have the disadvantages of high capital costs and less flexibility.

There are three types of pipelines for CO_2 transport: sub-spur pipelines for small CO_2 sources, spur pipelines for large sources or central points, and trunklines that act as main highways to storage sites. Distribution and sub-distribution pipelines connect trunklines to storage sites and individual injection wells[13]. The pipelines are typically made of carbon-manganese steel material, and different diameters are chosen for various flow rates[37,54].

CO_2 can be transported in gaseous, liquid, dense, or supercritical states, with supercritical being the standard due to its lower volume, higher density, and reduced pressure losses.

Compressors and Booster Stations

Compressor stations in CO_2 pipelines are divided into originating compressors at the start and booster stations along the pipeline. Booster stations compensate for pressure drops caused by friction and elevation changes, maintaining the CO_2 flow above the critical pressure. Onshore pipelines can have several booster stations, while offshore pipelines rely on higher inlet pressure from the originating compression due to the impracticality of intermediate booster stations. Pumps are needed to transport liquefied CO_2 to injection sites and refrigeration stations. Additional pumps and compressors may be required to maintain temperature, pressure, and flow specifications[39,54–57].

Metering stations are periodically placed along pipelines to monitor and manage CO_2 flow without hindering its movement, allowing for accurate tracking. Valves around compressor and metering stations and at injection sites control the pipeline's operations and can isolate sections for maintenance or in case of leakage. Sophisticated control systems are used to monitor the pipeline's status in real-time, with centralized control stations managing data from monitoring and compressor stations. These systems enable quick responses to equipment malfunctions, leaks, and unusual activities and allow remote operation of compressor stations to adjust flow rates as needed.

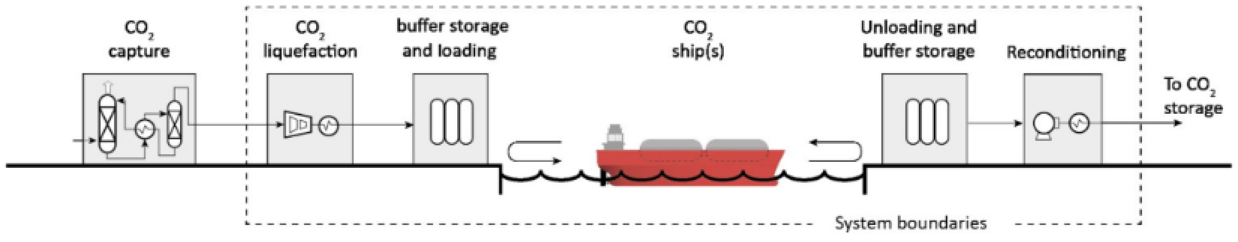
3.3.2 Transport via Trucks and Rails

CO_2 can also be transported by truck and rail. The transportation of gases and liquids via any of these methods is mature but hasn't been deployed at a large scale. Of all CO_2 transport modes, only pipelines are transporting CO_2 at a significant scale. Railcars can be cost-effective for small to medium volumes of CO_2 over longer distances if rail routes exist from near the source to the vicinity of storage. Rail transport may require constructing a liquefaction facility at the point of origin. Trucks may be cost-effective for minimal volumes of CO_2 traveling short distances. It can leverage existing infrastructure but also requires liquefaction facilities at the point of origin. Due to its small capacity and high operation costs, truck and rail transportation are unlikely to play a significant role in the CCS deployment[58].

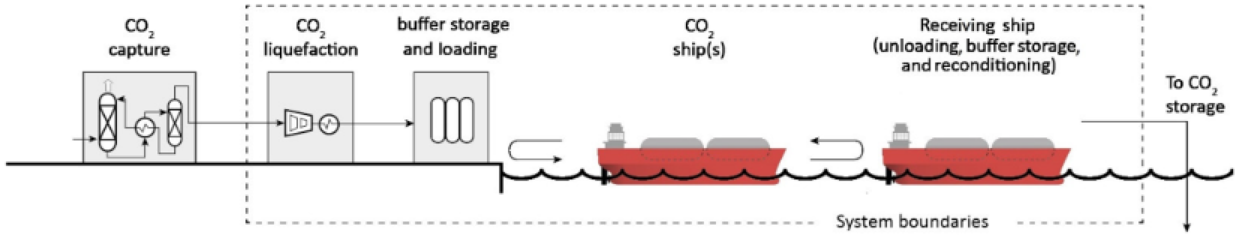
3.3.3 Transport via Ships

Besides pipelines, ships are also used commercially for CO_2 transportation in small volumes. It generally involves carrying CO_2 in a liquid state at pressures between 15 and 20 bar and temperatures between -20°C and -30°C, with ship capacities of about 1,000 tonnes[59]. Designing ships for CO_2 transportation in the context of carbon capture and storage involves decisions on tank sizes, pressure, and temperature conditions influenced by the location, CO_2 source structure, and CO_2 purity.

In addition to the ships, the process also requires liquefaction and reconditioning facilities, buffer storage, and loading/unloading equipment at onshore ports. Figure 9 shows two types of ship-based CO_2 transportation networks[60]. The liquefaction process involves cooling and compressing CO_2 to the desired temperature and pressure[13]. The buffer storage handles the continuous flow of CO_2 from emitters when ships are not in port. It ensures a steady supply of CO_2 despite the discrete nature of ship loading. Near the storage site, the transported CO_2 may need to be processed to suitable conditions before injecting into geological formations for storage. The appropriate condition falls typically between 50-400 bar and 15 to 20 °C, depending on the characteristics of the average reservoir[59].



(a) Based on shipping between two harbours



(b) Based on shipping to an offshore site

Figure 9 Two types of ship-based CO_2 *transportation networks*[60]

Unlike pipelines, ships are usually used to transport CO_2 in small amounts. It has been done for food-grade CO_2 transport at a small scale for over thirty years, but it hasn't been used on a larger scale for carbon capture and storage. Transporting CO_2 by ship and the necessary port facilities are much like those for liquefied natural gas (LNG) and liquefied petroleum gas (LPG). The technology readiness level (TRL) for CO_2 shipping is between 3 and 9[33].

3.4 Carbon Storage and Utilization

Captured CO_2 can be stored permanently or utilized for other purposes. The CO_2 storage includes underground geological storage in deep saline aquifers or depleted oil and gas fields (DOGF). Underground CO_2 injection is achieved by pumping supercritical CO_2 down to the formation through an injection well, where it remains trapped. Monitoring, verification, and accounting (MVA) are needed before the start (to set the baseline), during the injection, and after closure to ensure the CO_2 remains in place. CO_2 utilization includes injecting CO_2 into a petroleum reservoir for enhanced oil recovery (CO_2-EOR) or into deep and un-mineable coal seams to recover methane (CO_2-ECBM). Many operational CCS projects are for EOR purposes with CO_2 captured from natural gas processing. CO_2 can also be used in industry processes such as mineral carbonation, chemical and fuel production, and food processing[35,47,48].

3.4.1 CO_2 Storage

Passive CO_2 storage refers to storing the CO_2 in deep geological formations that will not be emitted, thus mitigating global warming. The storage locations can be either onshore or offshore. Examples of such formations are depleted oil and gas fields, coal formations, and saline aquifers, which are deep underground rock formations composed of permeable materials and highly saline fields [13]. The saline aquifers are most commonly used for existing CCS projects. One example is the Sleipner CCS facility, which has injected over 20 Mt of CO_2 into a deep saline formation since 1996 in the North Sea. It is the first use of CCS as a climate mitigation tool within a commercial operation. The carbon storage in depleted oil and gas fields is technically mature but has only been applied in demonstration projects[24]. Some other unconventional options for CO_2 storage include basalt and ultramafic rocks, but they are only in the research phase[33].

Storing CO_2 involves several phases. The first phase includes screening sites, examining the chosen sites in detail, and getting the necessary permits. The operational phase consists of preparing a site development plan, building and installing the required infrastructure, and starting the injection operation. Monitoring, measuring, and verifying are essential once the site is up and running and CO_2 is injected[13]. The final phase, closure, happens when the storage capacity is reached. At that point, the injection well and any offshore structures are decommissioned, and the well is sealed and abandoned.

The geological storage of CO_2 requires CO_2 to be compressed to very high pressure (above 74 bar). The storage formation must be at a depth of at least 800 m to ensure that the pressure is maintained[33]. The United States has one of the world's largest known CO_2 geological storage capacities, estimated to be about 3,000 gigatons of CO_2 [61].

3.4.2 CO_2 Utilization

CO_2 utilization refers to the applications where CO_2 is embedded in a product. It might be more economical than storage if using CO_2 improves the product and increases the price that can be charged or CO_2 can substitute fossil fuel inputs in the manufacturing process. The most common CO_2 utilization on the market today is urea production and enhanced oil recovery. Other CO_2 utilization routes have also been explored by industries and research institutes and evaluated for their technical and economic feasibility. The current gross global CO_2 utilization is less than 200 million tons annually. Compared to CO_2 storage, CO_2 utilization can provide revenue streams, offset some of the capture and transport costs, and be economically feasible under certain circumstances.

The use of CO_2 can be summarized into three categories: (1) injecting CO_2 into the formations for enhanced oil and coalbed methane recovery, (2) using CO_2 as feedstocks for fuel and chemical production, and (3) industrial use such as solvent, food packaging, etc.

CO_2 for Enhanced Oil Recovery and Coalbed Methane Recovery

CO_2-enhanced oil recovery (CO_2-EOR) injects CO_2 to replace oil from pore space in the subsurface reservoirs. The primary goal is to enhance oil recovery, not store CO_2. However, CO_2 is trapped in the pore space, which previously held hydrocarbons, and permanently stored during the EOR process. CO_2-EOR has been in operation for nearly 50 years with TRL 9. There are over 40 CO_2-EOR operations, with the vast majority hosted in the United States[35].

CO_2 has also been tested at a small scale to replace methane from coalbeds, which is called enhanced coalbed methane recovery (ECBM). During the process, CO_2 is injected into the coal seam, diffuses into these micropores, and is adsorbed, displacing the methane. ECBM is a viable technology and can increase methane production. The main challenge associated with ECBM is that the injection of CO_2 significantly reduces coal permeability due to coal swelling. Moreover, MCBM can only be applied to coal seams which will never be mined; otherwise, the stored CO_2 would be released during coal mining[47].

CO_2 for Fuel and Chemical Production

The main processes to obtain fuels from CO_2 are syngas from the reforming of CH4, gas hydrates, and biofuels from microalgae. CO_2 can react with CH4 to produce hydrogen with a dry reforming process (DRM). However, DRM is not considered industrially mature due to the high energy and long reaction time required for the process. CO_2 can also potentially replace CH4 in gas hydrates to maintain the ocean floor after recovering CH_4 gas. Moreover, CO_2 can be used for biofuel production via microalgae cultivation. CO_2 can react with H_2 to produce methanol, which is one of the most appropriate alternative fuels due to its relatively high energy content[4].

CO_2 can also be employed to produce chemicals. One example is the electro-carboxylation of organic substrates with CO_2. It may meet the economic and environmental requirements by alternating the traditional reactions, which require organometallic reagents[17]. Besides, CO_2 can be used to produce carbamic acids due to its affinity for interacting with nitrogen nucleophiles, but only limited lab-scale research has been done. Other chemicals that can be generated with CO_2 include urea, organic carbonates, polycarbonates and polyurethanes. Moreover, CO_2 can react with ashes from coal-fired power plants and stainless steel slag with a high CaO/MgO content for mineral carbonation, which has the benefit of storing CO_2 for long periods without leakage risks[35].

Synthetic aviation fuels (SAF) are liquid fuels obtained from a mixture of carbon monoxide and hydrogen (known as syngas). The syngas can be derived either from biomass or hydrogen. The advantage of synthetic aviation fuel is that it produces 70-100% less net CO_2 than fossil kerosene, depending on the production pathway, and can "drop in" to existing infrastructure and equipment with only minor modifications. Synthetic aviation fuel will play a significant role in the decarbonization of aviation due to its high energy density and limited available supply of biofuels. SAF can be produced using carbon captured from DACC or BECC[49].

CO_2 for Industry Processes

CO_2 has several advantages in food processing as a preserving and antimicrobial agent in low-pressure and temperature environments. CO_2 can also be used to prevent food oxidation. Research has been done using high-pressure carbon dioxide in food facilities for microbial inactivation[62].

The cement industry is one of the most intensive CO_2 emitters, accounting for 5-8% of global anthropogenic CO_2 emissions. Incorporation of CO_2 into cement-based materials involves a chemical reaction between CO_2 and cement hydrates. Numerous studies have shown the role of CO_2 in improving the characteristics of cement-based materials, such as decreasing the curing stage duration and increasing the strength[4,47,63].

CO_2 is also an attractive solvent with its easily accessible critical point, high diffusivity, low viscosity, and surface tension. It can be used as a solvent in both liquid and supercritical states. One example of using CO_2 as a solvent is during hydroformylation, an industrial process in manufacturing aldehydes from olefins and syngas. Some lab-scale experiments have shown satisfactory results with low cost using supercritical CO_2 replacing conventional solvent for the process[4]. A second application is hydrogenation in supercritical CO_2, which has been successfully developed on an industrial scale. Besides, supercritical CO_2 has been investigated as a reaction medium for partial oxidation of aliphatic, unsaturated, aromatic, and benzylic acids with different catalytic systems, with some promising results[35]. Moreover, under non-aqueous conditions, supercritical CO_2 can be used as a solvent during organic catalysis and polymer synthesis. However, both face some drawbacks due to CO_2 interaction with the catalyst and the low solubility of high molecular weight polymers in supercritical CO_2 under soft conditions.

The CO_2 storage and utilization pathways are at various stages of technology development. Figure 10 shows the maturity curve of some CO_2 storage and utilization technologies[14]. CO_2 EOR has the highest maturity level, whereas CO_2 utilization for the production of fuels, chemicals, and building materials is in development or small-scale deeployment.

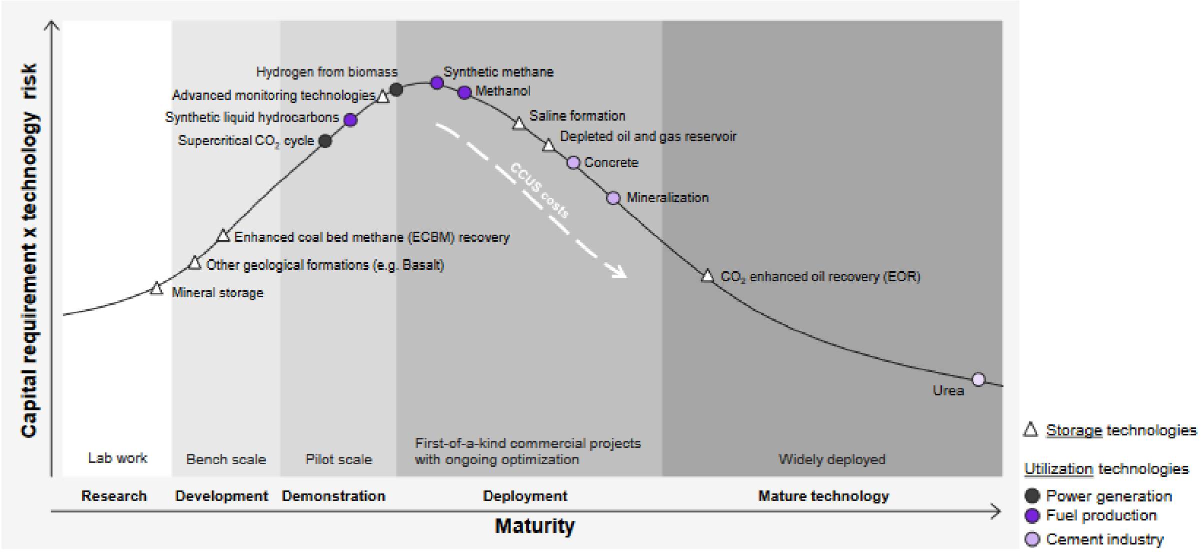


Figure 10 Maturity curve of CO_2 storage and utilization technologies[14]

IEA reported that about 230 million tons of carbon dioxide is used per year globally[64]. The largest consumer is the fertilizer industry, which consumes 130 Mt CO_2 in urea manufacturing, followed by oil and gas, which consumes 70-80 Mt CO_2 for EOR. Other commercial uses of CO_2 are predominantly in the food industry, which consumes about 30 Mtpa. IEA estimated that 60-240 gigatons of CO_2 could be stored underground in the EOR process[65]. The market for CO_2 use will likely remain relatively small in the short term. Still, with increasing interest from government, industry, and investors, new pathways, such as transforming CO_2 into fuels and chemicals, may become commercially viable.

Notably, CO_2 utilization can complement but not replace CO_2 storage to deliver significant emission reduction ambitions. In particular, CO_2 utilization can support investment in CO_2 capture opportunities and technology refinement in the near term. However, its anticipated scale in the long term is still relatively small compared to that of CO_2 storage.

3.5 CCS Cost

Although CCS has a strong CO_2 abatement potential, the adoption and implementation of CCS projects face obstacles such as high capital expenditure, long life cycles, and regulatory uncertainties. Government entities, industries, and Research & Development (R&D) institutes will rely on CCS cost information to make policy changes, CCS investments, technology development, and energy-related decision-making at various levels. Crucially, cost estimates are vital for determining CCS feasibility and scalability, underscoring the importance of ongoing research to reduce costs and promote widespread adoption in the global fight against climate change.

CCS costs have three main components: capture, transport, and storage. The main challenge of CCS cost estimation and comparison between various CCS studies is the inconsistency of performance metrics and underlying assumptions. Some commonly used metrics to report CO_2 capture, transport and storage costs include: (1) cost of CO_2 avoided (\$/tCO_2), which represents the total cost of CO_2 captured and stored and generally reported as part of a complete CCS system; (2) levelized cost of CCS in \$/tCO_2 which measures the cost of carbon capture, transport or storage amortized over the life of a project; and (3) unitary transport cost per unit distance and quantity transported. Besides, the obscure interfaces between interacting components and system boundaries of CCS projects make the levelized cost estimate of CCS projects even harder.

Several research groups have tried to standardize the cost estimates for CCS projects. Rubin et al. summarized CO_2 capture, transport, and storage costs from related studies published before 2015 and adjusted these estimates to a common basis for accurate comparison[66].

3.5.1 Capture Cost

The carbon capture cost generally decreases with increasing CO_2 concentration in the capture source. For direct air capture, the CO_2 capture cost is between $134 to $342 per ton of CO_2 due to the extremely low concentration of CO_2 in the air[20]. In contrast, carbon capture costs range from $40 to $120 per ton of CO_2 from power plants using pre- and post-combustion technologies. Multiple pieces of literature have reported carbon capture costs from power plants, and their values vary between 46 and 140 $/tCO₂ with a midpoint around 74 $/tCO₂[44,66,67]. Table 2 shows the reported CO_2 capture cost by industry source [67].

Table 2 CO_2 capture cost by industry[67]

CO_2 Capture by Industry	CO_2 capture cost, $/tCO₂		
	Low	High	Rep. Value
Direct air capture	165	421	293
Power generation	62	123	92
Cement	74	148	111
Iron and steel	49	123	86
Compression only	16	31	23
Hydrogen (SMR)	62	98	80
Ethylene oxide	31	43	37
Bioethanol	31	43	37
Ammonia	31	43	37
Coal to chemicals	18	31	25
Natural gas processing	18	31	25

3.5.2 Transport Cost

The CO_2 transport cost varies widely depending on transport technology, distance, flow conditions, and environmental settings [50]. Pipelines and ships are the primary options for large volumes of CO2 transport to meet the net-zero emission goals. Nearly 5,000 miles of CO_2 pipeline are in operation in the US, most connecting CO_2 sources to enhanced oil recovery injection sites. Capture facilities not located near an existing CO_2 pipeline may face hurdles in constructing new pipelines, with right-of-way issues, permitting, pipeline costs, and compression costs [68]. The US Department of Energy estimates that between 30,000 and 96,000 miles of CO_2 pipeline will be necessary for the US to meet its net-zero 2050 goals[68]. Shipping of CO_2 has also been explored as a potential mode of transport and is potentially economically viable at low CO_2 rates compared to pipeline [69]. Table 3 shows the normalized CO_2 transport cost by transport option, flow rate, and distance [50].

Table 3 Normalized CO_2 *transport cost by transport option, flow rate, and distance*[50]

Option	Distance, km	CO_2 transport cost, \$/tCO_2/100 mile				
		Flow rate, 1 Mtpa	Flow rate, 2.5 Mtpa	Flow rate, 5 Mtpa	Flow rate, 7.5 Mtpa	Flow rate, 10 Mtpa
Onshore pipeline	100	19.6	7.0	4.7	4.0	3.5
	250	20.6	8.4	5.6	4.7	3.7
	500	19.6	8.1	5.6	4.7	4.2
	750		7.8	5.6	4.7	4.0
Offshore pipeline	100	6.9	9.3	7.0	5.8	4.7
	250	33.8	10.2	6.5	5.6	4.7
	500		11.2	7.4	6.5	6.1
	750			8.4	7.1	5.9
Ship to harbor	100	33.4	27.9	25.6	23.3	22.1
	250	16.5	12.1	11.2	10.2	9.8
	500	8.5	6.5	6.1	5.6	5.4
	750	6.5	4.7	4.3	4.0	3.9
Ship to offshore	100	56.5	30.3	27.9	25.6	23.3
	250	23.0	14.0	13.0	11.2	10.2
	500	13.5	7.9	6.8	6.1	5.6
	750	9.2	5.6	4.8	4.3	4.0

3.5.3 Storage Cost

It is estimated that a storage capacity of 10,000-30,000 GtCO_2 exists worldwide, more than enough to potentially store the nearly 4,000 GtCO_2 associated with the estimated global petroleum and coal reserves. However, these potential storage reservoirs are not equally geographically distributed and are of varying reservoir quality, affecting the potential injection rates and regional volumes available for CO_2 storage [70]. Costs associated with CO_2 storage are dependent on the possible injection CO_2 rates, total potential storage capacity, type of reservoir, location (onshore vs offshore), and the requirements for new or additional injection wells for pressure management [71]. There is a wide variability in CO_2 storage costs reported in the literature. Table 4 shows the range of CO_2 storage cost in 2024 \$/tCO_2. The storage cost is close to the transport cost, and both are lower than the carbon capture cost.

Table 4 CO_2 storage cost by storage option[66]

CO_2 storage option	CO_2 storage cost, \$/tCO_2		
	Low	High	Rep. Value
Depleted O&G Field - reusing wells, onshore	2.0	14.3	6.1
Depleted O&G Field - no reusing wells, onshore	2.0	20.4	8.2
Saline formations, onshore	4.1	24.5	10.2
Depleted O&G Field - reusing wells, offshore	4.1	18.4	12.3
Depleted O&G Field - no reusing wells, offshore	6.1	28.6	20.4
Saline formations, offshore	12.3	40.9	28.6

One thing to note is that when estimating the costs of CO_2 capture, transport, and storage costs, it is assumed that the technologies are all mature and ready to deploy. That's why the cost numbers in the previous tables are all associated with relatively mature technologies such as pipeline or ship and aquifer storage. The reality is that different technologies are at different maturity stages, and their costs can be reduced in the future via learning by doing.

As mentioned before, the cost of CCS depends on many factors, including the applied technology, location, and scale. Besides, the facility's cost structure and lifetime also impact the normalized CCS cost per ton of CO_2. With assumptions of an asset life of 20 years, a discount rate of 12%, 100% equity financing, and a federal tax rate of 21%, the current CCS capacity in the United States from stationary point sources is about 20 Mtpa with an average cost of \$40/tCO_2. The cost for the CCS expansion phase with a capacity of 100

Mtpa is between \$50 and \$90 per ton of CO_2. At-scale CCS deployment will increase the CO_2 capture capacity up to 480 Mtpa from stationary point sources, and the associated CCS costs are between \$90-110/tCO_2. After that, there are still 80% stationary point CO_2 emissions left, which require even higher costs to capture and store. Continued research and development are needed to advance the capture and storage technology and reduce the cost substantially to make them economically feasible[6].

3.6 Carbon Policy

The overall cost of the CCS process is expected to be \$22-80 per ton of CO_2 by 2025, with CO_2 capture accounting for more than two-thirds of the total cost[33]. Governments implemented policies or provided tax credits for CCS projects to regulate CO_2 emissions and offset some carbon capture and storage costs.

A common political strategy to reduce CO_2 emissions is to charge emitters a fee for each ton of CO_2 they emit, known as a carbon price. There are 65 CO_2 pricing initiatives worldwide, covering 21.5% of global emissions in 2021[72]. Nordic countries were the first to introduce a carbon tax nearly 30 years ago. Today, Sweden has the highest carbon tax in the world at \$137 per tonne. While carbon taxes help reduce emissions, some countries or regions also use emissions trading schemes (ETS). The European Union has the largest ETS, covering about 1.7 GtCO_2 (45% of EU emissions) with prices above \$40 per ton. However, in some regions, ETS coverage is less extensive than in the EU, and prices are three to four times lower[47].

In 2009, the American Recovery and Reinvestment Act allocated \$3.4 billion to the U.S. Department of Energy (DOE) for carbon capture and storage projects. This funding has helped speed up the development and demonstration of CCS in the United States. More recently, the 2021 Infrastructure Investment and Jobs Act provides \$8.2 billion for CCS programs over the 2022-2026 periods. In addition, companies that capture and store CO_2 are also eligible for the section 45Q federal tax credit, which provides incentives for reducing federal revenue for using CCS. It offers varying credit amounts based on the type of carbon oxide captured and its end use, with higher credits for CO_2 stored in secure geological formations. The credit for carbon capture equipment placed in service after 2022 is currently $85 per metric ton if sequestered and $60 per metric ton if utilized commercially[73]. Eligible projects can claim the credit for up to 12 years and may transfer it to another entity. Projects must capture CO_2 or CO from industrial sources, power plants, or direct air capture facilities and securely store it in geological formations to qualify. Annual capture thresholds are set at 1,000 metric tons for direct air capture facilities, 12,500 metric tons for industrial facilities, and 18,750 metric tons for electric generating units. Projects must begin construction before January 1, 2033[73].

In addition to the 45Q Tax Credit, incentives for carbon capture include financing from the DOE Loan Program Office, United States Department of Agriculture (USDA) rural financing, other federal tax credits, and various state and regional policies. For example, California's low-carbon fuel standard (LCFS) provides tax credits of approximately $100 per ton of CO_2 [74]. However, these tax credits alone are insufficient to cover every CCS project's cost.

Chapter 4 CCS System Design and Engineering

4.1 CCS System Problem and Objectives

In this study, the area of interest is the CCS system in the United States. The total CO_2 emission in the United States in 2023 was about 5 Billion tons of CO_2, representing about 13.5% of global CO_2 emission. A study by Princeton University reported that 0.9 and 1.7 Gt CO_2 need to be captured and sequestered per year to achieve the net-zero goal in the United States for scenarios with continuing consumption of fossil fuels[75]. Correspondingly, it requires CO_2 capture from about 1000 facilities, transported through a 21,000 to 25,000 km interstate CO_2 trunk pipeline network with 85,000 km spur pipelines and thousands of injection wells for CO_2 sequestration [75].

The main objectives of CCS during the net-zero journey include three aspects: (1) reducing carbon emission from fossil fuel-based power and industrial plants, (2) removing carbon from the atmosphere and providing climate-neutral CO_2 for various applications, and (3) serving as a platform for low-carbon hydrogen production [2].

The current emission information from fossil fuel-based power plants and industry facilities is critical to planning carbon capture from those stationary point sources in the United States. The United States has over 6500 power and industrial facilities emitting 2.6 billion metric tons of CO_2 annually[44]. Table 5 lists the stationary greenhouse gas emissions from US industrial and power facilities. Figure 11 shows the distribution of emission facilities with emission levels higher than 0.1 Mtpa of CO_2 equivalent in the United States.

Achieving the second objective requires negative CO_2 removal systems, mainly bioenergy with carbon capture and sequestration (BECCS) and direct air capture (DAC) with CO_2 storage. BECCS captures and stores CO_2 from biomass conversion processes, such as biomass-based power plants and biofuel production. BECCS is relatively mature in terms of technology readiness. Four industrial-level CCS projects in the United States capture CO_2 during ethanol production from biomass and inject captured CO_2 either for EOR or geological storage with a total capacity of 1.8 Mtpa[2]. Dozens more BECCS projects will come into operation worldwide, mainly in the United States, to expand the capacity to over 20 Mtpa in the next few years[5]. The DACCS (direct air carbon capture and storage) refers to the direct capture of CO_2 from the ambient air and the subsequent storage of captured CO_2 in a permanent way. Both systems are considered as negative CO_2 emission pathways with permanent CO_2 storage.

Table 5 Stationary greenhouse gas emissions from industrial and power facilities in the U.S.[44]

Industry	# of facilities	Share of US Stationary emission	CO_2 emission, Mtpa	Biogenic CO_2 emission, Mtpa	Methane emission, Mtpa	Nitrous Oxide emission, Mtpa
Coal power plant	336	45%	1270.6	0.4	3	6.2
Gas power plant	963	21%	581.3	0.9	0.5	0.4
Refinery	121	6%	171.3	0	0.7	0.4
Metal and Mineral	1511	5%	101.1	5.3	42.3	0.4
Gas processing	1246	4%	88.9	0.2	9.9	0.1
Waste	1225	4%	11.1	17.5	86.7	0.4
Cement	149	3%	90.4	0.8	0.01	0.2
Hydrogen	79	2%	66.2	0	0.1	0.1
Steel	82	2%	58.5	0	0.3	0
Chemicals	266	2%	30.4	0.7	0.1	13.1
Petrochemicals	61	2%	46.1	0.1	0.5	0.1
Pulp & Paper	225	2%	37.1	112.2	5.2	0.5
Other power plant	118	1%	36.4	9.2	0.2	0.2
Ethanol	181	1%	31.2	9.2	0.1	0.1
Ammonia	23	1%	25.21	0	0	4.1
Total	6586	100%	2645.8	147.9	149.5	26.2

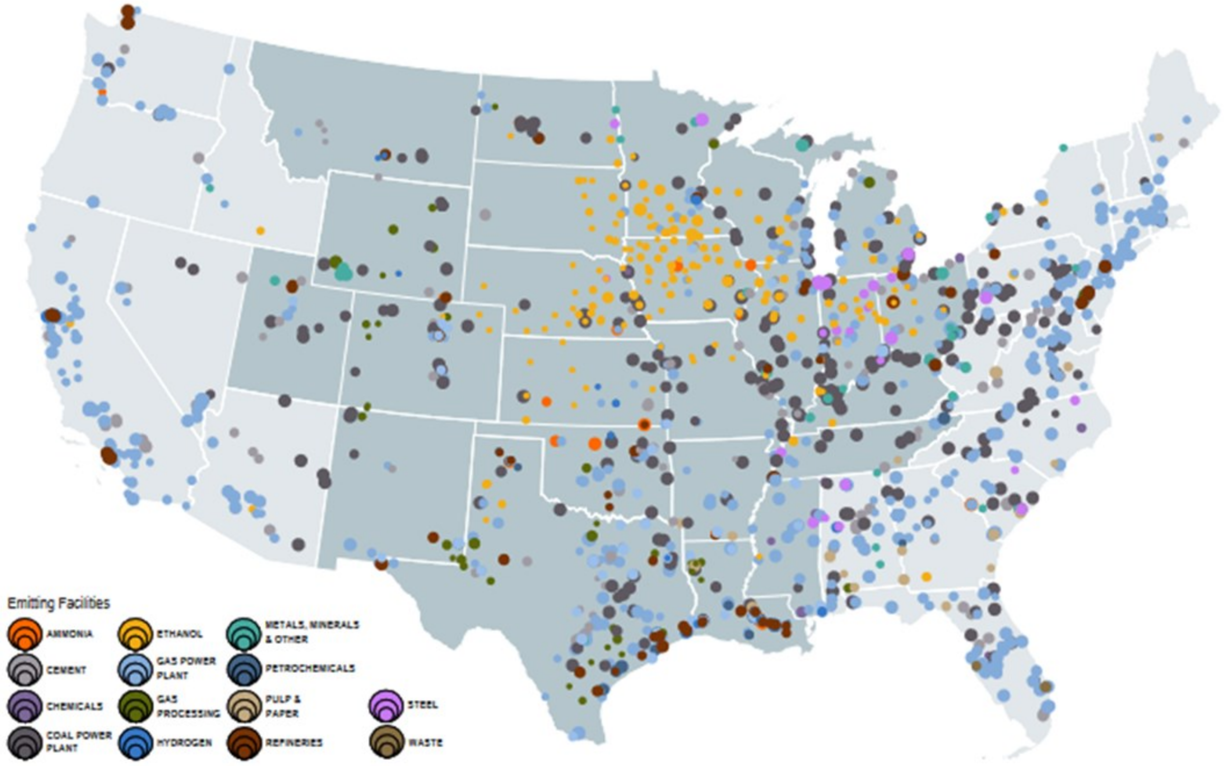


Figure 11 Distribution of stationary greenhouse gas emissions from industrial and power facilities in the U.S.[44]

Alternative energy sources are required to replace fossil fuels for power and heat generation to maintain economic growth while reducing carbon emissions. Besides natural renewable energy like wind and solar, hydrogen also plays a critical role in the net-zero models with high energy density. The potential application of hydrogen includes long-distance transportation, chemical and synthetic fuel production, and industrial heating. Hydrogen can be produced by water electrolysis but at a high cost. It can also be generated relatively cheaply through natural gas reforming and biomass gasification with CCS.

The system problem statement (SPS) of this study is to achieve the carbon capture and storage targets of the NetZero emission development scenario in the United States by designing and developing feasible and affordable CCS systems using system design and engineering approaches and methodologies.

4.2 CCS System Requirements

4.2.1 System Stakeholders

The CCS system has many stakeholders, including government entities, private sectors, research institutes, and the general public. Each stakeholder has its own needs and requirements for the CCS system. Figure 12 shows the identified system stakeholders and their needs at a high level.

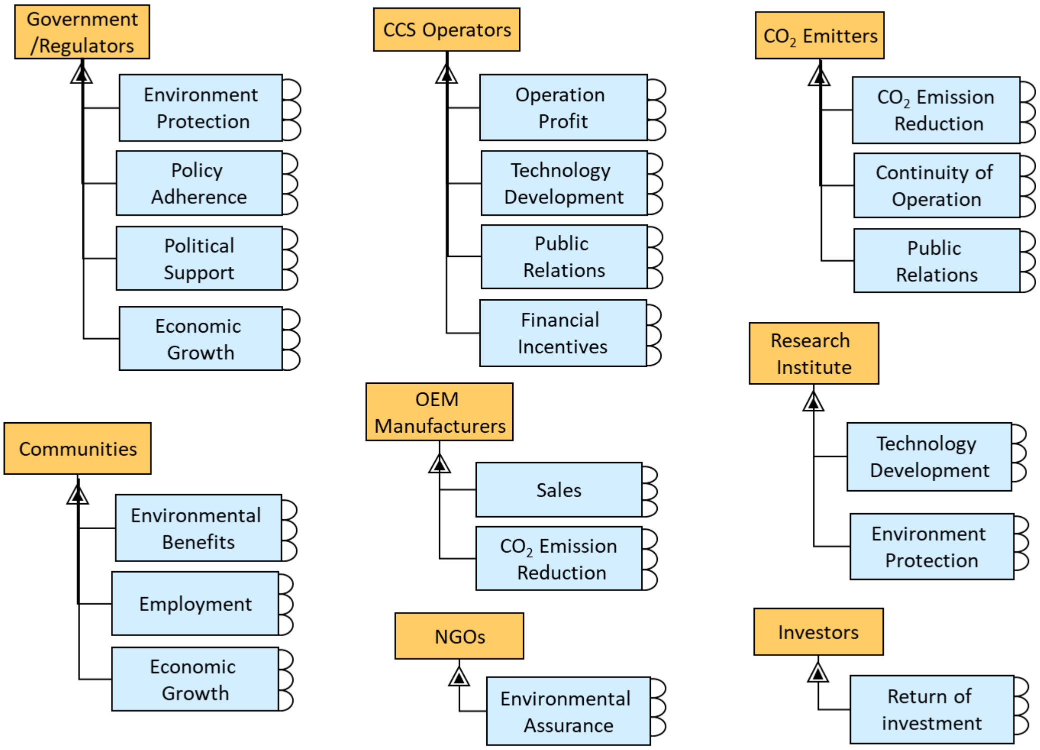


Figure 12 CCS System stakeholders and their needs

4.2.2 CCS System Requirements

The high-level requirements of the CCS system include:

1. The CCS system shall capture, transport, and store/utilize carbon dioxide at a target rate (e.g., 700 Million tons per year) by a specific date (e.g., 2050).
2. The CCS project shall be economically viable for CCS operators with government incentives in the short term and without government incentives in the long term.

3. The CCS system shall meet government regulations and compliance requirements regarding operational safety standards.
4. The CCS system must run continuously and efficiently during the project lifespan.
5. For permanent CO_2 storage, the injected CO_2 shall remain in storage formations for over 100 years.
6. The CCS system shall meet the requirements for government incentives if tax credits are included in the financial calculation.

4.2.3 CCS System Decomposition

When designing a carbon capture and storage (CCS) system, several key system considerations must be addressed to ensure its functionality, effectiveness, safety, and economic viability. Those considerations span the entire CCS value chain, from carbon capture to transport to storage or utilization.

Figure 13 shows the Level-1 (L1) and Level-2 (L2) decompositions and boundary of a CCS system. The main components of the CCS system are CO_2 capture, CO_2 transport, and CO_2 utilization or storage. A more detailed operational diagram of a typical CCS system is shown in Figure 14, with the primary system functions, boundaries, and relationships between operands, processes, and instruments.

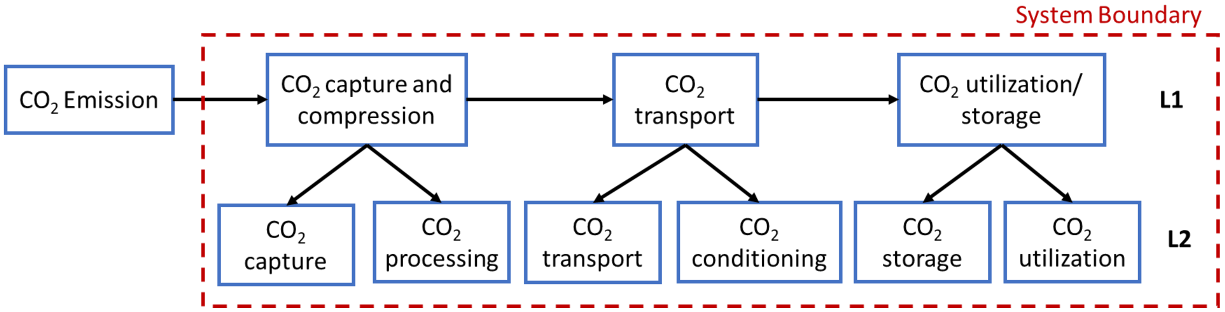


Figure 13 CCS system compositions at level 1 (L1) and level 2 (L2) and system boundary

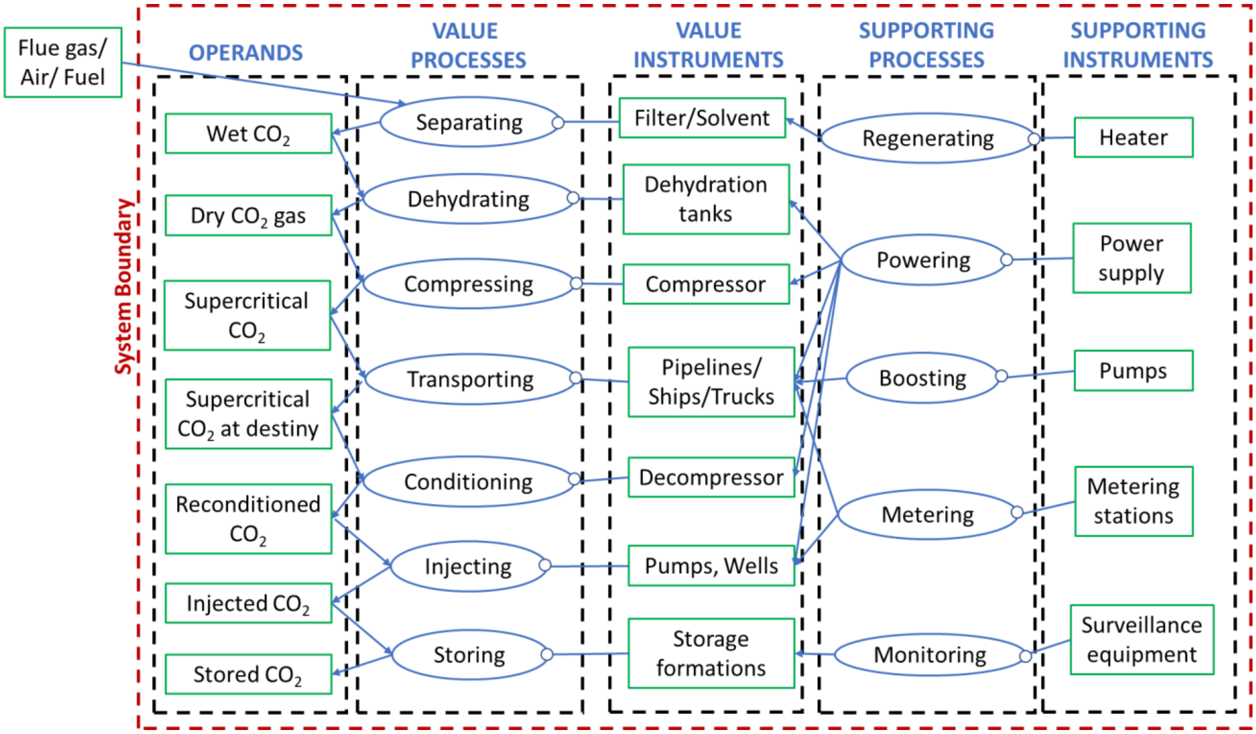


Figure 14 CCS system primary functions, boundaries, and relationships between operands, processes, and instruments

A CCS system starts with CO_2 separation from flue gas or air through a solvent or filter. The separated CO_2 is then dehydrated through dehydration tanks to remove the water vapor. After dehydration, the gathered CO_2 is compressed into fluid or supercritical condition by compressors to be suitable for transport via pipe, ship, truck, etc. Once the CO_2 arrives at the storage location, it will be reconditioned to the proper pressure and temperature for injection into geological formations for permanent storage. The diagram shown in Figure 14 is just a typical example of CCS systems; the operands and processes can change depending on the CCS system architecture design.

4.2.3 CCS System Considerations

A CCS system can consist of a single capture plant from a single CO_2 emission source, CO_2 transportation with a dedicated section of pipelines, and a single sequestration site. The existing CCS projects mostly follow this model within a narrow location range. A complicated CCS supply chain network can be a collection of multiple sources, capture plants, and utilization and storage sites connected via a network of pipelines to manage CO_2 for a large geographic region. Numerous sources can supply CO_2 in various amounts and meet variable demands for different utilization and storage sites [76].

CO_2 capture depends significantly on the emission sources. As shown in Table 1, each industry process has different emission levels and corresponding capture capacities to achieve the net-zero emission target. The CO_2 concentration in flue gases from industrial processes ranges from 4% to 95% and is as low as 0.04% in the ambient air. CO_2 capture from low CO_2 concentration sources requires more layers of separation and thus higher capture costs, so emission source types must be considered when designing CCS systems. In addition, some industrial emissions can be reduced by replacing fossil fuels with renewable energy sources, such as solar and wind. Therefore, CCS competitiveness among all decarbonization solutions will be evaluated for each industry sector.

There are several processes of carbon capture: post-combustion, pre-combustion, oxyfuel combustion, DAC, etc. Each process requires material and energy to separate CO_2 from other gases. Energy consumption and capturing efficiency are the primary performance measures of the carbon capture process. Besides, the carbon capture from stationary point sources is never standalone but integrated with the internal processes of different source plants. Thus, the complexity of integration with existing industrial processes to minimize disruptions to core operations also needs to be considered. In addition, to achieve the target capture capacity, the scalability of the capture technology is critical in the long term. The CCS system's scalability depends on technology maturity, future capture capacity, and cost reduction rate. Furthermore, the carbon capture cost is a determining factor in CCS design, which depends on the CO_2 source, capture efficiency, and capture technology.

During carbon transport, the primary options are pipelines, ships, trucks, and railcars. Each option requires a specific type of infrastructure network and operational safety and reliability standards. For example, the pipeline for carbon transport needs to use materials that can withstand high pressure and the potential corrosiveness of CO_2. The route design of new pipelines needs to be optimized to minimize cost and environmental impacts. Sometimes, retrofitting existing pipelines for CO_2 transport may also be an option. For long-distance CO_2 transport through pipelines, compressors and boosters may be needed to maintain the pressure of CO_2 in the pipe.

Though the pipeline has the highest potential for large volumes of CO_2 transport, there are regions where pipeline infrastructure is impractical. Ships, trucks, or railcars must be considered for carbon transport. For those discrete CO_2 transport, extra facilities such as storage buffers and CO_2 conditioning units are necessary to ensure the continuity of operation.

CO_2 transport costs greatly depend on transport technology (pipelines, ships, trucks, railcars), the volume transported (pilot scale vs. large scale), the distance, and the environment (onshore vs. offshore). The cost increases with flow rate and transport distance. Offshore transportation will be more expensive than onshore.

For passive CO_2 storage in geological locations, it's essential to understand the formation that will store CO_2, such as formation temperature and pressure, and its petrophysical properties like permeability and porosity. Those characteristics determine the feasible injection rate and storage capacity of CO_2. The seal integrity of the geological is critical for storage effectiveness. Various surveillance technologies can be used to monitor and assess the CO_2 storage status over time. The storage formation location is a significant factor in CCS design. The distance between the carbon capture location and storage site directly impacts the cost and feasibility of CO2 transport options. Besides, offshore CO_2 storage locations are generally associated with higher CO_2 transport and surveillance costs than onshore locations. The existing legacy wells may reduce the capital investment needed for CO_2 storage through retrofitting. Most CO_2-EOR projects have converted the previous oil producers to CO_2 injectors to save the cost of drilling new wells.

The carbon utilization design depends on the CO_2-derived product type and manufacturing process. The processing facilities are generally required to support CO_2 utilization. Existing industry infrastructure may be adapted for CO_2 utilization.

In addition to boosting stations, meters, and storage buffers, monitoring technologies and facilities are essential to ensure the operational safety and compliance of CCS projects with government regulations. When selecting monitoring facilities, it is necessary to consider the technology maturity, potential operational interruptions, government permitting requirements, and corresponding costs.

Additionally, the design of CCS systems needs to consider the project's lifecycle, from planning to decommissioning. The financial aspects such as capital investment, operational expenses, and maintenance are also crucial considerations. Funding options, government incentives, and potential revenue streams of CO_2 utilization are worth exploring to offset some of CCS costs.

Another vital consideration for CCS system design is scalability. Given the ultimate goal of achieving net-zero emission in the United States by mid-century, the technologies chosen and implemented for the system must reach the industrial scale and be economically viable. Two characteristics of CCS technology can be used to evaluate its scalability: technology maturity and target capacity of carbon capture, transport, and storage. The capacity of existing CCS projects commonly ranges between 0.5 and 1 $MtCO_2$ per year with a single capture plant and single storage. The new CCS systems need to expand easily and quickly into clusters with a capacity of over 10 Mtpa with groups of emitters from different industrial sectors and storage formations connected through massive transportation networks. Table 6 summarizes the options and considerations for each component of a CCS system.

Table 6 Options and considerations for CCS system design

	Options	Considerations
CO_2 source	Atmospheric CO_2, Stationary sources	Source type, source location, flue gas flow rate, flue gas composition, CCS potential, emission level, target capture capacity
CO_2 capture	Direct air capture, Post-combustion, Pre-combustion, Oxy-combustion	Capture technology maturity, Capture material, Feed CO_2 composition, Feed flow rate, Capture efficiency, Capture capacity, Capital investment, Operational cost, Feed CO_2 condition, Outflow condition
CO_2 transport	Pipelines, Ships, Trucks, Rail	Distance, Environment (Onshore vs. offshore), Accessibility, Transport capacity, Flow rate, CO_2 purity, Transport condition, Capital investment, Operational cost, Technology maturity
Supporting facilities	Boosting stations, Metering stations, Storage buffers, Conditioning facilities, Monitoring facilities	Accessibility, Capacity, Throughput rate, Capital investment, Operational cost, Input and output CO_2 conditions, Technology Maturity, Operation interruption, Regulation compliance
CO_2 storage/utilization	Geological CO_2 storage, CO_2-EOR, CO_2-ECBM, CO_2 utilizations (chemical and fuel production, other products)	Storage location, CO_2 price, Storage Capacity, Utilization demand, Technology maturity, Accessibility, Infrastructure, Capital investment, Operational cost

4.3 Design Vector and Performance Metrics

4.3.1 Architecture Decisions

The architectural decisions for a CCS system based on level 1 system decomposition are outlined in Table 7. It aligns with the system problem statement and enables a holistic view of the CCS system with all possible design options and performance assessments.

Table 7 CCS system architectural decisions

Architecture Decision	AD1	AD2	AD3	AD4	AD5	AD6
Description	Carbon source and capture	CO_2 transport type	Flow rate, Mtpa	Storage type	CO_2 utilization	Environment
Option 1	Natural gas processing	Pipeline	1	DOGF with legacy wells	EOR	Onshore
Option 2	Chemicals	Ship	2.5	DOGF without legacy wells	ECBM	Offshore
Option 3	Ethanol	Truck	5	Saline formation	Aggregates	
Option 4	Ammonia	Rail	7.5	None	Concrete curing	
Option 5	Hydrogen		10		Methane	
Option 6	Iron & Steel				Synfuels	
Option 7	Cement				Chemicals	
Option 8	Coal power plant				Fertilizer	
Option 9	Refinery				Food processing	
Option 10	Gas power plant				None	
Option 11	Air (DAC)					
Option 12	Bioenergy (BECC)					

A brief explanation of each architectural decision is clarified below:

- AD1 – Carbon source and capture refers to CO_2 capture from stationary sources (10 types), direct air capture (DAC), and bioenergy carbon capture (BECC). Each option has a corresponding emission source type, CO_2 concentration, emission levels, capture technology, and cost. The carbon capture and carbon source are combined into one architectural decision because of their interdependence and the smaller variety of mature CO_2 separation technology used across different industries and processes.
- AD2 – CO_2 transport type refers to the technology that transports conditioned CO_2 from capture location to storage/utilization sites. Four options are identified:

pipeline, ship, truck, and rail. Each option will be evaluated for its existing capacity, accessibility, and cost. The supporting system, such as storage buffers for ships and trucks and booster stations for long-distance transport, are included for corresponding transport options.

- AD3 – CO_2 flow rate refers to the transportation rate of CO_2. Five options are specified: 1 Mtpa, 2.5 Mtpa, 5 Mtpa, 7.5 Mtpa, and 10 Mtpa. The CO_2 flow rate directly impacts the transport capacity and cost.
- AD4 – Storage type refers to the CO_2 storage formation type. Three options are provided: saline aquifers and depleted oil and gas formations (DOGF) with and without legacy wells. The presence of legacy wells reduces the average cost of CO_2 storage in geological formations. The "None" option refers to the scenario where CO_2 is utilized instead of stored permanently.
- AD5 – CO_2 utilization refers to different CO_2 utilization pathways. Ten options are identified: CO_2 injection for enhanced oil recovery (EOR), CO_2 injection for enhanced coalbed methane (ECBM), CO_2 application in construction materials like aggregates and concentrate, CO_2 transformation for synthetic fuel, methane and chemical production, and CO_2 utilization in food and beverage industry. The "None" option refers to the case where the CO_2 is geologically stored.
- AD6 – Environment refers to the CO_2 transport and storage location onshore or offshore.

Following are some typical examples of existing CCS systems. The first example is Century Plant[47], operated by Occidental Petroleum in the natural gas processing sector and started in 2010. Using gas sweetening capture technology, the plant captures about 8 Mt of CO_2 annually from natural gas-producing fields in the Val Verde sub-basin. The captured CO_2 is then compressed and transported over a 100-mile pipeline to Permian Basin Fields for CO_2 EOR. It is the largest single industrial source CO_2 captured facility in North America.

A second example of a CCS system is the SaskPower Boundary Dam CCS project, the first largest-scale CCS in the power generation sector in Canada[47]. It captures about 1 Mt

CO_2 per year from a lignite-fired power plant using post-combustion technology starting in 2016. The captured CO_2 is then compressed and transported using pipelines for EOR application.

A third example of the CCS system is the Quest project in Canada[47], which uses post-combustion technology to capture CO_2 from the Steam Methane Reformer (SMR) hydrogen production process. The captured CO_2 is then compressed, transported through pipelines, and injected into a saline aquifer for permanent storage. The CCS system has captured and stored about 1.2 Mt CO_2 annually since 2015, reaching 5 Mt of CO_2 by July 2020.

A small-scale CCS project example is Port Jerome in France, which captures CO_2 from a blue hydrogen production process using an innovative cryogenic separation method as part of oxy-fuel combustion. It captures about 0.1 Mt CO_2 per year and transports the CO_2 using trucks to locations for agriculture production and food preservation[47].

Table 8 summarizes the architecture decision options for the CCS projects mentioned above.

Table 8 Architecture decision options of example CCS projects

Project	AD1	AD2	AD3	AD4	AD5	AD6
Century Plant	Natural gas processing	Pipeline	5	None	EOR	Onshore
Boundary Dam	Coal power plant	Pipeline	1	None	EOR	Onshore
Quest	Hydrogen	Pipeline	5	Saline formation	None	Onshore
Port Jerome	Hydrogen	Trucks	1	None	Food processing	Onshore

4.3.2 Performance Metrics

Based on the system requirements and considerations of CCS projects, specific metrics are chosen to assess and compare system performance against the established target. The performance metrics are selected based on system requirements and stakeholder preferences commonly found in the literature. For example, research institutes, governments, and CCS operators commonly use the CCS system cost, including the capital and operation cost and levelized cost of a unit amount of CO_2 captured and stored, to evaluate CCS financial performance and competitiveness against other climate change solutions. Additionally, the capacity of a CCS system is crucial in determining its impact on reducing CO_2 emissions. System efficiency, which relates to CO_2 capture and sequestration effectiveness, is also essential. Finally, the scalability of a CCS system is critical to achieving the long-term goal of NetZero emissions by midcentury. Table 9 shows the selected performance metrics for the CCS system evaluation and comparison.

Table 9 Performance metrics for the CCS system evaluation and comparison

Category	Name	Description	Measure and Units
Financial performance	Capital investment	The amount of capital required to enable the system operation for capture, transport, and store or utilize unit amount of CO_2	$/ ton of CO_2
	Operational cost	The cost to operate and maintain the system for capture, transport, and store or utilize unit amount of CO_2	$/ ton of CO_2
	Government incentives	The cost reduction from government incentives on CCS projects	$/ ton of CO_2
	Potential revenue stream	The revenue of carbon utilization or credit trading, besides government incentives	$/ ton of CO_2
Capacity	Annual capture capacity	The amount of CO_2 that can be captured, transported, and stored per year by the system	Mtpa CO_2
	Total capacity	The total amount of CO_2 that can be stored during the lifespan of the system	Mt CO_2
	Target capacity	The target capacity of carbon capture, transport, or storage/utilization in mid or long-term	Mtpa CO_2
Efficiency	CCS efficiency	The efficiency of CO_2 capture, transport, and storage/utilization using a specific technology	-
Scalability	Technology readiness level	The technology readiness level for carbon capture, transport, and storage or utilization	-
	Cost reduction rate/economies of scale	The cost reduction per year for a given CCS technology with economies of scale	%/year
	Technology competitiveness	The CCS competitiveness among potential solutions for given industry for carbon reduction	-

The performance metrics are split into four categories: financial performance, throughput capacity, efficiency, and scalability. Economic performance includes capital investment and operational costs to develop and operate the carbon capture, transport, storage/utilization system, government incentives like 45Q, and other potential revenue streams that can offset some costs. The capacity measures the annual and total capacity over the lifetime of carbon capture, transport, and storage with a given CCS technology. The efficiency is quantified for each step of carbon capture, transport, and storage for a given architectural design. The scalability evaluates the long-term potential of the CCS architecture design from four aspects: the technology readiness level, the cost reduction rate through economies of scale, the gap between current capacity and target capacity of CCS, and technology competitiveness. The technology competitiveness evaluates the advantage of CCS technology over other potential solutions like renewable energy for carbon reduction in different industry sectors. Details of the performance parameters of each design option will be shown in Chapter 5.

The technology readiness level (TRL) measures the CCS technology readiness. Table 10 shows the definition of each TRL level for CCS technologies [33]. Technologies categorized under Demonstration with high TRLs are considered mature and ready for upscaling when needed. Conversely, technologies in the Development and Research Categories are less mature, carrying significant uncertainties, and may not be easily scalable.

Table 10 Technology readiness level definition for CCS technologies

Category	TRL	Description
Demonstration	9	Normal commercial service
	8	Commercial demonstration, full-scale deployment in final form
	7	Sub-scale demonstration, fully functional prototype
Development	6	Fully integrated pilot tested in a relevant environment
	5	Sub-system validation in a relevant environment
	4	System validation in a laboratory environment
Research	3	Proof-of-concept tests, component level
	2	Formulation of the application
	1	Basic principles, observed, initial concept

4.4 Design Objectives and Constraints

Given the focus of this study on CCS systems in the United States, the primary constraints of CCS design include (1) the existing stationary CO_2 emissions in the U.S. with fixed locations and emission levels; (2) the existing infrastructure in the United States for CO_2 capture, transport, and storage; (3) the potential capacity of CO_2 utilization and storage; (4) the material and labor cost; (5) the federal and state-level government policies and incentives related to CCS projects; and (6) the target date to achieve NetZero emission of 2050.

Different from the CCS supply chain optimization to maximize capacity or minimize cost using the multi-integer method commonly found in literature, the main design objective in this study is to evaluate the CCS system performance from multiple aspects using systems engineering approaches and methodologies such as system design, and tradespace analysis, and sensitivity analysis.

Chapter 5 CCS Value Chain System Modeling

5.1 Modeling Approach and Assumptions

Based on the architecture decisions, a CCS system design includes the selection of carbon capture option, CO_2 transport method and rate, storage type and CO_2 utilization pathways, and transport and storage environment. It's a multi-scale problem with various solutions across time and geological spans.

Some key assumptions are made to build the system model:

1. The capture plants are co-located with CO_2 sources, which include the compression/liquefying/processing facility to process the captured CO_2 to meet the transport requirements with corresponding temperature and pressure conditions.
2. The capture cost only depends on the capture option. It also includes the processing cost associated with the CO_2 source type and capture option.
3. The transport process will deliver the processed CO_2 to the target storage/utilization location.
4. The normalized transport cost per unit amount of CO_2 and distance only depends on the transport type, flow rate, and environment.
5. The stationary point sources and their CO_2 emission levels are given and fixed. The existing pipeline network for CO_2 transport is a given.
6. The target CO_2 capture capacity by 2050 in the U.S. by industry sector for the NetZero emission scenario gathered from the literature is assumed as the target capacity for the system performance benchmark.

7. The normalized cost of capturing, transporting, and storing one ton of CO_2 is gathered from literature and used in the cost modeling of CCS systems, which includes the capital investment, operating, and maintenance cost of a CCS system with given architecture decision options. The overall cost is normalized by the total amount of CO_2 that can be captured and stored during the CCS system lifetime.
8. A wide range of normalized costs for carbon capture, transport, and storage is generally found in the literature. A representative or average value will be used for the base-case modeling.

The cost data gathered from the literature are mostly calculated or simulated based on the existing CCS projects. Two metrics are commonly used for the cost of CO_2 capture from electricity generation facilities: (1) capture cost, which reflects the increase in levelized cost of electricity (LCOE) per unit amount of CO_2 captured and is equivalent to the breakeven CO_2 sales price, and (2) avoided cost, which reflects the increase in LCOE per unit net reduction in CO_2 emission intensity of the plant, which is equivalent to breakeven CO_2 emission penalty.

The cost of CO_2 captured represents the minimum CO_2 plant gate sales price that will incentivize carbon capture relative to a defined reference non-capture plant. It's calculated using the following equation[50]:

$$Cost\ of CO_2\ captured(\$/tCO_2) = \frac{LCOE_{CCS} - LCOE_{ref}}{CO_2\ Captured}$$

The cost of CO_2 avoided represents the minimum CO_2 emissions price when applied to both the capture and non-capture plant, which will incentivize carbon capture relative to a defined reference non-capture plant. It's calculated using the following equation[50]:

$$Cost\ of\ CO_2\ avoided\ (\$/tCO_2) = \frac{LCOE_{CCS} - LCOE_{ref}}{(CO_2\ Emission)_{ref} - (CO_2\ Emission)_{CCS}}$$

where CCS – the capture plant for which the cost of CO_2/captured/avoided is being calculated; Ref – the reference non-capture plant; LCOE – the levelized cost of electricity, reported in \$/MWh (the CCS plant includes CO_2 compression to 15.3 Mtpa); CO_2 captured – the rate of CO_2 captured, reported in ton/MWh; CO_2 Emission – the rate of CO_2 emitted out the stack, reported in ton/MWh.

If no reference plant exists, estimating the CO_2-avoided cost will be hard, which is true for direct air capture, CO_2 transport, and storage. Therefore, the cost estimate in this study will focus on the cost of CO_2 captured, not avoided, including capital and operational expenses, required to capture, transport, and store unit amounts of CO_2 using different technologies from various CO_2 sources.

Most CO_2 capture, transport, and storage costs are gathered based on historical cost data from limited CCS projects. It expects the CCS cost to decrease over time with economies of scale. The CCS cost reduction rate quantifies the learning rate of developing and implementing CCS projects and related technologies. It measures the cost reduction with learning by doing for each technology, from a first-of-a-kind (FOAK) to an Nth-of-a-kind (NOAK) plant, through the CCS scaling over time.

5.2 CCS Performance

5.2.1 CO_2 Emission and Capture Performance

Regarding carbon capture, the performance measures include the capture capacity (current and target), capture efficiency, capture cost, and cost reduction rate. The majority of those factors are associated with carbon sources.

Table 11 shows the primary performance values collected from literature based on industry processes for carbon capture. The table is sorted based on the CO_2 concentration in the exhaust as it is the most impactful factor for the carbon capture process and cost. The CO_2 concentration is the highest among natural gas processing plants, fertilizer, and bio-ethanol production. The flue gases from hydrogen production, iron & steel, and cement production have medium CO_2 concentrations. The CO_2 concentration in the flue gas from power plants and refineries is the lowest among all the stationary point sources. Nevertheless, the CO_2 concentration in ambient air for direct air capture is much lower, at 0.04%, which makes the capture process complex and expensive.

Table 11 lists the 2022 CO_2 emission levels in the United States by industry sector. Power plants contribute the most to emissions, followed by refineries, iron & steel, and cement production facilities. Each industry sector's expected 2050 capture target is also listed based on the net-zero emission scenario. It is worth noting that those are simulated results and have significant uncertainties.

Figure 15 plots the current CO_2 emission and 2050 CO_2 capture capacity in the U.S. by industry sectors. In general, they are positively correlated. Higher emission levels require higher capture capacity. As DAC and BECC capture CO_2 from the atmosphere and bioenergy generation, both are considered zero-emission sources and don't fall on the trend. Still, they are expected to make a significant contribution to meet the total carbon capture target in the long term to achieve the NetZero emission goal.

Table 11 Carbon emission and capture performance parameters by industry sector

Capture Option /Industry sector	2022 US CO_2 emission, Mtpa[44]	2050 US capture target, Mtpa [44,49]	CO_2 conc. in exhaust [50]	CCUS potential[47], 1-5	TRL[2]	CO_2 capture eff.[34]	Average capture cost, $/t$CO_2$[49,77]	Cost reduction rate [78]
Natural gas processing	89	9	95%	5	9	95%	25	5%
Chemicals	76	23	95%	5	8	90%	37	8%
Ethanol	31	55	95%	3	7	90%	37	6%
Ammonia	25	3	95%	5	9	90%	33	8%
Hydrogen	66	16	45%	5	8	95%	80	8%
Iron & Steel	108	29	22%	5	7	65%	86	17%
Cement	90	43	19%	5	7	74%	111	16%
Coal power plant	1271	324	13%	3	8	90%	65	16%
Refinery	171	34	9%	3	8	95%	96	8%
Gas power plant	581	130	4%	3	7	90%	95	21%
Air (DAC)	300	300	0.04%	3	6	90%	293	25%
Bioenergy (BECC)	150	150	13%	5	6	90%	190	21%

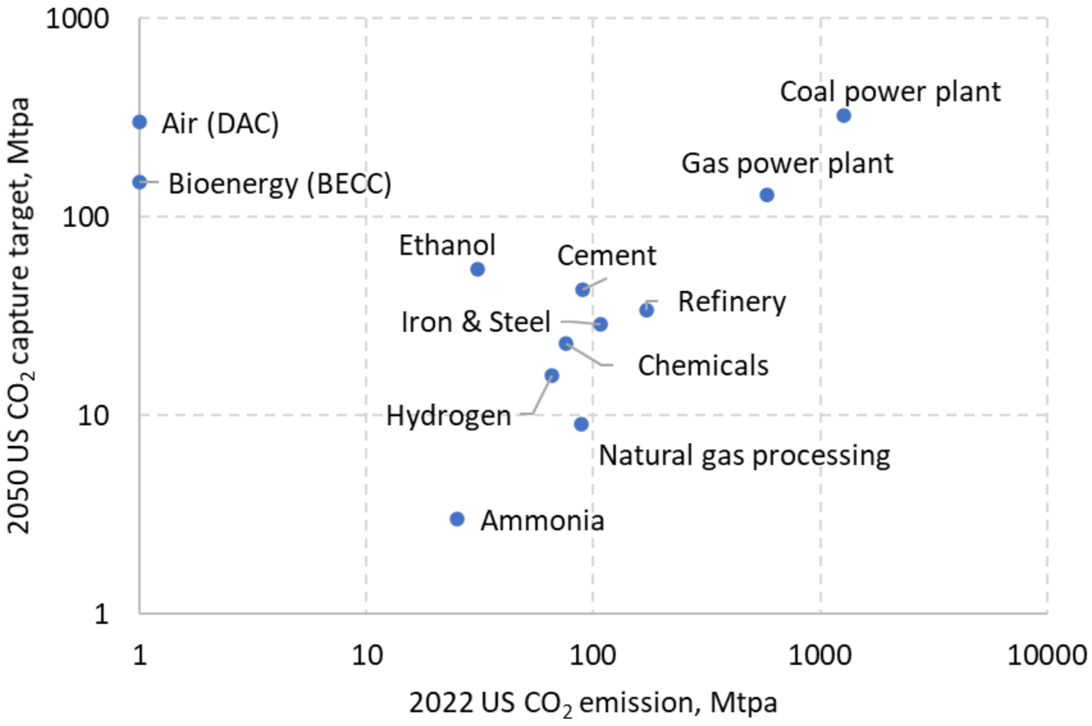


Figure 15 Current CO_2 emission and 2050 CO_2 capture capacity in the U.S. by industry sectors

The options in the upper-right quadrant of Figure 15 are major stationary point sources of CO_2, including coal and gas power plants. To reduce carbon emissions, these sources either need to be replaced by new, low-emission technologies or continue the current operation with CCS to maintain the power supply and support sustainable global economic growth. Thus, the expected carbon capture capacity is high for these carbon-intensive emitters if business continues as usual.

The share of capture capacity measures the ratio of emission level and capture target for each capture option to the total emission level and capture target, which is defined as,

$$S_i = \frac{emission_i}{\sum_i emission_i} \times \frac{capture\_target_i}{\sum_i capture\_target_i}$$

where *i* is the industry sector/capture option.

Figure 16 plots the share of capture capacity based on the current emission levels and expected capture capacities for NetZero Emission by capture option. The shares of capture capacity of different capture options vary across multiple orders of magnitude due to the wide range of emission levels and capture capacities among industry sectors. As DAC and

BECC are zero-emission sources, their emission levels are assumed to be the same as the future capture target to calculate their share of capture capacity.

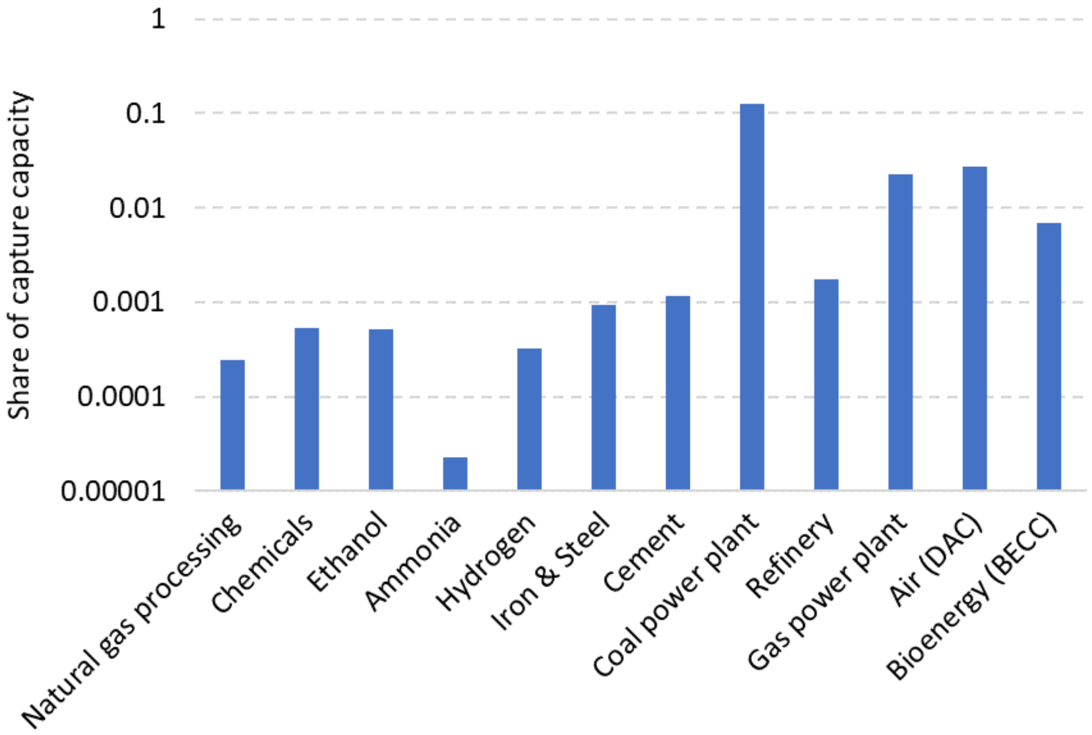


Figure 16 Share of capture capacity by capture option

The CCS potential is evaluated for each industry sector based on the competitiveness of CCS among all decarbonization technologies in each sector in the next few decades [47]. It ranges between 1 and 5, with 1 for the slightest potential of CCS and 5 for the highest potential of CCS to decarbonize that sector among all potential solutions. For example, carbon capture has the highest potential to decarbonize cement, iron & steel, and chemical sectors due to their intertwined processes and high-temperature heat requirement, which is hard to replace with other power technologies. However, for power plants, decarbonization can be achieved with renewable energy, including solar, wind, and even bioenergy. Thus, the CCS potential is at a medium level for power plants with a value of 3. For direct air capture of carbon dioxide, the potential is medium level in the near term due to the immaturity of the existing DAC technology and potential alternatives such as carbon capture from ocean water.

For each CO_2 source, there are multiple CO_2 separation technologies available for carbon capture. Amine-based solvent absorption is the most mature and widely used across industries. When CO_2 concentration is high in the exhaust, such as those from bioethanol production, only dehydration and compression are needed to separate CO_2 from vapor and compress it for transportation. Table 12 shows the primary and secondary carbon capture technologies used in industry processes.

Table 12 Primary and secondary carbon capture technologies used in industry processes (X: primary, Z: secondary, R: research, T: theoretical) [6]

Process	Absorption	Adsorption	Membranes	Cryogenic	Compress and dehydrate
Power generation	X		R	T	X
Refinery	X		Z	T	X
Cement	X		R	T	X
Chemical	X	Z		T	X
Iron& Steel	X		Z	T	X
Natural gas processing	X	Z	Z	T	X
Bio-ethanol					X

Regarding carbon capture performance, Table 10 lists the technology readiness level (TRL) of the primary capture process from each industry sector and carbon capture efficiency. With the maturity of carbon separation technology, carbon capture can generally achieve 90% capture efficiency. Extremely high efficiency of up to 99% can also achieved with more rounds of separation and higher capture cost.

Carbon capture costs from the literature generally include capital expenditure operation and maintenance costs. The capital costs generally include the cost of permitting, equipment, materials, and labor to construct a project from beginning to end. The operating costs relate to the fixed cost of fuel, consumables, and labor to produce the product. The capital and operating costs both depend on the plant size, CO_2 concentration in the source gas, and capture technology. The normalized cost of carbon capture per ton of CO_2 is generally calculated based on the plant size, the carbon capture capacity, the lifetime of the plant (e.g., 20-30 years), and an annual discount rate (e.g., 12%).

Table 13 Detailed carbon capture cost range per facility type [6]

Facility Type	Plant size	CO_2 conc. in exhaust gas	CO_2 Volume captured, Mtpa	Separation Notes	Capital cost, Low-High, \$M	Unit Total Cost, \$/tCO_2
Natural Gas Processing	140 MMCF/D	95-100%	0.024	Vented, no combustion	17-28	23-35
Ethanol Production	150 Million gal/year	95-100%	0.342	Vented, no combustion	21-36	24-34
Ammonia Production	907,000 tons/year	95-100%	0.389	Vented, no combustion	24-41	21-30
Hydrogen Production	87 MMCF/D	45%	0.34	Processed, no combustion	59-98	61-88
Steel/Iron Plants	2.54 Million Tons/year	26%	3.324	Process and combustion	805-1342	75-113
Cement Plants	1 Million Tons/year	21%	0.842	Process and combustion	148-247	64-95
Refinery Fluidized Catalytic Cracking Plants	60,000 barrels/d	16%	0.274	Processed, no combustion	136-227	97-150
Coal Power Plants	550 MW net	13%	3.089	Combustion	891-1485	83-124
			1.999			113-178
			1.272			166-268
Refining/chemicals	600 MMBTU/hr	8%	0.22	Combustion	92-153	110-171
Natural Gas Power Plants	560 MW net	4%	1.279	Combustion	399-666	93-140
			0.827			122-192
			0.527			179-290

Table 13 shows some examples of industrial plants and their corresponding cost range for carbon capture at the specified volume per year. The total cost of capturing one ton of CO_2, averaged through the lifetime of the capture plant for each facility type, is also listed in the table. Figure 17 plots CO_2 concentration in the exhaust and their average capture cost by industry sector. The carbon capture cost is higher with lower CO_2 concentration in the flue gas. The unit carbon capture cost throughout the plant's lifecycle also increases with a smaller capture volume for the same power plant. There are some discrepancies in the carbon capture cost values in Table 11 and Table 13, which are due to the difference in the assumptions of the plant size, fuel cost, capture efficiency, etc., for the carbon capture modeling in different literature. However, the overall trend of carbon capture unit cost vs. the facility type is the same across the literature. Table 13 also shows the ranges of capital and unit costs of CO_2 capture for a given type of facility at different locations.

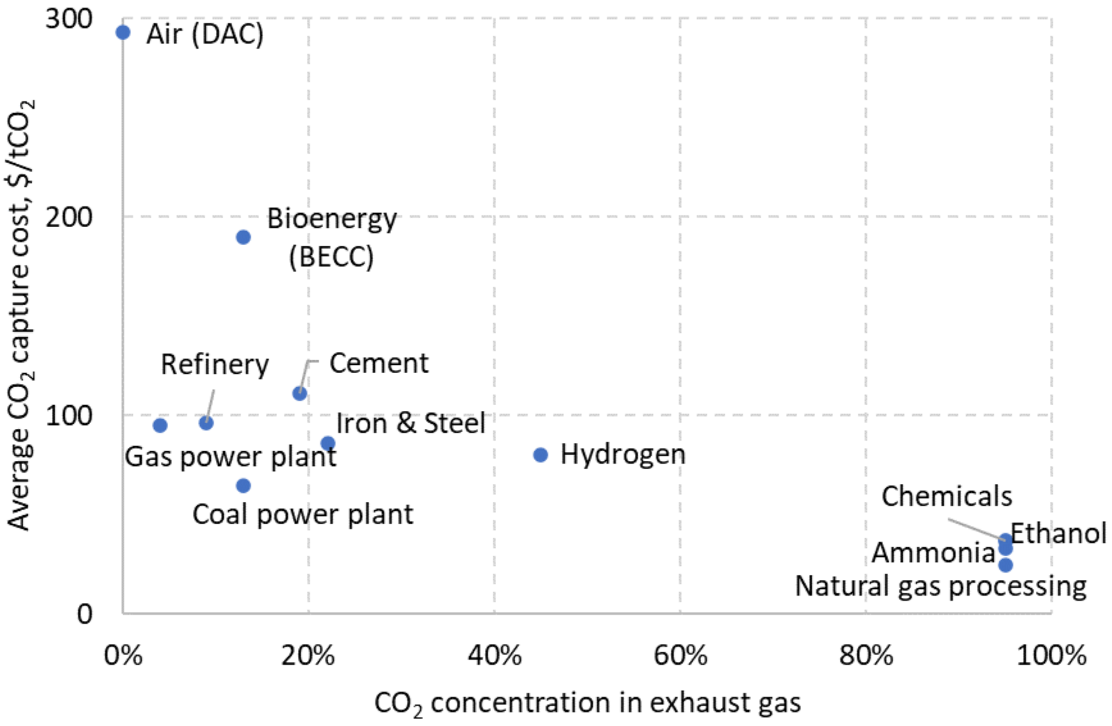


Figure 17 CO_2 concentration in the flue gas and average capture cost by industry sector

Direct air capture deals with extremely low CO_2 concentration (420 ppm), orders of magnitude lower than that in stationary point sources. Thus, it requires more energy and contactor area to effectively separate CO_2 from other gas molecules in the ambient air. Keith et al. estimated the DAC cost for various plant configurations[19]. The capture investment is 600-1000 \$/tCO_2 per year with an assumed discount rate and plant lifetime, and the Operating and Maintenance (O&M) cost is 23-42 \$/tCO_2. The wide range is due to the uncertainty around the energy cost of generating steam and electricity for the carbon capture process. If fossil fuels generate the energy consumed by DAC, extra CO_2 is emitted. The system needs to be powered by renewable energy sources like geothermal, wind, or solar to ensure a true negative emission technology for DAC.

The carbon capture cost is expected to decrease over time with learning by doing and economies of scale. Table 11 lists the cost reduction rate (i.e., learning rate) as the relative cost difference between the FOAK capture and the NOAK plant. The learning rate of relatively mature carbon capture technologies and processes is lower than those of innovative and immature technology, as shown in Figure 18. Given that the system will run for decades, the learning rate is an essential factor for the long-term planning of the CCS system.

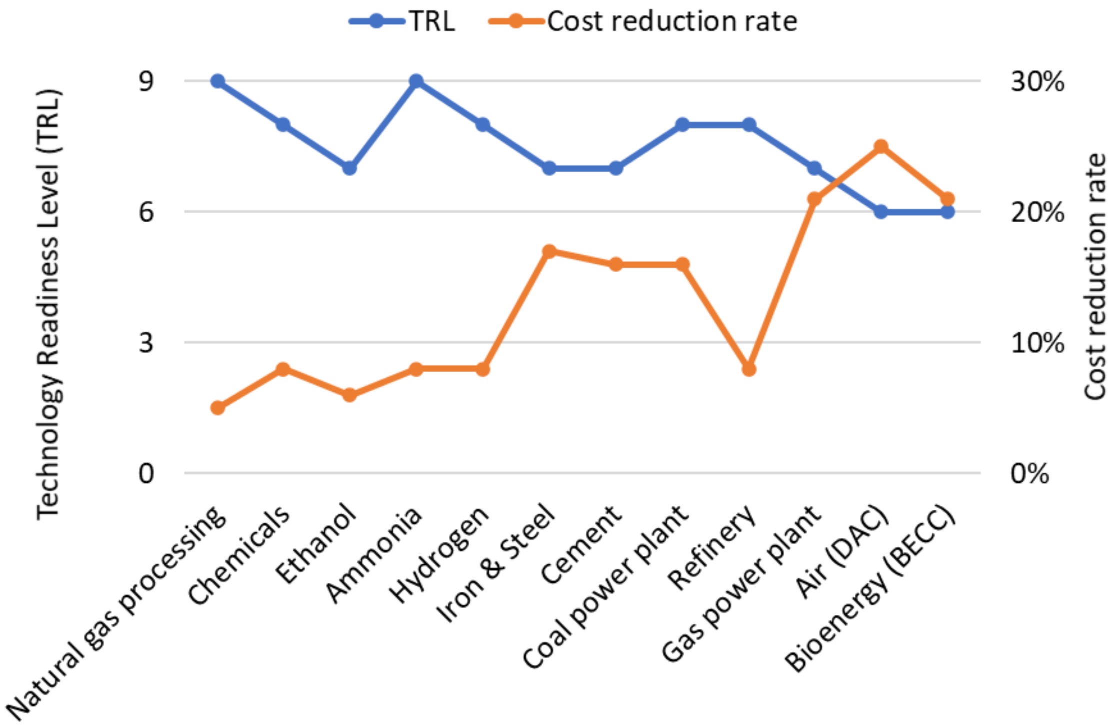


Figure 18 Technology maturity level (TRL) and cost reduction rate for carbon capture options

5.2.2 CO_2 Transport Performance

The performance metrics of the CO_2 transport system include the operating condition and transport capacity, the technology maturity, and the cost. Table 14 lists gathered performance parameters from the literature for the four CO_2 transport options: pipeline, ship, truck, and rail. Among the CO_2 transport options, pipelines have the highest operating capacity and technology maturity. The United States currently has a CO_2 pipeline network with a combined length of more than 5000 miles, which transports over 50 million tons of carbon dioxide per year, primarily for enhanced oil recovery purposes. The total capacity of these pipelines could potentially transport up to 250 million metric tons of CO_2 per year[5]. Table 15 shows the distribution of the existing CO_2 pipeline network by region.

Table 14 Performance parameters for carbon dioxide transport options

Transport method	Condition[4]	Current capacity, Mtpa[4]	Future capacity, Mtpa[44]	Flexibility, 1-5	TRL	Remarks[4]
Pipeline (onshore)	48-200 bar, 10 to 34°C	50	500	4	9	High capital cost, low operating cost, over 50 years of commercial experience
Pipeline (offshore)		1	250	3	7	
Ship	7-45 bar, -52 to 10°C	3	250	5	7	High operating cost, low capital cost compared to pipeline, more flexible, used in the food industry
Truck	17-20 bar, -30 to -20°C	1	5	5	6	2-30 tons per batch, not commercial for large-scale projects, distributed merchant uses
Rail	7-26 bar, -50 to -20°C	1	5	3	6	Feasible with existing rail lines, more advantageous over medium to long-distance

Table 15 Distribution of existing CO_2 pipelines in the United States[5]

Region	States	Length, mile
Permian Basin	West Texas, New Mexico, Colorado	2592
Gulf Coast	Mississippi, Louisiana, East Texas	738
Rocky Mountains	Colorado, Wyoming, Montana	729
Mid-Continent	Oklahoma, Kansas	477
Other	North Dakota, Michigan	214

Nowadays, only around 1000 tons of food-quality CO_2 are shipped in Europe annually from CO_2 point sources to coastal distribution terminals. Compared to pipeline transport of CO_2, CO_2 shipping offers more flexibility to offshore storage facilities, mainly with multiple offshore storage locations. Shipping generally involves lower upfront investment and shorter construction time than pipelines. However, large-scale transportation of CO_2 by ship has not yet been demonstrated.

CO_2 transport via train or truck is currently at minimal capacity. The application is limited to local CO_2 transport over short distances and small volumes[79]. Truck connections are available between capture sites and onshore shipping terminals. The CO_2 is transported in a liquid form at pressures between 10-20 bar and temperatures between -30°C and -20°C in ISO-tank containers with a unit capacity of 20 tCO_2. While rail and truck transport may be necessary for small-scale transport in the early years of CCS expansion, they are not expected to play a significant role in the large-scale rollout of CCS. Pipelines and ships are expected to be much more cost-effective in transporting megatons of CO_2 per year (Mtpa)[79].

The CO_2 transport cost varies for transport type, the distance between the capture plant and storage/utilization location, spatial configuration of the transport system, the inlet and outlet conditions, CO_2 flow rate, environmental setting (onshore vs. offshore), regional variation, and monitoring/regulatory requirements. The cost model accounts for the capital expenditure of equipment purchase and installation, labor, rights of way, operation, and maintenance. Detailed models have been built to estimate CO_2 transport cost through pipelines and ships, as those two are the most promising solutions for large quantities of CO_2 transport over long distances to meet the CCS target for net-zero emission scenario [36,55,56,79].

For CO_2 pipeline cost, the most impacting factor is the pipe diameter to accommodate a specific flow rate and the distance between the capture plant and storage sites. CO_2 transport cost models commonly assume that (1) CO_2 is provided by the capture plant at a pressure of 2200 psi, (2) CO_2 is transported in a dense phase liquid state, and (3) CO_2 exits the pipeline at a pressure of 1200 psi. The pipeline cost also varies among different geographical regions. For example, pipelines located in remote and sparsely populated regions cost about 50-80% less than in highly populated areas, and offshore pipelines can be 40-70% more expensive than onshore pipelines due to the more complicated offshore equipment required for construction on the ocean floor. There are substantial economies of scale based on pipeline capacity, with unit costs decreasing significantly with increasing CO_2 capacity. Pumping stations may be required to maintain CO_2 pressure in the pipe over long-distance transport, which increases the overall cost.

CO_2 shipping between the capture plant and storage or utilization location usually consists of several steps: (1) CO_2 liquefication and storage in tanks before loading onto ships for transport; (2) Transportation of CO_2 using ships; (3) Unloading to onshore or offshore platforms before conditioning and injection. CO_2 shipping may be viable for regional CCS clusters. The share of capital in total costs is higher for pipelines than for ships, and shipping can be the cheapest option for long-distance transport of small volumes of CO_2 (up to 2 Mt/year).

Table 16 shows some simulated CO_2 transportation costs via different options at different flow rates up to 10 Mtpa over various distances. Again, the literature has a wide range of cost values for CO_2 transport due to the condition and assumption differences[3,6,35,50,66,79]. Table 17 shows the normalized CO_2 transportation cost for high flow rates above 10 Mtpa via onshore pipelines. All those results are for the total cost of CO_2 transport, including capex, operation, and maintenance normalized by the total amount of CO_2 transported per year and the transport distances. The operation and maintenance (O&M) cost is about 6% of the total cost for onshore pipeline transport[54].

Table 16 Normalized CO_2 transport cost by transport option and flow rate[50]

	CO_2 transport cost, \$/tCO_2/100-mile				
Transport option	Flow rate, 1 Mtpa	Flow rate, 2.5 Mtpa	Flow rate, 5 Mtpa	Flow rate, 7.5 Mtpa	Flow rate, 10 Mtpa
Pipeline onshore	20.0	7.8	5.4	4.5	3.9
Pipeline offshore	20.3	10.2	7.3	6.3	5.3
Ship to harbor	16.2	12.8	11.8	10.8	10.3
Ship to offshore	25.5	14.4	13.1	11.8	10.8
Truck	13				
Rail	22				

Table 17 CO_2 transport cost range of onshore pipeline for high flow rate[79]

CO_2 flow rate, Mtpa	**Cost, 2024\$/tCO_2/100 mi**		
	Low	Mid	High
10	0.7	2.0	3.2
15	0.6	1.6	2.5
20	0.5	1.2	2.1
30	0.4	1.0	1.5
40	0.2	0.7	1.2
50	0.2	0.7	1.1

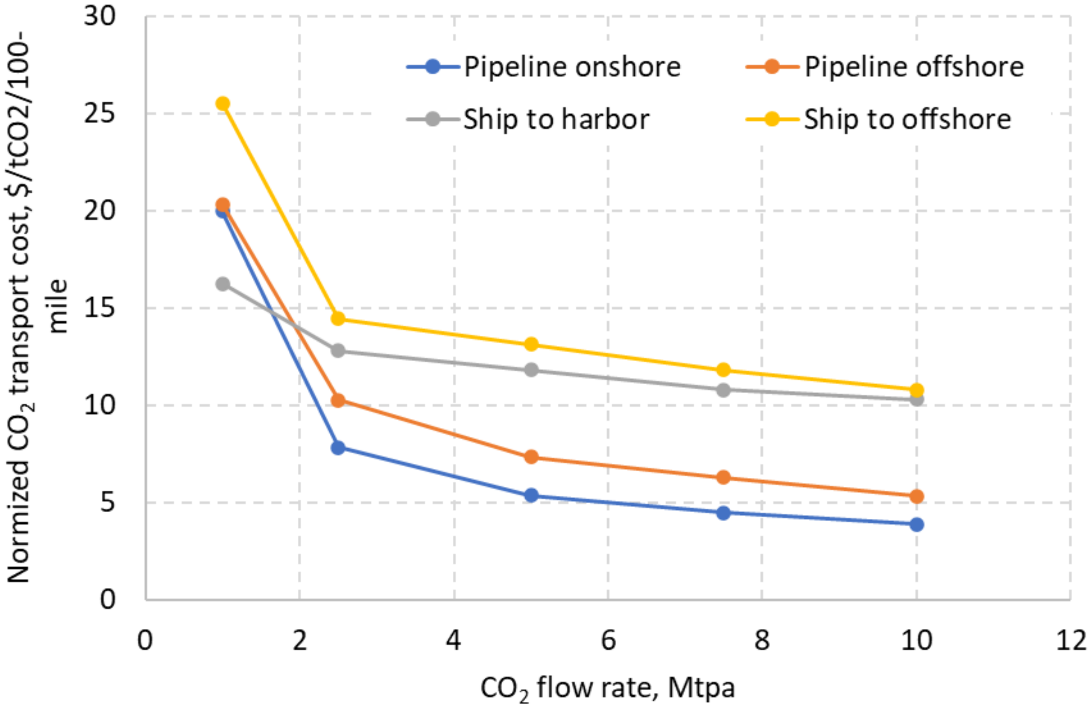


Figure 19 Normalized CO_2 transport cost by transport option and flow rate

Figure 19 plots the normalized CO_2 transport cost by transport option and flow rate up to 10 Mtpa. The normalized CO_2 transport cost decreases with increasing flow rate. The transport cost via offshore pipeline is higher than that through onshore pipeline. CO_2 shipping is much more expensive than pipeline shipping when the flow rate exceeds 2 Mtpa.

Given that the current CO_2 transport capacity is much lower than the target capacity of 0.9-1.7 gigatons per year by 2050[75], substantial growth is needed in the CO_2 transport infrastructure to enable CO_2 transport from over a thousand carbon capture facilities to target storage locations. With the expansion of the CO_2 pipeline network, economies of scale can be achieved by building small feeder lines to connect individual carbon capture plants to trunk lines.

There were suggestions from literature to repurpose some natural gas pipelines for CO_2 transport as some of those pipelines may be decommissioned in the next few decades due to less use of fossil fuels. However, it may not be practical for long-distance transportation over 100 miles with large quantities of CO_2 (e.g., 20 Mtpa) as CO_2 requires higher pressure than natural gas to stay in a liquid state, meaning thicker pipelines for CO_2 transport are generally needed than for natural gas [79].

Though shipping has not been widely used for CO_2 transport, the technology is mature for liquefied natural gas (LNG) and liquefied petroleum gas (LPG). Given the similar pressure required for LPG shipping and CO_2 shipping in tanks, LPG tankers can be repurposed for CO_2 for dual-purpose transport. However, tankers designed explicitly for CO_2 transport can be better optimized for capacity and investment cost [80].

It's worth mentioning that CO_2 shipping may not be a standalone solution for CO_2 transport from stationary point sources to geological storage and industry utilization sites, as shipping does not cover the onshore transportation part. For future transport infrastructure design and construction for CCS systems, offshore shipping may need to be combined with pipelines or trucks/rails to deliver CO_2 from source to sink.

5.2.3 Carbon Storage Performance

The main performance parameters for carbon storage are storage capacity, CO_2 injection rate, storage coefficient, storage duration, technology maturity, and cost. Carbon dioxide injection and storage are highly regulated areas. The U.S. Environmental Protection Agency (EPA) requires that the storage site comply with injection regulations, monitoring, and reporting. The National Energy Technology Laboratory (NETL) provides specific guidelines on the project contingency factor for different storage projects and the activity timelines. It recommends a 15-20% contingency factor for project and process contingency, five years for project preparation, including site screening, selection and characterization, permitting and construction, 30 years for operation, and another 50 years for post-injection site monitoring and closure [56].

Multiple surveys have been conducted to evaluate the CO_2 storage capacity in the U.S. territory. A wide range of values was generated depending on the different approaches used in the estimation. Table 18 shows the potential technical CO_2 storage capacities by storage formation type in the United States[81].

Table 18 Potential technical CO_2 storage capacity by formation type in the United States

Storage type	TRL[33]	Estimated US storage capacity for CO_2 in billion tons [81]		
		low	Med	High
Oil and gas reservoir	7	186	205	232
Unmineable coal	5	54	80	113
Saline formations	8	2379	8328	21633
Total		2619	8613	21978

Among the storage formation types, the saline formation has the highest potential capacity, and unmineable coal has the smallest capacity. By removing the areas where faulting or stratigraphic pinch-outs restrict subsurface lateral accessibility, places with surface access restriction, and difficult injection candidates like thin sand layers, the practical storage capacity was estimated between 406 and 631 Gt of CO_2 in the US [61]. It is about an order of magnitude smaller than the values shown in Table 18 but still can accommodate about 500 years of continuous injection with an annual injection rate of 1 $GtCO_2$ as targeted for the net-zero emission scenario in the United States.

The technology readiness levels of CO_2 injection and storage into different types of formations are also listed in Table 18. The CO_2 injection and storage in saline aquifers have the highest maturity, whereas CO_2 injection into coal mines has the lowest maturity, given the limited demonstrations on a large scale.

CO_2 storage cost is driven by the nature of the reservoir (saline aquifer vs. depleted oil and gas field), its accessibility (onshore vs. offshore), the existence of legacies (wells, infrastructures), its physical characteristics (size, porosity, permeability, pressure), and monitoring and regulatory requirements. The cost of carbon storage comprises the capital investment and operating cost. The capital investment depends on the location of the storage site and the facilities needed to enable the CO_2 injection into the target formation, such as compressors and injecting wells. The operating cost generally includes workforce, facility maintenance, power supply, and periodic surveillance for CO_2 storage status.

Roussanaly et al. estimated the cost of CO_2 storage based on injection rate and storage type [50]. The storage cost model assumed a project duration of 40 years with a discount rate of 8%. Table 19 shows simulated CO_2 storage costs at different injection rates and storage environments.

Table 19 CO_2 storage costs at different annual injection rates and storage environments (DOGF: Depleted Oil and Gas Field, SA: Saline Aquifer, legacy: re-usable wells)

Storage type	2050 Storage target, Mtpa	CO_2 storage cost, 2024\$/tCO_2 [50]				
		1 Mtpa	2 Mtpa	3 Mtpa	4 Mtpa	5 Mtpa
Onshore DOGF with legacy	100	6.1	4.0	3.5	3.2	3.2
Onshore DOFG without legacy	10	7.2	4.6	4.0	3.6	3.6
Onshore SA	3150	9.3	5.8	4.9	4.3	4.2
Offshore DOGF with legacy	100	12.3	8.0	6.7	6.1	6.1
Offshore DOGF without legacy	10	15.2	10.1	8.7	7.7	7.7
Offshore SA	1350	23.1	14.8	11.9	10.7	10.4

Based on the locations and characteristics of the potential storage formations for CO_2, Chris and Andrew did a comprehensive modeling of the CO_2 storage reserve and cost curve [82]. Figure 20 shows the results of the appraised, permitted, and developed CO_2 injection capacity by 2050 and the corresponding cost by storage basin [75]. The Gulf Coast area has the highest CO_2 storage capacity and lowest normalized cost, and the East region has a much smaller storage capacity and the highest average storage cost. The estimated annual injection rate in the map is much higher than in Table 19. However, the cost values are relatively higher due to different assumptions and modeling approaches, including the inlet and outlet pressure, CO_2 transport condition, etc.

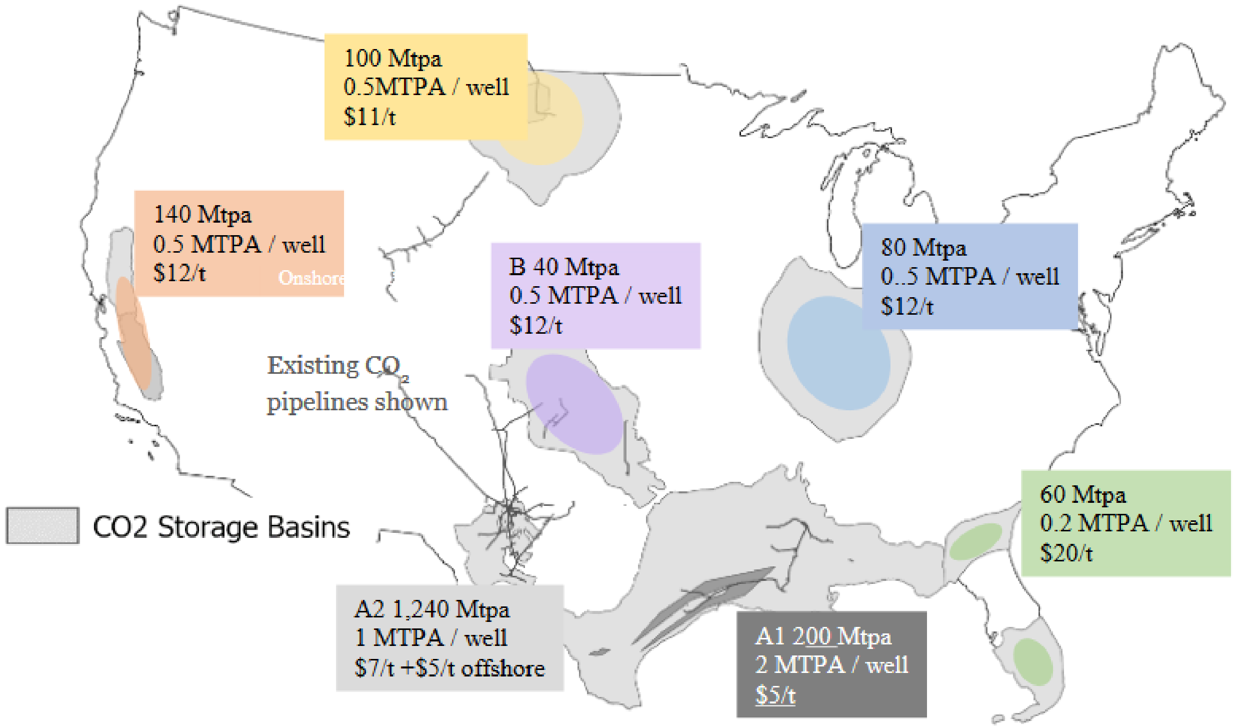


Figure 20 National co$_2$ storage capacity and cost for different basins in the US[75]

5.2.4 Carbon Utilization Performance

CO$_2$ utilization performance has many aspects. The duration of CO$_2$ sequestration measures how long the CO$_2$ is stored in the product before it is released into the atmosphere. For example, CO$_2$ integrated into building materials may stay there for decades, whereas the CO$_2$ used in urea or synthetic fuel production may only stay there for less than one year before it is released through consumption. The second aspect is the storage capacity, i.e., the demand for CO$_2$ for each utilization option. The current market share of CO$_2$ utilization is readily available. The oil industry is currently the largest consumer of externally sourced CO$_2$, with an estimated annual global consumption of around 75 Mt for EOR [2]. Today, between 0.3 and 0.6 tons of CO$_2$ are injected into EOR processes per barrel of oil produced in the United States. However, the future demand for CO$_2$ for industry utilization is hard to estimate because of the considerable uncertainty surrounding the future development of technologies and carbon policies. The third aspect is the technology maturity. Some CO_2 utilization has been commercialized at the industry level, such as urea production, EOR, and food packaging. However, most other CO_2 utilizations are still in the early stages of development, with small-scale tests or demonstrations, including CO_2 for enhanced coalbed methane, synthetic fuel production with CO_2, etc. Lastly, the cost is an essential measure of CO_2 utilization options. CO_2 costs vary widely for different applications and even within the same type of utilization or storage[71]. For example, the cost of CO_2 for EOR depends typically on the oil price and ranges from 15 to 30 \$/tCO_2. Table 20 summarizes the performance parameters for CO_2 utilization options gathered from the literature. The cost values present in the table are average values from the literature.

Table 20 CO_2 utilization performance parameters by application options

CO_2 utilization	Storage duration, years[52,58]	Current demand, Mtpa[49]	2050 technical capacity, Mtpa[49]	2050 practical capacity, Mtpa	TRL[14]	Net cost[49,71], \$/tCO_2,
EOR	50	87	200	200	9	-50
ECBM	50	0.1	10	1	7	-50
Aggregates	100	0.1	400	40	4	30
Concrete curing	100	0.1	50	5	4	70
Methane	<1	1	400	40	6	500
Synfuels	<1	1	300	30	6	930
Chemicals	<1	1	530	53	7	220
Fertilizer (Urea)	<1	110	270	270	9	-80
Food processing	<1	23	100	10	8	45

Among these CO_2 utilization options, the CO_2 integrated into building materials through carbon mineralization has the most extended sequestration duration. During the process, carbon dioxide is converted into various forms of rock via reaction with alkaline for use in building materials. The material typically remains as part of the building environment for many decades. CO_2 injected into oil reservoirs or coal mines for enhanced oil and gas recovery can also stay in the pore space for decades before being released into the atmosphere.

The dominant CO_2 utilization in urea production and EOR in the current market is mainly driven by the revenue of product sales, which offsets all the CO_2 purchase and transport costs and results in negative net costs of CO_2 utilization. CO_2 can be used to generate synthetic fuel and chemicals, but the production cost is much higher than that of conventional processes using fossil fuels. A carbon price or equivalent regulation will be necessary to make the production cost with CO_2 competitive. A notable example is CO_2 utilization for synthetic aviation fuel (SAF) production. If SAF is produced using carbon captured from direct air capture or bioenergy production, the lifecycle is considered carbon-neutral. For CO_2 sequestration in construction aggregates, the process is not essential to the delivered aggregate functionality and quality but will add about 20% to the cost of aggregates. Generally, CO_2 mineralization is more expensive than CO_2 storage underground. However, CO_2 sequestration in construction material can be an alternative for local CO_2 storage where geological storage is not readily available or the CO_2 transport infrastructure is not in place.

There is a significant uncertainty in the market demand for CO_2 utilization in the long term. The market uptake in 2050 for CO_2 utilization in Table 19 is theoretical values that assume that all the products in each category only use CO_2 for manufacturing or synthesis. For the system design and modeling, practical capacity values are assumed to be one-tenth of the technical values and are used for each CO_2 utilization option except for EOR and urea production, as both are already deployed at the industry scale for CCS system modeling. It is based on a similar level of downsizing of the practical capacity from the technical capacity for CO_2 storage in the United States [61].

Table 21 shows the practical capacity values for different CO_2 storage options. The onshore storage capacity per year is assumed to be proportional to the ratio of each storage capacity to the total capacity in Table 18. No data has been found for the practical storage capacity of the offshore storage options in the literature, and it is assumed that the offshore values are one-tenth of those of the onshore system.

Table 21 Performance parameters of co$_2$ storage options

CO$_2$ storage	Storage duration, years	Current demand, Mtpa	2050 practical capacity, Mtpa	TRL[2]	Net cost, $\$/tCO_2$[66]
Onshore DOGF with legacy	>100	0.1	20	8	6
Onshore DOFG without legacy	>100	0.1	20	7	7
Onshore SA	>100	1	1605	8	9
Offshore DOGF with legacy	>100	0.1	2	8	12
Offshore DOGF without legacy	>100	0.1	2	7	15
Offshore SA	>100	0.1	161	8	23

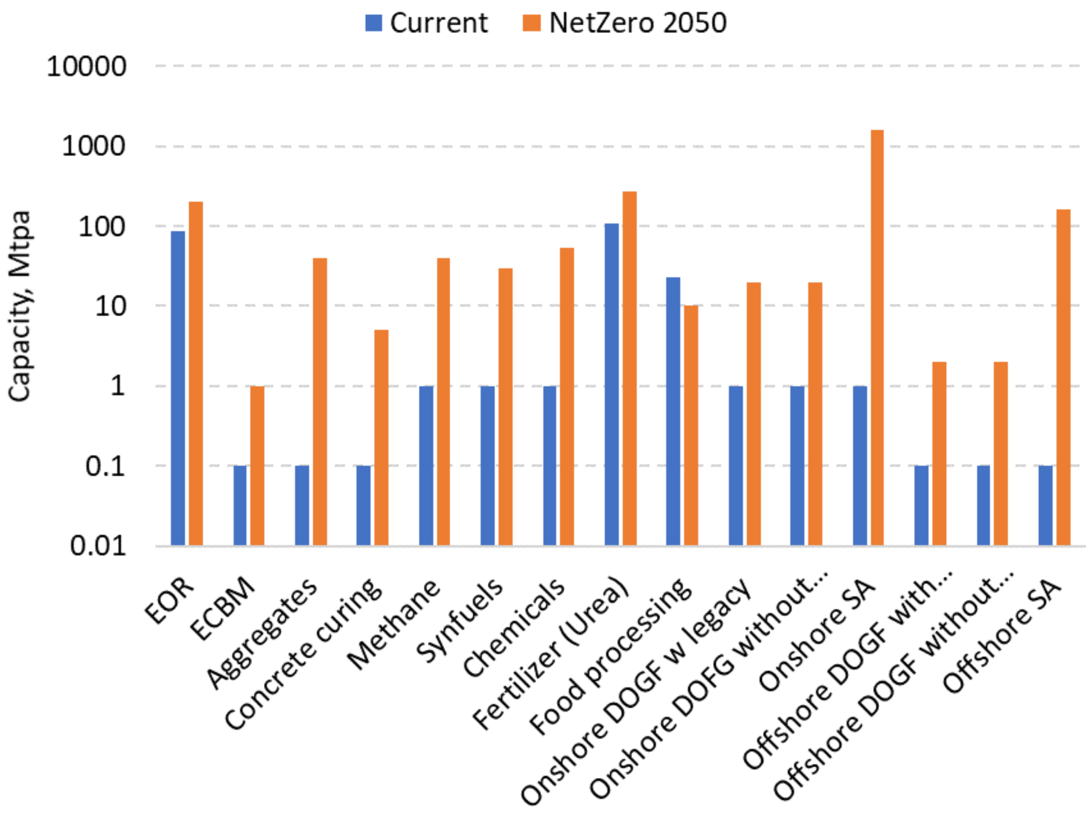


Figure 21 Current and NetZero 2050 practical capacity of different CO_2 storage and utilization options in the United States

Figure 21 shows the current and future practical capacity for NetZero Emission 2050 of different CO$_2$ storage and utilization options in the United States. The CO$_2$ storage in onshore saline aquifers dominates the future pathway for CO$_2$ storage with the highest potential capacity. Moreover, the high technology maturity and low cost make geological CO$_2$ sequestration in saline aquifers the leading player in the CCS future. In the net-zero scenario simulation for the United States, it is estimated that CO_2 sequestration in subsurface formations will take 80-95% of the captured CO_2 in most scenarios except the case where the fossil fuels are no longer used by 2050 for electricity generation and transportation and all captured CO_2 are only used for synthetic fuel and gas generation [75].

5.2.5 Potential Revenue Streams

Besides the revenue from sales of products based on CO_2 application, CCS operators can also receive some tax credits or government funding for CCS projects to compensate for the cost. In the United States, the 45Q tax code provides federal tax credits of up to $60 per ton of CO_2 for EOR and other utilization and $85 per ton of CO_2 for geological storage in saline formations. For CO_2 capture through DAC, the tax credit increases to $180 for permanent storage and $130 for CO_2 utilization. The criteria for the CO_2 capture plants to be qualified for those tax credits are 1) power plants capturing at least 18,750 tCO_2 per year; 2) other industrial facilities capturing at least 12,000 tCO_2 per year; and 3) direct air capture facilities that capture 1,000 tCO_2/year[73]. Besides, the Department of Energy (DOE) provides substantial funding for CCS research and development and infrastructure investment for CO_2 transport and storage. At the state level, multiple benefits are available, such as legal ownership of the pore space for storage, the expedited permitting process for CCS projects in the state, etc. For example, the California Low Carbon Fuel Standard (LCFS) offers credit of about $100/$tCO_2$ for carbon capture and sequestration, which can be traded in the market. When combined with the federal 45Q tax code, the total credit can reach $135 to $150 per ton of CO_2 captured or stored.

5.3 CCS System Model

The CCS system performance can now be modeled and compared among different design options with the gathered CCS performance parameters and the defined performance metrics.

The model assumptions and constraints are :

1. All carbon sources are considered onshore.
2. The CO_2 storage and CO_2 utilization options are exclusive.
3. Pipeline and ship options for CO_2 transport are compatible with both onshore and offshore environments.
4. The truck and rail option for CO_2 transport only works with onshore storage and CO_2 utilization.
5. All storage options are compatible with both onshore and offshore environments.
6. All CO_2 utilization options are considered onshore.
7. The pipeline and ship options are compatible with all CO_2 transport rates, but the truck and rail only work for CO_2 transport rates of 1 Mtpa.
8. The CO_2 storage and utilization options are compatible with all flow rate options.

Under those assumptions and constraints, a total of 2088 possible design vectors are generated for the CCS system with compatible combinations of design options.

The distance between each source and sink is needed to estimate the CO_2 transport cost of CCS systems with different combinations of CO_2 source, transport, and storage/utilization options. Figure 22 shows the distribution of CO_2 stationary point sources, existing CO_2 pipelines, and CO_2 storage formations of EOR fields and saline aquifers in the United States [44].

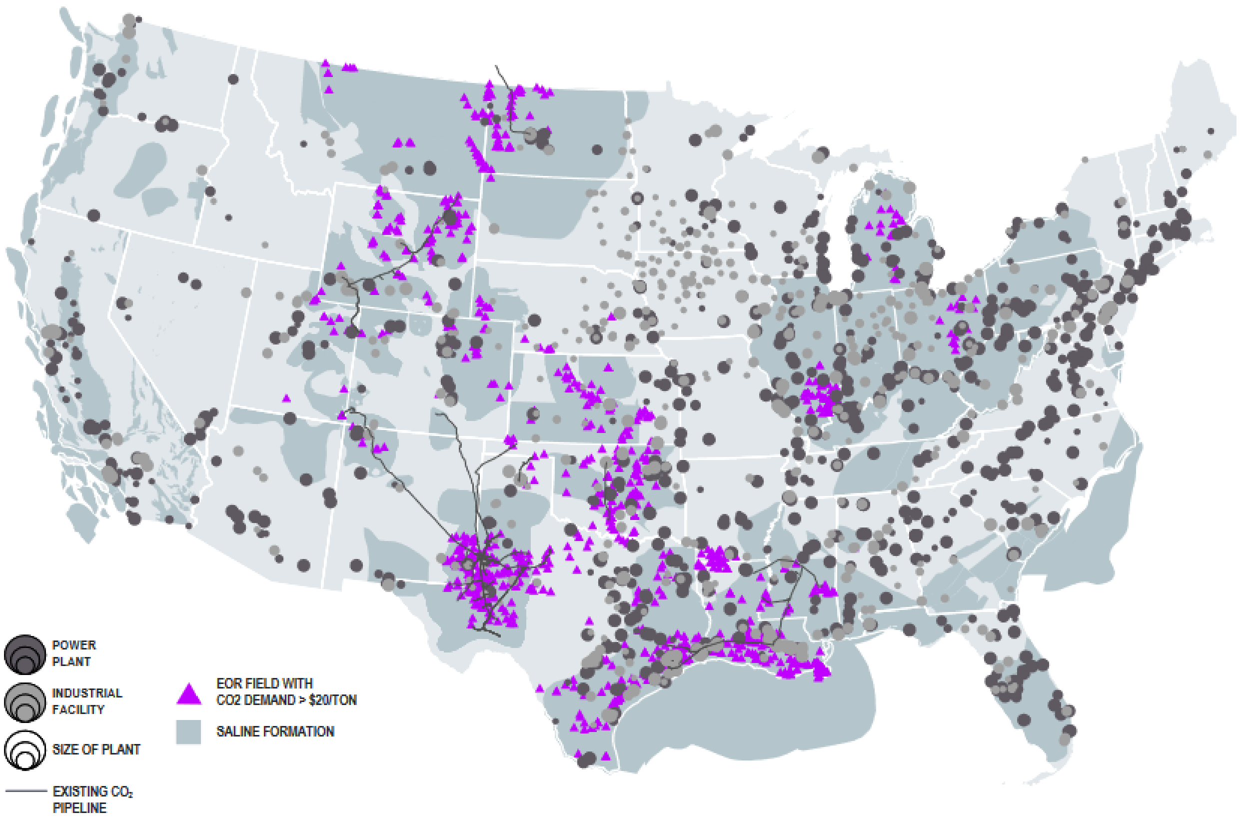


Figure 22 Distribution of co_2 *stationary sources, transport pipelines, and storage formations in the United States*[44]

Based on the distribution of CO_2 source and sink in the United States and results of expanded network of CO_2 capture, transport and storage by mid-century [44], the average distance between the CO_2 sources and storage locations are estimated following those steps: (1) a CO_2 source is always paired with the nearest possible sink of a given storage type; (2) a 60-mile distance is assumed if the CO_2 source and storage sink are overlapping on the map, (3) a 60-mile distance is assumed between all CO_2 source and CO_2 utilization options, (4) the average distance is estimated based on existing facility locations between a CO_2 source type and storage/utilization type, and (5) a zero-distance is assumed between DAC capture plants and onshore storage locations as future DAC facilities can be co-located with storage to save cost, and (6) a 100-mile distance is assumed between the loading harbor and all offshore storage locations, and the distance to CO_2 loading harbor is measured as the shortest distance between a CO_2 source type and the coastline of the United States. Table 22 lists the average transport distance between CO_2 capture and storage/utilization locations by capture type and storage type.

Table 22 Average transport distance between CO_2 capture and storage/utilization location

Industry sector	Average transport distance, mile			
	CO_2 utilization	Onshore O&G	Onshore aquifer	Distance to harbor for offshore storage
Natural gas processing	60	60	60	236
Chemicals	60	184	60	270
Ethanol	60	270	338	810
Ammonia	60	65	110	473
Hydrogen	60	60	60	70
Iron & Steel	60	169	60	386
Cement	60	60	60	405
Coal power plant	60	65	85	338
Refinery	60	60	60	116
Gas power plant	60	65	60	135
Air (DAC)	0	0	0	0
Bioenergy (BECC)	60	60	60	60

5.3.1 Performance Model and Utility Function

Given the multiple performance metrics of a CCS system, a multi-attribute utility function is defined and used to integrate them with weighting factors. It's worth noting that different stakeholders of CCS systems may have varied preferences on what aspect of the performance is more important than others, and the weighting factors can be adjusted accordingly for system performance evaluation.

Utility functions for carbon capture are defined as

$$U_{capture,c} = log\left(\frac{emission_i}{\sum_i emission_i} \times \frac{capture\_target_i}{\sum_i capture\_target_i}\right)/6 + 1$$

$$U_{capture,e} = Capture\_efficiency$$

$$U_{capture,s} = TRL/9 \times CCUS\_potential/5 \times min(1, cost\_reduction/0.1)$$

$$U_{capture} = \sum_n w_{capture,n} U_{capture,n}$$

Where c is for capacity, e is for efficiency, s is for scalability, i is the capture option, n = capacity, efficiency, scalability, and w is the weighting factor with its value shown in Table 23.

Table 23 Weighting factors of CCS system performance attributes

Weighting factor	Capacity	Efficiency	Scalability
Capture	0.5	0.1	0.4
Transport	0.8	0	0.2
Storage	0.4	0.4	0.2

The logarithm is taken on the emission and capture share of a given capture option to reduce the orders of magnitude difference between different capture options. Figure 23 shows the CO_2 capture capacity utility and CO_2 capture scalability by capture option. The plot shows that the power plants have the highest utility for capture capacity, followed by DAC and BECC. The high capture scalability belongs to CO_2 capture from ammonia and hydrogen production facilities and heavy industries.

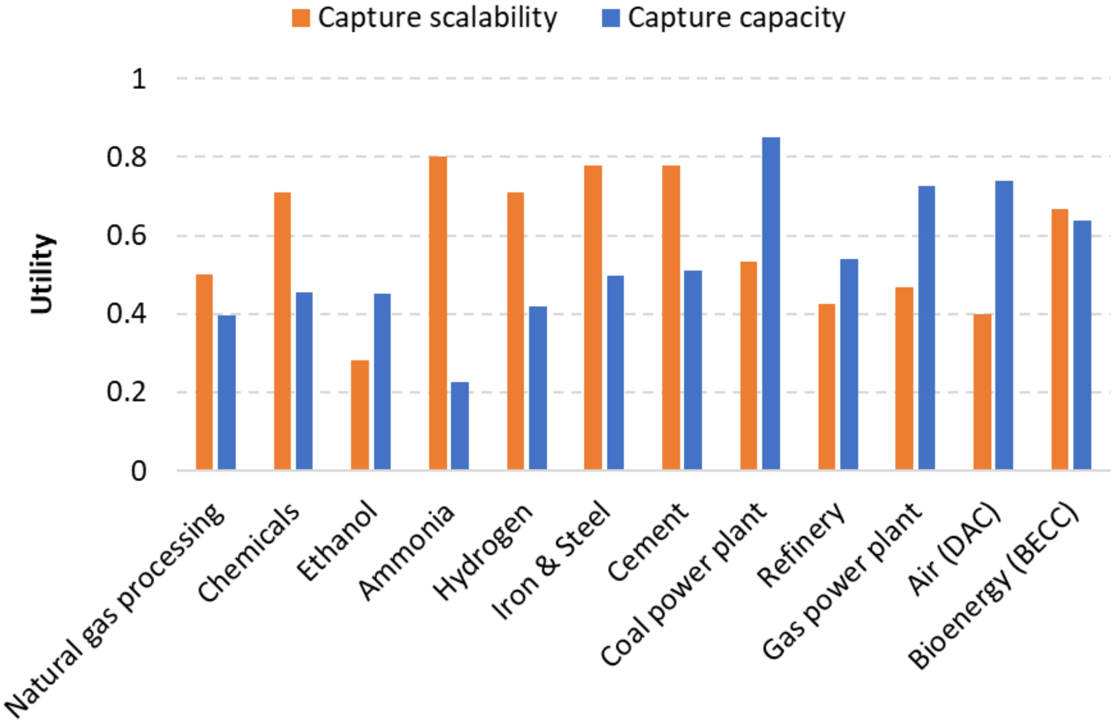


Figure 23 CO_2 capture capacity and scalability utilities by capture option

The total CO_2 capture utility by capture option can be calculated by applying the weighting factor. Their values are plotted against the cost of the corresponding capture option in Figure 24. When including all three performance aspects of CO_2 capture: capacity, efficiency, and scalability, CO_2 capture from power plants has the highest utility value. Generally, the higher the cost, the higher the utility value is expected for CO_2 capture. Most CO_2 capture options follow the trend, except BECC and DAC, which are still in the early stage of development with relatively high costs, but both will play prominent roles in the CCS portfolio in the future.

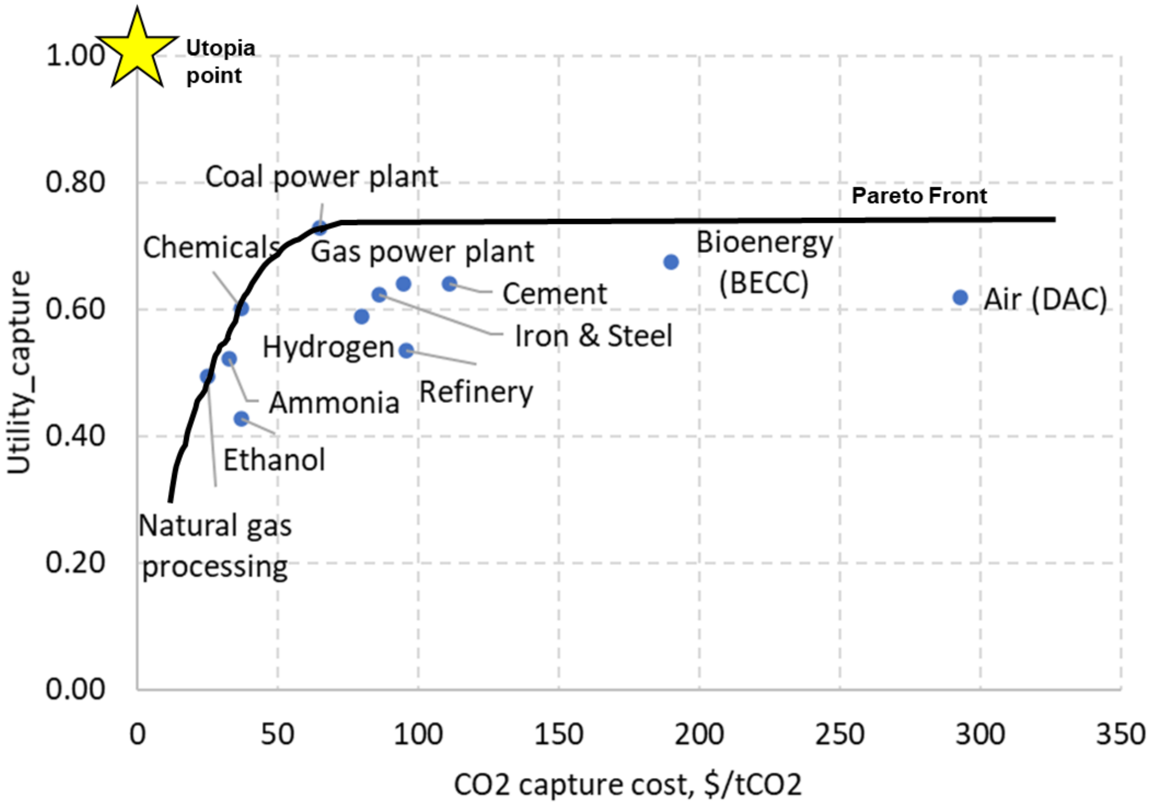


Figure 24 Tradespace plot of co₂ capture utility vs. cost by capture option

Utility functions for carbon transport are defined as

$$U_{transport,c} = \left(\frac{current\_capacity_j}{\sum_j current\_capacity_j}\right) \times (flexibility_j)/5 \times (flow\ rate_j)/10Mtpa$$

$$U_{transport,e} = 1$$

$$U_{transport,s} = \frac{Future\_capacity_j}{\sum_j Future\_capacity_j} \times \frac{TRL}{9}$$

$$U_{transport} = \sum_{n} w_{transport,n} U_{transport,n}$$

Where c is capacity, e is efficiency, s is for scalability, j is transport option, n = capacity, efficiency, scalability, and weighting factors w are shown in Table 23.

Figure 25 shows the transport utility values for capacity, scalability, total value, and the CO_2 transport cost for the different transport options at a flow rate of 1 Mtpa. The utility values are shown in the log scale. Among all the options, the onshore pipeline has the highest utility value, one order of magnitude higher than all other options. Regarding normalized cost for CO_2 transport at 1 Mtpa, the values for all transport options fall within a similar range between \$10-30/tCO_2/100-mile with all new infrastructure. As shown in Figure 25, the cost decreases when the CO_2 flow rate increases due to economies of scale.

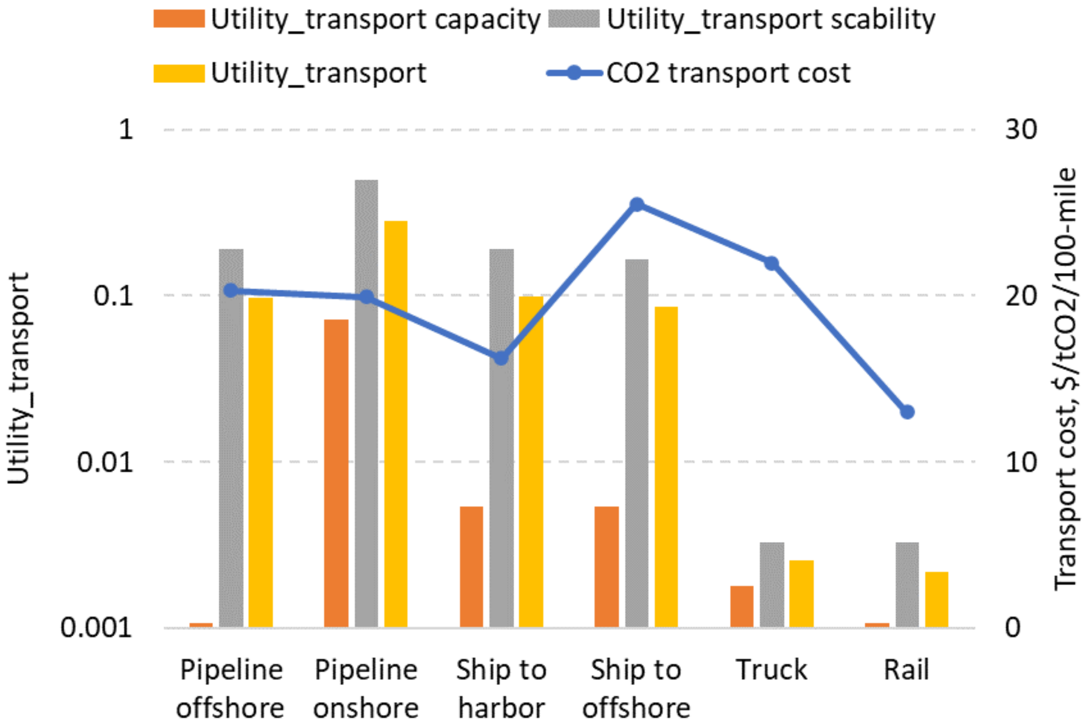


Figure 25 co₂ transport utility and cost for different transport options at 1 Mtpa flow rate

Utility functions for carbon storage and utilization are defined as

$$U_{storage,c} = \frac{capacity_k}{\sum_k capacity_k}$$

$$U_{storage,e} = f_{se}(Storage\_duration)$$

$$U_{storage,s} = \frac{Future\_capacity_k}{\sum_k Future\_capacity_k} \times \frac{TRL}{9}$$

$$U_{storage} = \sum_n w_{storage,i} U_{storage,n}$$

Where c is for capacity, e is for efficiency, s is for scalability, k is for storage or utilization option, n = capacity, efficiency, scalability, f_{se} is the utility value for storage efficiency shown in Table 24, and weighting factors w are shown in Table 23. The values of those weighting factors reflect the relative importance of different performance measures for CO_2 storage to meet the NetZero Emission goal.

Table 24 Utility function of storage efficiency of different storage durations

Storage duration, years	<1	50	100	>100
f_{se} utility value for storage efficiency	0.3	0.7	0.9	1

With these equations, the utility values can be calculated for all the CO_2 storage and utilization options. Figure 26 shows the utility values for storage capacity and scalability for all CO_2 storage/utilization options. They vary across orders of magnitude due to the wide range of their existing capacity and future capacity of the intake of CO_2 among different options. The EOR and Urea have the highest utility values due to their dominance in CO_2 utilization at the current state. It expects that the onshore CO_2 storage in saline aquifers will dominate and make an enormous contribution to meeting the NetZero emissions target by 2050.

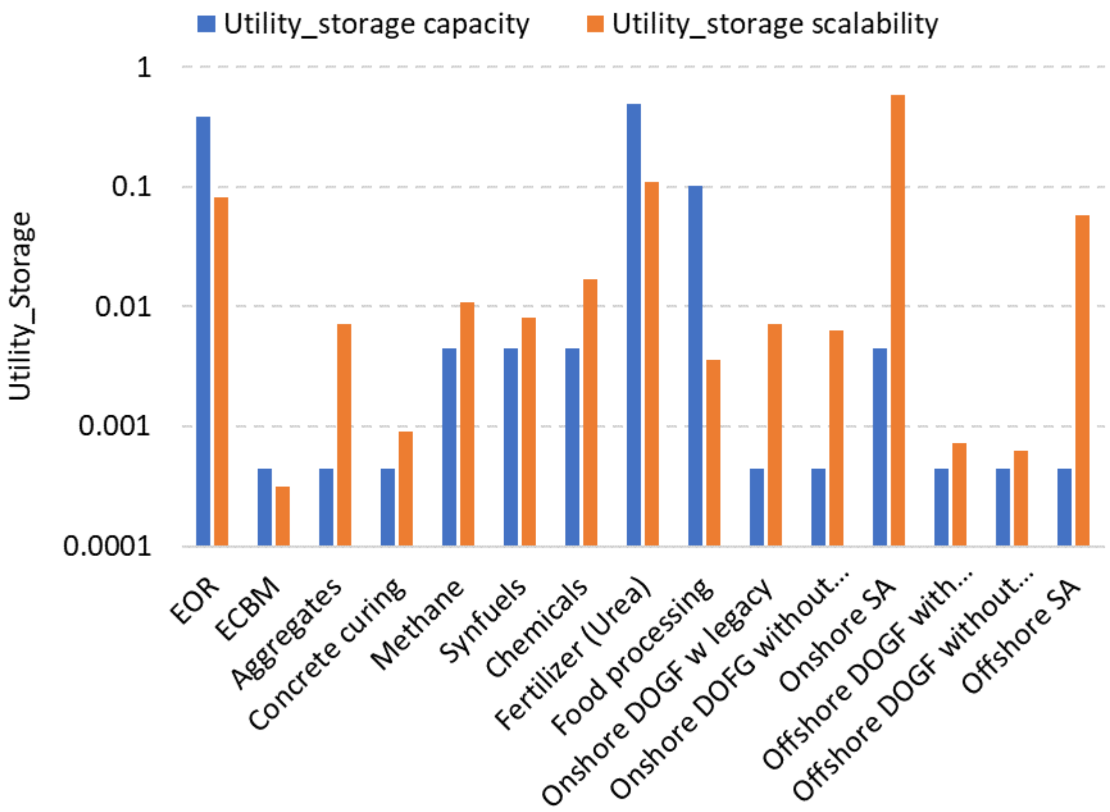


Figure 26 co₂ storage utility values by storage/utilization type

Figure 27 shows the tradespace of CO_2 storage utility vs. cost for various CO_2 storage/utilization options. Among all the options, the onshore saline aquifer storage has the highest utility value for CO_2 storage and relatively low cost. Some other options also fall on the Pareto Front, including fertilizer production and EOR; both have a net profit from using CO_2 with moderate utility values for CO_2 storage. The CO_2 storage in depleted oil and gas fields also has moderate utility values and meager cost, which may play an essential role in CCS in the future. In contrast, CO_2 utilization for the synthetic fuel production and methane synthesis with green hydrogen have relatively low utility given the limited capacity of CO_2 consumption. Meanwhile, their costs are high due to the early stage of technology development. Their positions in the tradespace may change if their deployment scale can be significantly expanded with technology maturity and cost be reduced with economies of scale.

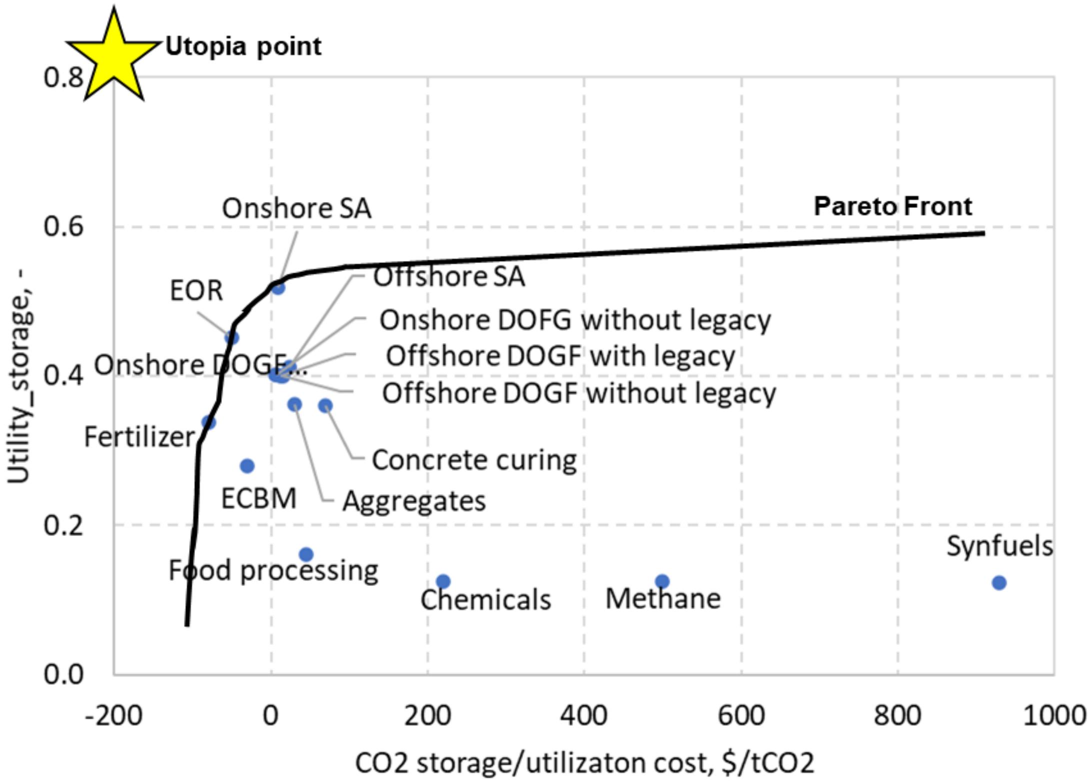


Figure 27 Tradespace plot of co₂ storage/utilization utility vs. cost (negative cost means net profit)

5.3.2 CCS System Utility and Cost Model

By combining the utility for CO_2 capture, transport, and storage, the CCS system utility can be calculated as follows:

$$U = U_{capture} \times U_{transport} \times U_{storage}$$

The total cost of a CCS system includes capture cost, transport cost, storage cost, and government incentives. The formula below shows the cost model for a CCS system.

$$Cost = \sum_n Cost_n + Tax\ credit$$

For onshore transport, the CO_2 transport cost can be calculated as

$$Cost_{Transport} = \text{Unit } CO_2\ transport\ cost\ *\ Distance$$

For offshore transport, the CO_2 transport cost can be calculated as

$$
\begin{aligned}
Cost_{Transport} = {} & Unit\ CO_2\ transport\ cost_{onshore\ pipeline} * Distance_{onshore} \\
& + Unit\ CO_2\ transport\ cost_{offshore} * 100\ mile
\end{aligned}
$$

$$
Cost_{Storage} = \begin{cases} CO_2\ storage\ cost, & for\ CO_2\ storage \\ CO_2\ utilization\ cost, & for\ CO_2\ utilization \end{cases}
$$

Table 25 shows the tax credit values of different CCS systems for total cost calculation.

Table 25 Tax credit values for different CCS systems

	DAC		Other CO_2 capture	
	CO_2 storage	CO_2 utilization	CO_2 storage	CO_2 utilization
Tax credit, \$/tCO_2	180	130	80	65

5.4 Trade Space Analysis

The tradespace analysis workflow is shown in Figure 28 below.

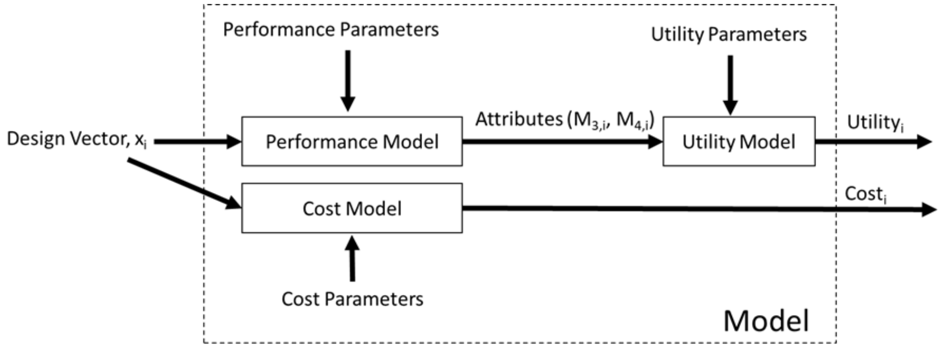


Figure 28 Tradespace analysis workflow

The workflow includes the following steps:

1. Identify a design vector that composes option of each architecture decision
2. Using the performance model to calculate the performance attribute values using the performance parameters
3. Calculate the system utility using the performance attributes and utility parameters
4. Calculate the system cost using the cost model with the corresponding cost parameters

5. Repeat the previous steps to calculate the utility and cost of all design vectors

The calculated utility and cost values of all possible design vectors of a CCS system are plotted in tradespace for analysis and comparison. Figure 29 through Figure 33 show the tradespace of CCS system utility vs. cost for all 2088 CCS design vectors.

Among all the CCS system design vectors, the total cost after applying tax credit varies between -\$150 and \$1100 per ton of CO_2 captured, transported, and stored. Negative cost values mean the net profits of a CCS system. The utility values range between 1e-5 to 0.25, given the wide range of performance parameters of different design vectors. The CCS system utility in the tradespace plots is shown in the log scale to demonstrate the performance variation among different CCS systems.

It is worth noting that the low utility values of all potential CCS systems result from the way CCS utility is defined in the systems engineering model. According to the utility function, the utility of a given architecture decision option is proportional to the ratio of that option's capacity to the total capacity of all alternatives combined. Since the capacity of a single CO_2 capture, transport, and storage option is small compared to the total capacity, its utility value is also low. The results highlight that the capacity of an individual CCS system is relatively minor compared to the total capacity required for the NetZero Emission scenario. Therefore, combining multiple CCS system concepts is necessary to meet the overall CCS capacity target and achieve higher utility. Nonetheless, the relative differences in utility values between CCS systems still reflect performance variations among different design options, providing valuable insights for operators in selecting their preferred CCS system concept.

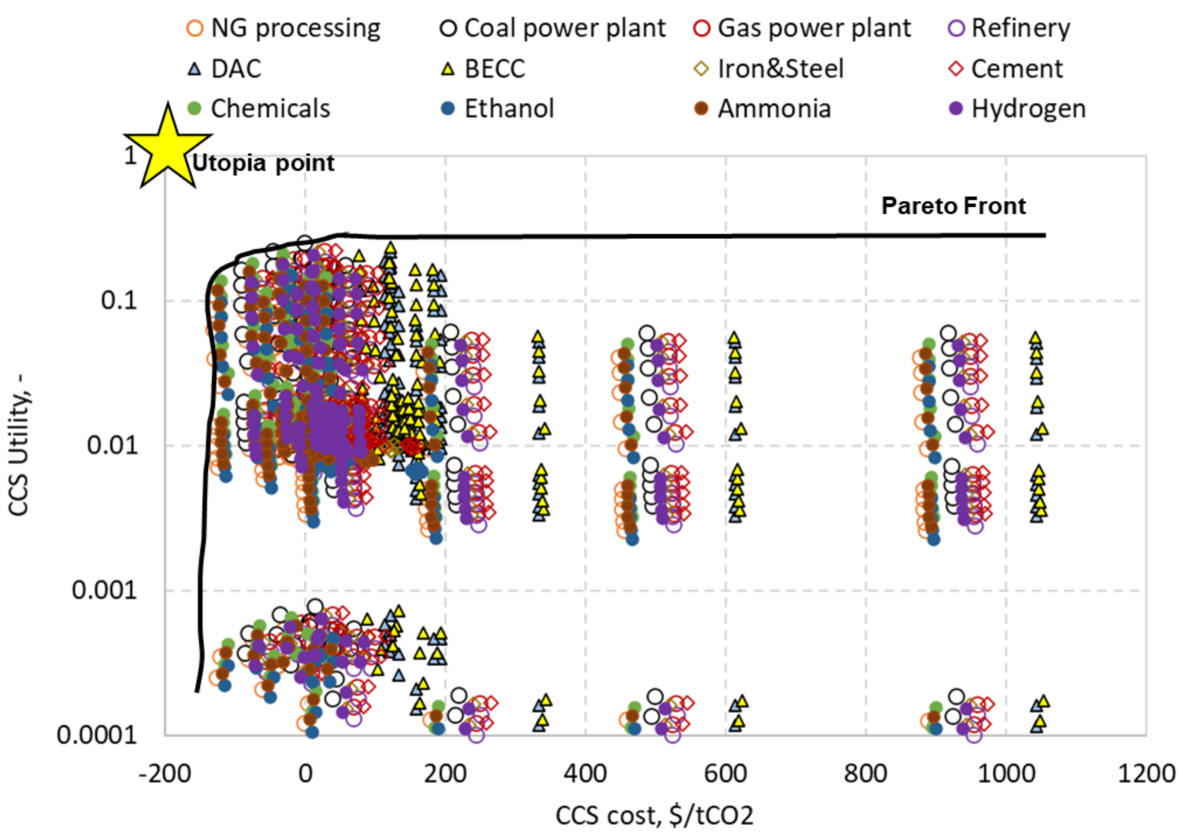


Figure 29 Tradespace of CCS systems by CO_2 *source with utility in logscale*

It is evident that the CO_2 source type is not the determining factor in distinguishing the CCS system utility, but it impacts the CCS system cost. Figure 30 shows the CCS system utility on a linear scale. CCS systems with CO_2 capture from multiple stationary point sources fall on the Pareto front, including natural gas processing, coal power plants, ammonia, and chemical production plants.

Figure 31 indicates that the transport approach differentiates the architecture decision for CCS system utility. The onshore pipeline option provides the CCS system with the highest utility because of its high capacity, technology maturity, and scalability. The CCS systems with offshore pipelines and shipping have similar utility values, one order of magnitude smaller than that of a CCS system with onshore pipelines. A CCS system with trucks or rails for CO_2 transport has the lowest utility due to its low capacity and scalability. The results reinforce the preference for online pipelines for future CCS system development in the United States.

Figure 32 shows that a higher flow rate of CO_2 transportation results in higher CCS system utility but not necessarily higher CCS cost per unit amount of CO_2 due to the economies of scale. Increasing the flow rate for CO_2 transport through pipelines requires more capital investment and slightly higher operational cost, but the normalized cost to transport and store per unit ton of CO_2 decreases. For CO_2 shipping, the operational cost increases proportionally with the flow rate. Thus, the benefits of economies of scale are not as dramatic as that of pipeline transport.

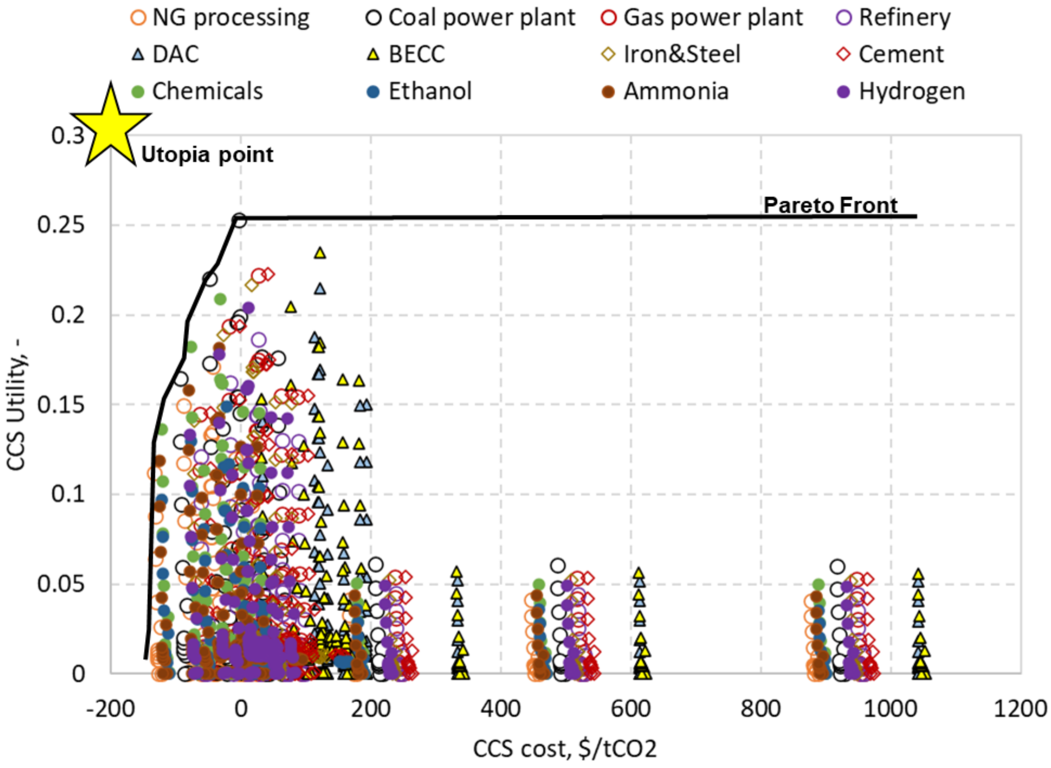


Figure 30 Tradespace of CCS systems by CO_2 source type

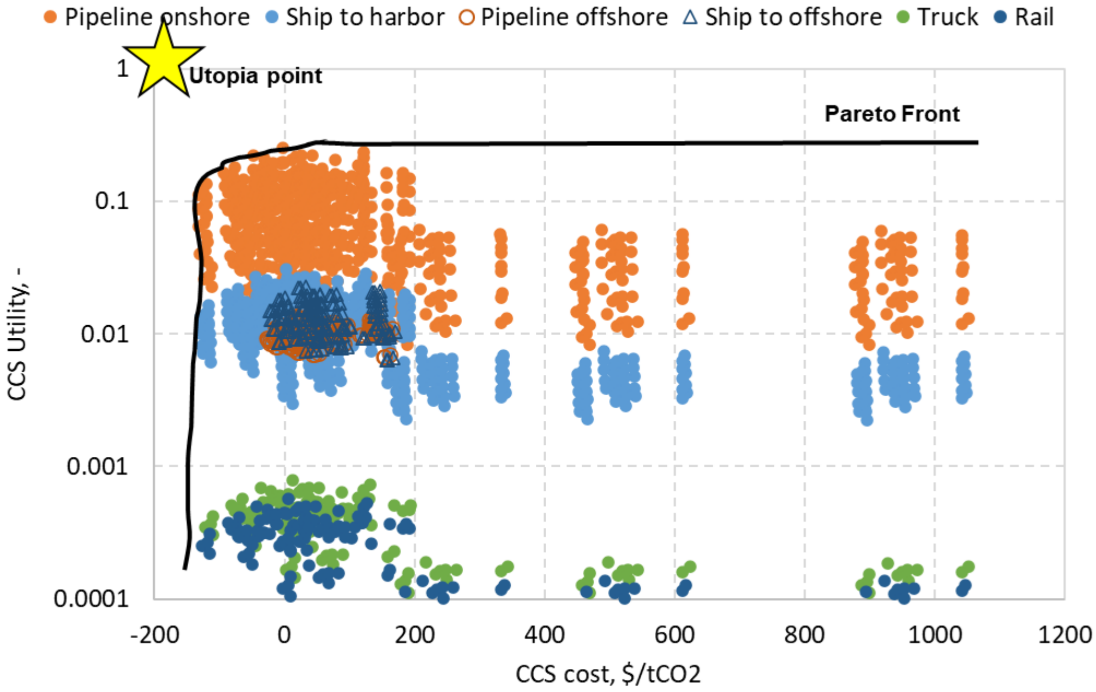


Figure 31 Tradespace of CCS systems by transport approach

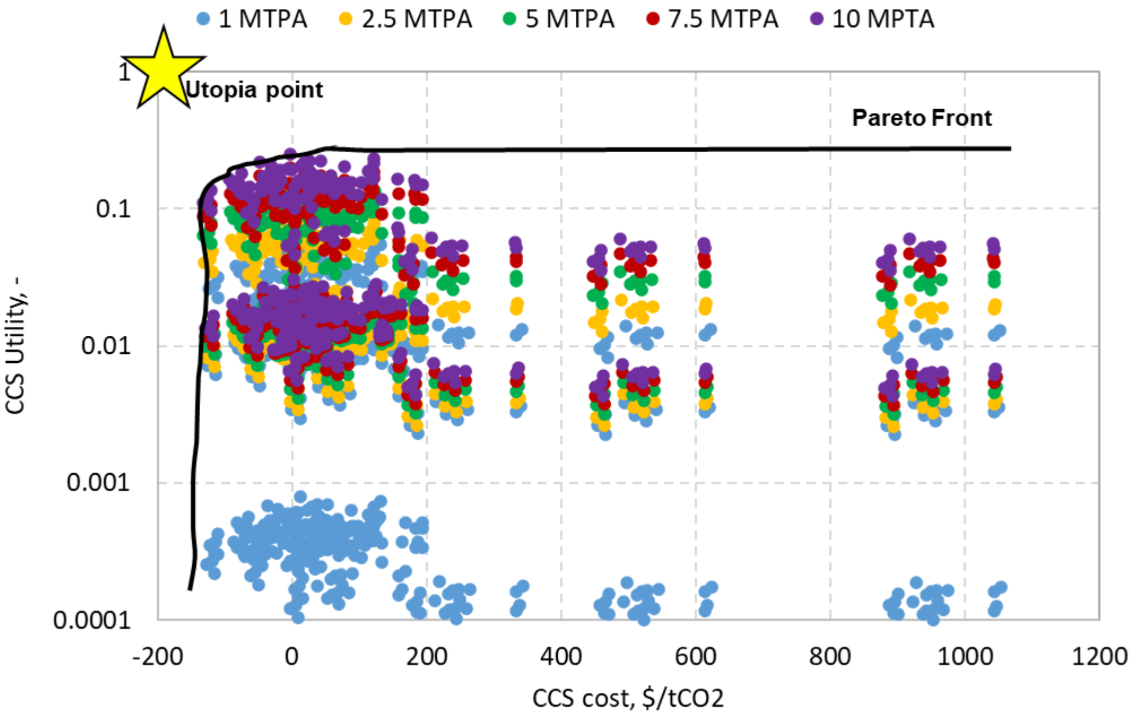


Figure 32 Tradespace of CCS systems by transport rate

Figure 33 indicates that the CO_2 storage architecture decision is the most distinguishing factor of CCS cost. CCS systems with CO_2 utilization for fertilizer production, EOR, and storage in onshore aquifers and depleted oil and gas fields (DOGF) all have similar utility ranges and slightly different costs. In contrast, the CO_2 utilization for chemical, methane, and synfuel production has relatively low utility and high cost, thus not preferred for CCS system design at the current stage.

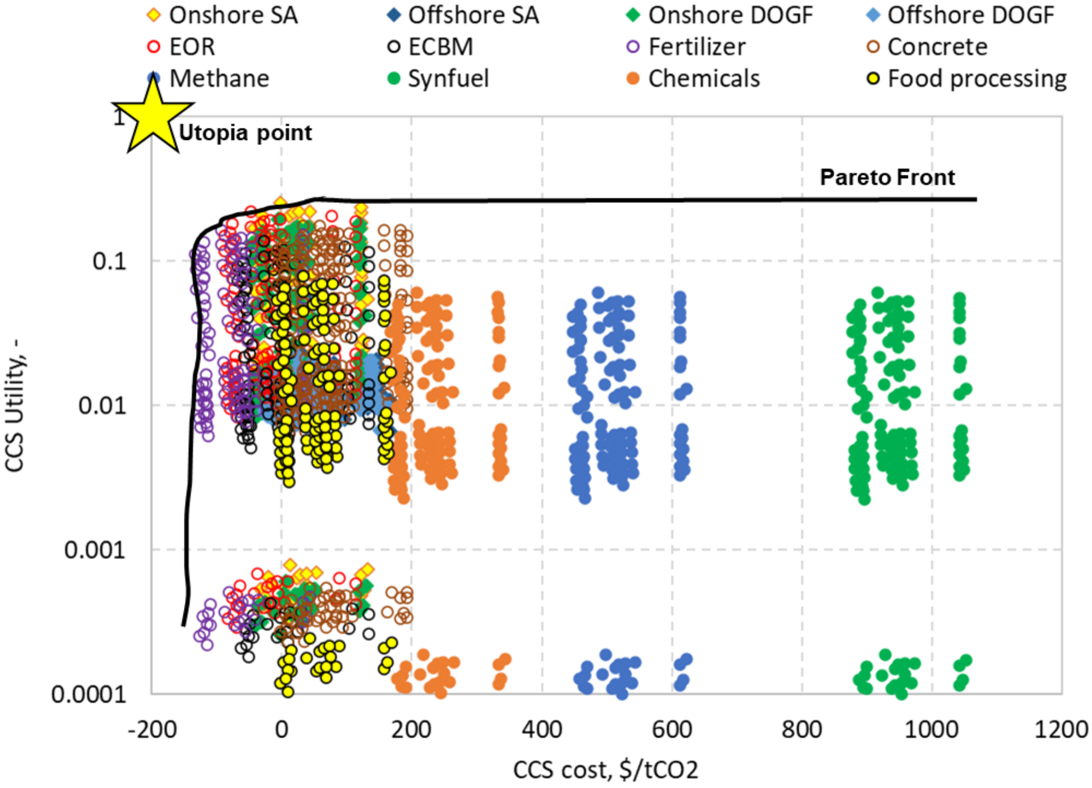


Figure 33 Tradespace of CCS systems by CO_2 storage and utilization option

The plots in Figure 29 through Figure 33 demonstrate that the best-performing CCS systems with relatively high utility and low cost include CO_2 capture from natural gas processing, coal power plants, ammonia and chemical production plants, CO_2 transport via onshore pipelines, and CO_2 storage in saline formations and CO_2 utilizations in industry processes except for fuel and chemical production. With that, the 2088 design vectors are filtered to remove those with CO_2 utilization for fuel and chemical production and only keep those with onshore pipelines for CO_2 transportation. It ends up with 540 design vectors, and Figure 34 and Figure 35 show the updated tradespace plots by CO_2 source and storage type with the filtered 540 design vectors on linear scales.

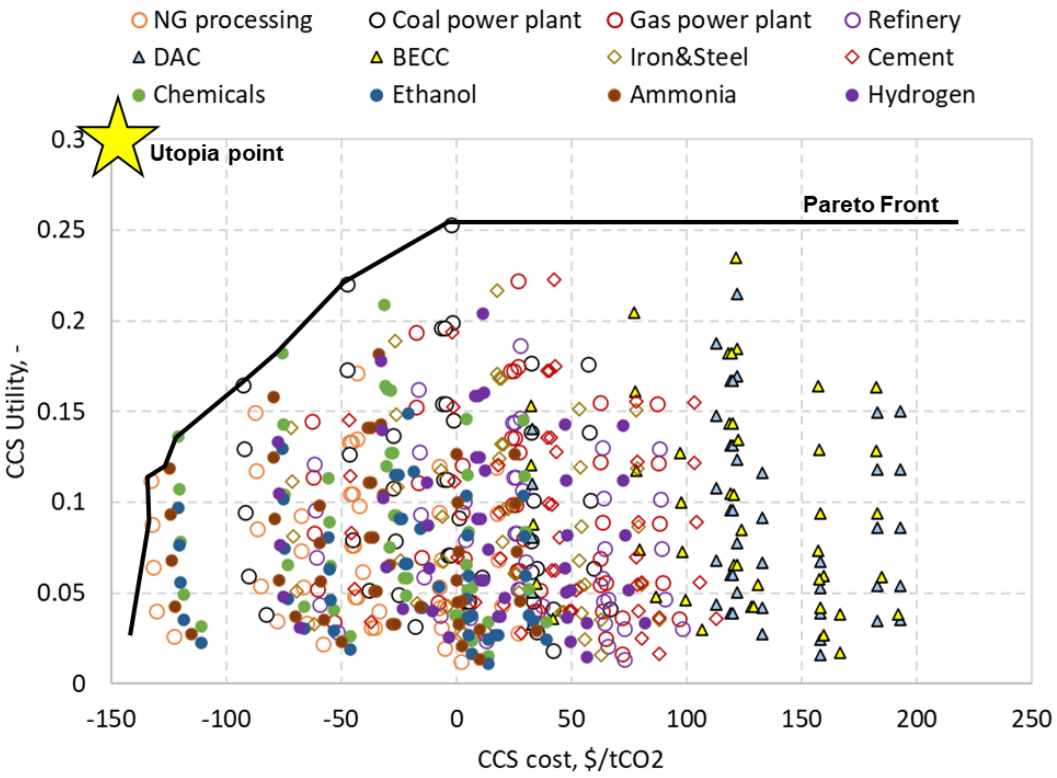


Figure 34 Tradespace for CCS system by co_2 source type with only onshore pipeline transport

The CO_2 systems on the Pareto Front in the tradespace are dominated by CO_2 capture from natural gas processing, coal power plants, ammonia and chemical production, CO_2 storage in onshore saline aquifers (SA), and application in EOR and fertilizer production.

The CCS concept involving CO_2 capture from coal-fired power plants, transported via onshore pipelines, and stored in onshore saline aquifers offers the highest utility with almost zero cost after government tax credits. It allows current power plant operators to reduce their carbon emissions at minimal cost while continuing their regular business. The United States emits over 1200 Mtpa from coal-fired power plants and has over 1500 Mtpa estimated CO_2 storage capacity in onshore saline aquifers, sufficient to meet the 900-1100 Mtpa CCS target for NetZero Emission.

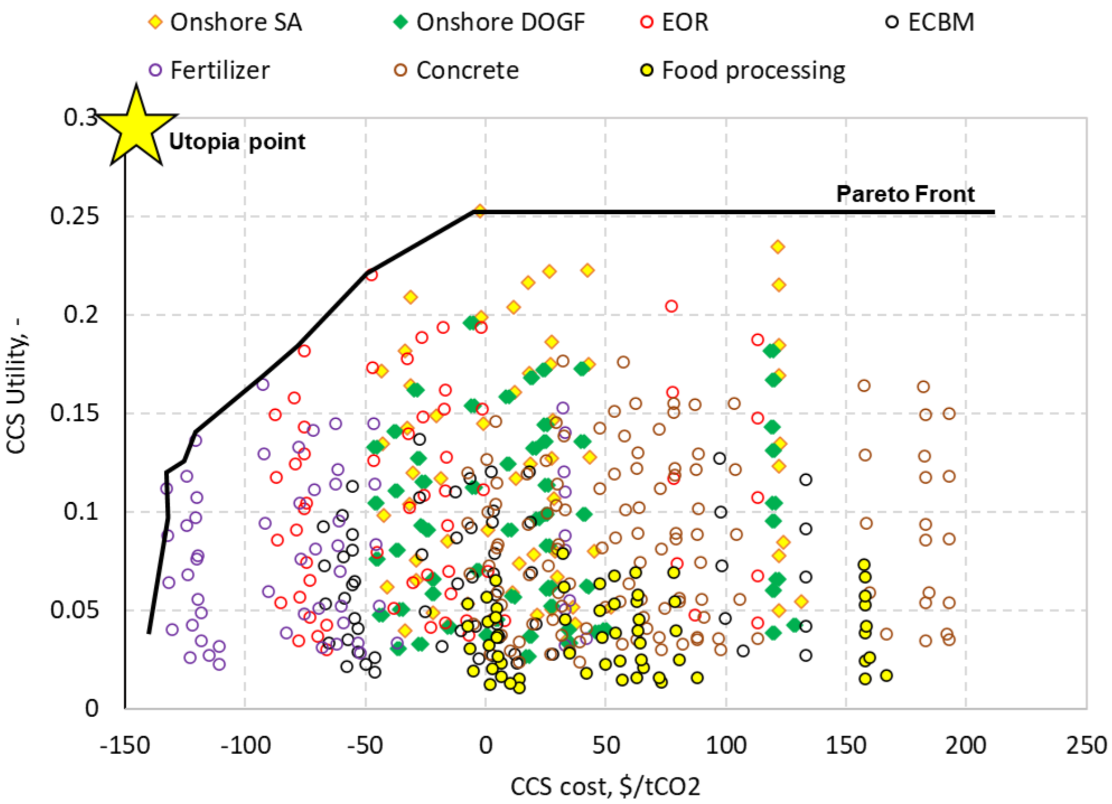


Figure 35 Tradespace for CCS system by storage type with only onshore pipeline transport

However, the implementation of the CCS system still faces challenges. The initial capital investment required to retrofit the current power plants, build new pipelines, and drill wells for CO_2 injection into saline formations is substantial. Although the average CCS cost per ton of CO_2 captured and stored is nearly zero after government incentives, significant upfront capital is needed to start the project. For a capture capacity of 1000 Mtpa from power plants and storage in onshore saline aquifers, the estimated annual cost is 80 billion dollars before tax credits. Assuming a 20-year lifespan of the project, a 9:1 capital and operational cost ratio, and a 10% discount rate, it requires around $680 billion in capital investment to enable the system, not including the time needed for permitting and construction.

Furthermore, the CCS system cost calculated by the model is an average value, and actual costs vary among specific power plants and formations. The following section will conduct a sensitivity analysis to reveal the impact of technology cost uncertainty on CCS system performance and cost.

When designing a CCS system, market dynamics must be considered as well. For example, emissions from coal-fired power plants are expected to decrease over time as low-emission energy sources like wind and solar will replace them. Consequently, the projected capture capacity target from power plants in 2050 is only around 400 Mtpa, which is only one-third of the current emission level. Although current emissions from power plants exceed the total capture capacity anticipated by the NetZero Emission scenario, this situation is not sustainable. CCS systems must also capture CO_2 from other sources to bridge the gap between the reduced capture capacity from power plants and the total capture capacity. As shown in Table 11, the majority of future CO_2 capture capacity comes from technologies like DAC and BECC due to the reduced CO_2 emissions in traditional power plants and heavy industries in the long-term future.

In addition to coal-fired power plants, CCS systems that capture CO_2 from facilities producing chemicals, ammonia, and methane can also be profitable when storing the captured CO_2 in onshore saline aquifers or using it for EOR and urea production. Thus, CCS clusters can be developed to integrate multiple capture facilities and utilization/storage locations and share transportation pipelines and supporting facilities to reduce the capital cost per plant. A clustered CCS system offers more flexibility for CO_2 sources and sinks and enhances the scalability of CCS systems for future expansion. Operators can select facilities with lower costs and higher capacities to meet overall CCS targets and reduce total costs. This approach leverages economies of scale and is the trend for current and future CCS projects.

5.5 Uncertainty Analysis

5.5.1 Uncertainties in the CCS System

There are many uncertainties associated with CCS system modeling. For example, the expected CO_2 capture capacity from different stationary point sources may change over time with the progress in technology and market shift, and the same is true for the demand for CO_2 utilization. These uncertainties will change the utility value of CO_2 capture and storage options. Other uncertainties in CCS system modeling include the cost of carbon capture, transport, and storage, which will change over time due to the change in material and labor costs, regulation, and technology maturity. Moreover, the tax credit provided by the government will expire after a specific date. All those uncertainties may generate different results from the one shown above.

Some representative design vectors are chosen to conduct the uncertainty analysis. Some concepts are selected based on their representation of typical CCS systems either in the current state or in the future, such as CO_2 capture from natural gas processing plants and storage in saline aquifers and direct air capture of CO_2 stored in saline aquifers. Other concepts are selected with a change of one architecture decision at a time for benchmark and sensitive analysis, such as CCS concepts with CO_2 capture from power plants with varied storage options like sequestration in saline aquifers or depleted oil and gas fields (DOGF) or utilization in EOR or fertilizer manufacture. Table 26 shows the details of the selected concepts, and Figure 36 shows their locations in the tradespace. The chosen concepts all transport CO_2 through onshore pipelines at a flow rate of 10 Mtpa, and the variation among them are the CO_2 source and storage options.

Table 26 Details of selected design vectors for sensitivity analysis

Label	AD1	AD3	Cost, $/tCO_2$	Utility	Concept
1	Natural gas processing	Saline aquifer	-43.43	0.17	CO_2 captured from natural gas processing plants, transported through onshore pipelines and stored in nearby saline aquifers
2	DAC	Saline aquifer	122.26	0.22	CO_2 captured directly from ambient air and stored in nearby saline aquifers
3	BECC	Saline aquifer	121.57	0.23	CO_2 captured from bioenergy generation plants, transported through onshore pipelines, and stored in nearby saline aquifers
4	Chemical	Saline aquifer	-31.43	0.21	CO_2 captured from chemical plants, transported through onshore pipelines, and stored in nearby saline aquifers
5	Iron & Steel	Saline aquifer	17.57	0.22	CO_2 captured from Iron & Steel plants, transported through onshore pipelines and stored in nearby saline aquifers
6	Cement	Saline aquifer	42.57	0.22	CO_2 captured from cement plants, transported through onshore pipelines, and stored in nearby saline aquifers
7	Coal power plant	Saline aquifer	-2.47	0.25	CO_2 captured from coal power plants, transported through onshore pipelines, and stored in nearby saline aquifers
8	Coal power plant	DOGF	-6.44	0.20	CO_2 captured from coal power plants, transported through onshore pipelines, and stored in nearby depleted oil and gas fields
9	Coal power plant	EOR	-43.82	0.22	CO_2 captured from coal power plants, transported through onshore pipelines, and utilized for EOR
10	Coal power plant	Fertilizer	-92.68	0.16	CO_2 captured from coal power plants, transported through onshore pipelines, and utilized for fertilizer production

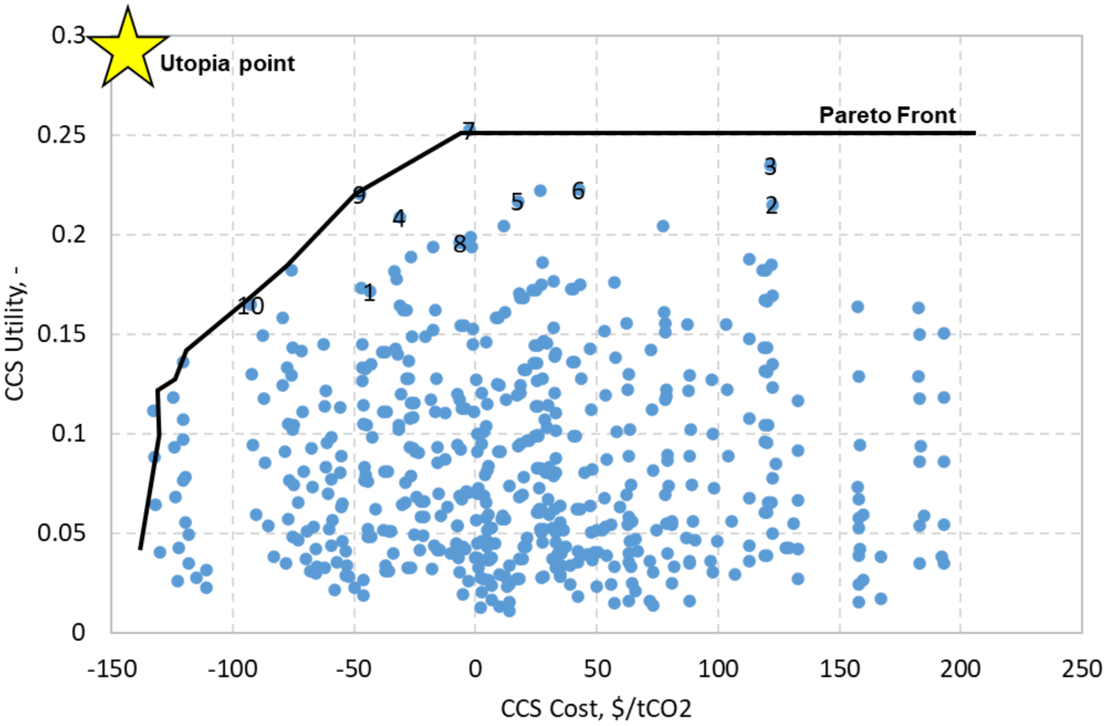


Figure 36 Distribution of selected concepts in the tradespace for sensitivity analysis

As shown in Figure 36, most of the selected CCS system concepts fall on the Pareto Front, and some do not. Some critical uncertainties related to the chosen concepts are identified and defined in Table 27. The baseline values are from the performance parameters tables, and the range of uncertainties is gathered from literature data. There are two main categories of uncertainties: the future target capacity for CO_2 capture and storage and the unit cost of CO_2 capture and storage. The uniform distribution represents the capacity distribution with minimum and maximum values, and the normal distribution is assigned to the cost uncertainty with mean and standard deviation (SD).

Table 27 Key uncertainty probability distribution functions (PDF) and associated baseline and variation parameters[2,6,35,39,41,49,54]

	Option	CCS utility	CCS cost	PDF type	Baseline	Min	Max	SD
Future capacity, Mtpa	Natural gas processing	x		Uniform	9	5	80	
	Chemicals	x		Uniform	23	20	70	
	Iron & Steel	x		Uniform	29	20	100	
	Cement	x		Uniform	43	20	80	
	Coal power plant	x		Uniform	324	200	700	
	Air (DAC)	x		Uniform	300	150	450	
	Bioenergy (BECC)	x		Uniform	150	100	200	
Carbon capture Cost, $/tCO_2$	Natural gas processing		x	Normal	25	18.45	30.75	2.1
	Chemicals		x	Normal	37	30.75	43.05	2.1
	Iron & Steel		x	Normal	86	49.2	123	12.3
	Cement		x	Normal	111	73.8	147.6	12.3
	Coal power plant		x	Normal	65	54.53	82.46	4.7
	Air (DAC)		x	Normal	293	164.82	420.66	42.6
	Bioenergy (BECC)		x	Normal	190	140	240	16.7
Future capacity, Mtpa	Onshore DOGF with legacy	x		Uniform	20	10	30	
	Onshore SA	x		Uniform	1605	1200	2000	
	EOR	x		Uniform	200	100	300	
	Fertilizer	x		Uniform	270	150	400	
CO_2 storage cost, $/tCO_2$	Onshore DOGF with legacy		x	Normal	6.07	5	7	0.3
	Onshore SA		x	Normal	9.26	8	11	0.5
	EOR		x	Normal	-50	-70	-20	8.3
	Fertilizer		x	Normal	-80	-90	-70	3.3

5.5.2 Monte Carlo Simulation and Results

With the defined uncertainties, a Monte Carlo simulation is conducted to evaluate the impact of those uncertainties on the CCS system performance for selected concepts. Figure 37 shows the Monte Carlo simulation procedure.

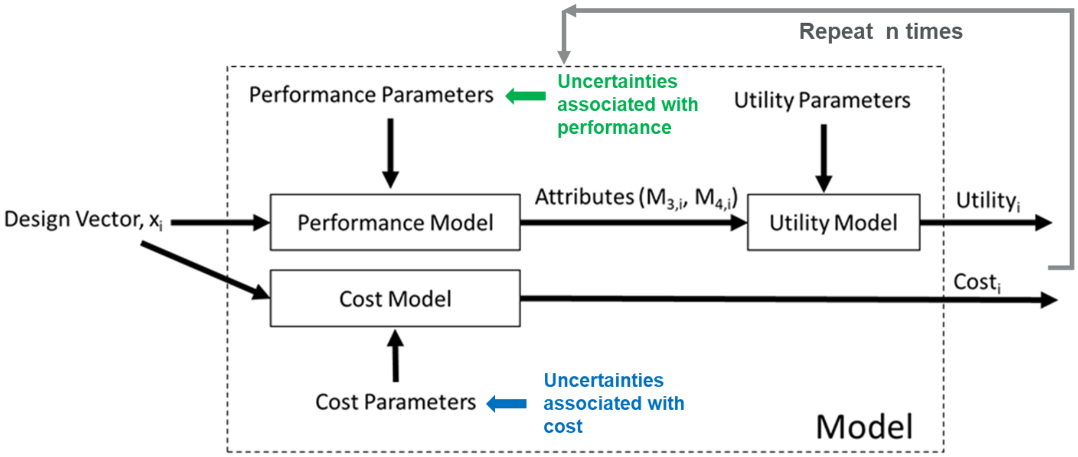


Figure 37 Monte Carlo simulation workflow of performance metrics calculation for each design vector/concept

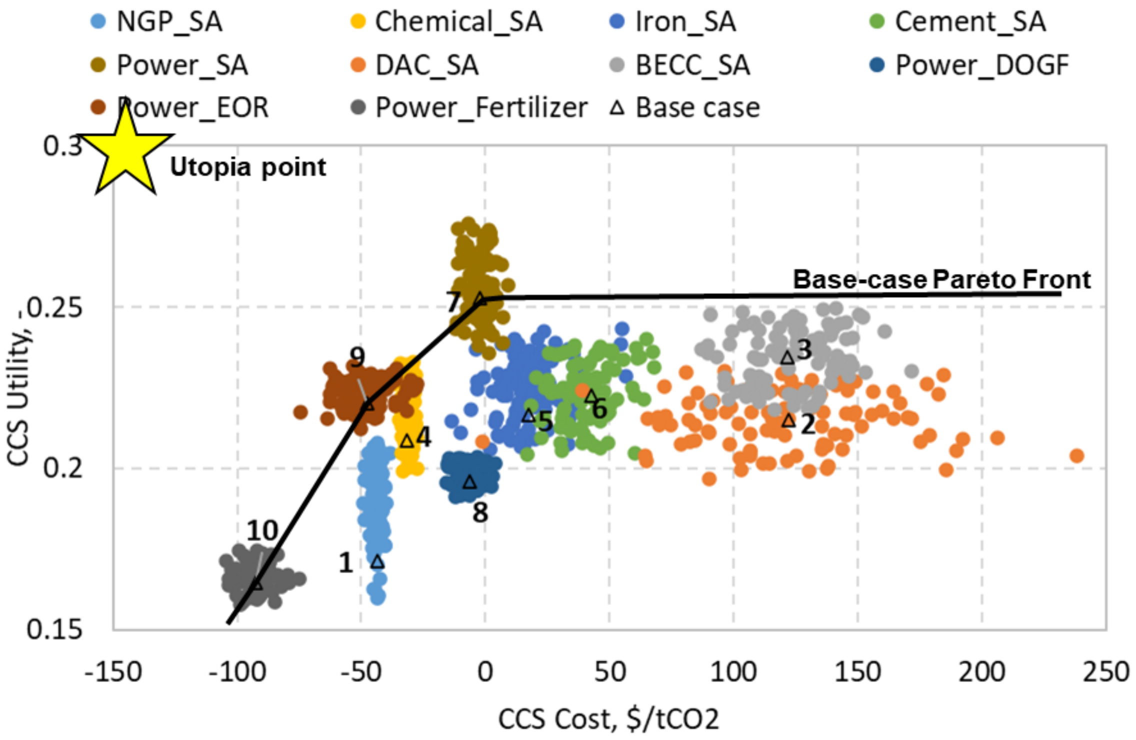


Figure 38 Monte Carlo simulation results for selected concepts

During the Monte Carlo Simulation, a value is generated for each uncertainty specified in Table 27 following its probability distribution function (PDF). The engineering model is then used to calculate the system utility and cost for each selected design vector with the corresponding performance and cost parameters. One hundred rounds of simulation were conducted for each concept, and the results are shown in Figure 38.

When introducing the uncertainty in the capture and storage capacity and cost, some of the preferred concepts in the base case still provide the best performance among all options, such as the CO_2 capture from power plants and storage in saline aquifers (#7). Some concepts that do not fall on the Pareto Front in the base case may be preferred when conditions change, such as the CCS concept #4, which captures CO_2 from chemical-producing plants and stores it in aquifers. The utility and cost ranges with uncertainties are narrow for the CCS concept with more mature technologies, such as CCS capture from power plants and used in fertilizer production. However, the current costs of CCS systems with innovative technologies, such as direct air capture and CO_2 capture from bioenergy production, are relatively high. Meanwhile, their cost and utility have wide ranges because of the considerable uncertainties. They may fall on the Pareto Front with technology improvement, cost reduction, and upscaling.

5.5.3 Other Sensitivity Analysis

Based on the previous discussion, it is clear that there is a big gap between the current CCS status and the future CCS target to achieve net-zero emissions by mid-century. The performance evaluation so far for CCS system designs uses equal weights for the current capacity and the future scalability to balance the current and future needs of CCS systems. The scope and target scale of the CCS system determines that it will develop in stages and ramp up gradually over several decades. The priorities of the CCS design and implementation performance considerations at different stages will change. Besides, the multiple stakeholders of CCS systems have various preferences regarding performance attributes based on their role in the big picture. For example, the government's priority is to foster new CCS technology development and upscaling the CCS system to reach the climate goal. In contrast, the CCS operators' priority is to make profits by operating CCS systems and gaining a share in the growing CCS market. The CO_2 emitters' consideration is focused on the potential future carbon tax and the continuation of their regular business operation, such as power generation and cement, iron & steel manufacturing. With that, different weighting factors may be chosen to reflect those other perspectives and preferences of CCS system design and performance evaluation.

Table 28 Weight factor for different scenarios of CCS performance modeling

	Weighting factor	Base	Current	Future
Capture	capacity	0.5	0.9	0.2
	efficiency	0.1	0.1	0.1
	scalability	0.4	0	0.7
Storage	capacity	0.4	0.6	0.2
	efficiency	0.4	0.4	0.4
	scalability	0.2	0	0.4

Three sets of weighting factors are chosen to reflect the performance change with a focus on current, future, or both. Figure 39 shows the results of the selected concepts in those three scenarios, and Table 28 shows the corresponding weighting factor in the modeling. Similar weighting factors are given to capacity and scalability for CO_2 capture and storage in the base case. In the Current case, more weight is given to the current capacity. In the Future case, more weight is given to the system scalability.

When the weighting factor changes, the CCS system utility also changes. As the cost factor hasn't changed, the concept in the tradespace only moves upwards or downwards vertically between those three scenarios. Compared to the base case, the CCS concepts in the Current case all have lower system utility except the one that captures carbon dioxide from coal power plants and stores it in fertilizer synthesis. It is becuase the CO_2 utilization for urea production has high utility currently but low utility in the future due to its relatively small and constant capacity compared to the total capture capacity expansion to reach the NetZero Emission target.

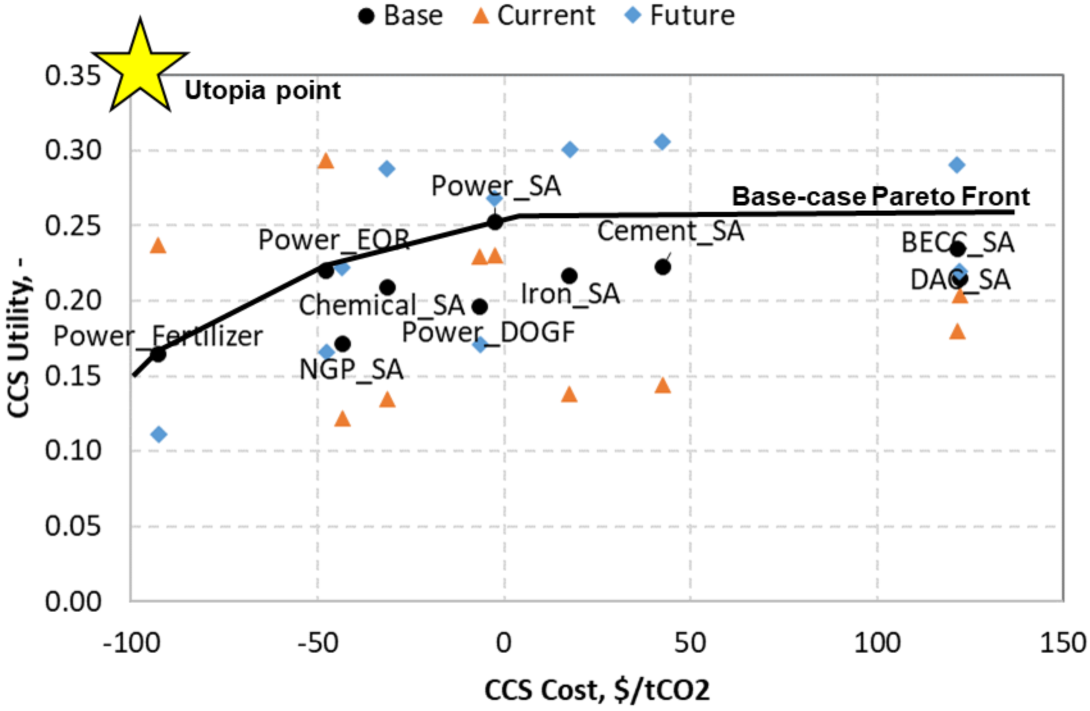


Figure 39 The utility shift of selected concepts in different scenarios

Another observation is that when the weighting factors of capacity and scalability change, the utility variation differs among the selected concepts. For example, the utility difference between the base case, Current case, and Future case of a CCS system capturing CO_2 from power plants and application for EOR is much smaller than that of a CCS system capturing CO_2 from ambient air and storing it in saline aquifers. That is because the difference between direct air capture's current and future capacity is more significant than that of the CO_2 capture from power plants. With that, some of the concepts on the Base-case Pareto Front may not necessarily be on the Pareto Front when performance matrices change, and vice versa. For example, the CCS system concept of CO_2 capturing from power plants and utilization in fertilizer production is on the Pareto Front for the Current scenario but not for the Future scenario. The CCS concept of capturing CO_2 from ambient air with CO_2 storage in saline aquifers is not on the Pareto Front for the Current scenario but is on the Pareto Front for the Future scenario. The analysis provides valuable insights to various stakeholders for strategic planning of CCS system design and development at different stages (short-term, mid-term, and long-term).

The second significant uncertainty is the government incentives. Figure 40 shows the impacts of the 45Q tax credits on CCS system performances. In the comparison, the utility value of a given CCS system concept does not change, so removing tax credit shifts the dots horizontally in the tradespace. As the tax credit has different values for different capture and storage/utilization options, the expiration of tax credits will change the relative location of the CCS system concepts to the Pareto Front. The results provide a direct view of the impact of government incentives on the preferred system concepts for CCS design, particularly for CCS operators who want to make profits out of CCS projects. Alternatively, it reflects the potential value of carbon tax that may enforce some CCS implementation by main carbon emitters to comply with government regulation while continuing their business of operation. Moreover, the engineering model and tradespace analysis can provide quantitative guidance on the tax credit value that the government can assign to promote a specific concept to fulfill the long-term goal of CCS.

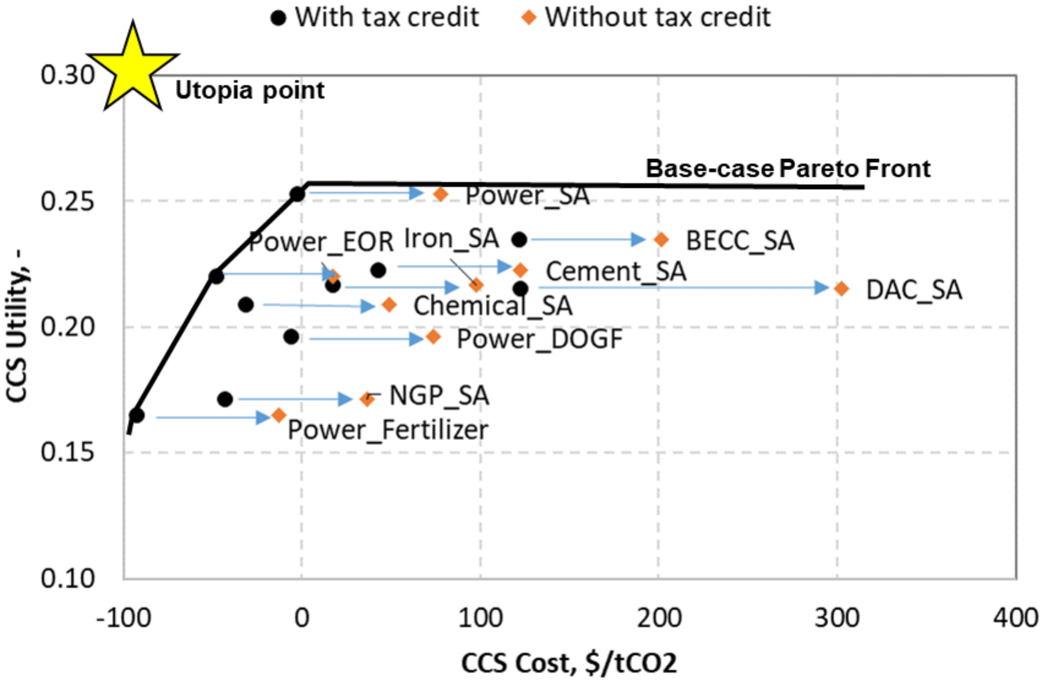


Figure 40 Impacts of tax credits on the performance of selected CCS system concepts

Chapter 6 Regional CCS System Analysis

In the previous chapters, the scope of CCS system design and performance evaluation includes the entire territory of the United States. However, CO_2 emissions levels, CO_2 transport infrastructure density and availability, and CO_2 storage capacity are not evenly distributed among the states. Huge differences exist between states in the U.S. regarding the current CO_2 emission levels and CCS potentials. Figure 41 shows the CO_2 emission levels (>20 Million tons) in 2022 by state in the U.S. and their share of the total U.S. CO_2 emission[83]. Texas has the highest CO_2 emission levels, almost twice that of Florida, second on the list.

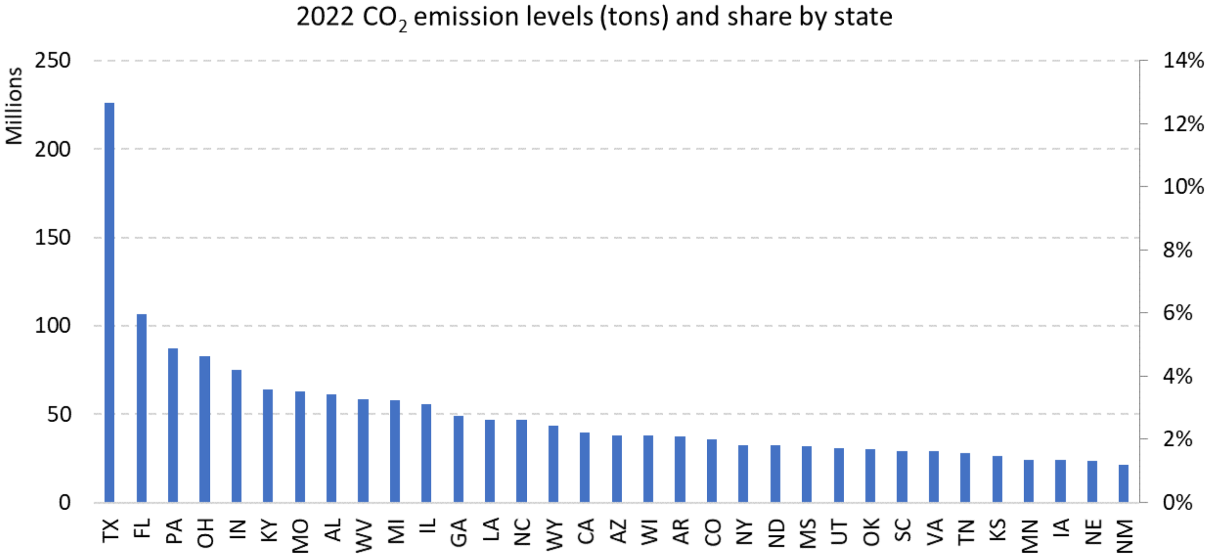


Figure 41 CO_2 Emission levels (>20 Million tons) in 2022 and share by state in the U.S.[83]

As mentioned above, CCS development will go through multiple stages, from early development to full industrial scale by the mid-century. In the near term, the CCS system development will focus on regional demonstrations that leverage the existing infrastructure. In this chapter, the CCS system will be designed and evaluated at a regional scale that may cover one or a few states.

6.1 Input Data and Parameters

Based on the distribution of existing CO_2 emission sources, CO_2 transport pipelines, and storage formation in the United States, three regions are chosen to evaluate the CCS potential and performance: Permian Basin & Mid-Continent, Gulf Coast, and Mid-West. Table 29 shows the states that are included in those three regions. Table 30 shows the CO_2 emission levels by industry sector in each region reported by the Environmental Protection Agency (EPA). Table 31 shows each region's existing capacity for CO_2 transport and storage and associated costs.

Table 29 States included in the selected regions

Region	State
Permian Basin & Mid-Continent	West Texas, New Mexico, Colorado, Oklahoma, Kansas
Gulf Coast	Mississippi, Louisiana, East Texas
Mid-West	Illinois, Indiana, Ohio, Pennsylvania, Wyoming, Kentucky, Michigan

Table 30 co_2 emission levels (Mtpa) in 2022 by industry sector in the selected regions[84]

Region	Chemical	Metals	Petroleum	Power	Refinery	Waste	Mineral
Permian Basin & Mid-Continent	30.8	0.4	59.3	193.3	33.2	0.6	8.6
Gulf Coast	57.1	2.0	43.3	170.4	54.0	0.7	4.3
Mid-West	8.2	22.4	5.2	361.4	19.6	4.4	22.3

Table 31 Regional co_2 transport and storage parameters[6,54]

Region	Pipeline Length, km	Transport capacity, Mtpa	Transport cost, $/tCO_2$/100 mile	Storage capacity, Mtpa	Storage capacity, Gt	Storage cost, $/tCO_2$
Permian Basin & Mid-Continent	4950	129	3.2	660	129	7.3
Gulf Coast	1190	31	3.2	820	135	5
Mid-West	345	9	3.9	80	54	12

6.2 Modeling Approach and Results

The following assumptions are made to model the CCS systems in the three regions:

1. The CCS systems will capture 80% of CO_2 emitted from each region's chemical, metal, petroleum, refinery, and power plants.
2. Onshore pipelines are used for CO_2 transportation between capture and storage locations. The operational cost of CO_2 transport with the existing pipeline is 6% of the total transport cost with new pipelines. The extra pipeline will be installed to fulfill the need to transport all captured CO_2 to storage locations.
3. The average transport distance between the capture and storage is 100 miles within each region.

In the Mid-West region, where the storage capacity is less than 80% of the CO_2 emission level, the excessive CO_2 will be shipped to offshore saline formations for CO_2 storage using offshore pipelines with a unit cost of \$5.3/tCO_2. The storage cost for CO_2 in offshore aquifers is \$23.14/tCO_2.

Based on those assumptions, the CCS system capacity and cost are calculated for each region. The results are shown in Table 32. Figure 42 shows the CCS capacity and annual capture, transport, and storage costs in the three regions.

Power plants have the highest emissions among all industry sectors in all three regions. However, the CO_2 emissions from power plants in the Mid-West are almost double that in the other two regions. The Permian Basin & Mid-Continent Region has the highest CO_2 emission from the petroleum production processes. In contrast, the Gulf Coast has the highest CO_2 emission from the chemical-producing plants and refineries. If CO_2 capture is from those stationary sources, the total capture capacity is similar in the three regions, with Mid-West having the highest number. The transport cost also differs among those three regions for two reasons. The first is that the majority of existing CO_2 pipeline capacity is present in the Permian-Basin & Mid-Continent region, which significantly reduces the capital cost to install new pipelines to fulfill the transport capacity. The second reason is the slightly higher labor and material costs, and consequently the CO2 transport costs, in the Mid-West area compared to the other two. The Mid-Continent and Gulf Coast have similar storage capacities, enough to store all the CO_2 captured in those two regions. However, the Mid-West's CO_2 storage capacity is smaller than the other two regions. And it is not enough to store all the CO_2 captured in the same region. Therefore, the extra captured CO_2 must be transported and stored in other regions or offshore areas. It has been assumed that the extra CO_2 will be stored in offshore aquifers using offshore pipelines. Though the existing transport infrastructure capacity is much higher in the Mid-Continent region than the Gulf Coast and Mid-West, the transport cost is a tiny portion of the total cost of CCS. Thus, the availability of transport facilities does not significantly contribute to the cost difference between the three regions. However, the limited onshore storage capacity in the Mid-West region requires extra transport distance and storage space in the offshore environment, dramatically increasing the total storage cost, as shown in Figure 42.

Table 32 CCS performance in the three selected regions in the United States

Performances	Permian Basin & Mid-Continent	Gulf Coast	Mid-West	Capture cost, \$/tCO_2
CO_2 emission from petroleum, Mtpa	59.3	43.3	5.2	25
CO_2 emission from Chemical, Mtpa	30.8	57.1	8.2	37
CO_2 emission from Metals, Mtpa	0.4	2.0	22.4	86
CO_2 emission from Power, Mtpa	193.3	170.4	361.4	80
CO_2 emission from Refinery, Mtpa	33.2	54.0	19.6	96
Capture capacity, Mtpa	253.7	261.4	333.4	
Annual capture cost, \$Billion	17.05	17.74	26.52	
Existing transport capacity, Mtpa	129	31	9	
Transport unit cost, \$/t**CO_2**	3.2	3.2	3.9	
Annual transport cost, \$Billion	0.4	0.7	2.6	
Storage capacity, Mtpa	660	820	80	
Storage unit cost, \$/t**CO_2**	7.3	5	12	
Annual storage cost, \$Billion	1.85	1.31	6.82	
CCS capacity, Mtpa	**253.7**	**261.4**	**333.4**	
Annual CCS cost, \$Billion	**19.33**	**19.79**	**35.95**	
Levelized CCS cost, \$/tCO_2	**76.19**	**75.73**	**107.84**	
CCS cost with tax credits, \$/tCO_2	**-8.81**	**-9.27**	**22.84**	

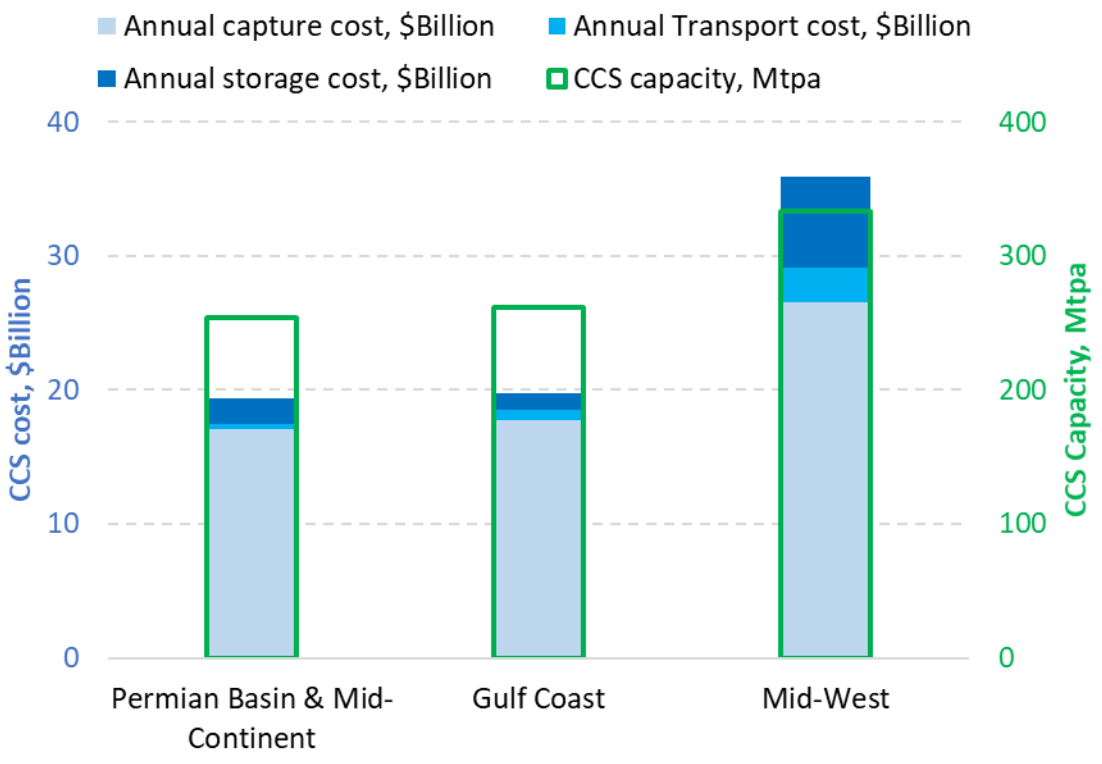


Figure 42 Comparison of CCS capacity and annual cost in three selected regions in the United States

Based on the results, it is clear that the preferred approach for stage development of the CCS system in the United States should start with the Permian & Mid-Continent and Gulf Coast areas, which provide both enough CO_2 sources and storage capacity. Over time, the system can expand to other regions to increase the overall capacity while leveraging the learning curve and reducing costs.

Table 32 also lists the levelized CCS cost with and without tax credits for those three regions. The Permian & Mid-continent and Gulf Coast have similar costs for one ton of CO_2 captured and stored within each region. With tax incentives, the CCS systems in those two regions are even profitable.

6.3 Discussion

The results from the national and regional CCS system modeling indicate the CCS can capture and store large volumes of CO_2 from industrial sources and power plants, which are among the largest emitters of greenhouse gases. With existing government incentives, CCS systems can be cost-neutral or even profitable using current infrastructures. Different from other decarbonization methods that focus solely on reducing emissions, CCS directly addresses the problem by preventing CO_2 from entering the atmosphere, thereby mitigating the impact of existing industrial activities while maintaining energy security and economic stability.

CCS can be applied to a wide range of industries beyond the energy sector, including cement, steel, and chemical production. These industries are challenging to decarbonize using traditional methods like electrification or fuel switching due to their reliance on high-temperature processes. Applying CCS to those industrial emitters can significantly reduce their carbon footprint without completely overhauling their operational processes.

CCUS also has a competitive edge when considering the transition timeline and existing infrastructure. While renewable energy sources such as wind and solar are essential for a sustainable future, their integration into the global energy mix requires significant time and investment to build new infrastructure and upgrade the grid. In contrast, CCS can be retrofitted to existing power plants and industrial facilities, providing an immediate solution to reduce emissions. This ability to leverage current infrastructure not only accelerates the decarbonization process but also reduces the overall cost and complexity of the transition. CCS also offers flexibility in technology selection and application targets and can be developed in stages, gradually increasing capacity without significant disruptions to current operations and economic conditions.

Furthermore, the CCS with CO_2 utilization provides economic opportunities by converting captured CO_2 into valuable products, such as fuel, chemicals, and building materials. The current CO_2 application in EOR and urea production are prominent examples that can offset the CCS cost. By creating revenue streams from CO_2 utilization, CCS can enhance its financial viability and attractiveness to investors and policymakers.

However, CCS has its limitations and should be part of a broader strategy that includes renewable energy adoption, energy efficiency improvement, and behavior changes to achieve the energy transition. The effectiveness of CCS in achieving the NetZero Emission goals depends on the scale of deployment, technological advancements, and supportive policies and incentives. Government regulations and financial mechanisms play a critical role in driving CCS adoption, ensuring that it can compete with other low-carbon solutions.

Chapter 7 Conclusion and Recommendation

7.1 Summary and Key Findings

Carbon capture, transport, storage/utilization (CCS) is crucial in the global effort to decarbonize the economy and achieve NetZero emissions by midcentury. With advancements in CCS technologies over the past decades and the urgency of its deployment, a systematic approach is essential for CCS system design and development. It ensures a successful deployment that meets the system requirements and exceeds the needs of stakeholders, including investors, researchers, policymakers, and the public.

In this study, the CCS system is analyzed holistically with its primary components and architecture design decisions. CCS systems compass CO_2 capture, transport, and storage/ utilization. The primary architecture decisions include CO_2 source type and capture technology, transport approach, CO_2 flow rate, storage and utilization pathways, and deployment environment. Each architecture decision offers multiple options based on common practices for the CCS system design. Critical system performance metrics are defined based on stakeholders' needs and system requirements.

Achieving NetZero emissions by midcentury requires CCS systems with high capacity, mature technology, scalability, and low lifecycle costs. Corresponding system requirements are defined using utility functions. Performance parameters are identified from the literature and extensive data from public databases and government reports, including CO_2 emission levels, current capture capacity, future capture targets, transport options, costs, etc. A system approach is applied to gather technically feasible combinations of architecture decision options and generates a total of 2088 design vectors with compatible options. System models are built to evaluate and benchmark different CCS systems for capacity, efficiency, scalability, and cost.

Tradespace analysis reveals that transport type has the highest impact on system utility, with options like pipelines, ships, trucks, and railcars showing significant differences in capacity and scalability. Higher flow rates result in higher utility without necessarily higher costs due to economies of scale. Capture source and technology have a remarkable impact on CCS system costs due to varying CO_2 concentrations in source gases and applicable capture technologies. CO_2 utilization in EOR and urea production provides the most revenue and cost offset. In contrast, CO_2 utilization for synfuel, methane, and chemical production is less viable due to high costs from immature technology and small-scale applications.

CCS systems capturing CO_2 from power plants, ammonia, and chemical production facilities, transported via onshore pipelines, and utilized in EOR or urea production or stored in saline aquifers offer relatively high utility and low cost. With government tax credits, the levelized CCS cost per ton of CO_2 is almost zero. However, as low carbon-intensity fuels and energy sources replace coal-fired power plants, alternative CO_2 sources must be considered for carbon capture, such as chemical, iron & steel, and cement production facilities. CCS clusters with varied source plants and shared pipelines and facilities can reduce unit costs and have been considered for the most recent CCS system development and deployment worldwide.

Sensitivity analysis evaluates CCS system performance with uncertainties in capture and storage capacities and costs. Some CCS concepts may no longer be the best performers under different scenarios. In contrast, others, like direct air capture and bioenergy with CCS, may move to the forefront with technological advances and cost reductions. These technologies can capture CO_2 even as stationary point source emissions decrease with the shift to renewable energy.

National CCS system modeling and evaluation extend to three regional systems. Results indicate that the Gulf Coast and Permian & Midcontinent regions perform better due to existing CO_2 emission facilities, transport and injection infrastructure, and ample storage capacity. Initial CCS development can leverage low costs and existing infrastructure in these areas and expand to other regions over time. This staged development allows for broader CCS deployment and adoption, provides time for technology maturation and cost reduction, and gives investors time to recover costs.

7.2 Future Work

The models in this study have limitations and rely on assumptions that may not be realistic. For example, the models assume a single type of CO_2 capture source, transport method, and storage/utilization option per CCS system. However, future CCS development trends towards clusters with multiple CO_2 sources and storage/utilization locations. More realistic models should include multiple capture and storage options for performance assessment and benchmarking.

Additionally, the cost model uses a constant distance for a given type of CO_2 source and storage location, while actual distances vary. Spatial network models can be built to include specific location information for more reliable transport distance and cost estimates.

In this study, the multi-attribute utility functions are defined to quantitively measure and compare the performance of CCS systems in multiple aspects: capacity, efficiency, scalability, and cost. The utility for CO_2 capture, transport, and storage capacity is measured as the ratio of each option's capacity in the architecture decision over the total capacity, resulting in tiny utility numbers in the tradespace plot. It indicates that a combination of varied CCS systems must be considered and deployed to reach the total capacity of CCS for NetZero emissions. Meanwhile, different utility functions can be defined with other performance metrics to measure system performance in various ways based on the stakeholders' needs.

Optimization can further improve system utility and reduce costs. The current model uses absolute costs per ton of CO_2 captured, transported, and stored from literature without distinguishing between capital and operational costs, which are critical for investment decisions. More detailed CCS models with system decomposition at sublevels can potentially provide more reliable evaluations.

Last but not least, the study provides a preliminary sensitivity analysis of some parameter uncertainty's impacts on the CCS system performance. A comprehensive uncertainty analysis can be conducted to include more system uncertainties and reveal the potential CCS performance and cost ranges.

Climate change is a global issue with varying CO2 emission levels and geological settings among nations, leading to different CCS potentials and design preferences. For example, European countries that rely heavily on renewable energies and have lower carbon emissions from power generation may focus more on direct air capture. In contrast, Asian countries like China and India, among the top emitters due to their power generation and industrial fossil fuel use, have initiated several new capture facilities and set ambitious plans to expand capacity by 2030. Additionally, the Middle East and Australia are investing in CCS technologies to mitigate emissions from their energy-intensive industries. The system approach with engineering models used in this study can be adapted to these regions by adjusting performance metrics to design CCS systems suited to their specific conditions.

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