REPUBLIC OF TÜRKİYE
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF SOCIAL SCIENCES
ECONOMICS
ECONOMICS (ENGLISH)

MASTER OF SCIENCE THESIS

PLANT HETEROGENEITY AND CCS: EVALUATING INVESTMENTS, ABATEMENT STRATEGIES, AND POLICY MEASURES

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21729017

THESIS ADVISOR
ASSOC. PROF. TUNÇ DURMAZ

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Demet TAÇ tarafından hazırlanan “PLANT HETEROGENEITY AND CCS: EVALUATING INVESTMENTS, ABATEMENT STRATEGIES, AND POLICY MEASURES” başlıklı çalışma, **04/12/2024** tarihinde yapılan savunma sınavı sonucunda oybirliği ile başarılı bulunmuş ve jürimiz tarafından İktisat Ana Bilim Dalı İngilizce İktisat Yüksek Lisans Programında **YÜKSEK LİSANS** tezi olarak kabul edilmiştir.

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ABSTRACT

PLANT HETEROGENEITY AND CCS: EVALUATING INVESTMENTS, ABATEMENT STRATEGIES, AND POLICY MEASURES

This study investigates the decision-making processes of carbon-emitting plants regarding the adoption of Carbon Capture and Storage (CCS) technology versus traditional abatement methods. Inspired on a theoretical framework from Golombek et al. (2023) [Policies to Promote Carbon Capture and Storage Technologies. *Environmental and Resource Economics*, 85(1), 267-302], the research evaluates the economic trade-offs associated with CO_2 abatement while emphasizing the role of government interventions. The analysis focuses on two primary strategies: traditional abatement techniques, including fuel switching and energy efficiency improvements, which are inherently limited in achieving full abatement; and CCS, which involves substantial fixed investment but offers full abatement and exemption from emissions taxes.

Key findings indicate that plants with high emissions tend to adopt CCS due to its long-term cost efficiency and the benefits of economies of scale, whereas plants with lower emissions continue to rely on traditional abatement methods paired with emissions tax payments. Government incentives, including innovation-driven policies and well-designed carbon taxes, are identified as essential for overcoming financial barriers and encouraging widespread CCS adoption. These policies not only enhance cost-effectiveness but also leverage economies of scale, learning-by-doing, and network efficiencies to make CCS a viable and impactful solution for emissions reduction.

Keywords: Carbon Capture and Storage (CCS), Abatement, Emissions Tax

ÖZET

TESİS HETEROJENLİĞİ VE KYD: YATIRIMLARIN, AZALTMA STRATEJİLERİNİN VE POLİTİKA ÖNLEMLERİNİN DEĞERLENDİRİLMESİ

Bu çalışma, karbon emisyonu yapan tesislerin Karbon Yakalama ve Depolama (KYD) teknolojisini benimsemesi ile geleneksel azaltım yöntemleri arasındaki karar alma süreçlerini incelemektedir. Golombek vd. (2023) [Policies to Promote Carbon Capture and Storage Technologies. *Environmental and Resource Economics*, 85(1), 267-302] tarafından geliştirilen teorik modelden ilham alan çalışma, devlet müdahalelerinin rolünü vurgularken, CO_2 azaltımıyla ilgili ekonomik ödünleşimleri değerlendirmektedir. Analiz, iki temel stratejiye odaklanmaktadır: düşük karbon salınımı yapan yakıtlara geçiş ve enerji verimliliği iyileştirmeleri gibi geleneksel azaltım teknikleri (bu yöntemler doğası gereği tam azaltım sağlamada sınırlıdır) ile yüksek maliyetli sabit yatırım gerektiren, ancak emisyonların tamamını yakalayabilen ve bu sayede karbon vergilerinden muafiyet sunan KYD teknolojisi.

Temel bulgular, yüksek emisyon üreten tesislerin uzun vadeli maliyet etkinliği ve ölçek ekonomilerinin avantajları nedeniyle KYD teknolojisini benimseme eğiliminde olduğunu, düşük emisyon üreten tesislerin ise emisyon vergisi ödemeleriyle birlikte geleneksel azaltım yöntemlerini uygulamaya devam ettiğini göstermektedir. Teknoloji odaklı politikalar ve etkili karbon vergileri de dahil olmak üzere devlet teşvikleri, finansal engellerin aşılması ve KYD'nin yaygın şekilde benimsenmesi için kritik bir öneme sahiptir. Bu politikalar yalnızca maliyet etkinliğini artırmakla kalmayıp, aynı zamanda ölçek ekonomileri, yaparak öğrenme süreci ve ağ verimliliklerinden faydalanarak KYD'yi emisyon azaltımı için uygulanabilir ve etkili bir çözüm haline getirmektedir.

Anahtar Kelimeler: Karbon Yakalama ve Depolama (KYD), Emisyon Azaltımı, Emisyon Vergisi

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Demet TAÇ

December 2024 , İstanbul

“Neredeyse gün doğacaktı
Herkes gibi kalkacaktınız
Belki daha uykunuz da vardı
Geceniz geliyor aklıma”

Melih Cevdet Anday

6 Şubat’ta kaybettiğimiz herkese, Hatay’a…

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LIST OF ABBREVIATIONS

BCCS	: Bioenergy with Carbon Capture and Storage
CCS	: Carbon Capture and Storage
CCUS	: Carbon Capture, Utilization, and Storage
CIF	: Carbon Capture and Storage Infrastructure Fund
CO_2	: Carbon Dioxide
DAC	: Direct Air Capture
EOR	: Enhanced oil Recovery
ETS	: Emissions Trading Systems
EU	: European Union
FEED	: Front-End Engineering and Design
G7	: Group of Seven
GDP	: Gross Domestic Product
GHG	: Greenhouse Gases
IEA	: International Energy Agency
IPCC	: International Panel on Climate Change
MB	: Marginal Benefit
MC	: Marginal Cost
MTPA	: Million Tons per Annum
NDCs	: Nationally Determined Contributions
NETL	: National Energy Technology Lab Operated by the U.S. Department of Energy
NOAA	: National Oceanic and Atmospheric Administration
NZE	: Net Zero Emissions
UNEP	: United Nations Environment Programme
UNFCCC	: United Nations Framework Convention on Climate Change
USA	: United States of America

1. INTRODUCTION

Addressing climate change has become an urgent global priority, necessitating the development and implementation of effective strategies to reduce carbon dioxide (CO_2) emissions. Carbon Capture and Storage (CCS) technology has emerged as a solution due to its potential to lower greenhouse gas emissions effectively. Unlike traditional abatement techniques -such as energy efficiency improvements and the transition to renewable energy sources- CCS offers a more comprehensive strategy to reduce emissions, especially in industrial sectors where emissions are challenging to mitigate.

Traditional abatement techniques focus on reducing energy consumption, improving the efficiency of existing systems, and switching to fuels that produce less emissions. For example, transitioning from coal to natural gas can significantly reduce CO_2 emissions. However, both approaches face significant challenges and limitations, particularly in hard-to-abate sectors. These industries often involve chemical processes that inherently generate CO_2 emissions, which cannot be fully addressed through efficiency improvements or switching to alternative fuels alone.

In contrast, CCS technology provides a way to capture and store CO_2 emissions from existing industrial processes and power generation, making it a crucial tool for sectors where emissions are difficult to eliminate. For instance, the calcination of limestone in cement production releases CO_2 as a byproduct, which cannot be avoided through efficiency improvements or fuel switching alone (Global CCS Institute, 2023a). Thus, CCS is a vital component of any comprehensive climate strategy, particularly for achieving the deep emissions cuts needed to meet international climate goals (IEA, 2023c).

This study explores the strategic decisions of industrial plants in choosing between CCS and traditional abatement methods, focusing on economic incentives and regulatory policies. One objective is to evaluate the cost implications of these choices. This involves a thorough analysis of the economic implications associated with CCS which include initial investment costs, operational expenses, and carbon taxes. By comparing these factors with those of traditional abatement methods, this study aims to provide a comprehensive understanding of the financial considerations influencing strategic decisions (Golombek et al., 2023).

Another objective is to examine the role of government interventions in promoting CCS adoption. Government policies like subsidies, tax incentives, and regulatory frameworks can shape the adoption of CCS technology (European Commission, 2023b). Therefore, the study analyzes how these economic incentives can facilitate CCS adoption and overcome barriers to its implementation.

This study also investigates network effects and economies of scale associated with the CCS value chain. Unlike Golombek's analysis, this research discusses network effects starting from the assumption of uniformly distributed emissions and examines spatial distribution scenarios based on how terminal locations impact costs.

As more plants adopt CCS technology, optimized transportation networks and storage hubs can reduce costs and improve economic viability. The study aims to assess how these network effects and economies of scale can enhance the CCS value chain.

The final objective of the study is to provide policy recommendations that could enhance the effectiveness of CCS based on the results.

Sections of this thesis are organized as follows: In chapter two, a literature survey is provided, discussing the global context of climate change and CO_2 emissions with a focus on renewable energy and nuclear alternatives. This chapter also introduces CCS technologies, covering aspects such as network effects, initial investment costs, economies of scale, the importance of CCS, innovations and technological developments, case studies and impacts, and the role of policies and regulations in promoting CCS are explored.

Chapter three presents the model. The theoretical framework and model used in the study are discussed, including the CCS cost function and the integration of Salop's Circle with CCS. Abatement and tax strategies are explained, with an emphasis on emission tax optimization and the application of the Lagrange Multiplier Method for cost minimization. The role of terminals and transmission hubs within the CCS value chain is also analyzed.

In chapter four, the results of the study are presented and discussed. The findings are examined in relation to the research objectives, and their implications for policy frameworks are analyzed.

Finally, in chapter five, the conclusions and recommendations are provided. The key findings are summarized, conclusions are drawn, and policy recommendations aimed at enhancing CCS technologies are proposed. The limitations of the study are discussed, and directions for future research are suggested.

2. LITERATURE SURVEY

2.1. Background on Climate Change and CO_2 Emissions

Climate change is primarily driven by the increase in greenhouse gas (GHG) emissions, especially CO_2, due to human activities such as burning fossil fuels, deforestation, and industrial processes. The Intergovernmental Panel on Climate Change (IPCC) reports have consistently highlighted the significant impact of these emissions on global warming, leading to severe weather patterns, rising sea levels, and biodiversity loss (IPCC, 2021).

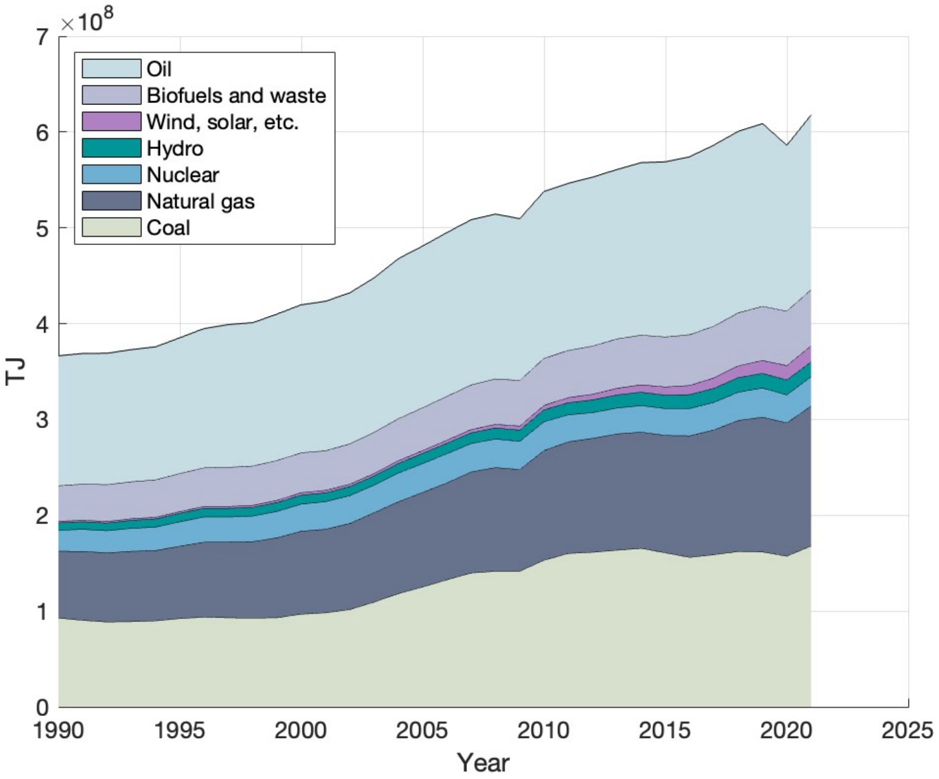
There is a clear relationship between humanity's ability to exploit energy resources and its development and growth. Looking back from today's fossil fuel-driven world to times when fossil fuels were not used, we observe energy scarcity and consequently slow development. From the moment fossil fuels started being used as the primary energy source, energy consumption exploded. In 2022, 82% of the total global energy usage still was derived from fossil fuels as in 2022 (Repsol, 2023).

Figure 1 presents the energy supply by source from 1990 to 2021. According to the graph, global energy supply continues to increase (IEA, 2023c). During this period alone, the total supply has increased by more than 50%. Meanwhile, oil and coal usage occupy a significant portion, with coal supply increasing until the 2010s but then stalling (IEA, 2023f ; 2024d).

Throughout this period, natural gas has become increasingly popular, and the use of wind and solar energy began to emerge. However, the supply of nuclear energy has remained unchanged over these 31 years. Some researchers argue that renewable energy -particularly solar energy- will be the main energy source in the long term (Mirandola & Lorenzini, 2016).

Nevertheless, as of 2023, fossil fuels still constitute approximately 81.5% of global primary energy consumption, despite significant investments in renewable technologies. Given the rising demand for energy -particularly in developing countries- fossil fuels are expected to remain a crucial part of the energy mix for the anticipated future (Energy Institute, 2024).

Figure 1. Total Global Energy Supply by Source (1990 – 2021)



Source: (IEA, 2023f ; 2024d)

Note: *TES here excludes electricity and heat trade. Coal also includes peat and oil shale where relevant.*

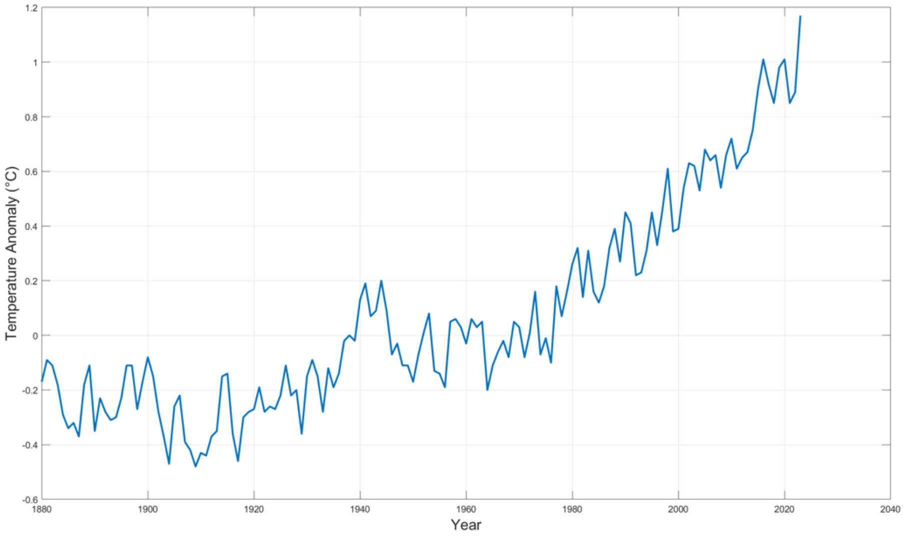
While the role fossil fuels have played in advancing our civilization is indisputable, their impact on climate change has become one of the most pressing issues for humanity. It is important to elaborate on the term *"climate change"* here. The climate on Earth has always fluctuated and will continue to do so. However, the critical concern is the contribution of human activities to the current climatic changes.

How significant is this contribution compared to other factors? Reports indicate that the planet is warming rapidly, and the main driver of this warming is greenhouse gases. The IPCC also highlights the increase in production-based CO_2 emissions over the last 150 years (IPCC, 2023).

Figure 2 shows the comparison of recorded global surface temperatures from 1880 to 2023 against the long-term average from 1951 to 1980. According to this data, the last decade has been the hottest period on record, and in 2023, the global average surface temperature was 1.36 °C warmer than the 19th century, setting a record (GISTEMP Team, 2024; Lenssen et al., 2019).

There are numerous climate model studies predicting future climate trends. These models present various temperature and emission forecasts with different confidence intervals, depending on scenarios and political pathways (NASA, 2024). While different models yield varying results, even in the most optimistic scenarios, temperatures are expected to continue rising for the foreseeable future.

Figure 2. Global Surface Temperature Compared to Long-Term Average (1951-1980)



Source: GISTEMP Team, 2024

2.1.1. The Role of CO_2 in Climate Change

CO_2 takes center stage in the quest for a carbon-neutral future, as it remains the most significant component of GHGs (Sahu & Kumar, 2023). Once released, CO_2 can remain in the atmosphere for 300 to 1,000 years. During this time, it traps heat and drives global warming. Without deep cuts to emissions, the effects will worsen. This will cause higher temperatures, more extreme weather events, and rising sea levels (Alan Buis, 2019). According to the National Oceanic and Atmospheric Administration (NOAA), human activities since 1990 have added 1.11 watts per square meter of heating to the atmosphere. CO_2 is responsible for 78% of this increase.

These data underline why reducing CO_2 emissions is prominent in slowing the pace of climate change (NOAA Global Monitoring Laboratory, 2024).

The fight against GHGs is conducted through the fundamental strategy known as *"net zero target"* or *"carbon neutrality"*. Carbon neutrality refers to achieving a balance where the amount of CO_2 emitted is offset by an equivalent amount of CO_2 removed from the atmosphere (Chen, 2021).

Carbon neutrality efforts typically focus on two main strategies: carbon offsetting and carbon pricing. Carbon offsetting involves institutions providing funding for projects that aim to neutralize their greenhouse gas emissions, such as renewable energy, serving as a compensatory mechanism (Gordic et al., 2023). This strategy is ideal for firms that cannot quickly reduce their emissions in the short term. Its disadvantages lie in implementation challenges related to intent and integrity issues.

Recent studies highlight significant concerns regarding intent and integrity in carbon offset strategies. For instance, research by West et al. (2023) demonstrated that tropical forest conservation projects often fail to deliver the claimed carbon reductions due to methodological flaws and insufficient monitoring, calling for urgent revisions in these practices. Similarly, Patel and Jones (2024) explored the potential of digital carbon assets to enhance the transparency and scalability of offsetting mechanisms, aiming to improve trust in carbon offset projects. These findings underscore the need for robust methodologies and enhanced transparency to address intent-related issues, such as whether firms genuinely aim to mitigate emissions or merely engage in greenwashing, and integrity-related issues, including the reliability and sustainability of offsetting projects (Jaffer et al., 2024; West et al., 2023).

With the US NDC plans, carbon offsetting is expected to create a new financial market (Strand, 2023). While the situation in China is more domestic and focused within the energy sector, in the EU, there is a practice of maintaining high standards (Evro et al., 2024).

In contrast to offsetting, carbon pricing assigns economic costs to greenhouse gas emissions. This strategy encourages emitters to reduce emissions through mechanisms such as carbon taxes and Emissions Trading Systems (ETS) (World Bank, 2024). A carbon tax directly charges for the carbon content of fossil fuels and is applied in 40 countries, covering about 15% of global GHG emissions (UNFCCC, 2024a). However, in many countries, plans are underway to implement carbon taxes.

While this policy is generally considered beneficial, concerns include the absence of a cap on total emissions and the penalization of fossil-based alternative fuels other than oil and natural gas, which may favor monopoly producers (Kiss & Popovics, 2021).

The ETS, as a market-based approach, incentivizes firms to reduce emissions by trading emission allowances (World Bank, 2024). One of the most successful plans in ETS is the European Union Emissions Trading System (EU-ETS), which began in 2005 and employs a cap-and-trade system.

EU-ETS achieved notable success in reducing emissions while supporting the economic performance of regulated firms. Research shows that, after the implementation of the EU-ETS, carbon emissions experienced statistically significant reductions, averaging around 10% across participating sectors (Dechezleprêtre et al., 2023). This reduction was achieved without compromising firm revenues, profitability, or employment levels.

Additionally, many firms have reinvested in energy-efficient systems and advanced technology, boosting productivity and even product quality (Dechezleprêtre et al., 2023; Kalantzis, 2024; Ren et al., 2022). By incentivizing emission allowance trading, the EU-ETS has prompted firms to innovate, enabling them to either reduce the costs of purchasing additional permits or increase revenue through selling surplus allowances (Kalantzis, 2024).

To further its climate objectives, the EU introduced ETS2 under Directive 2023/2413. ETS2, launching in 2027, aims to drive investments in building renovations and low-emission mobility, targeting a 42% reduction in emissions by 2030 compared to 2005 levels (European Commission, 2023a).

2.1.2. Global Emission Trends and Climate Cooperation Efforts

International agreements and national policies have been implemented to combat climate change. The 2015 Paris Agreement is a pivotal milestone, building on earlier initiatives like the IPCC (1990) and the UNFCCC (1992) (Palermo & Hernandez, 2020). At the Paris summit, 177 countries pledged to limit global temperature increases to below 2°C by 2030, with efforts to cap warming at 1.5°C by 2050 (UNFCCC, 2024b). The long-term goal is to establish a carbon-neutral economy by the second half of the century.

However, The UNEP 2023 Emissions Gap Report states that while progress has been made towards these targets as of 2023, it is not sufficient. At the time the agreement was adopted, GHG emissions in 2030 were projected to increase by 16% based on current policies. Today, this increase is estimated at 3%. The report also calculates that to achieve the Paris Agreement's 2°C target, emissions need to be reduced by 28% by 2030, and to achieve the 1.5°C target, they need to be reduced by 42%. New policies and technologies focused on energy efficiency and emission reductions are being developed to meet these goals (UNEP, 2023).

Regional emission patterns reveal that, as of 2021, four regions are responsible for nearly half of global emissions: China (26%), the USA (11%), India (7%), and the European Union (6%). These contributions have shifted significantly since 1990, when the USA was the largest emitter with 17%. At that time, China and India accounted for only 8.8% and 3.1% of global emissions, respectively (World Resources Institute, 2022). Over the past three decades, China's rapid economic growth has made it the world's top emitter, a position it is expected to hold in the coming years. India's emissions are also projected to rise as its economy continues to grow (Evro et al., 2024).

While regional approaches to carbon neutrality vary according to economic structures, capacities, and policy priorities, all align under the Paris Agreement through their NDCs (UNFCCC, 2024a). The EU has reduced emissions through initiatives such as the European Green Deal and the USA remains a major emitter. Emissions are expected to decrease in the EU and USA, but China aims to peak emissions by 2030 and achieve carbon neutrality by 2060 (Evro et al., 2024).

In summary, although the approaches to emissions reduction vary among regions, they share a commitment to achieving the Paris Agreement's long-term climate goals. Success will depend on a combination of effective policies, technological innovation, and sustained international cooperation to meet carbon neutrality targets in the coming decades.

2.1.3. Challenges in the Energy Transition

Fossil fuel dependence and the negative outcomes it produces have driven ongoing efforts in toward alternative technological solutions for quite some time. These efforts have highlighted the increasing use of renewable energy, alternative energy sources, and Carbon Capture and Storage technologies, alongside methods such as more efficient energy utilization (Singh et al., 2023).

As technological advancements lower the costs and improve the accessibility of clean energy solutions, complementary policy frameworks have been introduced to accelerate adoption. In many leading economies today, low-carbon alternatives—such as renewable and nuclear energy—are heavily promoted and incentivized.

Renewable energies are naturally replenishable, inexhaustible energy sources derived from solar, wind, hydroelectric, geothermal, and biomass energy. These sources can play a significant role in maintaining CO_2 concentrations in the atmosphere at desired levels. Humans have historically used renewable energies, from the discovery of fire to the conversion of wind and water into mechanical energy. This knowledge laid the foundation for modern hydroelectric systems through the construction of large dams (Hohmeyer, 2008).

Where does renewable energy stand in today's energy landscape? According to the IEA, in 2023, renewable energy accounted for 30.2% of global electricity generation (IEA, 2023d). This percentage is 0.7% higher than the previous year. While the general trend suggests an increase in the popularity of renewable energy, it has not yet reached a point where it can challenge the dominance of fossil fuels in the overall energy mix. Several factors hinder this transition. Practical challenges in implementation are prominent. If affordability and ease of deployment were improved, the shift to renewable energy would progress more rapidly. Fossil fuels are widely available and their applications highly standardized, giving them an advantage over renewables. Another issue is scaling up renewable energy. It is currently difficult to expand renewables to a level capable of meeting global energy demands.

Political factors also play a role. For example, developing economies often prioritize bridging development gaps quickly using inexpensive fossil fuels over investing in renewable energy innovations. This makes the transition to renewables even more challenging.

In addition to renewables, nuclear energy offers another low-carbon alternative. Nuclear energy accounts for approximately 10% of global electricity production and nearly 20% in advanced economies (IEA, 2023d). Nuclear energy is a low-carbon method compared to fossil fuels. However, while direct CO_2 emissions during operation of nuclear power plants are low, considering all lifecycle stages such as uranium mining, processing, enrichment, fuel production, plant construction and decommissioning, and the processing and storage of used fuel, nuclear energy is not entirely emission-free (Muellner et al., 2021).

Another aspect that promotes nuclear energy as an alternative is its efficiency. It is a type of energy that avoids scaling-up issues since large plants can meet a significant portion of energy demand on their own. Studies on G7 countries suggest that nuclear energy is more successful in reducing emissions compared to renewable energy (Nathaniel et al., 2021) . However, due to high initial costs, long construction periods, and challenges in timely delivery, nuclear energy projects struggle to compete with faster-deployed alternatives such as natural gas and modern renewable energy sources in some regions (IEA, 2022b).

Despite its potential, nuclear energy faces public resistance. Following the Fukushima disaster, the international community tightened safety standards for nuclear power plants (Zhan et al., 2021). Nonetheless, concerns over nuclear waste management and the risks of nuclear proliferation persist, limiting the widespread acceptance of nuclear energy.

2.2. Carbon Capture and Storage

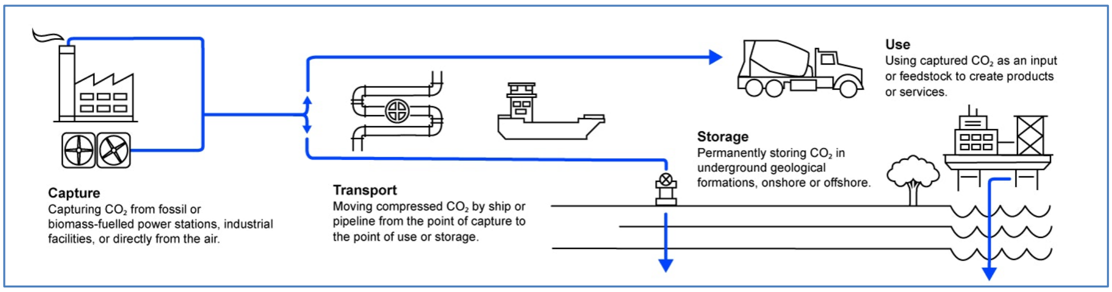
Carbon Capture and Storage aims to capture CO_2 emissions from sources such as power plants and industrial activities, and then transport and store them underground to prevent them entering the atmosphere. CCS consists of numerous components and sub-technologies, including pre-combustion capture, post-combustion capture, and oxyfuel combustion.

Pre-combustion capture involves gasifying fossil fuels to produce a mixture of hydrogen and CO_2, capturing the CO_2 before combustion. This method can achieve up to 90% CO_2 capture efficiency (Bui et al., 2018). On the other hand, post-combustion capture captures CO_2 from flue gasses after burning fossil fuels, with capture efficiencies of approximately 85-90% (Bui et al., 2018).

Oxyfuel combustion burns fossil fuels in pure oxygen, producing flue gas that consists primarily of CO_2 and water vapor. This simplifies the capture process and achieves up to 95% CO_2 purity (Whitmarsh et al., 2019).

Recent advances in CCS technology have enabled its application across various industries, including cement production and steel manufacturing. For instance, the Norcem CO_2 capture project in Norway aims to capture 400,000 tons of CO_2 annually from a cement plant (Norcem, 2021).

Figure 3. A Visual Overview of Each Step in The CCUS Process



Source: IEA

Note: *The captured CO_2 is used in various industrial processes. Common uses include enhancing oil recovery (EOR), producing chemicals, fuels, building materials, and other products. The utilization feature distinguishes CCUS from CCS.*

Once captured, the CO_2 must be transported to a storage site. The most common method for transporting large volumes of CO_2 over long distances is through pipelines. An example of a large-scale CO_2 transportation network is the Alberta Carbon Trunk Line (ACTL) in Canada. This system is designed to transport up to 14.6 million tons of CO_2 per year from industrial sources to enhanced oil recovery (EOR) sites (Clean Air Task Force, 2024).

For smaller quantities or shorter distances, CO_2 can also be transported by ships, trucks, or rail. One example is the Northern Lights project, a key component of Norway's *"Longship"* project. In this process, captured CO_2 is shipped as liquid to an onshore terminal, from where it is transported via pipeline to a permanent offshore storage site beneath the seabed of the North Sea (Equinor, 2024).

There are several options for storing CO_2. First, it can be injected into deep underground rock formations, such as depleted oil and gas fields or deep saline aquifers. Second, there is a mineral storage solution because CO_2 can react with naturally occurring minerals to form stable carbonate minerals.

2.2.1. Carbon Capture and Storage Cost

Cost is an important criterion for an investment to be attainable or implementable. In clean technologies, if the cost of a technology is higher than the cost that the firm must bear, investment will not be made.

The cost function of CCS is the sum of capture, transportation and storage costs. It is influenced by technological efficiency, scale of operation, and regulatory and policy frameworks. Technological progress and some policy choices (supporting policies such as subsidies and carbon pricing) may help reduce the cost of CCS projects (Edwards & Celia, 2018).

The cost function can be expressed as:

$$C_{CSS} = C_{capture} + C_{transport} + C_{storage}$$

$C_{capture}$ is the cost of capturing CO_2 at the source, $C_{transport}$ is the cost of transporting CO_2 to the storage site, and $C_{storage}$ is the cost of securely storing CO_2.

Capture costs come from removing CO_2 from industrial processes before it is released into the atmosphere and often account for a substantial portion of the total expenses. In some cases, capture costs can represent as much as 80% of the total CCS project cost (Guo & Huang, 2020). These costs, however, vary significantly based on the source of CO_2.

For example, capturing CO_2 is generally more economical for concentrated sources such as hydrogen production, coal-to-chemicals, and natural gas processing than for power generation, cement, steel production, or direct air capture (IEA, 2020a).

Transportation costs, on the other hand, typically make up less than a quarter of total CCS project costs, with pipelines being the preferred method for large CO_2 volumes. Costs for pipeline transport range from \$1-10 per ton per 250 km for onshore pipelines, while offshore pipelines can be 40-70% more expensive (Global CCS Institute, 2021a; IEA, 2020a).

The unit cost of transport decreases significantly with increased CO_2 volume, and further reductions can be achieved through economies of scale and by sharing infrastructure within industrial clusters or repurposing existing oil and gas pipelines (IEA, 2020a).

Storage costs include expenses for site selection and evaluation, injection operations, and monitoring and verification. Depleted oil and gas fields are attractive for CO_2 storage due to their demonstrated capacity to contain fluids and the potential for enhanced oil recovery, which can offset some costs (IEA, 2020a). Storage costs vary widely depending on the rate of CO_2 injection, reservoir properties, and the location of storage sites.

For CCS to become widely implemented, lowering costs across capture, transportation, and storage is essential. While achieving high capture rates of up to 98% is technically possible, it often requires extensive modifications to the CO_2 separation process and is not economically efficient (IEA, 2020a).

Cost reductions can be achieved through innovative solutions such as advanced solvents, improved integration with process plants, and pooling demand for transport and storage within industrial clusters. Shared infrastructure among multiple capture sites can reduce both capital and operational costs by facilitating economies of scale (IEA, 2020a).

High initial investment costs remain a challenge for CCS projects. These initial costs require significant capital expenditures that can be a deterrent for many stakeholders. However, government subsidies, private investments, and public-private partnerships can help mitigate these challenges (Guo & Huang, 2020; Whitmarsh et al., 2019).

In addition to addressing industrial emissions, CCS offers broader societal benefits. It can contribute to long-term economic and environmental gains, making it a publicly acceptable solution. These benefits should be factored into any assessment of CCS projects (Ilinova et al., 2021). By overcoming cost-related barriers and leveraging societal advantages, CCS has the potential to play a pivotal role in achieving global climate goals.

2.2.2. Network Effects, Initial Investment Costs, and Economies of Scale

As the number of CCS facilities and storage areas are developed grows, these projects will gradually evolve into a comprehensive network. The existence of such a network makes the system more valuable and efficient. Per unit costs decrease thanks to shared infrastructure and increased usage. This, in turn, leads to wider adoption of CCS and lower barriers to entry for new projects.

Economies of scale can be observed in the deployment of CCS, meaning that a higher rate of capture capacity leads to a lower unit cost. According to the Global CCS Institute (2021), for a single-train capture plant, doubling the capture capacity is expected to increase capital costs by around 50%. This reduction in unit cost is primarily driven by the "*learning-by-doing"* effect (Guo & Huang, 2020). This effect, along with technological advancements and expanded deployment, could reduce variable operating costs by nearly 30% by 2030 (Guo & Huang, 2020).

Additionally, cost-saving innovations include the standardization of capture units, modular construction, and off-site manufacturing, which can streamline both capital and operational expenses (IEA, 2020a).

In addition, the cumulative learning effect becomes more pronounced as more facilities join the CCS network. Shared knowledge, resources, and infrastructure result in further cost reductions and improved efficiency. Golombek et al. (2023) highlight that network effects can lead to significant economies of scale.

Large-scale CCS projects also address scaling-up challenges effectively. By spreading fixed costs over a larger volume of captured CO_2, these projects reduce the average cost per ton, making CCS more financially appealing to investors. This encourages broader adoption of the technology and supports its deployment on a larger scale.

Bae et al. (2020) highlight the importance of knowledge spillovers in CCS technologies, noting that larger projects tend to achieve better economic efficiencies and drive innovation.

Moreover, studies by Das et al. (2019) demonstrate that large-scale CCS projects can leverage bulk purchasing and optimized labor deployment to lower operational costs. These effects collectively enhance the financial viability of CCS projects and contribute to their long-term sustainability.

2.2.3. Importance of CCS

According to IEA, CCS could account for up to 15% of the cumulative reductions needed to meet global climate goals by 2050, equating to approximately 10 gigatons of CO_2 annually (IEA, 2020b). CCS is a critical option for reducing emissions in hard-to-abate industries, which require high-temperature heat for production. In these sectors, replacing fossil fuels with renewable energy sources is challenging.

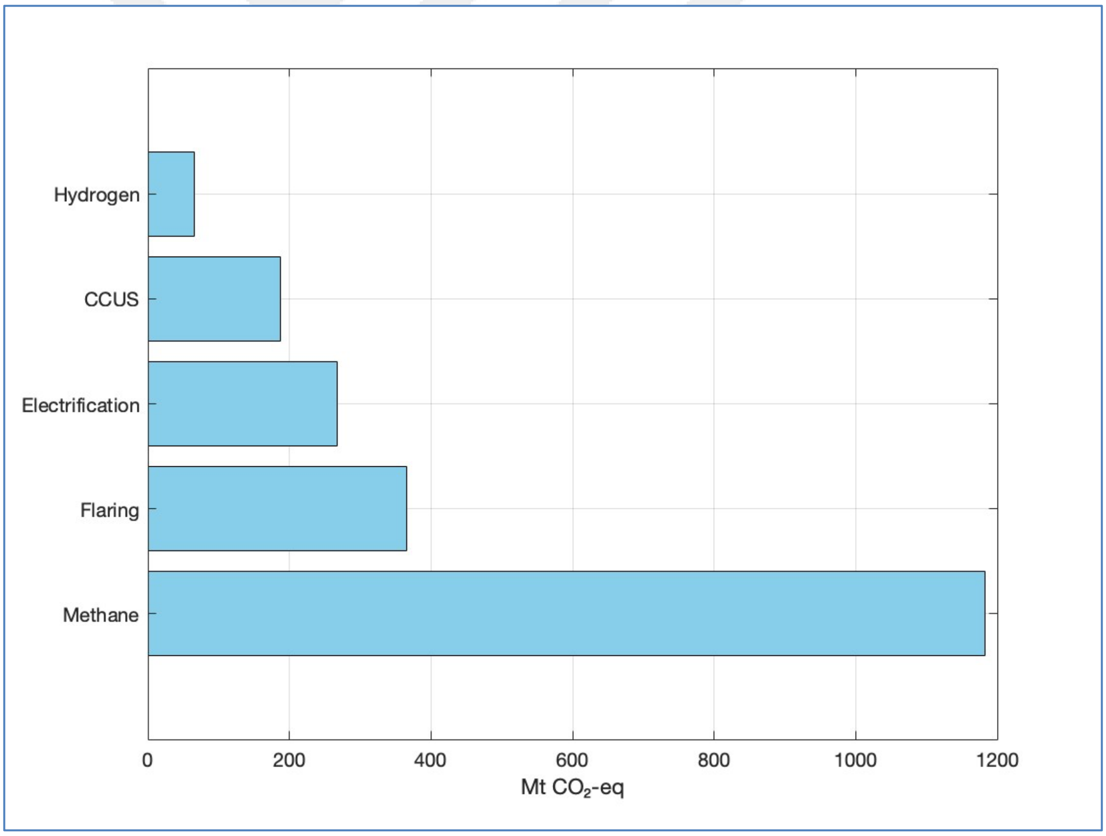
Additionally, a significant portion of emissions in these sectors springs from chemical reactions inherent to production processes, such as the calcination of limestone in cement production (Global CCS Institute, 2023a).

These industries also tend to operate with long-lived capital assets, meaning that existing facilities can continue emitting for decades. For example, a cement plant's average lifespan is 30 to 50 years (Global CCS Institute, 2023a). Products from these industries are traded globally, often with thin profit margins, which makes investment in low-carbon technologies difficult without robust policy support (Paltsev et al., 2021).

Notably, process emissions from cement production responsible for approximately 8% of global CO_2 emissions- cannot be fully addressed by efficiency improvements or renewable energy alone (Lehne & Preston, 2018).

In the steel industry, CCS captures CO_2 from blast furnaces and direct reduction processes, which are otherwisedifficult to decarbonize (Global CCS Institute, 2023a). Beyond these hard-to-abate industries, CCS can also be applied to existing fossil fuel-based energy and industrial facilities to reduce emissions without major disruptions to current production.

Figure 4. Reductions in Emissions from Oil and Gas Operations in 2030



Source: IEA, 2023c

Retrofitting characteristics of CCS enables these facilities to continue operating while addressing environmental goals (IEA, 2020a). The oil and gas industry plays a crucial role in emission reduction strategies essential for achieving the NZE target. According to the IEA’s scenario, emissions from this sector must decrease by 50% by 2030 (IEA, 2023a)

As shown in **Figure 4**, CCS is one of the key tools for reducing emissions, alongside electrification, flaring reduction, and methane control. While the primary contribution comes from reducing methane emissions, achieving the NZE target requires a holistic approach. This is why flaring reduction, electrification, and later CCUS and low-emission hydrogen play complementary roles (IEA, 2023c).

Currently, 90% of the CCS capacity in operation worldwide is within the oil and gas industry. However, only 40% of CCUS investments since 2010 have been directed toward the network of these sectors. Projects such as the Northern Lights initiative in Norway, where three oil companies collaborate to store CO_2, demonstrate the potential of CCS in this industry (IEA, 2023a).

Additionally, CCS provides economic benefits by helping industries avoid carbon taxes and other regulatory costs associated with GHG emissions. For instance, EU ETS imposes a cost on carbon emissions, incentivizing industries to adopt CCS to mitigate these expenses (European Commission, 2023b).

CCS requires large-scale investment, resulting in high fixed costs. As technological advancements improve efficiency and reduce costs, more facilities begin adopting this technology, leading to a reduction in fixed costs per project through economies of scale. Increasing investments also foster cumulative knowledge and experience, further enhancing efficiency and making CCS more economically feasible (Global CCS Institute, 2021b).

Moreover, integrating CCS with traditional abatement strategies offers additional benefits. According to the Global CCS Institute, combining CCS with traditional abatement measures could reduce global CO_2 emissions by an additional 14% by 2050 compared to using traditional methods alone (Global CCS Institute, 2020).

Finally, CCS supports the production of low-carbon hydrogen by capturing emissions from hydrogen production processes that rely on natural gas. It also contributes to emission reductions through bioenergy with CCS (BECCS) and direct air capture (DAC) technologies (IEA, 2020a, 2021).

2.2.4. Technological Developments in CCS

Global CCS Institute (2019) provides detailed insights into the estimated costs associated with CO_2 capture. Data from several facilities indicate a trend of decreasing capture costs over time, driven by technological advancements and improved operational efficiencies.

Two key projects—Boundary Dam and Petra Nova—exemplify this reducing cost trend. Boundary Dam, one of the first large-scale CCS applications, initially faced CO_2 capture costs exceeding $100 per ton, which was expected given the pioneering nature of the technology at the time (Global CCS Institute, 2019). Just three years later, the Petra Nova project managed to lower capture costs to $45 per ton, demonstrating the benefits of operational learning and optimization (Global CCS Institute, 2019; IEEFA, 2021).

Boundary Dam encountered significant operational challenges, including high maintenance costs and frequent inefficiencies, which hindered it from consistently achieving its target capture rate of 90% (Global CCS Institute, 2023b). Petra Nova, benefiting from the lessons learned at Boundary Dam, was able to achieve a 90% capture rate at a lower cost (Global CCS Institute, 2019, 2021; IEEFA, 2021).

Despite its setbacks, Boundary Dam has demonstrated the value of *learning by doing*—gradually improving operations, reducing costs, and providing valuable insights for future CCS projects.

As a pioneering project, Boundary Dam carried significant financial risks. However, the experience and knowledge gained from its implementation laid a crucial foundation for reducing costs in subsequent CCS facilities, such as Petra Nova (Global CCS Institute, 2019; IEEF, 2021).

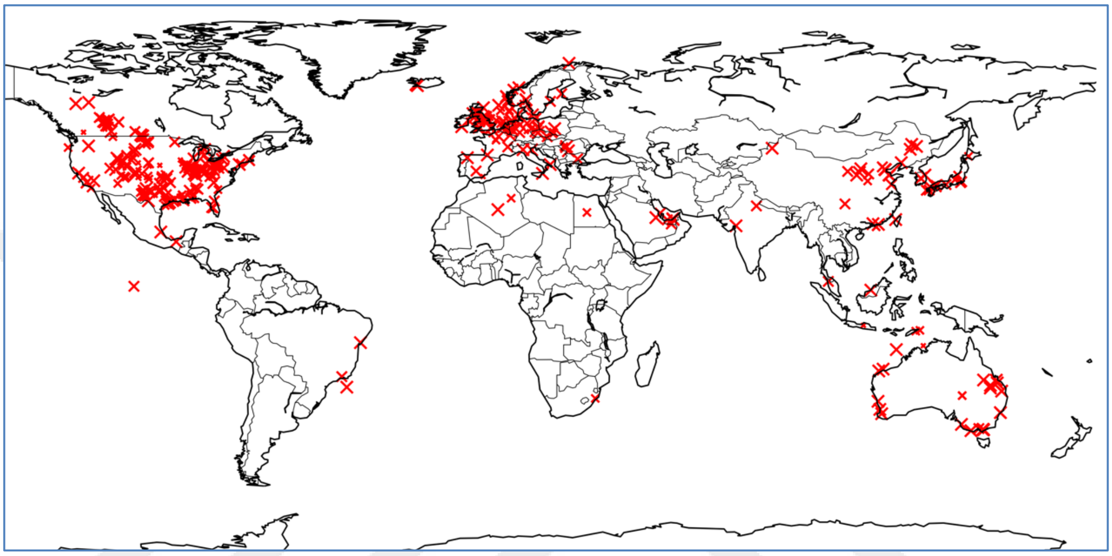
The technological momentum generated by these projects highlights the growing role of innovation and research in advancing CCS.

In terms of innovations in CCS, the United States leads with 12,181 patents, representing 17.2% of the total, followed by China with 8,393 patents and Japan with 8,342 (Li & Qin, 2021).

South Korea, Canada, and Australia also have significant patent counts, contributing to a combined 56.6% of global CCS technology patents (Li & Qin, 2021). The progress and deployment of CCS technologies have also surged in Europe, where the number of commercial-scale CCS projects has increased by 61%, reaching 119 projects in 2023 (Global CCS Institute, 2023a).

These technological advances underline the geographical concentration of CCS projects. If we analyze the geographical distribution of CCS projects in **Figure 5**, it is evident that these projects are not evenly dispersed across the globe. The uneven spread reflects the capital-intensive nature of CCS technologies and their dependency on robust economic frameworks to attract investments.

Figure 5. Global Distribution of CCS Projects (as of January 2023)



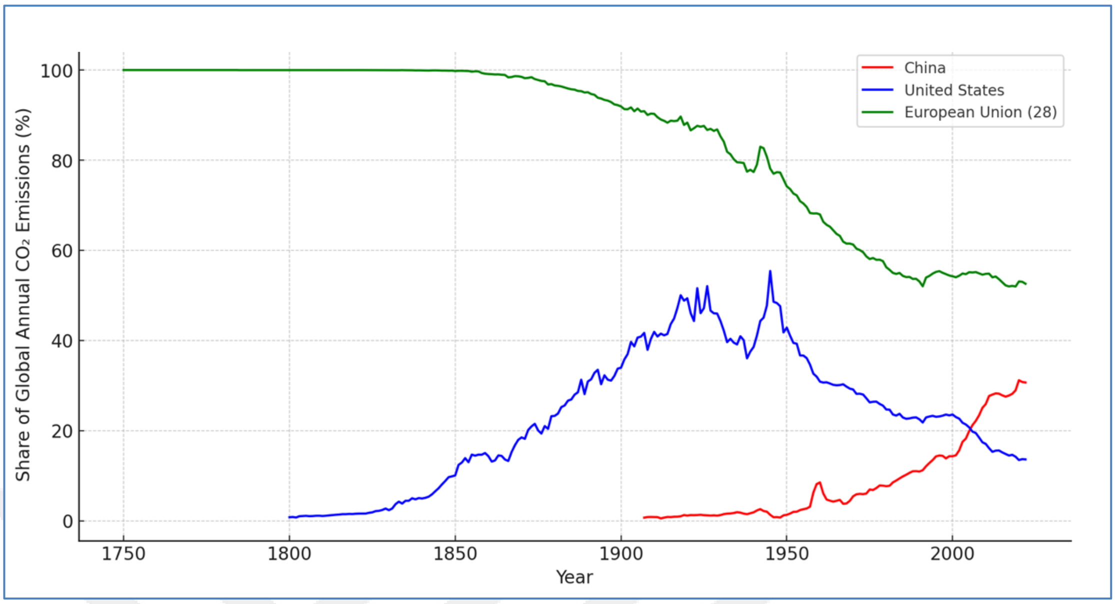
Source: The NETL CCS Database

Note: *As of April 2018, the database contained 305 total CCS projects worldwide, with 299 sites identified. The 299 site-located projects include 76 capture, 76 storage, and 147 for capture and storage in more than 30 countries across 6 continents. While several of the projects are still in the planning and development stage, and many have been completed, 37 are actively capturing and/or injecting* CO_2.

Consequently, the majority of these projects are concentrated in high-income regions, such as North America, Western Europe, and parts of East Asia. Moreover, when comparing the spatial alignment of these projects with global emission hotspots, we observe that the regions hosting the highest number of CCS projects align closely with the world's largest emitters, such as the United States, China, and parts of Europe (as highlighted in **Figure 6-7**) (Ritchie et al., 2023).

Recent developments highlight a growing momentum behind CCS. The IEA's reports indicate that over 30 commercial CCS facilities have been announced in recent years, with significant investments aimed at improving the technology and expanding its applications. The portfolio of projects now includes diverse applications from power generation and cement production to developing industrial hubs. This progress verifies CCS's essential role in achieving net-zero emissions (IEA, 2020a).

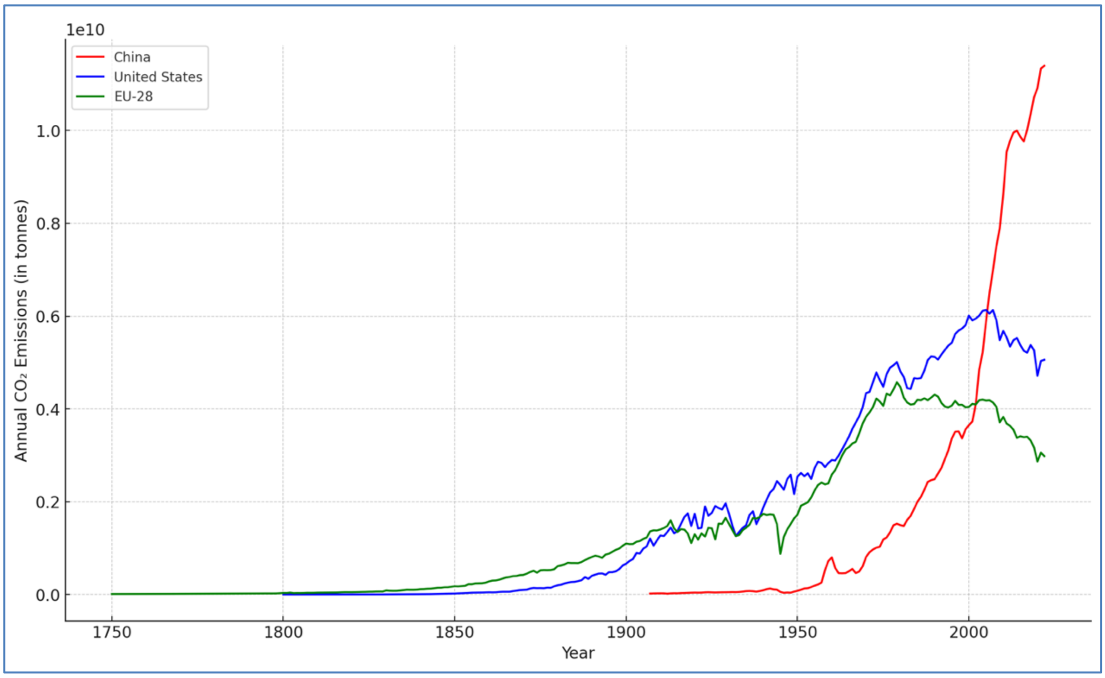
Figure 6. Historical Share of CO_2 Emissions: China, United States, and European Union (28)



Source: Ritchie et al., 2023

Note: *Fossil emissions: Fossil emissions measure the quantity of CO_2 emitted from the burning of fossil fuels, and directly from industrial processes such as cement and steel production. Fossil CO_2 includes emissions from coal, oil, gas, flaring, cement, steel, and other industrial processes. Fossil emissions do not include land use change, deforestation, soils, or vegetation.*

Figure 7. Annual CO_2 Emissions: China, United States, and European Union (28)



Source: Ritchie et al., 2023

2.2.5. Case Studies and Impacts

One notable example is the Sleipner CO_2 Storage project, located in the Norwegian sector of the North Sea, which has been operational since 1996. The project captures approximately one million tons of CO_2 annually, injecting it into a deep saline aquifer beneath the seabed for permanent storage (Global CCS Institute, 2023b). Its location near Norway's offshore oil platforms and industrial zones makes it an ideal site for CCS (IEA, 2020b). This project has also provided valuable data on how geological formations can securely store CO_2 without leakage over time.

Most CO_2 emitted from industrial processes is mixed with nitrogen, water vapor, and other gases. At Sleipner, the CO_2 is purified using amine scrubbing technology to ensure capture efficiencies exceeding 90% (Global CCS Institute, 2023b). This level of efficiency demonstrates how offshore storage technologies can provide a safe, long-term solution for CO_2 sequestration while minimizing risks to populated areas (IEA, 2020b).

Another significant example is the Midwest Carbon Express, which is designed to connect ethanol producers in Iowa, South Dakota, and Nebraska with a CO_2 pipeline network. The project targets a capture capacity of 18 million tons of CO_2 per year (Mtpa) by 2025, making it one of the largest CCS networks globally (Global CCS Institute, 2021a).

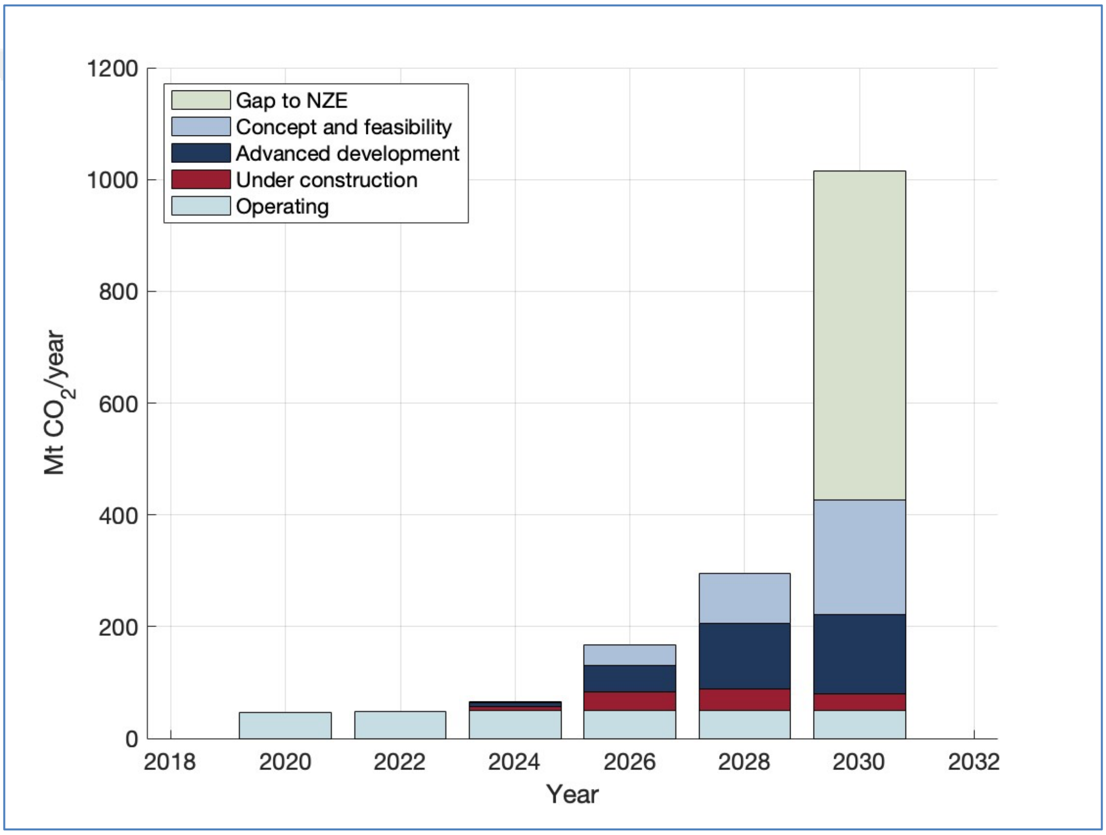
This project exemplifies how CCS technologies can be integrated into existing industrial processes, particularly in agriculture and biofuel production. However, the success of the project relies heavily on the development of long-distance pipelines that must cross multiple states and agricultural zones (Sanchez et al., 2018). Furthermore, gaining community acceptance remains a challenge, as the pipeline infrastructure affects both residential and farming areas (Global CCS Institute, 2021a).

Sanchez et al. (2018) analyzed the economic and environmental impacts of CCS in the context of US biorefineries, focusing on different CO_2 price scenarios. Their findings indicate that higher CO_2 prices incentivize emissions capture from more geographically isolated sources. However, this drives the need for extensive transportation and storage infrastructure, increasing the overall costs of CCS deployment. As a result, policy frameworks that support the development of infrastructure are essential to ensure the feasibility of CCS across different sectors.

2.2.6. Policy and Regulations

The deployment of CCS technologies plays a critical role in achieving the NZE by 2050 target. (IEA, 2024a). Nevertheless, **Figure 8** reveals that despite recent progress, the projected capacity for 2030 falls short of what is required to meet these ambitious goals. While 2023 projections show a 35% increase in carbon capture capacity and a 70% rise in storage capacity, this progress only accounts for 40% of the capture capacity and 60% of the storage capacity needed to meet the NZE target of 1 gigaton of CO_2 captured and stored annually (IEA, 2020a).

Figure 8. Capacity of Current and Planned Large-Scale CO_2 Capture Projects vs. The Net Zero Scenario, 2020-2030



Source: CCUS Projects Database, 2024

Note: *NZE = Net Zero Emissions by 2050 Scenario. Includes large-scale projects with a capture capacity over 100 000 t per year (1000 t per year for DAC). Capture projects for CO_2 use are included if CO_2 is used in fuels, chemicals, polymers, building materials, or for yield boosting. Within planned CCUS industrial hubs, only identified CO_2 capture projects are included (not the full potential capture capacity of industrial hubs for which capture sources are not specified).*

These percentages point out the significant gap between current efforts and future requirements, underscoring the need for both technological advances and coordinated policy frameworks to incentivize investments and accelerate CCS adoption. As such, the current project capacity remains insufficient to achieve the carbon neutrality goal.

Bridging this gap will not only demand increased CCUS investments but also the effective use of diverse policy instruments to foster a supportive environment for these investments.

Achieving the path to net zero requires the strategic use of a comprehensive policy toolbox, as outlined by the Global CCS Institute (2023b) which includes:

- Emission Trading Systems: Cap-and-trade mechanisms, carbon offsets, and baseline carbon credits, which enable the trading of emission permits and encourage reductions.
- Carbon Taxes: Direct taxation of carbon emissions to create financial incentives for emission reductions.
- Direct or Indirect Subsidies: Instruments such as tax credits, loans, grants, or loan guarantees that reduce the financial burden of implementing CCS.
- Command and Control Mechanisms: Regulatory mandates for the gradual elimination of emissions from specific industries.

These diverse policy instruments either raise the cost of emissions or reduce the cost of abatement, both of which help foster demand for CCS investments. Subsidies lower the initial investment cost bearing by firms, while carbon pricing mechanisms offer economic incentives for firms to adopt CCS (Golombek et al., 2023). This variety of tools ensures that countries with differing economic structures and constraints can tailor their policies effectively to meet their *unique needs*.

Additionally, the financial and operational variability of CCS projects—due to differing technologies, locations, and applications—means that policy frameworks must be flexible. **Table 1** highlights the types of policies implemented across various countries in the past three years, reflecting the diverse approaches used to promote CCS. Importantly, it shows that several countries—such as the United States, Norway, and the European Union—utilize multiple policy tools simultaneously, demonstrating the complementary nature of these instruments.

This complementary approach allows governments to tackle the various challenges across the CCS value chain. For example, the United States combines subsidies (e.g., the 45Q tax credit) with infrastructure investments through the Infrastructure Investment and Jobs Act to lower capital costs and build the physical infrastructure needed for large-scale deployment (CBO, 2023).

Table 1. Types of Policies Facilitating CCS Adoption

Tax Incentives • Malaysia (2023): Tax incentives for CCS, including Investment Tax Allowance, import duty, and sales tax exemptions. • United States (2022): Inflation Reduction Act changes to 45Q, providing tax credits for CO_2 storage and use. • Canada (2021-2022): Investment tax credit for CCUS projects.
Regulation and Legal Framework • Indonesia (2023): Legal and regulatory framework for CCUS. • South Korea (2021): Carbon Neutrality Bill. • European Commission (2022): Directive 2022/2464 on corporate sustainability reporting. • California, US (2022): SB 905 and SB 1314 regulations. • Colorado, US (2021): Clean heat plan requiring gas utilities to cut CO_2 and methane emissions.
Infrastructure Investments • Japan (2023): METI's CCS Long-Term Roadmap. • Norway (2020): Langskip project: Northern Lights • European Commission (2022): Innovation Fund. • Netherlands (2021-2022): SDE++ program. • United States (2021): Infrastructure Investment and Jobs Act.
Subsidies • United Kingdom (2022): CCUS Innovation 2.0 program. • Ireland (2021): National Recovery and Resilience Plan. • Estonia (2021): Strategic Plan grant programs. • Finland (2022): Green transition investment grants. • United States (2021): DOE funding programs and Carbon Negative Shot. • Luxembourg (2021): Climate Pact 2.0. • European Commission (2023): Net Zero Industry Act.
Policy Initiatives • Saudi Arabia (2021): Implements broad policy initiatives like the Saudi Green Initiative to promote CCS and other environmental goals.

Source: IEA/IRENA Renewable Energy Policies and Measures Database

Similarly, Norway utilizes infrastructure investments like the Northern Lights projects as a part of CCS value chain named Longship, alongside regulatory frameworks to provide legal clarity and reduce risks for investors. These efforts not only help attract private-sector involvement but also promote international collaboration. Because Northern Lights is not a local hub, it is distributed. Unlike other hubs that rely on compact industrial clusters connected by pipelines, this Norwegian hub will utilize ships to link carbon dioxide sources spread across various parts of Europe (Northern Lights, 2024; The CCUS Hub, 2023).

Table 2. Policy Examples and Their Effects on The Economy

Policy Implications	**Example**	**Benefit**
Financial Subsidies	The US Department of Energy's Carbon Capture Program offers funding for developing and deploying CCS technologies (US Department of Energy, 2023).	Reduces the initial capital costs of CCS projects, making them more financially viable for private investors.
Carbon Pricing Mechanism	The European Union Emissions Trading System (EU ETS) limits the total amount of greenhouse gasses emitted. It allows industries with low emissions to sell their extra allowances to more significant emitters (European Commission, 2023b).	Creates economic incentives for firms to reduce their carbon emissions and invest in CCS technologies.
Research and Development Investment	The Carbon Capture and Storage Infrastructure Fund (CIF) provides £1 billion to support CCUS projects, focusing on capital expenditure for transport and storage networks and industrial carbon capture projects to establish a new CCUS sector and support the UK's net-zero targets (UK Government, 2023).	Advances in CCS technologies make them more efficient and cost-effective.
Public-Private Partnership	The W.A. Parish post-combustion CO_2 capture and sequestration demonstration project in Texas is a notable example of a successful public-private partnership. This project, funded by NRG Energy and JX Nippon Oil & Gas Exploration in collaboration with the U.S. Department of Energy, demonstrated the commercial viability of capturing carbon dioxide from a coal-fired power plant and using it for enhanced oil recovery. This partnership facilitated sharing costs, risks, and technological advancements, signific (Kennedy, 2020).	Facilitates the sharing of costs and risks associated with CCS projects.
Regulatory Support	Norway's CCS regulations provide a comprehensive framework for storing CO_2, including requirements for site selection, monitoring, and reporting (Norwegian Ministry of Petroleum and Energy, 2023).	Establishes clear regulatory frameworks, streamlining the approval process for CCS projects and providing legal certainty.

Table 2 contains different policy implications and its benefits. It demonstrates that countries like the United States, the United Kingdom, and Norway provide significant financial support to encourage the adoption of CCS technologies. Although all these types of policies inherently increase the CCS incentive, they do so in different ways. Therefore, the benefits of each may have different structures.

As outlined in **Table 2**, policy tools not only address financial challenges but also streamline operations. Financial subsidies help lower initial costs, facilitating private-sector involvement. At the same time, regulatory frameworks reduce uncertainties, ensuring smoother project approvals and long-term sustainability (Carbon Capture Coalition, 2023, 2024; IEA, 2022a).

Public-private partnerships, exemplified by projects like the W.A. Parish in Texas, demonstrates how collaboration can effectively share risks and costs, facilitating broader adoption of CCS models (Kennedy, 2020). Norway stands as a pioneer in public-private partnerships within the CCUS value chain, where these collaborations, supported by robust regulatory frameworks, provide the legal certainty needed to attract investments and drive technological advancements (The CCUS Hub, 2023).

As a result, financial incentives accelerate project initiation, while infrastructure investments establish a physical foundation for long-term CCS investment. Carbon pricing mechanisms provide ongoing economic incentives, and public-private partnerships share risks, making CCS projects more financially viable. This integrated approach ensures that short-term financial barriers are addressed, while long-term project viability is achieved.

2.3. Theoretical Models on Carbon Capture and Storage

The study of CCS has evolved significantly, with theoretical models playing a pivotal role in elucidating the economic, policy, and technological dimensions of this strategy**.** **Table 3** summarizes the evolution of theoretical models on CCS from 1990 to 2023, reflecting the growing sophistication in addressing economic, policy, and technological dimensions of CCS.

Table 3. Theoretical Models on CCS in Literature (Sorted by year)

Authors	Year	Method	Main Findings
Chou & Shy	1990	Network Effects Analysis	Analyzes indirect network effects where utility derived from a product depends on the supply of a complementary product.
Gerlagh & Van der Zwaan	2006	Cost Efficiency Analysis	Discusses cost-efficiency concerns related to CCS and its role in achieving climate targets.
Van der Zwaan & Gerlagh	2009	Economic Feasibility	Examines cost efficiency of CCS considering geological CO_2 leakage.
Greaker & Heggedal	2010	Salop Model	Uses the Salop model to study indirect network effects, focusing on the demand for clean and dirty cars based on refueling network availability.
Rubin et al.	2015	Cost Estimates	Provides empirical cost estimates for large-scale deployment of CCS.
Greaker & Midttømme	2016	Tax Model	Imposing a temporary tax on the dirty network above the Pigouvian rate can coordinate the transition to the clean network.
Tunç Durmaz	2018	Theoretical Scenarios	Explores CCS investments across scenarios based on the cost of CCS relative to tax rates, highlighting complementary and substitutive relationships between CCS, fossil fuels, and clean energy.
Meunier & Ponssard	2020	Subsidy Policy Analysis	Examines indirect network effects in the market for alternative fuel cars, suggesting subsidies for both refueling stations and alternative fuel cars.
Golombek et al.	2023	Policy Analysis	Analyzes policies to promote CCS technologies, emphasizing the role of subsidies, carbon pricing, and regulatory frameworks in accelerating the adoption of CCS and reducing emissions.

Early studies, such as Chou & Shy (1990), emphasize network effects and the interplay between complementary products, while later works like Rubin et al. (2015) and Golombek et al. (2023) shift towards empirical cost estimates and policy analyses. Several studies, including those by Gerlagh & Van der Zwaan (2006) and Greaker & Midttømme (2016), explore cost efficiency and the economic implications of taxes, revealing the challenges of incentivizing CCS adoption. More recent research, such as Meunier & Ponssard (2020) and Tunç Durmaz (2018), examines subsidy policies and theoretical scenarios, offering insights into the complementary roles of CCS, clean energy, and fossil fuels.

Overall, the table reflects the growing complexity of CCS modeling, with increasing attention to policy instruments, market dynamics, and economic feasibility over time.

Golombek et al. (2023) and the Salop Model

According to the extended model by (Golombek et al., 2023), the Salop (1979) model is adapted to reflect the **s**tructures of the CCS value chain. In this modified version, the CO_2-emitting plants take the place of consumers in the original Salop model, while CO_2-collecting terminals substitute for the firms. This application provides a framework to examine the optimal location and number of terminal investment decisions for CCS value chain.

A fixed number of plants are uniformly distributed around a circle. Initially, all plants emit carbon, and total emissions are equal to E, where:

$$E \equiv \sum_{i=1}^{n} e_i,$$

with e_i denoting the emissions of plant i . Each plant pays a tax τ per unit of emission, equivalent to the social cost of carbon. The total tax cost for each plant is:

$$C_{\text{tax},i} \equiv \tau \cdot e_i.$$

Plants can either pay this carbon tax or invest in capture facilities and transport the captured CO_2 to terminals located on the circle's circumference.

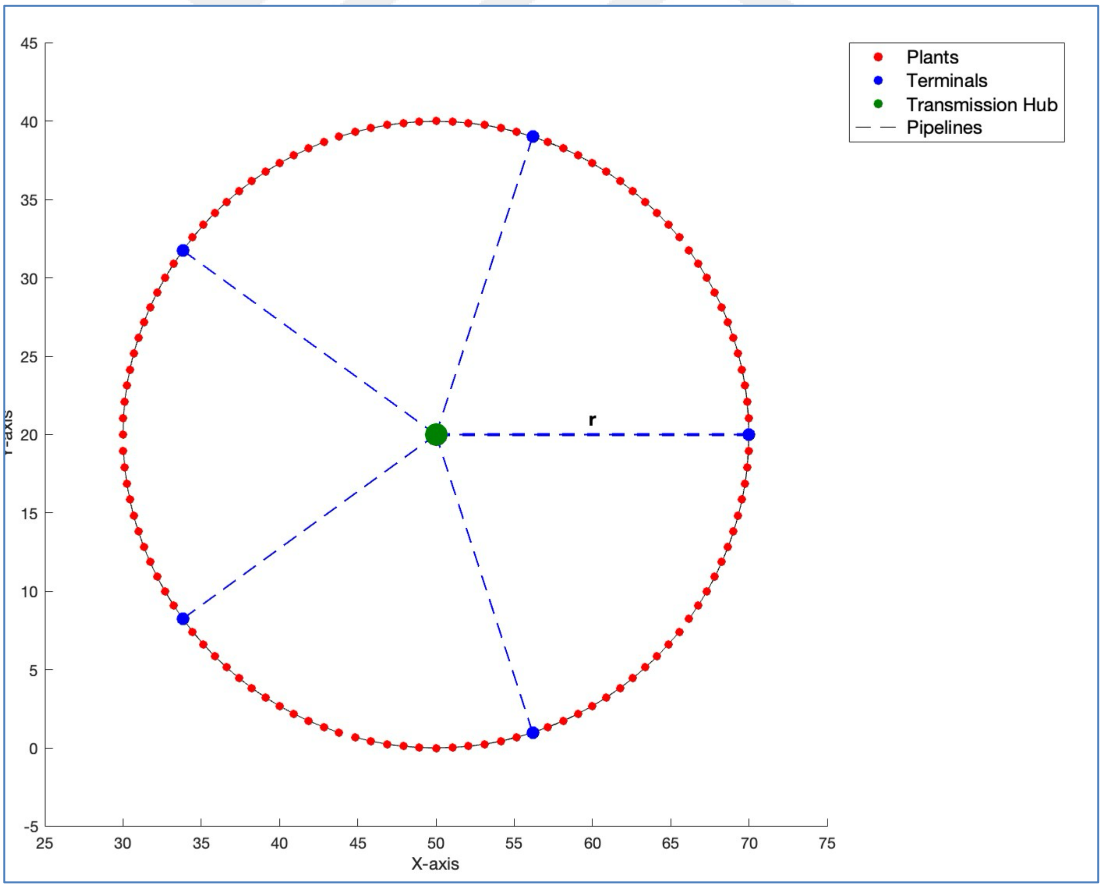
The investment cost per unit of emissions for capture facilities, x , varies across plants, representing the diversity in the sector (e.g., cement, aluminum, waste management, fossil fuel power). The investment cost is uniformly distributed within $\bar{x}$ (upper bond) and $\underline{x}$ (lower bound) to simplify the model.

As carbon taxes increase, the relative cost of emissions reductions through CCS becomes more competitive, prompting a higher percentage of plants to invest in this technology In this scenario, terminals incur fixed entry costs for establishing facilities and pipelines, and as more CO_2 is handled, economies of scale reduce the cost per unit of CO_2. A detailed explanation of the original Salop model and its integration into the CCS value chain is provided in **Annex 4**.

Figure 9 visualizes this model, plants are uniformly distributed around the circle. The Transmission Hub is located at the center of the circle. Terminals need to transport CO_2 to the Transmission Hub. If the terminals are not evenly distributed, some plants would have to transport CO_2 over longer distances, increasing the total transportation distance. Even distribution of terminals ensures that the distance from any plant to the nearest terminal is minimized.

Hence, the even distribution of terminals around the circumference minimizes the total transportation distance from the plants to the terminals. By evenly distributing the terminals around the circumference of the circle, the average transportation distance for each plant is minimized. The distance from each terminal to the central transmission hub remains constant because distance from center to circumference for circle is fixed. For further details on the transportation distance and cost calculations, refer to **Annex 5**.

Figure 9. Salop's Circle and CCS Network



This configuration ensures that the total transportation cost is minimized, making the CCS network more efficient with Salop's circle establishment. As the number of terminals increases, the distance from plants to the nearest terminal decreases, reducing overall transportation costs. This layout promotes efficient CO_2 transportation, enhancing the overall effectiveness of the CCS network.

Building on the theoretical insights and models reviewed in the previous chapter, we now turn to the development of our own framework. By addressing critical gaps identified in the literature and incorporating novel assumptions, the proposed model aims to provide a more comprehensive analysis of CCS investments and their interaction with traditional abatement techniques, carbon taxes, and emission levels.

3. THE MODEL

This chapter introduces the development of our theoretical model on plants' CCS investment preference. The analysis begins by examining traditional abatement techniques and the role of carbon taxes, focusing on their influence on the cost structures of CO_2-emitting plants.

This initial section lays the groundwork for understanding the economic pressures shaping plants' abatement strategies. Subsequently, the cost structure of CCS investments is explored, with a detailed examination of its functional form and key parameters.

The model then transitions to the decision-making process of plants, analyzing how cost minimization strategies vary depending on the adoption of CCS investments. By contrasting the costs of traditional abatement and carbon taxes with those of CCS, the model identifies the conditions under which plants are motivated to pursue CCS adoption.

Finally, the framework introduces the concept of a threshold emission level, which establishes the decision boundary between plants choosing traditional abatement with tax payments and those opting for CCS investments. The model, in its entirety, aims to elucidate the factors driving plants preferences between these two strategies and to explain the rationale behind these decisions.

By systematically analyzing the influence of key variables on plants choices, the framework seeks to provide a coherent and consistent method for understanding factors that interact in shaping CCS adoption preferences.

3.1. Model Description and Implementation

This study diverges from Golombek's work by assuming an infinitely large number of plants in the market, each generating emissions denoted by e. These emissions are uniformly distributed within the range $[\underline{e}\,,\overline{e}\,]$. While Golombek's study investigates uniformly distributed CCS investment costs, this research concentrates on uniformly distributed emission levels across plants. This assumption ensures that all emission levels within the range are equally probable, preventing any specific level from dominating the market.

The uniform distribution of both plants and emissions simplifies the analysis by making the likelihood of encountering any given emission level consistent across the market. Additionally, this distribution minimizes the risk of emission *"concentration"* at specific locations, supporting the rationale for a uniform spatial distribution of terminals along the circumference of the circle.

The function representing the total emissions E in the market can be written as follows:

$$E \equiv \int_{\underline{e}}^{\overline{e}} e \; dF(e) = \frac{\overline{e} + \underline{e}}{2}$$

Accordingly, the total emission E represent the average of $\overline{e}$ and $\underline{e}$ considering the emission levels of all plants and their distribution. This expression calculates the total emissions by considering the emission levels of all plants and their probabilities. A detailed derivation of this expression is provided in **Appendix 1.** for reference.

Each plants makes its abatement decision, and the total abatement R can then be calculated according to these decisions. When the government imposes a carbon tax on emissions, plants have two options.

First, plants can reduce their carbon emissions to a certain level using traditional abatement techniques and pay taxes for the remaining emissions. Traditional abatement techniques, such as energy efficiency improvements, fuel switching, and the adoption of renewable energy sources.

For instance, transitioning from coal to natural gas can significantly reduce CO_2 emissions due to the lower carbon content of natural gas (IEA, 2019). Specifically, coal-to-gas switching can reduce emissions by 50% when producing electricity and by 33% when providing heat (IEA, 2019). While these methods have significant short-term benefits, relying solely on fossil fuel switching does not present a viable long-term solution to the NZE target (IEA, 2019).

Energy efficiency measures, often termed the *"first fuel"* in clean energy transitions, offer some of the quickest and most cost-effective CO_2 mitigation options (IEA, 2024a). However, even with substantial energy productivity improvements, these measures are insufficient to achieve net-zero emissions targets (IEA, 2024a; Somers & Moya, 2020).

Heavy industry and aviation, traditional abatement techniques face significant limitations (IEA, 2020a; Rehfeldt et al., 2020). For example, in the cement industry, fuel switching alone cannot achieve net-zero greenhouse gas emissions, as it only mitigates combustion emissions while process and indirect emissions persist (Clark et al., 2024). The iron and steel industry has optimized material and energy flows over the years, and further incremental efficiency improvements can only reduce CO_2 emissions by about 10% (Somers & Moya, 2020). To address the substantial residual emissions and achieve deep decarbonization after 2030, new feedstocks, process switches to CO_2-neutral technologies, and innovative approaches are necessary (IEA, 2023d; Rehfeldt et al., 2020).

Alternatively, plants can invest in CCS technology, which allows for complete abatement of emissions. By adopting CCS, plants can capture and store all their CO_2 emissions, thereby eliminating the need to pay carbon taxes and significantly reducing their environmental impact (IEA, 2020a). That technology is addressing emissions that cannot be eliminated through energy efficiency or fuel switching alone (Global CCS Institute, 2021a; IEA, 2023a).

For instance, in the cement sector, processed CO_2 emissions represent over 2 billion tonnes per year, which CCS can effectively address (Global CCS Institute, 2021a). However, plants must cover the costs associated with capturing, transporting, and storing their emissions, which can be substantial (IEA, 2024a).

3.1.1. Abatement and Tax

3.1.1.1. Cost of Abatement

Let r represent the emission reduction undertaken by a plant, and let e denote the plant's total emissions without any abatement efforts. The constant A, represents the cost associated with abatement technologies, such as transitioning to more efficient energy sources or switching to low-carbon fuels. It is the sole parameter that reflects the cost structure of the abatement technology. Its positivity ensures that implementing emission reduction measures incurs a real and tangible cost, aligning with the economic reality that such efforts require investments in infrastructure, technology, and operational changes.

In other words, the suitability of the emission reduction technique to the plant's production structure and its stage of technological development directly impacts the associated costs.

The function $r(e)$, indicates a emission reduction function r, depends on total emissions e. The marginal cost of abatement z per unit of emission reduced as:

$$z \equiv A\left(\frac{r(e)}{e - r(e)}\right)$$

This functional form highlights how the marginal cost increases as the level of reduction approaches total emissions, reflecting the diminishing returns and escalating costs of achieving near-zero emissions. A step-by-step derivation of these results is provided in **Appendix 2.** for reference. The parameter A, therefore, acts as a critical determinant of how these costs scale with increasing reduction efforts.

The total cost Z incurred by the plant for reducing emissions by an amount r is given by:

$$Z \equiv A\int_0^r \frac{r}{e - r}\,dr = A\left[e \ln\left(\frac{e}{e - r}\right) - r\right]$$

The plant aims to minimize its total abatement cost Z with respect to r:

$$\min_r Z = A\int_0^r \frac{r}{e - r}\,dr$$

To analyze the dynamics of the abatement cost function, there are two assumptions:

Assumption 1: *Full abatement* $(r(e) \to e)$

$$\lim_{r(e) \to e} \frac{r(e)}{e - r(e)} \to \infty$$

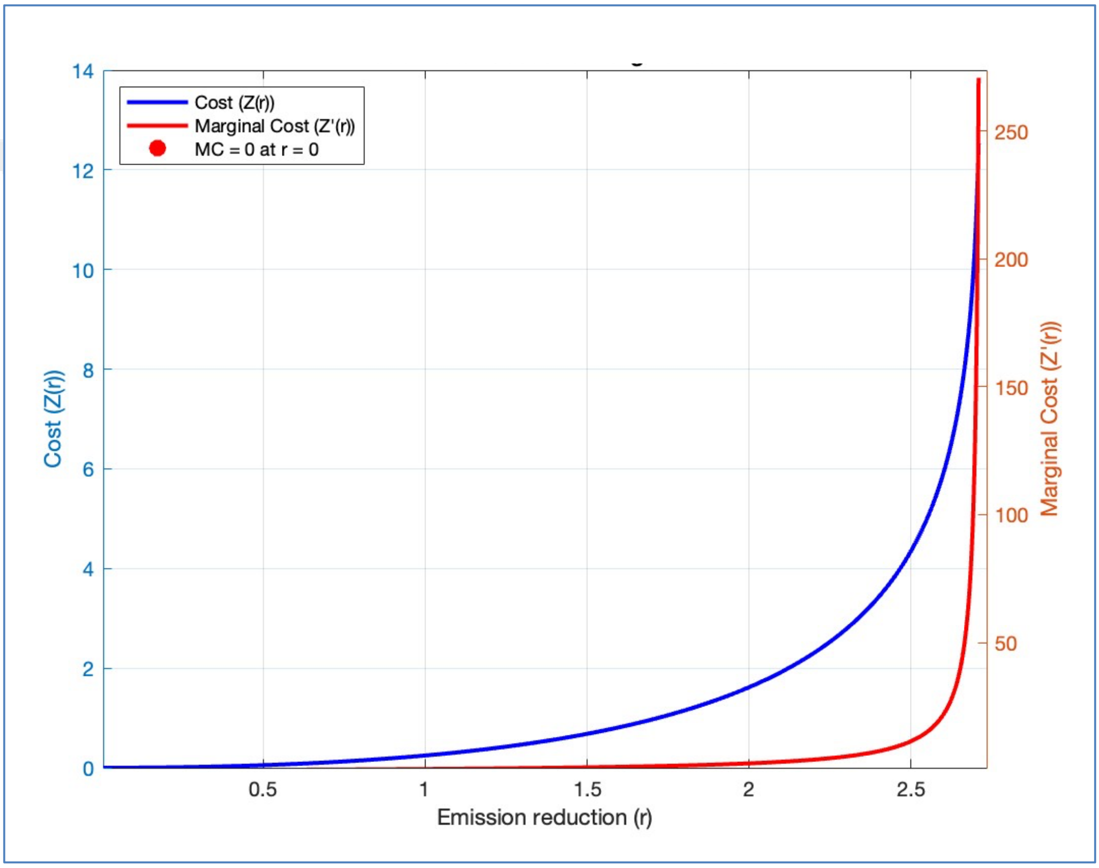
As the plant tries to abate all emissions, the term $(\frac{r(e)}{e-r(e)})$ tends to infinity. Which implies that the total cost of abatement also tends to infinity. Therefore, as the amount of reduced emissions approaches the total emissions, the marginal cost increases significantly, making full abatement economically impossible.

Assumption 2: *No abatement* $(r(e) \to 0)$

$$\lim_{r(e) \to 0} \frac{r(e)}{e - r(e)} = 0$$

In this scenario, the term $(\frac{r(e)}{e-r(e)})$ tends to zero, which implies that the total cost of abatement Z is minimal when no emissions are abated. This aligns with the previous finding reflecting that without external incentives or regulatory pressures, the plant has little economic motivation to reduce emissions. For reference, the derivation of the marginal benefit and its role in determining the optimal level of abatement is detailed in **Appendix 3**.

Figure 10. Total Cost and Marginal Cost of Regular Abatement Techniques



As it can be seen in **Figure 10**, the total cost function $Z(r)$ is convex, indicating increasing marginal costs of abatement.This convex nature of the MAC curve is also evident in real-world scenarios. For example, Shi et al. (2023) analyzed China's industrial CO_2 emissions and observed that the MAC curve remains relatively stable for cumulative emission reductions of 20–40%. However, as reductions approach 50%, costs begin to increase significantly, with a steep rise occurring between 95–100% reductions.

This trend highlights the escalating difficulty of addressing *“hard-to-abate”* emissions at higher reduction levels, where cost-effective options are depleted, leaving only high-cost measures available (Shi et al., 2023). These findings align with the conclusion that for sectors with hard-to-abate emissions, regular abatement techniques become economically inefficient, making investments in technologies like CCS a more viable and efficient alternative.

Similarly, Hallegatte (2023) stressed the need to distinguish between marginal and transformational approaches to abatement. While marginal reductions may allow for low-cost measures, achieving near-total reductions requires tackling emissions that are economically impractical to abate through traditional means. This shift demands a comprehensive strategy that balances cost-effectiveness with systemic transformation, such as adopting renewable energy or reengineering industrial processes (Hallegatte, 2023).

In summary, while regular abatement techniques may seem cost-efficient for small-scale reductions, relying on them for significant carbon reductions can result in unsustainable long-term costs. Therefore, transformative approaches, including CCS investments, are crucial for managing the economic challenges of substantial emission reductions.

3.1.1.2. Government Intervention: Emission Tax

To address the negative externalities of CO_2 emissions, the government imposes a carbon tax τ per unit of emission. Plants should make their abatement decisions based on their emission levels and the carbon tax rate, aiming to minimize their total costs.

The tax liability for a plant is given by:

$$\tau \cdot \int_{r}^{e} 1 \, de = \tau \cdot (e - r)$$

Therefore, the tax liability for a plant is given by:

$$\tau(e - r)$$

The plant's total cost function now includes tax liabilities of that plant:

$$\text{Total Abatement Cost} = \mathrm{A} \int_{0}^{\mathrm{r}} \frac{\mathrm{r}}{\mathrm{e} - \mathrm{r}} \, \mathrm{dr} + \tau \cdot \int_{\mathrm{r}}^{\mathrm{e}} 1 \, \mathrm{de}$$

Differentiating the total cost function, we get:

$$A\left(\frac{r(e,\tau)}{e-r(e,\tau)}\right)-\tau=0$$

which simplifies to:

$$\tau=A\left(\frac{r(e,\tau)}{e-r(e,\tau)}\right)$$

This equation shows that the plant will continue to increase its emission reduction r until the marginal cost of abatement z equals the carbon tax τ. A carbon tax set by the government internalizes the external cost, aligning the plant's private cost with the social cost. By doing so, the government ensures that plants consider the external damages their emissions cause, leading to a socially optimal level of emissions reduction. This level encourages plants to reduce emissions to the point where the private marginal cost of abatement equals the tax rate.

3.1.2. CCS Investment

The total cost of CCS can be represented cost function:

$$C_{CCS}\equiv f+c(s,t)\cdot r+(e-r)\tau$$

where:

Fixed Cost (f): Represents the initial investment required to implement CCS technology. This includes expenses such as the construction of capture facilities, installation of transport infrastructure (e.g. pipelines) and development of storage sites (e.g. geological formations). These costs are independent of the number of emissions being processed. It is important to note that the fixed cost for CCS is significantly higher compared to regular abatement techniques.

Marginal Cost $(c(s,t))$: This is the expense of capturing and storing each additional unit of emissions includes storage cost s and the transportation cost per unit of emissions t. It encompasses operational expenses such as energy costs for capturing CO_2, maintenance of the infrastructure, and other variable costs directly associated with each unit of CO_2 captured.

Reduction Function (r): Represents the reduction in emissions achieved through the application of CCS technology. It quantifies the effectiveness of CCS in terms of emissions reduced.

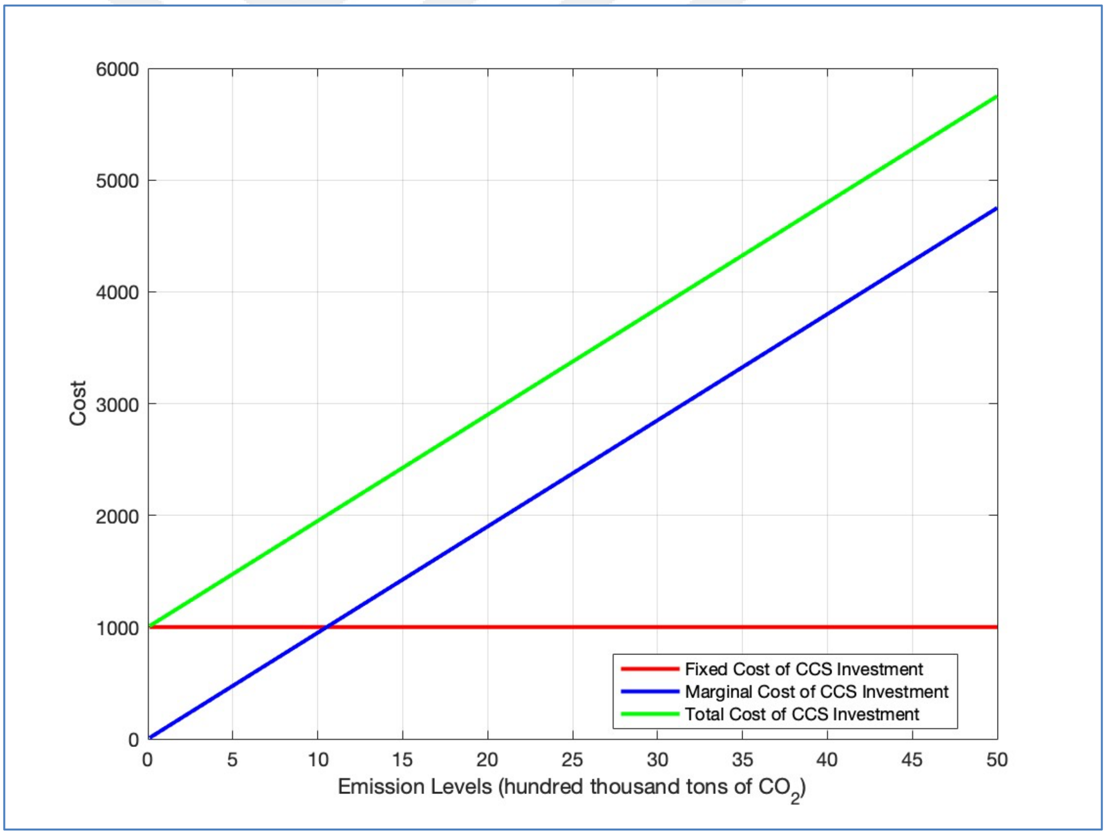
Tax Liability $((e - r)\tau)$: The government imposes a tax per unit of emissions τ. Therefore, the plant's tax liability is $((e - r)\tau)$, where e is the initial amount of emissions and r is the amount of emissions reduced by CCS.

For the purpose of further analysis, we will proceed with the simplified total cost function:

$$C = f + c \cdot r + (e - r)\tau$$

Figure 11 demonstrates that the total cost function incorporates fixed costs, variable costs, and an emission tax component. The fixed cost f is independent of the production level, while the variable cost $(c \cdot r)$ increases linearly with the amount of emissions captured. The emission tax component $((e - r)\tau)$ decreases as r approaches the emissions e.

Figure 11. Fixed, Marginal, and Total Cost of CCS Investment



According to the International Energy Agency, (2020a), there are no technical limitations to achieving capture rates significantly above 90% for most well-established capture technologies. While capturing 100% of CO_2 is generally restricted by thermodynamic laws, capture rates of 98% or more are technically achievable with adjustments to the CO_2 separation process. Therefore, we can assume that the emission reduction level r is approximately equal to the emission level e in firms investing in CCS.

When $r = e$, the emission tax obligation disappears, the total cost C_{CCS} for implementing CCS is:

$$C_{CCS} = f + c.e$$

By comparing the total costs of abatement with and without CCS, the plant can decide whether investing in CCS technology is economically viable. If the total cost of CCS is less than the combined cost of abatement and emission taxes without CCS, the plant has a financial incentive to adopt CCS technology.

The marginal cost, derived as:

$$\frac{dC(r)}{dr} = c - \tau$$

indicates the cost of producing one additional unit. At $r = e$, the marginal cost equals the variable cost c, since the emission tax no longer applies. This analysis highlights the impact of fixed costs, variable costs, and emission taxes on total and marginal costs, offering insights for optimizing emission strategies and minimizing costs.

3.1.3. Lagrange Multiplier Method for Cost Minimization Problem

3.1.3.1. Cost Minimization without CCS Investment

Objective Function

Minimize the total abatement cost Z for a plant that reduces its emissions by an amount r:

$$Z = A\left(e \, ln\left(\frac{e}{e-r}\right) - r\right) + (e-r)\tau,$$

Subject to:

$$0 \leq r \leq e$$

where:

A: Positive constant representing the abatement cost parameter and is bigger than zero ($A > 0$).

e: Total emissions without any abatement.

r: Emission reduction amount.

τ: Carbon tax per unit of emissions not abated.

Lagrangian Formulation

To solve this constrained optimization problem, we construct the Lagrangian function:

$$\mathcal{L}(r, \lambda_1, \lambda_2) = A\left(e\, ln\left(\frac{e}{e-r}\right) - r\right) + (e-r)\tau + \ \lambda_1(-r) + \lambda_2(r-e),$$

where λ_1 *and* λ_2 are the the Lagrange multipliers associated with the constraints $r \geq 0$ and $r \leq e$, respectively.

Karush-Kuhn-Tucker (KKT) Conditions

1. Stationarity:

$$\frac{\partial \mathcal{L}}{\partial r} = A\left(\frac{e}{e-r} - 1\right) - \tau - \lambda_1 + \lambda_2 = 0$$

2. Primal Feasibility:

$$0 \leq r \ \leq e$$

3. Dual Feasibility:

$$\lambda_1 \geq 0, \quad \lambda_2 \geq 0$$

4. Complementary Slackness:

$$\lambda_1 r = 0, \quad \lambda_2(r-e) = 0$$

The complementary slackness conditions $\lambda_1 \cdot r = 0$ and $\lambda_2(e-r) = 0$ imply that $(r = 0)$ or $(r = e)$.

Possible Cases

Case 1: $(r = 0)$

Complementary Slackness:

$$\lambda_1 \geq 0, \qquad \lambda_1 r = 0 \Longrightarrow \lambda_1 \cdot 0 = 0$$

$$\lambda_2 = 0, \text{ since } (e > 0)$$

Stationarity Condition:

$$A\left(\frac{e}{e} - 1\right) - \tau \ \ implies\ that\ \ \lambda_1 = -\tau$$

Since $\tau > 0$ and $\lambda_1 < 0$ violates the dual feasibility condition, $(\lambda_1 \geq 0)$, $r = 0$ is not optimal.

Case 2: $(r = e)$

Complementary Slackness:

$$\lambda_2(e - e) = \lambda_2 \cdot 0 = 0 \text{ implies that } \lambda_2 \geq 0$$

$$\lambda_1 r = 0,\ \lambda_1 = 0,\ \text{since } (r = e > 0)$$

Stationarity Condition:

$$A\left(\frac{e}{e - e} - 1\right) - \tau - 0 + \lambda_2 = 0$$

If $r = e$, then λ_2 can take any value and $\lambda_1 = 0$. However, the term ($\frac{e}{e-e}$) is undefined, indicating that the marginal cost tends to infinity. This makes full abatement economically unfeasible.

This mathematical analysis confirms that high levels of emission reduction are associated with extremely high costs with regular abatement techniques.

Case 3: $(0 < r < e)$

Complementary Slackness:

$$\lambda_2 = 0,\ \lambda_1 = 0$$

Stationarity Condition:

$$A\left(\frac{e}{e - e} - 1\right) - \tau = 0$$

The equation $A\left(\frac{e}{e - r^*} - 1\right) - \tau = 0$ is solved to determine the optimal abatement level r^*.

A must be greater than zero, as it reflects the cost structure and technology parameter influencing the cost function. Since $A > 0$, only the term inside the parentheses can equal zero to balance the equation.

$$\frac{Ae}{e - r^*} - A = \tau$$

Solving for $e - r^*$:

$$e - r^* = \frac{Ae}{A + \tau}$$

Rearranging further to express r^* :

$$r^* = e - \frac{Ae}{A+\tau} = e\left(\frac{\tau}{A+\tau}\right)$$

Thus, the optimal abatement level r^* is a fraction of total emissions (e). The plant reduces emissions up to the point where the marginal cost of abatement equals the carbon tax (τ). This relationship ensures that the plant minimizes its total costs by balancing the cost of reducing emissions with the tax it would otherwise incur.

Total Cost of Abatement:

$$\mathrm{C}_{\mathrm{abatement}} = \mathrm{A}\left(\mathrm{e}\ \ln\left(\frac{\mathrm{e}}{\mathrm{e} - \mathrm{r}^*}\right) - \mathrm{r}^*\right) + (\mathrm{e} - \mathrm{r}^*)\tau$$

Substituting $r^* = e\left(\frac{\tau}{A+\tau}\right)$ into the equation simplifies it to:-

$$C_{\mathrm{abatement}} = Ae\ln\left(1 + \frac{\tau}{A}\right)$$

This formulation captures both the technological cost component (associated with A) and the policy-driven cost component (linked to the carbon tax τ).

3.1.3.2. Cost Minimization with CCS Investment

Minimze the total cost C when the plant invest in CCS technology:

$$\min_{r} C = f + c \cdot r + (e - r)\tau$$

Subject to:

$$0 \leq r \leq e$$

where,

f : Fixed cost of implementing CCS.

c: Marginal cost per unit of emissions captured.

τ: Carbon tax per unit of emissions not captured.

r : The amount of emissions reduced (captured by CCS).

e: Total emissions without any capture.

Lagrangian Formulation

Construct the Lagrangian function:

$$\mathcal{L}(r, \lambda_1, \lambda_2) = f + c \cdot r + (e - r) \cdot \tau + \lambda_1(r - e) + \lambda_2(-r),$$

where λ_1 and λ_2 are the the Lagrange multipliers associated with the constraints. $r \geq 0$ and $r \leq e$, respectively.

KKT Conditions

1. Stationarity:

$$\frac{\partial \mathcal{L}}{\partial r} = c - \tau + \lambda_1 - \lambda_2 = 0$$

2. Primal Feasibility:

$$0 \leq r \leq e$$

3. Dual Feasibility:

$$\lambda_1 \geq 0, \quad \lambda_2 \geq 0$$

4. Complementary Slackness:

$$\lambda_1 r = 0, \; \lambda_2(r - e) = 0.$$

Possible Cases

We consider three cases based on the relationship between carbon tax τ and marginal cost of capture c.

Case 1: $\tau > c$

Stationarity Condition:

If $\tau > c$, from $\frac{\partial \mathcal{L}}{\partial r} = c - \tau + \lambda_1 - \lambda_2 = 0$, we get $-(\tau - c) + \lambda_1 - \lambda_2 = 0$.

Complementary Slackness:

If $r = 0$, then $\lambda_1 > 0$ and $\lambda_2(0 - e) = -e\lambda_2 = 0, \lambda_2 = 0, \; (e > 0)$.

$-(\tau - c) + \lambda_1 = 0, \lambda_1 < 0$, violates the dual feasibility condition ($\lambda_1 \geq 0$)

If $r = e, \lambda_1 = 0$ and $\lambda_2 = \tau - c, \; \lambda_2 \geq 0$ satisfies dual feasibility

All KKT conditions are satisfied, as $\lambda_1 > 0$.

The optimal solution is $r = e$. The plant captures all emissions since the tax τ is higher than the marginal cost c. Therefore, when $\tau > c$, the marginal cost of CCS is $c - \tau + \lambda_1 = 0$, indicating that it is optimal to capture all emissions.

Case 2: $\tau < c$

Stationarity Condition:

If $\tau < c$, from $\frac{\partial \mathcal{L}}{\partial r} = c - \tau + \lambda_1 - \lambda_2 = 0$ we get $(c - \tau) + \lambda_1 - \lambda_2 = 0$.

Complementary Slackness:

If $r = e$, $\lambda_1 = 0$ and $\lambda_2 < 0$, violates the dual feasibility condition ($\lambda_2 \geq 0$).

If $r = 0$, $\lambda_2 = 0$ and $\lambda_1$can be any non-negative value.

$r = 0$ is optimal as $\lambda_1 \geq 0$.

The marginal cost of capturing c is higher than the carbon tax τ, making it cheaper to pay the tax.

Case 3: $\tau = c$

Stationarity Condition:

$\tau = c$, from $\frac{\partial \mathcal{L}}{\partial r} = c - \tau - \lambda_1 + \lambda_2 = 0$ and $\lambda_2 = \lambda_1$.

Complementary Slackness:

If $r = e$, $\lambda_1 = c - \tau$ and $\lambda_2 = 0$

If $r = 0$, $\lambda_1 = 0$ and $\lambda_2 = c - \tau$

Both λ_1 and λ_2 are zero, satisfying dual feasibility.

The plant is indifferent between capturing any amount of emissions since the tax equals the marginal cost. The marginal cost of capturing equals the carbon tax, making the total cost the same for any r in $[0, e]$.

Based on the analysiz, when $\tau > c$, the optimal emission reduction is If r*= *e,* otherwise, there is no CCS investment.

Total Cost with CCS

$$C_{CCS} = f + c \cdot e + (e - e)\tau = f + c \cdot e$$

3.2. Demermining the Threshold Emission Level

In the context of this model, plants must decide how to manage their emissions in a cost-effective manner. They face two main options:

1. Invest in CCS Technology: This eliminates all emissions ($\tau > c$) and avoids any tax liabilities. However, it comes with a high fixed cost (f), making it viable only under economies of scale.
2. Use Existing Abatement Techniquess: This reduces a portion of the emissions ($\tau < c$) while paying taxes on the remaining emissions.

The threshold emission level e^* is the point at which the total cost of using abatement techniques equals the total cost of investing in CCS. At this point, the plant is indifferent between the two options. This condition can be expressed as:

$$C_{\text{abatement}} = C_{CCS}$$

Substituting the cost expressions:

$$Ae^* \, ln\left(1 + \frac{\tau}{A}\right) = f + c \cdot e^*$$

Rearranging to solve for e^* :

$$e^* = \frac{f}{Al\,n\left(1 + \frac{\tau}{A}\right) - c}$$

Interpretation of e^*

The threshold emission level e^* represents the point where the plant's total cost of using abatement technologies equals the total cost of investing in CCS. It divides plants into two categories:

- Plants with $e > e^*$: These plants find it more cost-effective to invest in CCS because the high tax liability and abatement costs for massive emissions make CCS the better option.
- Plants with $e < e^*$: These plants prefer abatement technologies, as their lower emissions result in lower tax liabilities, making abatement less costly than CCS.

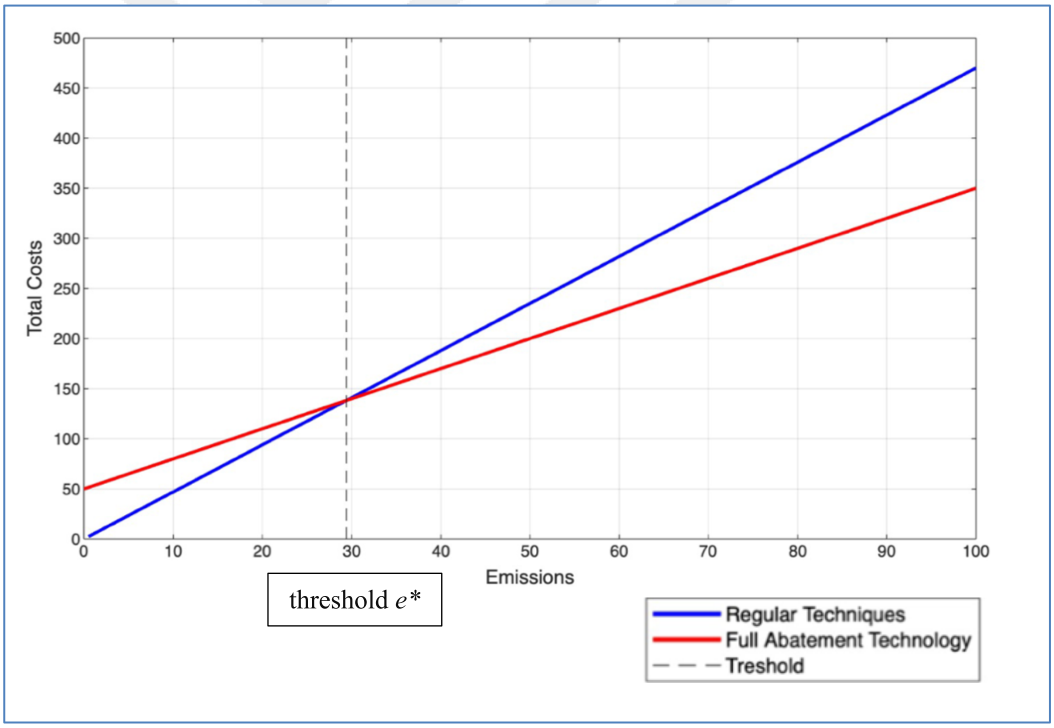
Table 4. Threshold Emission Level Analysis

Parameter	**Effect on Threshold Emission Level (e^*)**	**Derivative Analysis**
A (Abatement Cost)	Higher A increases the cost of abatement, lowering e^*.	Decreases ($\partial e^*/\partial A < 0$)
τ (Carbon Tax)	Higher τ increases the cost of remaining emissions, making CCS relatively more attractive and decreasing e^*.	Decreases ($\partial e^*/\partial \tau < 0$)
c (Variable CCS Cost)	Higher c makes CCS less competitive, increasing e^* .	Increases ($\partial e^*/\partial c > 0$)
f (Fixed CCS Cost)	Higher f increases the upfront cost of CCS, making it less viable for plants with lower emissions.	Increases ($\partial e^*/\partial f > 0$)

In the **Table 4.** the threshold emission level e^*marks the point where plants are indifferent between adopting CCS technology or applying standard abatement techniques. Plants with emissions greater than e^* will find it more cost-effective to invest in CCS technology, as the cost of using regular techniques (i.e., partial abatement and paying taxes on the remaining emissions) becomes higher than the cost of investing in CCS beyond this point. Conversely, plants with emissions below e^* will prefer to abate and pay the tax.

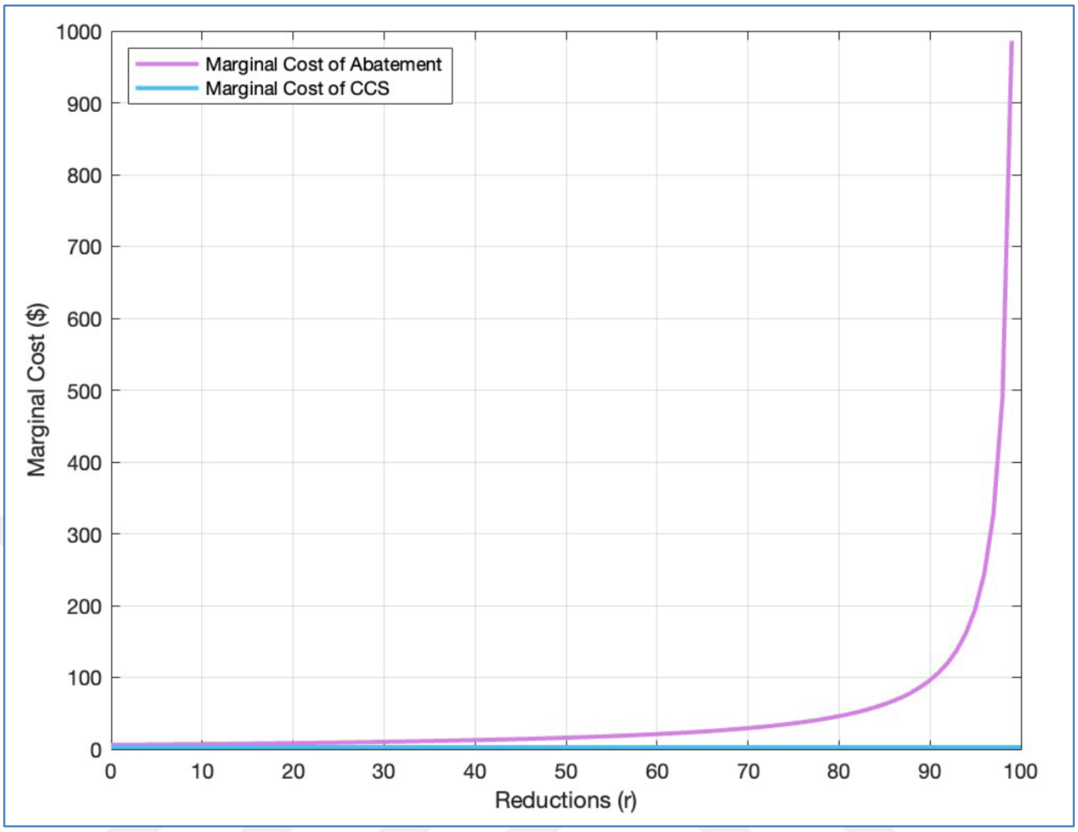
Figure 12 depicts the emission threshold $e*$ at which plants are indifferent between regular abatement techniques and investing CCS. Right side of threshold is for plants that find it optimal to adopt CCS technology under a specific carbon tax rate. It demonstrates that as the carbon tax rate increases, the emission threshold for CCS adoption decreases. This suggests that plants with lower emissions are more likely to invest in CCS technology when faced with higher carbon taxes. This highlights the role of carbon tax policy in driving the adoption of CCS, particularly for plants with moderate to high emissions.

Figure 12. Emission Thresholds for CCS Adoption with Carbon Tax



While **Figure 12** illustrates the conditions under which plants adopt CCS based on emission levels and tax policies, further insights into the economic dynamics of these choices can be gained by examining the marginal costs associated with each method. Understanding how marginal costs evolve relative to emission reductions provides deeper clarity on the long-term feasibility and scalability of CCS investments.

Figure 13. Marginal Cost of Abatement and Marginal Cost of CCS Comparison



In **Figure 13**, Marginal Costs of Regular Techniques (e.g. Fuel switching) tends to infinity as r approaches e, while the Marginal Cost of CCS Investment remains constant. The horizontal axis in the graph represents the percentage of emission reductions r, ranging from 0% to 100%. Therefore, apart from a substantial fixed cost, the constant Marginal Cost of CCS can be more advantageous for plants with economies of scale in the long run. Nevertheless, the magnitude of the fixed cost can negate this advantage, underscoring the necessity for technological investments and government support for CCS investments in cases of high fixed costs.

4. RESULTS AND DISCUSSION

CCS has a gap-filling role in industries whose production structures cannot be easily changed and which produce intense particulate emissions. This study examined the factors influencing the decision of carbon-emitting plants to invest in CCS and its interplay with tax policies.

The theoretical framework was provided by Golombek et al. (2023). In Golombek's model, a fixed number of plants emit carbon, and the government imposes a carbon tax on each unit of emission. These plants face two options: either pay the tax for all emissions or invest in CCS technology, capturing emissions to avoid the tax burden. Plants that opt for CCS must also transport the captured CO_2 to terminals, which then transport it to a central storage hub.

Building on this model, we introduced the assumption of an infinite number of plants, with emissions uniformly distributed between a lower and upper bound. In this framework, each plant's cost function varies based on its emission levels. Plants that do not invest in CCS use regular abatement techniques, such as fuel switching, to optimize their tax payments.

Trying to reduce emissions with the help of regular abatement is associated with an increasing marginal cost, making it impossible to reduce all emissions in this way. Nevertheless, as regular abatement techniques provide plants with tools tailored to their specific structures, we may encounter reduced emission outputs overall. The fact that each plant reduces emissions optimally for itself (to a greater or lesser extent) and pays taxes on the remaining emissions aligns with the overarching goal of carbon reduction.

Since CCS is a large-scale, high-cost, and capital-intensive investment, not every plant will find the CCS option optimal. The emission amount at which the total cost of the two options is equal is called the threshold emission level, as plants are indifferent between these two options at this point. The variables that determine the threshold emissions of plants are the amount of emissions they produce and the carbon tax level.

Plants with emissions above the threshold level find it optimal to invest in CCS, benefiting from economies of scale. Conversely, increasing the tax level—that is, raising the price of carbon—may lower the threshold level to include plants with lower emissions, and vice versa.

5. CONCLUSION

Many methods such as reducing emissions, popularizing renewable energy sources, increasing efficiency and obtaining more output with the same input are implemented for our goal of leaving a livable world for the future. The breadth of this tool set gives us the necessary opportunity to apply a specific recipe in different production structures, different geographical conditions and different economies.

Our study highlights the pivotal role of CCS in industries characterized by rigid production structures and high particulate emissions. By incorporating CCS, these industries can effectively reduce their carbon emissions provided that the investment is economically viable. Using the theoretical model of Golombek et al. (2023), we identified the threshold emission level at which CCS becomes cost-effective. This threshold is influenced by both the emission levels of plants and the prevailing carbon tax rate.

Plants with emissions above the threshold benefit from economies of scale and find CCS investments advantageous. Higher carbon taxes further reduce the threshold, expanding CCS adoption to plants with lower emissions. However, the capital-intensive nature of CCS limits its feasibility to high-emission plants without substantial financial support.

Policy implications from our findings indicate that governments should implement higher carbon taxes to reflect the true cost of pollution, thereby incentivizing plants to adopt CCS and significantly reducing overall emissions. To further support CCS adoption, providing financial assistance through subsidies and incentives is critical for overcoming high initial investment costs and encouraging broader utilization of the technology. Additionally, regular abatement techniques, despite their increasing marginal costs, offer a flexible interim solution by enabling plants to reduce emissions to an optimal level before paying taxes on the remainder, contributing to a balanced and effective carbon reduction strategy.

The underlying issue lies in the fact that pollution has historically been unpriced. Incorporating pollution costs into economic decision-making adds complexity but also aligns incentives with environmental objectives. Policymakers must not only incentivize carbon reduction technologies but also educate and engage the public to understand the importance of these initiatives. This dual approach—technological advancement and public awareness—is essential to achieving a sustainable and livable future.

APPENDIX

1. Derivation of the Total Emissions Function

The function representing the total emission E in the market can be written as follows:

$$E \equiv \int_{\underline{e}}^{\overline{e}} e \, dF(e) = \int_{\underline{e}}^{\overline{e}} e \, \frac{1}{\overline{e} - \underline{e}} \, de$$

Solving this integral:

$$E = \frac{1}{\overline{e} - \underline{e}} \int_{\underline{e}}^{\overline{e}} e \, de = \frac{1}{\overline{e} - \underline{e}} \left[\frac{e^2}{2} \right]_{\underline{e}}^{\overline{e}} = \frac{1}{\overline{e} - \underline{e}} \left(\frac{\overline{e}^{\,2}}{2} - \frac{\underline{e}^2}{2} \right)$$

Simplifying this expression:

$$E = \frac{\overline{e}^{\,2} - \underline{e}^2}{2(\overline{e} - \underline{e})} = \frac{(\overline{e} + \underline{e})(\overline{e} - \underline{e})}{2(\overline{e} - \underline{e})} = \frac{\overline{e} + \underline{e}}{2}$$

This confirms that the total emissions E represent the average of $\overline{e}$ and $\underline{e}$ considering the emission levels of all plants and their distribution.

2. Derivation of the Total Cost of Abatement and Its Derivatives

The total cost of abatement depends on r (reduction of emission):

$$Z(r) \equiv A \left[e \, ln \left(\frac{e}{e - r} \right) - r \right]$$

The first derivative of the cost function with respect to r is:

$$\frac{\partial Z}{\partial r} = A \left(\frac{e}{e - r} - 1 \right) = A \left(\frac{e - (e - r)}{e - r} \right) = A \left(\frac{r}{e - r} \right)$$

The second derivative of the cost function with respect to r is:

$$\frac{\partial^2 Z}{\partial r^2} = A \frac{\partial}{\partial r} \left(\frac{r}{e - r} \right)$$

Using the quotient rule:

$$\frac{\partial^2 Z}{\partial r^2} = A \left(\frac{(1)(e - r) - (r)(-1)}{(e - r)^2} \right) = A \left(\frac{e - r + r}{(e - r)^2} \right) = A \left(\frac{e}{(e - r)^2} \right)$$

Convexity of $Z(r)$: Since A is positive and $(e > r \geq 0), ((e-r)^2)$ *is* always positive. The second derivative $(\frac{\partial^2 Z}{\partial r^2})$ is positive.

3. Derivation of Marginal Cost, Marginal Benefit, and Optimal r^*

Because the plant does not account for the external cost of emissions, the marginal benefit (MB) of reducing emissions is zero:

$$MB = 0$$

To find the optimal reduction r^* set the marginal cost equal to the marginal benefit:

MC = MB

From the total cost function:

$$MC = A\left(\frac{r}{e-r}\right)$$

At $MB = 0$, marginal cost MC determines the economically viable r^*, emphasizing that in the absence of external incentives, the plant will opt for no abatement. Matematical properties capture the economic challenge of achieving full emission reduction due to the prohibitively high costs as abatement approaches the emissions level e .

$$A\left(\frac{r}{e-r}\right) = 0$$

Where A is a positive constant, e represents the emissions, and r is the emission reduction. The constraints for this optimization problem are:

$$0 \leq r \leq e$$

In the absence of abatement, the marginal cost is zero, reflecting no expenditure for emission reduction. This aligns with the finding that, without external incentives or regulatory pressures, the plant has little economic motivation to reduce emissions.

4. Integrating Salop's Circle with CCS

Salop's article titled *Monopolistic Competition with Outside Goods*, published in 1979, created a basic framework for the circular city model, spatial economy and monopolistic competition. This model positions firms evenly spaced around a circle to simulate a market without edge effects. Therefore, it represents perfect competition. Consumer preferences in the model are influenced by transportation costs and product differentiation. Each plant's location affects its competitive strategy and market share (Salop, 1979).

In the Salop Circle model, n plants are equidistantly placed on a circle with circumference L. Each plant offers a differentiated product, and consumers are uniformly distributed along the circle. The distance between two adjacent plants is $Ln,$ and consumers incur a transportation cost proportional to this distance, denoted as t per unit distance. The total cost for a consumer choosing a plant at a distance d is given by the sum of the product price p and the transportation cost td (Salop, 1979).

Golombek et al. (2023) replaced consumers with CO_2-emitting plants and plants with CO_2 collection terminals. They extended the Salop model to analyze the CCS value chain. Now the plants are uniformly distributed and the demand for terminals will be set according to distance. This application provides a framework to examine the optimal lcation and number of terminal investment decisions for CCS.

5. Transportation Distance and Cost Calculations in the Salop Model

In the Salop model adapted for the CCS value chain, the transportation distances between plants and terminals are critical to minimizing total costs. The maximum, minimum, and average distances from a plant to its nearest terminal are as follows:

The maximum distance between a plant and a terminal is:

$$d_{max} = \frac{L}{2n},$$

where L is the circumference of the circle and n is the number of terminals.

The minimum distance is:

$$d_{min} = 0$$

The average distance between a plant and its nearest terminal is:

$$d_{\text{avg}} = \frac{L}{4n}.$$

The transportation cost for a plant per unit of CO_2 is therefore:

$$C_{\text{transport}} = t \cdot d_{\text{avg}} = \frac{tL}{4n},$$

where t is the transport cost per unit of distance.

Each plant evaluates whether to adopt CCS technology by comparing the transportation cost and investment costs with the carbon tax cost. The decision is influenced by the distribution of costs, leading to a proportion q of plants opting for

CCS versus those continuing with traditional abatement practices. This proportion depends on the carbon tax level and the relative costs of transportation and CCS investment, demonstrating the economic trade-offs involved in the adoption of CCS within the Salop model framework.

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