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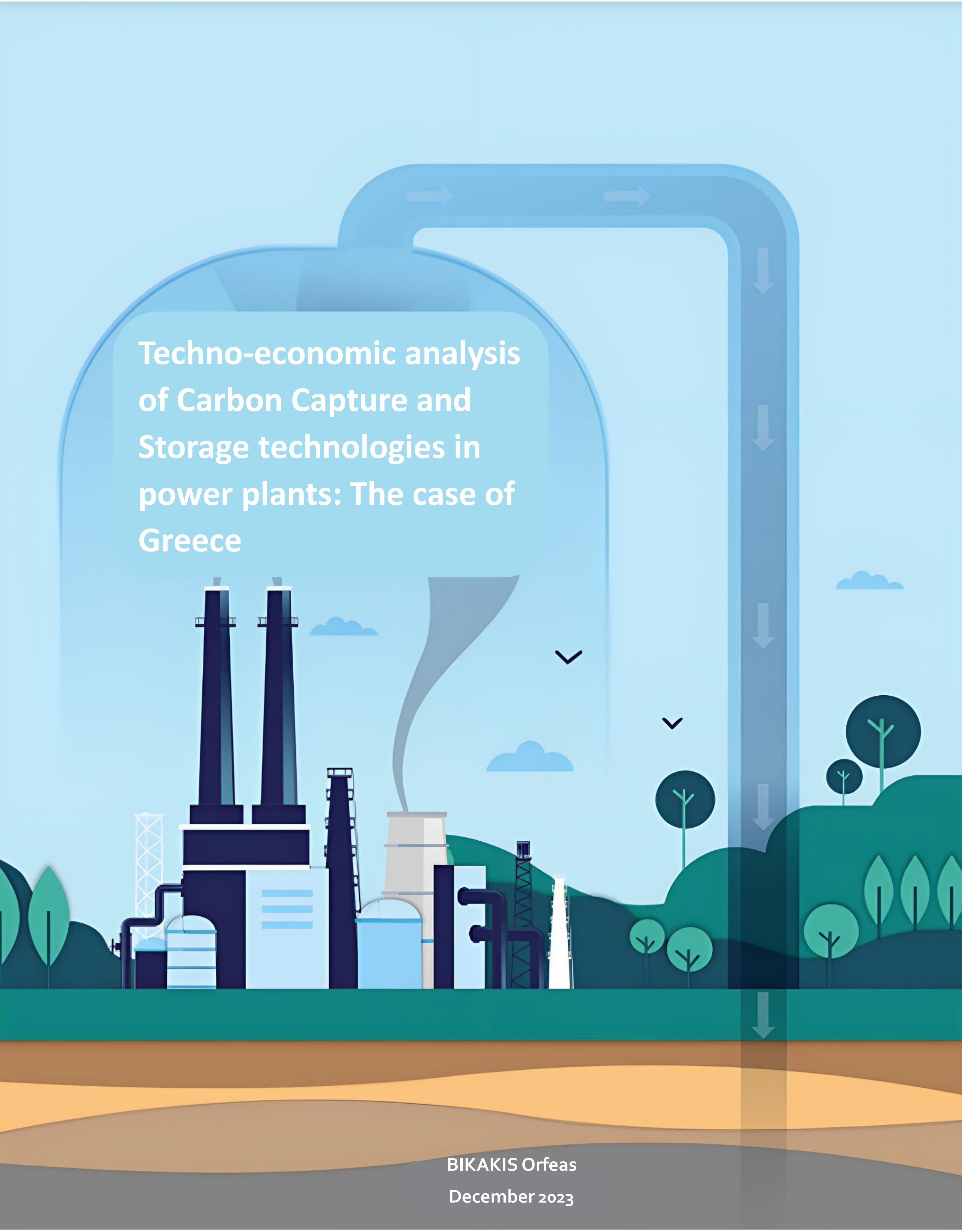

Techno-economic analysis of Carbon Capture and Storage technologies in power plants: The case of Greece

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Abstract

With increasing worries about the effects of climate change and the harmful implications of increased greenhouse gas emissions, carbon capture and storage (CCS) technology adoption has become a higher priority in the global energy landscape. This thesis investigates CCS implementation in the context of power production, with a specific emphasis on its prospective application in a natural gas-fired power plant in Greece.

The thesis starts with an extensive review of the available technologies for carbon capture, transportation, and storage, indicating all their technical aspects. The examination of global and domestic CO_2 storage capacity sets the groundwork for understanding the feasibility of CCS deployment.

Methodologically, the thesis outlines a rigorous data collection process, utilizing advanced analysis techniques and models to assess the viability of CCS technologies. The overview of power generation in Greece that follows, offers information on the country's current energy mix, regulatory rules, and emission profiles of the power plants.

The study also explores the policies surrounding CCS implementation, analyzes the European framework for deployment, and evaluates Greece's decarbonization strategy. In addition, potential sources of funding for these projects are discussed to assess the financial aspects of integrating CCS technologies into Greek power plants.

Following that, the techno-economic study assesses the potential of various technologies, considering their cost and performance characteristics as well as the barriers to their adaptation. The study involves a cost estimation, a performance rating, and an economic feasibility assessment. Based on the findings, a case study is carried out to show the use of the most efficient technology in a selected power plant.

The conclusions of the cost and performance analysis, the economic feasibility evaluation, and the discussions of environmental advantages and problems are presented in the final chapter. Policy implications and recommendations are offered, with an emphasis on the policy framework, economic incentives, and finance mechanisms essential for effective CCS implementation. The purpose of this research is to inform stakeholders and policymakers so that they may make better decisions for a more sustainable future.

Keywords: Carbon Capture and Storage (CCS), power plants, techno-economic analysis, Greece, greenhouse gas emissions, economic viability.

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List of abbreviations

CCS – Carbon Capture and Storage

CCUS – Carbon Capture, Utilization and Storage

GHG – Greenhouse Gas

CO_2 – Carbon Dioxide

IPCC – Intergovernmental Panel on Climate Change

EU – European Union

ETS – Emissions Trading System

LCA – Life Cycle Assessment

O&M – Operations and Maintenance

CAPEX – Capital Expenditure

OPEX – Operating Expenditure

EOR – Enhanced Oil Recovery

MEA – Monoethanolamine (a solvent used in CO_2 capture)

PC – Pulverized Coal (a type of power plant)

NGCC – Natural Gas Combined Cycle

CCGT – Combined Cycle Gas Turbine

SCPC – Supercritical Pulverized Coal

IGCC – Integrated Gasification Combined Cycle

CFB – Circulating Fluidized Bed

BECCS – Bioenergy with Carbon Capture and Storage

DAC – Direct Air Capture

LCOE – Levelized Cost of Electricity

WACC – Weighted Average Cost of Capital

ROI – Return on Investment

NPV – Net Present Value

IRR – Internal Rate of Return

MT – Metric Tons

R&D – Research and Development

EIA – Energy Information Administration

PCC – Post-Combustion Capture

OXY – Oxy-fuel Combustion

1. Introduction

1.1 Background and motivation

Global concern about climate change and its negative consequences has created an urgent demand for sustainable, low-carbon energy solutions. Power generation, which contributes significantly to greenhouse gas emissions, has come under fire for its environmental impact. In response to this problem, several tactics and technologies for reducing carbon dioxide (CO_2) emissions from power plants have been investigated. Carbon Capture and Storage (CCS) is one potential solution that includes capturing CO_2 from power plant emissions and storing it underground to prevent it from entering the environment.

The impetus for this research originates from Greece's unique energy environment. Greece, like many other nations, is confronted with the combined issue of fulfilling rising energy consumption while transitioning to a low-carbon economy. Greece, as a country primarily reliant on fossil fuels, has acknowledged the necessity to investigate alternative energy sources and technologies to minimize its carbon footprint and meet international emission reduction goals.

Furthermore, Greece's distinct geographical and geological characteristics present prospective chances for CCS deployment. Greece has large offshore and onshore storage potential, which might help with long-term CO_2 storage. Despite these benefits, research, and analysis on the techno-economic viability of CCS systems in the Greek power sector are scarce.

As a result, the fundamental goal of this research is to undertake a thorough techno-economic analysis of CCS technology in Greek power plants. This research aims to provide valuable insights and inform policymakers, industry stakeholders, and energy planners about the potential of CCS as a viable solution for reducing greenhouse gas emissions in the energy sector by assessing the economic viability, environmental benefits, and challenges associated with CCS implementation. Overall, this research is motivated by the need to address climate change and the need for sustainable and decarbonized power generation.

1.2 Research objectives

The research objectives of this thesis on the techno-economic analysis of CCS technologies in power plants, with a focus on the case of Greece, are the following:

1. To investigate and assess the present state of CCS technologies: This goal entails performing a thorough literature analysis to better understand the many types of CCS technologies, their applications in power production, and their global deployment status. The goal is to lay a strong basis for understanding CCS technology, including its potential advantages and limits.
2. To determine the techno economic viability of CCS technology in Greek power plants: This goal entails creating a solid approach for assessing the techno-economic implications of incorporating CCS technology into current or prospective power plants

in Greece. The analysis will involve cost estimation, performance evaluation, and an economic viability assessment.

3. To assess the environmental advantages and obstacles of using CCS in Greek power plants: This goal is to quantify the possible decrease in greenhouse gas emissions caused by CCS systems. It entails assessing the environmental effect of capturing and storing CO_2 emissions from power plants, as well as evaluating the accompanying obstacles, such as transportation and storage issues.
4. To carry out a case study on the use of CCS in selected Greek power plants: This goal entails identifying representative power facilities in Greece and assessing the technical and economic viability of incorporating CCS technology into these specific situations. The case study will give practical insights into CCS technology deployment and will help to confirm the techno-economic analysis.
5. Policy implications and suggestions for CCS implementation in Greece will be provided: This objective seeks to provide policy suggestions and directions for boosting the deployment of CCS technology in Greece based on the findings of the techno-economic analysis and case study. Identifying the essential legislative frameworks, economic incentives, and financial mechanisms to enable the deployment of CCS technology in the Greek power industry is part of this.

The accomplishment of these research goals will lead to a better understanding of the techno-economic feasibility, environmental effect, and policy implications of CCS systems in Greek power plants. This study intends to give significant insights to policymakers, industry stakeholders, and researchers interested in the decarbonization of the Greek energy sector by undertaking a comprehensive examination.

This thesis attempts to bridge the knowledge gap and provide practical recommendations for the integration of CCS technology in Greek power plants by addressing the research goals. The ultimate objective is to help reduce greenhouse gas emissions, improve energy security, and promote Greece's transition to a more sustainable and low-carbon energy system.

1.3 Scope and contribution

Scope:

The scope of this thesis on the techno-economic analysis of CCS technologies in power plants, focusing on the case of Greece, is defined by the following parameters:

- The study focuses on a variety of CCS technologies typically used in power production, including post-combustion capture, pre-combustion capture, and oxy-fuel combustion. The analysis will evaluate the techno-economic feasibility of these chosen CCS systems in the context of Greek power plants.
- Greek Power facilities: The research will focus on integrating CCS technology into current or new Greek power facilities. To undertake the case study, a representative sample of power plants will be chosen, assuring a broad mix of fuel sources, capacity ranges, and geographic locations.
- The fundamental goal of the study is to examine the techno-economic aspects of CCS technology in Greek power plants. To identify the possible financial viability and

advantages of CCS deployment, this analysis will include cost calculation, performance evaluation, and economic feasibility assessment.

- Environmental Impact: The research will analyze the environmental advantages and problems associated with CCS systems, with a primary focus on greenhouse gas emissions reduction. In the Greek context, the research will analyze the possible environmental effect of capturing and storing CO_2 emissions from power plants.

Within the realm of carbon capture and storage (CCS) technologies, this thesis is a distinctive endeavor, focusing on a nuanced examination of the techno-economic landscape specifically within the context of Greek power plants. Its uniqueness is discernible in several key dimensions, setting it apart from other related studies. Unlike broader investigations that offer generalized insights, this research is intricately woven into the fabric of the Greek energy landscape. It meticulously delves into the integration of CCS technology into existing and prospective Greek power facilities, a deliberate effort to align findings with the idiosyncrasies of the Greek energy sector. This contextual specificity ensures that the recommendations and conclusions drawn are finely attuned to the intricacies of the local power infrastructure.

Furthermore, the thesis deviates from the norm by not confining its scrutiny to a single CCS technology. In contrast to studies that often concentrate on a particular facet of CCS, this research broadens the scope by encompassing various technologies, including post-combustion capture, pre-combustion capture, and oxy-fuel combustion. This deliberate diversification provides a more comprehensive view of the potential applications and challenges within the Greek power sector. What makes this work notably distinctive is its holistic approach. While economic considerations form the crux of the analysis, the research ventures beyond conventional boundaries by incorporating a meticulous assessment of environmental impacts. The primary focus remains on the reduction of greenhouse gas emissions, aligning with global imperatives for sustainable energy practices. By intertwining economic feasibility with environmental responsibility, this thesis aspires to furnish a nuanced understanding of the overall viability of CCS implementation in Greek power plants.

In essence, the synthesis of a localized focus, consideration of diverse CCS technologies, and a holistic analytical lens renders this thesis a unique contribution to the discourse. Its tailored approach, intrinsic to the Greek context, and its comprehensive evaluation, grounded in both economic and environmental facets, collectively distinguish this work and augment its pertinence to the specific challenges and opportunities inherent in the Greek energy landscape.

2. Methodology

2.1 Data collection

Data collection is the linchpin of our study, laying the groundwork for subsequent analyses and evaluations. Our approach integrates both primary and secondary data sources to provide a comprehensive understanding of the subject matter.

Primary Data:

- Face-to-face meetings: In-depth discussions with plant management, engineers, and technical personnel provided valuable insights into the specific challenges and opportunities associated with implementing CCS technologies at the plant level. These interactions shed light on the technical complexities, operational considerations, and potential barriers to CCS adoption.
- Interviews with stakeholders: Engaging with regulatory organizations, energy experts, and environmental groups facilitated the collection of crucial perspectives on the policy landscape, regulatory frameworks, and environmental implications of CCS technologies. These conversations enriched the understanding of the broader context surrounding CCS implementation in Greece.

Secondary statistics:

- Academic literature review: Extensive research was conducted to gather comprehensive information on global advancements in CCS technology, including recent breakthroughs, technological specifications, and performance metrics. This involved a thorough examination of academic journals, industry whitepapers, and scientific publications.
- Government studies analysis: Government reports and statistics on energy production, consumption, and greenhouse gas emissions provided historical trends and insights into the current energy landscape of Greece. This data was essential for assessing the potential impact of CCS technologies on the national energy profile.

2.2 Analysis techniques

To analyze and assess the information, multiple analysis approaches were used:

Quantitative Analysis:

- Statistical analysis: The acquired data was subjected to rigorous statistical analysis to identify trends, correlations, and patterns. This included calculating cost estimates, evaluating efficiency rates, and quantifying potential emission reductions associated with CCS implementation.
- Cost-benefit analysis: A comprehensive cost-benefit analysis model was developed to assess the economic feasibility of adopting CCS systems in Greek power plants. The model analyzed long-term costs and benefits, considering factors such as capital investments, operational expenses, carbon emission reductions, and potential revenue streams.

Qualitative Analysis:

- Thematic analysis: Interviews and surveys were analyzed using thematic analysis to uncover recurring themes, perspectives, and concerns regarding CCS technologies. This qualitative approach provided a deeper understanding of the social and organizational factors influencing CCS adoption.

- Comparative analysis: A comparative analysis was conducted to evaluate various CCS technologies based on critical parameters such as cost, efficiency, capture rates, maturity level, and suitability for Greek power plants. This comparison allowed for the identification of the most promising technologies for implementation.

2.3 Models/tools used

Our analytical arsenal comprises a diverse array of models and tools, each meticulously chosen to elevate the depth and precision of our study. The utilization of these tools was not arbitrary but aligned with the specific demands of our research objectives.

- **Cost-Benefit Analysis Model**: Purpose: This model served as the cornerstone for evaluating the economic feasibility of incorporating CCS systems in Greek power stations. It facilitated a nuanced comparison of costs and benefits over time, factoring in variables such as initial investment, operational expenses, and potential long-term gains. The model provided a robust quantitative foundation, allowing us to assess the financial viability of implementing carbon capture and storage technologies.

- **Spreadsheet Software**: Functionality: Microsoft Excel emerged as an indispensable tool, playing a multifaceted role in our methodology. It served as a central hub for data organization, enabling systematic categorization and manipulation of vast datasets. Beyond mere tabulation, Excel facilitated intricate calculations, including complex statistical analyses, and allowed for the creation of visually compelling graphs and charts, enhancing the clarity and interpretability of our findings.

- **Visualization tools**:

  Power BI:

  Visualization Capability: Power BI was harnessed for its powerful visualization capabilities. It allowed us to create dynamic and interactive dashboards, translating complex data sets into easily understandable visual representations. This not only enhanced the clarity of our findings but also provided stakeholders with an intuitive means of engaging with the data.

  IBM Cognos Analytics:

  Data Exploration: IBM Cognos Analytics played a crucial role in data exploration. Its robust analytics capabilities enabled us to delve deep into the intricacies of our dataset, uncovering hidden patterns and insights. The tool's ability to handle large datasets ensured that no nuance was overlooked, contributing to the comprehensiveness of our analysis.

  Python:

  Custom Analysis and Scripting: Python, a versatile programming language, was employed for custom analysis and scripting. Its flexibility allowed us to tailor analytical processes to the specific demands of our research. Python scripts were particularly beneficial in automating repetitive tasks, ensuring efficiency and accuracy in data processing..

3. Literature Review

3.1 Overview of Carbon Capture technologies

Carbon Capture and Storage (CCS) is a set of technologies aimed at capturing carbon dioxide (CO2) emissions from power plants and industrial sources, so that it does not enter the atmosphere. The captured CO2 is then transported and stored underground, or it can be utilized for various applications. CCS technologies can play a critical role in addressing climate change. Technology Readiness Levels (TRL) is a scale from 1 to 9 that distinguishes a series of transitional development stages that all technologies must pass through before being commercially implemented. This may be used to debate the maturity of various CO2 collection systems. There are numerous CO2 capture technologies available, including [43]:

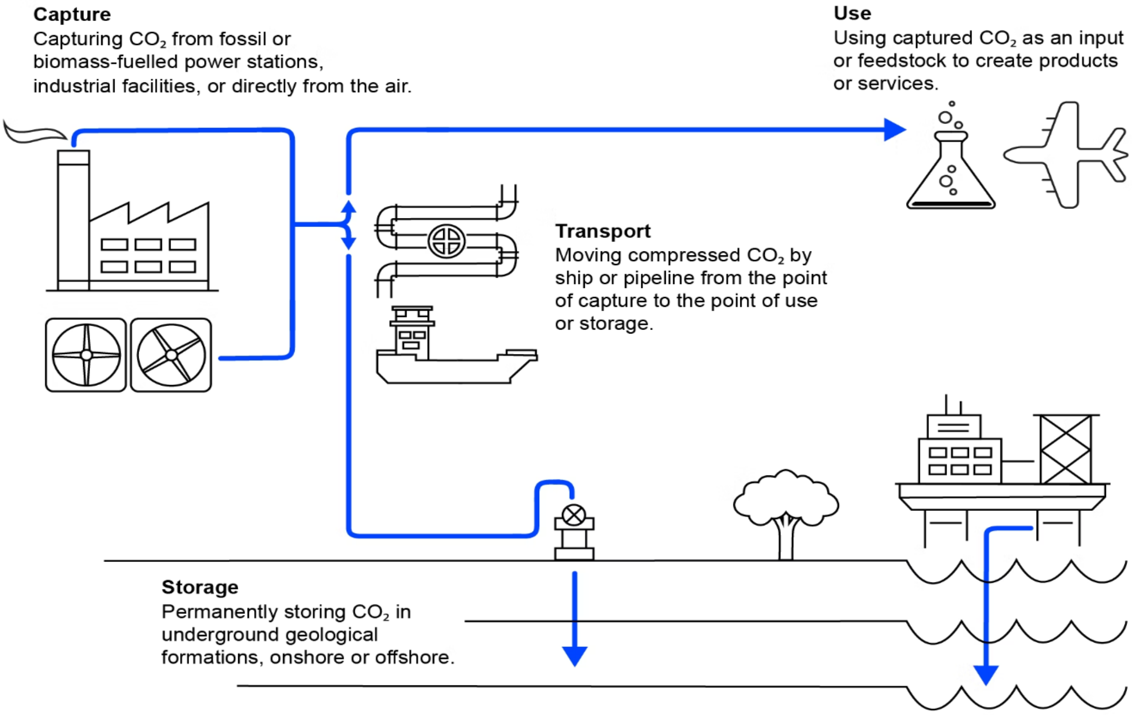


Figure 1: The value chain of CCUS [30]

Pre-Combustion CO2 Capture

Pre-Combustion Capture refers to CO2 capture used to create syngas (CO/H2) from a carbonaceous fuel before combustion. These include gaseous streams of 15-40 mol% CO2 at pressures ranging from 14 to 41 bar. The CO in the generated syngas stream is converted to CO2 in shift converters utilizing a water-gas shift reaction, and the H2 that remains after purification can be used as fuel in fuel cells, boilers, furnaces, turbines, and refinery activities. The extra benefit of this technology is that solvent regeneration is feasible via pressure decrease rather than heat addition. Pre-CC physical solvents include Selexol (a dimethyl ether/polyethylene glycol combination), Purisol (N-methyl pyrrolidone), Rectisol (chilled methanol), and Fluor (propylene carbonate).

The provided illustration showcases the process of pre-combustion capture within the context of a gasification facility. The regulation of the quantity of air or oxygen (O_2) within the gasifier is meticulously orchestrated during gasification reactions, ensuring that only a fraction of the fuel undergoes complete combustion. This process, known as "partial oxidation," generates the necessary heat for the chemical breakdown of the fuel, resulting in the creation of synthesis gas (syngas). Syngas is composed of hydrogen (H_2), carbon monoxide (CO), and minor quantities of other gaseous elements. Subsequently, the syngas is subjected to processing within a water-gas-shift (WGS) reactor. This reactor converts CO into CO_2 and augments the concentrations of CO_2 and H_2 molecules within the syngas stream to approximately 40% and 55%, respectively. At this juncture, the CO_2 exhibits a substantial partial pressure, which enhances its efficacy as a driving force for various separation and capture technologies. Once the CO_2 is extracted, the resulting syngas, enriched with H_2, become nearly pure hydrogen, suitable for various sustainable energy system applications. One of these applications involves employing H_2 as a fuel in a combustion turbine to generate electricity as part of an efficient combined cycle plant. Additional electricity generation occurs through the utilization of energy harvested from the combustion turbine flue gas via a heat recovery steam generator (HRSG). Further applications encompass the synthesis of liquid transportation fuels, ammonia, or chemicals, along with the use of hydrogen as a zero-carbon fuel source.

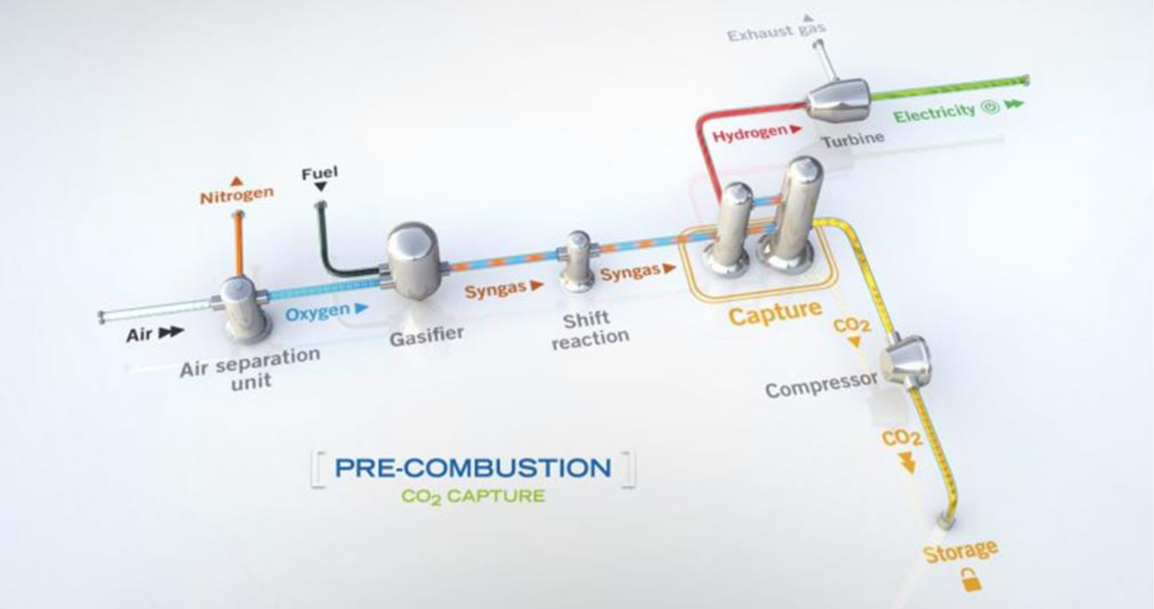


Figure 2: Pre-combustion systems [14]

Post-Combustion CO_2 Capture

Post-combustion CO_2 capture is predominantly utilized in the realm of natural gas and pulverized coal-fired (PC) power generation. In a standard PC power plant, fuel is combusted with air in a boiler to produce steam, which, in turn, propels a turbine for electricity generation. The primary constituents of the boiler exhaust, or flue gas, comprise nitrogen (N_2)

and CO_2. Separating CO_2 from this flue gas stream is a complex undertaking for several reasons [3]:

1. CO_2 exists at low pressure, slightly above ambient, and at a diluted concentration (typically around 13 to 15 volume percent for PC power plants and 3 to 4 percent for natural gas-fired plants). Consequently, a substantial volume of gas must be managed.
2. The presence of impurities in the flue gas, such as particulate matter, sulfur dioxide (SO_2), and nitrogen oxides (NO_2), can deteriorate sorbents and hinder the effectiveness of specific CO_2 capture methods.
3. Collecting CO_2 at low pressure necessitates subsequent compression to pipeline pressure (around 2,000 psia), imposing a significant auxiliary power load on the overall power plant system.

The accompanying image portrays a post-combustion CO_2 capture absorption technique reliant on chemical solvents like amines. While diverse processes have been developed and put into commercial use in the refinery and chemical sectors, their application in PC power plants has primarily been limited to smaller-scale, slipstream applications. There is currently no comprehensive cost analysis available for a full-scale CO_2 capture facility in this context. However, in 2022, preliminary baseline assessments by NETL, assuming the use of the Shell CANSOLV CO_2 capture process (designed to recover high-purity CO_2 from low-pressure streams containing O_2, such as flue gas from coal-fired power plants, combustion turbine exhaust gas, and other waste gases), indicated that this would raise the levelized cost of electricity from a new supercritical PC power plant by 66 percent.

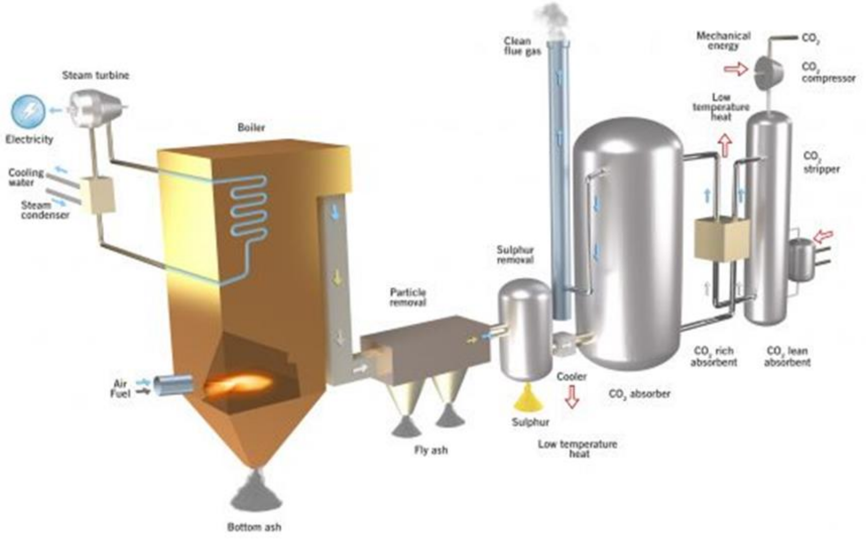


Figure 3: Post-combustion CO_2 capture [14]

Oxy-Combustion CO_2 Capture

The objective of this combustion is to utilize pure oxygen, mixed with recovered CO_2 or water (H_2O), for burning coal in an oxygen-enriched environment. This process is visually represented in the accompanying diagram. Under these conditions, the primary byproducts of combustion are CO_2 and H_2O, and the CO_2 can be captured by condensing the water in the exhaust stream. Extensive large-scale laboratory tests and system analysis have revealed several additional advantages of oxy-combustion [45]:

1. Substantial reduction in NOx emissions, around 60-70 percent less compared to air-fired combustion. This reduction is primarily attributed to the recycling of flue gas and lower thermal NOx levels due to the reduced nitrogen available. Nevertheless, some nitrogen enters the system through air infiltration and the nitrogen inherent in the coal matrix.
2. Enhanced removal of mercury. Studies involving oxy-fuel combustion using PRB coal have shown increased mercury oxidation, allowing for downstream removal of mercury in the electrostatic precipitator and flue gas desulfurization systems.
3. Applicability to both new and existing coal-fired power plants. The fundamental concepts of oxy-combustion, including air separation and flue gas recycling, have been proven commercially.

Both pre-combustion and oxy-combustion employ air separation to facilitate burning coal in an oxygen-enriched atmosphere. However, it's important to note that the oxygen requirements for oxy-combustion applications are considerably higher than those for pre-combustion applications, leading to increased CO_2 collection costs. Additionally, a higher-quality oxygen stream would be necessary. While low-temperature (cryogenic) air separation is commonly used for oxygen production, innovative oxygen separation methods that are cost-effective at smaller scales are being developed to reduce costs.

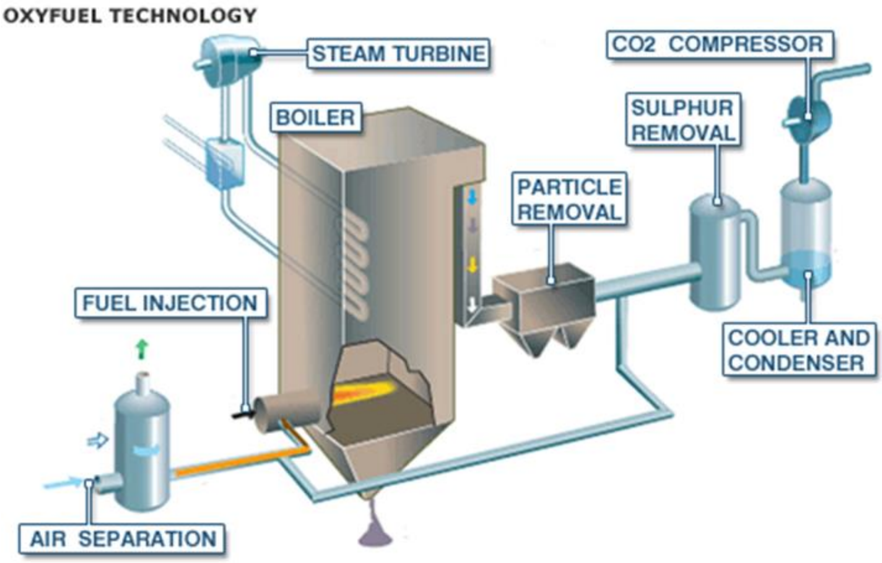


Figure 4: Oxy-Combustion CO_2 Capture [25]

3.2 Carbon capture in power generation

Power generation is a significant contributor to global greenhouse gas emissions, making it a prime area for implementing CCS technologies. Electricity and heat generating accounted for the greatest absolute rise in emissions in 2022. Emissions from the electricity and heat sectors climbed by 1.8% (or 261 Mt), hitting an all-time high of 14.6 Gt. Global energy consumption climbed by 2.7%, but the overall carbon intensity of power generation decreased by 2.0%, resuming a nine-year trend that began in 2021.

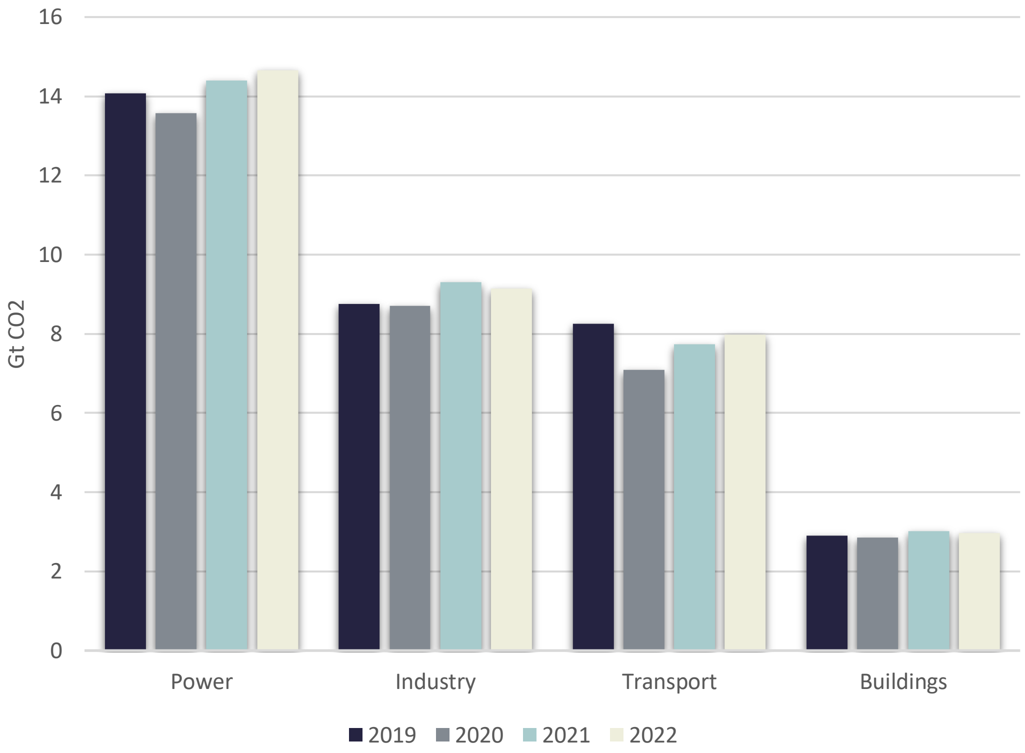


Chart 1: Global CO_2 emissions by sector, 2019-2022 [38]

These figures indicate that implementing carbon capture technology in power plants is critical since it will lead to a significant decrease in emissions in the most polluting industry. On a worldwide basis, we can see that numerous applications involving power plants are deployed either partially or entirely. Carbon capture, utilization, and storage will be placed on 315 GW of electricity generating capacity by 2040. This translates to approximately 15 GW of retrofit and new-build CCUS capacity installed per year on average over the next two decades. Annual investment in fossil-fueled facilities outfitted with carbon capture technology surpasses USD 30 billion per year, with the majority of this expansion coming in the second half of the projected period. CCUS-equipped plants will generate 1 900 TWh, or 5% of global electricity, in 2040, up from 470 TWh, or 1.5%, in 2030 [67]. Facilities equipped with carbon-capture technologies generate 40% of the remaining coal-fired electricity output. The 160 GW of coal-fired capacity employing these technologies will deliver 1000 TWh, or 2.6% of world power output, in 2040, with emissions of 90-100 gCO2/kWh. This is based on 90% CO2 capture rates; however, recent research has shown that higher capture rates are attainable with only a slight increase in capture costs. Without these technologies, coal plants run at very low capacity factors, well below 20% for all but the most efficient plants, and produce roughly 1400 TWh by 2040.

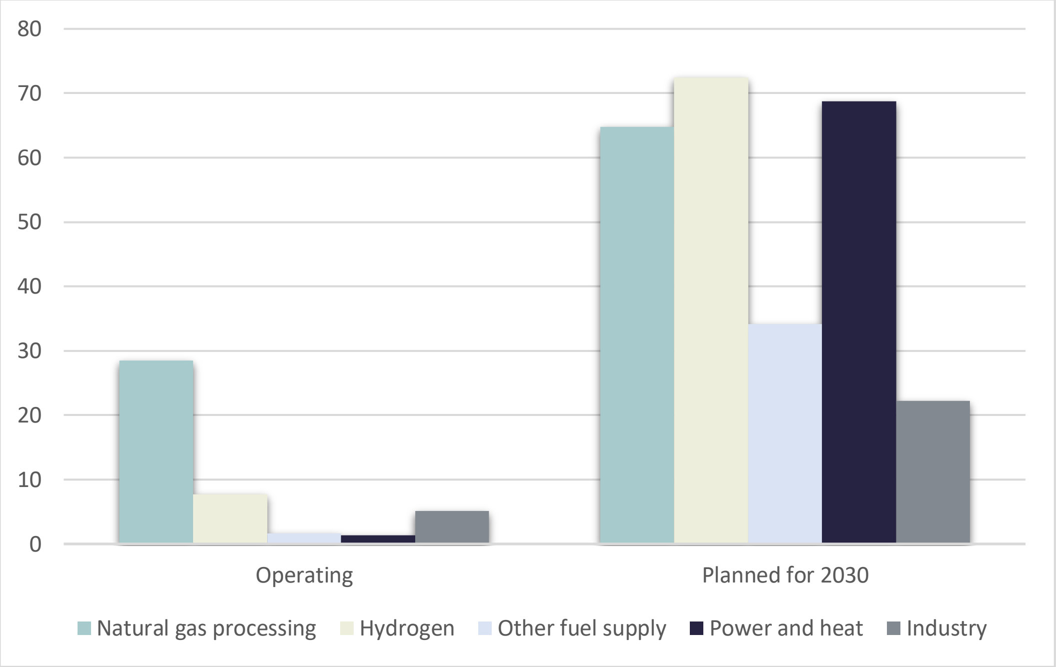


Chart 2: Operating and projected CO2 capture by application facilities, 2022 [50]

To provide some context for where the world stands with these various technologies, only around 4.5 Mt/y of worldwide operating CCS capacity is post-combustion. However, post-combustion CCS capacity is predicted to rise, since is better suited for a larger range of sectors and industries, such as power plants and industrial facilities. Especially when we are talking about retrofitting existing facilities post-combustion is less costly whereas pre-combustion technology is better in new build facilities[63].

3.3 Carbon Transportation

When CO_2 is captured from a power plant, it must be delivered to a site where it will be used or stored. CO_2 must be compressed into a liquid state at around 100 times atmospheric pressure, or 10 times the pressure of a common liquid propane gas tank, for effective delivery. Tanks, pipelines, and ships are used for commercial-scale CO_2 transfer of both gaseous and liquid carbon dioxide. Because liquid CO_2 takes up considerably less volume than gas CO_2, it is frequently compressed before shipping. Pipelines have been and will continue to be the most popular way of transferring the massive amounts of CO_2 required in CCS. CO_2 pipeline operators have specified minimum composition criteria. The CO_2 is measured, compressed, and delivered to the storage location when it has been dried (to avoid corrosion) and fulfills the transportation conditions. Carbon dioxide is safer to transport than many other compounds because, unlike oil and gas, it does not generate combustible or explosive combinations with air. Furthermore, CO_2 is not immediately hazardous to humans or wildlife when released into the atmosphere, unless the release is catastrophic (very quick and in extremely large quantities). Common safety features, such as an auto shut-off mechanism when pipeline pressure lowers, make a catastrophic leak extremely improbable.

Compression and transportation of CO_2 for commercial usage is frequently conducted in the United States using over 50 separate pipelines with over 4,500 miles in length. The great bulk of this network, which is centered in the Midwest, serves EOR activities. The majority of CO_2 delivered by these pipelines comes from geology (natural gas generation) rather than human causes. Almost all of the 22 large-scale CCUS facilities that are now in operation across the world rely on pipes to carry CO2 from the source to the storage locations. The existing US CO2 pipeline network transports roughly 68 million metric tons of CO2 each year. Decarbonization scenarios that incorporate CO2 capture, on the other hand, may need shipping hundreds or even thousands of million metric tons. According to a recent National Academies research, roughly 10,000 miles of "trunk lines" are required by 2035 to carry up to 250 million metric tons per year [18].

Figure 5. Ways that CO2 can be transported [46]

Given the probable requirement for significant new pipeline infrastructure to transport collected CO2, studies have looked into the use of existing natural gas pipes for CO2 transport.

Another factor to consider while transporting CO2 is the absence of clear regulatory control over the present transportation network. The Pipeline and Hazardous Materials Safety Administration regulates pipes carrying thick liquid CO2 primarily for safety. FERC and the Surface Transportation Board have neither exercised price regulation power over CO2 pipes. Different regulatory agencies' definitions have led to uncertainty concerning jurisdiction. A network strategy has been utilized in several projects throughout the world. The Alberta Carbon Trunk Line (ACTL) project in Canada now carries CO2 from facilities in the Edmonton area to depleted oil and gas sites 240 kilometers distant. The Langskip (or Longship) project in Norway is building the infrastructure to transport, inject, and store CO2 from regional emitters throughout Europe by 2024 (by ships and a storage pipeline). The Humber and Teesside cluster (or East Coast Cluster) in the United Kingdom proposes to absorb and store 27 Mtpa by 2030, accounting for roughly half of all UK industrial emissions [46].

3.4 Global & domestic CO2 storage capacity

Captured CO2 can be used in two ways: permanently stored (CCS) or converted into goods (CCU). The possibility for CCUS is greatly dependent on elements such as the source of the emissions, industry, capture technology, transportation, and the location and kind of storage. There are thousands of CO2 point source facilities that might be suitable for carbon capture and storage (CCS), with various CO2 concentrations in the flue gas and varying proximity to storage sites, which can impact their feasibility for CCS.

Three primary technologies are now being researched for storing CO2 for an extended length of time (hundreds to thousands of years): (a) geologic storage, (b) ocean storage, and (c) mineral carbonation. Each of these technologies is in various phases of development and use. Geologic storage is the most advanced form of CO2 storage and the only one that has been utilized commercially.

CO2 can be preserved in deep geological formations in the same way that oil and gas have been for millions of years. Captured CO2 is compressed and injected deep beneath the earth's surface into a reservoir of porous rock lying behind an impervious layer of rock (referred to as cap-rock). This serves as a seal. The cap rock, as well as other "trapping mechanisms" linked to how CO_2 behaves in the subsurface, restrict CO_2 from moving to the surface. Deep saline formations and exhausted oil and gas reservoirs have the most capability for CO_2 storage among the reservoir types.

Injecting collected CO_2 at large depths into the ocean has the physical ability to store massive amounts of carbon, equivalent to hundreds of years of US power sector emissions at current rates. This technology has yet to be tried on a significant scale. It is now only available for analysis, modeling, and early study. Most ocean storage concepts involve injection at depths more than 3,000 meters, where CO_2 is heavier than sea water and would sink rather than rise to the surface and re-enter the atmosphere.

Another emerging decarbonization process is "mineral carbonation," which involves combining CO_2 with metal oxides like magnesium and calcium oxides to generate carbonates. Carbonation, commonly known as "mineral storage," is a storage and usage method. The latter is true if the carbonates' intended purpose goes beyond storing CO_2 for use as a material, such as in the building sector. Mineral storage can take place in situ, which is analogous to geologic storage [7].

Future emission sources might be near facilities that employ collected CO_2 to make goods like fuels, chemicals, and construction materials, as well as near oil and gas wells where it can be used for improved oil and gas recovery (EOR/EGR). Utilization, as opposed to CCS, offers the extra benefit of producing income to offset the cost of capture and transportation [61]. Many, if not most, CCUS projects are now economically challenged, with high collection costs for dilute point sources and a restricted number of revenue streams accessible. Lowering costs may be critical for CCUS to reach the levels required to meet net-zero promises. Creating cross-industry hubs that share CCUS infrastructure and resources across numerous enterprises may lessen the risks associated with the initial investment capital that individual emitters may be unwilling to bear on their own. Many, if not most, CCUS projects are now economically challenged, with high capture costs for dilute point sources. Globally, roughly 700 CCUS hubs might be created. The majority of these hubs are on or near possible storage locations and EOR/EGR sites, with more than 60% located within 50 miles of potential storage sites.. Lowering costs may be critical for CCUS to reach the levels required to meet net-zero promises. Creating cross-industry hubs that share CCUS infrastructure and resources across numerous enterprises may lessen the risks associated with the initial investment capital that individual emitters may be unwilling to bear on their own.

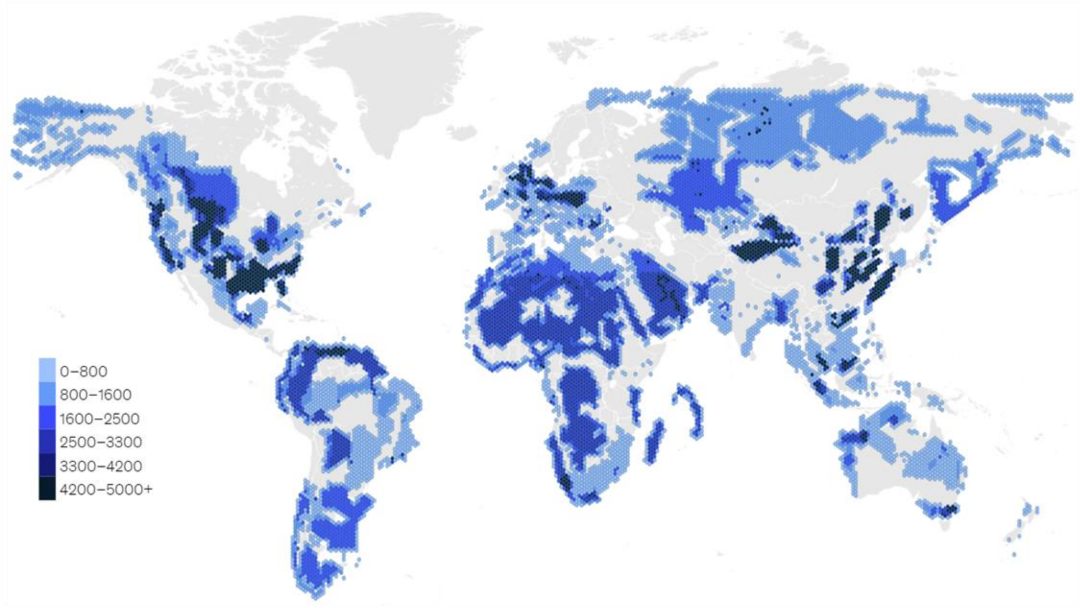


Figure 6. Potential sink location map, estimated CO_2 storage capacity, and Mt

Storage capacity is available in most regions of the world, and, importantly, in countries responsible for a large share of global CO_2 emissions (China, USA, the EU). Many scenarios consistent with at least a 66% chance of keeping warming below 2°C relative to pre-industrial levels show that 15-20 gtons of CO_2/year would need to be geologically stored, during the 2nd part of the century. Considering this it will take us 460 years to exhaust the capacity. In 1996, the Sleipner offshore gas field in Norway commissioned the first large-scale CO_2 capture and injection facility with specialized CO_2 storage and monitoring. The initiative has already stored more than 20 Mt of CO_2 in a deep saline deposit, which is equivalent to removing 4.3 million passenger vehicles from the road for a year. A new project in Norway (Snhvit), as well as developments in Canada (Quest), the United States (Illinois Industrial), and Australia (Gorgon), have expanded storage capacity to roughly 8 million tonnes per year. Oilfield operators utilize and inadvertently store an additional 34 Mt of CO_2 through improved oil recovery. Concerns that CO_2 stored underground might escape have called into doubt the efficiency of CCUS as a climate mitigation technique, as well as possible safety issues. Decades of experience with large-scale CO_2 storage have shown that leakage risks are minor and manageable, but careful storage site selection and evaluation, as well as thorough CO_2 monitoring systems, are essential [60].

Greece's CO_2 storage potential is primarily limited to aquifers and a few oil sources. The potential for CO_2 storage in Greek oil and gas fields is offshore, in the Prinos-Kavala basin in NE Greece, but the majority of point source CO_2 emissions originate in NW Greece. Lignite resources, which have been extensively exploited for electricity generation, also offer storage potential [56]. The first agreements in principle for carbon dioxide storage in the planned underground storage facility at the depleted Prinos deposit (managed by Energean) have already been made with cement and refinery businesses, with substantial interest from the power generation industry. Energean has a 100% working interest and operates the Prinos license, which is a hybrid license with exploration/exploitation rights and 25-year production rights. The Prinos, Prinos North, and Epsilon fields are located in the Gulf of Kavala, 18 kilometers south of the peninsula of Northern Greece, in sea depths ranging from 30 to 38 meters.

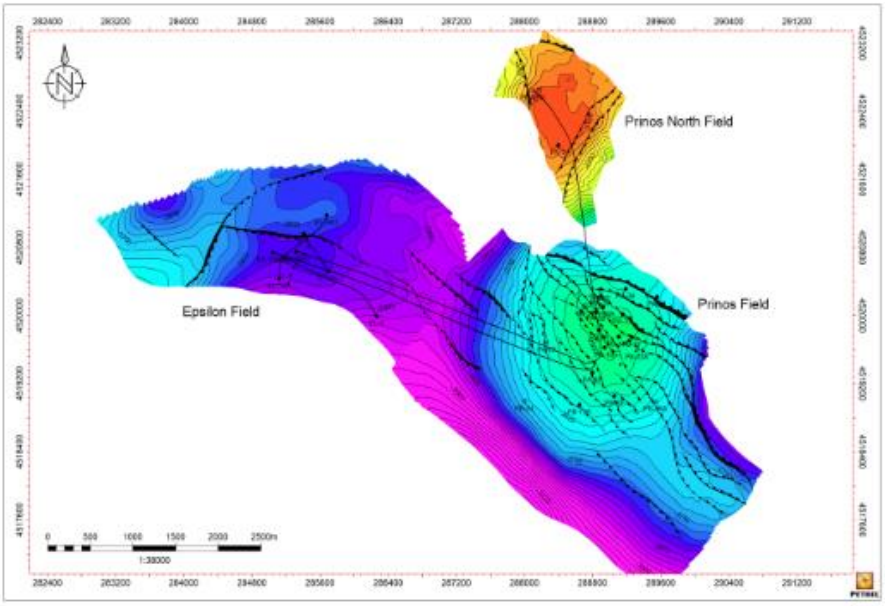


Figure 7. Storage capacity of Prinos [51]

Energean believes that the Prinos subsurface volumes are large enough to sequester up to 100 million tons of CO_2, accounting for up to half of all yearly emissions from the Greek industrial sector over 20 years [51].

4. Overview of Power Generation in Greece

4.1 Energy mix and power generation sources

Greece is enacting substantial energy sector changes to accelerate decarbonization and promote competitive markets. The administration is committed to a just and affordable energy transition for all residents. Greece has established goals of reducing greenhouse gas emissions by more than 56% by 2030 compared to 2005, and of becoming a climate-neutral economy by 2050.

The Greek electrical generating mix shifted substantially between 2005 and 2021, with lignite-fired electricity declining from 60% to 10%. Increased gas-fired production, which increased from 14% to 41% of total generation, as well as gains in wind (2% to 20%) and solar PV (0.02% to 10%), have mostly compensated for the loss of lignite-fired power. Hydro generation and electrical imports both play large but volatile roles, with hydro accounting for 4.1% of generation in 2007 and 13% in 2010, and imports accounting for 2.9% in 2012 and 20% in 2019. Greece continues to rely on oil for a substantial share of its electricity generation, 7.4% in 2021 compared to the IEA average of 2% in 2020. Oil-fired electricity is mostly used on Greek islands.

Greece was heavily reliant on Russian fossil fuel imports. Russia contributed 96% of hard coal imports, 41% of natural gas imports, 21% of crude oil imports, and a minor percentage of oil product imports in 2021. Imports of hard coal are mostly utilized in the industrial sector, notably for steel manufacturing. Gas-fired power is critical to the Greek electrical grid, and gas is also used in building heating and industrial. Greece is taking significant measures to reduce national and EU reliance on Russian energy supplies. A new floating storage unit at the liquefied natural gas (LNG) terminal began operations in August 2022; as a result of the new unit, LNG shipments have more than quadrupled year on year, while Russian imports have plummeted from 40% to less than 20% of Greece's gas supply. One of Greece's largest gas importers has agreed to replace nearly all of the country's remaining Russian gas shipments.

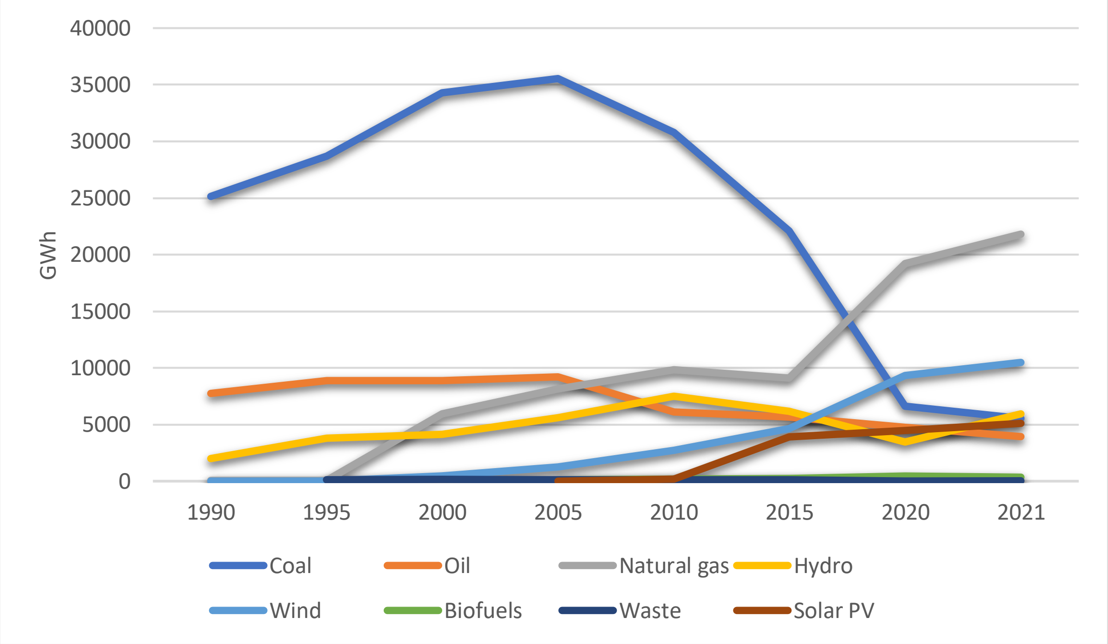


Chart 3: Electricity generation in Greece

The construction of a new floating LNG terminal began in May 2022 and is expected to be completed by the end of 2023, nearly doubling Greece's LNG import capacity. Additional LNG terminal developments are being considered. Greece raised its lignite stockpiles as a safety net in case of gas supply problems. Greece has significantly expanded efforts to deploy renewables and enhance energy efficiency as essential instruments to minimize dependency on Russian energy since Russia's invasion of Ukraine [36].

4.2 Regulatory framework of the Greek energy sector

According to the current institutional framework, holders of an Electricity Generation License granted by RAE are permitted to produce electricity under the provisions of Law 4001/2011 (Government Gazette A'179) and the Regulation of Electricity Generation and Supply Licenses (Government Gazette B'1498 / 8.12.2000). It should be noted that, for the interconnected System and following the provisions of the Hellenic Electricity Transmission System Operation Code, "dispatchable units" are defined as conventional fuel units, large hydroelectric units with capacities greater than 15 MW, and CHP units with capacities greater than 35 MW. Greek legislation guarantees non-discriminatory access to transmission and distribution infrastructure in both the electricity and natural gas sectors.

The development, building, commissioning, and operation of any form of RES power plant (e.g., wind, solar photovoltaic, hydro, biomass) is controlled by many detailed administrative decisions and actions under Greek energy sector legislation. In particular, Law 3468/2006, as it now stands, establishes a wide legal framework for the licensing of renewable energy-producing units in Greece. To build and operate a RES station, the following primary licenses must be obtained (unless exempted by a particular legislation provision):

- an electrical production license or a producer's certificate
- approval of environmental terms (or exemption from them)
- an installation license
- an operating license

Following the enactment of draft legislation now under public consultation, several changes to the RES licensing procedure are envisaged. Finally, a separate license from RAE is necessary for the delivery and trade of energy. Conventional power plants (generating electricity from coal, oil, or natural gas) are likewise subject to a licensing process overseen by RAE.

In Greece, natural gas operations are strictly controlled, and licenses are necessary to operate and maintain an independent natural gas transmission infrastructure, as well as to engage in natural gas distribution and supply activities. RAE issues these licenses upon application by the interested party. In some cases (for example, if a transmission system serves the public interest, a distribution grid is subsidized by domestic or EU sources, or many applications are to be presented for a specific region), RAE may need to conduct a bidding procedure to issue the appropriate license [59].

The Licensing Regulation governs the form and substance of applications for the award, change, or revocation of the following licenses, which are necessary to carry out the relevant natural gas activity:

- a license for an independent natural gas system
- a license for an independent natural gas system operator
- a license for a natural gas distribution network
- a license for a natural gas operation
- a license for a natural gas supply

Tariffs for natural gas transmission and LNG terminal access and usage are set annually in RAE's decision based on a tariff list issued by DESFA. Tariffs for access to natural gas distribution networks (currently operated by DEPA Infrastructure SA subsidiaries) are calculated using the methodology defined in the Natural Gas Distribution Tariff Regulation, as implemented by RAE Decision No. 1434/2020 (Tariff Regulation), and the tariffs for use issued by each EDA. RAE is in charge of approving the methodology for calculating distribution tariffs, the level of tariffs applied annually by DSOs, the weighted average cost of capital, the regulatory asset base, and all capital and operational expenditures incurred by distribution system operators. Furthermore, RAE is the responsible body for approving the terms and conditions for allowing third-party access to distribution networks to distribution users, as well as distribution network growth plans. The appropriate independent TSO determines third-party access prices to INGS LNG facilities, which are reflected in terminal use agreements with terminal customers.

4.3 Natural Gas fired power plants in Greece

Greece currently has 15 gas-fired power plants. Existing gas-fired power plants have installed capacities ranging from 49MWe to 811MWe, with the majority of them being around 400MWe. The majority of the units are in the southern region of the NNGTS, with just two units located north of Nea Messimvria (Thessaloniki). In addition to the existing gas-fired power plants, DESFA has received applications for the connection of new gas-fired power plants to the NNGTS, as indicated below. These new power plants have a larger nominal capacity than current plants (over 800 Mw) and are mostly located in the northern region of the NNGTS [69].

Natural gas power stations play an important part in Greece's energy environment, considerably contributing to the country's electricity output. These power facilities use the region's substantial natural gas supplies to provide a greener and more efficient alternative to conventional fossil fuel power plants. The combined-cycle gas turbine (CCGT) plant is a popular kind of natural gas power plant in Greece. High efficiency and environmental performance are hallmarks of CCGT facilities. To create power, they use both gas turbines and steam turbines.

Several natural gas power plants are strategically positioned throughout Greece. The Megalopolis Power Plant is one of the largest and most prominent of these facilities. The Megalopolis Power Plant, located in the Peloponnese area, has traditionally used lignite coal as its principal fuel source. However, plans are in the works to convert it into a natural gas-fired plant to meet the country's objective of lowering carbon emissions and shifting to cleaner energy sources.

The Aliveri Power facility is another notable natural gas power facility in Greece. This combined-cycle power station, located in the Boeotian area, contributes considerably to Greece's electricity supply. Similarly, the Thisvi Power Plant, situated in Central Greece, is another significant natural gas-fired combined-cycle power plant. It plays a crucial role in meeting the energy demand of the region, utilizing natural gas to generate electricity efficiently and with lower emissions compared to conventional fossil fuel plants.

The use of natural gas in electricity generation has several advantages for Greece. Natural gas is a generally clean-burning fossil fuel that emits less greenhouse gases and pollutants than coal and oil. As a result, natural gas power plants can help to reduce air pollution and enhance air quality. Furthermore, natural gas power plants are operationally flexible, allowing them to adapt swiftly to changes in energy demand while still providing stable power to the grid. Greece's concentration on natural gas power stations is consistent with the country's objective of diversifying its energy mix and lowering its reliance on traditional fossil fuels. While natural gas serves as a bridge fuel on the way to a more sustainable future, Greece is also aggressively investing in renewable energy sources such as solar and wind power to improve energy resilience and reduce carbon emissions.

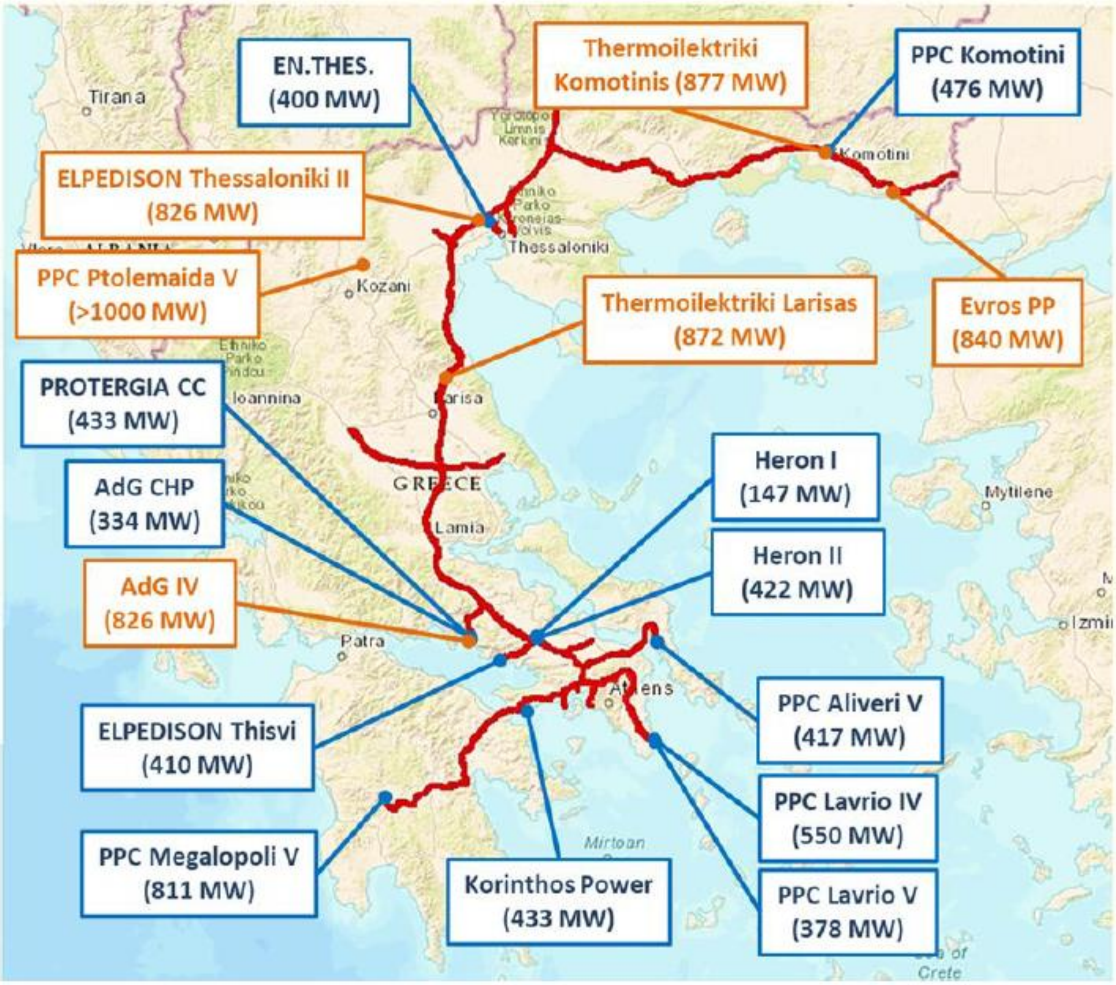


Figure 8. Existing and projected/planned/under-construction PPs in Greece [69]

5. Policy Implications and Recommendations

5.1 EU ETS Allowances

EU ETS allowances, also known as EU ETS carbon allowances or carbon credits, are permits that allow the holder to emit one metric ton of CO_2 into the atmosphere. These allowances are largely provided to enterprises that operate in areas covered by the EU ETS, such as power generation, heavy industry, and aviation. The system's purpose is to restrict and eventually reduce overall emissions from these sectors, helping the EU meet its climate commitments. The European Union Emissions Trading System (EU ETS) is a critical component of the European Union's climate change and greenhouse gas emission reduction plan. It is one of the world's most extensive cap-and-trade systems. The EU ETS works on the basis that enterprises are assigned a specific amount of emissions permits, which may then be sold among participants. In this chapter, we will look at the EU ETS, and how it works, and present a table of historical EU ETS allowance pricing.

The EU ETS operates in several stages, which are designed to reduce emissions gradually and in a manner that aligns with EU climate policy objectives. These stages include:

1. **Pilot Phase (2005-2007):** The EU ETS began its first phase as a pilot program comprising 12 EU member states and addressing emissions from power plants and industrial sites. It was a learning period that allowed participants to adjust to the system.
2. **Phase II (2008-2012):** Building on the experiences learned during the pilot phase, Phase II included new sectors and the implementation of a national allocation strategy for each participating member state. Allowance auctioning has also begun.
3. **Phase III (2013-2020):** This phase concentrated on more aggressive emission reductions. It established overall allowance ceilings, with permits gradually decreased to encourage carbon reductions. The aviation industry has been included.
4. **Phase IV (2021-2030):** The current phase is a big step toward the EU's climate goals. Allowances are being decreased further, and many measures, including the Market Stability Reserve (MSR), are aimed at stabilizing allowance prices.

The price of EU ETS credits has changed dramatically over time. The price of allowances was unusually low in the early years of the system due to several variables, including a surplus of allowances and the global financial crisis. However, the price of permits has progressively grown in recent years, hitting a record high of more than €90 per tonne in May 2022.

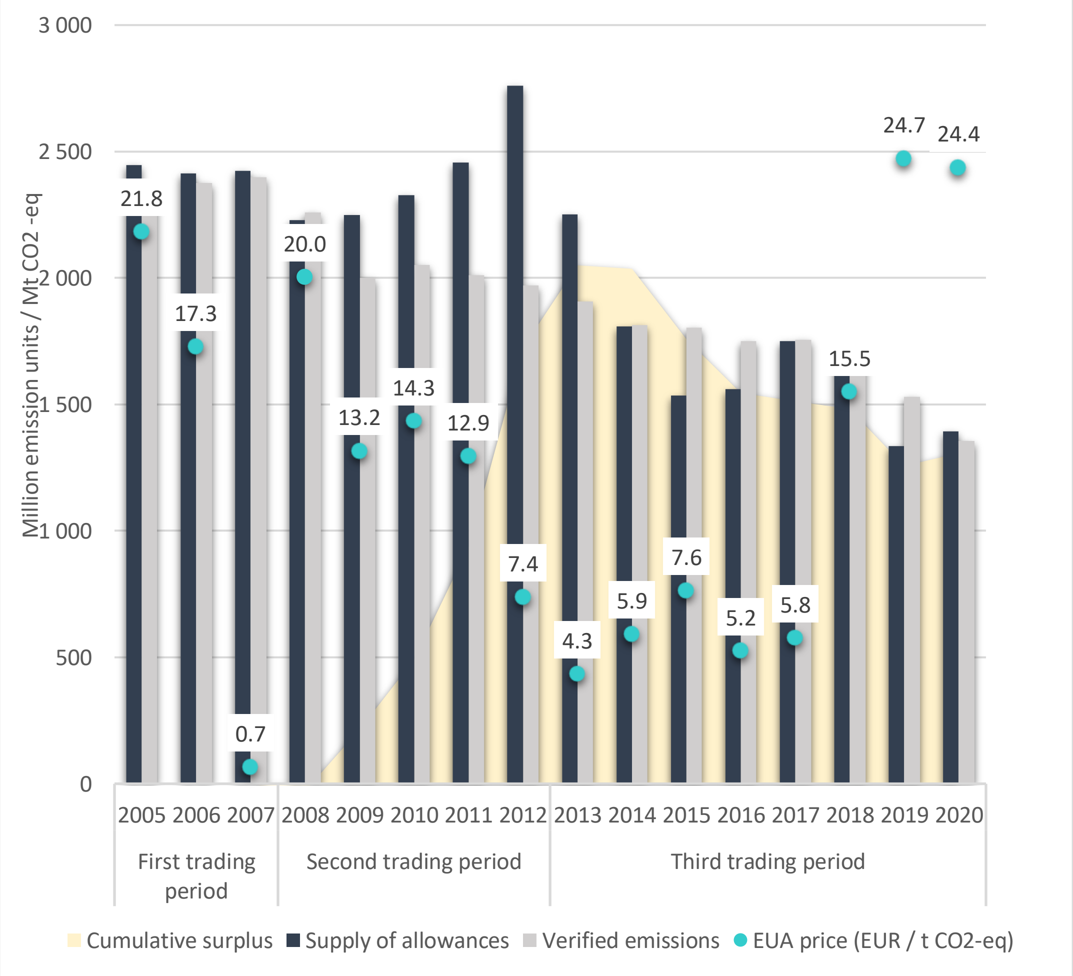


Chart 4. EU ETS emissions, allowances, surplus, and pricing, 2005-2020 [29]

Carbon prices are predicted to rise across several carbon trading schemes globally from 2026 to 2030, compared to 2022 to 2026. According to a poll of International Emissions Trading Association members, the average EU ETS carbon price is estimated to be 84.4 euros per metric ton of CO_2 from 2022 to 2025, but it is likely to grow to over 100 euros per metric ton of CO_2 from 2026 to 2030. In February 2022, the EU ETS carbon price reached 90 euros per metric ton of CO_2, and in February 2023, it surpassed 100 euros per metric ton of CO_2 [32].

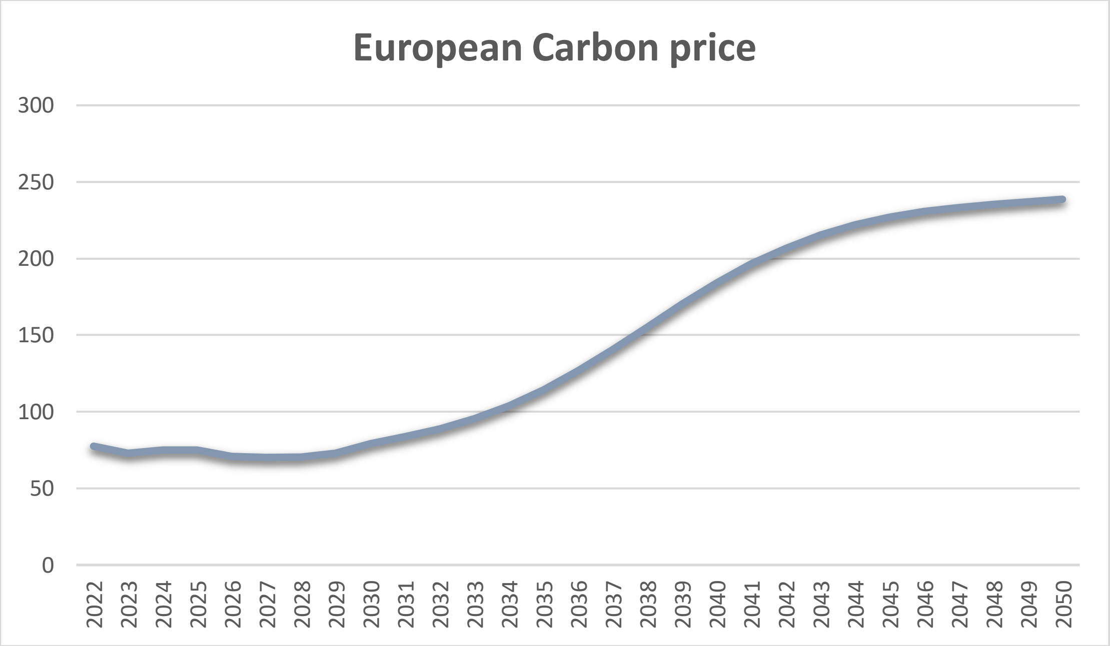


Chart 5. EUA forecast to reach €238/t CO_2 by 2050 [33]

5.2 European framework for CCS implementation

CCUS projects have been built and are currently operational in numerous countries throughout the world, including the United States, China, Canada, Australia, and Norway. Among these, Norway is an example of EEA (European Economic Area) implementation of the Directive 2009/31/EC on the geological storage of carbon dioxide, while other useful European regulatory tools for this framework are the Environmental Liability Directive (Directive 2004/35/EC of 21 April 2004 on environmental liability concerning the prevention and remedying of environmental damage [2004] OJ L143/56 (ELD) and the Emission Trading Scheme Directive (Directive (Directive 2003/87/EC of 13 October 2003 on establishing a scheme for greenhouse gas emission allowance trading within the Community [2003] OJ L275/32, as amended by Directive 2009/29/EC [2009] OJ L140/63).

As part of its efforts to decrease greenhouse gas emissions and attain climate neutrality by 2050, the European Union has been actively involved in promoting Carbon Capture and Storage (CCS) [4].

1. **EU CCS Directive (2009/31/EC)**: The EU's main legal instrument for CCS is the 2009 CCS Directive, which was adopted to create a legal framework for the environmentally safe capture, transport, and geological storage of carbon dioxide. It includes requirements for the permitting, operation, closure, and post-closure obligations of CCS sites.

2. **Revised EU Emissions Trading System (ETS)**: The EU ETS, which is a cornerstone of the EU's policy to combat climate change by reducing industrial greenhouse gas emissions cost-effectively, has been revised several times. CCS installations are included under the EU ETS and are subject to its cap-and-trade system. This is expected to provide a financial incentive for CCS as carbon prices increase.
3. **NER 300 Programme**: This was one of the world's largest funding programs for innovative low-carbon energy demonstration projects. The program aimed to support a range of low-carbon and renewable energy technologies, including CCS.
4. **Horizon Europe**: The EU has funded research and innovation in CCS through its framework programs for research and innovation. Horizon Europe, which succeeded Horizon 2020, is expected to continue supporting CCS research and innovation.
5. **Innovation Fund**: This fund is one of the world’s largest funding programs for the demonstration of innovative low-carbon technologies. It aims to support innovative low-carbon technologies, including CCS.
6. **TEN-E Regulation**: The Trans-European Networks for Energy (TEN-E) regulation aims to help ensure that all EU countries have access to an integrated energy network, and CCS networks are considered Projects of Common Interest under this regulation. This allows for potential financial support and streamlined permitting.
7. **European Green Deal**: Introduced in December 2019, the European Green Deal is an ambitious package of measures aiming to make Europe the world’s first climate-neutral continent by 2050. The European Green Deal includes various measures that could support the further development and deployment of CCS.

5.3 Greece's decarbonization strategy

Greece's National Energy and Climate Plan (NECP) lays out a thorough plan for a long-term transition to a green, carbon-neutral country by proposing several activities and targets to be accomplished by 2030. The majority of them seek the country's progressive decarbonization and the establishment of a sustainable, circular, and green economy. CCUS is a pioneering technology that contributes not only to the decarbonization plan but also to the circular economy, through the re-use of collected carbon dioxide and re-storage after usage, for a complete and recurring loop [39]. The NECP mentions CCUS in Policy Measure M8: "Reduction in emissions in the agricultural sector" of the goal of "Climate change, emissions and removals of greenhouse gases." As outlined in Policy Priority PP1.5: "Actions for reducing emissions in the agricultural sector," CCUS is referred to as contributing to the decarbonization of the agricultural sector by being included in forest ecosystems.

CCUS is also mentioned in the NECP's objective "Research, innovation, and competitiveness," in Policy Measure M2: "Development of innovative decarbonization technologies, as well as applications for carbon capture, storage, and utilization," where it is in correlation with Policy Priorities PP6.1: "Innovative applications with a high potential for domestic added value and strengthening of enterprise openness" and PP6.3: "Development of innovative decarbonization technologies, as well as applications for carbon capture CCUS is a cutting-edge technology that will aid in the reduction of GHG emissions intensity and the smooth transition to a green, low-carbon economy to attain zero net emissions on a national scale.

Since it is referenced in PP6.1 and PP6.3 about innovation, it should be noted that its originality consists in simultaneously offering an alternative energy source with zero CO_2 emissions, through circular re-capture and re-use, while also contributing to the circular economy. As a result, CCUS should contribute to the Ministry of Environment and Energy's (2019) aim of increasing the country's competitiveness in Research and Innovation.

5.4 Sources of funding for CCUS Projects

The Directive 2003/87/EC1 established the Innovation Fund. It aspires to help in the promotion of cutting-edge low-carbon technologies that are critical to meeting the EU's competitiveness and climate goals outlined in the Energy Union and Industrial Policy Plan. The Innovation Fund covers all energy-intensive industry sectors, as well as programs such as renewable energy, energy storage, and carbon capture and utilization storage (CCUS). Large-scale projects are those with total capital expenditures (CAPEX) that surpass EUR 7.5 million for the Innovation Fund, whereas small-scale projects have CAPEX that is less than EUR 7.5 million. The money is distributed in the form of one-time payments upon achievement of defined project milestones. The Innovation Fund will cover up to 60% of the proportional expenses of the 233 initiatives [41].

This means that the project's promoters will be responsible for covering the remaining expenditures with public or private cash. When a project has both an innovative and an infrastructure component, the expenses associated with the new technology and the infrastructure costs can be separated. The creative component is submitted to the Innovation Fund, while the infrastructural component is submitted to a support program such as the "Connecting Europe Facility", "InvestEU", or "Member State support" (European Commission, 2020). PCIs are critical cross-border infrastructure projects that connect the energy networks of EU member states. They are intended to help the EU achieve its energy policy and climate change goals, such as providing all people with cheap, secure, and sustainable energy and long-term economic decarbonization under the Paris Agreement. PCI designation has been granted by the North Sea Port, Port of Antwerp, and Port of Rotterdam Authority under its joint alliance "CO_2 TransPorts" [15]. As a result, because the European Union considers CCUS to be an essential weapon in addressing climate change, the PCI designation would boost financing to prospective Greek CCUS centers.

Following the first and second calls for projects, the EU Innovation Fund, which seeks to spend about €38 billion by 2030 on new clean technologies in Europe (based on the auctioning of 450 million permits from 2020 to 2030), announced its first successful award winners. Four of the seven approved applications in the initial request for projects in 2021 have a CCS component. CCS facilities in Finland, Belgium, Sweden, and France will all get financing to boost their various CCS initiatives in hydrogen, chemical, bioenergy, and cement production.

Seven CCS and CCU projects were funded as a result of the second request, which was announced in 2022. Projects in Bulgaria, Iceland, Poland, France, Sweden, and Germany have been chosen, ranging from low-carbon cement manufacturing to the creation of carbon mineral storage sites and sustainable aviation fuel production. To speed the green transition, the next third call will feature a financing pool of roughly €3 billion, up from €1.5 billion in the last call [54].

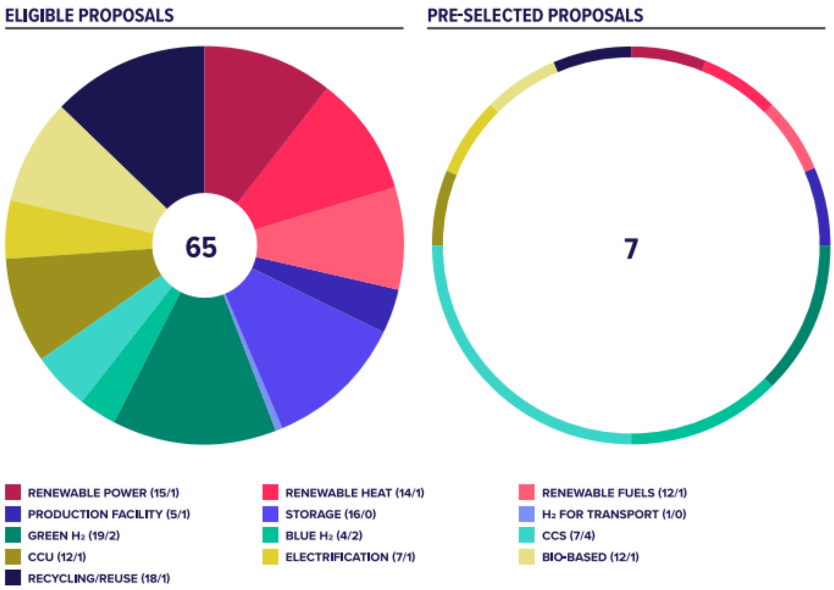


Figure 9. Applications for EU innovation funding and ccs contenders - first call (number of applications/numbers of pre-selected proposals) [54]

In response to the third Innovation Fund request for large-scale initiatives, the European Commission received 239 submissions from innovative clean tech companies. The project concepts submitted for four distinct themes will now compete for a €3 billion overall call budget. The money for the Innovation Fund is derived directly from the EU's Emissions Trading System (ETS).

The following are the number of applications received in the key Innovation Fund categories:

- 42 for renewable energy
- 26 for energy storage
- 171 for energy-intensive industries, including carbon capture, use, and storage

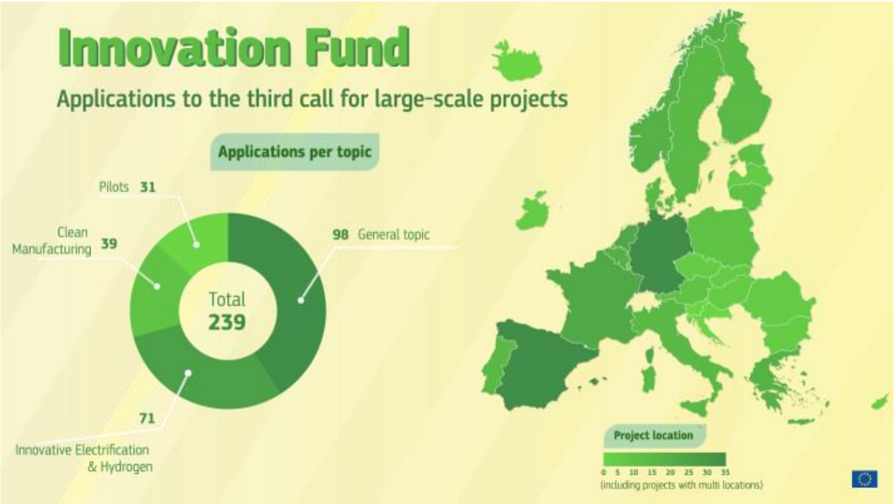


Figure 10. Applications to the third call for large-scale projects [42]

5.5 CCUS Projects around the world

Over 130 nations have made initiatives to decrease their carbon footprint. Countries such as the United States, the European Union, and the United Kingdom are particularly focused on attaining carbon neutrality by 2050. According to the Global Status of CCS study, there were 51 large-scale carbon capture projects in 2019, with 19 of them operating. European nations are increasingly participating in carbon capture programs guided by groups such as the Clean Air Task Force. In response to these activities, the CCUS Projects Network was established in 2019 to assist. Commercialize current CCUS initiatives in the long run. The purpose of the network is to develop a unified strategic framework to solve the issues that sectors engaged in CCUS initiatives confront. It covers three areas; (i) policy, regulation, and public aspects (ii) CO_2 capture and utilization, and (iii) CO_2 transport and storage.

As of now, six separate European initiatives are storing CO_2 in subsurface formations, as indicated in Table 3. The CarbFix Project is noteworthy because, since 2014, 86374 tonnes of CO_2 have been effectively injected into undersea basalts using a unique storage technology. The Athos, Porthos, Carbon Collectors, and Ervia CCUS projects permanently trap CO_2 in the North Sea's offshore sandstone gas deposits, while the Acorn project geologically stores CO_2 in a 971 km2 deep saline aquifer. Several initiatives augment the scope of CCUS, such as the LEILAC project, which is solely used as a CO_2 Capture project.

Table 1. CCUS project list in Europe [70]

Project	Country	Process	Comment	Status
Acorn [1]	UK	CO_2 Transport & Storage	Storage in Deep saline aquifer	Ongoing
Athos [6]	Netherlands	Full-chain CCUS	Storage in Depleted Gas field	Ongoing
CarbFix [11]	Iceland	CO_2 Storage	Storage in Basaltic rocks	Ongoing
Carbon Collectors [16]	Netherlands	CO_2 Shipping Transportation	Storage in Depleted Gas field	Ongoing
CEEGS [49]	Spain	CCS integration to renewable energy storage system	Scientific knowledge increase on transcritical CO_2 cycle and CCS	Ongoing
Ervia CCUS [12]	Ireland	Full-chain CCUS	Storage in Depleted Gas field	Ongoing
LEILAC [21]	Belgium Germany	CO_2 Capture	CCS industrialization attempt which stores CO_2 in deep saline	Pending

			aquifer	
Longship [19]	Norway	Industrial Fullchain CCS	CCS industrialization attempt which stores CO_2 in deep saline aquifer	Pending
Norcem [13]	Norway	CO_2 Capture	Part of the Longship project. Associated with CO_2 capture from cement plants	Ongoing
Northern Lights [48]	Norway	CO_2 Transport and Storage	CO_2 shipping and storage in Deep saline aquifer	Pending
PilotSTRATEGY [26]	France	CCS scenario investigation	Detailed research on deep saline aquifers in regions of Southern and Eastern Europe	Ongoing
Porthos [52]	Netherlands	CO_2 Transport and Storage	Pipeline transportation and storage in depleted gas field	Ongoing
RISCS [37]	UK	Framework management of CCS sites	CCS environmental assessment	Closed

CCUS initiatives are not confined to Europe, since 13 large-scale CCS plants are now operational in North America. The Great Plains Synfuels facility in North Dakota, where 38 million tons of CO_2 have been utilized for EOR in Canada's Weyburn and Midale fields since 2000, and the Shute Creek gas processing plant in Wyoming, where 7 Mtpa (million tonnes per annum) of CO_2 may be stored, are two examples. In terms of China and Japan, 9 and 5 CCUS projects are included, independent of their present condition, respectively.

5.6 Carbon Capture in Greece

Coal burning accounts for 39% of Greece's total CO_2 emissions. Three operating power stations are specifically linked to these high CO_2 emissions. Western Macedonia's operational electricity power stations are the Agios Dimitrios, Kardia, and Meliti stations, which are located in the industrial zone of Western Macedonia. The aforementioned power plants, however, will be retired by 2023 and replaced by a new station, Ptolemaida V, which will include CCS in its function, according to the Greek National Energy and Climate Plan.

Table 2. Emission criteria for the operation of Greek power plants [28]

Power Plant	CO_2 Emissions (t/y)	CO_2 (%v/v)	T(°C)	Flow Rate (Nm3/h)
A.Dimitrios	6.840.000	12	151	571.831
Kardia	2.870.000	10.375	147,52	756.324,67
Meliti	1.410.000	12-14	65-96	786.133,61

The STRATEGY CCUS project investigated the feasibility of trapping CO_2 generated by Ptolemaida V. As noted in the preceding section, STRATEGY CCUS was a CCS scenario creation project in which Greece participated as one of 17 affiliated partners through the Centre for Research and Technology Hellas (CERTH). Among the options presented, one recommends capturing the projected 4.5 Mt of CO_2 per year released by Ptolemaida V.

Table 3. EU projects in which Greece was involved [70]

Project Name	Leading European Country	Duration
ASSOCOGS [5]	UK	2003-2006
ENCAP [31]	Sweden	2004 - 2009
CAL-MOD [10]	Germany	2010 - 2013
COAL2GAS [27]	Romania	2014-2017
SCARLET [20]	Germany	2014 - 2017
ECCSEL [34]	Norway	2015 - 2017
CLARA [24]	Germany	2018 - 2023
STRATEGY CCUS [66]	France	2019 - 2022
LEILAC2 [22]	France	2020 - 2025
ConsenCUS [17]	Netherlands	2021-2025
AC2OCem [2]	Germany	2021-2023

Even though no new CO_2 capture plans including Greek case sites have been announced yet, Greek Institutes and Organizations have actively engaged in European initiatives studying and implementing CO_2 capture technology.

6. Techno-economic analysis of CCS technologies

6.1 Selection of suitable technologies for natural gas-fired power plants

When we are asked to choose the most appropriate technology for a natural gas-fired power plant we need to look at the strengths and weaknesses of each technology as well as the technology readiness level (TRL) of each application. TRL stands for Technology Readiness Level, a NASA scale used to gauge the maturity of evolving technologies. It consists of nine levels, ranging from TRL 1 (basic principles observed and reported) to TRL 9 (full application of the technology). The TRLs are broken down as follows [62]:

- **TRL 1** - Basic principles observed and reported: Initial scientific research is conducted to test the feasibility of a concept or technology.
- **TRL 2** - Technology concept formulated: A technology concept or application is formulated. The basic principles from TRL 1 are extrapolated to define the concept.
- **TRL 3** - Analytical and experimental critical function and/or characteristic proof of concept: Experiments or analyses are conducted to validate that the concept works as expected.
- **TRL 4** - Component and/or breadboard validation in a laboratory environment: The concept is tested in a laboratory environment to demonstrate that the components can function together as a system.
- **TRL 5** - Component and/or breadboard validation in the relevant environment: The system is tested in a relevant environment, more closely simulating the real-world application of the technology.
- **TRL 6** - System/subsystem model or prototype demonstration in a relevant environment: A model or prototype of the system is demonstrated in a relevant environment.
- **TRL 7** - System prototype demonstration in an operational environment: The prototype is demonstrated to function in its intended operational environment.
- **TRL 8** - Actual system completed and qualified through test and demonstration: The final system is thoroughly tested and demonstrated. The system is ready for final review before deployment.
- **TRL 9** - Actual system proven through successful mission operations: The technology is used in its final form and under real-world conditions. It's a mature product that's been proven through operations.

Figure 11. Technology Readiness Levels [62]

6.1.1. Post-Combustion technology overview:

A commercial technique using TRL 9 is post-combustion capture with chemical absorption utilizing aqueous MonoEthanol Amine (MEA) and various amine mixes. TRL of 5-7 is achieved by post-combustion capture using the Chilled Ammonia Process (CAP), polymeric membranes, amino silicones, and other solid sorbents. TRL 5 is assigned to ionic liquids, biphasic, and other encapsulated solvent-based capture methods [57].

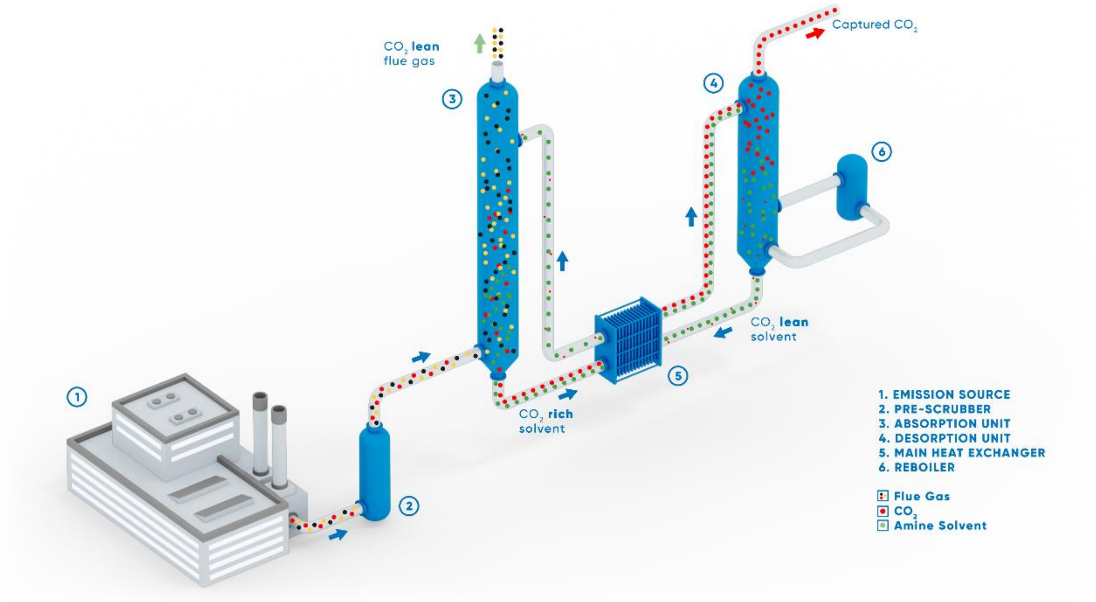


Figure 12. Chemical absorption / desorption process [23]

As shown in the process flow diagram, for an amine-based solvent, the CO2-rich flue gas from the industrial process first enters a pre-scrubber where it is cooled (or quenched) and further treated to remove certain contaminants (acid gases, particulate matter,...) that would degrade the solvent. The flue gas is then routed into the absorption unit (or absorption column), where the solvent constantly absorbs (or scrubs) the CO2. The reversible chemical interaction of CO2 with the solvent is used in the absorption process. The CO2 lean and clean flue gas exits the absorber at the top and flows towards the stack. The CO2-rich solvent is transported to the stripper (or desorption unit). The desorption unit is filled with hot and partially new solvent from the reboiler, which causes the CO2 to be stripped out of the solvent. As a result, a pure CO2 stream is collected at the stripper's top. The CO2 lean solvent is then regenerated and returned to the absorber. The pure CO2 stream is further purified before being compressed, transported, or stored for later use (enhanced oil recovery, chemical synthesis, geological storage, etc.) [64].

Chemical absorption-based Post-combustion capture strengths:

- ✓ The efficiency of absorption is great (>90% CO2 in the flue gas).
- ✓ The most developed technique for retrofitting CO2 separation in industry is absorption.
- ✓ The process can handle low CO2 partial pressure streams and has faster capture kinetics.

Chemical absorption-based PCC limitations:

- ✗ CO_2 concentration affects absorption capacity.
- ✗ Absorbent regeneration needs a lot of heat.
- ✗ Corrosion may develop as a result of solvent breakdown.
- ✗ Plant footprint expansion.

Table 4. PCC Technologies [57]

Technology	Solvent/Sorbent/Separator
Absorption	Amine solvents/blends Alkali carbonates Chilled ammonia Aqua ammonia
Adsorption	Zeolites Activated carbons Metal-Organic Frameworks (MOF) Amine-functionalized adsorbents
Membrane Separation	Organic (polymeric) Inorganic Mixed matrix Membrane contractor system
Cryogenic Distillation	Packed bed Dehydrator/ Heat Exchanger

6.1.2. Pre-Combustion technology overview:

Rectisol, Selexol, and Fluor have TRLs of 9 for pre-combustion capture using hot K_2CO_3 (Benfield process). Several new physical solvents, such as ionic liquids and fluorinated solvents, are under development with TRLs ranging from 2 to 5.

Pre-Combustion capture Technologies' General Strengths:

- ✓ This technology, like PCC, has been industrially validated.
- ✓ Because CO_2 is already produced at high pressures, downstream compression is reduced.
- ✓ If the flue gas stream is sufficiently cleaned and pressured, the physical solvents utilized in Pre-Combustion capture might likewise be used in post-combustion capture.

Weaknesses of Pre-combustion capture Technologies:

- ✗ Prior treatment for syngas, such as drying or impurity removal, is necessary.
- ✗ Integrated gasification mixed cycle systems have a high CAPEX and OPEX.
- ✗ It is costly and difficult to integrate new technology into existing facilities.

6.1.3. Oxy-fuel Combustion technology overview:

Oxy-fuel combustion is an alternative technology that uses O_2/CO_2 combustion rather than air to create high-purity CO_2 (>99%). This technique may be used in cement factories, power plants, refineries, and other sectors. To begin, Oxy-fuel combustion reduces the presence of N_2 by using an air separation device capable of producing reasonably pure O_2 (95-99%). Cryogenic distillation, polymeric membranes, multi-bed pressure swing adsorption, and other air separation methods are used. The benefit of this separation is that NOx emissions can be decreased by up to 50% when compared to air combustion. Because pure O_2 is utilized for combustion, high adiabatic flame temperatures are necessary in this technology. As a result, CO_2 is recycled with O_2 to keep the furnace temperature stable.

An air separation device, an oxy boiler, conventional air quality control systems, and a gas processing unit are currently used in pilot-scale Oxy-fuel combustion applications. This technology has a TRL of 5-8, with certain aspects of the process, such as the air separation unit, having a higher TRL, and others, such as the oxy-fuel burner, requiring more development.

Some of the challenges related to Oxy-fuel combustion include:

- The requirement for an air separation unit is due to the enormous amounts of O_2 required in the process, which raises CAPEX and OPEX.
- If there is air leakage in the system, performance might suffer.
- To avoid corrosion, the concentration of water vapor in the system must be kept between 50 and 100 ppm.

In our case the implementation of carbon capture technology will be done in an existing plant, therefore the most suitable technology for retrofit is -post-combustion.

6.2 Cost breakdown of the selective technology

The selection of post-combustion carbon capture technology with chemical absorption is a strategic choice driven by its suitability for retrofitting in existing power plants and its high Technology Readiness Level (TRL). Among various carbon capture methods, post-combustion technology stands out for its versatility and compatibility with existing natural gas-fired power plants, allowing us to make substantial strides toward reducing greenhouse gas emissions. Additionally, chemical absorption-based systems have advanced to a high TRL, ensuring a reliable and efficient approach to capturing carbon dioxide (CO_2) from flue gas streams.

Capturing, transporting, and sequestering CO_2 were the three obvious CCS value chain segments into which the cost analysis was divided. The cost analysis of CO_2 capture encompasses both capital expenditure (CAPEX) and operating expenditure (OPEX) components to provide a comprehensive view of the financial implications and potential benefits of adopting this cutting-edge solution. The analysis of the cost concludes also other critical factors like the cost of the solvents and the energy penalty cost. Previous data from similar projects and studies on this technology show that the CAPEX ranges between 725.000€/MW and 1.600.000€/MW of installed capacity [58] (depending on factors such as capture efficiency or the location of the power plant [65]) while the OPEX ranges from 45€ to

85€ per ton of CO_2, or between 115.500€ and 212.500€/MW of installed capacity [40] (which also depends on the capture efficiency or the amines we use).

Table 5. Cost of CO_2 Capture [44]

Cost Category	Cost Estimation (euros/MW)
Capital Cost	**725.000 - 1.600.000**
– Construction and Equipment	
– Engineering and Design	
– Site Preparation	
– Other Ancillary Costs	
Operating and Maintenance Costs	**112.500 - 212.500**
– Labor and Personnel	
– Chemicals and Solvents	
– Electricity Consumption	
– Routing Maintenance	
Solvent Costs	200.000 - 300.000
Energy Penalty	37.500 -75.000

6.3 Transportation and storage cost of CO_2

Much analytical effort has been devoted to assessing the cost and performance of various CO_2 capture systems, but less emphasis has been placed on assessing the cost of CO_2 transit and storage. Many integrated assessment modeling studies assume a consistent cost for CO_2 transit and storage throughout all locations, which is generally approximated at \$10/t CO_2. In reality, the cost of CO_2 transportation and storage does not remain constant at \$10/t CO_2 but rather fluctuates depending on geographic, geology, and institutional factors [53]. Carbon Limits' new interactive tool for CATF attempts to visualize the cost of capturing, transferring, and storing CO_2 from 2,170 industrial and energy-producing sites across the European Economic Area and the United Kingdom. Each of these facilities emits at least 100,000 tons of carbon pollution each year, totaling more than 1.2 billion tonnes of capturable emissions. The application also allows the user to investigate how increased CO2 infrastructure development can help reduce those expenses across three distinct dashboards.

At each emitter, the overall cost is a mix of two major factors: the 'capture cost,' which is determined by the relative difficulty of separating CO_2 from other gases, and the cost of conveying and permanently storing CO_2 underground. The tool provides a choice of high and low estimates based on research literature to reflect the degree of uncertainty and variability in both of these costs: the higher value is likely to be more representative of first-mover projects with poor economies of scale, and the lower value is indicative of more optimized processes and shared infrastructure. The tool's initial dashboard focuses on how CO_2 transport costs vary across the area, shown by a heat map with deeper colors representing greater prices. These transport cost estimates are based on the distance to the nearest acceptable CO_2 storage facility and the form of CO_2 transport that is most available to the emitter, which might be rail, pipeline, river barge, or sea-going ship. Even if just those storage locations that have been mentioned are located in the North Sea, there are numerous places in interior and Eastern Europe where the existing lack of infrastructure and restricted access to local storage renders transit costs unreasonably expensive. However, Europe has vast expanses of ideal geology for CO_2 storage. Choosing the long long-term' scenario demonstrates how transport costs might be drastically lowered if storage sites can be created in places where geology and present rules allow, with practically the whole region now displaying prices of less than €60 per tonne. These locations may not be ready today, but many of them may be by 2030 if planning begins soon. The mapping tool also allows the user to instruct the model to create additional pipelines, which lowers the cost for most locations and removes any residual zones of high cost. This might be an essential alternative for places that do not manage or choose not to create adjacent storage facilities.

The emitting plants are now brought to this underlying environment of various transit costs, with the size of each circle reflecting the volume of emissions and darker colors indicating greater costs. The cost of CO_2 capture is now included in the total for each source, based on average cost ranges for each industry. Each source is also rated by cost in a marginal abatement cost curve, which ranges from roughly €70 per tonne to around €250 per tonne if we confine ourselves to the storage sites now under construction. At current carbon pricing of about €100 per tonne, carbon capture and storage can already make economic sense for emitters at the lower end of this range. This is one of the reasons why industry carbon capture plans have exploded in the last year, albeit these early projects often require more targeted incentives to move further.

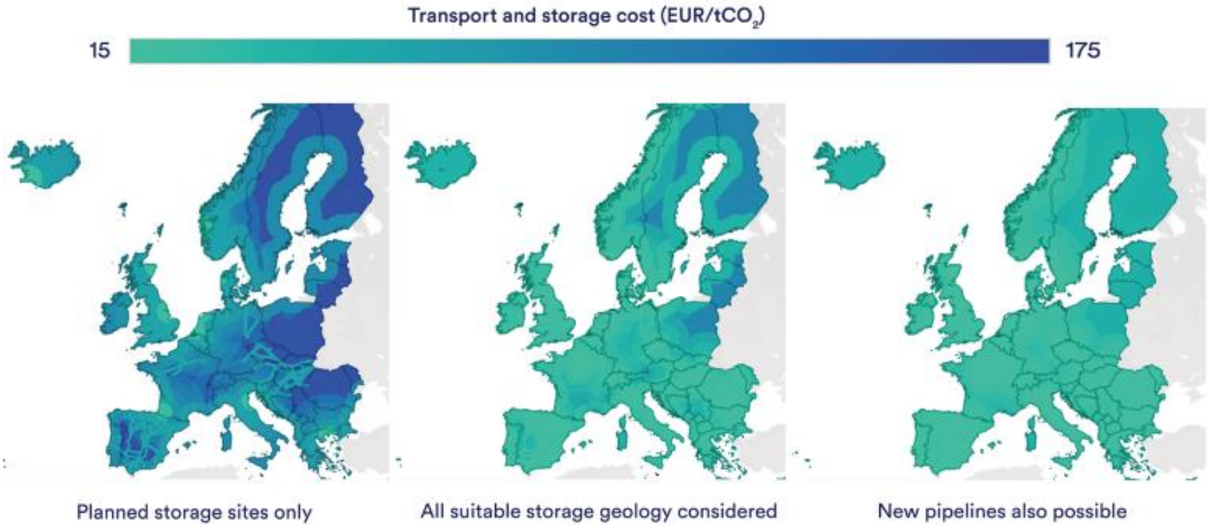
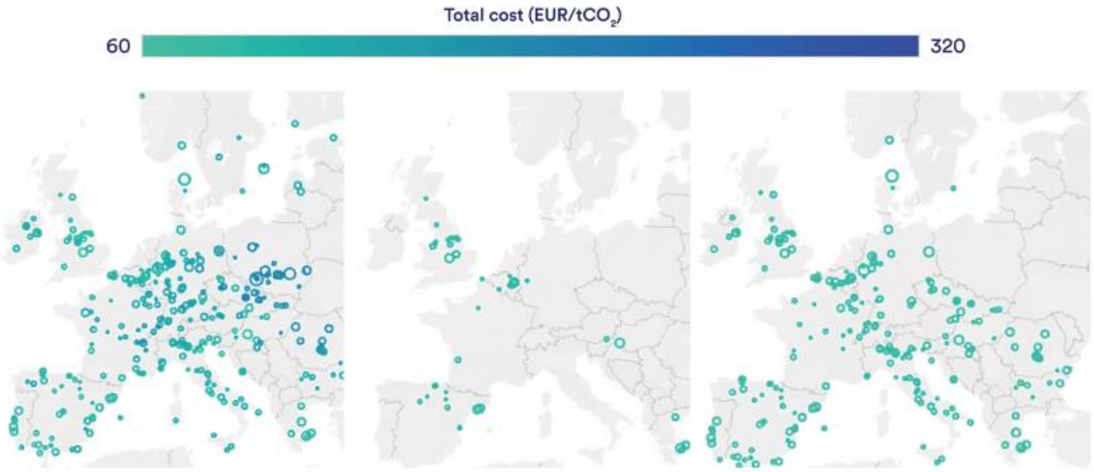


Figure 13. Map with storage sites and new pipelines in the EU [35]

Setting the 'total carbon capture and storage cost' slider to a slightly more conservative €90 per tonne limits the selection to sites that can meet this benchmark, which are primarily offshore oil and gas production sites, refineries, and power plants clustered around the North Sea, as well as the few storage sites proposed in Southern Europe. When we consider the long-term view, everything changes. At a carbon price of €90 per tonne, approximately half of the facilities may be able to install carbon capture, as they already have access to storage sites in many regions where geology allows.



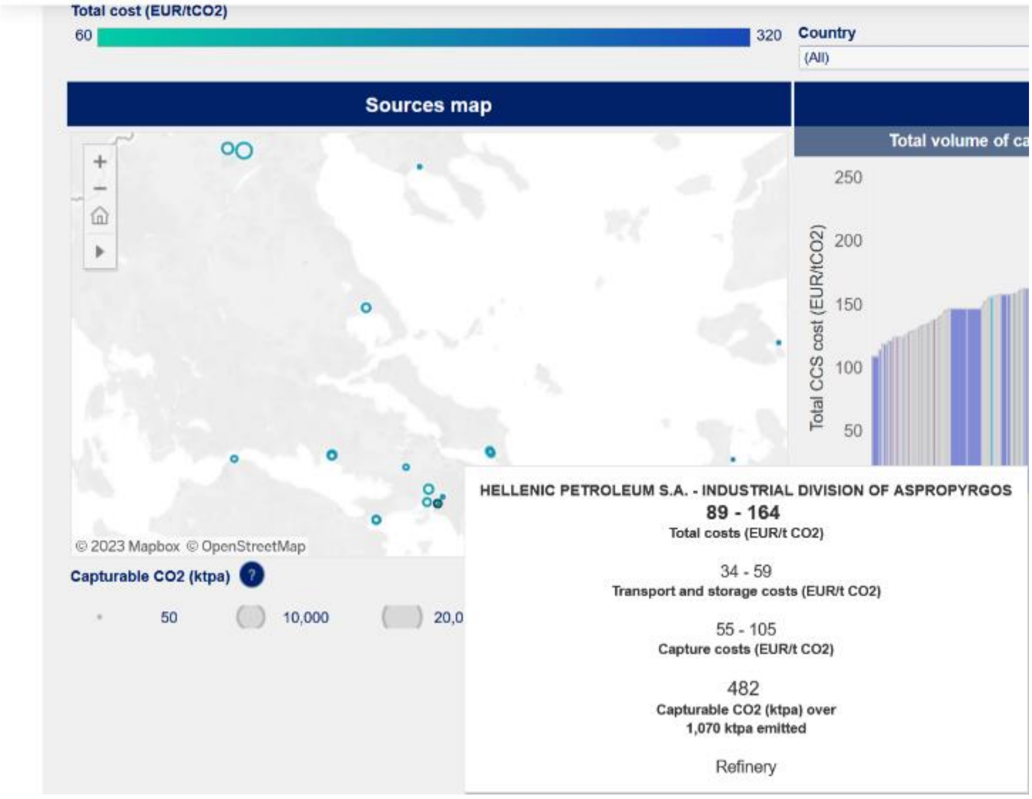
All 343 facilities for cement, lime, and other non-metallic minerals

The 42 non-metallic mineral facilities with an estimated total cost of <€90/tCO$_2$ (low estimate)

All possible storage locations considered: 238 facilities have an estimated total cost of <€90/tCO$_2$

Figure 14. Map with total facilities for cement, lime and other non-metallic minerals [35]

Using the model for the case of Greece, we made two cost assumptions from two different points in Aspropyrgos and Lavrio and saw that the cost of transport and storage of carbon dioxide ranges from 34 to 59 euros per tonne of carbon dioxide. It is worth noting that the cost of capture in the two cases showed a small variation and its values start from 55 to 115 euros per tonne of carbon dioxide. This is because in the first case, we analyzed a refinery in the Aspropyrgos area and in the second a power plan of the PPC group, therefore the binding procedures in these two facilities do not have the same costs.



HELLENIC PETROLEUM S.A. - INDUSTRIAL DIVISION OF ASPROPYRGOS

89 - 164
Total costs (EUR/t CO2)

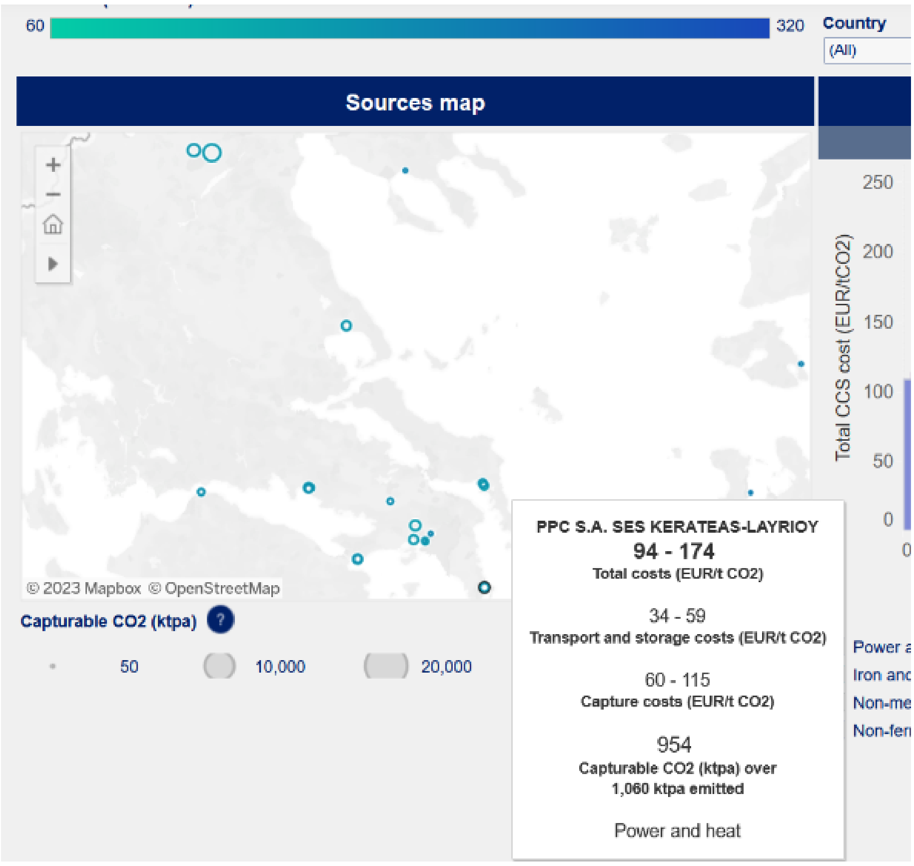
34 - 59
Transport and storage costs (EUR/t CO2)

55 - 105
Capture costs (EUR/t CO2)

482
Capturable CO2 (ktpa) over
1,070 ktpa emitted

Refinery

Figure 15. Cost analysis for HELLENIC PETROLEUM S.A-INDUSTRIAL DIVISION OF ASPROPYRGOS [35]



PPC S.A. SES KERATEAS-LAYRIOY

94 - 174

Total costs (EUR/t CO2)

34 - 59

Transport and storage costs (EUR/t CO2)

60 - 115

Capture costs (EUR/t CO2)

954

Capturable CO2 (ktpa) over 1,060 ktpa emitted

Power and heat

Figure 16. Cost analysis for PPC S.A. SES KERATEAS-LAVRIOY[35]

Considering the above results, the cost of transport and storage of CO_2 is estimated at approximately €30 per tonne of CO_2.

Table 6. Transportation and Storage cost of CO_2

Cost Category	Cost Estimation
Storage Cost (€/tnCO2)	30
Transportation Cost (€/tnCO2)	30

6.4 Implementation timetable and technical barriers to the technology

The construction of an innovative CCS facility or the integration of CCS technology into an already established facility constitutes a significant industrial endeavor that requires a comprehensive range of investigations, starting from the initial idea stage and progressing through pre-feasibility and feasibility assessments, before the initiation of detailed engineering studies. The process of identifying and negotiating commercial agreements with counterparties, such as CO_2 offtake agreements, and completing environmental impact assessment processes, as well as obtaining the required tenements and approvals for geological storage of CO_2 from regulators, typically entails a significant amount of time, often spanning several years. This statement presupposes the existence of suitable laws for the regulation of carbon capture and storage (CCS), which remains lacking in many countries. The progression of a carbon capture and storage (CCS) project exhibits several parallels with mining, mineral processing, as well as oil and gas production endeavors. The realization of a substantial and intricate CCS project typically entails a period of around ten years, commencing with the conceptualization phase and culminating in operational implementation [55].

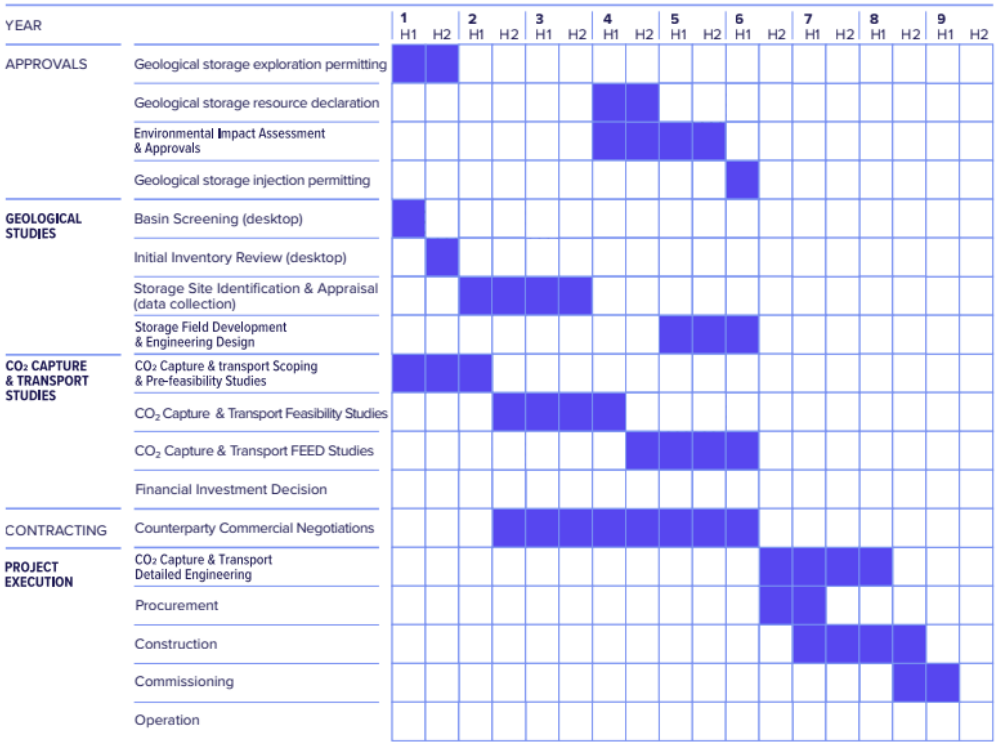


Figure 17. Chart for a CCS project [55]

In the case of a simple retrofit of a power plant in which we put a proven carbon capture technology, such as post-combustion, the project implementation time can drop to two years. However, the implementation process may encounter several technical obstacles. The aforementioned items encompass:

- The performance and degradation of solvents: The selection of a solvent is a crucial factor in determining the efficiency of the technology. The technological issues of utmost importance are guaranteeing the solvent's long-term performance, reducing deterioration, and resolving the possible loss or leakage of the solvent.
- Energy Penalty: The capture process necessitates increased energy consumption, leading to a decrease in the net power output of the power plant. The formidable technical issue lies in surmounting the energy penalty and maximizing energy use while maintaining the overall efficiency of the plant [9].
- System Integration: The process of integrating the post-combustion capture system with the pre-existing infrastructure of a natural gas-fired power plant requires meticulous design and engineering to prevent any operational delays and guarantee smooth and uninterrupted working.
- Safety and Environmental Considerations: The process of capturing and processing carbon dioxide (CO_2) has inherent safety and environmental concerns. The implementation of rigorous safety standards, the assurance of secure CO_2 transport, and the mitigation of any environmental repercussions are essential technological issues.

- Cost Optimization: The attainment of cost optimization poses a notable hurdle, as it necessitates the delicate equilibrium of capital and operating expenditures, all while upholding the economic feasibility of the technology [8].

Successfully overcoming these technological obstacles requires the collective efforts of relevant parties, ongoing research and development endeavors, and a steadfast dedication to fostering innovation and resolving challenges.

7. Case Study: Application of CCS in Greek Power Plants

7.1 Selection of power plant for the case study

This chapter will explain why we chose a power plant for the case study. Our choice revolves around a 400MW power plant in Greece, which serves as the main point for our in-depth techno-economic research of CCS technology.

This choice is not random; rather, it is the result of careful consideration of numerous crucial variables. Because of its representative capacity, which is typical of many power production facilities in Greece, the 400MW power plant serves as an excellent model for our study. We want to get insights and recommendations from focusing on a typical power plant that can be applied to a larger range of power-producing facilities in the region. The capacity of power plants in Greece has a standardized capacity of 400MW, making them the iconic representations of the country's power-producing infrastructure. When it comes to retrofitting CCS systems, this standardization provides a distinct benefit. In comparison to retrofitting bigger, more complicated facilities, the uniform size and layout of these power plants allow for a more simplified and cost-effective adoption of CCS systems.

The size of the power plants has a direct impact on retrofitting costs, as installing CCS technology is less expensive in smaller, standardized power plants. As a result, we will place a strong focus on these 400MW power plants in our thorough techno-economic study, recognizing their predominance and the viability of CCS integration. To ensure a comprehensive grasp of the economic feasibility, we will compute scenarios ranging from the lowest-cost, most favorable scenario to the worst-case scenario, considering a variety of potential cost variations and problems.

7.2 Cost-benefit analysis of the implementation

The capital cost (CAPEX) in the study was determined using a comprehensive approach that included estimating individual factors and considering the volume flow of treated gases and the concentration of CO_2 in the flue gas emitted from each stack at the respective sites. The annualized capital expenditure (CAPEX) is determined using a 17-year lifespan, of which 1 year is allocated for building, and a rate of return of 7.5%.

The primary component of operating expenses (OPEX) is the expense associated with heat supply for solvent regeneration. However, OPEX also includes other costs such as utilities, maintenance, and personnel. The operating expenses may be classified into two categories:

fixed OPEX and variable OPEX. Fixed costs include expenses related to maintenance and personnel, and are not contingent upon the level of plant usage. Utilities are classified as services provided by external systems and are thus regarded as operating expenses without the need for investments. Utilities include the expenses associated with the provision of steam, energy, and cooling water, which are essential for the operation of the process. These costs are intrinsically linked to the quantity of CO_2 that is collected.

In our analysis, we need to consider both the expenses associated with transporting and storing CO_2, as well as the potential revenues gained from the elimination of necessary allowances. To calculate these allowance costs, we will consider their projected future prices, which were extensively examined in Chapter 5 for the duration of our investment. We will then multiply these prices by the total volume of CO_2 emissions expected from a power plant of the scale we are currently examining.

Table 7. EU ETS allowances price prediction

Year	Emissions cost (€/tnCO_2)
2025	75,2
2026	71
2027	70,2
2028	70,4
2029	73,1
2030	79
2031	83,7
2032	88,8
2033	95,4
2034	103,9
2035	114,3
2036	126,7
2037	140,6
2038	155,3
2039	170
2040	183,9

CO_2 emissions from a 400 MW combined cycle natural gas power station might vary based on several factors, including the technology utilized, the plant's efficiency, and the kind of natural gas used. On average, a power plant of this type may release 400-600 grams of CO_2 per kWh of energy generated. To calculate the annual emissions in metric tonnes of CO_2, we need to take the annual amount of electricity produced multiplied by the tonnes of CO_2 emitted per MWh.

Let's assume the power plant operates at a 60% capacity factor, which is a reasonable estimate for a combined cycle natural gas power plant.

In this case:

- Plant Capacity = 400 MW

- Capacity Factor = 0.60
- tCO_2/MWh = 0.4 [47]
- Hours per Year = 7.260 (assuming the plant operates 22 hours a day for 330 days per year due to 35 days of maintenance per year)
- Annual Generation (MWh) = 645.918 [47]

As a result, the total cost of EU ETS allowances is as follows:

Table 8. Total cost of EU ETS allowances

Year	Cost of needed allowances
2025	19.429.198 €
2026	18.344.057 €
2027	18.137.363 €
2028	18.189.037 €
2029	18.886.628 €
2030	20.410.993 €
2031	21.625.318 €
2032	22.942.990 €
2033	24.648.212 €
2034	26.844.331 €
2035	29.531.348 €
2036	32.735.099 €
2037	36.326.400 €
2038	40.124.395 €
2039	43.922.390 €
2040	47.513.692 €

Considering the costs of transport and storage of carbon dioxide amounting to 60 euros per tonne of CO_2 and the operating costs (OPEX) amounting to 50 euros per tonne of CO_2 we capture, our analysis will be carried out for 3 different cases. In the first case, we will consider the best-case scenario for CAPEX according to our analysis in the previous chapter while in the second case, we will take the worst-case scenario for CAPEX. Finally, in the third case, we will conduct a what-if analysis to find the CAPEX we need in combination with the funding program, to make the investment profitable for our current data. In our research, we will augment our findings with a sensitivity analysis that examines the correlation between variations in the Internal Rate of Return (IRR) and Net Present Value (NPV) concerning the Capital Expenditure (CAPEX). Furthermore, we intend to conduct a two-level sensitivity analysis, wherein we will concurrently assess the costs associated with carbon dioxide storage and transportation in comparison to CAPEX. This will help us ascertain the threshold at which these carbon-related expenses become a determining factor in the profitability of our investment.

Best case Scenario: Low CAPEX and Transportation-Storage Costs

Table 9. Low CAPEX and Transportation-Storage Costs

Year	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
Year of Revenues	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Cost of needed allowances (€)		19.429.198	18.344.057	18.137.363	18.189.037	18.886.628	20.410.993	21.625.318	22.942.990	24.648.212	26.844.331	29.531.348	32.735.099	36.326.400	40.124.395	43.922.390	47.513.692
Cost of CO2 Storage (€)		-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505
Cost of CO2 Transportation (€)		-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505
Total CAPEX	-290.000.000																29.000.000
Total OPEX		-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350
SUM	-290.000.000	-1.240.162	-2.325.303	-2.531.997	-2.480.323	-1.782.732	-258.367	955.958	2.273.630	3.978.852	6.174.971	8.861.988	12.065.739	15.657.040	19.455.035	23.253.030	55.844.331

WACC	**7,5%**
NPV	**-243.883.579**
IRR	**-5%**

Worst Case Scenario: High CAPEX and Transportation-Storage Costs

Table 10.High CAPEX and Transportation-Storage Costs

Year	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
Year of Revenues	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Cost of needed allowances (€)		19.429.198	18.344.057	18.137.363	18.189.037	18.886.628	20.410.993	21.625.318	22.942.990	24.648.212	26.844.331	29.531.348	32.735.099	36.326.400	40.124.395	43.922.390	47.513.692
Cost of CO2 Storage (€)		-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010
Cost of CO2 Transportation (€)		-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010	-7.751.010
Total CAPEX	-640.000.000																64.000.000
Total OPEX		-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350
SUM	-640.000.000	-8.991.172	-10.076.313	-10.283.007	-10.231.333	-9.533.742	-8.009.377	-6.795.052	-5.477.380	-3.772.158	-1.576.039	1.110.978	4.314.729	7.906.030	11.704.025	15.502.020	83.093.321

WACC	**7,5%**
NPV	**-653.735.945**
IRR	**-11%**

Base case scenario: Low CAPEX and Transportation-Storage Costs in combination with subsidy (90% in CAPEX)

Table 11.Low CAPEX and Transportation-Storage Costs in combination with subsidy

Year	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
Year of Revenues	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Cost of needed allowances (€)		19.429.198	18.344.057	18.137.363	18.189.037	18.886.628	20.410.993	21.625.318	22.942.990	24.648.212	26.844.331	29.531.348	32.735.099	36.326.400	40.124.395	43.922.390	47.513.692
Cost of CO2 Storage (€)		-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505
Cost of CO2 Transportation (€)		-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505	-3.875.505
Total CAPEX	-43.500.000																29.000.000
Total OPEX		-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350	-12.918.350
SUM	-43.500.000	-1.240.162	-2.325.303	-2.531.997	-2.480.323	-1.782.732	-258.367	955.958	2.273.630	3.978.852	6.174.971	8.861.988	12.065.739	15.657.040	19.455.035	23.253.030	55.844.331

WACC	**7,5%**
NPV	**2.616.421**
IRR	**8%**

Sensitivity Analysis

CAPEX SENSITIVITY ANALYSIS (NPV)

	CAPEX	NPV
		-333.735.945 €
30%	416.000.000 €	-433.856.728 €
25%	400.000.000 €	-417.169.931 €
20%	384.000.000 €	-400.483.134 €
15%	368.000.000 €	-383.796.337 €
10%	352.000.000 €	-367.109.539 €
5%	336.000.000 €	-350.422.742 €
0%	320.000.000 €	-333.735.945 €
-5%	304.000.000 €	-317.049.148 €
-10%	288.000.000 €	-300.362.350 €
-15%	272.000.000 €	-283.675.553 €
-20%	256.000.000 €	-266.988.756 €
-25%	240.000.000 €	-250.301.959 €
-30%	224.000.000 €	-233.615.161 €

Table 12. Sensitivity Analysis CAPEX-NPV

CAPEX SENSITIVITY ANALYSIS (IRR)

	CAPEX	IRR
		-8%
30%	416.000.000 €	-10%
25%	400.000.000 €	-10%
20%	384.000.000 €	-9%
15%	368.000.000 €	-9%
10%	352.000.000 €	-9%
5%	336.000.000 €	-8%
0%	320.000.000 €	-8%
-5%	304.000.000 €	-7%
-10%	288.000.000 €	-7%
-15%	272.000.000 €	-7%
-20%	256.000.000 €	-6%
-25%	240.000.000 €	-6%
-30%	224.000.000 €	-5%

Table 13. Sensitivity Analysis CAPEX-IRR

Table 14. Sensitivity analysis CAPEX-STORAGE-TRANSPORTATION Cost

		Storage Cost (€/tCO$_2$)												
		39	**37,5**	**36**	**34,5**	**33**	**31,5**	**30**	**28,5**	**27**	**25,5**	**24**	**22,5**	**21**
Transportation Cost (€/tCO$_2$)	**39**	376.249.491 €	399.277.662 €	394.672.028 €	390.066.394 €	385.460.759 €	380.855.125 €	376.249.491 €	371.643.857 €	367.038.223 €	362.432.589 €	357.826.954 €	353.221.320 €	348.615.686 €
	38	392.369.211 €	373.370.970 €	369.341.040 €	365.311.110 €	361.281.180 €	357.251.250 €	353.221.320 €	349.191.390 €	345.161.460 €	341.131.530 €	337.101.601 €	333.071.671 €	329.041.741 €
	36	364.505.124 €	344.355.474 €	340.970.333 €	337.585.192 €	334.200.051 €	330.814.910 €	327.429.769 €	324.044.628 €	320.659.487 €	317.274.345 €	313.889.204 €	310.504.063 €	307.118.922 €
	35	334.538.565 €	314.650.861 €	311.925.822 €	309.200.784 €	306.475.745 €	303.750.707 €	301.025.668 €	298.300.629 €	295.575.591 €	292.850.552 €	290.125.514 €	287.400.475 €	284.675.436 €
	33	304.840.722 €	286.446.711 €	284.348.432 €	282.250.152 €	280.151.872 €	278.053.593 €	275.955.313 €	273.857.033 €	271.758.753 €	269.660.474 €	267.562.194 €	265.463.914 €	263.365.634 €
	32	277.424.109 €	261.424.726 €	259.882.490 €	258.340.255 €	256.798.019 €	255.255.783 €	253.713.548 €	252.171.312 €	250.629.077 €	249.086.841 €	247.544.605 €	246.002.370 €	244.460.134 €
	30	253.713.548 €	240.604.545 €	239.524.980 €	238.445.415 €	237.365.850 €	236.286.286 €	235.206.721 €	234.127.156 €	233.047.591 €	231.968.026 €	230.888.461 €	229.808.896 €	228.729.331 €
	29	234.451.025 €	224.330.104 €	223.612.193 €	222.894.283 €	222.176.372 €	221.458.461 €	220.740.551 €	220.022.640 €	219.304.729 €	218.586.819 €	217.868.908 €	217.150.997 €	216.433.087 €
	27	219.735.476 €	212.376.891 €	211.924.608 €	211.472.324 €	211.020.040 €	210.567.756 €	210.115.473 €	209.663.189 €	209.210.905 €	208.758.622 €	208.306.338 €	207.854.054 €	207.401.770 €
	26	209.165.677 €	204.134.021 €	203.864.912 €	203.595.803 €	203.326.694 €	203.057.585 €	202.788.476 €	202.519.368 €	202.250.259 €	201.981.150 €	201.712.041 €	201.442.932 €	201.173.824 €
	24	202.034.972 €	198.805.666 €	198.654.965 €	198.504.264 €	198.353.563 €	198.202.862 €	198.052.161 €	197.901.460 €	197.750.759 €	197.600.058 €	197.449.358 €	197.298.657 €	197.147.956 €
	23	197.524.708 €	195.584.433 €	195.505.315 €	195.426.197 €	195.347.079 €	195.267.961 €	195.188.844 €	195.109.726 €	195.030.608 €	194.951.490 €	194.872.372 €	194.793.254 €	194.714.136 €
	21	194.856.548 €	193.768.676 €	193.729.908 €	193.691.140 €	193.652.372 €	193.613.604 €	193.574.836 €	193.536.069 €	193.497.301 €	193.458.533 €	193.419.765 €	193.380.997 €	193.342.230 €

7.3 Evaluation of economic feasibility

In the quest to assess the economic feasibility of our investment, it becomes clear that our endeavors lie at the crossroads of optimism and pessimism, embodied by the best- and worst-case scenarios. Regrettably, our findings indicate that, in both instances, our investment does not present a profitable outlook. To steer our investment toward a more promising revenue trajectory, a substantial subsidy in the capital expenditure (CAPEX) domain, amounting to approximately 90%, becomes a requisite. It is important to note that these findings pertain to the anticipated outcomes over the extended time frame of our project, extending until the year 2040.

The sensitivity analysis reveals a critical threshold: when transport and storage prices fall below €30 per tonne of CO2, the investment becomes profitable, particularly when the capital expenditure (CAPEX) exceeds €240 million. Notably, a mere reduction of capital costs by 30% does not yield favorable results, as evidenced by a notably negative Net Present Value (NPV). This underscores the significance of the financing aspect in the initial stages of full-scale applications, highlighting that the overall economic viability is intricately tied to factors beyond mere reductions in capital expenditure. Thus, strategic financial planning and support are imperative during the early phases of implementing such technologies.

It is imperative to recognize the shifting dynamics of the global energy landscape. As the price of emission permits continues to surge within Europe, the urgency and necessity of adopting carbon capture technology in power plants become increasingly evident. This underscores the importance of our ongoing commitment to explore the realms of CSS. Over the years, as storage and transport applications mature, and installation technologies evolve and become more standardized, the overall cost associated with our specific technology is poised to witness a significant reduction. This trend will undeniably render our technology more financially appealing, thereby potentially altering the economic feasibility landscape in our favor.

In summary, while our current evaluation suggests a less-than-ideal economic outlook for our investment, the evolving energy market and technology advancements could hold the promise of transforming our prospects as time unfolds. Careful monitoring of these changing dynamics and continued dedication to cost-effective solutions will be integral to our endeavor's success in the long term.

8. Conclusion

8.1 Limitations and future research

Despite the valuable insights gained from this research, certain limitations should be acknowledged:

1. Data Availability: The analysis heavily relies on the availability and accuracy of data related to CCS technologies, energy prices, and other relevant factors. Data limitations, such as incomplete or outdated information, may have influenced the accuracy and comprehensiveness of the cost analysis.
2. Technological Advancements: The research primarily focuses on the current state of CCS technologies. However, the field of CCS is rapidly evolving, and ongoing technological advancements may have implications for cost analysis. Future research should consider incorporating emerging technologies and their potential impact on the economic feasibility of CCS implementation.
3. Policy Dynamics: The economic viability of CCS technologies is closely tied to government policies, regulations, and carbon pricing mechanisms. The research assumes a static policy environment, and changes in policies over time may affect the financial considerations associated with CCS technologies.
4. Site-Specific Factors: The cost analysis provides generalized estimations and ranges for CCS technologies in Greece. However, site-specific factors, such as geological conditions, regional infrastructure, and energy demand patterns, can significantly impact the actual costs and feasibility of CCS implementation in specific locations.

To address the limitations and advance the understanding of CCS technologies in the Greek energy sector, future research can focus on the following areas:

1. Long-Term Cost Trajectories: Conducting a longitudinal study to track the cost trajectories of CCS technologies can provide insights into the potential cost reductions and scalability of these technologies over time. This can be achieved by monitoring and analyzing ongoing CCS projects and capturing real-world data on capital costs, operational expenses, and storage costs.
2. Policy and Regulatory Analysis: Examining the policy landscape and evaluating the impact of specific policy measures, incentives, and support mechanisms on the economic feasibility of CCS technologies can enhance understanding of the role of policy frameworks in promoting CCS implementation. Future research can also explore the potential synergies and trade-offs between CCS and other energy policies, such as renewable energy targets and energy efficiency measures.
3. Technological Innovation and Integration: Investigating emerging CCS technologies, such as novel capture methods, advanced storage techniques, and utilization pathways, can shed light on their potential impact on the cost-effectiveness and overall performance of CCS systems. Additionally, research can explore the integration of CCS technologies with renewable energy sources and other low-carbon technologies to create hybrid systems that maximize the environmental and economic benefits.
4. Case Studies and Demonstration Projects: Conducting detailed case studies and pilot demonstration projects specific to the Greek energy sector can provide valuable insights into the practical challenges and opportunities of implementing CCS

technologies. These studies can assess the technical and economic feasibility of CCS in different power plant settings, considering site-specific factors and operational considerations.

By addressing these limitations and pursuing future research directions, a more comprehensive understanding of CCS technologies in the Greek energy sector can be achieved, facilitating informed decision-making, policy formulation, and strategic planning for a sustainable and low-carbon energy future.

8.2 Discussion of the results

The analysis reveals a nuanced picture of the current state and future prospects of carbon capture and storage. As of now, the financial feasibility of CCS appears challenging, given its costs and the economic landscape. However, a pivotal factor lies in the evolving dynamics of the EU ETS allowances. Anticipating an increase in their costs, CCS is poised to emerge as a more viable and attractive solution, aligning with the economic incentives that support carbon reduction strategies. Moreover, the ongoing testing and application of CCS technologies across various contexts hold promise for a future where the economic barriers begin to crumble. With increased experience and scalability, there is a reasonable expectation that the costs associated with CCS will decline, rendering it a more accessible option for power plants seeking sustainable practices.

The significance of small-scale projects should not be understated. These endeavors not only contribute to the overall body of knowledge surrounding CCS but also play a crucial role in mitigating the gap identified in the literature, particularly in terms of capital expenditure (CAPEX). The data generated from these smaller initiatives pave the way for more accurate assessments, refining our understanding of the most suitable technologies and capturing methods for widespread application.

As for now, with just two full-scale applications in a coal-fired power plant in the US, the adoption CCS technologies entails a substantial financial commitment. For companies to navigate this considerable risk, the availability of corresponding financing is paramount. In this context, the onus falls on European funding bodies and Member States to play a pivotal role in shouldering a significant portion of the capital costs associated with this technology. Our investment analysis underscores that, particularly in light of the escalating costs of emission permits, such financial support renders the investment in CCS notably lucrative. The profitability quotient, intertwined with the evolution of emission permit costs, positions CCS as a financially viable and appealing solution for companies daring to embark on the path of sustainability, thus aligning economic interests with environmental imperatives. This underscores the critical role that financial backing and supportive policies play in catalyzing the widespread adoption of CCS technologies in the pursuit of a greener and more sustainable energy landscape.

As regards transportation and storage costs the analysis underscores the economic advantages of pipeline networks, which emerges as the most cost-effective solution by circumventing potential expenses inherent in transportation via vessels, such as liquefaction and fuel costs. However, the complexity deepens when delving into storage options. While onshore storage proves to be a viable and economical choice, the finite capacity of these sites necessitates exploration of underwater storage solutions, some of which are located at considerable depths. As onshore storage approaches saturation, the transition to offshore storage becomes inevitable, albeit at a higher cost. This shift raises concerns about the equitable distribution of storage burdens among nations. Countries endowed with more geographical space may find themselves becoming inadvertent pollution hubs as storage areas encroach upon their borders. The reliance on sea-based storage at great depths poses challenges, both economic and environmental, as it necessitates costlier infrastructure and introduces potential geopolitical complexities.

The scenario of pollutants being transported to foreign countries for storage, due to domestic storage limitations, brings to light the intricate interplay of international relations in shaping the reported transport and storage costs. Depending on diplomatic ties and global partnerships, some nations may witness a shift in their role from mere emitters to receivers of stored pollutants.

It is crucial to acknowledge that the legislative framework governing these processes will play a pivotal role in shaping more stable and standardized rules. As CCS technologies evolve and become more integral to global carbon reduction strategies, establishing a robust regulatory environment will be imperative to address the challenges associated with the international transport and storage of captured carbon. The formulation of clear and consistent regulations will not only ensure the effective implementation of CCS but also contribute to a more equitable and sustainable global approach to carbon mitigation.

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