From Capture to Storage: Understanding the Viability and Challenges of Carbon Capture and Sequestration Initiatives

by

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ABSTRACT

This thesis explores the implementation of Carbon Capture and Sequestration (CCS) technologies, focusing on the stages of capture, transportation, and sequestration. Utilizing a system dynamics model, the research evaluates CCS's effectiveness and economic viability across various scenarios, including those outlined by the International Energy Agency (IEA). The baseline model suggests that even under favorable assumptions, CCS permanently sequesters only a small fraction of total global emissions.

The economic analysis reveals a slight decrease in total costs, attributed to the learning curve, but offset by increasing costs as more complex projects are undertaken. The model also highlights the energy penalty associated with high energy requirements for capture. Additionally, the alignment of capacities across capture, transportation, and sequestration phases is important because discrepancies can lead to inefficiencies and bottlenecks.

This research acknowledges limitations, including the use of aggregated data and assumptions across many parameters. These limitations emphasize the need for further research to refine these estimates and enhance the model's accuracy. Despite these challenges, the model serves as a beneficial tool for testing policy interventions and assessing the potential of CCS as a component of global climate strategy.

Overall, the findings highlight the complexities and challenges of deploying CCS technologies at scale, emphasizing the importance of coordinated policy, technological innovation, and infrastructure development. This research provides a foundation for future studies and policy discussions to better understand CCS's role in achieving climate goals.

Disclosure: The following content is the author's, and responsibility is taken for all content. Noting this, it was generated by the author with the assistance of an AI-based system to augment the effort.

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Chapter 1

Introduction

1.1 Motivation

In 2015, the Paris Agreement established a framework to prevent the harmful effects of climate change. The international agreement requires countries to set targets for reducing greenhouse gas emissions and work towards increasing those targets. The primary goal of the Paris Agreement is to reduce global emissions and is focused on limiting global temperature increases to less than 2°C above pre-industrial levels [1].

Climate change is an increasingly concerning threat to humanity and ecosystems worldwide. Carbon dioxide (CO2) concentration in the atmosphere continues to rise, increasing global temperatures. The increasing temperatures are causing extreme worldwide events, such as sea-level rise, unpredictable weather, and biodiversity loss [2]. To mitigate against these impacts and attempt to meet the targets set out in the Paris Agreement, countries must explore all possible approaches. No one solution "solves" climate change. Some possible approaches include transitioning to renewable energy, focusing on energy efficiency, and investigating technologies to reduce carbon emissions to the atmosphere. Carbon capture and sequestration (CCS) is a potential approach that could contribute to mitigation efforts by reducing emissions from significant industrial sources that are hard to reduce today [3].

CCS is a process by which CO2 is captured from facilities with high emissions, such as power plants or factories, then transported and permanently stored in geological formations or other repositories [3]. Yet, many questions remain about how CCS can help achieve the Paris Agreement's temperature goals. For CCS to successfully support climate change mitigation, it must be deployed globally and capture significant emissions across many facilities. CCS has significant technical, economic, and logistical factors that could constrain how quickly the industry can grow to the scale required to impact rising temperatures [4]. There is a limited supply of CO2 storage formations, making it more complex over time to store CO2. Additionally, transportation bottlenecks may limit the amount transported from high emitters to storage locations. From a cost perspective, CCS initiatives have high capital and operating costs that may make CCS initiatives currently unable to compete with cheaper alternatives [5].

1.2 Research Objectives

To better understand the potential for CCS to reduce emissions in the future, the scalability of CCS initiatives at each stage is key - capture, transport, and sequestration. Increasing understanding includes further exploring the limitations on geological storage reservoirs as cumulative sequestration increases and how transportation bottlenecks impact deployment rates of CCS. As with many new technologies, learning curves, economies of scale, and technological innovation also impact the use of CCS over time [6].

This research explores the key issues around the scalability of CCS by analyzing:

1. Potential of technical bottlenecks constraining capture, transport, and storage capacity ramp-up.
2. Projected cost forecasts and economic competitiveness of CCS as deployment increases.
3. The impact of supply curves for components like CO2 capture systems and geological storage reservoirs.

The above analysis will be modeled with varied parameters to better understand the impacts on the global scalability of CCS. The results can inform policy, investment, and research priorities.

Chapter 2

Literature Review

2.1 Modeling the Future State and Scalability of CCS

Numerous studies examine the current state of CCS and model its future scalability at both local and global levels. These models typically consider factors such as technological advancements, economic feasibility, regulatory frameworks, and environmental impacts. Many of the models projecting the future of CCS are integrated assessment models (IAM). IAMs "quantify key processes in the human and earth systems and their interactions" [7].

For instance, the International Energy Agency's (IEA) World Energy Outlook (2023) includes scenarios that model the deployment of CCS under different policy and investment conditions. The IEA's Announced Pledges Scenario suggests that CCS must capture over 3.5 gigatons of CO2 annually by 2050, while the Net Zero Emissions Scenario requires over 6 gigatons of CO2 annually [8]. Similarly, Stanford developed a model to achieve net zero by 2050 in the United States, and all of their scenarios assume CO2 is captured and stored in geologic formations, with some scenarios as high as 1.7 gigatons per year [9]. This data is only based on US emissions. IAM scenarios have increasingly incorporated negative emissions technologies, including CCS, to achieve net zero pathways [10]. Additionally, Kotagodahetti et al. developed a system dynamics model analyzing the long-term feasibility of CCS in Canada, indicating that CCS could play a critical role in reducing emissions from industrial sectors, especially in regions with substantial fossil fuel dependence [11].

Other models beyond the global IAMs include those by Van der Zwaan and Smekens (2009), which explore the cost-effectiveness and potential deployment pathways for CCS in Europe, and the work by Heuberger et al. (2017) that integrates CCS into energy system models to evaluate its impact on energy costs and emissions reduction [12] [13].

2.2 Arguments for the Large-Scale Growth of CCS

Several studies and reports advocate for the large-scale growth of CCS as a necessary component of global emissions reduction strategies. The Intergovernmental Panel on Climate Change (IPCC), in its latest update to the Report on Mitigation of Climate Change (2022), emphasizes that CCS is essential for limiting global warming to 1.5°C. Among the 97 assessed pathways that aim to keep global warming below 1.5ºC with minimal overshoot, there is a wide range of potential deployment levels for CCS technology. On average, these pathways suggest a median of 665 gigatons of CO2 could be captured and stored cumulatively by 2100 [10]. Similarly, the IEA's Energy Technology Perspectives (2023) outlines the critical role of CCS in achieving sustainable energy transitions, suggesting that without CCS, the cost of meeting climate goals would be significantly higher [14]. The Global CCS Institute, an international think tank that aims to speed up the use of carbon capture and storage, provides annual reports and scenarios that project the growth of CCS capacity worldwide. Their research indicates that with adequate investment and policy support, CCS could scale significantly to meet global climate targets by mid-century [15].

In the United States, the National Petroleum Council (2019) claims that CCS "is essential to meeting the dual challenge of providing affordable, reliable energy while addressing the risks of climate change at the lowest cost" [16]. The report discusses the economic benefits of creating new jobs and developing infrastructure. Furthermore, the European Union implemented policies and funding mechanisms, such as the Innovation Fund, to support CCS development, reflecting the stance that CCS is crucial for achieving climate neutrality by 2050 [17].

Literature by Wei et al. (2021) not only suggests CCS is required to meet a 2-degree climate target but also lays out the optimal matching of emission sources and possible carbon sinks [18]. McLaughlin et al. (2023) also support the large-scale deployment of CCS, suggesting that with appropriate policies, social acceptance and high costs can improve [19].

2.3 Arguments Against Large-Scale Investment in CCS

Despite the potential benefits, some researchers and analysts argue that CCS is too expensive and risky, and resources should focus more on clean energy solutions.

Friends of the Earth International, a network of environmental and social justice activists, criticizes CCS as an expensive and unproven technology that diverts attention and resources from renewable energy development. They argue that investment should focus on wind, solar, and energy efficiency measures instead [20]. Oil Change International, an environmental organization opposing the use of oil, reports that governments have already spent over $20 billion on CCS projects and have committed up to $200 billion more in public funds. Despite this significant investment, most CCS projects have not progressed beyond the initial stages or pilot projects [21].

Stanford University researcher Mark Jacobson has expressed skepticism about the economic viability of CCS, particularly in comparison to the rapidly falling costs of renewable energy sources like solar and wind. He states in his research, "Even if you have 100 percent capture from the capture equipment, it is still worse, from a social cost perspective, than replacing a coal or gas plant with a wind farm because carbon capture never reduces air pollution and always has a capture equipment cost. Wind replacing fossil fuels always reduces air pollution and never has a capture equipment cost" [22]. Similarly, Charles Harvey, a professor at MIT, has been vocal in his criticism of CCS as a primary solution to climate change. Harvey argues that CCS is not a feasible large-scale solution due to its high costs and technical challenges. He advocates for more investment in renewable energy sources and energy efficiency measures, suggesting that these alternatives offer more sustainable and cost-effective pathways for reducing greenhouse gas emissions than CCS [23] [24]. Harvey and Jacobson's perspectives highlight the ongoing debate within the scientific community about the use of CCS for mitigating climate change.

2.4 Pathways to Enhance CCS Scalability and Support Emissions Reduction

For CCS to become more scalable and effectively support global emissions reductions, several key changes are necessary. These include but are not limited to technological advancements, financial incentives, regulatory support, and public acceptance.

Technological advancements are critical for reducing costs and improving the efficiency of CCS processes. Innovations in capture technologies, such as developing more efficient solvents and membranes, can significantly lower energy consumption and operational costs [25] [26]. Additionally, advancements in monitoring and verification technologies are essential for ensuring the long-term safety and effectiveness of CO2 storage sites [27] [28].

Financial incentives are required to offset the high capital and operational costs associated with CCS. Governments can play a significant role by providing subsidies, tax credits, and direct funding for CCS projects. Research from Comello and Reichelstein showcases that a combination of tax incentives that induce early adoption can improve learning rates and result in only a modest increase in electricity when implementing CCS [29]. Stechow et al. compared policy schemes for CCS and concluded that "a CCS bonus incentive or a CO2 price guarantee, perform best in comparison with the other assessed instruments" [30]. Additionally, Yao et al. developed a dynamic model to optimize the effective use of incentive policies in combination with investor funds [31]. The consensus and often criticism in the literature is that government financial incentives are essential to jump-start CCS.

Regulatory frameworks must be strengthened to create a supportive environment for CCS development. Clear and consistent regulations are needed to streamline permitting processes, establish liability frameworks, and ensure environmental protection. The establishment of comprehensive CCS policies in regions like the EU and the US has shown positive impacts on project development and investor confidence [32]. Burton et al. stress the importance of regulations supporting early projects and a longer-term view on monitoring and widespread adoption [33].

Public acceptance and awareness are also vital for the successful deployment of CCS. Addressing public concerns about the safety and environmental impact of CCS through transparent communication and engagement can build trust and support for CCS projects. A study in the Netherlands concluded that public acceptance can be enhanced by involving local communities in the planning process and demonstrating the benefits of CCS for climate mitigation [34]. Another study conducted in Switzerland showed that people put more emphasis on pipelines near their homes and are less concerned when CO2 comes from a biogas-fired plant [35]. Initiatives such as the Barendrecht CCS project have been canceled in the past due to public opposition. A report from the Energy Research Centre of the Netherlands, including interviews with relevant stakeholders, cites shortcomings in communication as a lesson for future CCS projects [36].

In conclusion, the literature on CCS presents a complex picture with diverse perspectives. While some studies and models underscore the necessity and feasibility of scaling up CCS to meet global climate goals, others highlight significant economic and technical challenges. This literature review provides a foundation for understanding the current debates around CCS and will inform the subsequent analysis and modeling of this research.

Chapter 3

CCS Initiatives as a System

CCS initiatives are designed to mitigate climate change by capturing CO2 emissions at their source and securely storing them underground. Viewing CCS as an integrated system highlights the connections between its three main components at a project level: carbon capture, transportation, and sequestration. This systemic approach helps in understanding the complexities involved in implementing CCS on a global scale. This section will cover the components and operations of CCS, exploring its significance, challenges, and current global state.

3.1 Capture, Transport, and Sequestration

CCS involves three main stages: carbon capture, transportation, and sequestration. These stages enable the capture, transfer, and secure storage of CO2 to prevent its release into the atmosphere, as depicted in Figure 3.1.

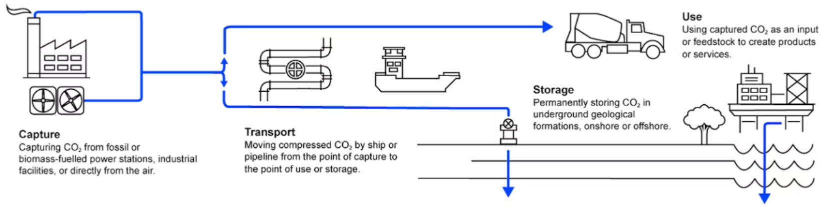


Figure 3.1: *The CCUS Chain published by the IEA [37]*

Carbon capture is the initial step in the CCS process. CO2 emissions are captured at their source before they are released into the atmosphere. High CO2 emitting facilities include large industrial operations such as coal-fired power plants, natural gas processing plants, cement factories, and steel mills. In these facilities, the CO2 is captured and then compressed into a dense fluid for transportation [3].

Carbon capture has the potential to reduce CO2 emissions from major industrial sources. By capturing CO2 at the source, CCS can lower the carbon footprint of industries that are difficult to decarbonize through other means [37]. However, implementing capture technology in a facility poses challenges. The technology required for capturing CO2 is often expensive and energy-intensive. Additionally, retrofitting existing plants with carbon capture technology can be technically complex and costly [38]. It is important to note that even with a carbon capture facility, not all emissions are captured. Carbon capture efficiency can vary significantly depending on the technology and specific facility conditions. Typically, projects claim capture rates ranging from 80% to 90%, but actual performance can be much lower [39]. The Boundary Dam project in Canada aimed to capture 90%, but the project's long-term capture rate as of 2023 was 57% [40]. Similarly, Gorgon Gas Processing facility in Australia has a running capture rate of 45% [41].

Globally, countries are investing in carbon capture technology as part of their strategy to meet climate goals. Examples of operational CCS facilities include Norway's Sleipner project and Canada's Boundary Dam project, which have successfully captured and stored millions of tonnes of CO2 [3][40].

Once captured, the CO2 must be transported to a suitable storage site. The most common method of transporting CO2 is via pipelines, although it can also be transported by ship, rail, or truck if pipelines are unavailable [3]. CO2 pipelines are similar to natural gas pipelines but require specific materials and safety measures to handle the high-pressure, dense phase of CO2 [15].

The transportation of CO2 connects the point of capture with the storage site. Building and maintaining a CO2 transportation network poses several challenges. Pipeline infrastructure requires significant capital investment and must navigate regulatory approvals, land acquisition issues, and potential public opposition. Furthermore, the safety of CO2 transportation is key, as leaks can pose environmental and health risks [42].

The development of CO2 transportation infrastructure varies in different parts of the world. In regions with existing oil and gas infrastructure, such as North America and Europe, integrating CO2 pipelines is more feasible. For instance, the United States has an extensive network of CO2 pipelines primarily used for enhanced oil recovery (EOR), which can be expanded for CCS purposes [43]. In emerging economies such as China and regions of Africa, CO2 transportation infrastructure faces additional challenges due to high costs, regulatory frameworks, and human resource capabilities [44] [45].

The final step in the CCS process is carbon sequestration, where the captured CO2 is injected into deep geological formations for long-term storage. Suitable storage sites include depleted oil and gas fields, deep saline aquifers, and unmineable coal seams [14]. The CO2 is injected into these formations at high pressure, where it becomes trapped by impermeable rock layers, effectively isolating it from the atmosphere [3]. In some cases, the captured CO2 is used in EOR, a process in which CO2 is pumped into existing oil fields to increase the oil recovery rate. Adding CO2 increases the pressure of an oil reservoir, resulting in increased oil being sent towards production wells. In EOR, "some portion of the injected CO2 remains below the ground. If the CO2 that returns to the surface is separated and reinjected to form a closed loop, this results in permanent CO2 storage" [46]. According to industry estimates, in well-managed EOR operations, about 30% to 40% of the injected CO2 is permanently sequestered in the reservoir, while the remaining is typically produced along with the oil, of which 60% to 90% is then recaptured and reinjected [47]. In the Permian Basin, Occidental Petroleum utilizes circular CO2 systems facilitated by its extensive CO2 processing infrastructure, which includes recovery plants and a network of pipelines designed to handle the CO2 throughout its lifecycle [48] [49]. Such closed-loop systems require additional capital investment to purchase compression equipment, pipeline infrastructure, and monitoring equipment, raising the cost per tCO2 sequestered [50] [51]. And the additional oil produced by CO2-based EOR generates CO2 emissions when used, reducing the net sequestration rate [46].

Sequestration also presents challenges, such as identifying suitable storage sites to ensure the formations can securely contain CO2. Additionally, the long-term monitoring of storage sites is essential to detect and address any potential leaks[4].

3.2 Current State of Projects Globally

The global landscape of Carbon Capture and Sequestration projects shows significant potential for reducing greenhouse gas emissions but also presents several challenges. According to the IEA, the current capacity for CO2 capture worldwide stands at approximately 50 million tonnes per year (Mt CO2/year), while the capacity for CO2 storage is around 19.2 Mt CO2/year. These capacities include full-chain CCS projects, capture projects, and utilization projects for capture, and full-chain, transport and storage, and storage projects for sequestration [52]. The data from the IEA was summarized from their database based on its definitions and a project status of operational.

A primary constraint to the growth of CCS is the technical difficulty of implementation. Retrofitting existing industrial plants with capture technology is complex and often requires significant engineering changes. Economic factors also play a role; the high operational and capital costs of CCS projects reduce adoption [53]. Although some regions offer financial incentives, these may be insufficient to encourage widespread adoption.

Despite these challenges, several countries have made progress in implementing CCS. Norway's Sleipner project has been operational since 1996, successfully storing CO2 in a deep saline aquifer and serving as a model for other initiatives worldwide[3]. In Canada, the Boundary Dam project captures CO2 from a coal-fired power plant [40]. The United States has an extensive network of CO2 pipelines primarily used for EOR, providing a foundation for expanding CCS infrastructure [15]. The Petra Nova project is one of the largest carbon capture facilities on a coal-fired power plant in the world and can reportedly capture approximately 1.4 million tonnes per year [54]. Many existing projects are used for EOR today but can lead towards projects for more permanent sequestration in the future.

In developing and emerging economies, the progress of CCS projects is often slower and faces more obstacles. China has initiated several pilot and demonstration projects to capture CO2 from industrial sources. However, scaling these projects to full operational capacity remains challenging due to high costs and technical barriers[55] [56] [57].

3.3 Global Incentives

Revenue generation or cost avoidance is a key factor in deciding on CCS projects. Incentives play a determining role in advancing CCS projects by offsetting the costs and risks of developing and deploying these technologies. Various countries have implemented a range of incentives to promote CCS, including tax credits, direct investments, and policy frameworks designed to encourage private sector involvement. These incentives are not always in the form of $ per tonne of CO2 but can be estimated for cost comparison purposes. While not an incentive for CCS alone, a carbon tax is an economic mechanism encouraging facilities to reduce their carbon emissions. By imposing a financial cost on each tonne of CO2 emitted, a carbon tax motivates companies to adopt cleaner technologies and reduce their carbon footprint. In the context of CCS, a carbon tax can make carbon capture more economically attractive as it can offset the costs of implementing CCS technologies. This section provides an overview of global incentives for CCS, examining recent changes and their impact on project development.

3.3.1 United States

The United States has made progress in promoting CCS through legislative measures such as the Inflation Reduction Act (IRA). The IRA includes several provisions that enhance incentives for Carbon Capture, Utilization, and Storage (CCUS)[58]. One of the key components is the enhancement of the 45Q tax credit, which provides financial incentives, up to $85 per tonne of CO2, for capturing and storing CO2. Recent amendments increased the credit amount and extended the eligibility period, making it more attractive for investors and project developers [59]. According to Jeremy DuMuth, managing director for federal tax services at the Deloitte accounting firm (as cited by S&P Global), only 12 of 26 US CCS projects he knew about "made economic sense," but after the IRA, they all could be financed. [60]. Additionally, the Department of Energy has allocated substantial funding for CCS research and development, further supporting the sector's growth [59].

3.3.2 European Union

The European Union (EU) has also been proactive in supporting CCS through a combination of funding programs and regulatory frameworks. The EU's Innovation Fund, financed by revenues from the Emissions Trading System, provides significant financial support for large-scale CCS projects. The fund aims to support innovative technologies that can contribute to the EU's goal of achieving net zero by 2050 [17].

Several member states within the EU have introduced their own national incentives. For example, the Netherlands has the SDE++ (Stimulation of Sustainable Energy Production and Climate Transition) scheme, which provides financial support for CCS projects by covering the difference between the cost of CO2 capture and the carbon market price[61]. The United Kingdom has committed to developing CCS clusters with government-backed funding and support for infrastructure development[62].

3.3.3 Norway

The Norwegian government has supported CCS through substantial public funding and policy initiatives. The government's recent Longship project represents a significant investment in CCS infrastructure, providing financial support for the development of new capture facilities and the establishment of the Northern Lights CO2 transport and storage network. The project is "Europe's first complete value chain for the capture, transport, and storage of industrial CO2 emissions"[63]. Norway's approach combines direct investment with regulatory support to drive CCS development.

3.3.4 China

China, as the world's largest emitter of CO2, has recognized the importance of CCS in its climate strategy. The Chinese government has included CCS in its national climate plans and has started providing financial incentives and policy support to encourage the development of CCS projects. These incentives include grants for research and development, subsidies for pilot projects, and support for infrastructure development [64].

Recent changes in global incentives for CCS suggest a growing recognition of the importance of this technology in achieving climate goals. Many countries have introduced new incentives and enhanced existing ones to make CCS more financially viable. These changes include increasing tax credit amounts, extending eligibility periods, providing direct funding for research and development, and creating supportive regulatory frameworks.

3.4 CCS Costs

CCS initiatives face both high capital and operating costs and require a significant amount of energy at each stage. These costs can vary significantly depending on the project's location, complexity, and specific industry. The economic feasibility of CCS initiatives is determined by understanding these cost components.

3.4.1 Capital Costs

Capital costs are the upfront investments required to build the infrastructure necessary for each stage of CCS. Capital costs are often higher on a per tonne basis for capture initiatives due to the complex technology needed to separate CO2 from industrial emissions and then compress the CO2 [65]. For instance, the Petra Nova project in the United States had an estimated capital cost of $1 billion for capturing 1.4 million tonnes of CO2 annually, translating to about $30 per tonne of CO2 captured per year over the expected life of the project [66] [67]. Capital costs can also be high for transportation and sequestration projects. These projects may face increased costs due to delays in approvals or public opposition [30]. For example, the Alberta Carbon Trunk Line in Canada, which captures and transports CO2, had a capital cost of approximately $1.2 billion, or about $75 per tonne of CO2 transported ($2 per tonne over the expected lifetime of the asset) [68].

3.4.2 Operating Costs

Operating costs include labor, maintenance, and utilities. For the capture phase, operating costs typically range from $20 to $30 per tonne of CO2. For example, the Boundary Dam project in Canada incurs annual operating costs within this range based on annual operating costs and the amount of CO2 captured [40] [69]. Transport and storage costs are generally lower but can range from $4 to $45 per tonne of CO2, covering maintenance and monitoring. Many IAMs assume a combined cost for CO2 transport and storage that is uniform in all regions at a lower $10/tCO2 [70].

3.4.3 Energy Cost and Associated Energy Penalty

Energy costs are a significant component of the overall costs of CCS, especially for the capture phase. The energy required for capturing CO2 imposes an "energy penalty," as plants must increase their gross primary energy use or reduce energy output to cover this additional energy demand. Energy costs for capture technology are substantial and can increase the total energy consumption of a power plant by 20-30 percent, effectively reducing the plant's overall efficiency [65]. There is limited data on energy costs for transport and sequestration, but it is estimated to be much lower with minimal impact on total CCS cost [71].
Integrating CCS technology into existing facilities can significantly impact the overall cost structure. In power plants, for example, integrating capture technology requires substantial modifications and additional energy input, affecting both capital and operating costs [72]. Applying CCS to a range of industries increases the complexity and specific requirements of each facility and can lead to wide variations in cost estimates, as seen in US cost data in Figure 3.2. These cost dynamics are important when evaluating the economic feasibility of CCS initiatives.

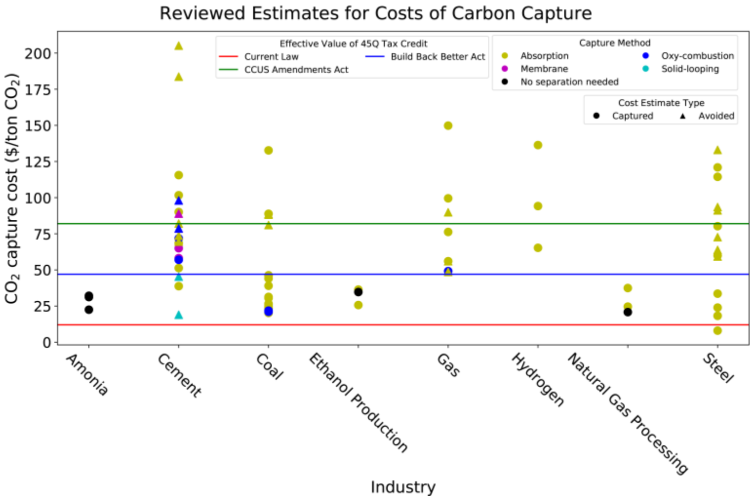


Figure 3.2: Representation of historical cost ranges by different industries. Cited with approval [72].

3.5 Suitable Facilities for Carbon Capture

This section explores facilities with significant CO2 emissions, highlighting their potential for carbon capture. Globally, total CO2 emissions from energy are composed of both non-point and point sources equal to approximately 37.4 gigaton per year in 2023 [8]. Non-point sources, such as transportation and agriculture, come from many different sources and are generally not feasible for CCS technologies. In contrast, point sources, like industrial facilities and power plants, provide concentrated emissions that can be targeted for capture. Of the stationary sources, only a subset is large enough today to justify the installation of carbon capture facilities. This analysis focuses on these significant emitters. Emissions from facilities documented in the 2022 EDGAR database were used to identify the facilities that could benefit from CCS. The database provides global emissions data at precise locations based on industry classifications [73].

3.5.1 Selection Criteria and Data Characteristics

A threshold of facilities emitting more than 1 million tonnes of CO2 per year was applied to identify substantial point source emissions facilities suitable for CCS. This criterion ensures that the facilities have enough emissions to make them suitable for CCS deployment. The dataset includes the following key attributes for each facility: location (global latitude and longitude coordinates), industry classification, and total CO2 emissions per year (in million tonnes). The industries selected for this research are in Table 3.1 with their associated emissions percentages illustrated in Figure 3.3.

Industry	**Examples**
Power Industry	Coal and Natural Gas Power Plants
Non-ferrous Metals Production	Aluminum and Copper Production
Iron and Steel Production	Iron and Steel Manufacturing
Chemical Processes	Various Chemical Manufacturing
Oil Refineries and Transformation Industry	Crude Oil Processing
Non-metallic Minerals Production	Cement and Lime Production

Table 3.1: EDGAR Database Industries [74]

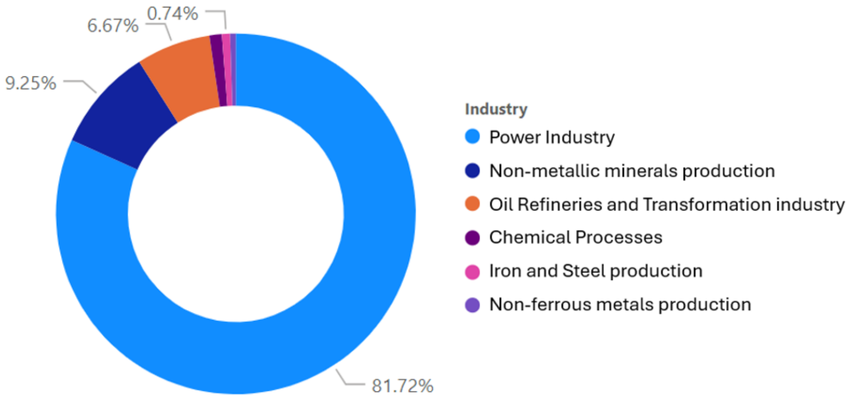


Figure 3.3: Industry breakdown by emissions [74]

The selected facilities, as illustrated in Figure 3.4, provide a list of sites where CCS technology could be integrated into existing infrastructure. Total emissions from these facilities in 2022 was 16.25 gigatons. By focusing on industries with significant CO2 emissions and selecting facilities that emit more than 1 Mt CO2/year, this analysis highlights potential sites for CCS deployment.

Figure 3.4: Map of Emission sources included in Research [74]

3.6 CCS Risks

Implementing CCS presents several risks that must be managed and understood to ensure the safety and effectiveness of the projects. These risks include but are not limited to public opposition, environmental concerns, and policy uncertainties. To support CCS scalability, it is important to leverage examples from CCS and similar industries to better understand these risks.

3.6.1 Public Opposition

Public opposition is a significant risk factor for CCS projects. Communities near proposed CCS sites may have concerns about the safety, environmental impact, and overall necessity of such projects. Public opposition can delay or halt CCS initiatives, as seen with other large infrastructure projects.

For instance, opposition to pipeline projects, such as the Keystone XL pipeline in the United States, highlights the challenges of gaining public acceptance. Concerns about potential leaks, land use, and long-term environmental impacts led to widespread protests and legal battles, ultimately contributing to the project's cancellation [75]. Similarly, CCS projects may face resistance due to fears of CO2 leakage, perceived environmental risks, and lack of trust in regulatory bodies.

In the Netherlands, the Barendrecht CCS project was canceled due to strong local opposition. Residents feared potential CO2 leaks and questioned the project's necessity, leading to significant delays and eventual abandonment [30].

3.6.2 Environmental Risks

Environmental risks associated with CCS include potential CO2 leaks, groundwater contamination, and induced seismicity. These risks are not specific to CCS and share similarities with other industrial activities, such as fracking and underground gas storage.

One primary environmental concern is the potential for CO2 leakage from storage sites. Although monitoring and verification technologies are designed to detect and address leaks, the possibility remains a significant risk. Lessons can be drawn from incidents in underground gas storage. For example, the Aliso Canyon gas leak in California in 2015 resulted in the release of a substantial amount of methane, a potent greenhouse gas, highlighting the potential for underground storage failures [76] [77]. This not only creates a concern for the local residents but also negates the environmental impact of sequestering the CO2 in the first place.

Groundwater contamination is another concern, similar to issues observed in fracking operations. Fracking has been linked to water contamination due to the chemicals used in the process seeping into aquifers [78]. Although CCS does not involve injecting chemicals, the movement of CO2 underground could potentially mobilize contaminants.

Induced seismicity, or human-induced earthquakes, is a risk associated with injecting large volumes of CO2 into geological formations. This risk has been observed in geothermal energy projects and wastewater injection from oil and gas operations [79]. The possibility of induced seismicity in CCS projects requires careful site selection, monitoring, and risk management strategies.

The concept of delayed harm is particularly relevant in the context of CCS. The long-term impacts of storing CO2 underground may not become apparent until many years after injection begins. This delayed harm can result in acute side effects that are only realized once more CCS initiatives are deployed and more data becomes available. Historical examples from other industries, such as the delayed recognition of health risks from asbestos exposure, underscore the importance of long-term monitoring in CCS projects [80].

3.6.3 Policy Risks

Policy risks involve uncertainties in regulatory frameworks, inconsistent policies, and the potential for changes in government priorities. These risks can create an unstable environment for CCS investment and development.

Regulatory and policy issues further complicate the deployment of CCS projects. In many regions, regulatory frameworks are inconsistent and lack robust policies to support CCS [11]. This regulatory uncertainty can delay project approvals and implementation and increase costs. For example, the varying regulations across states in the U.S. can complicate the permitting process for CO2 pipelines, as different states may have different requirements and approval processes[81] [82]. This inconsistency can hinder the development of a cohesive CCS infrastructure.

Unpredictable changes in government priorities and policies also pose a significant risk. Political shifts can result in the withdrawal of financial support, changes in regulatory requirements, or even the reversal of previously supportive policies. The shift in U.S. federal policies on climate change and energy under different administrations exemplifies how political changes can impact the stability and predictability of CCS project development [83].

Chapter 4

Methodology

4.1 System Dynamics Modeling

System dynamics is a methodology for studying and managing complex feedback systems. It was initially developed in the 1950s by Jay Forrester at MIT to help corporate managers improve their understanding of industrial processes that involved long delays and feedback loops [84]. System dynamics modeling has been applied to various issues, from epidemiology to climate change to business strategy.

System dynamics involves developing computer simulations of problems or systems by depicting the key interrelationships, feedback loops, stocks, and flows within the system[85]. Understanding the nonlinear effects enables a more comprehensive system-level perspective than traditional methods.

The model developed for this research aims to simulate the life cycle of global CCS projects, including the dynamics from initiation to completion (fully documented and link to model can be found in A). The model was developed using an academic license of Vensim® PLE Version 10.1.3, a systems dynamics software by Ventana Systems, Inc. The model highlights projects in capture, transportation (pipeline), and sequestration and their impacts on possible CO2 reduction. Viewing carbon capture from the perspective of the projects and their associated carbon reduction gives insights into the policy levers and key project decisions. This phased approach allows the model to account for various delays and factors that influence the progression of projects through these stages [85]. The model is replicated for each stage and includes a section for projects with capacity limitations, costs with learning curves, and CO2 movement. Additionally, the model contains a revenue-to-cost evaluation, including the supply curve determining the marginal cost of CCS as the industry grows, and emission scenarios for testing the model.

4.1.1 Projects

The model begins with the *Capacity in Development* stock, representing projects that have been proposed but not yet started. The *Capacity Development Starting* rate feeds into this stock and is determined by comparing projected costs and expected benefits. This rate captures the decision-making process determining whether new projects are started based on economic considerations (more details in the cost evaluation section).

Projects move from the *Capacity in Development* stock to the *Capacity in Construction* stock at the *Capacity Construction Starting Rate*. This rate is a function of available resources, regulatory approvals, and other related factors.

Projects under construction progress to the completed *Capacity* stock at the *Capacity Completing Rate*. This rate is constrained by the *Construction Capacity* stock, representing the maximum number of projects that can be completed within a given time. The construction capacity factor incorporates the availability of required labor, equipment, and other resources.

The phased approach to project management captures the inherent delays within large-scale CCS projects [85]. Delays, including technical difficulties, regulatory and permitting processes, funding constraints, and stakeholder engagement, can arise. The system dynamics model represents the project lifecycle by modeling these phases and their associated rates [86].

4.1.2 Capacity Limitation and Development

For CCS initiatives and similar capital-intensive projects, construction capacity can determine how many projects can move from the construction phase to completion [87]. Construction capacity incorporates supply chain logistics, availability of trained human resources, and necessary materials and parts for carbon capture, transportation, and sequestration projects.

Construction Capacity represents the current resources and infrastructure available to support ongoing and new projects. The flow into and out of this stock is influenced by the desired capacity, which is determined by the backlog of projects in the pipeline.

1. *Desired Capacity* is calculated based on the number of projects in the queue waiting to be completed over the normal time it takes to complete a construction project. When there is a significant backlog of projects, the desired capacity increases, signaling the need to expand construction capacity to meet demand. Alternatively, if the number of pending projects decreases, the desired capacity reduces, indicating that a lower construction capacity might be acceptable [85].

2. *Time to Change Capacity*: Changes in construction capacity cannot occur instantaneously. There is an adjustment time, representing the delay in scaling up or scaling down the capacity. This delay accounts for the time required to make these changes, reflecting real-world constraints in ramping up large-scale infrastructure projects [85].

3. *Utilization of Construction Capacity*: The model incorporates a table function to illustrate how construction capacity will be utilized. Construction managers prefer to reduce utilization gradually rather than taking more extreme approaches when production needs are below capacity, maintaining higher utilization than standard. If no orders are in the backlog, activity stops, and no inventory accumulates. Utilization can exceed capacity when high production demands, but this increase slows and maxes out at 125% of normal capacity [85, Figure 15-4].

The completion of capacity is limited by the construction capacity bottleneck. As a limitation, the model does not reflect price changes due to this phenomenon and only incurs a penalty on time.

4.1.3 Learning Curve

The model incorporates a learning curve effect to capture the impact of accumulated experience on the costs. The learning effect is a critical component, reflecting how cumulative experience in CCS operations can reduce capital costs, operation and maintenance (O&M) costs, and energy requirements over time [88]. This section provides a detailed explanation of how the learning effect is modeled and its expected outcomes.

The learning curve effect is modeled by comparing the cumulative experience in CCS to the initial experience level. As more CCS facilities are developed and operated, the accumulated experience increases, leading to potential improvements in efficiency and cost reductions. The model assumes that these improvements follow a learning curve, where the cost reduction and efficiency improvement rate depend on the strength of the learning effect [85].

The learning curve is quantified by a learning rate, which indicates the percentage reduction in costs or energy requirements for each doubling of cumulative experience [85]. The curve is represented as Equation 4.1.

$$\frac{\ln(1 - \text{"Cost Reduction per Doubling of Experience"})}{\ln(2)} \tag{4.1}$$

Different learning curve strengths are applied to three main areas: capital costs, operation and maintenance costs, and energy requirements. These three make up the components that determine project viability.

1. Capital Costs: The learning effect is expected to reduce the capital costs of CCS projects. As cumulative capacity completion experience grows, project planning, design, and construction efficiencies emerge, leading to lower initial investment costs for new projects.
2. Operation and Maintenance Costs: Similar to capital costs, O&M costs are anticipated to decline with increased experience. Time spent operating capacity improves operational procedures and maintenance practices, which contribute to reducing the ongoing expenses associated with running CCS facilities.
3. Energy Requirements: Energy consumption for CCS processes is another critical area influenced by the learning curve. As operators gain more experience, advancements in energy efficiency are expected, resulting in lower energy requirements while maintaining a minimum energy level due to the laws of thermodynamics [38].

Due to the limited development of CCS projects globally, the learning rate is not yet known; instead, data from similar processes are used to estimate its impact.

As learning reduces capital costs, O&M costs, and energy requirements, the overall cost efficiency of CCS improves. The model dynamically adjusts these costs based on cumulative experience and the specified learning rates, providing a complete view of how learning influences the economic viability of CCS projects over time.

4.1.4 CO2 Flows

In the model, the flow of CO2 through capture, transport, and sequestration ultimately determines the amount of CO2 prevented from entering the atmosphere. The model determines how much CO2 can be captured, transported, and sequestered, accounting for capacities and limitations at each stage.

CO2 is captured at industrial facilities such as power plants and factories. The amount of CO2 captured depends on the facility's capacity, which is influenced by technology and plant size. Capture operations do not capture 100 percent of emissions, so only 80 to 90 percent on average are captured, and the remaining is released into the atmosphere [39]. Once captured, the CO2 is compressed for transport. Captured CO2 is transported via pipelines or other methods. The model sets a transport capacity limit based on infrastructure capabilities. If CO2 capture exceeds transport capacity, the excess CO2 must be vented due to limited onsite storage. This highlights the need for transportation infrastructure to match capture capacities. Transported CO2 is injected into geological formations for long-term storage. Sequestration capacity depends on the size and suitability of storage sites. The model includes this capacity limit, ensuring only as much CO2 as can be stored is transported.

Leakage can occur during transport and sequestration, reducing the amount of CO2 permanently stored. The model applies a leakage percentage to both stages, accounting for potential losses. The average leakage rate for CO2 pipelines is not easily found but was estimated from PHMSA pipeline incident data over 12 years as 3.1e-5 per km-year [89]. Sequestration leakage has been estimated to range from 0.01% to 0.1% per year [90].

4.1.5 Cost Evaluation

The model compares the possible revenue per tonne of CO2 and the cost of CCS initiatives to evaluate the economic viability of CCS projects. Revenue typically comes from two main sources: EOR and government subsidies.

Government subsidies can vary widely across different regions and countries. The subsidies can take the form of direct financial support, tax credits, or cost avoidance through carbon taxes [91]. Due to the variability and complexity of global subsidies, the model uses a generic range to represent the possibility of subsidies, carbon tax benefits, and EOR revenues. The incentive versus cost analysis in the model determines the Project Initiation Rate by comparing and assuming a log-normal distribution for possible project costs.

The model determines the ratio of desired CCS projects based on the cumulative log-normal distribution comparing Incentives ($/tCO2) and Cost ($/tCO2). The mathematical approximation of the log-normal cumulative distribution was determined using the hyperbolic tangent function. As the cost of projects decreases or the possible incentive increases, more CCS projects will be initiated. This function can be seen in Figure 4.1. For example, if the incentive-to-cost ratio is 0.8, approximately 40 percent of possible CCS projects will be

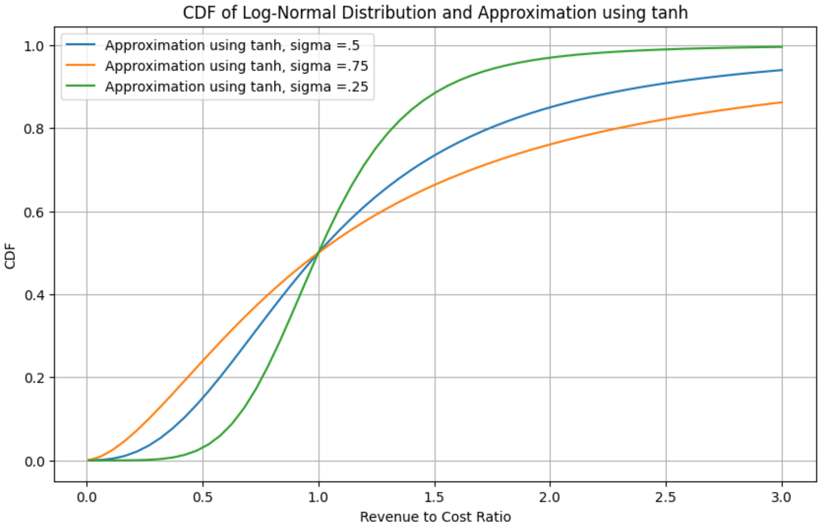


Figure 4.1: *Approximation of LogNormal Cumulative Distribution used to determine the ratio of CCS projects to be initiated.*

initiated. These projects represent the lower-cost initiatives relative to the average revenue. This curve is adjusted using a parameter, sigma, to test the sensitivity of varying the standard deviation of the distribution of project costs, with a baseline of 0.5.

4.1.6 Supply Curve

The model incorporates a supply curve to reflect the increasing costs of CCS projects as more accessible and easier-to-abate sources of CO2 are depleted [38] [92]. Initially, CCS projects are likely to target low-hanging fruit, such as large point sources of emissions that are easier and cheaper. As these projects are completed, the remaining potential projects tend to be more complex and costly [38]. This is due to several factors:

1. Increased Complexity: More challenging projects may involve smaller or lower carbon concentrations, requiring more advanced capture technologies and higher costs [53].
2. Lack of Transportation Infrastructure: Projects with existing pipeline infrastructure will be targeted first, but as additional projects are developed, additional transportation infrastructure may be required [42].
3. Availability and Proximity of Sequestration Sites: Early projects will likely utilize nearby sequestration sites with favorable geological conditions. Suitable sequestration sites may be less convenient with additional projects, increasing the cost and complexity [93].

Creating accurate supply curves for CCS is challenging due to limited global data and conflicting information regarding the costs of each CCS stage. However, by reviewing data from various sources an approximation can be made [92] [94] [95] [96] [97] [98]. Figure 4.2 shows the assumed supply curve for CCS. The vertical axis shows capital costs relative to a

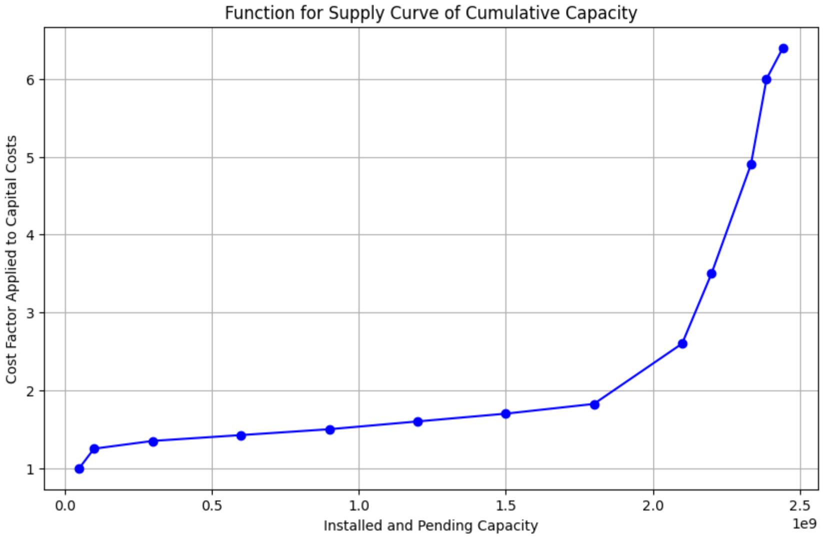


Figure 4.2: *Supply Curve Approximation*

reference value representing capital costs when total capacity is small. As industry capacity, including installed and pending capacity, increases, the marginal cost of new projects rises. Note that capital costs will also fall with cumulative installations, representing learning as the industry gains more experience. The assumed function shows relatively modest increases in capital cost until total global capacity approaches 2 gigatons per year; at this point, marginal costs increase much more steeply, capturing the idea that the low-cost sites will have been developed, leaving more complex and more expensive opportunities.

Ideally, a detailed evaluation of project costs at all levels across the three stages of CCS would provide more accurate supply curves. For this model, the approximation shows that costs rise with expanded capacity due to the complexities and challenges of scaling CCS technologies. This increasing cost trend must be balanced against potential incentives to determine the feasibility of continuing CCS efforts.

4.1.7 Emissions Scenarios

To test the model for CCS projects, emission scenarios published by the IEA were incorporated. The IEA provides four main emissions scenarios: STEPS, APS, NZE, and SDS. These scenarios, starting from 2022, project different paths for global emissions through 2050, incorporating CCS contributions. The values from each scenario were adjusted by adding back the estimated annual emissions reductions from CCS to avoid double counting.

1. STEPS (Stated Policies Scenario): This scenario assumes that current policy settings and announced policy intentions will be implemented. It represents a slight increase in emissions over time.

2. APS (Announced Pledges Scenario): This scenario includes all announced climate pledges, even if detailed policies do not yet back them. It shows a moderate decrease in emissions.

3. SDS (Sustainable Development Scenario): This scenario aims to achieve the energy-related Sustainable Development Goals in full, including climate action, universal access to modern energy, and reduced air pollution. It also shows a significant decrease in emissions.
4. NZE (Net Zero Emissions by 2050 Scenario): This ambitious scenario outlines a pathway to achieving net-zero emissions by 2050. It shows a steep decline in emissions.

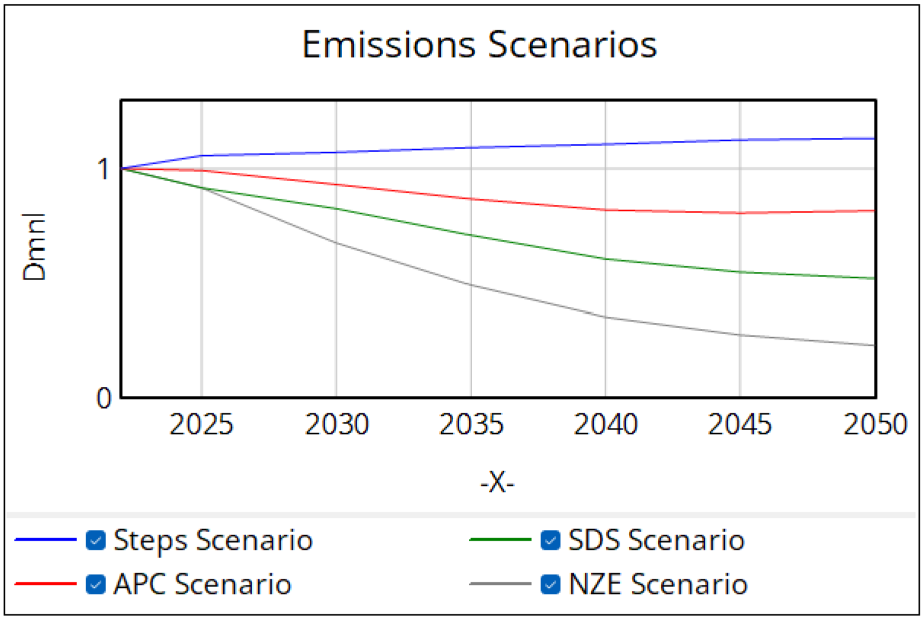


Figure 4.3: IEA Emissions scenarios

After adding back in emissions from CCS, the adjusted emissions scenarios were then turned into factors to be used with the total number of emissions from facilities that could have CCS deployed, as seen in Figure 4.3. This approach, found in Appendix D, provides an estimation but effectively illustrates the deployment and scalability of CCS in different climate scenarios. The model's 2022-2050 time frame aligns with the IEA's projections, supporting the analysis of the role of CCS in achieving global climate goals.

4.2 Parameter Estimates

The model incorporates a variety of parameters that influence the outcomes of capture, transportation, and sequestration projects and capacity. Given the complexity and variations in CCS technologies, many parameters are derived from averages and estimates found in existing literature and then varied through sensitivity analysis. This approach is necessary because precise data for several parameters are either unavailable, reported as ranges in different studies, or calculated considering different factors.

Table 4.1 contains parameters that apply to the CCS system as a whole. These parameters encompass broader factors such as emissions data and economic considerations. Table

Parameter	Amount	Range
Incentive (\$/tCO2) Description: Average revenue generated from either EOR and/or government incentive. Sources: [59][61] [64] [99] [14] [4]	50	0-100
Price of Energy (\$/GJ) Description: Average cost of energy based on current market Sources: [100] [101]	15	10-100
Initial Emissions from Facilities (tCO2/Year) Description: Total 2022 annual emissions from existing facilities with emissions over 1MtCO2/Year. Industries include chemical processes, iron and steel production, non-ferrous metals production, non-metalic minerals production, oil refineries and transformation industry, power industry. Sources: [74]	1.625e+10	1.2-1.8e+10
Leakage from Transport Capacity Description: Estimated rate of leakage from pipelines due to equipment failures. Sources: [102] [90]	0.001	0.0001-0.01
Sequestration Leakage Rate Description: Rate of leakage once CO2 has been permanently sequestered underground. Sources: [90] [103] [104] [12]	0.01	0.001-0.1

Table 4.1: Additional Model Parameters

4.2 presents parameters specific to the three main phases of CCS: capture, transportation, and sequestration. These parameters include costs, efficiency rates, and operational factors critical to each phase. In both tables, the sources and descriptions of these parameters are included to provide context and support for the values chosen. These values have been set as the base case for model evaluation.

The ranges presented in both tables are important since there is significant variability in the available data. Sensitivity analysis is important due to the inherent uncertainties in the data. By varying the parameters within their respective ranges, the model can assess the robustness of the results and identify which variables most influence the performance and feasibility of CCS projects (As discussed in the Results section).

Parameter	Capture	Range	Transportation	Range	Sequestration	Range
Initial Unit Capital Cost ($/tCO2) Description: Initial/current capital cost per tCO2 in USD over the expected life of the facility. Sources: [69] [65] [105] [70][72][106] [107] [108]	30	15-100	3	1-10	10	5-30
Initial Unit O&M Cost ($/tCO2) Description: Initial/current operating and maintenance cost per tCO2 in USD. Sources: [69] [65] [105] [70][72][106] [107] [108]	20	10-40	5	1-10	15	5-40
Initial Unit Energy Required (GJ/tCO2) Description: Initial energy required to process 1 tonne of CO2. Sources:[109][71] [110] [107]	2.5	1-10	0.2	0.05-0.4	0.1	0.01-0.3
Capital Reduction per Doubling of Experience Description: Fractional reduction in capital cost per doubling of cumulative capacity completion experience. Sources: [111] [112]	0.08	0-0.2	0.01	0-0.05	0.03	0-0.1
O&M Cost Reduction per Doubling of Experience Description: Fractional reduction in O&M cost per doubling of cumulative capacity operating experience. [111] [112]	0.08	0-0.2	0.01	0-0.05	0.05	0-0.1
Energy Reduction per Doubling of Experience Description: Fractional reduction in energy requirement per doubling of cumulative capacity operating experience. Sources: [111] [112]	0.05	0-0.2	.005	0-0.02	0.02	0-0.15
Capacity Adjustment Time (Years) Description: The amount of time on average it takes for a project to move into the planning stage from desired. Sources: [113] [114] [115] [116] [117] [118] [53]	2	1-5	2	1-5	2	1-5
Project Initiation Cycle Time (Years) Description: The amount of time on average it takes for a project to move into the construction stage from capacity in development. Sources: [113] [114] [115] [116] [117] [118] [53]	4	2-10	6	3-12	4	2-10
Normal Project Construction Time (Years) Description: The amount of time on average it takes for a project to complete construction and based on available utilization, progress projects to available capacity. Sources: [113] [114] [115] [116] [117] [118] [53]	3	2-10	3	2-10	3	2-10

Table 4.2: Model Parameters for Capture, Transportation, and Sequestration

Chapter 5

Results

5.1 Model Simulation

The model was run with the baseline parameters as detailed in Table 4.1, Table 4.2, and Appendix C. The baseline model analysis across the IEA scenarios demonstrates that even with projected advancements, the amount of CO2 captured remains a small fraction of total emissions from facilities capable of implementing CCs; these facilities represent only a portion of global emissions.

5.1.1 Injection Amounts and Emissions Coverage

Under the baseline model, the highest projected CO2 injection by 2050 occurs in the STEPS scenario, which forecasts the highest emissions. The model estimates a net injection amount (injection minus leakage) of approximately 1.3 gigatons of CO2 annually in 2050. All four IEA scenarios can be seen in Figure 5.1. This volume represents substantially less than the emissions from facilities that could feasibly implement CCS, highlighting the limited impact. Figure 5.2 illustrates the difference between facility emissions and injection/leakage amounts. This SDS scenario has much lower expected emissions compared to Steps and APC while still only injecting less than 15% of facility emissions by 2050. Furthermore, an estimated 5-10% of the injected CO2 is expected to leak over the same period. This leakage reduces the net effectiveness of CCS in mitigating emissions.

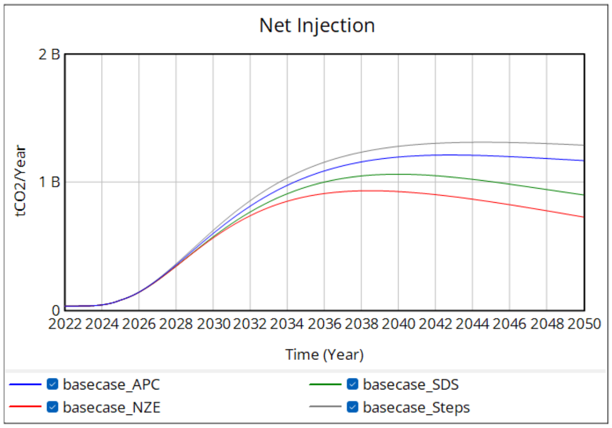


Figure 5.1: Net Injection for IEA Scenarios (baseline)

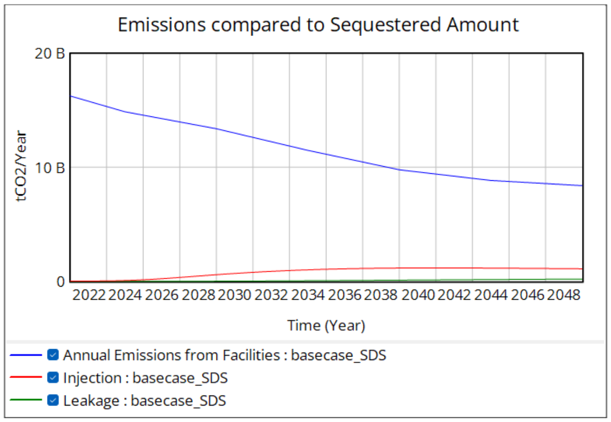


Figure 5.2: Expected emissions from facilities eligible for CCS compared to injection and leakage amounts (SDS scenario).

5.1.2 Economic Considerations and Cost Dynamics

The economic analysis within the baseline model reveals important cost trends associated with CCS deployment. The marginal cost of capturing and sequestering CO2 shows a modest decrease, dropping from approximately $140 per tonne of CO2 to a range between $110 and $138, depending on the scenario (Figure 5.3). CRU Group, a business intelligence company, shared in 2023 that a carbon price of $200 would be required to meet the "full costs of CCS," including "the initial investment, financing, energy use" [109]. The Global CCS Institute illustrates prices ranging from $60 to $130 per tonne of CO2, reflecting a more optimistic view [106]. The results in Figure 5.3 fall within the industry-published ranges.

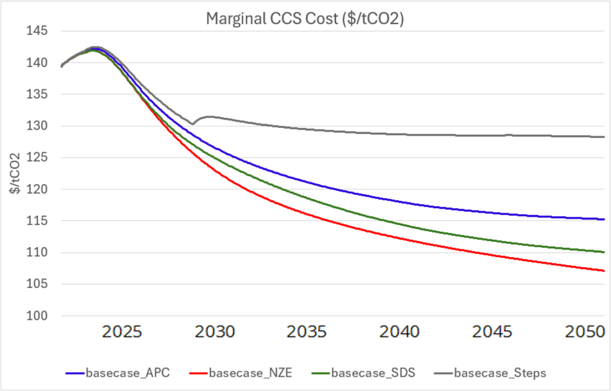


Figure 5.3: Marginal cost per tonne of CO2 through all three stages of projects.

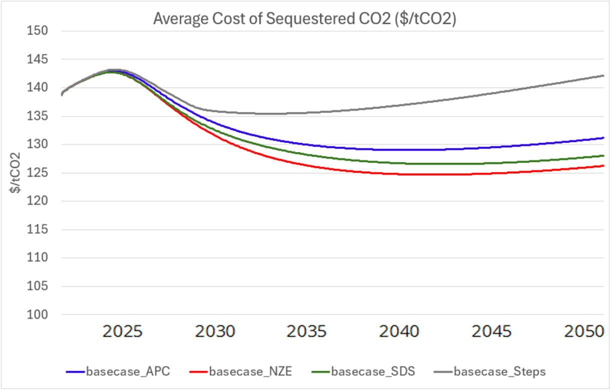


Figure 5.4: Average cost of permanently sequestered CO2.

This decline is driven by the learning curve, which reduces costs as experience with CCS technologies grows. However, this cost reduction is partially offset by the effects of the supply curve, which introduces higher costs as increasingly complex and less accessible facilities are targeted for CCS. The results for the APC (a middle outcome scenario) in Figure 5.5 illustrate the marginal cost per tonne of CO2 if the model only incorporated a learning curve versus only incorporating a supply curve plus the overall impact on the marginal cost. When the supply curve effect is applied without incorporating the learning curve, costs tend to rise, reflecting the increased expense of developing more complex and less accessible CCS projects. Conversely, when the learning curve is applied without the influence of the supply curve, costs decrease significantly as efficiencies improve and technology becomes more widespread. In scenarios where both the learning curve and supply curve are considered, the result is a modest overall cost decline, with the learning curve playing the dominant role. If capacity decreases due to the decommissioning of facilities, the impact of the supply curve is reduced. This is because lower-cost facilities, which were previously unavailable, may now be reused for future CCS initiatives, further mitigating potential cost increases.

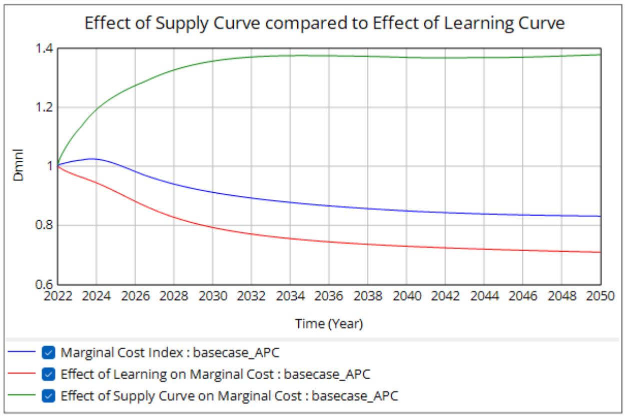


Figure 5.5: Marginal Cost with Learning Curve vs Supply Curve (APC Scenario)

A key aspect of the economic evaluation is the distinction between the marginal capture cost and the average cost of sequestered CO2. The model indicates that while marginal capture costs decrease slightly, the average cost of CO2 that is permanently sequestered exhibits a different trend. Initially, the average cost decreases, reflecting the reduced expenses associated with early CCS projects and the learning curve. However, as the cumulative leakage increases, the average cost for permanently sequestered CO2 rises (Figure 5.4).

The relationship between leakage rates and average costs is significant. If leakage were zero, the average cost curve would mirror the marginal capture cost curve, showing a steady decline. However, with higher leakage rates, the average cost of permanently sequestered CO2 increases. This increase in costs at higher leakage rates highlights the importance of ensuring the long-term security of stored CO2 to maintain the economic viability and effectiveness of CCS projects.

5.1.3 Impact of Supply Curve Shifts

The cost of CCS is uncertain, and published estimates for both current costs and the steepness of the industry supply curve (the rate at which marginal costs rise with growing CCS deployment) vary substantially [92] [94] [95]. To explore the sensitivity of results to these uncertainties, Figures 5.6 and 5.7 show the results of a simulation in which the assumed supply curve is made significantly steeper. The test has two direct impacts: it raises the initial marginal cost per tonne of CO2 for CCS projects, from approximately $140 to nearly $200 per tonne of CO2, and also steepens the supply curve. The higher initial cost reduces the number of projects that are economically viable, reducing total CCS development. The reduction in CCS capacity has a dual impact: it dampens both the supply curve effect and the learning curve effect.

As fewer projects are developed, the costs associated with advancing up the supply curve do not increase as much since more complex and expensive projects are not pursued. Concurrently, the lack of new capacity being built means there are fewer opportunities for cost reductions through increased experience and techno- logical advancements. The steeper supply curve discourages project development, limiting the impact of the steeper supply curve on CCS deployment.

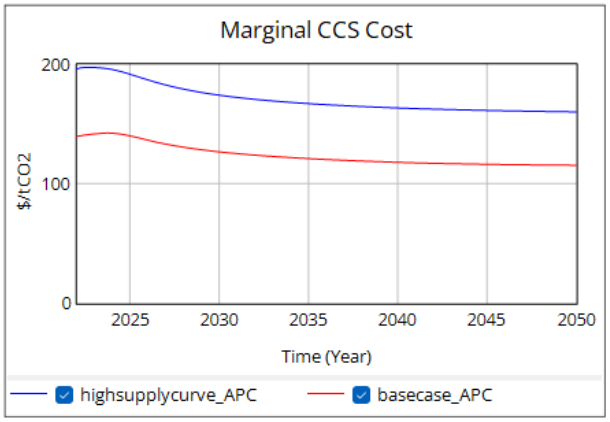


Figure 5.6: Marginal Cost under different supply curves (APC Scenario)

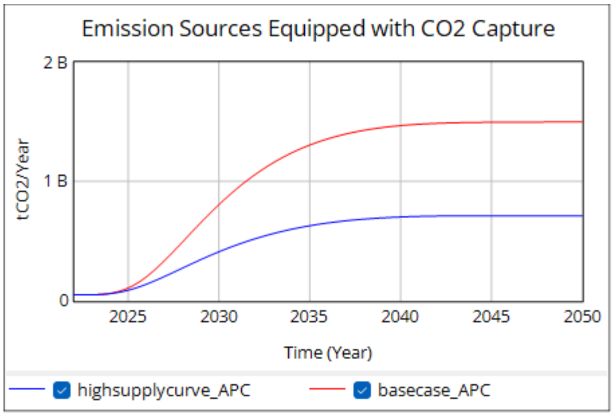


Figure 5.7: Capture Capacity under different supply curves (APC Scenario)

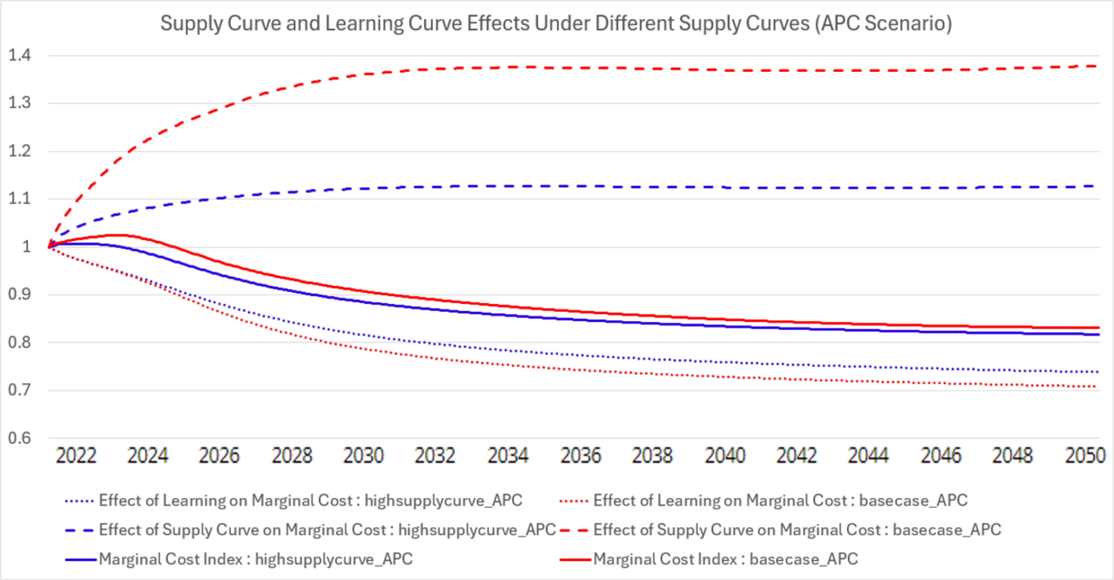


Figure 5.8: Marginal Cost with Learning Curve vs Supply Curve under different supply curves (APC Scenario)

Interestingly, the net effect on overall costs in scenarios with a steeper supply curve is much smaller than might be expected. The reduction in project development mitigates the anticipated cost increases from moving up the supply curve. Figure 5.8 illustrates the difference between the baseline and steeper supply curve scenarios in terms of their impacts on the learning curve, supply curve effect, and overall marginal cost. In both cases, the learning curve remains the dominant factor influencing costs, highlighting its crucial role in determining the economic viability of CCS initiatives

5.1.4 Evaluation of Projections

The IEA's NZE scenario presents a more ambitious outlook, suggesting CO2 capture totals will reach 1.2 gigatons per year by 2030 and 6.2 gigatons per year by 2050 [119]. This projection is over three times higher than the baseline model's estimates. However, the IEA acknowledges that the global CCS market is not currently on track to meet these targets [120]. The baseline model's conservative estimates are partly due to high projected costs and the assumption of only $50 per tonne CO2 in incentives, potentially leading to an overly pessimistic outlook.

While the NZE scenario's projections are optimistic, some reports (including more recent articles from the IEA) argue that these estimates may be overzealous. Critics suggest that the IEA's projections do not fully account for the high costs, technical complexities, and political challenges associated with scaling up CCS [53] [121]. The need for substantial financial incentives and regulatory support is critical for achieving the levels of CO2 capture envisioned in the NZE scenario. The model suggests that, under the current baseline assumptions, the role of CCS in global emissions reduction may be limited without significant policy interventions and technological advancements.

5.1.5 Energy Penalty

Carbon capture is a highly energy-intensive process, often requiring significant amounts of energy that affect the efficiency and output of the existing emissions source. In many cases, the energy required for carbon capture is sourced from the plant itself, resulting in either increased fuel consumption or a reduction in power generation efficiency [65]. This energy penalty can reduce the net energy output of a plant and increase total emissions, as additional energy production leads to more CO2 emissions.

The model includes this higher energy use and assumes that emissions from this increased energy consumption can also be captured at the same capture rate. The model's output shows the total emissions compared to emissions with CCS and the ratio of captured versus released CO2, as depicted in Figure 5.9. This analysis compares scenarios for the years 2030 and 2050 under both the STEPS and NZE scenarios, representing the range from high to low possible emissions outcomes. The results indicate that a substantial percentage of emissions are still released despite CCS, and the overall emissions generated are higher due to the additional energy consumption for the capture process.

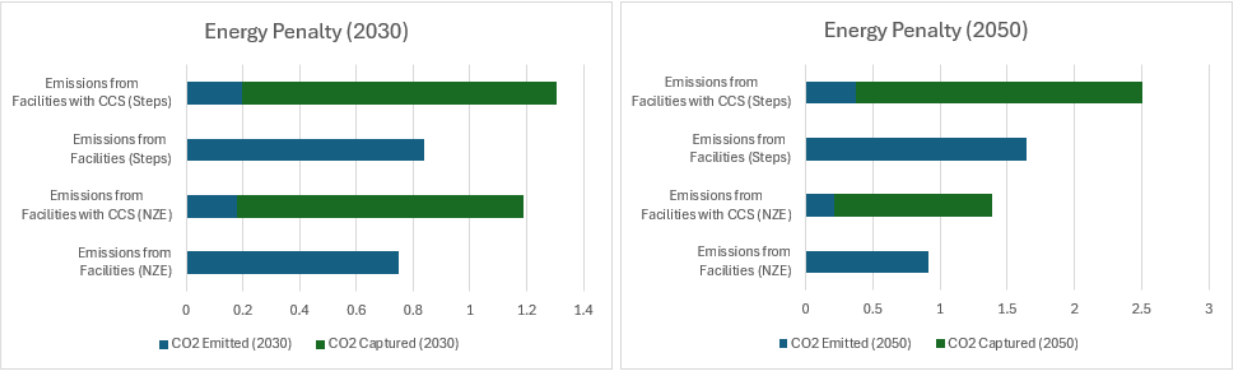


Figure 5.9: Energy Penalty for 2030 and 2050 (Steps and NZE Scenarios).

5.1.6 Dynamics of the Entire Chain

Effective CCS implementation requires aligning the capacities for capture, transportation, and sequestration. The model assumes the desired capacities for all three stages should match the expected amount of CO2 to be captured, including emissions from the energy required for the capture process. However, the model parameters also show that the capacity to build pipelines for CO2 transport takes longer to develop than the capture infrastructure. This leads to scenarios with excess capture capacity without sufficient transportation infrastructure to deliver CO2 to sequestration sites. Capture facilities have some ability to store CO2 temporarily, but often, this capacity is limited. Capture facilities have two options when there is no capacity to transport the CO2, turn off the capture part of the facility or capture and then vent the the excess CO2. Turning carbon capture facilities on and off is not typically straightforward due to the complexities involved in their operation; therefore, the model assumes the CO2 would be captured but then vented [122].

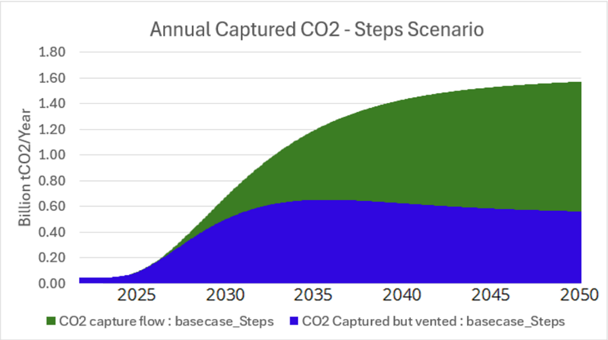


Figure 5.10: Vented CO2 amounts compared to Injection (Steps Scenario).

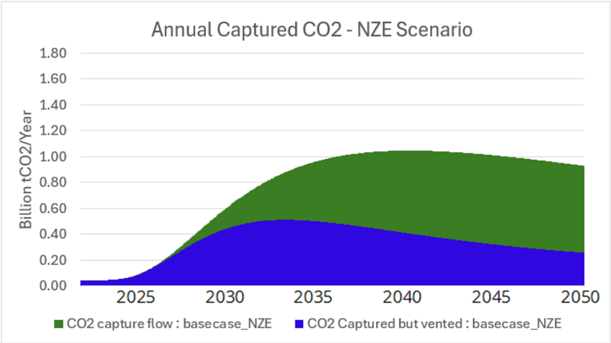


Figure 5.11: Vented CO2 amounts compared to Injection (NZE Scenario).

In the model, this misalignment results in a bottleneck, where captured CO2 cannot be transported and stored efficiently. Figure 5.10 and Figure 5.11 highlight the high and low emissions scenarios and possible venting amounts due to limited transportation capacity. It is critical to ensure that the capacities for capture, transportation, and sequestration are developed in harmony. This may be one of the reasons the Boundary Dam project and others have not reached their projected capture rates [40]. Additionally, optimizing the geographical placement of capture facilities and sequestration sites can minimize the need for extensive transportation infrastructure. Research by Wei et al. has demonstrated the benefits of creating carbon source clusters and aligning them with potential sequestration sites globally. This can reduce transportation requirements and enhance the overall efficiency of the CCS process [18].

5.2 Sensitivity Analysis

Sensitivity analysis is necessary due to the presence of uncertainty in many relevant parameters, many of which are derived from averages or estimates that vary significantly across existing studies. To facilitate testing sensitivity, parameters were included for cost, learning rate, and adjustment times to allow for the simultaneous variation of these variables by uniform amounts.

5.2.1 Key Sensitivity Factors

The initial sensitivity analysis aimed to identify the key variables impacting both the total volume of sequestered CO2 over the study period. Univariate sensitivity testing was used to determine which variables had the most significant impact cumulative sequestration. Every parameter is varied over its expected range. The results are ordered from highest to lowest impact on the chosen output variable (cumulative sequestration in this example). The most influential parameters are:

1. *Standard deviation of the lognormal distribution of CCS costs*: This parameter determines the fraction of plants implementing CCS and plays a significant role in shaping the overall adoption rate within the model.
2. *Incentive Amount*: Financial incentives are a major driver for the adoption of CCS technologies. Variations in incentive levels directly affect project viability and the extent of CO2 capture and storage.
3. *Cost Sensitivity Parameter*: This parameter affects the initial CCS initiative costs, influencing the overall cost-effectiveness of CCS projects.
4. *Leakage Rate*: A higher leakage rate reduces the efficiency of CO2 sequestration, increasing the average cost per tonne of CO2 and decreasing the total amount of permanently sequestered CO2.

These variables are expected to be the main drivers, as the cost-benefit analysis of CCS projects heavily depends on incentives and costs. Additionally, a high leakage rate not only undermines the environmental integrity of sequestration but also escalates costs, thereby reducing the attractiveness of these projects. Conversely, variables such as the adjustment time sensitivity variable, the supply curve sensitivity variable, and the capture fraction did not exhibit significant sensitivity in the model. This suggests that while these factors may influence the overall dynamics, their impact is less pronounced than the variables identified.

5.2.2 Monte Carlo Simulation Results

To further explore the impact of key variables, a Monte Carlo simulation was conducted by varying the parameters as shown in Table 5.1 (.cmd and .vsc file in Appendix B). The simulation results provide a range of potential outcomes, illustrating the model's best-case scenario with the given parameters. The findings illustrated in Figure 5.12 suggest that even under the most favorable combination of assumptions, approximately 2 gigatons of CO2 could be permanently sequestered annually by 2050.

Parameter	Distribution	Min	Max
Adjustment Time Sensitivity Variable	UNIFORM	0.5	1.5
Capture Fraction	UNIFORM	0.6	0.95
Cost Sensitivity Variable	UNIFORM	0.5	1.5
Incentive per tCO2	UNIFORM	0.0	100
Learning Curve Sensitivity Variable	UNIFORM	0.5	1.5
sigma	UNIFORM	0.25	0.75
Scenario Switch	UNIFORM	1	4
Sequestration Leakage Rate	UNIFORM	0.001	0.1

Table 5.1: Monte Carlo Simulation Paramters

The results, depicted in Figure 5.13, reveal a wide range of potential costs, particularly with a long tail at the higher end. This indicates that under certain conditions, especially with shifts in the supply curve, project costs can become prohibitively high. Despite incorporating a learning curve, which aims to reduce costs over time through increased experience and efficiency, the model indicates that cost reductions may not be sufficient to mitigate the high costs associated with some scenarios.

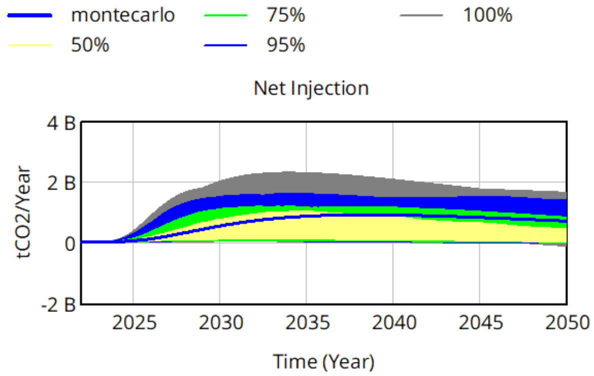


Figure 5.12: Annual Net Injection amount of CO2 with applied monte carlo analysis.

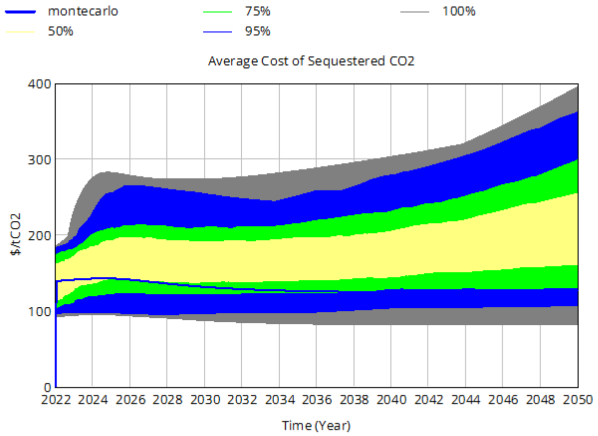


Figure 5.13: Average cost of permanently sequestered CO2 with applied monte carlo analysis.

This sensitivity analysis highlights the importance of accurately estimating key parameters and understanding their potential variability.

5.3 Limitations and Conclusion

This research has several limitations due to the aggregation of costs, delay times, learning rates, and other key variables across different locations and facility types. The model relies on averages and estimates for variables such as energy requirements, costs, and operational timelines. This aggregation can obscure the unique characteristics of different feedstocks and capture technologies. Additionally, where specific data are unavailable, similar data or common-sense approximations were used, with sensitivity analysis to account for uncertainty.

One major assumption is the learning rate and its impact on cost reductions. The data on learning rates is not widely available and can be conflicting. Higher learning rates could alter the economic viability of CCS projects, which is captured through sensitivity in the current model. Another significant limitation is the assumption that plants will only shut down after a certain period, disregarding the possibility that facilities may discontinue capture operations if they become financially nonviable over time.

These limitations suggest several areas for further evaluation. Future work could include a more granular model development, distinguishing between different capture technologies and locations. More accurate learning rate data would also refine the model's projections on cost improvements. Additionally, the model should consider dynamic decision-making processes at facilities, including periodic financial assessments.

Finally, the model only considers CCS as a climate mitigation solution. To test the longer-term impact and scalability of CCS fully, this model should be integrated with a model incorporating other sustainability alternatives. En-ROADS is a system dynamics-based tool developed by Climate Interactive and the MIT Sloan Sustainability Initiative that allows users to explore dynamics across energy, emissions, climate, and economic impacts [123]. Incorporating CCS scalability factors with En-ROADS' simulation will provide insight into if and how CCS could contribute to achieving the Paris Agreement's climate targets. The results can inform policy, investment, and research priorities.

Appendix A

Vensim Diagram

The figures below are screenshots from the final CCS Vensim model.

Vensim model file can be found here: Zenodo file repository

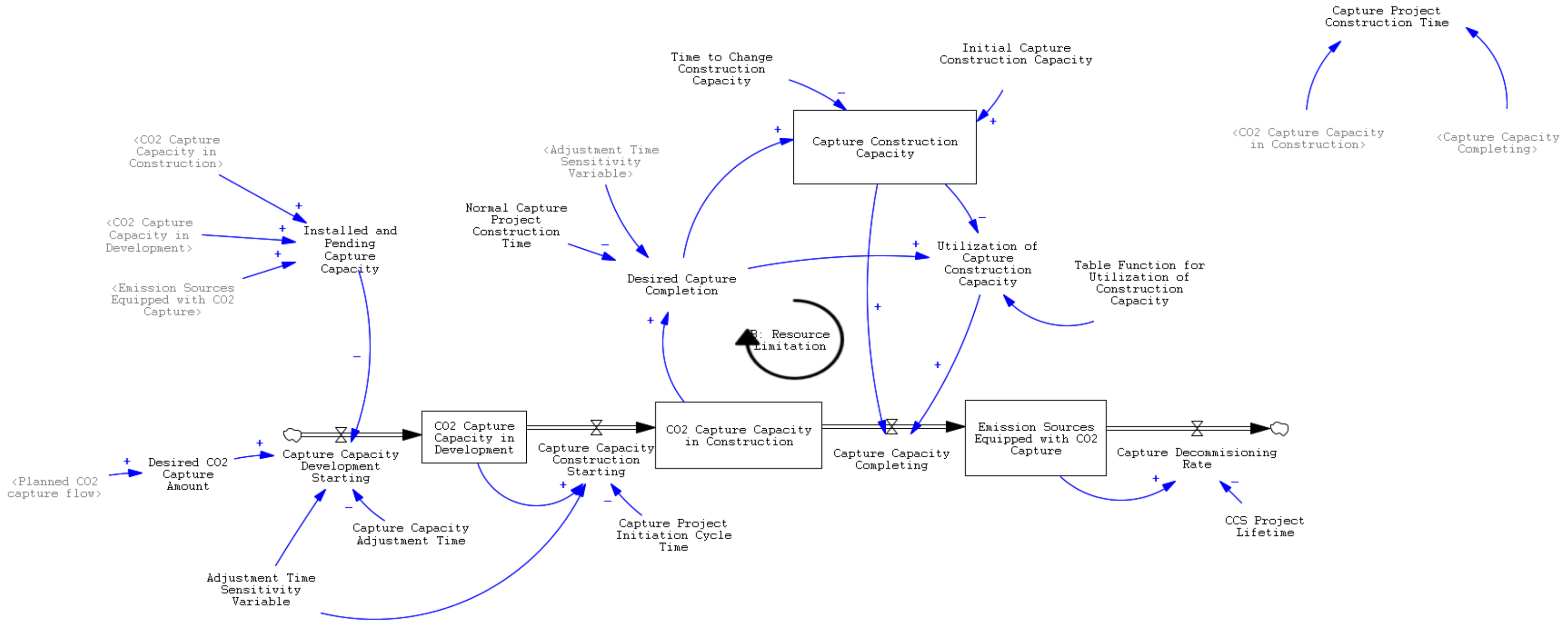


Figure A.1: Capture Projects Model View

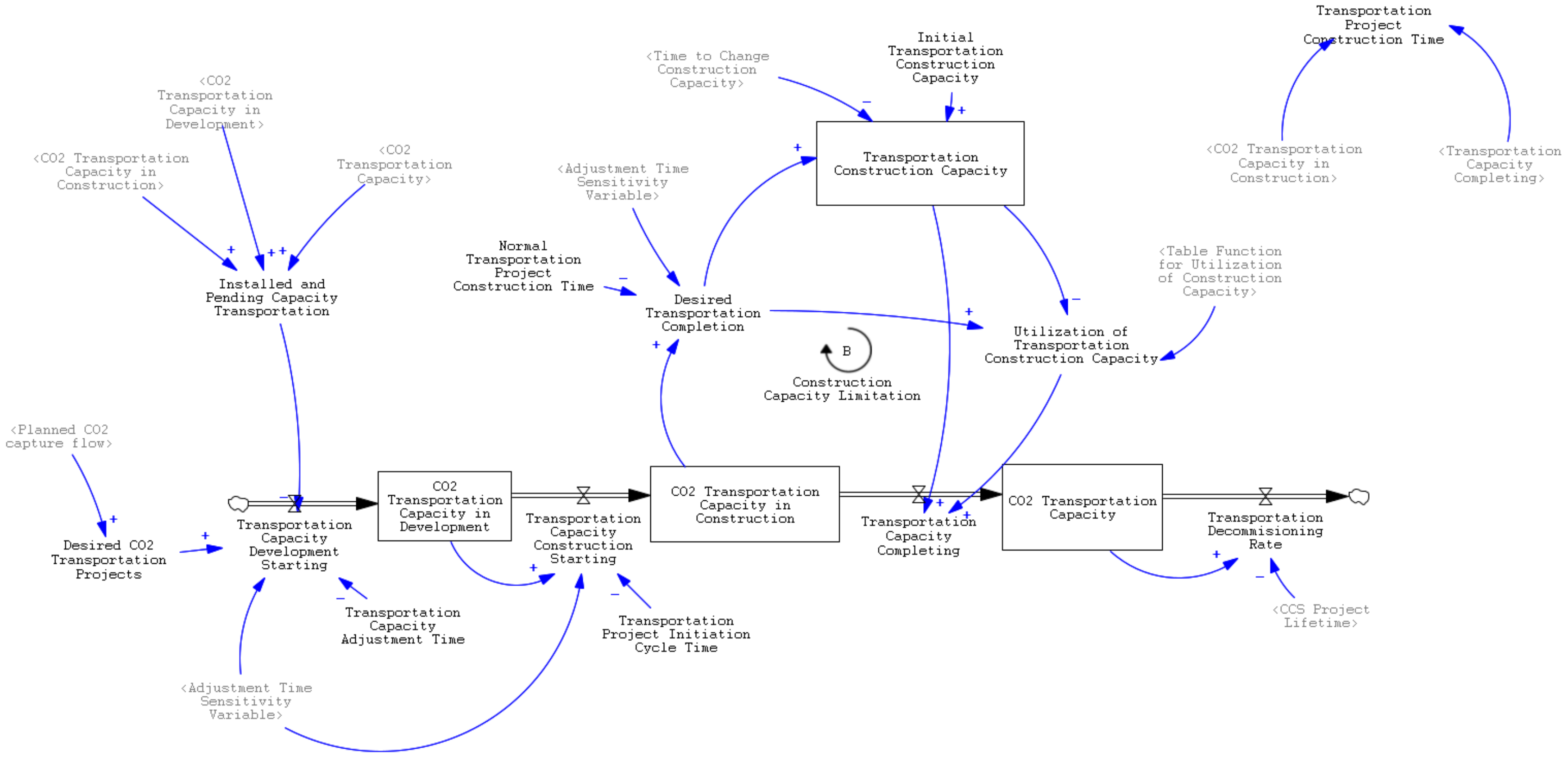


Figure A.2: Transportation Projects Model View

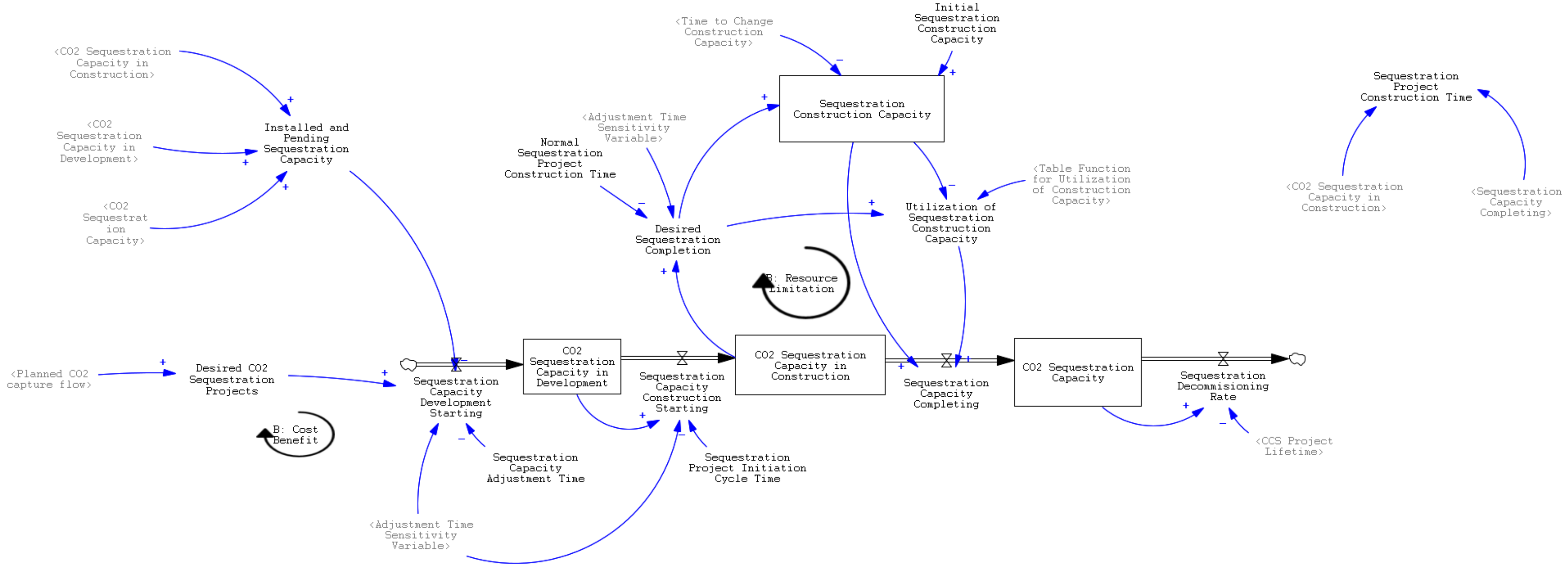


Figure A.3: Sequestration Projects Model View

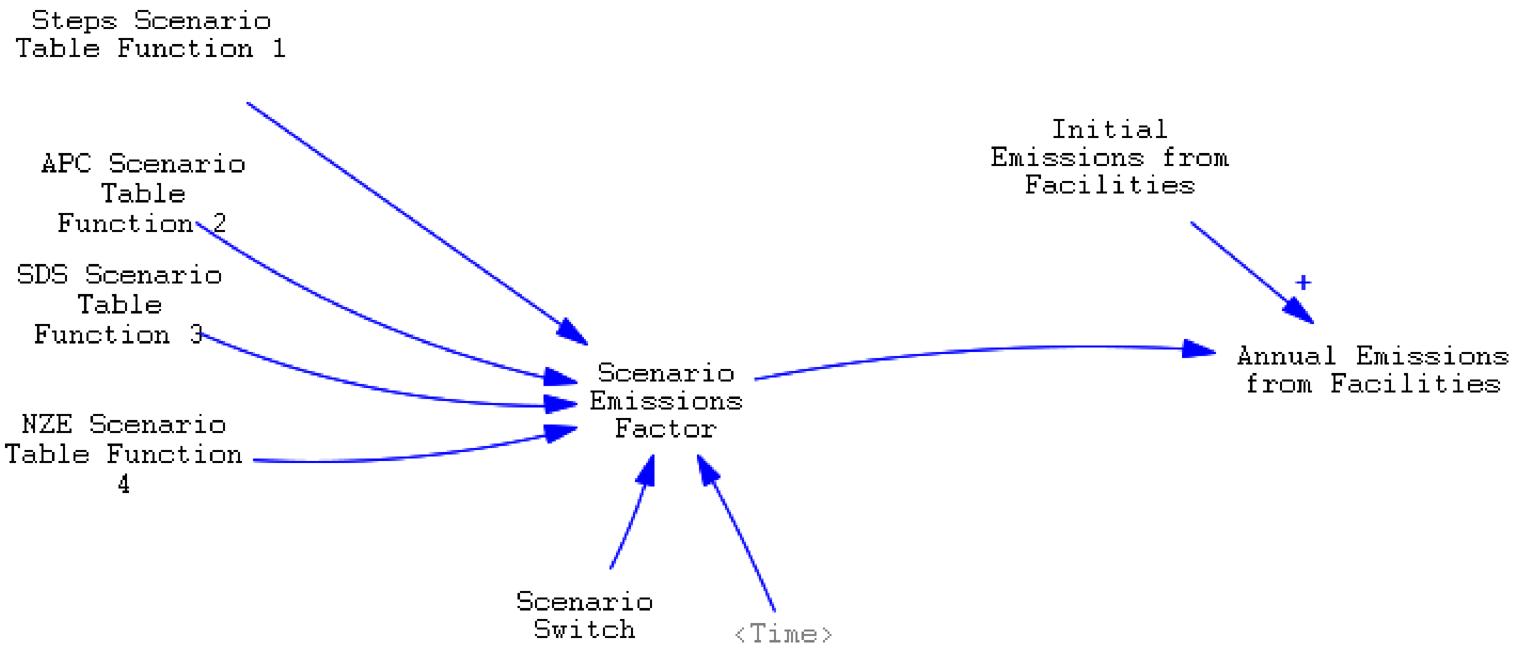


Figure A.4: Facilities with Emissions Scenarios View

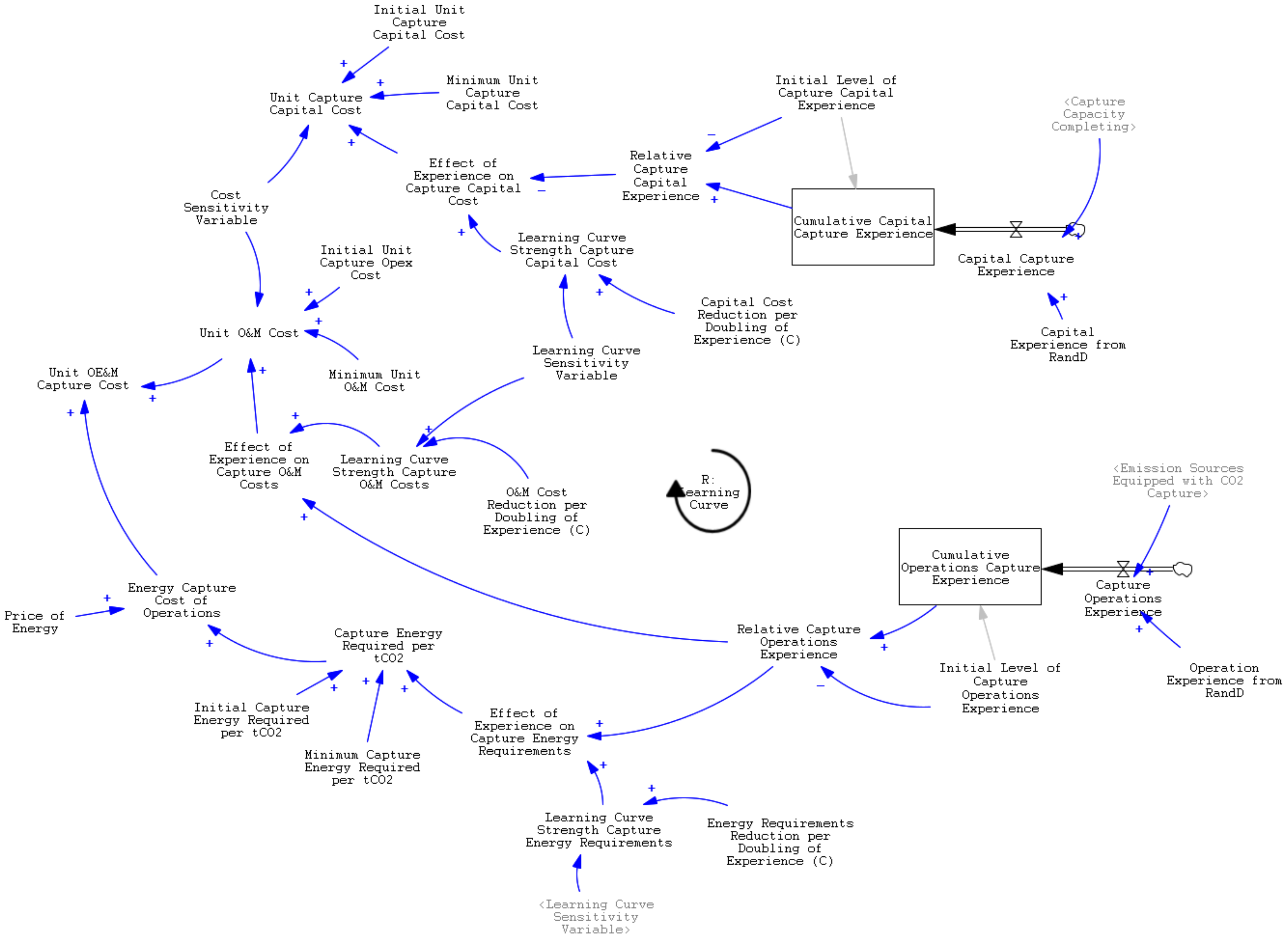


Figure A.5: Capture Costs View

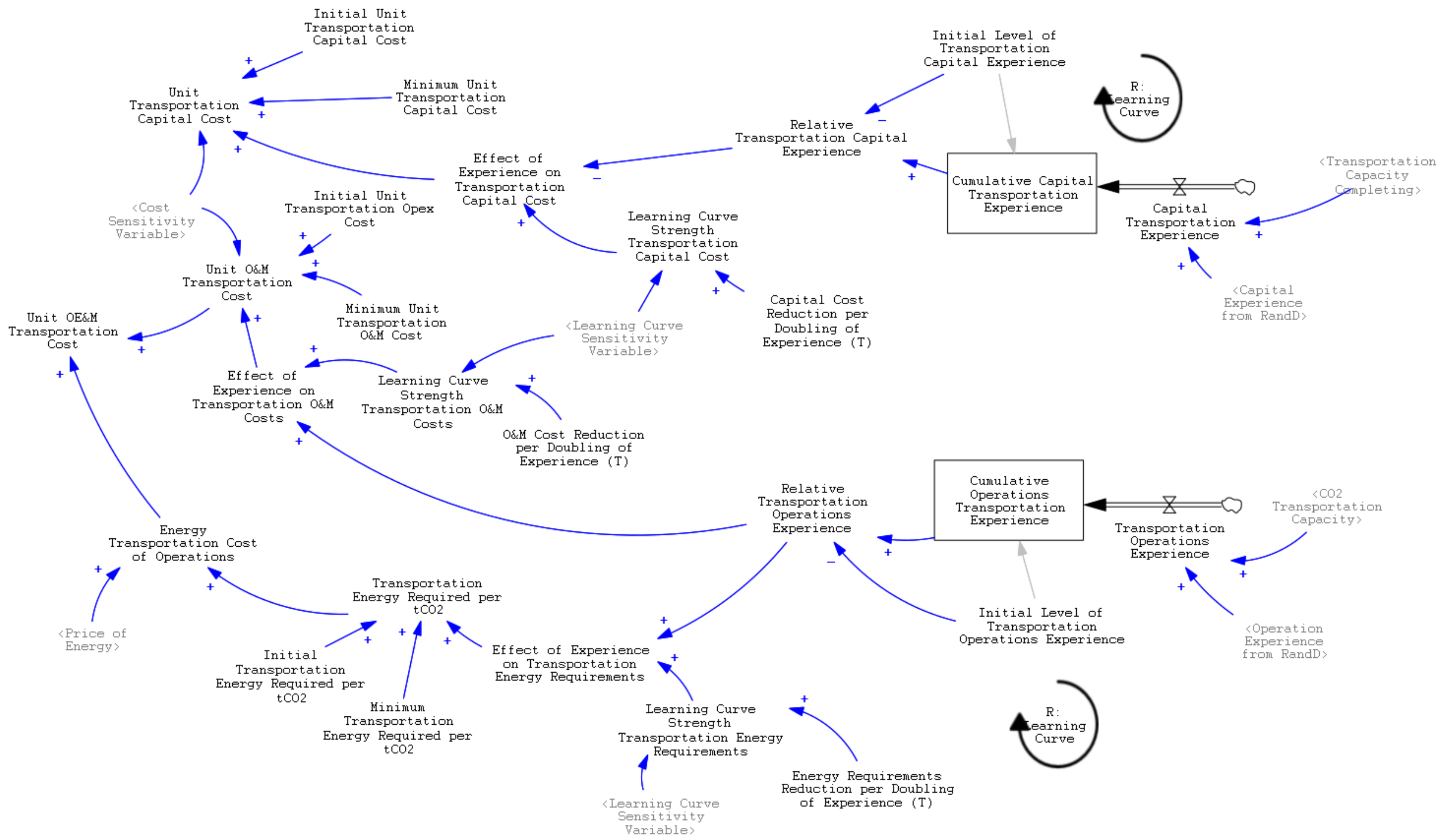


Figure A.6: Transportation Costs View

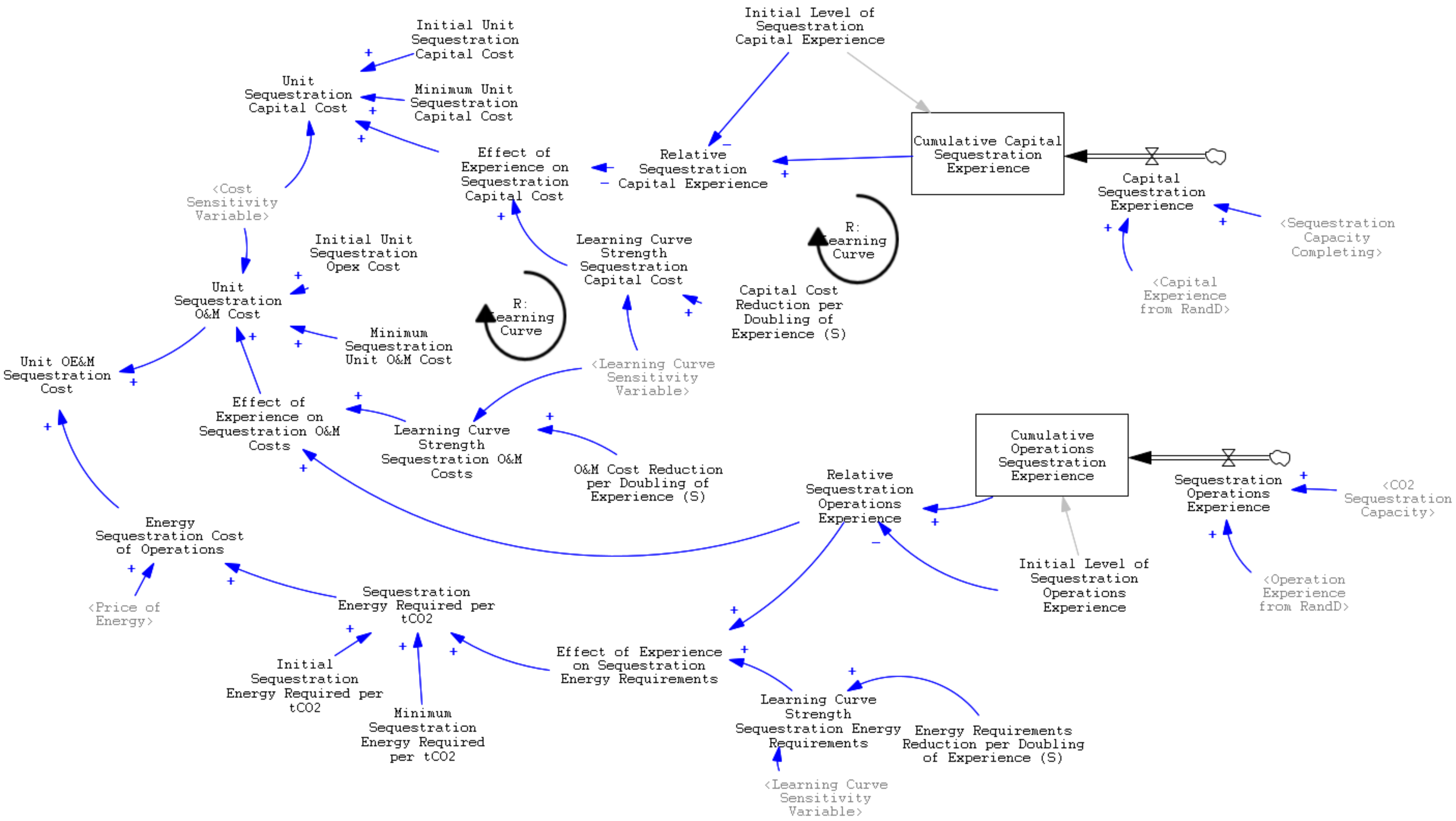
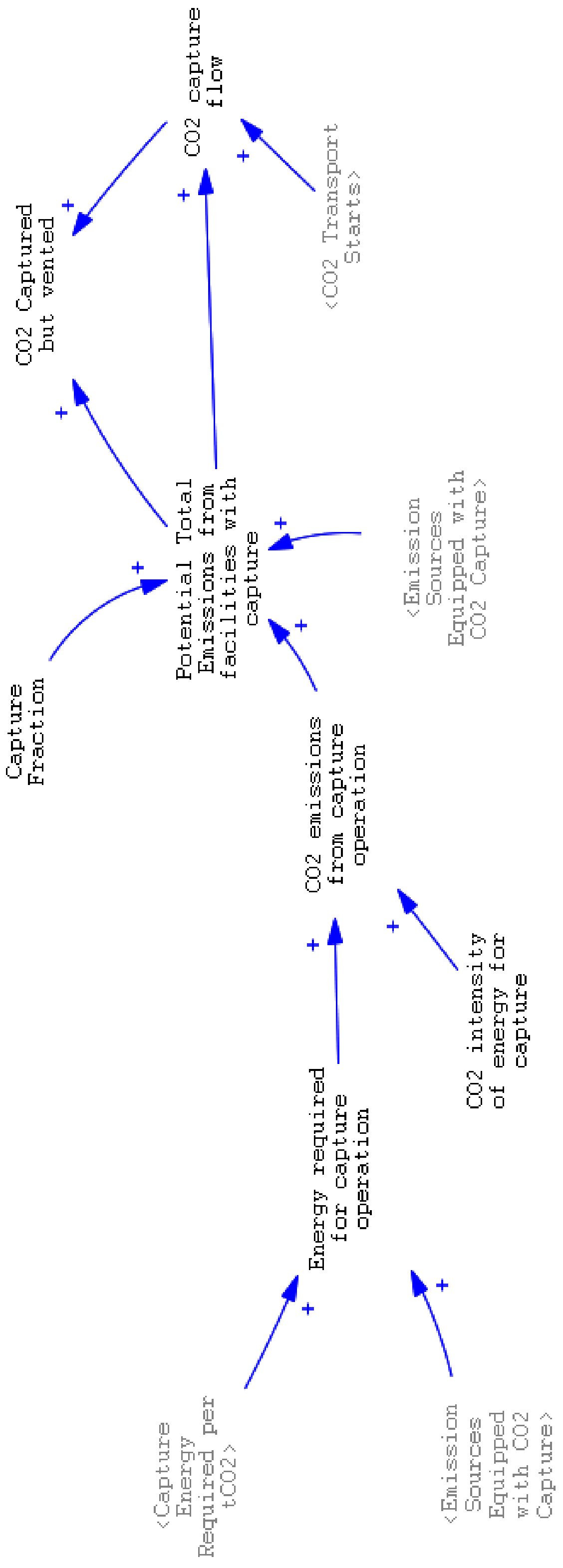
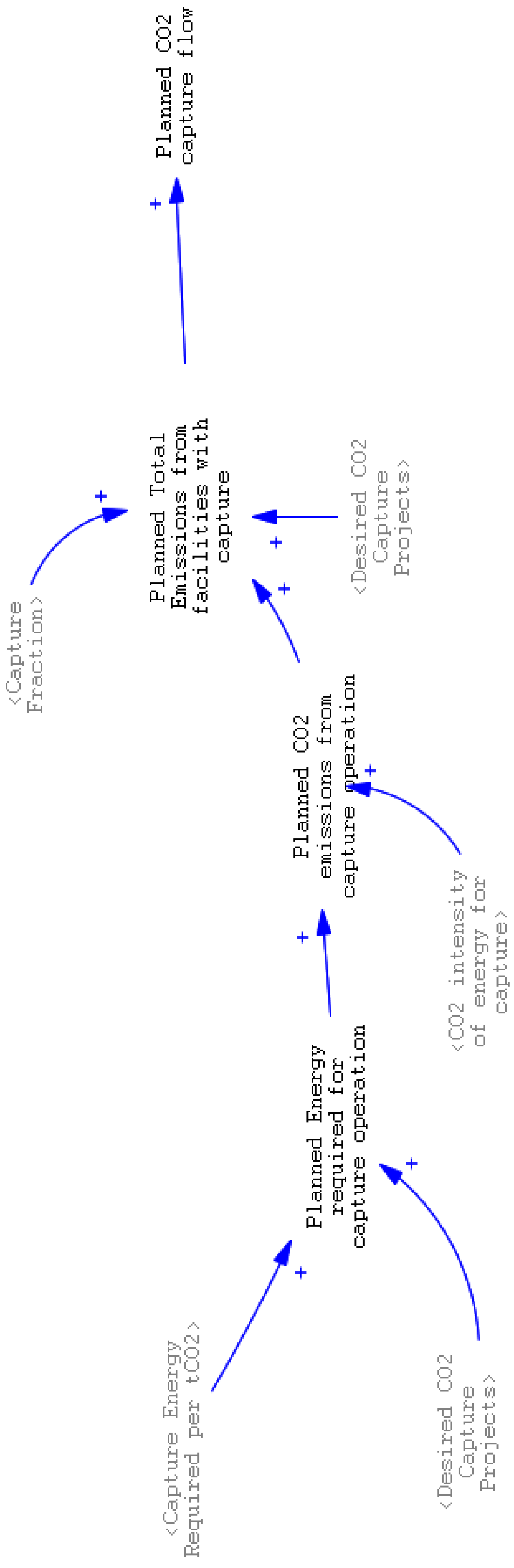


Figure A.7: Sequestration Costs View


Capture Fraction
Potential Total Emissions from facilities with capture
CO2 Captured but vented
CO2 capture flow
<CO2 Transport Starts>
<Emission Sources Equipped with CO2 Capture>
CO2 emissions from capture operation
Energy required for capture operation
CO2 intensity of energy for capture
<Capture Energy Required per tCO2>
<Emission Sources Equipped with CO2 Capture>


Planned CO2 capture flow
Planned Total Emissions from facilities with capture
<Capture Fraction>
<Desired CO2 Capture Projects>
Planned CO2 emissions from capture operation
<CO2 intensity of energy for capture>
Planned Energy required for capture operation
<Capture Energy Required per tCO2>
<Desired CO2 Capture Projects>

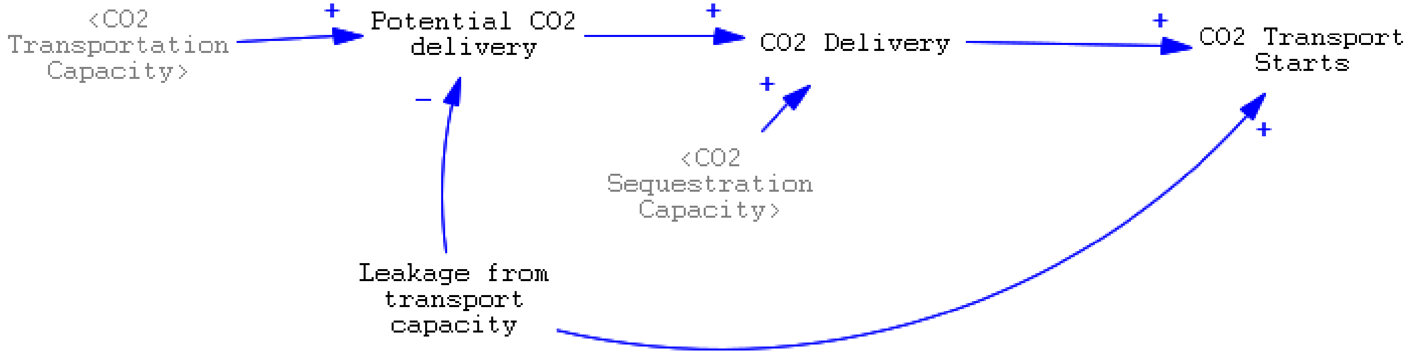


Figure A.9: Transportation Amount CO2

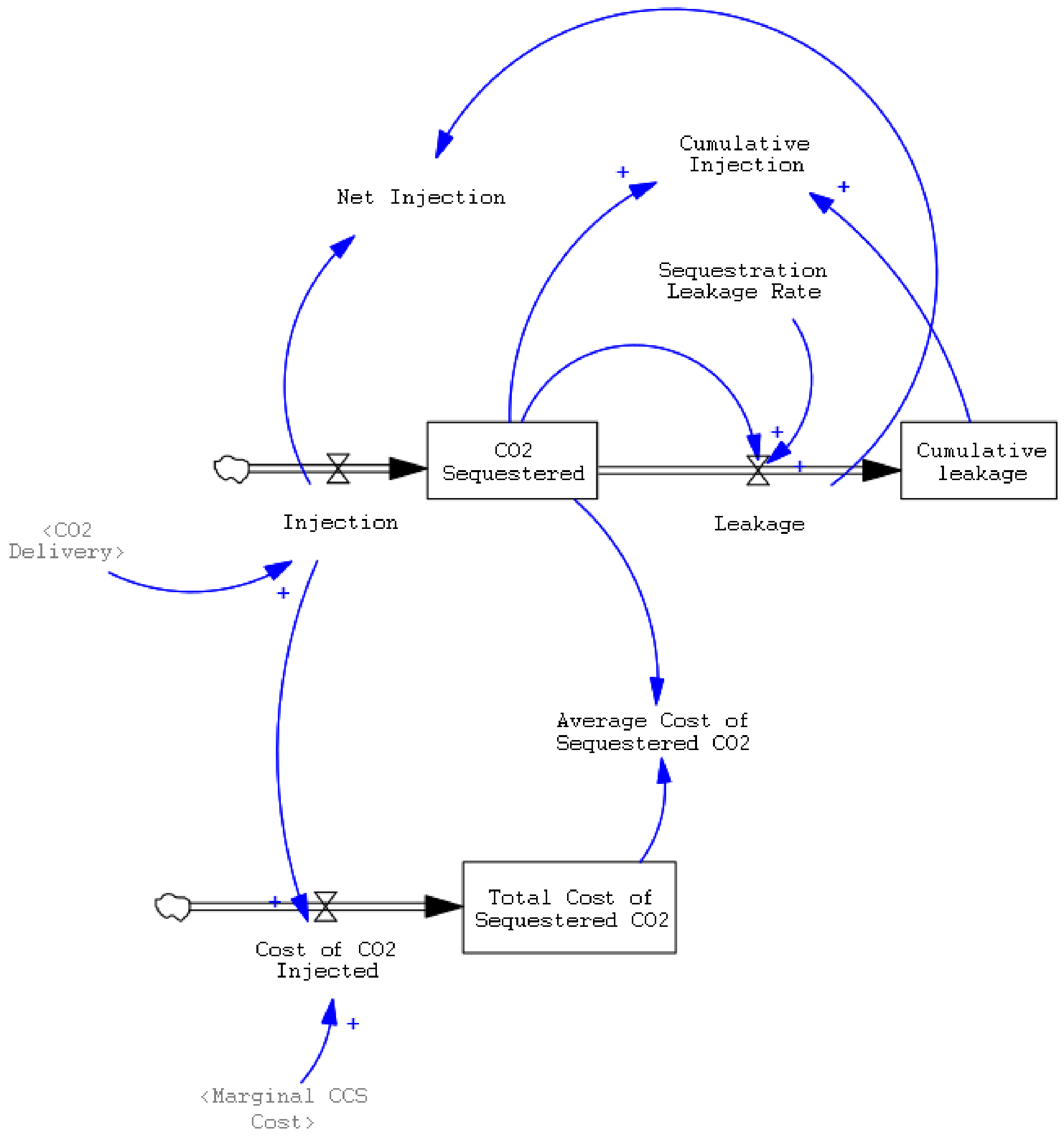


Figure A.10: Sequestered Amount CO2

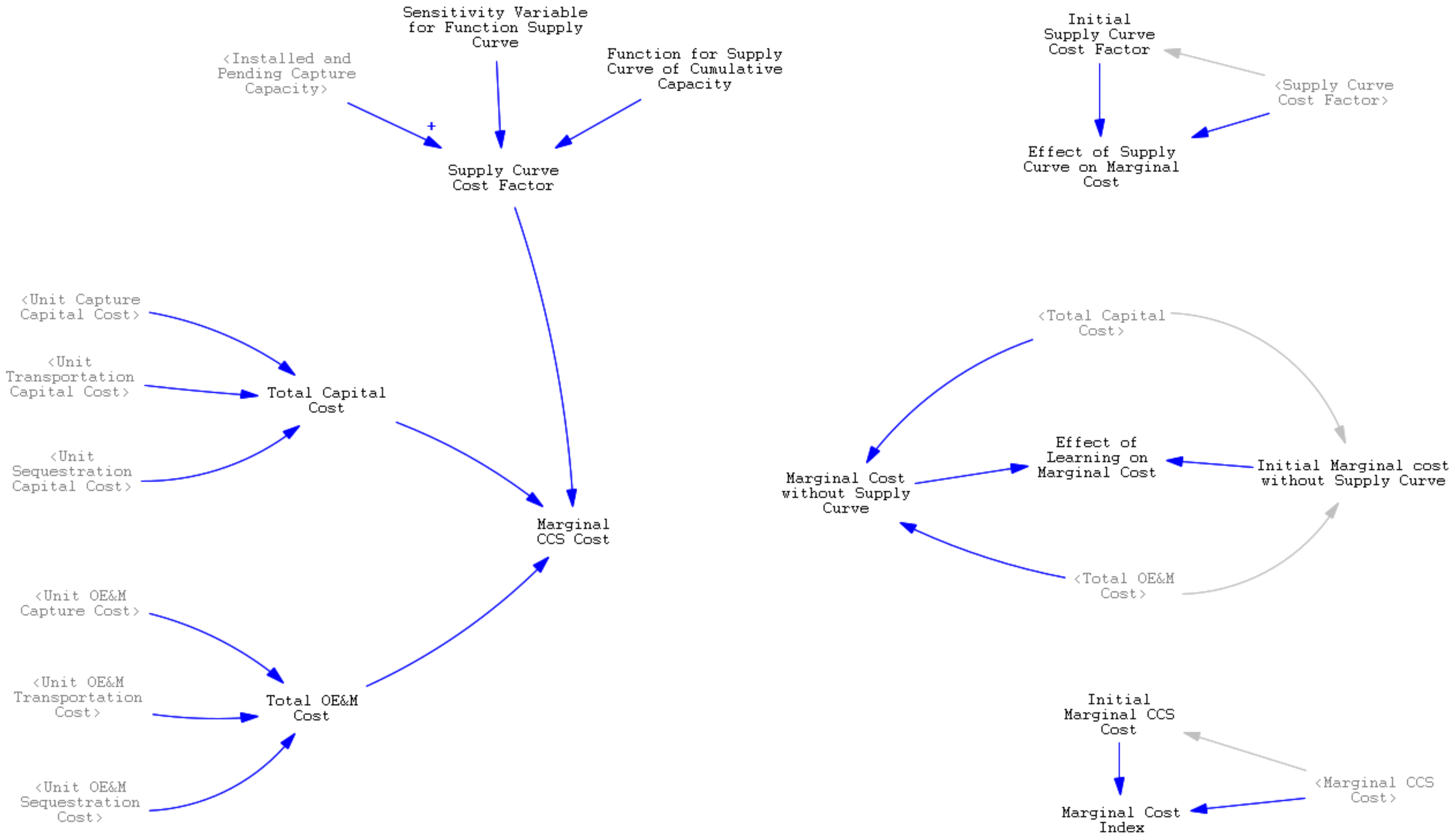


Figure A.11: Total Cost View

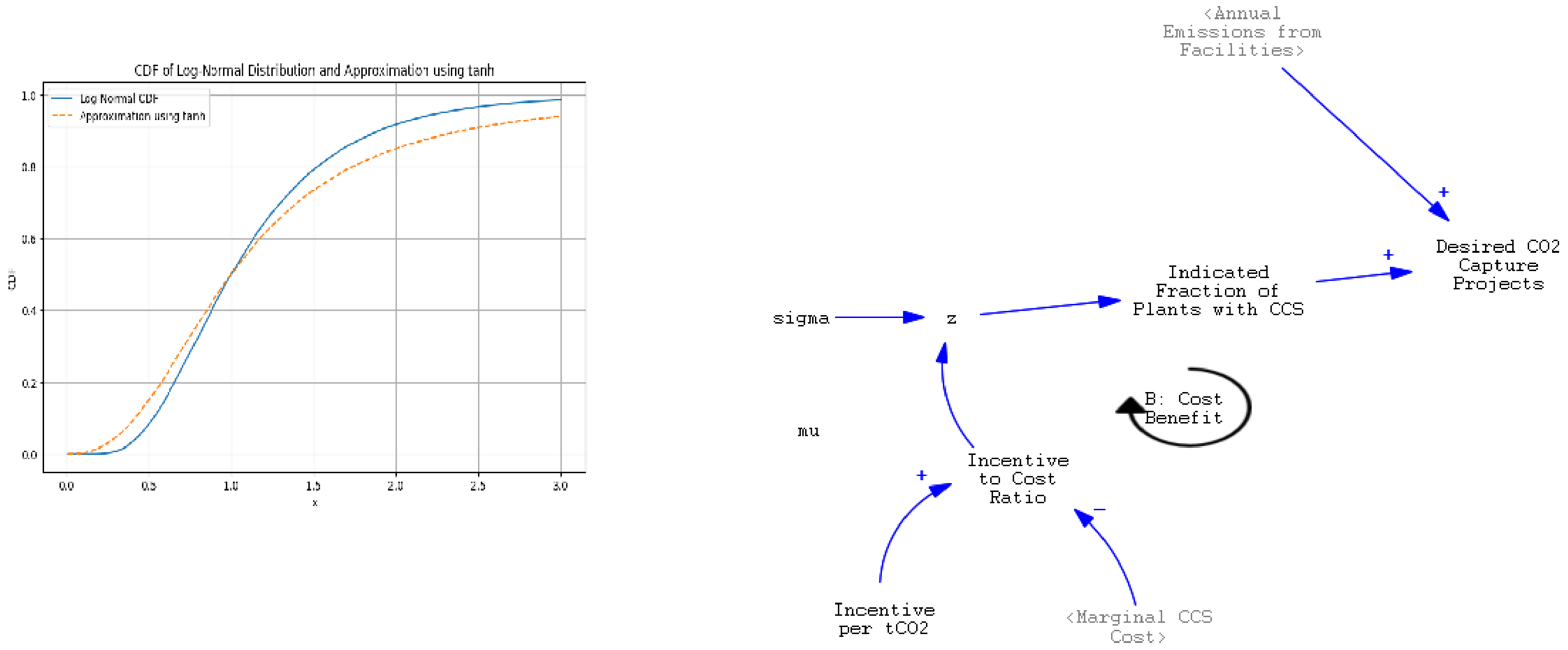


Figure A.12: Cost to Revenue Analysis View

Appendix B

Vensim Command File

Command file and VSC file used to run simulations: Zenodo file repository

```
SPECIAL>LOADMODEL|james-ltjames-sm-sdm-2024-thesis.mdl SPECIAL>CLEARRUNS

SIMULATE>SETVAL | Scenario Switch = 1
SIMULATE>RUNNAME | basecase_STEPS |o
MENU>RUN|o

SIMULATE>SETVAL | Scenario Switch = 2
SIMULATE>RUNNAME | basecase_APC |o
MENU>RUN|o

SIMULATE>SETVAL | Scenario Switch = 3
SIMULATE>RUNNAME | basecase_SDS |o
MENU>RUN|o

SIMULATE>SETVAL | Scenario Switch = 4
SIMULATE>RUNNAME | basecase_NZE |o
MENU>RUN|o

SIMULATE>SETVAL | Scenario Switch = 2
SIMULATE>SETVAL | Sensitivity Variable for Function Supply Curve = 2
SIMULATE>RUNNAME | highsupplycurve_APC |o
MENU>RUN|o

SIMULATE>RUNNAME|montecarlo|o
SIMULATE>SENSITIVITY|montecarlo.vsc
MENU>RUN_SENSITIVITY|o
```

Appendix C

Vensim Variable Equations

Output from Vensim for all variables and parameters in the model: Zenodo file repository

Adjustment Time Sensitivity Variable= 1
Units: Dmnl
Variable used to change the adjustment times throughout CCS project phases to all in order to test for sensitivity.

Annual Emissions from Facilities= Initial Emissions from Facilities*Scenario Emissions Factor
Units: tCO2/Year
Applying the IEA scenario factor to the initial emissions from facilities over time to represent changes in emissions between 2022 and 2050.

APC Scenario Table Function 2([(0,0)-(2050,1)],(2022,1), (2025,0.99115), (2030,0.929204), (2035,0.865782), (2040,0.817109), (2045,0.803835), (2050,0.814159))
Units: Dmnl
!Year Announced pledges scenario (APC) scenario from IEA

Average Cost of Sequestered CO2= ZIDZ(Total Cost of Sequestered CO2, CO2 Sequestered)
Units: $/tCO2

Capital Capture Experience= Capture Capacity Completing+Capital Experience from RandD
Units: tCO2/Year/Year
Increased experience in CCS with completion of CCS projects and a factor from investment in R&D

"Capital Cost Reduction per Doubling of Experience (C)"= 0.08
Units: Dmnl [0,0.2,0.01]
The fractional reduction in capital cost per doubling of cumulative capacity completion experience.

"Capital Cost Reduction per Doubling of Experience (S)"= 0.03
Units: Dmnl [0,0.1,0.01]
The fractional reduction in capital cost per doubling of cumulative capacity completion experience.

"Capital Cost Reduction per Doubling of Experience (T)"= 0.01
Units: Dmnl [0,0.05,0.01]

The fractional reduction in capital cost per doubling of cumulative capacity completion experience.

Capital Experience from RandD= 100000
Units: tCO2/Year/Year
Increased capital experience through R&D

Capital Sequestration Experience= Sequestration Capacity Completing+Capital Experience from RandD
Units: tCO2/Year/Year
Increased experience in CCS with completion of CCS projects and a factor from investment in R&D

Capital Transportation Experience= Transportation Capacity Completing+Capital Experience from RandD
Units: tCO2/Year/Year
Increased experience in CCS with completion of CCS projects and a factor from investment in R&D

Capture Capacity Adjustment Time= 2
Units: Year [1,5,0.5]
The amount of time on average it takes for a project to move into the planning stage.

Capture Capacity Completing= Capture Construction Capacity*Utilization of Capture Construction Capacity
Units: tCO2/Year/Year
Rate in tCO2/Year/Year that projects that are under construction get completed based on utilization of available construction capacity.

Capture Capacity Construction Starting= CO2 Capture Capacity in Development/(Capture Project Initiation Cycle Time*Adjustment Time Sensitivity Variable)
Units: tCO2/Year/Year
Rate in tCO2/Year/Year that projects move from planned to under construction.

Capture Capacity Development Starting= MAX(0,(Desired CO2 Capture Amount-Installed and Pending Capture Capacity)/(Capture Capacity Adjustment Time*Adjustment Time Sensitivity Variable))
Units: tCO2/Year/Year
Rate in tCO2/Year/Year that projects are initiated and move to the planned phase.

Capture Construction Capacity= SMOOTH3I(Desired Capture Completion, Time to Change Construction Capacity, Initial Capture Construction Capacity)
Units: tCO2/Year/Year
Capacity available for construction of CCS projects. Adjusts based on time to adjust and desired completion rate.

Capture Decommissioning Rate= Emission Sources Equipped with CO2 Capture/CCS Project Lifetime
Units: tCO2/Year/Year
Rate at which facilities are decommissioned over time.

Capture Energy Required per tCO2= Minimum Capture Energy Required per tCO2+((Initial Capture Energy Required per tCO2-Minimum Capture Energy Required per tCO2)*Effect of Experience on Capture Energy Requirements)
Units: GJ/tCO2
Amount of energy needed to capture and process a tCO2 multiplied by the learning curve effect. Theory is that as more projects are completed, the learning from past projects should make future projects more efficient and require less energy. Minimum thermodynamic required energy incorporated.

Capture Fraction= 0.85
Units: Dmnl [0.6,0.95,0.05]
Percent of emissions able to be captured.

Capture Operations Experience= Emission Sources Equipped with CO2 Capture+Operation Experience from RandD
Units: tCO2/Year
Increased experience in CCS with operations of CCS projects and a factor from investment in R&D

Capture Project Construction Time= ZIDZ(CO2 Capture Capacity in Construction, Capture Capacity Completing)
Units: Year
Little's Law: under steady-state conditions, the average number of items in a queuing system equals the average rate at which items arrive multiplied by the average time that an item spends in the system.

Capture Project Initiation Cycle Time= 4
Units: Year [2,10,0.5]
The amount of time on average it takes for a project to move into the construction stage from capacity in development.

CCS Project Lifetime= 40
Units: Year [20,60,5]
Amount of time in years on average a CCS facility operates.

CO2 Capture Capacity in Construction= INTEG (Capture Capacity Construction Starting-Capture Capacity Completing, 4e+07)
Units: tCO2/Year
Total tCO2/year capture projects currently under construction on facilities globally.

CO2 Capture Capacity in Development= INTEG (Capture Capacity Development Starting-Capture Capacity Construction Starting, 1.5e+08)
Units: tCO2/Year
Total tCO2/year capture projects in planning phases on facilities globally.

CO2 capture flow= MIN(Potential Total Emissions from facilities with capture, CO2 Transport Starts)

Units: tCO2/Year
Amount of CO2 captured and not vented based on the available capacity in transportation and sequestration.

CO2 Captured but vented= Potential Total Emissions from facilities with capture-CO2 capture flow
Units: tCO2/Year
If capacity is not available in the chain, the CO2 from capture operations and emissions from facilities will be vented.

CO2 Delivery= MIN(Potential CO2 delivery,CO2 Sequestration Capacity)
Units: tCO2/Year
Possible amount delivered is limited by the minimum of potential delivery amount and the capacity to sequester the amount delivered. Amount will not be transported if not possible to sequester.

CO2 emissions from capture operation= Energy required for capture operation*CO2 intensity of energy for capture
Units: tCO2/Year
Emissions from the energy needed to operate the capture facility.

CO2 intensity of energy for capture= 0.3
Units: tCO2/GJ [0.2,0.5]
The amount of CO2 created based on the energy required to operate capture facilities on average. (.25-.5 tCO2/GJ)

CO2 Sequestered= INTEG (Injection-Leakage, 0)
Units: tCO2
Total amount of CO2 sequestered minus any leakage.

CO2 Sequestration Capacity= INTEG (Sequestration Capacity Completing-Sequestration Decommissioning Rate, 3e+07)
Units: tCO2/Year
Total tCO2/year currently operating on facilities globally.

CO2 Sequestration Capacity in Construction= INTEG (Sequestration Capacity Construction Starting-Sequestration Capacity Completing, 2e+07)
Units: tCO2/Year
Total tCO2/year capture projects currently under construction on facilities globally.

CO2 Sequestration Capacity in Development= INTEG (Sequestration Capacity Development Starting-Sequestration Capacity Construction Starting, 1e+08)
Units: tCO2/Year
Total tCO2/year capture projects in planning phases on facilities globally.

CO2 Transport Starts= CO2 Delivery/(1-Leakage from transport capacity)
Units: tCO2/Year
Amount expected to be transported at the start. Incorporating minimum capacity and leakage back into CO2 amounts.

CO2 Transportation Capacity= INTEG (Transportation Capacity Completing-Transportation Decommissioning Rate, 4e+07)
Units: tCO2/Year
Total tCO2/year currently operating on facilities globally.

CO2 Transportation Capacity in Construction= INTEG (Transportation Capacity Construction Starting-Transportation Capacity Completing, 3e+07)
Units: tCO2/Year
Total tCO2/year capture projects currently under construction on facilities globally.

CO2 Transportation Capacity in Development= INTEG (Transportation Capacity Development Starting-Transportation Capacity Construction Starting, 1e+08)
Units: tCO2/Year
Total tCO2/year capture projects in planning phases on facilities globally.

Cost of CO2 Injected= Injection*Marginal CCS Cost
Units: $/Year
Cost for each tCO2 injected based on cost at that given time.

Cost Sensitivity Variable= 1
Units: Dmnl
Variable used to change the initial opex and capex costs in order to test for sensitivity.

Cumulative Capital Capture Experience= INTEG (Capital Capture Experience, Initial Level of Capture Capital Experience)
Units: tCO2/Year
Total amount of CCS capital experience based on completion rate and a factor from investment in R&D.

Cumulative Capital Sequestration Experience= INTEG (Capital Sequestration Experience, Initial Level of Sequestration Capital Experience)
Units: tCO2/Year
Total amount of CCS capital experience based on completion rate and a factor from investment in R&D.

Cumulative Capital Transportation Experience= INTEG (Capital Transportation Experience, Initial Level of Transportation Capital Experience)
Units: tCO2/Year
Total amount of CCS capital experience based on completion rate and a factor from investment in R&D.

Cumulative Injection= CO2 Sequestered+Cumulative leakage
Units: tCO2
Total amount of CO2 sequestered/injected underground.

Cumulative leakage= INTEG (Leakage, 0)

Units: tCO2
Total amount of CO2 leakage from sequestration.

Cumulative Operations Capture Experience= INTEG (Capture Operations Experience, Initial Level of Capture Operations Experience)
Units: tCO2
Total amount of CCS experience based on completion rate and a factor from investment in Technology.

Cumulative Operations Sequestration Experience= INTEG (Sequestration Operations Experience, Initial Level of Sequestration Operations Experience)
Units: tCO2
Total amount of CCS experience based on completion rate and a factor from investment in Technology.

Cumulative Operations Transportation Experience= INTEG (Transportation Operations Experience, Initial Level of Transportation Operations Experience)
Units: tCO2
Total amount of CCS experience based on completion rate and a factor from investment in Technology.

Desired Capture Completion= CO2 Capture Capacity in Construction/(Normal Capture Project Construction Time*Adjustment Time Sensitivity Variable)
Units: tCO2/(Year*Year)
Desired Rate of completion of capture projects based on the current number in backlog and normal construction time.

Desired CO2 Capture Amount= Planned CO2 capture flow
Units: tCO2/Year
Desired Capture projects are set as equal to the amount of planned CO2 capture amounts to ensure capacity is available through the entire chain.

Desired CO2 Capture Projects= MAX(0, (Annual Emissions from Facilities*Indicated Fraction of Plants with CCS))
Units: tCO2/Year
Based on revenue/cost, the associated supply curve, and the amount of existing emissions, this captures the emissions tCO2/year that should feed into capture projects.

Desired CO2 Sequestration Projects= Planned CO2 capture flow
Units: tCO2/Year
Desired Sequestration projects are set as equal to the amount of planned CO2 capture amounts to ensure capacity is available through the entire chain.

Desired CO2 Transportation Projects= Planned CO2 capture flow
Units: tCO2/Year
Desired Transportation projects are set as equal to the amount of planned CO2 capture amounts to ensure capacity is available through the entire chain.

Desired Sequestration Completion= CO2 Sequestration Capacity in Construction/(Normal Sequestration Project Construction Time*Adjustment Time Sensitivity Variable)
Units: tCO2/(Year*Year)
Desired Rate of completion of capture projects based on the current number in backlog and normal construction time.

Desired Transportation Completion= CO2 Transportation Capacity in Construction/(Normal Transportation Project Construction Time*Adjustment Time Sensitivity Variable)
Units: tCO2/(Year*Year)
Desired Rate of completion of capture projects based on the current number in backlog and normal construction time.

Effect of Experience on Capture Capital Cost= Relative Capture Capital ExperienceL̂earning Curve Strength Capture Capital Cost
Units: Dmnl
Costs decline by a fixed fraction for every doubling of cumulative experience, capturing learning by doing.

Effect of Experience on Capture Energy Requirements= Relative Capture Operations ExperienceL̂earning Curve Strength Capture Energy Requirements
Units: Dmnl
Required energy declines by a fixed fraction for every doubling of cumulative experience, capturing learning by doing.

"Effect of Experience on Capture O&M Costs"= Relative Capture Operations Experience"̂Learning Curve Strength Capture O&M Costs"
Units: Dmnl
Costs decline by a fixed fraction for every doubling of cumulative experience, capturing learning by doing.

Effect of Experience on Sequestration Capital Cost= Relative Sequestration Capital ExperienceL̂earning Curve Strength Sequestration Capital Cost
Units: Dmnl
Costs decline by a fixed fraction for every doubling of cumulative experience, capturing learning by doing.

Effect of Experience on Sequestration Energy Requirements= Relative Sequestration Operations ExperienceL̂earning Curve Strength Sequestration Energy Requirements
Units: Dmnl
Required energy declines by a fixed fraction for every doubling of cumulative experience, capturing learning by doing.

"Effect of Experience on Sequestration O&M Costs"= Relative Sequestration Operations Experience"̂Learning Curve Strength Sequestration O&M Costs"
Units: Dmnl
Costs decline by a fixed fraction for every doubling of cumulative experience, capturing learning by

doing.

Effect of Experience on Transportation Capital Cost= Relative Transportation Capital ExperienceL̂earning Curve Strength Transportation Capital Cost
Units: Dmnl
Costs decline by a fixed fraction for every doubling of cumulative experience, capturing learning by doing.

Effect of Experience on Transportation Energy Requirements= Relative Transportation Operations ExperienceL̂earning Curve Strength Transportation Energy Requirements
Units: Dmnl
Required energy declines by a fixed fraction for every doubling of cumulative experience, capturing learning by doing.

"Effect of Experience on Transportation O&M Costs"= Relative Transportation Operations Experience"̂Learning Curve Strength Transportation O&M Costs"
Units: Dmnl
Costs decline by a fixed fraction for every doubling of cumulative experience, capturing learning by doing.

Effect of Learning on Marginal Cost= Marginal Cost without Supply Curve/Initial Marginal cost without Supply Curve
Units: Dmnl
Ratio of Marginal cost without the supply curve effect to its initial value. Shows the net effect of the learning curves affecting capital, O and M, and energy costs.

Effect of Supply Curve on Marginal Cost= Supply Curve Cost Factor/Initial Supply Curve Cost Factor
Units: Dmnl
Ratio of the supply curve effect on marginal cost to its initial value. Shows the supply curve effect alone (without the impact of learning on marginal cost).

Emission Sources Equipped with CO2 Capture= INTEG (Capture Capacity Completing-Capture Decommissioning Rate, 5e+07)
Units: tCO2/Year
Total tCO2/year currently operating on facilities globally.

Energy Capture Cost of Operations= Capture Energy Required per tCO2*Price of Energy
Units: $/tCO2
Cost for the energy required per tCO2.

Energy required for capture operation= Emission Sources Equipped with CO2 Capture*Capture Energy Required per tCO2
Units: GJ/Year
The energy needed to run the capture operation based on capacity.

"Energy Requirements Reduction per Doubling of Experience (C)"= 0.05

Units: Dmnl [0,0.2,0.01]
The fractional reduction in energy requirement and associated cost per doubling of cumulative capacity operating experience.

"Energy Requirements Reduction per Doubling of Experience (S)"= 0.02
Units: Dmnl [0,0.15,0.01]
The fractional reduction in energy requirement and associated cost per doubling of cumulative capacity operating experience.

"Energy Requirements Reduction per Doubling of Experience (T)"= 0.005
Units: Dmnl [0,0.02,0.005]
The fractional reduction in energy requirement and associated cost per doubling of cumulative capacity operating experience.

Energy Sequestration Cost of Operations= Sequestration Energy Required per tCO2*Price of Energy
Units: $/tCO2
Cost for the energy required per tCO2.

Energy Transportation Cost of Operations= Transportation Energy Required per tCO2*Price of Energy
Units: $/tCO2
Cost for the energy required per tCO2.

FINAL TIME = 2050 Units: Year
The final time for the simulation.

Function for Supply Curve of Cumulative Capacity([(0,0)-(2,1)],(5e+07,1), (1e+08,1.25), (3e+08,1.35), (6e+08,1.425), (9e+08,1.5), (1.2e+09,1.6), (1.5e+09,1.7), (1.8e+09,1.825), (2.1e+09,2.6), (2.2e+09,3.5), (2.33401e+09,4.9), (2.38713e+09,6), (2.44296e+09,6.4))
Units: Dmnl
Supply curve for CCS to represent the percentage of facilities that would adopt CCS capture facilities based on the revenue to cost analysis.

Incentive per tCO2= 50
Units: $/tCO2 [0,100]
Exogenous variable representing incentive that could be obtained through EOR and/or subsidies for each tCO2. This would vary by policy and can be used to test the model.

Incentive to Cost Ratio= Incentive per tCO2/Marginal CCS Cost
Units: Dmnl
Ratio of incentives compared to cost for economic viability decision. Determines the ratio of plants that will decide to incorporate CCS based on the economics of the projects.

Indicated Fraction of Plants with CCS= 0.5 * (1 + TANH((SQRT(3.14159) / 2) * z))
Units: Dmnl
The mathematical approximation of the log-normal cumulative distribution was determined using

the hyperbolic tangent function. As the cost of projects decreases or the possible incentive increases, more CCS projects will be initiated.

Initial Capture Construction Capacity= 1e+06
Units: tCO2/Year/Year
Initial amount of capture construction capacity for supporting projects.

Initial Capture Energy Required per tCO2= 2.5
Units: GJ/tCO2 [0.5,10,0.5]
Initial energy required to process 1 tonne of CO2.

Initial Emissions from Facilities= 1.625e+10
Units: tCO2/Year
Total annual emissions from existing facilities with emissions over 1MtCO2/Year Industries: 2022: Chemical processes, iron and steel production, non-ferrous metals production, non-metallic minerals production, oil refineries and transformation industry, power industry EDGAR data.

Initial Level of Capture Capital Experience= 4.5e+07
Units: tCO2/Year
Initial amount of CCS experience based on the current state of R&D and completed projects.

Initial Level of Capture Operations Experience= 4.5e+07
Units: tCO2
Initial amount of CCS Operations experience based on the current state of R&D and completed projects.

Initial Level of Sequestration Capital Experience= 2.5e+07
Units: tCO2/Year
Initial amount of CCS experience based on the current state of R&D and completed projects.

Initial Level of Sequestration Operations Experience= 2.5e+07
Units: tCO2
Initial amount of CCS Operations experience based on the current state of R&D and completed projects.

Initial Level of Transportation Capital Experience= 3.5e+07
Units: tCO2/Year
Initial amount of CCS experience based on the current state of R&D and completed projects.

Initial Level of Transportation Operations Experience= 3.5e+07
Units: tCO2
Initial amount of CCS Operations experience based on the current state of R&D and completed projects.

Initial Marginal CCS Cost= INITIAL(Marginal CCS Cost)
Units: $/tCO2
The initial marginal cost of CCS per TCO2.

Initial Marginal cost without Supply Curve= INITIAL(Total Capital Cost+"Total OE&M Cost")
Units: $/tCO2
The initial value of the marginal cost without the supply curve (thus the initial cost showing only the impact of the learning curve).

Initial Sequestration Construction Capacity= 1e+06
Units: tCO2/Year/Year
Initial amount of capture construction capacity is tCO2/Year/Year.

Initial Sequestration Energy Required per tCO2= 0.1
Units: GJ/tCO2 [0.01,0.3,0.01]
Initial energy required to process 1 tonne of CO2.

Initial Supply Curve Cost Factor= INITIAL(Supply Curve Cost Factor)
Units: Dmnl
The initial effect of the supply curve on marginal cost. Supply Curve Cost Factor - Supply curve illustrates the increasing costs of developing additional CCS capacity.

INITIAL TIME = 2022 Units: Year
The initial time for the simulation.

Initial Transportation Construction Capacity= 1e+06
Units: tCO2/Year/Year
Initial amount of capture construction capacity is tCO2/Year/Year.

Initial Transportation Energy Required per tCO2= 0.2
Units: GJ/tCO2 [0.05,0.4,0.05]
Initial energy required to process 1 tonne of CO2.

Initial Unit Capture Capital Cost= 30
Units: $/tCO2 [15,100,5]
Initial/current capital cost per tCO2 in USD over the expected life of the facility.

Initial Unit Capture Opex Cost= 20
Units: $/tCO2 [10,40,5]
Initial/current operating and maintenance cost per tCO2 in USD.

Initial Unit Sequestration Capital Cost= 10
Units: $/tCO2 [5,30,0.1]
Initial/current capital cost per tCO2 in USD over the expected life of the facility.

Initial Unit Sequestration Opex Cost= 15
Units: $/tCO2 [5,40,0.5]
Initial/current operating and maintenance cost per tCO2 in USD.

Initial Unit Transportation Capital Cost= 3

Units: $/tCO2 [1,10,0.5]
Initial/current capital cost per tCO2 in USD over the expected life of the facility.

Initial Unit Transportation Opex Cost= 5
Units: $/tCO2 [1,10,0.5]
Initial/current operating and maintenance cost per tCO2 in USD.

Injection= CO2 Delivery
Units: tCO2/Year
Assumption that all amounts delivered to Sequestration capacity will be injected into the site.

Installed and Pending Capacity Transportation= CO2 Transportation Capacity+CO2 Transportation Capacity in Development+CO2 Transportation Capacity in Construction
Units: tCO2/Year
Total amount of projects in planned, under construction, and completed.

Installed and Pending Capture Capacity= Emission Sources Equipped with CO2 Capture+CO2 Capture Capacity in Development+CO2 Capture Capacity in Construction
Units: tCO2/Year
Total amount of projects in planned, under construction, and completed.

Installed and Pending Sequestration Capacity= CO2 Sequestration Capacity+CO2 Sequestration Capacity in Construction+CO2 Sequestration Capacity in Development
Units: tCO2/Year
Total amount of projects in planned, under construction, and completed.

Leakage= CO2 Sequestered*Sequestration Leakage Rate
Units: tCO2/Year

Leakage from transport capacity= 0.02
Units: Dmnl [0.001,0.1,0.001]

Learning Curve Sensitivity Variable= 1
Units: Dmnl
Variable used to change the learning curve factor applied to all in order to test for sensitivity.

Learning Curve Strength Capture Capital Cost= ln(1 - ("Capital Cost Reduction per Doubling of Experience (C)"*Learning Curve Sensitivity Variable))/ln(2)
Units: Dmnl
The learning curve strength (exponent in the learning curve formulation).

Learning Curve Strength Capture Energy Requirements= ln(1 - ("Energy Requirements Reduction per Doubling of Experience (C)"*Learning Curve Sensitivity Variable))/ln(2)
Units: Dmnl
The learning curve strength (exponent in the learning curve formulation).

"Learning Curve Strength Capture O&M Costs"= ln(1 - ("O&M Cost Reduction per Doubling of

Experience (C)"*Learning Curve Sensitivity Variable))/ln(2)
Units: Dmnl
The learning curve strength (exponent in the learning curve formulation).

Learning Curve Strength Sequestration Capital Cost= ln(1 - ("Capital Cost Reduction per Doubling of Experience (S)"*Learning Curve Sensitivity Variable))/ln(2)
Units: Dmnl
The learning curve strength (exponent in the learning curve formulation).

Learning Curve Strength Sequestration Energy Requirements= ln(1 - ("Energy Requirements Reduction per Doubling of Experience (S)"*Learning Curve Sensitivity Variable))/ln(2)
Units: Dmnl
The learning curve strength (exponent in the learning curve formulation).

"Learning Curve Strength Sequestration O&M Costs"= ln(1 - ("O&M Cost Reduction per Doubling of Experience (S)"*Learning Curve Sensitivity Variable))/ln(2)
Units: Dmnl
The learning curve strength (exponent in the learning curve formulation).

Learning Curve Strength Transportation Capital Cost= ln(1 - ("Capital Cost Reduction per Doubling of Experience (T)"*Learning Curve Sensitivity Variable))/ln(2)
Units: Dmnl
The learning curve strength (exponent in the learning curve formulation).

Learning Curve Strength Transportation Energy Requirements= ln(1 - ("Energy Requirements Reduction per Doubling of Experience (T)"*Learning Curve Sensitivity Variable))/ln(2)
Units: Dmnl
The learning curve strength (exponent in the learning curve formulation).

"Learning Curve Strength Transportation O&M Costs"= ln(1 - ("O&M Cost Reduction per Doubling of Experience (T)"*Learning Curve Sensitivity Variable))/ln(2)
Units: Dmnl
The learning curve strength (exponent in the learning curve formulation).

Marginal Cost Index= Marginal CCS Cost/Initial Marginal CCS Cost
Units: Dmnl
Index showing the marginal cost of CCS relative to its initial value.

Marginal Cost without Supply Curve= Total Capital Cost+"Total OE&M Cost"
Units: $/tCO2
Cost without incorporating the supply curve cost factor. Used for output only.

Minimum Capture Energy Required per tCO2= 0.5
Units: GJ/tCO2
Thermodynamic minimum energy required.

Minimum Sequestration Energy Required per tCO2= 0.001

Units: GJ/tCO2
Thermodynamic minimum energy required.

"Minimum Sequestration Unit O&M Cost"= 1
Units: $/tCO2 [1,5,0.5]
Theoretical Minimum O&M cost required to operate and maintain capacity.

Minimum Transportation Energy Required per tCO2= 0.05
Units: GJ/tCO2
Thermodynamic minimum energy required.

Minimum Unit Capture Capital Cost= 5
Units: $/tCO2
Theoretical Minimum capital cost required to build capacity.

"Minimum Unit O&M Cost"= 5
Units: $/tCO2
Theoretical Minimum O&M cost required to operate and maintain capacity.

Minimum Unit Sequestration Capital Cost= 5
Units: $/tCO2
Theoretical Minimum capital cost required to build capacity.

Minimum Unit Transportation Capital Cost= 0.5
Units: $/tCO2
Theoretical Minimum capital cost required to build capacity.

"Minimum Unit Transportation O&M Cost"= 1
Units: $/tCO2
Theoretical Minimum O&M cost required to operate and maintain capacity.

mu= 0
Units: Dmnl
Mu (mean) value for estimating lognormal using tanh.

Net Injection= Injection-Leakage
Units: tCO2/Year
Net amount of injection minus leakage each year.

Normal Capture Project Construction Time= 3
Units: Year [2,10,0.5]
The amount of time on average it takes for a project to complete construction and based on available utilization, progress projects to available capacity.

Normal Sequestration Project Construction Time= 3
Units: Year [2,10,0.5]
The amount of time on average it takes for a project to complete construction and based on available

utilization, progress projects to available capacity.

Normal Transportation Project Construction Time= 3
Units: Year [2,10,0.5]
The amount of time on average it takes for a project to complete construction and based on available utilization, progress projects to available capacity.

NZE Scenario Table Function 4([(0,0)-(10,10)],(2022,1), (2025,0.914454), (2030,0.672566), (2035,0.486726), (2040,0.348083), (2045,0.269911), (2050,0.224189))
Units: Dmnl
!Year IEA Net Zero Emissions Scenario (NZE)

"O&M Cost Reduction per Doubling of Experience (C)"= 0.08
Units: Dmnl [0,0.2,0.01]
The fractional reduction in O&M cost per doubling of cumulative capacity operating experience.

"O&M Cost Reduction per Doubling of Experience (S)"= 0.05
Units: Dmnl [0,0.1,0.01]
The fractional reduction in O&M cost per doubling of cumulative capacity operating experience.

"O&M Cost Reduction per Doubling of Experience (T)"= 0.01
Units: Dmnl [0,0.05,0.01]
The fractional reduction in O&M cost per doubling of cumulative capacity operating experience.

Operation Experience from RandD= 100000
Units: tCO2/Year
Increased Operations experience through R&D.

Planned CO2 capture flow= Planned Total Emissions from facilities with capture
Units: tCO2/Year
Planned amount of capture not limited by constraints. Drives desired capacity amounts for capture, transportation, and sequestration.

Planned CO2 emissions from capture operation= Planned Energy required for capture operation*CO2 intensity of energy for capture
Units: tCO2/Year
Planned emissions from the energy needed to operate the capture facility.

Planned Energy required for capture operation= Capture Energy Required per tCO2*Desired CO2 Capture Projects
Units: GJ/Year
The planned or expected energy needed to run the capture operation.

Planned Total Emissions from facilities with capture= (Desired CO2 Capture Projects+Planned CO2 emissions from capture operation)*Capture Fraction
Units: tCO2/Year
Planned emissions captured from facilities with CCS and the captured energy from operating facility.

Potential CO2 delivery= CO2 Transportation Capacity*(1-Leakage from transport capacity)
Units: tCO2/Year
Percentage of CO2 leaks from pipeline due to maintenance, reliability, or other issues. The amount delivered is the capacity to deliver minus the leakage.

Potential Total Emissions from facilities with capture= (Emission Sources Equipped with CO2 Capture+CO2 emissions from capture operation)*Capture Fraction
Units: tCO2/Year
Emissions captured from facilities with CCS and the captured energy from operating facility.

Price of Energy= 15
Units: $/GJ [10,100,1]
Exogenous variable: cost of energy based on current market global averages.

Relative Capture Capital Experience= ZIDZ(Cumulative Capital Capture Experience,Initial Level of Capture Capital Experience)
Units: Dmnl
Total experience compared to initial level of experience in CCS.

Relative Capture Operations Experience= ZIDZ(Cumulative Operations Capture Experience, Initial Level of Capture Operations Experience)
Units: Dmnl
Total experience compared to initial level of experience in operations of CCS facilities.

Relative Sequestration Capital Experience= Cumulative Capital Sequestration Experience/Initial Level of Sequestration Capital Experience
Units: Dmnl
Total experience compared to initial level of experience in CCS.

Relative Sequestration Operations Experience= ZIDZ(Cumulative Operations Sequestration Experience, Initial Level of Sequestration Operations Experience)
Units: Dmnl
Total experience compared to initial level of experience in operations of CCS facilities.

Relative Transportation Capital Experience= ZIDZ(Cumulative Capital Transportation Experience,Initial Level of Transportation Capital Experience)
Units: Dmnl
Total experience compared to initial level of experience in CCS.

Relative Transportation Operations Experience= ZIDZ(Cumulative Operations Transportation Experience,Initial Level of Transportation Operations Experience)
Units: Dmnl
Total experience compared to initial level of experience in operations of CCS facilities.

SAVEPER = TIME STEP
Units: Year [0,?]

The frequency with which output is stored.

Scenario Emissions Factor= IF THEN ELSE(Scenario Switch=1, Steps Scenario Table Function 1(Time), IF THEN ELSE(Scenario Switch=2, APC Scenario Table Function 2(Time), IF THEN ELSE(Scenario Switch=3, SDS Scenario Table Function 3(Time), NZE Scenario Table Function 4(Time))))
Units: Dmnl
Using the Scenario Switch, this variable determines which emissions scenario is applied.

Scenario Switch= 4
Units: Dmnl [1,4,1]
Switch for applying emissions scenarios: 1=Steps Scenario; 2=APC Scenario; 3=SDS Scenario; 4= NZE Scenario.

SDS Scenario Table Function 3([(0,0)-(10,10)],(2022,1), (2025,0.914454), (2030,0.823009), (2035,0.70649), (2040,0.60177), (2045,0.544248), (2050,0.516224))
Units: Dmnl
!Year Sustainable development scenario (SDS) from IEA.

Sensitivity Variable for Function Supply Curve= 1
Units: Dmnl [0,2,0.1]
Since the supply curve is an estimation and table function, this variable will allow sensitivity analysis to be conducted by varying the curve with a parameter.

Sequestration Capacity Adjustment Time= 2
Units: Year [1,5,0.5]
The amount of time on average it takes for a project to move into the planning stage.

Sequestration Capacity Completing= Sequestration Construction Capacity*Utilization of Sequestration Construction Capacity
Units: tCO2/Year/Year
Rate in tCO2/Year/Year that projects that are under construction get completed based on utilization of available construction capacity.

Sequestration Capacity Construction Starting= CO2 Sequestration Capacity in Development/(Sequestration Project Initiation Cycle Time*Adjustment Time Sensitivity Variable)
Units: tCO2/Year/Year
Rate in tCO2/Year/Year that projects move from planned to under construction.

Sequestration Capacity Development Starting= MAX(0,(Desired CO2 Sequestration Projects-Installed and Pending Sequestration Capacity)/(Sequestration Capacity Adjustment Time*Adjustment Time Sensitivity Variable))
Units: tCO2/Year/Year
Rate in tCO2/Year/Year that projects are initiated and move to the planned phase.

Sequestration Construction Capacity= SMOOTH3I(Desired Sequestration Completion, Time to Change Construction Capacity, Initial Sequestration Construction Capacity)

Units: tCO2/Year/Year
Capacity available for the construction of CCS projects. Adjusts based on time to adjust and desired completion rate.

Sequestration Decommissioning Rate= CO2 Sequestration Capacity/CCS Project Lifetime
Units: tCO2/Year/Year
Rate at which facilities are decommissioned over time.

Sequestration Energy Required per tCO2= Minimum Sequestration Energy Required per tCO2+((Initial Sequestration Energy Required per tCO2-Minimum Sequestration Energy Required per tCO2)*Effect of Experience on Sequestration Energy Requirements)
Units: GJ/tCO2
Amount of energy needed to capture and process a tCO2 multiplied by the learning curve effect. Theory is that as more projects are completed, the learning from past projects should make future projects more efficient and require less energy. Minimum thermodynamic required energy incorporated.

Sequestration Leakage Rate= 0.01
Units: 1/Year [0.001,0.1,0.001]
Rate of leakage once CO2 has been permanently sequestered underground.

Sequestration Operations Experience= CO2 Sequestration Capacity+Operation Experience from RandD
Units: tCO2/Year
Increased experience in CCS with operations of CCS projects and a factor from investment in R&D.

Sequestration Project Construction Time= ZIDZ(CO2 Sequestration Capacity in Construction, Sequestration Capacity Completing)
Units: Year
Little's Law: under steady-state conditions, the average number of items in a queuing system equals the average rate at which items arrive multiplied by the average time that an item spends in the system.

Sequestration Project Initiation Cycle Time= 4
Units: Year [2,7,0.5]
The amount of time on average it takes for a project to move into the construction stage from capacity in development.

sigma= 0.5
Units: Dmnl
Sigma (standard deviation) value for estimating lognormal using tanh.

Steps Scenario Table Function 1([(0,0)-(10,10)],(2022,1), (2025,1.05605), (2030,1.0708), (2035,1.09145), (2040,1.10619), (2045,1.12537), (2050,1.13274))
Units: Dmnl
!Year IEA stated policies scenario (STEPS)

Supply Curve Cost Factor= (Sensitivity Variable for Function Supply Curve * Function for Supply Curve of Cumulative Capacity(Installed and Pending Capture Capacity)-1)+1
Units: Dmnl
Supply curve illustrates the increasing costs of developing additional CCS capacity.

Table Function for Utilization of Construction Capacity([(0,0)-(10,10)],(0,0), (0.25,0.35), (0.5,0.65), (0.75,0.85), (1,1), (1.25,1.1), (1.5,1.18), (1.75,1.23), (2,1.25))
Units: Dmnl
Table function to illustrate how construction capacity will be utilized (Sterman, 2000 Figure 15-4).

TIME STEP = 0.0625 Units: Year [0,?]
The time step for the simulation.

Time to Change Construction Capacity= 2
Units: Year [0.5,4]
Time in years it takes to change construction capacity through ramping up supply chains, workers, etc., or ramping down.

Total Capital Cost= Unit Capture Capital Cost+Unit Sequestration Capital Cost+Unit Transportation Capital Cost
Units: $/tCO2
Sum of capital costs from capture, transportation, and sequestration.

Marginal CCS Cost= (Total Capital Cost*Supply Curve Cost Factor)+"Total OE&M Cost"
Units: $/tCO2
Total cost for end-to-end CCS projects, including increasing costs as capacity increases due to the supply curve.

Total Cost of Sequestered CO2= INTEG (Cost of CO2 Injected, 0)
Units: $
Sum total amount of the cost of injected CO2.

"Total OE&M Cost"= "Unit OE&M Capture Cost"+"Unit OE&M Sequestration Cost"+"Unit OE&M Transportation Cost"
Units: $/tCO2
Sum of operations, energy, and maintenance costs from capture, transportation, and sequestration.

Transportation Capacity Adjustment Time= 2
Units: Year [1,5,0.5]
The amount of time on average it takes for a project to move into the planning stage.

Transportation Capacity Completing= Transportation Construction Capacity*Utilization of Transportation Construction Capacity
Units: tCO2/Year/Year
Rate in tCO2/Year/Year that projects that are under construction get completed based on utilization of available construction capacity.

Transportation Capacity Construction Starting= CO2 Transportation Capacity in Development/(Transportation Project Initiation Cycle Time*Adjustment Time Sensitivity Variable)
Units: tCO2/Year/Year
Rate in tCO2/Year/Year that projects move from planned to under construction.

Transportation Capacity Development Starting= MAX(0,(Desired CO2 Transportation Projects-Installed and Pending Capacity Transportation)/(Transportation Capacity Adjustment Time*Adjustment Time Sensitivity Variable))
Units: tCO2/Year/Year
Rate in tCO2/Year/Year that projects are initiated and move to the planned phase.

Transportation Construction Capacity= SMOOTH3I(Desired Transportation Completion, Time to Change Construction Capacity, Initial Transportation Construction Capacity)
Units: tCO2/Year/Year
Capacity available for construction of CCS projects. Adjusts based on time to adjust and desired completion rate.

Transportation Decommissioning Rate= CO2 Transportation Capacity/CCS Project Lifetime
Units: tCO2/Year/Year
Rate at which facilities are decommissioned over time.

Transportation Energy Required per tCO2= Minimum Transportation Energy Required per tCO2+((Initial Transportation Energy Required per tCO2-Minimum Transportation Energy Required per tCO2)*Effect of Experience on Transportation Energy Requirements)
Units: GJ/tCO2
Amount of energy needed to capture and process a tCO2 multiplied by the learning curve effect. Theory is that as more projects are completed, the learning from past projects should make future projects more efficient and require less energy. Minimum thermodynamic required energy incorporated.

Transportation Operations Experience= CO2 Transportation Capacity+Operation Experience from RandD
Units: tCO2/Year
Increased experience in CCS with operations of CCS projects and a factor from investment in R&D.

Transportation Project Construction Time= ZIDZ(CO2 Transportation Capacity in Construction, Transportation Capacity Completing)
Units: Year
Little's Law: under steady-state conditions, the average number of items in a queuing system equals the average rate at which items arrive multiplied by the average time that an item spends in the system.

Transportation Project Initiation Cycle Time= 6
Units: Year [3,12,0.5]
The amount of time on average it takes for a project to move into the construction stage from capacity in development.

Unit Capture Capital Cost= Minimum Unit Capture Capital Cost+(((Initial Unit Capture Capital Cost*Cost Sensitivity Variable)-Minimum Unit Capture Capital Cost)*Effect of Experience on Capture Capital Cost)
Units: $/tCO2
CAPEX unit costs per tCO2 varied by the learning curve effect from capital costs. Minimum floor for costs, cannot drop to zero.

"Unit O&M Cost"= "Minimum Unit O&M Cost"+((Initial Unit Capture Opex Cost*Cost Sensitivity Variable)-"Minimum Unit O&M Cost")*"Effect of Experience on Capture O&M Costs"
Units: $/tCO2
O&M costs reduced by the effect of experience learning curve for O&M. Minimum cost to prevent costs from unrealistically dropping to zero.

"Unit O&M Transportation Cost"= "Minimum Unit Transportation O&M Cost"+((Initial Unit Transportation Opex Cost*Cost Sensitivity Variable)-"Minimum Unit Transportation O&M Cost")*"Effect of Experience on Transportation O&M Costs"
Units: $/tCO2
O&M costs reduced by the effect of experience learning curve for O&M. Minimum cost to prevent costs from unrealistically dropping to zero.

"Unit OE&M Capture Cost"= "Unit O&M Cost"+Energy Capture Cost of Operations
Units: $/tCO2
Total energy costs and operating and maintenance costs in USD per tCO2.

"Unit OE&M Sequestration Cost"= "Unit Sequestration O&M Cost"+Energy Sequestration Cost of Operations
Units: $/tCO2
Total energy costs and operating and maintenance costs in USD per tCO2.

"Unit OE&M Transportation Cost"= "Unit O&M Transportation Cost"+Energy Transportation Cost of Operations
Units: $/tCO2
Total energy costs and operating and maintenance costs in USD per tCO2.

Unit Sequestration Capital Cost= Minimum Unit Sequestration Capital Cost+(((Initial Unit Sequestration Capital Cost*Cost Sensitivity Variable)-Minimum Unit Sequestration Capital Cost)*Effect of Experience on Sequestration Capital Cost)
Units: $/tCO2
CAPEX unit costs per tCO2 varied by the learning curve effect from capital costs. Minimum floor for costs, cannot drop to zero.

"Unit Sequestration O&M Cost"= "Minimum Sequestration Unit O&M Cost"+((Initial Unit Sequestration Opex Cost*Cost Sensitivity Variable)-"Minimum Sequestration Unit O&M Cost")*"Effect of Experience on Sequestration O&M Costs"
Units: $/tCO2
O&M costs reduced by the effect of experience learning curve for O&M. Minimum cost to prevent costs from unrealistically dropping to zero.

Unit Transportation Capital Cost= Minimum Unit Transportation Capital Cost+(((Initial Unit Transportation Capital Cost*Cost Sensitivity Variable)-Minimum Unit Transportation Capital Cost)*Effect of Experience on Transportation Capital Cost)
Units: $/tCO2
CAPEX unit costs per tCO2 varied by the learning curve effect from capital costs. Minimum floor for costs, cannot drop to zero.

Utilization of Capture Construction Capacity= Table Function for Utilization of Construction Capacity(ZIDZ(Desired Capture Completion,Capture Construction Capacity))
Units: Dmnl
Utilization of construction capacity based on desired and available.

Utilization of Sequestration Construction Capacity= Table Function for Utilization of Construction Capacity(ZIDZ(Desired Sequestration Completion, Sequestration Construction Capacity))
Units: Dmnl
Utilization of construction capacity based on desired and available.

Utilization of Transportation Construction Capacity= Table Function for Utilization of Construction Capacity(ZIDZ(Desired Transportation Completion, Transportation Construction Capacity))
Units: Dmnl
Utilization of construction capacity based on desired and available.

z= (ln(Incentive to Cost Ratio)-mu)/(sigma*SQRT(2))
Units: Dmnl
Calculated variable used for an equation to approximate cumulative lognormal distribution.

Appendix D

Emissions Scenarios

Emissions data was collected from the IEA World Energy report (2023), the IEA Net Zero by 2050 report (2021), and the Energy Technology Perspectives report (2023) to illustrate four possible emission scenarios. This data can be found in Table D.1. Additionally, data from these reports was used to estimate the expected amount of CO2 to be captured and stored through CCS for each scenario (Table D.1). To leverage these scenarios with the existing facilities with emissions data, the scenarios were converted to factors (Table D.3 [124] [8] [14]

Year	Steps	APC	SDS	NZE
2022	34.8	33.7	33.4	33.2
2025	35.7	33.3	30.6	30.2
2030	36	30.6	26.7	21.1
2035	36.3	27.5	21.6	12.9
2040	36.4	24.9	16.9	6.3
2045	36.4	23.1	12.9	2.6
2050	36	22.1	9.9	0

Table D.1: CO2 emissions from energy and industry (gigatons per year).

Year	Steps	APC	SDS	NZE
2022	0.045	0.045	0.045	0.045
2025	0.1	0.3	0.4	0.8
2030	0.3	0.9	1.2	1.7
2035	0.7	1.85	2.35	3.6
2040	1.1	2.8	3.5	5.5
2045	1.75	4.15	5.55	6.55
2050	2.4	5.5	7.6	7.6

Table D.2: Estimated capture emissions (gigatons per year).

Year	Steps	APC	SDS	NZE
2022	1	1	1	1
2025	1.027	0.996	0.927	0.932
2030	1.042	0.933	0.834	0.686
2035	1.062	0.87	0.716	0.496
2040	1.076	0.821	0.61	0.355
2045	1.095	0.808	0.552	0.275
2050	1.102	0.818	0.523	0.229

Table D.3: Global CO2 emissions from energy and industry (gigatons per year)

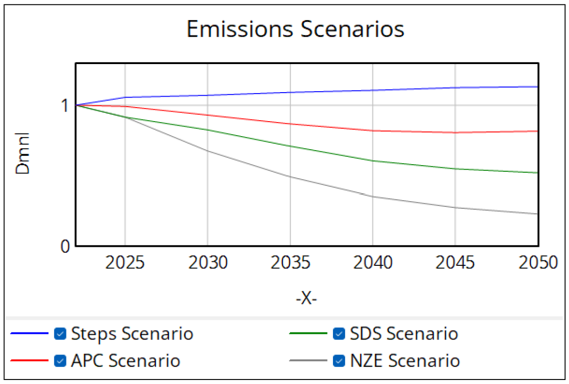


Figure D.1: Emissions scenarios.

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