# Implementing CCUS Hubs in Greece: A Cost Benefit Analysis

## EXTENDED SUMMARY


An IENE Study (M76)

Athens, March 2025

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March 2025

# The Institute of Energy for South East Europe (IENE)

The Institute of Energy for South-East Europe (IENE) is an independent organization operating on a regional basis in SE Europe, covering the whole spectrum of the energy sector, with a strategy focused on sustainability and energy transition. IENE provides regular information to its members on developments in Greece and the region, prepares studies and research, organizes events (conferences, workshops, webinars) and educational seminars. For more information see www.iene.eu.

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**Implementing CCUS Hubs in Greece: A Cost Benefit Analysis**

An IENE Study Project (M76)

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- DESFA
- HELLENiQ ENERGY
- HEREMA
- Asprofos Engineering



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## Study Sponsors

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## Preface

Expanding on the groundwork established by the previous Carbon,Capture, Utilization and Storage (CCUS) study conducted by IENE in 2023, the current work aims to examine in more detail the complexities involved in the development and operation of CCUS hubs. The previous IENE study, titled "CCUS Technologies in Greece:Prospects for Implementation", proposed the establishment of a number of CCUS hubs corresponding to specific geographical areas of the country.

The present follow up study is a comprehensive analysis which aims to look into the economics of setting up and running a CCUS hub in a specific location, and is written from the operator's perspective. The aim is to establish the range of costs and financing conditions which will enable the operator, whoever happens to be, to provide a competitively priced service to industry which will provide the bulk of the prime material, ie $CO_2$ and related green house gases. Hence, the cost-benefit chapter of the study is crucial in assessing the economic viability of such systems.

The financial and technical support provided by a group of interested companies in Greece was crucial in enabling the Institute to carry out such a demanding investigation. Therefore, on behalf of IENE, I wish to sincerely thank Helleniq Energy and their HELPE Upstream subsidiary, the National Natural Gas System Operator (DESFA),the Hellenic Hydrocarbons and Energy Resources Management Company (HEREMA) for funding this multi client project. In addition, I would especially like to thank Asprofos Engineering for providing most valuable engineering advice which enabled the study team to site and cost the proposed CCUS using actual, ie pragmatic, data. And last but not least I wish to extend a warm thank you to all members of the study team who worked methodically and conscientiously in tackling the various, often complex, technical and economic issues involved.

Costis Stambolis,

Chairman and Executive Director,IENE

Athens, March 2025

# Chapter 1. Introduction

Expanding on the groundwork established by the previous Carbon Capture, Utilization, and Storage (CCUS) study conducted by IENE and concluded in October 2023, the current investigation aims to delve even deeper into the complexities of the CCUS hub outlined in the earlier examination. This follow-up study is meticulously crafted to conduct a comprehensive analysis, with a specific focus on the financial feasibility and a nuanced cost-benefit analysis for the proposed hub.

The primary objective is to provide decision-makers with a thorough set of insights derived from an in-depth exploration of the financial feasibility assessment, and the cost-benefit analysis. Through this analysis, the study aims to empower decision-makers with the knowledge required to make well-informed and strategic choices regarding the implementation of the CCUS hub.

At its core, this research seeks to address critical questions regarding the viability and sustainability of the CCUS hub. By scrutinizing the financial underpinnings and assessing potential benefits against incurred costs, the study aims to provide a thorough understanding of the hub's potential.

The anticipated findings are poised to serve as a valuable resource, equipping stakeholders with the necessary technical and economic information to navigate the complexities of decision-making and contribute to the broader discourse on sustainable energy solutions. The insights derived from this study are expected to play a pivotal role in shaping the trajectory of CCUS hub initiatives, ensuring alignment with both economic and environmental objectives.

In Greece, five CCUS projects are currently underway, reflecting the country's commitment to decarbonisation and innovative solutions to address net to zero challenges. These projects include Prinos, IFESTOS, IRIS, OLYMPUS, and Apollo $CO_2$.

- Energean's Prinos $CO_2$ Storage project is the first initiative of its kind in Southeastern Europe and the Eastern Mediterranean. Initial studies, both internal and external, have confirmed that the field can support a storage capacity of 1 million tonnes of $CO_2$ per year ($MtCO_2$/year) during the first phase of development. The second phase of the project is designed to accommodate an injection capacity in the range of 3 $MtCO_2$/year of liquid $CO_2$ by Q4 2028-Q1 2029 for approximately 20 years.
- The IFESTOS project involves the development of a state-of-the-art carbon capture facility at TITAN's Kamari plant in Athens, Greece. Once operational, this facility will capture approximately 1.9 MtCO2/year, effectively reducing emissions from cement production. The captured $CO_2$ will be transported to a permanent geological storage site in the Mediterranean. As a result, TITAN will be able to produce approximately 3 million tonnes per year of zero-carbon cement.
- The IRIS project aims to significantly reduce the environmental footprint of the Motor Oil refinery in Agioi Theodoroi by implementing carbon capture technology at the Steam Methane Reformer (SMR). Additionally, it will establish the refinery as a key producer

of ultra-low emission hydrogen. The project will integrate various industrial processes, such as liquefaction and energy integration across units, at a scale and complexity not previously seen in an independent refinery. Most of the captured $CO_2$ will be stored in an offshore geological formation in the North Aegean Sea, while a smaller portion will be used to produce 10,000 tonnes of synthetic methanol per year. Overall, the IRIS project is expected to prevent 8.58 million tonnes of $CO_2$ emissions over its first ten years of operation.

- The OLYMPUS project is focused on the green transformation of the Heracles cement production plant in Milaki, Evia, with the goal of converting it into a net-zero carbon facility. This will be achieved through the implementation of innovative technologies designed to reduce complexity and optimize the efficiency of $CO_2$ collection. Captured $CO_2$ will be liquefied and transported by sea to the Prinos sequestration facility for long-term storage. Scheduled to be operational by 2028, the OLYMPUS project aims to capture and store 0.9 $MtCO_2$/year.
- DESFA's Apollo CO2 project involves the development of a pipeline system that will collect the emissions captured at industrial facilities and transport them to the liquefaction unit in Revithousa. There, the $CO_2$ will be converted into a liquid state, allowing it to be loaded onto ships and transported for permanent storage, either in Prinos or at a facility abroad.

Four of these projects (Prinos, IFESTOS, IRIS, OLYMPUS), are funded by EU facilities while the Apollo CO2 has applied to Connecting Europe Facility (CEF) for funding.

# Chapter 2. Background

## 2.1. $CO_2$-capture

Integrating Carbon Capture and Storage (CCS) into industrial operations involves both costs and benefits. $CO_2$ capture, the most expensive part of the CCS value chain, follows three engineering pathways: atmospheric capture, post-combustion capture, and pre-combustion capture. Costs include capital and operational expenditures, influenced by facility scale, with full-scale implementation reducing costs per tonne of $CO_2$ compared to pilot projects.

Despite some technologies reaching TRL-9, risks remain, impacting cost-benefit analyses. $CO_2$ partial pressure plays a key role, with capture costs ranging from over $180/tonne at pressures below 1 kPa to under $50/tonne above 20 kPa. Benefits of CCS include emission reductions, regulatory compliance, and corporate social responsibility advantages. Companies may also avoid future carbon pricing penalties and contribute to job creation.

To optimize costs, modularization—off-site construction and delivery of $CO_2$ capture plants—can be used. Additionally, utilizing industrial waste heat can reduce capture costs by $10-20/tonne.

## 2.2. $CO_2$ storage

Estimating $CO_2$ storage costs for investment cost-benefit analysis (CBA) is complex, varying by region, facility type, emission volume, geological conditions, and storage technology. Limited experience with geological sequestration further complicates cost assessments. Costs are categorized into one-time expenses (e.g., pipeline construction) and ongoing costs (e.g., operation, maintenance, monitoring).

Onshore saline aquifers are the most common CCS storage sites, while depleted hydrocarbon fields offer lower R&D costs due to prior exploitation knowledge. Storage costs range from $3 to $11 per tonne of $CO_2$, with U.S. tax credits under the 45Q policy providing incentives of up to $50/tonne by 2026. Factors like permeability, depth, and porosity influence the number of wells required, affecting feasibility. Increased injection rates, automation, and digitalization can reduce costs.

In Greece, a $CO_2$ storage investment in the Prinos saline aquifer is estimated at €1 billion. Storage in depleted hydrocarbon fields with Enhanced Oil Recovery (EOR) is more financially viable. Cost considerations include well selection (high-corrosion alloys), new vs. existing wells, and project life-cycle phases such as permitting (€1M), pre-FID site assessment (€1M per injection test), monitoring (CAPEX & OPEX), operational costs (~15% of CAPEX), closure/post-closure (~15% of CAPEX), and EU liability fees (€0.2–€2 per tonne $CO_2$). Compression costs also impact storage economics, with power requirements of 40 MW or more requiring multiple compressors.

## 2.3. $CO_2$ transportation

$CO_2$ transportation is a critical part of the CCS value chain, with costs varying based on the transport method, distance, scale, and regional factors. Transportation options include pipelines, ships, railways, and trucks, categorized by whether they require $CO_2$ compression (pipelines) or liquefaction (ships, rail, trucks).

Key cost factors include:

1. Transport method (pipeline, ship, rail, or truck)

2. Onshore vs. offshore transport

3. $CO_2$ source(s)

4. Distance to storage site

5. Scale ($CO_2$ quantity transported)

6. $CO_2$ conditioning (compression or purification)

7. Local economic and regulatory conditions

Pipelines are the most cost-effective for large-scale, long-distance transport, while ships are preferable for overseas routes. Onshore pipelines are 50-100% cheaper than offshore ones, and networked pipeline systems can be up to 75% more economical. Smaller projects with short-distance transfers benefit from trucks or rail. For ship transport, liquefaction costs (€5.3/tonne $CO_2$) must be considered but remain viable for longer distances.

A cost-benefit analysis should assess capital and operational costs, approval and construction timelines, and decommissioning. Ultimately, the optimal transport method depends on project scale, distance, and $CO_2$ volume, with CAPEX and OPEX playing a crucial role in economic feasibility.

*Table 1: Indicative transportation costs of $CO_2$ (EUR/tonne) for CCS operations of 2.5 Mtpa typical $CO_2$ capacity.*

| **Distance (km)** | **180** | **500** | **750** | **1,500** |
|---|---|---|---|---|
| Onshore pipeline | 5.4 | n.a | n.a | n.a |
| Offshore pipeline | 9.3 | 20.4 | 28.7 | 51.7 |
| Ship | 8.2 | 9.5 | 10.6 | 14.5 |

## 2.4. Social costs

While CCUS is a promising technology, it also brings significant costs and societal challenges.

- High Costs for Industries
  i. The transition to clean energy, including CCUS, involves high reconstruction costs for industries, which could lead to electricity price increases of 50-80%, presenting a substantial financial barrier.
- Social Barriers - NIMBY Effect
  i. Public awareness around CCUS is limited, and the "Not In My Backyard" (NIMBY) effect, where people oppose local CCUS facilities, can hinder the deployment of this technology due to insufficient information and understanding.
- Job Creation and Economic Benefits
  i. According to the IEA, CCUS could create 80,000-100,000 jobs in the construction of CCUS projects and 30,000-40,000 jobs in the operation of CCUS facilities by 2050.

ii. A more ambitious report from the National Petroleum Council (2019) suggests that CCUS investments could generate 9,000 jobs annually in the activation phase, with up to 194,000 jobs at full deployment, contributing $16.3 billion to GDP annually.

- Barriers and Opportunities in Greece
  i. Greece faces technical and commercial barriers in deploying CCUS, along with an absence of a regulatory framework for CCUS despite CCS being on the agenda for two decades.
  ii. However, these barriers may actually present opportunities for growth, including job creation, improved competitiveness, and attracting foreign direct investment, which is crucial for Greece's recovery from its financial crisis.

While Greece doesn't face significant societal or economic barriers, the lack of a legal framework remains a challenge. Prompt action is needed to align with the 2050 environmental, energy, and climate targets.

In conclusion, while CCUS faces financial and social challenges, it also offers significant economic benefits, particularly in terms of job creation and energy transition. In Greece, overcoming regulatory and commercial barriers could provide unique opportunities for growth and investment.

# Chapter 3. Carbon Capture, Utilization, and Storage (CCUS) Hub Design Principles

## 3.1. Introduction

Carbon Capture, Utilization, and Storage (CCUS) is a critical technology for mitigating greenhouse gas emissions and combating climate change. By capturing carbon dioxide ($CO_2$) from industrial sources, processing it, and securely storing it underground, CCUS hubs can significantly reduce the amount of $CO_2$ released into the atmosphere.

This document provides a detailed overview of a CCUS hub, describing its main components: the liquefaction plant, pipelines, temporary storage facilities, and the transportation system to a geological permanent storage site. Each section delves into the function, design, operation, and importance of these components, illustrating how they collectively contribute to the overall effectiveness of the CCUS hub.

In its study "CCUS Technologies in Greece – Prospects for implementation" IENE proposed the establishment of a series of hubs in different geographical areas in Greece. The function of these hubs is to have a cluster approach which can serve groups of industries in various locations in the country, in view of the fact that potential underground storage facilities are not to be found everywhere in Greece. Therefore, there is a need for a decentralised approach.

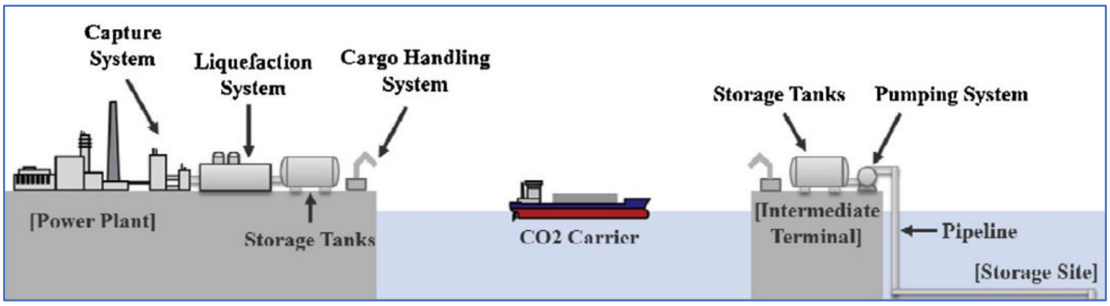



*Figure 1: Concept of ship-based CCS hub (Source: Seo Y. et al., 2016)[1].*

## 3.2. Components of the CCUS Hub

The basic design of the proposed hub is shown in block diagram in Figure 1. The main components of these hubs are as follows:

- $CO_2$ Capture
- Pipelines
- Liquefaction Plant
- Temporary Storage Facilities
- Transportation to Permanent Geological Storage
- Geological Storage Sites

[1] Seo, Y., Huh, C., Lee, S., & Chang, D. (2016). Comparison of CO2 liquefaction pressures for ship-based carbon capture and storage (CCS) chain. International Journal of Greenhouse Gas Control, 52, pp 1–12, ISSN 1750-5836, https://doi.org/10.1016/j.ijggc.2016.06.011.

## 3.3. Proposed CCUS Hub

IENE's proposed Carbon Capture, Utilization, and Storage (CCUS) hub involves several key steps from capturing $CO_2$ emissions to transporting them to a geological storage site. Here's a detailed procedure for such a hub (**Figure 2**):

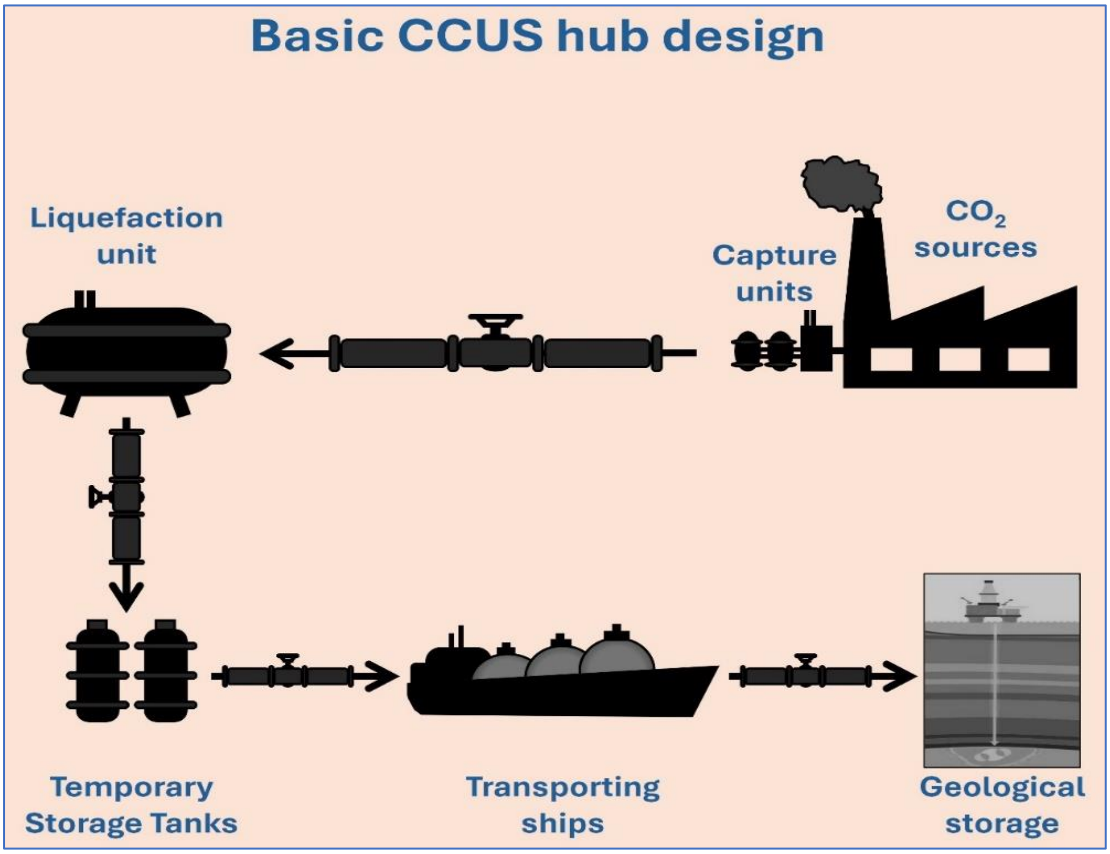



*Figure 2: The proposed basic CCUS hub design.*

- Identification of $CO_2$ Sources: Identify industrial facilities such as power plants, refineries, cement plants, or other large $CO_2$-emitting sources. Mainly sources from the Attica, Viotia and Corinth region are identified as the potential $CO_2$ sources. Mainly emissions from refineries and cement plants.
- Capture Units Installation: Install carbon capture units at the identified $CO_2$ sources. These units can use various technologies such as absorption, adsorption, or membrane separation to capture $CO_2$ from flue gases or other emissions.
- $CO_2$ Compression and Purification: After capture, $CO_2$ is compressed to increase its density for efficient transportation. It may also undergo purification to remove impurities that could affect transportation and storage.
- Liquefaction Unit: $CO_2$ is then cooled and liquefied using refrigeration units.
- Temporary Storage Tank: Liquefied $CO_2$ is stored temporarily in onsite storage tanks before transportation. These tanks ensure a stable supply for loading and transport logistics.
- Transportation by Ship: Liquefied $CO_2$ is loaded onto specialized ships designed for the transportation of cryogenic liquids.
- Delivery to Geological Storage Site: The ships transport the liquefied $CO_2$ to a designated geological storage site (such as Prinos).

# Chapter 4. CAPEX Estimation

## 4.1. Introduction

Carbon Capture, Utilization, and Storage (CCUS) represents a transformative technology essential for mitigating greenhouse emissions and combating climate change. By capturing carbon dioxide ($CO_2$) from industrial sources, processing it, and securely storing it underground, CCUS hubs offer a practical solution to significantly reduce atmospheric CO2 levels. A $CO_2$ hub is a centralized system that facilitates the capture, transportation, utilization, and storage of carbon dioxide.

These hubs are integral to strategies aimed at curbing greenhouse gas emissions and advancing CCUS efforts. Serving multiple emitters within a region, $CO_2$ hubs leverage economies of scale to minimize costs and overcome logistical hurdles associated with CCUS implementation. They are particularly critical in supporting global climate targets, especially in hard-to-decarbonize industries.

Following the findings of the study "CCUS Technologies in Greece – Prospects for Implementation," the Institute of Energy for South-East Europe (IENE) recommends establishing multiple CCUS hubs across Greece. These hubs would adopt a cluster-based approach to cater to industrial regions, particularly given the uneven distribution of underground storage sites.

Recognizing the complexity of cost estimation for such infrastructure, IENE proposes segmenting the analysis into individual components to address the variability and uncertainties in investment and operational costs. Consequently, the proposed hub includes: a) the carbon capture system, (b) the $CO_2$ pipeline network, (c) the liquefaction plant, (d) temporary storage facilities, and the transportation infrastructure leading to a permanent geological storage site. This hub is expected to have a maximum capture and storage capacity of 5 million tonnes per annum (MTPA), with captured emissions injected into suitable geological formations.

Accordingly, the aim of this study is to assist IENE by outlining the key components of a CCUS hub and providing technical insights to create a realistic foundation for estimating capital expenditures (CAPEX) and operational expenditures (OPEX). The analysis is informed by assumptions and data provided by IENE regarding the hub's components. However, the study primarily relies on desk-based research, including bibliographic sources, analysis of relevant case studies, and published data from comparable European and international projects. Furthermore, cost estimation data are drawn from ASPROFOS's extensive expertise, supplemented by vendor inputs, historical data, and advance software tools. Notably, no direct data or input was received from the stakeholders involved in the process.

The study evaluates two scenarios for the design of CCUS hub with a maximum capacity of 5 MTPA, where captured emissions are transported and stored via injection into deep geological formations, such as depleted oil and gas reservoirs or saline aquifers.

Scenario 1: A cluster comprising three industrial emitters – two refineries and one cement plant – utilizes the hub's full storage capacity of 5 MTPA.

- 2 refineries each with a capacity of 1.5 MTPA
- 1 cement plant with a capacity 2 MTPA

Scenario 2: A larger and more diverse group of six emitters is considered, maintaining the same 5 MTPA hub capacity but including a broader mix of industries.

- 2 refineries each with a capacity of 1 MTPA
- 1 cement plant with a capacity 1.5 MTPA
- 3 power plants each with a capacity of 0.5 MTPA

The following diagram presents the primary components of a Carbon Capture, Transport, and Storage hub (**Figure 3**).

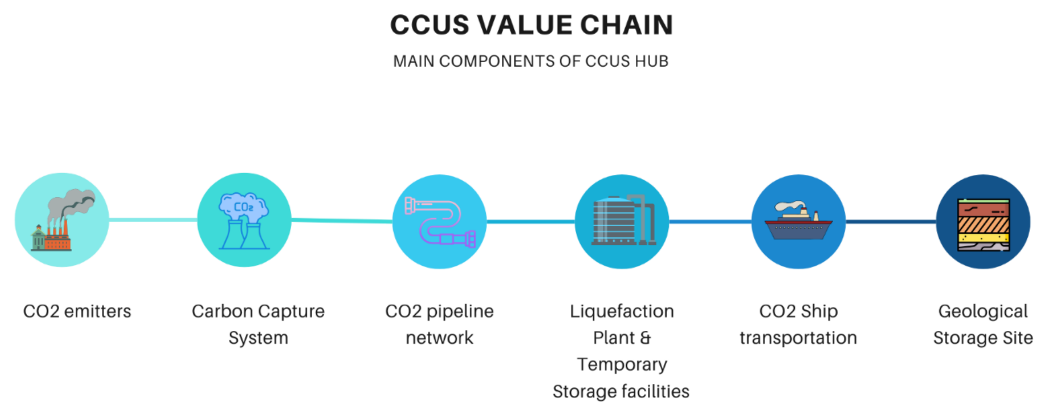



*Figure 3: CCUS Value Chain.*

$CO_2$ Emitters: A broader mix of industries has been chosen. In this case, two refineries (HELPE AIC & EIC), one cement plant (TITAN) and three power plants (PROTERGIA, ELPEDISON & HERON).

Carbon Capture System: Each industry will implement its own technology. In this context, the recommended options are first- and second-generation oxyfuel technology, as well as post-combustion technology.

Pipeline Network: The proposed network is based on assumptions and specific siting criteria, enabling the calculation of its average length for cost estimation purposes.

Liquefaction plant: the installation is proposed within the Municipality of Elefsina, with the Elefsis Industrial Complex identified as a recommended location. This site offers the advantage of an existing loading pier, which would streamline the transport of $CO_2$ to the geological storage facility.

Temporary Storage Facilities: Will be situated near the liquefaction plant to hold the $CO_2$ until it is transferred to the geological storage site.

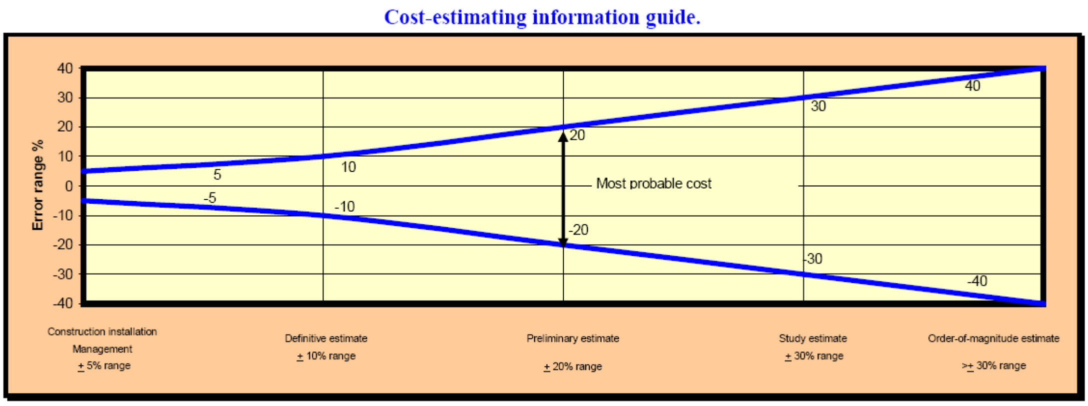
Transportation to Permanent Storage Facilities: Ships will be utilized to transport the liquid $CO_2$ to the geological storage site.

Cargo Handling System (including jetty and loading facilities): A ship loading facility will be installed at the pier, consisting of loading arms and all necessary supporting utilities.

Geological Storage Site: Permanent storage of the liquid $CO_2$ achieved by injecting it into a depleted oil and gas reservoir.

The hub's operational lifecycle is considered 20-years.

Regarding the cost estimation for the individual components of the hub, at the current stage of the project, which corresponds to a feasibility study, the accuracy range is estimated to be between -20% and +40% as indicated in the following diagram (**Figure 4**).




| Construction installation Management | Detailed Design | Feed | Basic Design | Conceptual Feasibility study |
|---|---|---|---|---|
| Class I<br>Detailed estimate<br>± 5% range | Class II<br>Definitive estimate<br>± 10% range | Class III<br>Preliminary estimate<br>± 20% range | Class IV<br>Study estimate<br>± 30% range | Class V<br>Order-of-magnitude estimate<br>>± 30% range |

*Figure 4: Cost Estimation Guide*

### Foreseeable challenge

Regulatory and policy frameworks are critical for the successful domestic development of CCUS. Currently, legislation addresses only the permanent storage of $CO_2$ and does not regulate $CO_2$ pipeline transportation. However, the issuance of relevant regulations governing pipeline transportation is anticipated by the end of the year. This study follows the applicable European and national legislative frameworks, including regulations governing natural gas pipelines and any other relevant directives currently in force pertaining to the study's scope.

## 4.2. Carbon Capture System

Various $CO_2$ capture technologies exist, allowing emitters to choose based on their specific emission profiles. This study focuses on first- and second-generation oxyfuel combustion and post-combustion cryogenic capture technologies. These systems typically include a primary capture unit, followed by pre-treatment involving compression and dehydration.

After capture, $CO_2$ is compressed to 179 barg, exceeding supercritical conditions for pipeline transport. Compression involves low-pressure (LP) and high-pressure (HP) stages, with triethylene glycol (TEG) dehydration in between to remove moisture. Interstage coolers aid in heat dissipation during LP compression, while HP compression finalizes the process before $CO_2$ is cooled and transported at 100-110 barg.

$CO_2$ capture is a complex, multi-stage process that varies based on technology, plant design, fuel type, and scale. The CAPEX and OPEX of a 1 MTPA Carbon Capture System with a 45,000 kW operational cycle were estimated through literature review, vendor consultations, and case studies from projects like Porthos (Netherlands), Petra Nova (Texas), and Northern Lights (Norway).The results for CAPEX, OPEX, and 20-year lifecycle OPEX are summarized in the table below (**Table 2**).

*Table 2: CAPEX & OPEX for 1 MTPA CCS PLANT.*

| CCS PLANT | CAPEX | OPEX | Lifecycle OP |
|---|---|---|---|
| **1 MTPA** | €150 - 200 million | €70 – 75 million | €1,400–1,500 million |

For the OPEX estimation, key operational parameters were considered, including a heat demand of 2 GJ per tonne of $CO_2$ captured, a heat cost of €32 per GJ (according to average market price[2]), annual O&M costs of 3% of CAPEX, and labor costs ranging from 2 to 5 million euros per year.

### 4.3. $CO_2$ Pipeline Network

To estimate the capital and operating expenditures (CAPEX and OPEX) of the pipeline network, the pipeline route needed to be determined first, allowing for an approximate calculation of

the pipeline length required for each scenario. A methodology was followed for route estimation, based on siting criteria aligned with existing legislation for natural gas pipelines, as no specific national regulatory framework currently exists for $CO_2$ transport pipelines.

As part of the proposed design, a backbone pipeline was identified, complemented by smaller branches serving individual emitters. This design allows for future expansion and extension of the network. To enhance the realism of the scenarios, initial considerations were made regarding the specific routes the pipeline network would follow. For this analysis, siting criteria and existing energy corridors—such as those used for natural gas or oil pipelines—were reviewed. These corridors were selected to facilitate connections between the proposed $CO_2$ emitters and the pipeline network.

- Positioning criteria for CO2 transport pipeline network
- The positioning criteria considered are briefly outlined.
- Proximity to $CO_2$ Sources
- Proximity to Storage Sites
- Environmental Impact and Permitting
- Safety and Population Density

[2] Average Market Price estimated through ADMIE (October 2023-2024): https://www.admie.gr/agora/statistika-agoras/kyrioi-deiktes-dashboard/mesostathmiki-timi-agoras

- Compatibility with Infrastructure
- Economic Viability
- Regulations and Legal Requirements
- Climate Conditions

## 4.4. $CO_2$ transportation from Aspropyrgos to Elfesina Refinery – Restrictions & Challenges

During the integration of all emitters into the network, a connectivity challenge between the Aspropyrgos refinery and Elefsis was encountered. All available options were explored, including onshore and offshore pipelines, as well as the possibility of ship transportation. Below are the limitations and challenges associated with each option.

- Transportation via Onshore Pipeline
- Transportation via Offshore Pipeline
- Transportation via Ship

Transporting $CO_2$ from the Aspropyrgos to the Elefsis refinery by ship could be a viable option; however, it is not economically efficient. This approach would require an additional liquefaction plant at the Aspropyrgos refinery as well as a designated loading facility for the ship.

Subsequently, after considering the above criteria, we determined the indicative routing shown in the following map (**Figure 5**).

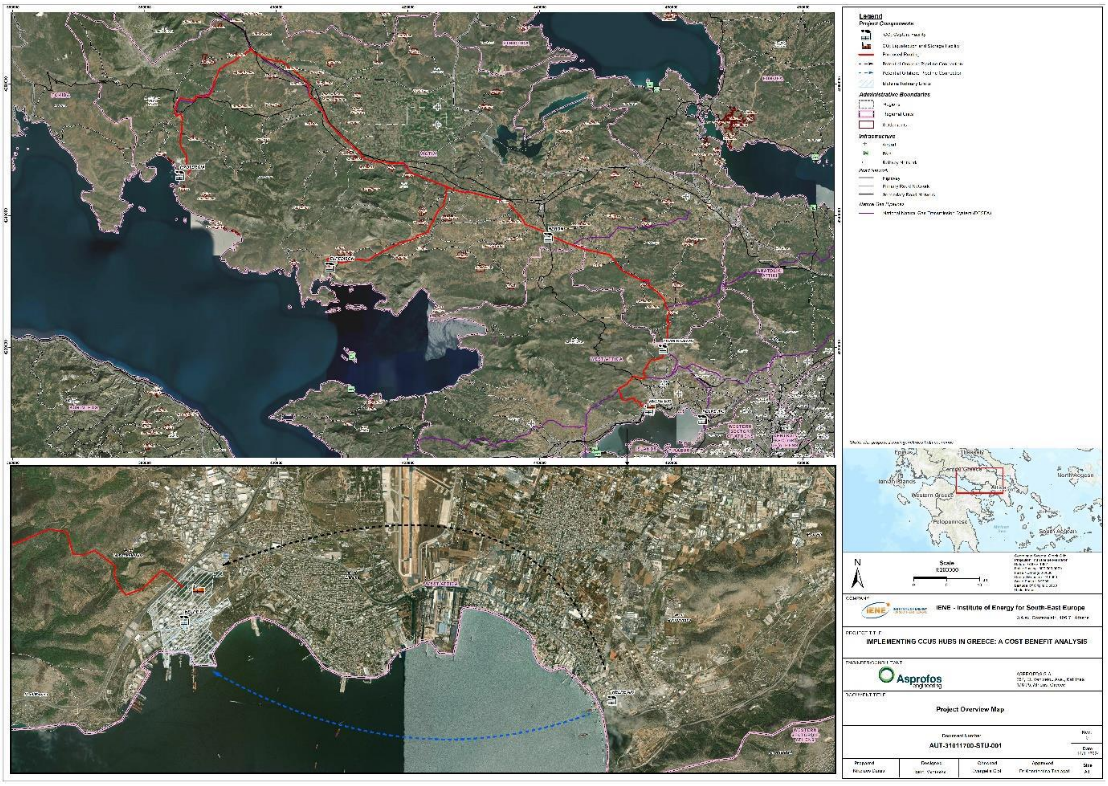



*Figure 5: Project Overview.*

Additionally, to better illustrate the routing, three maps were created, grouping related positioning criteria together. Specifically, the first map was designed to consider the geological and geomorphological features, as well as the hydrology of the broader area (**Figure 6**).

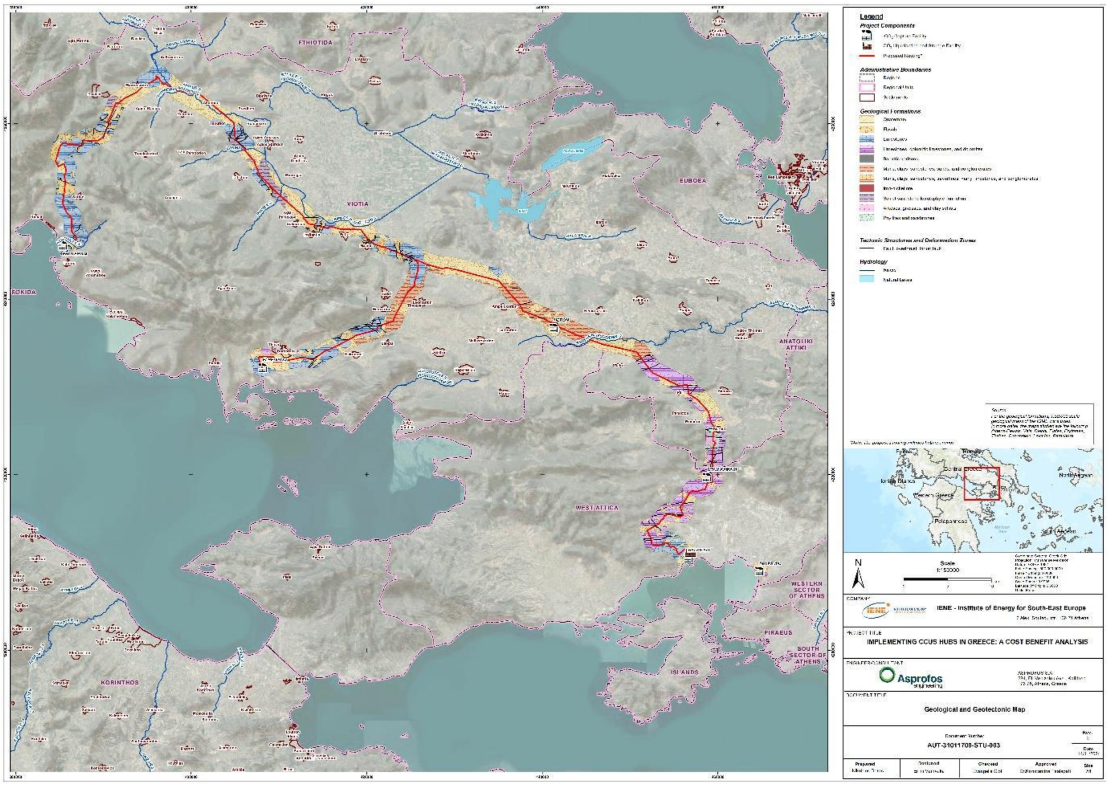



*Figure 6: Geological and Geotectonic map.*

The second map (**Figure 7**) displays protected areas, cultural heritage sites and environmentally sensitive zones.

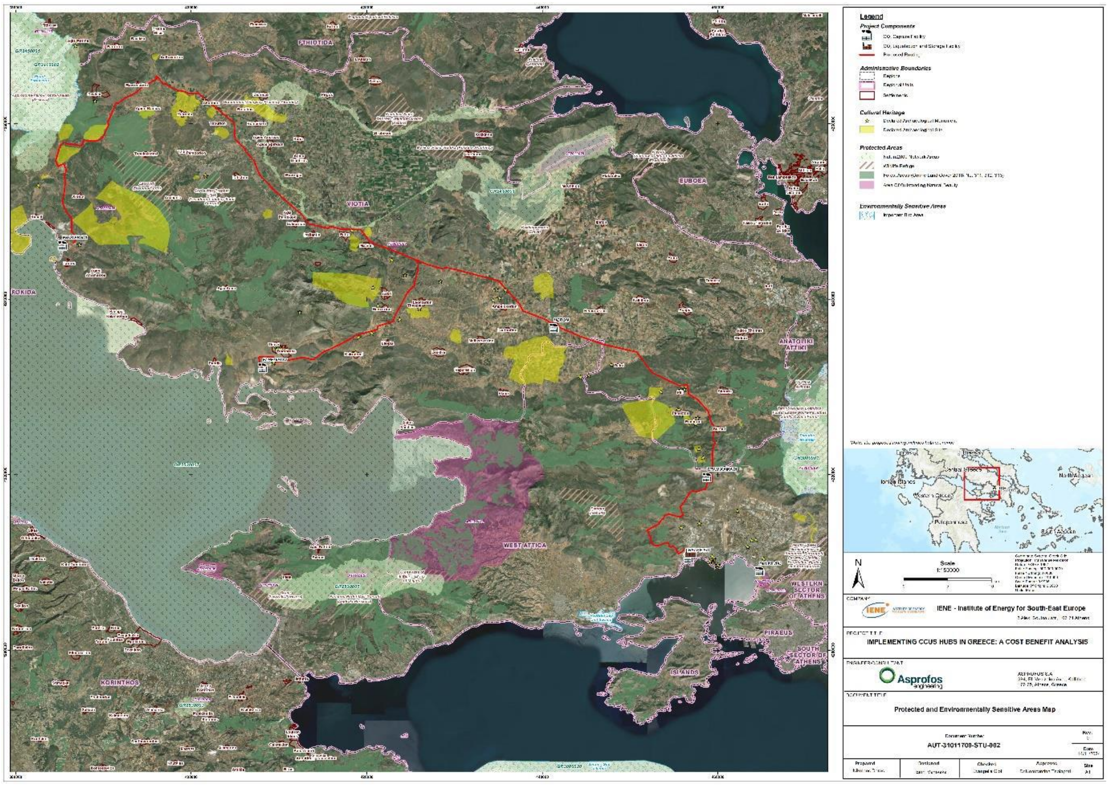



*Figure 7: Protected and Environmentally Sensitive Areas Map.*

Finally, the third map (**Figure 8**) incorporates land use, infrastructure and socioeconomic environment.

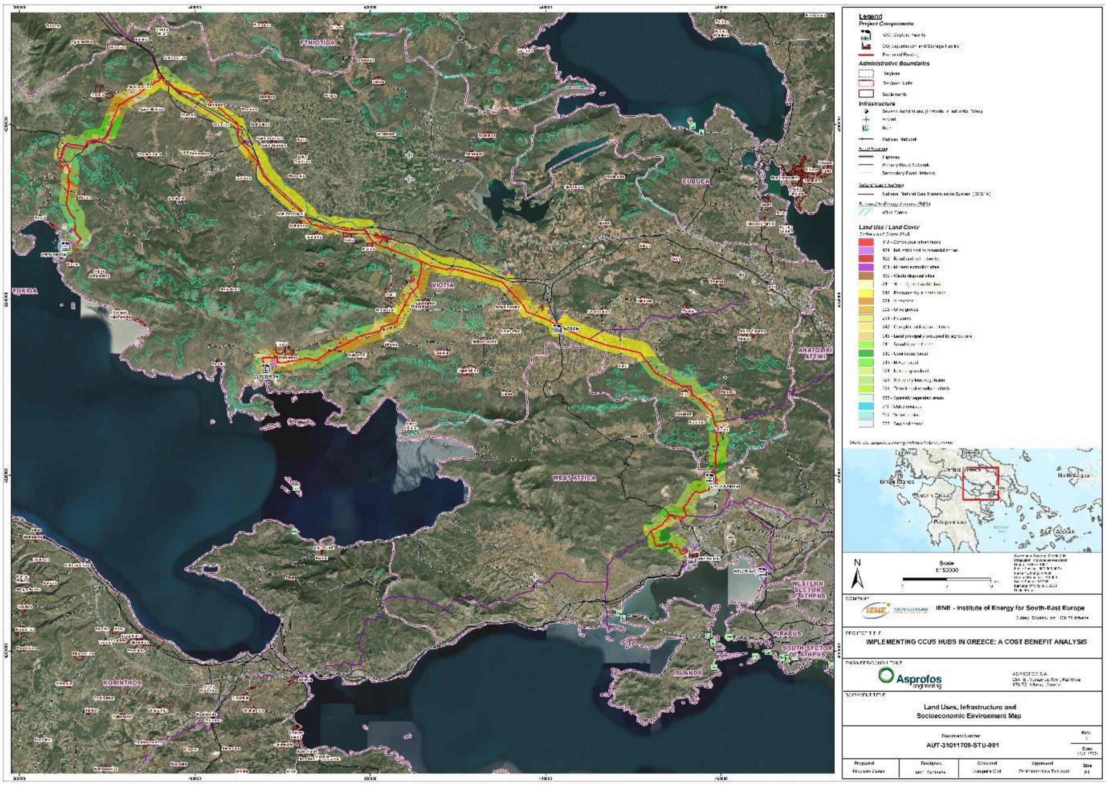



*Figure 8: Land Uses, Infrastructure and Socioeconomic Environment Map.*

Once the sitting was determined, the total length for each scenario was subsequently calculated. Considering that $CO_2$ is transported under supercritical conditions (pressure: 100-

110 bar and temperature: 20°C), the specific characteristics of the main pipeline and its branches were then assessed. The findings are summarized in the table below (**Table 3**).

*Table 3 Design characteristic of pipeline network for both scenarios.:*

| **Material:** | **Max. Capacity: 5 MTPA** | | **Length** | |
|---|---|---|---|---|
| **Carbon steel** | **Scenario I** | **Scenario II** | | |
| Protergia branch | 0.5 | - | 30 km | |
| Elpedison branch | 0.5 | - | 26 km | |
| Heron branch | 0.5 | - | 0.5 km | |
| Titan branch | 1.5 | 2 | 0.5 km | |
| AIC branch | 1 | 1.5 | 10 | |
| EIC branch | 1 | 1.5 | 1 | |
| Main pipeline | *5* | *5* | 20 km | 106 km |
| Total length | | | 32 km | 174 km |

The cost of the piping network was then estimated, which includes the pipelines and peripheral facilities, civil and mechanical work, as well as project management, detailed design, procurement services and construction supervision. The cost of expropriation is not included. Additionally, OPEX was estimated with annual O&M costs set at 2% of CAPEX. The table below (**Table 4**) presents the total CAPEX, OPEX and 20-year lifecycle OPEX for both scenarios.

*Table 4: CAPEX & OPEX for pipeline network.*

| **Pipeline network** | **Length** | **CAPEX** | **OPEX** | **Lifecycle OPEX** |
|---|---|---|---|---|
| **Scenario I** | 32 km | €247 million | €5 million | €99 million |
| **Scenario II** | 174 km | €388 million | €8 million | €155 million |

## 4.5. Liquefaction Plant

Following discussions with IENE, the proposed site for the liquefaction and temporary storage facility has been identified within the Elefsis municipality. After reviewing available land use and potential sites, one option emerged within the Elefsis refinery grounds. This site benefits from an existing loading pier, facilitating $CO_2$ transport to the geological storage location, which serves as a collection terminal point.

The collection terminal facility is designed to comprise pipeline terminals for receiving captured $CO_2$ from emitters, a compression station to maintain pipeline pressure as needed, a treatment unit, a liquefaction facility followed by buffer storage tanks, as shown in Figure 11 and export infrastructure.

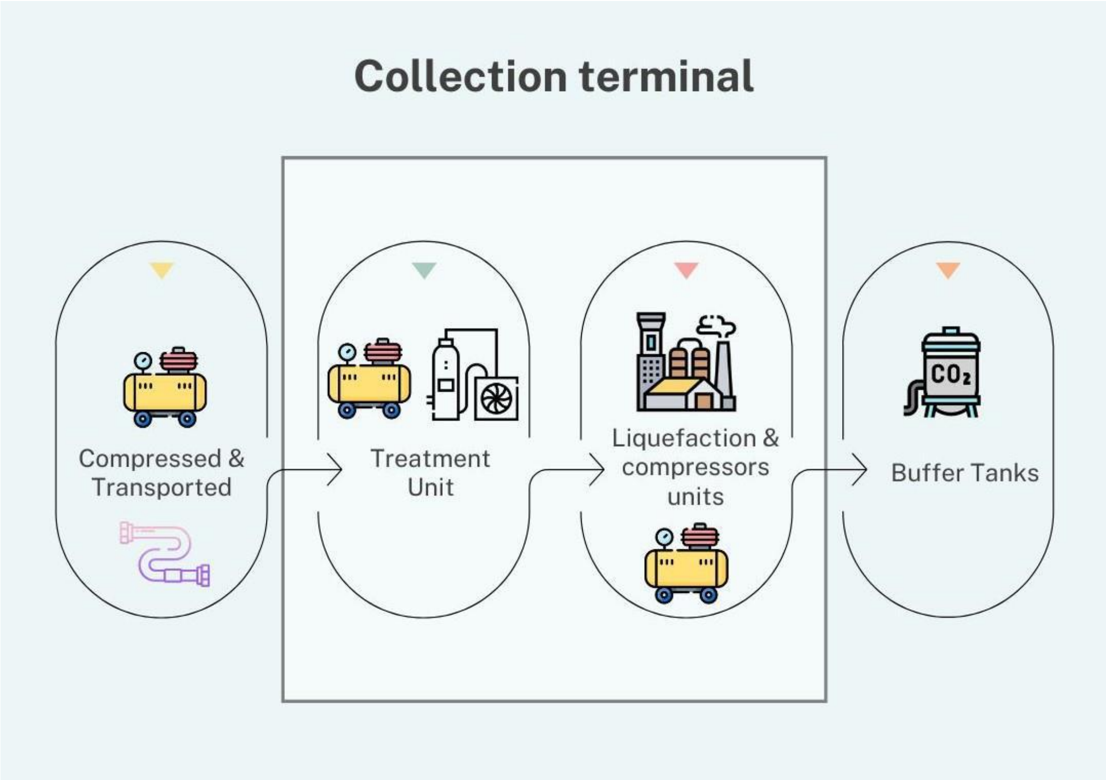



*Figure 9: Illustration of Collection terminal.*

In detail,

<u>Treatment Unit:</u> This includes a dehydration and $CO_2$ purification system, along with multi-stage compressors to compress $CO_2$ to a pressure of 30-50 bar.

<u>Cooling and Liquefaction Unit:</u> Utilizing heat exchangers, cooling towers, and refrigeration systems, this unit reduces pressure to 7 bar and temperature to -50°C.

<u>Buffer Tanks:</u> The liquefied $CO_2$ is then transferred to buffer storage tanks.

Export infrastructure: From the buffer tanks, the $CO_2$ is prepared for transfer via the loading and export systems.

The capital expenditure (CAPEX) and operational expenditure (OPEX) for a liquefaction facility of 5 MTPA capacity which includes compression, treatment unit and cooling – liquefaction unit was estimated through desk-based research.

The results for CAPEX, OPEX, and 20-year lifecycle OPEX are summarized in the table below (**Table 5**).

*Table 5: CAPEX & OPEX for a 5 MTPA Liquefaction Facility.*

| Liquefaction facility | CAPEX | OPEX | Lifecycle OPEX |
|---|---|---|---|
| **5 MTPA** | €250-300 million | €57–84 million | €1.140–1.680 million |

For the OPEX estimation, key operational parameters were considered, including energy cost for liquefaction 90-120 kWh per ton of $CO_2$, a heat cost of €115 per MWh (according to average market price[3]), annual maintenance costs of 2-4% of CAPEX annually, and labor costs ranging from 2 to 5 million euros per year.

## 4.6. Temporary Storage Facilities

Following the liquefaction facility, a temporary storage facility is required to store liquefied $CO_2$ in insulated tanks maintained at low temperature and pressure prior to its transportation to the geological storage site. In this study, it is assumed that a storage capacity of 55,000 $m^3$ is necessary to accommodate the liquefied $CO_2$. To estimate the space required for the temporary storage, several key assumptions were made (**Table 6**).

*Table 6: Vessel trip assumptions.*

| **Assumptions of transport cycle** | |
|---|---|
| Distance (Elefsis – Prinos Storage Facility) | 333.36 km |
| Ship velocity | 22.22 km/hr |
| Flow rate (loading) | 1000 t/hr |
| Flow rate (unloading) | 500 t/hr |
| Shipment required | 15 hr |
| Loading time | 20 hr |
| Unloading | 40 hr |
| Total transport cycle | 90 hr |

A vessel requires approximately 3.75 days to complete a full transport cycle. With a liquefaction capacity of 5 MTPA, the assumed $CO_2$ inlet flow is 13,000 tonnes per day. To accommodate this, a storage facility must hold around 50,000 tonnes (60,000 $m^3$) of $CO_2$.

Since the $CO_2$ enters storage at low pressure and temperature, it has a higher density, reducing volume requirements. Based on this, a 55,000 $m^3$ storage facility was deemed necessary. CAPEX and OPEX estimates for temporary storage were derived from literature, vendor consultations, and case studies from projects like Porthos, Petra Nova, and Northern Lights.

Two buffer storage options were considered—cylindrical and spherical tanks. Spherical tanks were chosen due to their higher volume capacity, resulting in a facility with 10 spherical tanks of 5,500 $m^3$ each.The cost of the temporary storage was then estimated, which includes necessary equipment, piping, instruments, electrical, civil works and painting & insulations works. Additionally, OPEX was estimated with annual O&M cost set at 3% of CAPEX.

The table below (**Table 7**) presents the total CAPEX, OPEX and 20-year lifecycle OPEX for both scenarios. The results for CAPEX, OPEX, and 20-year lifecycle OPEX are summarized in the table below.

*Table 7: CAPEX & OPEX for 55,000 m3 temporary storage.*

| **Temporary Storage** | **CAPEX** | **OPEX** | **Lifecycle OPEX** |
|---|---|---|---|
| **55,000 $m^3$** | €93 million | €3 million | €56 million |

[3] Average Market Price estimated through ADMIE (October 2023-2024): https://www.admie.gr/agora/statistika-agoras/kyrioi-deiktes-dashboard/mesostathmiki-timi-agoras

## 4.7. Transportation to permanent storage facilities

To transport 5 MTPA at a permanent storage facility, a cycle of three vessels, each with a capacity 20.000 tonnes, is required.

## 4.8. Cargo Handling System System (jetty, loading facilities etc.)

The ship loading station is designed to transfer the liquid $CO_2$ from the temporary storage tanks to a $CO_2$ transport tanker docked at the port. Its main components are ship loading pumps and three loading arms (one for ship loading, one for vapor return, and one as back-up). The vapor return line allows the pressure in the onshore storage vessels to be maintained while the liquid is being loaded into the ship vessel.

The cost of the temporary storage was then estimated, which includes necessary equipment, piping, instruments, electrical, civil works and painting & insulations works. Additionally, OPEX was estimated with annual O&M cost set at 3% of CAPEX. The results for CAPEX, OPEX, and 20-year lifecycle OPEX are summarized in the Table 8 below.

*Table 8: CAPEX & OPEX for Loading Station Facility.*

| Loading Station | CAPEX | OPEX | Lifecycle OPEX |
|---|---|---|---|
| **Tanker 20.000 tonnes** | €20 million | €0.6 million | €12 million |

## 4.9. Geological Storage Site

Permanently stored via injection into deep geological formations, such as depleted oil and gas reservoirs.

## 4.10. Conclusion and Remarks

In this study key components of a CCUS hub were described by providing technical insights along with an estimate of capital expenditures (CAPEX) and operational expenditures (OPEX) was provided at an accuracy of -20 to + 40%.

Difficulties in estimating the cost were identified, particularly concerning the Carbon Capture System technology and the liquefaction costs, as suppliers only provided bibliographic data rather than specific details related to their technology.

Regarding the pipeline network, a safety study is required due to the high pressure associated with long distances. Further research and study are necessary for connecting the Aspropyrgos refinery, especially if a legislative framework for such pipelines is introduced.

Areas with steep slopes, such as Thisvi and Aghios Nikolaos, will require additional analysis and study before construction.

Although $CO_2$ is non-flammable and non-toxic, it is asphyxiant at high concentrations (displacing oxygen), so a safety study is required. The safety aspects of $CO_2$ storage should be considered in the basic design. The initial safety analysis of a $CO_2$-storage facility should be conducted early in the project to prevent unexpected changes.

The storage size, along with the frequency and reliability of ship arrivals, should also be assessed. At present, small vessel with a capacity of approximately 2.000-5.000 $m^3$ are commonly used for $CO_2$ transportation, while larger vessels are under construction, adding another important factor to consider.

Design pressure estimates, based on bibliographic data, need further investigation, particularly for storage and shipping loading, potentially in close cooperation with relevant shipping operators.

A Front-End Engineering and Design (FEED) study should be conducted for the entire Carbon Capture project, including storage and shipping.

Constructability also should be assessed.

A summary table of the CCUS hub components can be found at the Appendix.

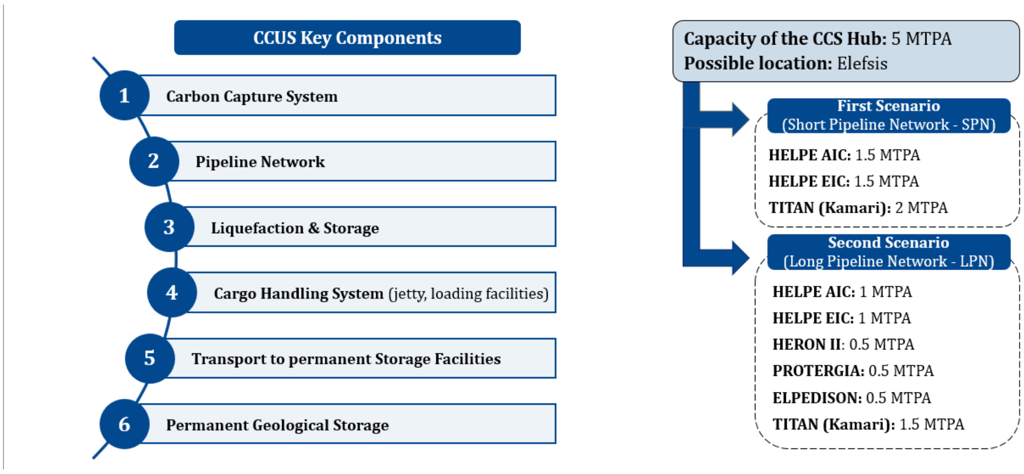
# Chapter 5. Cost Benefit Analysis and Financial Model

## 5.1. Methodology

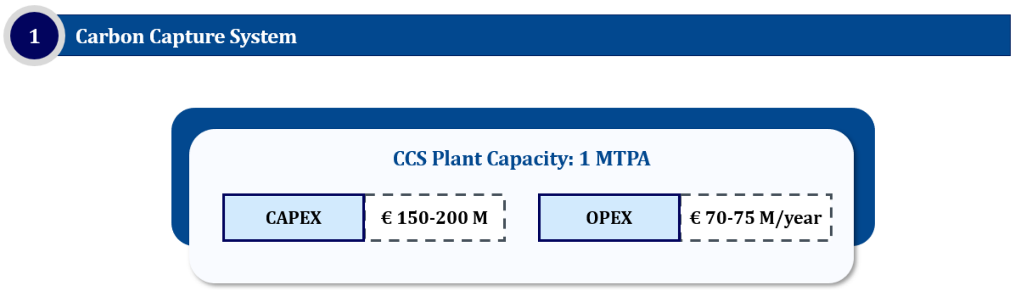
The methodology chosen for the development of the Cost Benefit Analysis (CBA) is the Discounted Cash Flow (DCF) Method.

## 5.2. Cost Benefit Analysis Steps

The CCUS procedure involves six distinct steps, forming the foundation for two proposed scenarios for implementing a 5 MTPA Hub possibly in the wider region of Elefsis.




**Step 1: Carbon Capture System – Capex & Assumptions**




**Assumptions:**

- ❑ Each industry shall install its own CCS Plant and all emitters will install the same technology

**Recommended technology:**

- ❑ First and second generation oxyfuel & Post combustion cryogenic

## Step 2: Pipeline network – Criteria & Assumptions

**2 Pipeline network**

**Preferred: Elefsis**

**Location Criteria**

- Geological and topographical conditions: stable soil, accessible terrain (flat or mild topography)
- Protected areas: pipelines should not cross such areas
- Aquatic ecosystems: crossing of rivers or lakes requires specific studies and permits.
- Cultural & archaeological sites.
- Safety & population density: avoid densely populated areas, urban areas and residential or industrial areas
- Usually, pipelines are sited alongside existing roads, railways or other infrastructures to reduce costs and reduce environmental impact.
- Already existing energy corridors where natural gas or oil pipelines may be used for positioning.

**Assumptions**

- The cost of expropriation is not included.
- Safety study is necessary – high pressure due to long distance.
- This study does not take into account the location and cost of valve stations.
- Connection between AIC & EIC will be made through offshore pipeline or ship.
- Areas with steep slope (i.e. Thisvi & Aghios Nicholaos) require further analysis and study prior construction.
- Constructability not taken into account.

**2 Pipeline network**

**$CO_2$ Transportation Characteristics:**

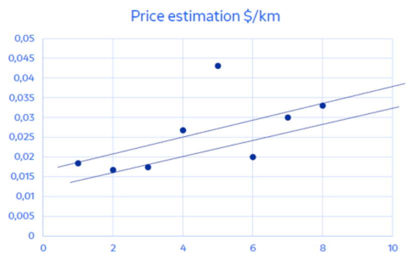
| 9-12 inches | High Pressure (<25bar) |
|---|---|

**Short Pipeline Network (SPN)**

- 32 km of pipeline
- **CAPEX:** € 247 M
- **OPEX:** € 5 M/year

**Long Pipeline Network (LPN)**

- 174 km of pipeline
- **CAPEX:** € 388 M
- **OPEX:** € 8 M/year




## Step 3: Liquefaction & Storage & Step 4: Liquefaction & Storage Transport to permanent Storage Facilities – CAPEX/OPEX

**3 Liquefaction & Storage**

| CAPEX | € 343M – 393M | OPEX | € 60-87 M /year |
|---|---|---|---|

**4 Cargo handling system (jetty, loading facilities)**

| CAPEX | € 20M | OPEX | € 0,6 M/year |
|---|---|---|---|

OPEX was estimated with annual O&M cost set at 3% of CAPEX.

### Step 5: Cargo handling system & Step 6: Permanent Geological Storage - OPEX

**5 Transport to permanent Storage Facilities**

| OPEX | € 15 – 25/tonne $CO_2$ |
|---|---|

**6 Permanent Geological Storage**

| OPEX | € 25/ tonne $CO_2$ |
|---|---|

## 5.3. Financial Model

### Assumptions of the Financial Model (Discounted Cash Flow Method)

**General Assumptions**

- The methodology for the development of the CBA is the **Discounted Cash Flow** (DCF) Method
- The model has a duration of 20 years (2026 onwards)
- Cost of *Step 1: CC System* has not been included in the financial model as the companies have received funding for it
- Financial Cashflows for Shareholders are deducted by 22% (Greek tax rate)
- The desired return on equity amounts to 12%

  *Desired return on equity=20year Greek bond rate+beta[1]*Equity Risk[1] Premium for Greece=3,74+1*8,26=12%*

**Benefit Assumptions**

The price of emission allowances is set at €80 per tonne of $CO_2$ equivalent until 2030, as outlined in the NECP. For the 2031-2045 period, the corresponding prices are shown in the table below. While the 2035, 2040 and 2045 prices are specified in the NECP, the intermediate prices have been calculated by evenly distributing the difference between each of these specified prices across five-year intervals. More specifically:

| Item/Year | 2026-30 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 | 2041 | 2042 | 2043 | 2044 | 2045 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Price(€/t) | 80 | 92 | 104 | 116 | 128 | 140 | 170 | 200 | 230 | 260 | 290 | 318 | 346 | 374 | 402 | 430 |

For the benefits (revenues), two different scenarios were used, in the first one all the benefit returns to the investment (100%), while in the second one, only 50% returns to the investment.

[1]NYU Stern data

**Capex Assumptions**

Two scenarios and two sub-scenarios have been considered and analysed:

1. **Short Pipeline Network (SPN):** with CAPEX € 247 M and duration of two years *(equally distributed)*

   **$SPN_{Min}$:** CAPEX and OPEX Values are at lowest based on assumptions

   **$SPN_{Max}$:** CAPEX and OPEX Values are at highest based on assumptions

2. **Long Pipeline Network (LPN):** with CAPEX €388 M and duration of three years *(Pipeline Network is structured in all 3 years equally and other CAPEX components are distributed equally in years 2 and 3)*

   **$LPN_{Min}$:** CAPEX and OPEX Values are at lowest based on assumptions

   **$LPN_{Max}$:** CAPEX and OPEX Values are at highest based on assumptions

## Capex Assumptions

**1** Short Pipeline Network (SPN) CAPEX

$SPN_{Min}$

| # | Item/Year | 2026 | 2027 | 2028 | Total |
|---|---|---|---|---|---|
| Step 2 | Pipeline Network | 123.500.000 € | 123.500.000 € | €- | 247.000.000 € |
| Step 3 | Liquefaction & Storage | 171.500.000 € | 171.500.000 € | €- | 343.000.000 € |
| Step 4 | Cargo Handling System | 10.000.000 € | 10.000.000 € | €- | 20.000.000 € |
| | Total | 305.000.000 € | 305.000.000 € | €- | 610.000.000 € |

$SPN_{Max}$

| # | Item/Year | 2026 | 2027 | 2028 | Total |
|---|---|---|---|---|---|
| Step 2 | Pipeline Network | 123.500.000 € | 123.500.000 € | €- | 247.000.000 € |
| Step 3 | Liquefaction & Storage | 196.500.000 € | 196.500.000 € | €- | 393.000.000 € |
| Step 4 | Cargo Handling System | 10.000.000 € | 10.000.000 € | €- | 20.000.000 € |
| | Total | 330.000.000 € | 330.000.000 € | €- | 660.000.000 € |

## Capex Assumptions

**2** Long Pipeline Network (LPN) CAPEX

$LPN_{Min}$

| # | Item/Year | 2026 | 2027 | 2028 | Total |
|---|---|---|---|---|---|
| Step 2 | Pipeline Network | 129.333.333 € | 129.333.333 € | 129.333.333 € | 388.000.000 € |
| Step 3 | Liquefaction & Storage | | 171.500.000 € | 171.500.000 € | 343.000.000 € |
| Step 4 | Cargo Handling System | | 10.000.000 € | 10.000.000 € | 20.000.000 € |
| | Total | 129.333.333 € | 310.833.333 € | 310.833.333 € | 751.000.000 € |

$LPN_{Max}$

| # | Item/Year | 2026 | 2027 | 2028 | Total |
|---|---|---|---|---|---|
| Step 2 | Pipeline Network | 129.333.333 € | 129.333.333 € | 129.333.333 € | 388.000.000 € |
| Step 3 | Liquefaction & Storage | | 196.500.000 € | 196.500.000 € | 393.000.000 € |
| Step 4 | Cargo Handling System | | 10.000.000 € | 10.000.000 € | 20.000.000 € |
| | Total | 129.333.333 € | 335.833.333 € | 335.833.333 € | 801.000.000 € |

## Capital Structure Assumptions

Two scenarios for capital structure have been considered and analysed:

**Scenario with Grant**

- 40% Grant
- 30% EIB Loan
- 30% Equity

**Scenario without Grant**

- 0% Grant
- 30% EIB Loan
- 70% Equity

## OPEX/Costs Assumptions

- Liquefaction & Storage amount to 60 M €/year in min scenarios 87 M €/year in max scenario
- Cargo handling OPEX amount to 600k. € per annum
- Permanent Geological Storage amount to 25€/ tonne $CO_2$
- Ship Transportation amount to 15€/ tonne $CO_2$ in min scenarios and 25€/tonne $CO_2$ in max scenarios
- Costs are inflated with a rate of 2%

## Debt/Loan Assumptions

- Duration of Loan: 20years
- Interest Rate: 3,5%
- Grace Period: 5years
- VAT Loan has a duration of 1 year and is repaid in the next year with interest rate 4,5%
- VAT Loan interest payments are capitalized until the end of the Grace Period

## Results of the Financial Model

Scenario 1

**1 Short Pipeline Network (SPN)**

| # | Subscenarios | Payback Period | NPV | IRR |
|---|---|---|---|---|
| SPN1 | 100% Revenues, $SPN_{Min}$ Capex and Opex, with grant | 4 years | 1.733.705.811,17 € | 41,76% |
| SPN2 | 100% Revenues, $SPN_{Min}$ Capex and Opex, without grant | 6 years | 1.527.519.586,68 € | 29,90% |
| SPN3 | 100% Revenues, $SPN_{Max}$ Capex and Opex, with grant | 7 years | 1.294.867.434,75 € | 30,68% |
| SPN4 | 100% Revenues, $SPN_{Max}$ Capex and Opex, without grant | 8 years | 1.071.780.700,05 € | 23,31% |
| SPN5 | 50% Revenues, $SPN_{Min}$ Capex and Opex, with grant | 13 years | -61.020.381,50 € | 10,92% |
| SPN6 | 50% Revenues, $SPN_{Min}$ Capex and Opex, without grant | 14 years | -267.206.605,99 € | 8,25% |
| SPN7 | 50% Revenues, $SPN_{Max}$ Capex and Opex, with grant | 17 years | -568.548.797,98 € | 3,1% |
| SPN8 | 50% Revenues, $SPN_{Max}$ Capex and Opex, without grant | 18 years | -791.635.532,68 € | 1,68% |

- The investment is marginal in the case where revenues are shared 50% with industries. Further sensitivity analysis is needed to determine a realistic percentage of revenues.

## Results of the Financial Model

Scenario 2

**2 Long Pipeline Network (LPN)**

| # | Subscenarios | Payback Period | NPV | IRR |
|---|---|---|---|---|
| LPN1 | 100% Revenues, $LPN_{Min}$ Capex and Opex, with grant | 6 years | 1.549.136.862,02 € | 34,57% |
| LPN2 | 100% Revenues, $LPN_{Min}$ Capex and Opex, without grant | 7 years | 1.315.330.602,90 € | 25,97% |
| LPN3 | 100% Revenues, $LPN_{Max}$ Capex and Opex, with grant | 8 years | 1.151.975.899,15 € | 27,22% |
| LPN4 | 100% Revenues, $LPN_{Max}$ Capex and Opex, without grant | 9 years | 903.079.898,79 € | 21,02% |
| LPN5 | 50% Revenues, $LPN_{Min}$ Capex and Opex, with grant | 14 years | -124.546.769,74 € | 9,83% |
| LPN6 | 50% Revenues, $LPN_{Min}$ Capex and Opex, without grant | 15 years | -358.353.028,85 € | 7,06% |
| LPN7 | 50% Revenues, $LPN_{Max}$ Capex and Opex, with grant | 17 years | -577.538.952,42 € | 2,65% |
| LPN8 | 50% Revenues, $LPN_{Max}$ Capex and Opex, without grant | 17 years | -826.434.952,78 € | 1,03 |

- Complementary to the conclusion of the SPN scenario, it is clear that for the LPN scenario, a project subsidy of at least 40% is required.

# Chapter 6. Conclusions

The implementation of CCUS hubs in Greece represents a first-class opportunity to achieve net zero targets for the hard to abbate industries, while strengthening industrial sustainability and economic development. This study by focusing in one typical hub location in Attica, evaluates a scenario for capturing up to 5 MTPA through the establishment of a CCUS infrastructure with two options – a Short Pipeline Network (SPN) and a Long Pipeline Network (LPN) – each offering a unique balance of cost, scale, and regional applicability. By addressing the technical and economic parameters involved, this analysis demonstrates the potential of employing CCUS technology in mitigating $CO_2$ industrial emissions.

## 6.1. CCUS Hub Design

The proposed CCUS hub concept relies on a decentralised cluster-based approach, serving as the cornerstone for enabling industrial decarbonisation across Greece.

- Hub Development and Industry Clusters

The study adopts a hub cluster model, where each CCUS hub is designed to serve groups of industries located in specific geographical regions. For example, the Attica-based hub would initially target key emitters such as refineries, cement plants, and power facilities, optimising infrastructure efficiency and lowering per-tonne transportation costs through economies of scale.

- Ship Transportation for Liquefied $CO_2$

Recognising Greece's lack of immediate onshore storage options for $CO_2$, the study proposes ship-based transportation to carry liquefied $CO_2$ from temporary storage facilities, to be located next to the liquefaction plant in Elefsis, to designated geological storage sites. The geological storage is primarily proposed at Prinos, a depleted hydrocarbon reservoir, but elsewhere in the country or overseas storage options remain a viable option given current infrastructure limitations.

- Flexible and Decentralised System

The decentralised design of CCUS hubs allows Greece to adapt to regional industrial emission profiles while addressing site-specific challenges. This flexibility ensures long-term scalability of CCUS infrastructure and integration with emerging technological advancements.

## 6.2. Economic Feasibility and Financing Requirements

The crux of the present study concerns the economic viability and financial segments involved in the development and operation of CCUS hubs in different locations in Greece.

Without the full understanding of the economics involved in setting up and operating CCUS hubs it is pointless to propose their adoption and development.

Hence, this study sought to examine the economics through a cost benefit type approach (as explained in Chapter 4) for one such typical hub, namely the one to be located in Attica.

In short, the economic analysis reveals that while CCUS hubs offer significant benefits, their feasibility is strongly dependent on subsidies and external funding. The economic feasibility and financial requirements can be summarised as follows:

- Capital Expenditures (CAPEX) and Operational Costs (OPEX)

The cost of the CCS capturing plant (to be borne by the emitters concerned) is expected to have a CAPEX ranging from €150-200 million, while the OPEX falls between €70-75 million. For the pipeline, two scenarios are considered. In SPN, where the pipeline spans 32 km, the CAPEX is estimated at €247 million, with an associated OPEX of €5 million. LPN, covering a more extensive distance of 174 km, increases the CAPEX to €388 million and the OPEX to €8 million. These variations underscore the impact of distance on transportation costs.

As far as the liquefaction plant of 5 MTPA which includes compression, treatment unit and cooling, CAPEX is ranging from €250-300 million, reflecting the complexity and scale of the infrastructure. Its OPEX varies significantly from €57-84 million, depending on operational factors, including energy cost for liquefaction, heat cost, annual maintenance costs and labour costs.

The temporary storage facility, designed to hold 55,000 $m^3$, has a CAPEX of €93 million, and an OPEX of €3 million and finally, the cargo handling component, required for transferring the liquefied $CO_2$, has a CAPEX of €20 million and an OPEX of €0.6 million.

In short, the proposed CCUS hub in Attica, excluding the costs for the CCS capturing plant, has a total CAPEX which ranges between €610-801 million and an OPEX ranging between €66-96 million.

In addition, transportation cost to the permanent storage facilities site is estimated $15-25/tonne $CO_2$ and OPEX at the permanent geological site is estimated $25/tonne $CO_2$.

This breakdown highlights the financial implications of developing a CCUS system, emphasising both the upfront investment and the ongoing costs required for its operation and sustainability.

- <u>Financial Model</u>

The study highlights that while NPV and IRR (calculated with a desired return on equity=12%) are highly positive under 100% revenue (calculated on the basis of emission allowances prices) assumptions and EU-funded grants, CCUS implementation is currently not feasible without substantial "grant-type" funding. Regarding the SPN scenario (pipeline spans 32 km), the investment is marginal in the case where revenues are shared 50% with industries and further sensitivity analysis is needed to determine a realistic percentage of revenues. In addition to this, it is clear that for the LPN scenario (pipeline spans 174 km), a project subsidy of at least 40% is required.

- EU Funding for Ongoing Projects

In Greece five CCUS projects (Prinos, IFESTOS, IRIS, OLYMPUS, Apollo CO2) are currently in progress. Four of them (Prinos, IFESTOS, IRIS, OLYMPUS), are funded by EU facilities while the Apollo CO2 has applied to Connecting Europe Facility (CEF) for funding. This underscores the crucial role of public-sector financing and European initiatives in supporting CCUS infrastructure development at this early stage. Expanding access to such facilities will be essential for enabling broader adoption and project viability.

## 6.3. Challenges and Future Recommendations

While the findings confirm the technical and financial feasibility of CCUS hubs in Greece, under certain conditions, several key challenges must be addressed in order to realise their full potential:

- Preliminary results suggest that significant grant-type funding is required to overcome high CAPEX and initial operational costs. Continued access to EU funding mechanisms and innovative financing solutions will be vital to bridge the economic viability gap.
- While Prinos offers a local geological storage solution, future infrastructure plans should include assessments for alternative domestic storage sites and potential overseas partnerships to ensure long-term storage capacity and flexibility.
- The ship-based transportation method must be scaled up, with incentives to promote investments in new $CO_2$ carrier fleets, ensuring reliable and cost-effective transport logistics.

## 6.4. End Remarks

This study comes to reinforce IENE's originally proposed roadmap (October 2023) for the implementation of CCUS hubs in Greece, reaffirming their importance and economic viability in decarbonising energy-intensive industries, supporting climate targets, and driving economic recovery. The hub-cluster model, serving regional groups of emitters, coupled with decentralised systems and ship-based $CO_2$ transportation, presents a flexible, scalable, and practical solution for $CO_2$ management in Greece.

The preliminary cost-benefit results demonstrate clear environmental and economic benefits but highlight the need for grant-based funding to enable project feasibility. Without such subsidies, widespread CCUS implementation remains economically challenging.

Moving forward, Greece has a unique opportunity to leverage its existing industrial infrastructure and EU-funded initiatives to establish itself as a leader in CCUS technology in Southeastern Europe. By addressing funding and technical challenges, Greece can unlock the full potential of CCUS hubs, driving meaningful progress toward a low-carbon, sustainable future.

# Chapter 7. Study Contributors

**Mr. Costis Stambolis,** Chairman and Executive Director, IENE

Mr. Costis Stambolis who is the Executive Director of IENE, has a background in Physics and Architecture having studied at the University of London, the North East London Polytechnic (NELP) and the Architectural Association in London from where he holds a Graduate Diploma in Architecture and Energy Studies (AA Dip. Grad). He also holds a professional practice license from the Technical Chamber of Greece (TEE), and a Masters Degree from the Said Business School, University of Oxford, where he studied "Strategy and Innovation".

Costis has carried out numerous studies and projects on Renewable Energy Sources in developing countries. He has consulted widely on solar building applications for both private and institutional clients in various European countries. He has worked as a consultant and strategy advisor on natural gas, oil markets and energy security issues for large multinational companies, international organizations and governments.

Costis has lectured widely on energy issues and has organised several national, regional and international conferences, seminars and workshops. He has published several books, conference proceedings, research papers and studies on energy policy, solar energy, RES and energy markets. Among pthers he is the editor of the "S.E. Europe Energy Outlook (2011,2017, 2022)", which considered a basic reference on energy for SE Europe.

Since 2001 he supervises and edits daily Greece's foremost energy sitewww.energia.gr. He is a founding member of the Institute of Energy for South East Europe (IENE), which he currently chairs. He is a member of the Energy Institute (UK), the International Passive House Association (IPHA), The Technical Chamber of Greece (TEE). Since 2018 he also serves as a full member of the Greek government's standing committee on Energy and Climate Change (NECP).

**Mr. Kostis Oikonomopoulos,** Petroleum Geoscientist – Research Fellow, IENE

Before joining IENE as a Research Fellow in September 2023, Kostis Oikonomopoulos spent over six years at HEREMA SA, Greece, where he served as the primary seismic interpreter and petroleum geoscientist, specialising in prospectivity analyses and regional understanding. In this capacity, he also coordinated two important oil and gas Lease Agreements ("West of Crete" and "Southwest of Crete"), offering technical subsurface expertise on licensing matters, stewardship and monitoring of licence work programmes and activities. Also, he assisted in compiling and reviewing contracts regarding seismic acquisition and processing projects and at the same time supervised and managed HEREMA's data repositoty as well as its digitization and restructuring.

Prior to his tenure at HEREMA SA, Kostis worked as a Business Development geoscientist in the UK, for Spectrum Geo Ltd (now TGS) from 2012. In this role, he managed, initiated, and evaluated seismic acquisition and processing projects while liaising and engaging in negotiations with government authorities and National Oil Companies in the Mediterranean Sea, Black Sea and sub-Saharan Africa.

Kostis holds a Bachelor's degree in Geology from the University of Athens and pursued further education with two Master's degrees—one in hydrocarbons management from the University of Aberdeen and another in petroleum geoscience from the Royal Holloway, University of London. His career began in 2007 as a Petroleum Geologist with Hellenic Petroleum SA (HelleniQ), where he was involved in hydrocarbon exploration work (geological and geophysical) in Egypt.

**Dr. Nikolaos Koukouzas,** Director of Research, Dr. Geologist, Centre for Research and Technology-Hellas (CERTH)

Dr Koukouzas holds a PhD in Industrial Mineralogy from the UK and has over 30 years of experience in industrial geology, energy technologies, geomechanics, applied petrology and $CO_2$ geological storage. Since 2003, he is the Director of Research at the Centre for Research & Technology Hellas / Chemical Process and Energy Resources Institute (CERTH/CPERI) and Scientific Responsible at over 55 EU research projects, with a team of more than 40 scientists. Previously, he held positions as Policy Officer, Detached National Expert in the European Commission, Direction General for Energy (DG ENER) (2020-2022), Coordinator of EU experts and Gulf countries experts on Carbon Capture and Storage for the EU-Gulf Countries Clean Energy Network (2010-2013) and, Scientific Officer, Detached National Expert in the European Commission, Direction General for Energy and Transport (1999-2003). Furthermore, Dr Koukouzas has served as a member of the Board of Directors of the Greek Institute for Geology and Mineral Exploration (IGME) and a Consultant to energy, construction and cement industries.

He has over 250 publications in Scientific Journals, 3,300 citations and is a member of various Editorial Boards in International Magazines and University Boards. Dr Koukouzas has extensively participated in the RFCS Programme over the last 20 years.

**Dr. Myrsini Gazela,** Business Development Engineer, Asprofos Engineering S.A.

Dr. Myrsini Gazela is a seasoned Business Development Engineer with over 20 years of experience in the energy sector, specializing in oil, gas, and renewable energy markets. She holds a PhD in Electrical & Computer Engineering from Aristotle University of Thessaloniki and an MSc in Environmental Studies from the National & Kapodistrian University of Athens. Currently leading business development initiatives at Asprofos S.A., Dr. Gazela excels in proposal management, market analysis, and strategic partnerships. Her extensive project portfolio includes key roles in energy infrastructure projects, feasibility studies, and regulatory consulting for major clients such as the Hellenic Navy, DEPA S.A., and the Electricity Authority of Cyprus. A member of the Technical Chamber of Greece and the International Solar Energy Society, she combines technical expertise, innovative problem-solving, and effective communication to drive impactful energy solutions.

**Dr. Konstantina Tsalapati,** Business Development Engineer, Asprofos Engineering S.A.

Dr. Konstantina Tsalapati is an accomplished environmental scientist and business development engineer with expertise spanning over a decade in environmental consulting, project management, research, and education. She holds a PhD in Public Understanding of Environmental Science, focusing on media influence on public behavior, and has excelled in roles involving Environmental and Social Impact Assessments, stakeholder engagement, and sustainability projects within the energy sector. With advanced skills in GIS, and project management, Dr. Tsalapati has contributed to critical projects, including the EastMed Pipeline and national environmental permits, while also mentoring and teaching at esteemed institutions such as Harokopio University and University of the Aegean. She is a dynamic professional with a proven ability to bridge academic insight and practical solutions in environmental and energy-related domains.

**Mr. Dimitrios Bakogiannis,** Chemical Engineer, Head of Cost Estimating Department, Asprofos Engineering S.A.

Dimitrios Bakogiannis is a highly experienced chemical engineer with over 30 years of expertise in cost estimation and project management within the oil, gas, refinery, and natural gas sectors. As the Head of the Cost Estimating Department at Asprofos Engineering, he has been instrumental in preparing investment cost evaluations for large-scale infrastructure projects across Greece and internationally, including compressor stations, LNG facilities, and refinery upgrades. Dimitrios holds a Master's in Organic Chemical Technology and is adept in project services, cost control, and net present value estimation. His leadership has driven the successful delivery of major projects for clients such as DESFA, Hellenic Petroleum, and international entities like CEYPETCO and Equinox Advisory.

**Mr. Nikos Daras,** Survey Engineer, Head of Survey Department, Asprofos Engineering S.A.

Nikos Daras is a highly skilled Survey Engineer with over 12 years of experience in land surveying, 3D laser scanning, and civil engineering. He holds an MSc in Rural & Surveying Engineering from the National Technical University of Athens and an MSc in Environmental Design from the Hellenic Open University. Currently serving as the Survey Department Head at Asprofos Engineering S.A., Nikos leads multidisciplinary teams, oversees complex infrastructure projects, and develops innovative survey methodologies. His expertise spans land surveys, deformation analysis, pipeline and cable route studies, and GIS-based spatial analysis. Fluent in English and proficient with industry-standard tools like AutoCAD, Civil 3D, ArcGIS, and Faro SCENE, Nikos combines technical proficiency with strategic leadership. A member of the Technical Chamber of Greece, he has contributed to high-impact projects such as the EastMed pipeline and HELPE refinery upgrades, showcasing his commitment to precision and excellence in engineering.

**Mr. Konstantinos Koutsogiannis,** Business Development Director, Asprofos Engineering S.A.

Konstantinos Koutsogiannis is a dynamic Business Development Director with over 15 years of expertise in the energy, oil, gas, and maritime sectors. Holding an Executive MBA from the International Hellenic University and an MEng in Mechanical Engineering from Aristotle University of Thessaloniki, he specializes in project management, strategic planning, and contract management. Konstantinos has played a pivotal role in expanding operations in Southeast Europe and the Middle East, driving growth and innovation at Asprofos Engineering S.A. He has led significant projects, including offshore wind farm business plans and hydrogen development initiatives, while cultivating strong client relationships and fostering team collaboration. A member of the Technical Chamber of Greece and the Project Management Institute, Konstantinos combines technical acumen and leadership skills to deliver sustainable and impactful solutions across industries

**Mr. Theodore Terzopoulos,** Chemical Engineer (MSc), Gas Engineer (CEng), MBA, Energy & Renewable Gases Consultant

With a distinguished career spanning over 35 years in the gas distribution sector, Theodore Terzopoulos has held several prominent leadership positions, including General Manager of the Gas Distribution Department at DEPA SA, and General Manager of Strategy and Renewable Gases at DEDA SA and ENAON SA. His extensive expertise and forward-thinking approach have made him a pioneer in advancing the energy landscape in Greece.

Throughout his career, Theodore Terzopoulos has been at the forefront of introducing and implementing innovative gas distribution technologies in Greece. Notable achievements include the adoption of high-density polyethylene pipes, 4-bar distribution pressure technology, tree-shaped grid designs, and underground boring techniques—technological advancements that have significantly modernized the nation's gas distribution infrastructure.

A trailblazer in organizational transformation, Theodore Terzopoulos played a critical role in the privatization of gas distribution companies, the unbundling of distribution from gas trading activities, and the development of Greece's regulatory and legislative frameworks for gas distribution. Additionally, he was instrumental in establishing the biomethane market in the country, paving the way for a more sustainable energy future.

As CEO of EDA SA and DEDA SA for four years, Theodore Terzopoulos led significant milestones, including the expansion of gas distribution networks into new regions, the deployment of LNG technology for onshore supply, and the nationwide rollout of Greece's first smart gas meters. Under his leadership, DEDA SA also adopted cloud hosting technology, enhancing operational efficiency and driving digital transformation.

## APPENDIX

## Summary Table of the CCUS Hub Components

## Summary table of the components of a CCUS Hub

| Component | Detailed Description | Size (length, capacity etc.) | Estimated CAPEX | Estimated OPEX / year | Other comments |
|---|---|---|---|---|---|
| $CO_2$ Capturing System | Recommended technologies are first and second-generation oxyfuel and post-combustion cryogenic capture technologies. Typically, the process of these technologies comprises a primary carbon capture system, followed by a pre-treatment phase that includes both a compressor and a dehydration unit. | The size and capacity of both oxyfuel combustion and post-combustion cryogenic $CO_2$ capture technologies depend on the specific plant design, fuel used and the scale of the installation. Capacity: 1 MTPA | 150-200 million € | 70-75 million € | This CAPEX is an estimation of a typical CCS with a capacity 1 MTPA and a nominal operational cycle 45.000kW. For the OPEX estimation, key operational parameters were considered, including a heat demand of 2 GJ per ton of $CO_2$ captured, a heat cost of 32 euros per GJ (according to average market price[1]), annual O&M costs of 3% of CAPEX, and labor costs ranging from 2 to 5 million euros per year. |
| Pipelines | | | | | |
| Pipeline 1 | A backbone pipeline connecting $CO_2$ emitters to the transmission system and liquefaction plant. | Recommended pipeline size: 16’’<br>Scenario I Length: approximately 20 km<br>Scenario II length: approximately 106 km | | | |
| Pipeline 2 | Branch of power-plant Protergia | Recommended size 6’’<br>Length: approximately 30 km | | | |
| Pipeline 3 | Branch of power-plant Elpedison | Recommended size 6’’<br>Length: approximately 33,5 km | | | |

[1] Average Market Price estimated through ADMIE (October 2023-2024): https://www.admie.gr/agora/statistika-agoras/kyrioi-deiktes-dashboard/mesostathmiki-timi-agoras

| | | | | | |
|---|---|---|---|---|---|
| Pipeline 4 | Branch of power-plant Heron II | Recommended size 4’’<br>Length: 0,5 km | | | |
| Pipeline 5 | Branch of cement plant TITAN | Recommended size 8’’<br>Length: 0,5 km | | | |
| Pipeline 6 | Branch of refinery Elefsis | Recommended size 8’’<br>Length: 1 km | | | |
| Pipeline 7 | Branch of refinery Aspropyrgos | Recommended size 8’’<br>Length: 10 km | | | |
| Pipeline Network Scenario I | Material: carbon steel | 32 Km | 247 million € | 5 million € | The cost of the piping network includes the pipelines and peripheral facilities, civil and mechanical work, as well as project management, detailed design, procurement services and construction supervision. The cost of expropriation is not included. Additionally, OPEX was estimated with annual O&M costs set at 2% of CAPEX. |
| Pipeline Network Scenario II | Material: carbon steel | 174 km | 388 million € | 8 million € | ’’ |
| Liquefaction Plant | This plant is designed to comprise pipeline terminals for receiving captured $CO_2$ from emitters, a compression station to maintain pipeline pressure as needed, a treatment unit, a liquefaction facility followed by buffer storage tanks. | Capacity: 5 MTPA | 250-300 million € | 57-84 million € | The CAPEX and OPEX for a liquefaction facility of 5 MTPA capacity which includes compression, treatment unit and cooling – liquefaction unit.<br>For the OPEX estimation, key operational parameters were considered, including energy cost for liquefaction 90-120 kWh per ton of $CO_2$, a heat cost of 115 euros per MWh (according to average market price[2]), annual maintenance costs of |

[2] Average Market Price estimated through ADMIE (October 2023-2024): https://www.admie.gr/agora/statistika-agoras/kyrioi-deiktes-dashboard/mesostathmiki-timi-agoras

| | | | | | |
|---|---|---|---|---|---|
| | | | | | 2-4% of CAPEX annually, and labor costs ranging from 2 to 5 million euros per year |
| Temporary Storage Facilities | A temporary storage facility is required to store liquefied $CO_2$ in insulated tanks maintained at low temperature and pressure prior to its transportation to the geological storage site. | Recommended capacity: 55.000 $m^3$. Proposed facility consists of 10 spherical tanks of 5.500 $m^3$ each. | 93 million € | 3 million € | It was estimated that a vessel would require 3,75 days to complete a full transport cycle. Given the liquefaction capacity is 5 MTPA, it was also assumed that its inlet flow would be 13.000 tons of $CO_2$ per day. As a result, adequate storage capacity is considered necessary to accommodate the $CO_2$ produced during this period, amounting to approximately 50.000 tons or 60.000 $m^3$. Furthermore, it was assumed that the $CO_2$ entering the storage facility would be at low pressure and temperature, resulting in a higher density and therefore requiring less volume. Based on these considerations, it was concluded that a storage facility with a capacity of approximately 55.000 $m^3$ would be necessary. |
| Transportation to Permanent Storage Facilities | To transport 5 MTPA at a permanent storage facility, a cycle of three vessels, each with a capacity of 20.000 tons. | Vessel capacity: 20.000 tons | xxx | | |
| Cargo Handling System (jetty, loading facilities etc.) | Ship loading facility | | 20 million € | 0,6 million € | |
| Geological Storage Site | | | | | |
| TOTAL | | | | | |