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POSTGRADUATE DISSERTATION

STRATEGIC ANALYSIS AND ECONOMIC VALIABILITY OF CARBON
CAPTURE AND STORAGE SYSTEMS (CCS) IN GREECE: THE PRINOS CASE STUDY

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Abstract

Research Overview, Methodology, and Strategic Conclusions

This thesis is being written at a time of fundamental change for the global energy and industrial system. The climate crisis, as documented by the reports of the Intergovernmental Panel on Climate Change (IPCC,2023), requires an immediate and drastic reduction in greenhouse gas emissions. The European Union, through the Green Deal and the European Climate Law, has set a legally binding target of climate neutrality (Net Zero) by 2050.

However, the path to Net Zero is neither linear nor uniform for all sectors of the economy. While the power generation sector is achieving rapid decarbonisation through the penetration of Renewable Energy Sources (RES), heavy industry faces an existential impasse. Sectors such as cement production, oil refining, steelmaking, and fertilizer production are characterized as "Hard-to-Abate Sectors.". In these industries, carbon dioxide (CO₂) emissions do not only come from the combustion of fossil fuels for energy, but are inherent in the chemical production process (process emissions). A typical example is cement production, where the conversion of limestone into clinker inevitably releases CO₂, which cannot be eliminated even if the plant operates on 100% green energy (IEA, 2021).

The subject of the study is the CCS supply chain, in this context, Carbon Capture and Storage (CCS) technology emerges as the only viable solution for maintaining industrial production in Europe. The subject of this thesis is not limited to a technical description of carbon capture. Instead, it focuses on the study of CCS as an integrated supply chain system (Global CCS Institute,2022).

Research interest focuses on the design, sustainability, and strategic management of CO₂ flow from source to sink. This chain includes three distinct nodes (IPCC, 2005):

- Capture & Conditioning: Separating CO₂ at the source and converting it into liquid form.
- Transport: Moving the cargo via pipelines or ships.
- Storage: Permanent geological storage.

In particular, the study examines the case of Greece and the "Prinos CCS" project, which is being developed by Energean in the depleted oil field of Prinos, in Kavala. The choice of this particular topic was dictated by the strategic importance of the project, as it is the first attempt to create a storage hub in the Eastern Mediterranean, with the potential to serve not only domestic industry but also neighboring countries (Energean, 2023).

Although the literature on CCS is extensive at a technical level (mechanical), there is a lack of research approaching the subject from the perspective of logistics and strategy, particularly for the Mediterranean region. This paper fills that gap by answering some key questions (European commission, 2023):

- What's the best transport model (pipeline vs. shipping) for Greece's fragmented geography?
- Is the development of the chain economically viable under the current prices of the European Emissions Trading System (EU ETS)?
- What are the social and environmental risks and how can they be turned into opportunities in the context of a Just Transition?

The complexity of the problem, which spans technical, economic, and social fields, necessitated the adoption of a holistic research strategy. This dissertation does not limit itself to a one-dimensional technical description but adopts the philosophy of Pragmatism. This choice allows us to focus on practical results and combine different analytical tools to solve the central problem: the sustainability of CCS in Greece (Saunders et al., 2019).

The main research strategy chosen was a case study of the "Prinos CCS" project. This method was considered the most appropriate because it allows the phenomenon to be examined in its real-life context. Data collection was carried out through a systematic review of secondary sources (Secondary Data Review), drawing on technical reports from the European Commission, feasibility studies by Energean, and international literature in databases such as ScienceDirect and Google Scholar.

Data analysis was performed using the triangulation method, combining three analytical tools:

- Techno-economic Assessment (TEA): To calculate the life cycle cost and compare it with the prices on the emissions trading market.
- SWOT Strategic Analysis: To assess the opportunities and threats in the macro environment.
- Qualitative Social Analysis: To assess social acceptance and employment prospects.

The research initially confirmed that Greece possesses a rare geological advantage. The technology for storage in depleted hydrocarbon deposits (Depleted Oil & Gas Fields) is assessed at the highest level of technological readiness (TRL 9). The Prinos reservoir, consisting of sandstones and covered by impermeable layers of evaporites (salt), offers guaranteed impermeability. Unlike saline aquifers, where uncertainty is high, Prinos has 40 years of historical performance data, minimizing the risk of CO₂ leakage (Saunders et al., 2019).

However, the most critical technical finding concerns the design of the supply chain. The geographical peculiarities of Greece (insularity, mountainous terrain, seismicity) make the development of an extensive network of land pipelines technically difficult and economically unviable. The research identified the "Hub and Spoke" model using maritime transport as the optimal solution. In this model (Al Baroudi et al., 2021):

- Spokes are emission sources (e.g., Titan Cement, ELPE Refineries) where CO₂ is captured and liquefied.

- The "Hub" is the floating or fixed facility in Prinos.
- The connection is made via a "Virtual Pipeline" consisting of a fleet of liquefied CO₂ carriers (LCO₂ Carriers).

The analysis also highlighted the technical challenges of this model. Liquefying CO₂ is an energy-intensive process. To make the gas liquid and transportable, it must be cooled (to -26°C for medium pressure or -50°C for low pressure) and compressed. It has been calculated that this process consumes approximately 90 to 120 kWh of electricity per ton, creating a significant "energy penalty." This finding leads to the conclusion that the sustainability of the system depends entirely on the availability of cheap, green energy. If liquefaction is carried out using energy from lignite or natural gas, the environmental benefits of the project are dramatically reduced (AI Baroudi et al., 2021).

About the Break Even Point and the necessity of the Economies of scales. The economic assessment was at the core of the research, as the success of CCS is ultimately judged in the marketplace. Through Levelized Cost of Storage (LCOS) analysis, the study determined the total cost of the chain (Capture + Transport + Storage) to be in the range of €65 to €120 per ton of CO₂ (Global CCS institute, 2021).

The large discrepancy in costs can be explained by two factors (ZEP 2011):

- The source of CO₂: Industries with high CO₂ concentrations in their exhaust gases (such as ammonia or hydrogen production) have low capture costs (~€40/t). In contrast, power plants or cement plants have higher costs (~€80/t).
- Economies of Scale: The analysis showed that shipping costs decrease exponentially as volume increases. In the pilot phase (1 Mtpa), costs are high. At full scale (3+ Mtpa), the use of larger ships reduces marginal costs.

Comparing these figures with the price of emission allowances in the European Union Emissions Trading System (EU ETS), which ranges between €80 and €90 per ton, leads to the conclusion that the project is marginally viable. There is a clear "viability gap" in the early stages of implementation. The market alone cannot cover the high initial risk (CAPEX) of ships and infrastructure. Therefore, the study concludes that hybrid financing tools are needed. Carbon Contracts for Difference (CCfDs) emerged as the most critical support mechanism, as they guarantee investors a stable price, covering the difference when the ETS price is low (European Commission 2023).

Last but not least this research took into account the Environmental, Social Findings, and Strategy. The environmental analysis, based on the Life Cycle Assessment (LCA) methodology, confirmed that CCS is a necessary tool, but not a panacea without conditions. The system's Net Reduction Efficiency was calculated at 80-85% rather than 100% due to emissions produced by the transport ships and compression units themselves (Cuellar-Franca & Azapagic, 2015). In addition, the risks to the sensitive ecosystem of the North Aegean Sea were examined. The possibility of CO₂ leakage from the subsea pipeline or injection point, although small, could cause local acidification of the water, affecting marine life. The

research highlighted the need to install advanced monitoring systems (MMV), such as acoustic sensors and bubble detectors, the cost of which must be included in the project budget. With regard to induced seismicity, it was found that the use of a depleted field such as Prinos is safer than the use of aquifers, as the pressure in the reservoir is currently low and the injection of CO₂ will simply restore it gradually to its original, natural levels.(Verdon et al., 2013)

In the field of social analysis, the thesis addresses the fear of the "Social License to Operate." While the risk of the NIMBY ("Not In My Backyard") phenomenon is real, the offshore location of Prinos acts as a protective shield, eliminating the visual disturbance that often causes reactions to onshore projects (Ashworth et al., 2012).

The most important social finding, however, is positive and concerns employment. CCS is emerging as the pillar of Just Transition for Greece. In an era of decarbonization, the project offers a double benefit:

- **Job Security:** It allows energy-intensive industries (cement, refineries) to continue operating under a Net Zero regime, saving thousands of jobs that would otherwise be lost due to relocation (carbon leakage).
- **Creating New Jobs:** The development of the Hub creates demand for specialized personnel (engineers, geologists, sailors). The research highlights the potential for reskilling the oil industry's workforce, transforming hydrocarbon expertise into carbon management expertise.

Furthermore, this opens up a huge opportunity for Greek shipyards, which can undertake the construction and maintenance of the LCO₂ fleet(SINTEF, 2018).

The synthesis of all the above findings through strategic SWOT analysis leads to the final conclusion of the thesis: Greece must aggressively pursue the role of Regional Storage Hub. The surplus capacity of Prinos (100Mt) more than covers national needs (Energean, 2023). This creates an opportunity to provide storage services to neighboring countries that lack suitable geology (Bulgaria) or face saturation (Italy). Greek merchant shipping, which controls most of the global gas fleet, can realize this vision by creating a "maritime carbon corridor" in the Mediterranean (UGS, 2023).

The success of this venture will have multiple benefits: it will strengthen the competitiveness of Greek industry, create a new source of revenue from CO₂ import and storage, and upgrade the country's geopolitical role in Europe's energy map. This paper aims to serve as a roadmap for understanding and implementing this national goal.

CHAPTER 1: Literature Review - EU Energy Policy and Institutional Framework

1.1 Transitioning from Energy Security to Climate Neutrality

The European Union's (EU) energy policy has come a long way, transitioning from a model that focused primarily on security of supply and market liberalization to a holistic strategic framework with the primary goal of decarbonization and sustainability. The literature shows that this shift is not merely an environmental choice, but a fundamental restructuring of the European economy, which directly affects the oil and gas sector. Companies in the sector are now called upon to evolve from fossil fuel producers to carbon management entities, utilizing Carbon Capture, Utilization, and Storage (CCUS) technologies. Understanding the complex web of European directives and regulations is essential for assessing the sustainability of CCS projects and their supply chain (European Commission, 2019).

1.2 The European Green Deal as a Strategic Pillar

In December 2019, the European Commission presented the European Green Deal, a new development strategy that aims to transform the EU into a fair and prosperous society with a modern, competitive, and resource-efficient economy (European Commission, 2019). The central ambition of the Green Deal is to make Europe the first climate-neutral continent in the world by 2050.

Unlike previous policy initiatives, the Green Deal integrates climate policy into all areas of EU action: energy, industry, transport, agriculture, and finance. For the energy sector, the strategy envisages decoupling economic growth from resource use. In this context, CCS is recognized as an essential technology, especially for energy-intensive industrial sectors (e.g., cement, steel) where electrification options are limited or technically unfeasible (hard-to-abate sectors). The literature emphasizes that the Green Deal creates the political basis for the development of CO₂ transport and storage infrastructure, as without it, the 2050 target becomes practically unattainable (IEA, 2020).

1.3 European Climate Law

The political commitment of the Green Deal has been transformed into a legal obligation with the adoption of Regulation (EU) 2021/1119, known as the European Climate Law. This law establishes a binding target for achieving climate neutrality by 2050 and sets an interim target of reducing net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels (Regulation (EU) 2021/1119).

The importance of the Climate Law for the CCS supply chain is critical. By enshrining the targets in law, it creates an environment of investment certainty. Investors in infrastructure projects, such as CO₂ pipelines or liquefaction terminals, get the message that reducing emissions is a one-way street and not a temporary policy choice. In addition, the law

provides for the establishment of a carbon budget and progress monitoring, which puts pressure on member states, including Greece, to speed up licensing procedures for emission reduction projects such as "Prinos CCS" (EU, 2019).

1.4 Fit for 55 Package

To achieve the 55% reduction target by 2030, the EU presented the "Fit for 55" legislative package in 2021. This is a set of proposals to revise and update EU legislation and introduce new initiatives. An analysis of the "Fit for 55" package reveals direct implications for the oil and gas supply chain (European Commission, 2019):

- **Revision of the Renewable Energy Directive (Renewable Energy Directive III):** It increases the targets for renewable energy sources (RES), pushing fossil fuels out of the energy mix for electricity generation and shifting the focus of Oil & Gas to the production of blue hydrogen, which requires CCS.
- **Regulation on the deployment of alternative fuels infrastructure (Alternative Fuels Infrastructure Regulation) AFIR:** This directly affects logistics, as it promotes the use of clean fuels in transport.
- **FuelEU Maritime Initiative:** Particularly critical for CO₂ transport by ship. This regulation sets limits on the carbon intensity of the energy used by ships. This affects the design of CO₂ carriers, which will need to be energy efficient or use alternative fuels (LNG, methanol, ammonia) to be sustainable within the supply chain.

1.5 European Union Emissions Trading System as an Economic Lever (EU ETS)

The cornerstone of European policy on reducing emissions is the Emissions Trading System (EU ETS). Operating on the principle of "cap and trade," the ETS sets a maximum level (Cap) on the total amount of certain greenhouse gases that installations covered by the system can emit. Within this cap, companies receive or purchase emission allowances, which they can trade among themselves (Directive 2003/87/EC).

The revision of the ETS under "Fit for 55" (Phase 4 of the ETS, 2021-2030) has dramatically changed the economics of CCS:

- **Increase in the price of carbon:** Lowering the emissions cap at a faster rate leads to an increase in the European Union Allowance price (EUA price). When the price of an emission allowance exceeds the cost of capturing, transporting, and storing one ton of CO₂ (Levelized Cost of CCS), then the CCS project becomes economically viable. Recent analyses show that prices above €80-90/ton make many CCS projects attractive (S&P Global, 2023).
- **Reduction of Free Allowances:** The phasing out of free allowances for industry increases operating costs for polluters, forcing them to seek permanent CO₂ storage solutions instead of paying fines/allowances.

- **Innovation Fund:** The ETS finances the Innovation Fund, which is one of the largest funding programs worldwide for demonstrating innovative low-carbon technologies. Many CCS projects in Europe (e.g., Kairos@C, Porthos) have received significant funding from this mechanism, reducing the investment risk (CAPEX) for the oil & gas companies and logistics companies involved (European Commission, 2019).

1.6 Carbon Border Adjustment Mechanism (CBAM)

Complementary to the ETS is the Carbon Border Adjustment Mechanism (CBAM). This mechanism imposes carbon prices on imports of certain products (cement, iron, steel, aluminum, fertilizers, electricity, and hydrogen) from non-EU countries to avoid the risk of "carbon leakage". For the CCS supply chain, CBAM is crucial because it protects the competitiveness of European industries that choose to invest in CCS. Without CBAM, a Greek cement company that pays for CO₂ transport and storage in Prinos would be at a disadvantage compared to a cement company in a third country (e.g., Turkey) that does not have carbon costs. CBAM levels the playing field, making the cost of the CCS supply chain more acceptable to industrial users (European Commission, 2019).

1.7 The Geological Storage Directive (Directive 2009/31/EC)

While the ETS provides the economic incentive, the legal framework governing technical safety and licensing of the CCS value chain is set out in Directive 2009/31/EC (CCS Directive). This directive is of fundamental importance to the supply chain, as it defines the conditions under which captured CO₂ is considered "stored" rather than "emitted," thereby exempting the polluter from the obligation to surrender ETS allowances (European Parliament, 2009).

For the Oil & Gas sector, the Directive sets strict standards for CO₂ stream composition. The gas entering the transmission network (pipeline or ship) must consist of "overwhelmingly" of carbon dioxide, without impurities that could damage the integrity of the transmission infrastructure or storage facility. This creates technical requirements for liquefaction and purification facilities at the source (capture plants), which are the first node in the supply chain. In addition, the Directive regulates the crucial issue of liability. During operation and for a period after closure of the storage site, the operator is liable for any leaks. Only when the long-term stability of the reservoir has been proven (usually after 20 years) is liability transferred to the state. This provision significantly affects the insurance costs and risks assumed by companies such as Energean in Prinos.

1.8 Net-Zero Industry Act (NZIA): The Obligation of Oil Companies

The most recent and perhaps most influential legislative intervention for the CCS supply chain is the Net-Zero Industry Act (NZIA), which was proposed in 2023. The NZIA recognizes CCS as a "Strategic Net-Zero Technology" and sets an ambitious target for the EU: to achieve an annual injection and storage capacity of 50 million tons of CO₂ by 2030 (European Commission, 2023).

Article 10 of the NZIA introduces a revolutionary regulation that directly concerns the subject of this thesis: the obligation of oil and natural gas producers to contribute. Holders of hydrocarbon production licenses in the EU are required to contribute to the development of CO₂ storage capacity in proportion to their share of oil and gas production (IOGP, 2023). This regulation transforms CCS from an optional business activity into a regulatory obligation (license to operate) for the Oil & Gas sector. For Greece, this means that the development of the storage site in Prinos is not just a commercial opportunity for Energean, but part of a broader framework of compliance with European regulations (European Commission, 2023).

1.9 The Trans-European Network for Energy Regulation (TEN-E)

The CCS supply chain depends on the creation of a transport network connecting industrial emission sources with geological storage sites. Regulation (EU) 2022/869 on Trans-European Energy Networks (TEN-E Regulation) was recently revised to include CO₂ transport infrastructure among priority projects.

This revision is crucial for maritime CO₂ transport. While the regulation initially covered only pipelines, the new version recognizes that for many areas of Europe (such as Greece and the Mediterranean basin), pipeline transport is technically difficult or economically unviable. Thus, projects involving transport by ship and/or train, as well as the necessary port facilities for liquefaction and temporary storage (buffer storage), can now be included in the Projects of Common Interest (PCI) (European Parliament, 2022). (European Parliament, 2022). The inclusion of the "Prinos CO₂ Storage" project in the 6th list of PCIs (November 2023) ensures (European Commission, 2023):

- Fast-track permitting.
- Access to funding from the Connecting Europe Facility (CEF).
- Policy support for the creation of cross-border value chains (e.g., CO₂ transport from Italy or Bulgaria to Prinos).

That is a fact that will lower the cost and the risk of these projects.

1.10 Transboundary Movement and the London Protocol

A major legal barrier to the international CCS supply chain was Article 6 of the London Protocol, which prohibited the export of waste (including CO₂) for disposal at sea. However, in 2009, an amendment was adopted allowing the export of CO₂ for storage purposes, and in 2019, its provisional application was permitted by states that so desired (IMO, 2019). For Greece to function as a storage hub for the wider Mediterranean region, it is necessary to conclude dual agreements with those countries where the CO₂ originates, based on the London Protocol. This is a crucial step in the legal shaping of the supply chain, as without these agreements, CO₂ transport ships cannot legally cross borders carrying their cargo (International Maritime Organization, 2019).

1.11 The National Framework: The Role of Hellenic Hydrocarbons and Energy Resources Management Company (HEREMA) and the Work of Prinos

At the national level, Greece has harmonized the CCS Directive and has enacted its own Climate Law (Law 4936/2022). The Hellenic Hydrocarbon and Energy Resources Management Company (HEREMA) plays a central role in the value chain. HEREMA has been designated as the competent authority for issuing CO₂ exploration and storage permits.

During the summer of 2022, HEREMA granted the first exploration license for CO₂ storage to Energean for the Prinos area (HEREMA, 2022). This framework is crucial for the supply chain because it sets out the technical specifications for CO₂ reception. Energean is developing the project with a design that includes the construction of onshore infrastructure near Kavala city for the reception of CO₂ from ships (shipping terminal), temporary storage, and re-gasification before injection into the reservoir of Prinos via a pipeline. The success of the project depends on the creation of a clear regulatory framework for tariffs for the use of the network and storage space, which is currently being developed by the Regulatory Authority for Energy, Waste and Water (RAE). (Energean, 2023)

1.12 Conclusion Of This Chapter

An analysis of the institutional and regulatory framework shows that the European Union has created a complex but comprehensive environment for the development of the CCS supply chain. The transition from voluntary action to mandatory compliance (through ETS and NZIA) and financial support for transport infrastructure (through TEN-E and the Innovation Fund) provide the necessary guarantees for investment. In the case of Greece, the combination of the favorable European framework with the unique geological characteristics of Prinos and the country's strategic position in shipping creates a unique opportunity to promote the country as a regional carbon management hub. However, implementation requires the synchronization of regulatory steps (bilateral agreements, transport regulatory framework) with technical investments in the value chain.

CHAPTER 2: Theoretical Background and Technological Analysis of the CCS Value Chain

2.1 Introduction: The CCS Value Chain as a Logistics System

Humanity in the 21st century faces a dual challenge: meeting the ever-increasing demand for energy, which is essential for economic growth and social prosperity, while at the same time drastically reducing greenhouse gas (GHG) emissions. According to the Special Report of the Intergovernmental Panel on Climate Change (IPCC), carbon dioxide (CO₂) concentrations in the atmosphere have reached record levels, leading to an increase in global average temperatures. Human activity has already increased the average global temperature to rise by approximately one 1oC compared to pre-industrial levels. To achieve the Paris Agreement goal of limiting global warming to below 2oC (with an ideal target of 1,5oC) compared to pre-industrial levels, requires a complete transformation of the global energy system towards a net zero emissions model by 2050 (IPCC,2022).

Despite the rapid growth of renewable energy sources (RES) such as solar and wind energy, fossil fuels (oil, natural gas, coal) still cover about 80% of global energy needs. Their complete and immediate replacement is not technically and economically feasible in the short term, due to the intermittency of RES and the need for stability in electricity grids (base load). In this context, Carbon Capture and Storage (CCS) technology is emerging as a critical pillar of the energy transition. CCS allows the continued use of fossil fuel infrastructure for the period required until the transition is complete, "decoupling" energy production from harmful emissions (IEA, 2023).

The term CCS describes a chain of technological processes aimed at preventing the release of large quantities of CO₂ into the atmosphere from industrial and energy sources. This process involves three distinct stages: (a) capturing CO₂ at its source (e.g., power plants, refineries, cement plants), (b) compressing and transporting it via pipelines or ships, and (c) injecting and permanently storing it in deep geological formations, such as depleted hydrocarbon reservoirs or saline aquifers. The fundamental difference between CCS and other emission reduction strategies is that it allows critical industrial infrastructure to continue operating during the energy transition, while neutralizing its environmental footprint (Global CCS Institute, 2020).

The necessity of CCS becomes absolute when we consider heavy industry. Sectors such as cement, steel, and chemical production are responsible for a significant proportion of global emissions. In these cases, emissions are not only "energy-related" (i.e., from burning fuel for heat), but also "process-related" (process emissions). A typical example is the cement industry: when limestone (CaCO₃) is converted to lime (CaO) carbon dioxide is released chemically, regardless of the fuel used in the kiln. Therefore, even if a cement plant operated on 100% renewable energy, it would still emit huge amounts of CO₂ due to the chemical reaction. For these "hard-to-abate sectors," CCS is the only way to decarbonize (EU Commission, 2018).

Beyond environmental necessity, the development of CCS is now also driven by strong economic incentives, particularly within the European Union. The EU Emissions Trading System (EU ETS) requires industries to pay for every ton of CO₂ they emit. As the price of emission allowances rises (often exceeding €80-90 per ton), the cost of pollution becomes prohibitive for businesses. Investing in CCS technologies is shifting from an environmental obligation to an economic necessity for sustainability. By storing CO₂, industries are exempt from the cost of purchasing allowances, making these projects economically attractive in the long term. The European Green Deal and the Net Zero Industry Act now set specific targets for creating CO₂ storage capacity within the EU of 50 million tons per year by 2030 (EU Commission, 2023).

On the European CCS map, Greece occupies a strategic position through the "Prinos Storage" project developed by Energean. The Prinos basin in Kavala, which is home to the only oil production in the country's history, is being transformed into a storage hub. The geological suitability of the depleted Prinos reservoirs has been certified by independent bodies, as the rocks that have held oil and natural gas under high pressure for millions of years guarantee the safe and permanent trapping of CO₂. This project, which is part of the EU's Projects of Common Interest (PCI), aims to serve not only Greek industry but also neighbouring Mediterranean countries, creating a new industrial value chain in the region and positioning Greece as a leader in the green transition in Southeast Europe (Energean, 2023).

In conclusion, CCS is not merely a technological possibility, but a necessary prerequisite for maintaining the sustainability of the planet and the economy. This paper will examine in detail the capture technologies, the transport process, and the geological storage mechanisms, focusing on their specific characteristics and prospects for application in Greece.

2.2 Capture Technologies

The first stage of the supply chain is capture. The choice of capture technology determines the quality characteristics of the CO₂ stream (pressure, temperature, impurities), which in turn dictate the requirements for transport and storage design. The literature distinguishes three main capture methodologies (Leung et al., 2014).

One of those three capture methods is the **Post-Combustion Capture**. Post-combustion capture is the most technologically mature method and dominates existing applications. It involves removing CO₂ from the exhaust gases produced after the combustion of fossil fuels or biomass in the air. The most common technique is based on chemical absorption using amine solvents, such as monoethanolamine (MEA). The process involves two main columns (Rochelle, 2019):

- Absorber tower: the emissions are cooled and come in contact with the solvent, which selectively capture the CO₂.
- Stripper tower: The rich in quantity solvent is heated (usually from 120 – 140 Celsius degrees to release the pure CO₂ and recycle the solvent.

The significance for the Supply Chain: The CO₂ produced is highly pure (>99%), but it is at atmospheric pressure and saturated with water vapor. This means higher energy

requirements in the next stage of compression/liquefaction compared to other methods (Wang et al., 2017).

Then a second method is the **Pre-Combustion Capture**. This method is directly linked to the oil and gas industry and hydrogen production. The primary fuel (natural gas or coal) is first converted through gasification or reforming into synthesis gas (syngas), a mixture of carbon monoxide (CO) and hydrogen (H₂). Through the water-gas shift reaction, CO is converted into CO₂ and additional H₂. CO₂ is separated before hydrogen combustion. This technology is the basis for the production of "Blue Hydrogen." For Energean and other companies in the industry, this offers a double benefit: production of clean fuel (H₂) for the market and CO₂ capture. Logistics advantage: CO₂ is produced at a higher partial pressure, which reduces the compression work required for transport (Jansen et al., 2015).

Also, there is the method **Oxy-fuel Combustion**. In oxy-fuel technology, combustion is carried out using almost pure oxygen (>95%) instead of air. Because nitrogen is absent, the exhaust gases consist mainly of CO₂ and water vapor. Simply condensing the water vapor (cooling) produces a stream of highly concentrated CO₂. However, this stream often contains residual oxygen (O₂), which is extremely corrosive to transport pipelines and requires additional purification steps ("polishing unit") before entering the logistics network (Stanger et al., 2015).

2.3 Stream Conditioning

After the capture stage, the CO₂ stream is rarely ready for direct injection into the transmission network. A series of purification and conditioning processes are required to ensure the integrity of the supply chain infrastructure and operational safety (Peletiri et al., 2018).

The most important stage of processing is dehydration. CO₂ from combustion processes is saturated with water vapor. If the water is not removed, two serious risks arise for the logistics network (Metz et al., 2005):

- **Corrosion:** CO₂ reacts with free water to form carbonic acid (H₂CO₃), which is extremely corrosive to carbon steel, the main material used in the construction of pipelines and ship tanks. Without strict dehydration usually <50 part per million (PPM) water, the use of extremely expensive stainless-steel alloys would be required, driving up the cost (CAPEX) of the supply chain.
- **Hydrate Formation:** At high pressures and low temperatures, water and CO₂ form solid crystals (clathrate hydrates). These hydrates can clog valves, nozzles, and pipelines, causing flow interruptions and serious operational accidents.

In addition, depending on the source, other impurities such as **Sulfur Oxides** (SO_x) **Nitrogen Oxides** (NO_x), **Hydrogen Sulfide** (H₂S), may need to be removed, as these affect the phase diagram of CO₂, changing the pressure at which the gas liquefies (De Visser et al., 2008).

2.4 Compression and Liquefaction Strategies

To design the transport system, it is necessary to understand the phase diagram of pure CO₂. Carbon dioxide has specific characteristics that determine the transport methods (Zhang et al., 2006):

- Critical Point: Located at 31.1°C and 73.8 bar. Above these conditions, CO₂ enters a "supercritical" state.
- Triple Point: Located at -56.6°C and 5.2 bar. Below this pressure, liquid CO₂ cannot exist; the gas is converted directly into a solid (dry ice).

These properties dictate two distinct transport strategies in the supply chain: dense phase transport via pipelines and liquid phase transport via ships. In conclusion, at critical point the pipelines are the best way to transport the CO₂ to the storage location, on the other hand the triple point at -56.6 degrees and 5.2 bars dramatically reducing the size of the CO₂ and the transportation cost as a result is lower, so in this case ship transportation is has the advantage.

For transporting massive quantities of CO₂ through pipelines, the best practice is to keep the fluid in a supercritical or dense phase. This is achieved by compressing the gas to pressures above 80 bar (usually 85-150 bar). In this state, CO₂ combines the advantages of both phases (Zhang et al., 2006):

- It has a high density (similar to that of liquid), allowing large masses to be transported in smaller diameter pipelines.
- It has low viscosity (similar to that of a gas), minimizing pressure losses due to friction along the pipeline .

Operation in dense phase requires careful design so that the pressure never falls below the critical threshold during transport, in order to avoid two-phase flow (gas + liquid), which causes vibrations and damage to the pipeline.

In the case of Greece and the Prinos CCS project, which involves maritime transport, compression technology is not sufficient. Liquefaction is required, as transporting gas by ship is economically unviable due to the enormous volume. The liquefaction of CO₂ differs from that of natural gas (LNG). Because its triple point is at -56.6°C, CO₂ cannot be liquefied at atmospheric pressure (unlike LNG, which liquefies at -160°C at 1 atm). Therefore, CO₂ ships are pressure vessels. The literature (Al Baroudi et al., 2021; DNV, 2022) distinguishes three categories of liquefaction conditions:

- High Pressure (HP): ~45 bar at +10°C (ambient). Used in small truck tanks, but considered uneconomical for large ships due to the weight of the tank walls.
- Medium Pressure (MP): ~15-20 bar at -26°C. This is the industry standard for existing small CO₂ transport vessels (used in the food industry).
- Low Pressure (LP): ~7 bar at -50°C. This technology is now being developed for large CCS projects (such as Northern Lights and possibly Prinos). It

allows the use of larger tanks and reduces steel costs but requires more complex cooling and boil-off gas management systems.

The choice between MP and LP is currently the subject of intense techno-economic analysis, as it affects the entire design of the supply chain (ports, storage tanks, ship type).

2.5 Pipeline and Shipping Transportation.

Pipeline transport is the most mature and widespread method of CO₂ transport worldwide, mainly due to extensive experience in the US oil industry. In the context of a CCS supply chain, pipelines act as the "fixed infrastructure" connecting large emission hubs with storage sites.

From a technical point of view, CO₂ transport pipelines operate almost exclusively in supercritical or dense phase (pressure > 80 bar). This is chosen because the high density of the fluid allows large amounts of mass flow rate to be transported through smaller diameter pipes, reducing material costs (CAPEX). However, maintaining this pressure requires careful design to avoid pressure dropping below the critical point, which would lead to two-phase flow (gas/liquid) and possible system instability (cavitation/vibration) (Peletiri et al., 2018).

The literature distinguishes between two categories:

- Onshore pipelines: These have a lower construction cost per kilometer, but face significant obstacles in terms of licensing and social acceptance (the NIMBY phenomenon - Not In My Backyard), as well as difficulties in passing through densely populated areas or mountainous terrain (case of mainland Greece) (Knoope et al., 2013).
- Offshore Pipelines: These are required for connection to offshore storage facilities (such as Prinos). They have significantly higher construction and maintenance costs due to the demanding conditions of the marine environment (external pressure, corrosion, difficulty of repair). (Knoope et al., 2013)

Transporting CO₂ by ship is emerging as the optimal logistics solution for Europe, and especially for the Mediterranean, due to the geographical dispersion of emission sources and the existence of island clusters. Unlike pipelines, shipping offers flexibility: a ship can serve multiple sources or change destination if a storage facility is taken out of service. The maritime transportation chain comprises three distinct stages (AI Baroudi et., 2021):

- Export Terminal: Includes the liquefaction unit and buffer storage tanks at the loading port. The capacity of the buffer tanks must be at least 1.5 times the capacity of the ship to ensure continuous operation of the industry even if the ship is delayed (Logistics Redundancy).
- The Transport Ship (LCO₂ Carrier): These are specialized gas tankers, similar to LPG/LNG carriers, but designed for the higher density of CO₂. As discussed in the previous section, the design is moving towards low pressure conditions (7 bar, -50°C)

to allow for the construction of large capacity ships (e.g. 20,000 - 50,000 m³), reducing transport costs per ton (Economies of Scale).cubic meters (m³)

- Offloading: In the case of Prinos, offloading can be done either on a fixed platform or via submerged turret loading (STL) systems directly into the injection pipeline, minimizing the need for permanent offshore structures.

The choice between pipeline and ship is primarily a matter of technical and economic optimization. The European Zero Emissions Platform (ZEP, 2011) and more recent studies (Geske et al., 2015) have determined the break-even points between the two means of transport:

- Pipelines: These are characterized by high initial investment costs (High CAPEX) but low operating costs (Low OPEX). They are more cost-effective for large volumes of CO₂ (>3-5 Mtpa) and short/medium distances. The cost increases linearly with distance.
- Ships: They have lower initial infrastructure costs (low CAPEX) but higher operating costs (high OPEX) due to fuel and crew. They are the optimal solution for smaller volumes or long distances.

For offshore transport, the break-even distance is estimated at approximately 1,000-1,500 kilometers. However, for smaller volumes (e.g. < 1 Mtpa, which is typical for individual Greek industries), ships become competitive even at much shorter distances (e.g. 500 km) due to the avoidance of the huge fixed costs of laying an underwater pipeline.

Taking the above into account, Greece's case is oriented towards the "Hub and Spoke" logistics model.

- Spokes: Scattered industrial areas (Thriasio, Boeotia, Corinth, but also ports in neighboring countries such as Italy). There, CO₂ is captured and liquefied.
- Transport: Small and medium-sized ships collect the cargo ("milk run" logistics).
- Hub: Prinos (Energean) acts as the central storage hub, where cargoes are gathered for permanent storage.

This model allows for economies of scale (sharing infrastructure), as many small industries share the cost of the same storage space and fleet of ships, making the project sustainable.(Koukouzas et al., 2021)

2.6 Geological Structure of Prinos Basin

The selection of the Prinos Basin in the North Aegean Sea as the first CO₂ storage project in Greece and the Eastern Mediterranean is not accidental. It is based on geological data collected over more than 40 years of hydrocarbon production.

The reservoir consists of highly permeable sandstones, which offer excellent fluid storage capacity. However, the most important factor for storage safety is the caprock. In Prinos, this consists of thick layers of evaporites (salt), which act as a perfect sealing material. Evaporites are plastic in behavior and impermeable to gases, as evidenced by the fact that they have

retained natural gas and oil under high pressure for millions of years. This geological profile drastically reduces geological uncertainty compared to aquifers, where the impermeability of the cap rock must be proven from scratch. (Energean, 2023).

In supply chain design, sink node capacity determines the viability of the entire network. According to Energean's studies and the exploration license granted by HEREMA:

- Phase 1 (Pilot/Initial): The goal is to store approximately 0.5 to 1 million tons of CO₂ per year (Mtpa). This phase will most likely serve local industries (e.g., fertilizers) and serve as proof of concept.
- Phase 2 (Full Development): Scaling up capacity to 2.5-3 Mtpa covering a significant portion of the country's industrial emissions.

Total Capacity: Prinos is estimated to be able to store a total of up to 100 million tons of CO₂ (Energean 2023)

This phased approach allows for the gradual development of logistics (increase in the number of ships and port facilities) as the market matures (market ramp-up).

2.7 The Last Mile: From Ship to Infusion

A critical technical issue concerning logistics that is often overlooked is the interface between the transport vessel and the injection well. CO₂ arrives by ship in liquid form and at a low temperature (e.g., -50°C or -26°C). However, the geological reservoir is located at a depth of 2-3 kilometers and has a high temperature (approximately 60°C - 90°C).

If cold CO₂ is injected directly into the hot rock, thermal shock will occur. The sudden contraction and expansion can cause cracks in the rock or cement of the well, compromising the safety of storage. Therefore, the supply chain at the Prinos terminal (whether onshore or on an FSO floating unit) must include regasification and heating units. The CO₂ must be heated and compressed to the appropriate pressure in order to enter the reservoir smoothly. This process requires significant amounts of energy, which must be taken into account in the operating costs (OPEX) of the storage hub (Ringrose, 2020).

Also, the value chain is not completed with the injection. Directive 2009/31/EC imposes a strict MMV (Measurement, Monitoring, and Verification) framework. In the case of Prinos, this means that permanent monitoring systems (seismographs, pressure sensors) must be installed to monitor:

- The spread of the CO₂ "plume" (plume migration) within the reservoir.
- The impermeability of the cap rock (for any micro-leaks).
- Induced seismicity due to increased pressure.

The existence of a reliable MMV plan is a prerequisite for the transfer of responsibility to the state after the end of operation and is an integral part of the operating license.

Chapter 3: The Potential of CCS in Greece: Strategic Importance and Applications

3.1 Introduction: The Necessity of CCS in the Greek Energy System

Greece is at a critical turning point in its energy transition. Having committed to the complete delignitization of its energy mix earlier than most EU member states, the country is now turning its attention to the next big challenge: the decarbonization of industrial sectors .

According to the revised National Energy and Climate Plan (NECP) for 2023, Greece aims to reduce greenhouse gas emissions by 55% by 2030 and achieve climate neutrality by 2050 (Ministry of Energy, 2023). However, analysis of the country's industrial profile reveals that a significant proportion of emissions come from so-called "hard-to-abate sectors" , such as cement production, oil refining, and metallurgy. For these industries, electrification or the use of renewable energy sources is not sufficient, as emissions are often "process emissions" and not just the result of combustion.

In this context, CCS is recognized by the Greek government and HEREMA as a one-way technology. Without the ability to store CO₂, Greek heavy industry risks losing competitiveness due to the rapid increase in the cost of emission allowances (EU ETS), which could lead to disinvestment or "carbon leakage."

3.2 Prinos as a National Storage Hub

The focus of Greece's CCS strategy is the depleted Prinos oil field in the Kavala offshore area. This project, managed by Energean, is the only mature storage solution in the Eastern Mediterranean and has been included in the EU's Projects of Common Interest (PCI Project) and the Recovery and Resilience Facility (RRF) with approved funding (European Commission, 2022).

An important comparative advantage of Prinos is the possibility of repurposing existing infrastructure. The existence of pumping platforms (e.g., Alpha, Beta platforms), subsea pipelines, and onshore processing facilities "Sigma" in Nea Karvali, drastically reduces the initial investment cost (CAPEX) and the environmental impact of constructing new facilities. The conversion of existing production wells into injection wells is a technical challenge that is being studied, with the most likely solution being the drilling of new, specially designed wells for well integrity reasons (Ringrose, 2020).

3.2.1 Mapping of Greek Emission Sources (Industrial Emitters)

In order to assess the potential of CCS, the demand side must be analyzed. Who needs Prinos? The industrial geography of Greece shows a strong concentration of resources (industrial clusters), which favors the creation of economies of scale.

Cement production is the largest "customer" of CCS in Greece. Approximately 60% of emissions in cement production come from the chemical reaction of calcination and not from combustion. Therefore, CCS is the only viable solution for decarbonizing the industry (IEA, 2018).

TITAN Group (Project IFESTOS): The Titan factory in Kamari, Biotia, is a flagship project. Through the IFESTOS program, which secured funding from the EU Innovation Fund, it is expected to capture 1.9 million tons of CO₂ annually. This project will make the plant one of the largest carbon capture projects in Europe. The captured CO₂ is expected to be transported to Prinos (TITAN, 2023).

HERACLES Group (Holcim - Project OLYMPUS): Similarly, the HERACLES Group plans to install a carbon capture unit at its factory in Milaki, Evia, with the aim of achieving a zero carbon footprint (Holcim, 2022).

Greece has one of the strongest refining sectors in the Mediterranean (Helleniq Energy, formerly ELPE, and Motor Oil Hellas). The refineries in Corinth, Elefsina, and Thessaloniki are major CO₂ producers, both from furnaces and hydrogen production units (SMR - Steam Methane Reformers). CCS offers Greek refineries the opportunity to transition to Blue Hydrogen production. By capturing CO₂ from SMR units, refineries can produce low-carbon fuels and prepare for the era of synthetic fuels (e-fuels), maintaining their sustainability in a world of reduced oil demand (Koukouzas et al., 2021).

Although PPC's lignite-fired units are being phased out, modern natural gas-fired units (CCGT) will remain in the system as base load and balancing units for several decades. The CCS project in Prinos opens up the prospect of applying carbon capture to new CCGT plants (such as that of PPC/DEPA in Alexandroupolis, Komotini or Mytilineos in Boeotia), making them compatible with Net Zero targets (low-carbon power generation) (Koukouzas et al., 2021).

3.2.2 The Mediterranean Hub Strategy: Cross-Border Value Chains

The capacity of the Prinos Basin (estimated at up to 100 Mt CO₂) more than covers the needs of domestic industry for the coming decades. This "surplus" storage space creates a unique commercial opportunity for the country: its conversion into a CO₂ import and storage hub (Carbon Storage Hub) for the wider region of Southeast Europe and the Mediterranean (Energean, 2023).

Energean has already entered into strategic agreements and Memoranda of Understanding (MoUs) with industrial groups from neighboring countries, forming a cross-border transport network that upgrades Greece's geopolitical role (EU Commission, 2023):

- Bulgaria has heavy industry but limited geological storage options. Transporting CO₂ by rail or pipeline to the ports of northern Greece (Thessaloniki, Kavala) and from there to Prinos is the most realistic carbon capture scenario for the neighboring country.
- Italy & Adriatic: Although Italy is developing its own project in Ravenna (Eni - Project Ravenna CCS), demand from industry in northern Italy is enormous and exceeds local capacity. Prinos can operate as a complementary or backup storage solution, enhancing the region's energy security.
- Eastern Mediterranean (Egypt, Croatia): There are active discussions on the maritime transport of liquefied CO₂ from the wider Mediterranean basin.

The implementation of this plan is legally based on the activation of bilateral state agreements under the London Protocol (2009 Amendment), which now allows the export of CO₂ for storage purposes, subject to strict environmental controls and transnational cooperation (IMO, 2019).

3.3 The Role of Greek Merchant Shipping and the "Virtual Pipeline"

One aspect that is often underestimated in international literature, but which is crucial in the Greek case, is the synergy with Greek merchant shipping. Due to Greece's island morphology and the great depths of the Aegean Sea, the construction of long submarine pipelines is often technically difficult and economically prohibitive (Koukouzas et al., 2021).

The solution lies in the creation of a "Virtual Pipeline" via sea. Greek shipowners, who control the largest share of the global fleet (>20%), are leaders in gas transportation (LNG/LPG). This expertise is directly transferable to the new, emerging market of LCO₂ Carriers (ships for transporting liquefied CO₂) (Union of Greek Shipowners, 2023).

The development of this sector offers Greece the opportunity for vertical integration of the service:

- The country does not only offer storage space (Prinos).
- It also offers logistics services (Transport Service Provider).

This model creates added value, as freight rates remain with Greek companies and new highly skilled jobs are created in shipyards, ports, and crews (DNV, 2022).

3.4 Economic Analysis: Costs, ETS, and Financing

The economic viability of CCS in Greece is determined not only by technology, but also by the cost-benefit ratio within the European carbon market .

The main economic incentive for Greek industries is the Emissions Trading System (EU ETS). With allowance prices (EUAs) remaining consistently high (between €80 and €100 per tonne in the period 2023-2024), the cost of inaction has become prohibitive (Ember, 2024).

As technology matures and economies of scale are achieved through hubs, the cost of CCS is falling, making it cheaper than paying emissions penalties (Global CCS Institute, 2022).

The development of Prinos as a hub allows for infrastructure sharing. Instead of each industry (Titan, Helleniq Energy, Motor Oil) to develop its own storage space—something that is geologically and economically impossible—they all share the operating costs of Prinos. This drastically reduces the marginal cost per ton of stored CO₂.

In addition, the geographical proximity of industries in areas such as Elefsina and Corinth allows for the creation of shared liquefaction facilities and port infrastructure, further reducing CAPEX (Koukouzas et al., 2021).

The European Union actively supports these projects to bridge the funding gap in the early stages of implementation through the three following economical support packages:

- EU Innovation Fund: Titan's "IFESTOS" project secured a €234 million grant, proving that Greek projects are competitive at the European level (Eu Commission, 2023).
- Connecting Europe Facility (CEF): The inclusion of "Prinos CO2" in the list of PCIs (Projects of Common Interest) paves the way for the financing of transport infrastructure (pipelines, ports) (Eu Commission, 2023).
- Recovery Fund (RRF): The Greek government has allocated funds for the development of CCS technology in the National Recovery Plan "Greece 2.0." (Hellenic Republic, 2021)

An analysis of Greece's potential shows that CCS is not a luxury, but a prerequisite for the survival of the country's heavy industry on the road to Net Zero. Greece has a rare combination of advantages: an ideal geological reservoir (Prinos), a strong industrial base that needs immediate decarbonization solutions, and a world-class shipping fleet that can carry out the transport work. The successful development of the Hub in Prinos will turn an environmental problem into a commercial activity, attracting investment and creating a new "Carbon Economy" ecosystem in the Southeast Mediterranean.

CHAPTER 4: RESHEARCH METHODOLOGY

4.1 The Research Framework

This chapter analyses the methodological approach adopted to investigate the sustainability and strategic importance of the CCS supply chain in Greece. The selection of the appropriate methodology is crucial to ensuring the validity and reliability of the research results. The structure of the chapter follows the "Research Onion" model as described by Saunders, Lewis, and Thornhill (2019). The process starts from the outer layer of the research philosophy and moves inward toward the selection of the strategy (Case Study), the data collection method, and finally, the analysis techniques (SWOT & Cost-Benefit Analysis).

The philosophical basis of this thesis is rooted in Pragmatism. According to this approach, the most important element of research is the research question and the practical application of the results. Given that the subject of study (the CCS supply chain in Prinos) is a real, existing, and complex technical-economic problem, pragmatism allows the researcher to focus on "what works" and combine different analytical perspectives (strategic and economic) to provide solutions (Creswell, 2014).

In terms of research approach, the Abductive Approach is adopted. The study begins with the observation of an empirical phenomenon (the development of Prinos CCS) and moves towards theory, using existing theoretical frameworks (Logistics Management, Environmental Economics) to explain and evaluate the phenomenon (Kovacs & Spens, 2005).

To achieve the objectives of the thesis, the Case Study strategy was chosen. According to Yin (2018), case studies are the most appropriate strategy when:

- The research questions are of the "how" and "why" type (e.g., "How can the CCS supply chain be developed sustainably in Greece?").
- The researcher has little or no control over the events (unlike in an experiment).
- The phenomenon is studied within its real-life context.

Specifically, this paper follows the design of the "Single Case Study with Embedded Units."

- The Case: Greece's National CCS System.
- Units of Analysis:
 - o Energean's Prinos CCS project (Technical core).
 - o The regulatory framework of the EU and Greece (Institutional environment).
 - o The economic cost-benefit analysis (Economic dimension).

The choice of case study allows for an in-depth understanding of the complex interactions between technology, politics, and economics, something that a simple statistical survey could not achieve (Yin, 2018).

The nature of the research is mainly qualitative, enriched with quantitative data from secondary analysis. Qualitative research was chosen because CCS in Greece is still in its infancy. There are no historical data sets available to run complex statistical models. Instead, we are called upon to interpret strategic intentions, legislative texts, and technical feasibility studies. However, to answer the cost questions (Cost Benefit Analysis), the methodology incorporates quantitative data analysis tools, using cost estimates from the international literature and adapting them to Greek data (Cresweel & Plano Clark, 2018).

The research is based exclusively on secondary data. The use of secondary sources is acceptable and widespread in academic strategic analysis research, as it allows access to high-quality data collected by large organizations (Saunders et al., 2019).

Data sources are categorized as follows:

- Institutional & Legal Documents
 - o EU Directives and Regulations (EUR-Lex) on ETS, the CCS Directive, and the Net-Zero Industry Act.
 - o National legislation (Government Gazette) and reports by the Hellenic Regulatory Authority for Energy (HEREMA).
- Corporate Reports:
 - o Annual Sustainability Reports by Energean, TITAN Group, and Helleniq Energy.
 - o Investor Presentations containing technical details about Prinos CCS.
- Academic & Industry Literature:
 - o Publications from databases such as ScienceDirect and Google Scholar on capture and transport technologies.
 - o Technical Reports from international organizations such as the Global CCS Institute, the IEA (International Energy Agency), and the ZEP (Zero Emissions Platform).

The collection process followed the Systematic Literature Review method, using keywords such as "CCS Supply Chain," "CO2 Shipping Cost," "Prinos Storage," and "Mediterranean CCS Hub" to identify the most recent and relevant data (2018-2024).

4.2 Data Analysis Techniques and Validity

After collecting secondary data, this thesis adopts a triangulation approach for their analysis. Strategic analysis tools (SWOT) are combined with economic evaluation tools (Cost-Benefit Analysis) to produce a holistic conclusion on the sustainability of the project.

SWOT Analysis

To answer the research questions concerning Greece's strategic positioning on the CCS map, the SWOT (Strengths, Weaknesses, Opportunities, Threats) method was chosen. According to the literature on Strategic Management (Helms & Nixon, 2010), SWOT analysis is not simply a classification of characteristics, but a tool for "Strategic Fit." Its goal is to match the internal capabilities of the system (Internal Factors) with the external environment (External Factors).

In the context of this case study, the application of the tool is specified as follows:

- **Internal Environment (Strengths/Weaknesses):** The resources and capabilities of the Greek system are analysed. This section examines the geological characteristics of Prinos, Energean's expertise, the state of infrastructure, and the readiness of the Greek commercial fleet.
- **External Environment (Opportunities/Threats):** The macro-environment (PESTLE context) is analyzed. This section examines European legislation (ETS, NZIA), geopolitical developments in the Mediterranean, technological trends in shipping, and social acceptance.

The combination of these factors will enable the formulation of strategic proposals for exploiting opportunities and minimizing risks.

Cost Benefit Analysis (CBA)

Given that CCS is a capital-intensive investment, the strategic analysis must be supported by economic data. The methodology incorporates elements of Techno-economic Assessment, which focuses on determining the Levelized Cost for each link in the supply chain. The approach is based on the guidelines of the European Zero Emissions Platform (ZEP, 2011) and the Global CCS Institute. The key indicators to be analyzed (through a literature review) are:

- **CAPEX (Capital Expenditure):** The cost of constructing capture facilities, LCO₂ ships, and injection infrastructure.
- **OPEX (Operating Expenses):** Energy, ship fuel, maintenance, and monitoring costs (MMV).
- **LCOS (Levelized Cost of Storage):** The average storage cost per ton of CO₂ over the lifetime of the project.

In that case the benefit analysis is defined as the avoidance cost. That is the economic benefit result from not paying the emission allowances (EUA prices) under the EU ETS. The study will compare the total cost of the chain (Capture + Transport + Storage) with the projected price of carbon to determine the break-even point of the investment.

In order for a thesis to be considered scientifically sound, it must meet the criteria of Validity and Reliability (Yin, 2018).

- **Construct Validity:** Ensured through the use of multiple sources of information (Data Triangulation). For example, the capacity data for Prinos reported by the

company (Energean) is cross-checked with independent reports by HEREMA and studies by the European Commission (PCI lists) in order to avoid bias.

- **External Validity:** This concerns the possibility of generalizing the results. Although this is a case study, the conclusions for the shipping-based CCS model can be generalized analytically to other Mediterranean countries with similar geographical characteristics (e.g., Italy, Spain).
- **Reliability:** This is ensured through detailed recording of sources and the data collection process (Audit Trail), so that another researcher can follow the same steps and reach similar conclusions.

However, it is important to mention that there are some limitations in the existing research. Firstly, is the data availability. As the project it is in design phase and not in operation phase, the financial data are based on estimates and not in historical data or economical reports from the company.

Also, the confidentiality of certain technical details of contracts or geology details me be covered by commercial confidentiality that is limiting the accuracy of cost analysis (Rubin et al., 2015).

Finally, is the Dynamic Environment. The regulatory framework and energy prices are changing rapidly, making the analysis a "snapshot in time." Especially in our days that the energy market facing extraordinarily strong pressure that come from the restrictions against Russian Energy (Eu Commission, 2023).

CHAPTER 5 INTERGRATED COST BENEFIT ANALYSIS

5.1 Introduction and Methodological Framework for Analysis

This section attempts a holistic assessment of the CCS project in Prinos and the wider supply chain in Greece. Unlike traditional financial approaches that focus exclusively on profitability, this analysis adopts the framework of Societal Cost-Benefit Analysis (SCBA). In accordance with the European Commission's guidelines for major infrastructure projects, this method quantifies and integrates four distinct dimensions: Technology, Economy, Environment, and Society (Eu Commission, 2023).

The aim is to answer the central question: "Do the long-term benefits of decarbonisation and technological upgrading outweigh the high initial costs and environmental/social risks?"(Eu Commission, 2023)

The technological dimension of cost-benefit analysis focuses on technology readiness level (TRL), system integration complexity, and energy operating costs. One of the most important technological advantages (Pros) of the Prinos project is the high level of technological readiness (Eu Commission, 2023).

- **Storage Maturity:** Gas injection technology in depleted reservoirs has been fully tested. Energean has decades of experience in managing the Prinos reservoir, while the availability of geological data drastically reduces the exploration risk that usually burdens aquifer projects.
- **Repurposing Potential:** The ability to repurpose existing infrastructure, such as production platforms and Sigma onshore facilities, is a significant technological advantage. It reduces lead time and minimizes the need for new, complex constructions in virgin environments (Greenfield projects) (Koukoulas et al., 2021).

On the other hand, the most significant technological cost (Con) is the so-called "Energy Penalty." The operation of the CCS chain requires significant amounts of energy, which reduce the overall efficiency of the industrial system (Rubin et al., 2015).

- **Capture stage:** The chemical absorption process (amine scrubbing) consumes heat and electricity. It is estimated that applying CCS to a power plant can reduce its efficiency by 8-12 percentage points. This "parasitic load" increases the consumption of primary fuel for the production of the same end product (IPCC, 2005).
- **Liquefaction Stage:** Liquefying CO₂ for transport by ship is an energy-intensive process. Cooling to -26°C (Medium Pressure) or -50°C (Low Pressure) requires powerful compressors and refrigeration cycles. Bibliographic references estimate that liquefaction consumes approximately 90-120 kWh per ton of CO₂ (Al Baroudi et al., 2021).

The choice of maritime transport, although offering flexibility, introduces technological challenges that act as a "cost" to the system:

- **Boil-off Gas (BOG):** During transport, part of the liquefied CO₂ evaporates due to heat influx from the environment. Unlike LNG, where BOG can be used as fuel for the ship, CO₂ does not burn. Therefore, ships must have advanced re-liquefaction units on board, increasing technological complexity and maintenance costs (Al Baroudi et., 2021).
- **Ship-Storage Interface:** The technology for heating CO₂ prior to injection (to avoid thermal shock) requires the installation of large heat exchangers on the Prinos platform. Managing this thermal process in an offshore environment is technically demanding and increases the likelihood of operational downtime (Cuéllar-Franca & Azapagic, 2015) .

In conclusion, the technological analysis shows that the project is feasible and poses low geological risk. However, dependence on energy-intensive processes (capture/liquefaction) necessitates continuous optimization of energy efficiency. If the energy used for CCS comes from fossil fuels, then the net benefit is reduced. Therefore, a technological prerequisite for a positive assessment is the coupling of CCS with Renewable Energy Sources (e.g., use of wind energy to operate compressors in Prinos).

5.2 Financial Analysis and Investment Evaluation

The financial sustainability of the project is examined using the Levelized Cost method. This method allows all costs (investment and operating) to be converted to a single price per ton of CO₂, enabling comparison with the price of carbon on the emissions trading market (EU ETS).

The analysis is divided into the three main links in the value chain: Capture, Transport, and Storage.

Capital Expenditures (CAPEX) represent the initial construction and installation costs. According to the European Technology Platform ZEP (Zero Emissions Platform, 2011) and recent studies (IEA, 2021), the distribution of CAPEX in the value chain is uneven:

- **Capture:** This is the most expensive part, accounting for approximately 60-70% of total CAPEX. The cost relates to the installation of absorption towers, solvent regeneration units, and compressors in industrial facilities (e.g., cement plants). For a typical 1 Mtpa unit, the cost can range from €300 to €500 million, depending on the concentration of CO₂ in the flue gas.
- **Transport (Shipping):** CAPEX here refers to the purchase of LCO₂ ships and the construction of port facilities for liquefaction and temporary storage (buffer storage). The shipping option has lower initial CAPEX compared to the construction of a long submarine pipeline (e.g., from Attica to Prinos) but requires gradual investment as the fleet expands.
- **Storage (Prinos):** This includes the drilling of new injection wells, the retrofitting of platforms, and the installation of monitoring systems (MMV). In the case of Prinos, CAPEX is significantly reduced due to the existing infrastructure, however Energean estimates the initial cost of Phase 1 at approximately €90-100 million (Energean Investor Presentation, 2022).

Operational Expenditures (OPEX) are critical to long-term sustainability, especially in times of energy crisis.

- **Energy:** The main component of OPEX is the cost of electricity and heat for the operation of the capture and liquefaction units. An increase in the kilowatt-hour price (MWh price) has a linear effect on operating costs (Rubin et al., 2015).
- **Marine fuels:** Unlike pipelines, which have minimal OPEX, ships have high variable costs due to bunker fuels. The transition to "green" marine fuels (e.g., methanol, ammonia) to reduce the transport footprint will further increase OPEX (ZEP, 2011).
- **T&S Fees:** The cost of access to the storage facility (Tariffs) that the polluter will pay to Energean to cover the operating and maintenance costs of the field.

- **Levelized Cost of Energy.** The decisive factor for the Final Investment Decision (FID) is the comparison of the total cost per ton with the price of the emission allowance.

Based on international literature (Global CCS Institute, 2022) and adjusted data for Greece:

- Capture cost: ~€40-80/ton (depending on the source).
- Transportation Cost (Ship): ~15-25 €/ton (for distances within the Mediterranean).
- Storage Cost: ~€10-15/ton.
- Total Chain Cost: €65-120/ton.

Comparison with ETS: With the EU ETS price ranging between €80-100/ton (2023/24), CCS projects become marginally viable or profitable ("in the money"), especially for industries with high CO₂ concentrations (e.g., chemicals, refineries) where capture costs are lower. In other cases, state aid or Carbon Contracts for Difference (CCfDs) are needed to cover the "viability gap."

At this point it is important to consider about the **Sensitivity Analysis**. Given the uncertainty of the parameters, the sensitivity analysis examines how the net present value (NPV) of the project changes in three scenarios:

- Scenario A: Fall in Emissions Price (Low ETS Price): If the ETS price falls below €60/ton (due to political decisions or economic recession), the project becomes unprofitable without subsidies. This highlights the greatest financial risk: Regulatory Risk (IEA, 2021).
- Scenario B: High Energy Cost: A 50% increase in electricity costs could increase Leveraged Cost of Storage (LCOS) by 20-30%, making the technology uncompetitive. This highlights the need for bilateral green energy supply contracts (PPAs) at fixed prices (Element Energy, 2018).
- Scenario C: Economies of scale (hub effect): If the volume of stored CO₂ increases from 1 Mtpa to 3 Mtpa, the cost of transport and storage per unit decreases dramatically (by up to 40%), rapidly improving profitability (ZEP, 2011).

In conclusion, the financial analysis shows that the Prinos CCS project is viable under current carbon market conditions but remains exposed to energy and emissions price volatility. Its profitability depends heavily on rapid scale-up to reduce unit costs and secure risk mitigation financing instruments.

5.3 Environmental Analysis and Project Life Cycle

The environmental assessment of the CCS supply chain is characterized by an inherent contradiction: while the global goal is positive (reducing climate change), the operation of the chain entails local environmental risks. The analysis is based on the Life

Cycle Assessment (LCA) methodology according to ISO 14040, examining the environmental footprint "from cradle to grave."

The most critical question in environmental analysis is: "How much CO₂ is emitted to store one ton of CO₂?" The process of capture, liquefaction, and transport is energy intensive. If the energy used comes from fossil fuels, the net benefit is dramatically reduced (Cuéllar-Franca & Azapagic, 2015) .

In the case of Greece, where transport is by ship (shipping), the logistics footprint is significant and characterized by Direct Emissions as the ships that are transport the CO₂ consuming naval fuels (VLSFO or Marine Diesel). Is astimated that for every 1000 kilo meters of transport a ship emits approximately 1-2% of the cargo it carries. Also, there are indirect Emissions for example the electricity that consumed from compressors in Prinos (IPCC, 2005) .

Last but not least, The literature shows that the net emission reduction of a complete CCS system ranges from 70 to 85% (and not 100%). The remaining 15 to 30% are "process emissions." To optimize this indicator, Greek CO₂ ships must in future run on alternative fuels (e.g., ammonia or methanol) and the facilities in Prinos must be powered by RES(Cuéllar-Franca & Azapagic, 2015).

About the environmental analysis it is important to consider that Prinos is located in a sensitive marine area of the North Aegean Sea, with significant fishing activity and tourism (Thasos, Kavala). The main environmental concern relates to the possibility of CO₂ leakage from the subsea pipeline or the injection point.

Although CO₂ is not toxic like oil, a sudden spill of large quantities into the sea causes local acidification. CO₂ dissolves in water to form carbonic acid, sharply reducing the pH. Impacts: Acidification can affect benthic organisms (organisms that live on the seabed) and shellfish, disrupting the local food chain. Mitigation Measures: The environmental study requires the installation of permanent pH sensors and acoustic bubble detection systems around the infrastructure so that any leaks can be detected immediately and the flow stopped(Blackford et al., 2014).

The injection of fluids into the subsoil under pressure can, in theory, activate existing faults and cause micro-earthquakes. Given that Greece is an earthquake-prone country, this issue is a central point of environmental licensing.

Here is the advantage of Prinos. Because Prinos is a depleted field, the reservoir pressure is currently very low (due to decades of oil pumping). CO₂ injection will essentially "restore" the pressure to its original levels, reducing the risk of fracturing compared to injection into a virgin aquifer that is already in pressure equilibrium. Micro-seismic Monitoring: A network of micro-seismic sensors must be installed to monitor rock stability on a 24-hour basis. (Verdon et al., 2013).

It is worth pointing out that installing the necessary safety systems involves a specific investment cost that adds to the total CAPEX of the project. According to technical studies by IEAGHG (2012) and adjustments for offshore fields:

- **Leak Detection Systems** (Sonar/Bubble detection): The installation of a comprehensive network of active acoustic sensors (Active Acoustic Monitoring) on the seabed around the injection point and wellheads is estimated at between €2 and €5 million per field. This cost includes transponders, subsea cabling, and signal processing software.
- **Micro-seismic Monitoring** (Micro-seismic Array): The development of a permanent seabed array or downhole sensors to monitor induced seismicity is more expensive. For a field the size of Prinos, 3-5 observation stations need to be installed. The installation and calibration costs range from €5 to €10 million, while the annual operating costs (OPEX) for data analysis by seismologists amount to approximately €300,000-500,000 per year.

Although these amounts seem high, they represent less than 5-7% of the total investment budget and are absolutely necessary to secure a "social license to operate" and minimize environmental risk (IEAGHG. (2012).

5.4 Social License to Operate

Social acceptance is the third and often most unpredictable component of cost-benefit analysis. In international literature, the term used is "Social License to Operate" (SLO). This is not a legal document, but rather the level of trust and legitimacy that the local community and stakeholders provide to the project (Ashworth et al., 2012).

The history of CCS in Europe has shown that the lack of SLO can lead to the cancellation of technically sound projects (a typical example is the Barendrecht project in the Netherlands, which was cancelled due to opposition). In the case of Prinos, the social analysis focuses on three axes: the Not In My BackYard (NIMBY) phenomenon, risk perception, and Just Transition (Ashworth et al., 2012).

An important social advantage (Social Pro) of the Prinos CCS project is its location. The strongest NIMBY (Not In My BackYard) social reactions are observed in onshore storage projects, where residents fear that they are living above a "gas bubble" (L'Orange Seigo et al., 2014).

On the contrary, Prinos is offshore tha are translated to the following feelings from the local society:

- **Visual Disturbance:** The facilities are not visible from the coast of Kavala or Thasos, as they are located deep in the sea.
- **Sense of Distance:** Psychological distance ("out of sight, out of mind") drastically reduces residents' anxiety (Tcvetkov et al., 2019).
- **Familiarity:** The local community of Kavala has coexisted with oil extraction and platforms for over 40 years. The transition from "oil extraction" to "CO2 storage" is perceived as a continuation of existing activity rather than a new, unknown threat (Koukouzas et al., 2021).

Despite familiarity, there is a latent social risk arising from a lack of technical understanding. Public opinion surveys (Eurobarometer) show that the general public often confuses CO₂ with other substances (L'Orange Seigo et al., 2014):

- **Confusion with Carbon Monoxide:** Many people believe that CO₂ is toxic or poisonous (like carbon monoxide - CO).
- **Fear of Explosion:** There is a misconception that CO₂ is flammable or explosive like natural gas.

This misunderstanding ("Information Gap") can be exploited by pressure groups. Therefore, the social cost of the project must include funds for information and consultation campaigns, explaining that CO₂ is an inert gas (used in soft drinks and fire extinguishers) and that storage is permanent (ZEP, 2021).

The strongest social argument in favor of the project (Major Social Benefit) is its contribution to the Just Transition. The shift away from coal and toward green energy threatens thousands of jobs in traditional industries. CCS acts as a "protective shield" for jobs.

Without CCS, industries such as cement and refineries would be forced to close or relocate outside the EU (delocalization) due to prohibitive emissions costs. CCS allows these plants to operate sustainably, saving thousands of industrial jobs. Also, during the development of the hub in Prinos it will be the requirement of new specialized personnel. The Construction Phase also requires specialized personnel in shipyards (for ship conversion), pipeline and facility construction and maintenance. Last but not least is the Operational phase that requires Engineers, Geologists, LCO₂ ship crew and safety technicians.

According to estimates by the Norwegian organisation SINTEF for similar projects, every €1 billion invested in CCS creates approximately 15,000 person-years of employment (direct and indirect). For the region of Kavala, which has been hit hard by deindustrialization (e.g., the phosphate fertilizer industry), the project is a vital boost (SINTEF, 2018) .

Beyond the quantitative dimension (number of jobs), a qualitative analysis of employment highlights two critical parameters for the national economy: skills transfer and the revitalization of the shipbuilding and repair zone. There are two opportunities that are necessary to mentioned according to (CCSA, 2021).:

- **Skills Transferability:** CCS is unique in that it requires almost the same skills as the hydrocarbon industry. Geologists, reservoir engineers, drilling technicians, and chemical engineers currently working in Prinos or refineries are not becoming obsolete. Instead, through reskilling and upskilling programs, they are transformed into green economy executives. This prevents the devaluation of human capital and limits the brain drain phenomenon, keeping highly skilled scientists in the country.
- **The Opportunity for Greek Shipyards:** The choice of ship transport creates a huge secondary labor market. The construction of new LCO₂ ships or the retrofitting of existing LPG ships, as well as the construction of floating storage units (FSOs), can be assigned to Greek shipyards (Elefsina, Syros, Skaramagas). According to studies

on the shipping value chain, for every 1 direct job in a shipyard, 3 to 4 indirect jobs are created in the supply chain of materials and services (Economic Multiplier Effect), boosting local income in areas with traditionally high unemployment.

To conclude, the social balance of the project is positive, mainly due to its offshore nature and the prospect of maintaining industrial employment. However, "social license" is not a given. It requires ongoing transparency on safety issues and proof that the benefits are spread throughout the local community (local content requirement), and not just the profits of multinationals.

5.5 SWOT ANALYSIS

The completion of the multi-criteria analysis (Tech-Econ-Enviro-Social) leads to the need for an overall strategic assessment. This section adopts the SWOT (Strengths, Weaknesses, Opportunities, Threats) framework, not as a static recording tool, but as a dynamic decision-making mechanism (Wehrich, 1982; Helms & Nixon, 2010).

The aim is to identify "Strategic Fits": How the unique advantages of Prinos and Greek Shipping can be leveraged in the favorable European context (Opportunities), while neutralizing economic risks (Weaknesses) and external threats (Threats).

The table below summarizes the findings of the survey, categorizing them into Internal (Internal Environment) and External (External Environment) factors.

Internal Environment	Strengths	Weaknesses
<p>Recourses, Abilities, Infrastructures</p>	<p>Geological Security: Empty deposit with proven caprock integrity.</p> <p>Existing Infrastructure: Alpha/Beta platforms and "Sigma" land unit (Reduced CAPEX/Time-to-market).</p> <p>Maritime Superiority: Leading force in gas logistics (LPG/LNG carriers).</p>	<p>Absence of Pipeline Network: Lack of land-based CO2 transport infrastructure due to geomorphology.</p> <p>Energy Costs: High dependence on expensive electricity for capture and liquefaction.</p> <p>Limited Phase 1 Capacity: 1 Mtpa is not sufficient for economies of scale initially.</p>

	Industrial Concentration: Refinery/cement clusters near the sea (Elefsina, Corinth).	Technical Complexity: Risk at the Ship-Tanker Interface (Offshore offloading risks).
External Environment	Opportunities	Threats
Market, Politics, Society	<p>Mediterranean Hub: Import of cargo from Italy, the Balkans, and Egypt (Revenue from Gate Fees).</p> <p>EU funding: Access to the Innovation Fund and RRF to cover the financing gap.</p> <p>Blue Hydrogen: Development of a market for clean hydrogen from refineries.</p> <p>Retraining: Retaining scientific talent through Just Transition</p>	<p>ETS price volatility: A possible drop in the price of emissions makes the investment unprofitable.</p> <p>Social Reaction (NIMBY): Fear of leakage or seismicity despite offshore location.</p> <p>Competition: Development of Ravenna Hub (Italy) targeting the same customers.</p> <p>Legal Gap: Delays in transnational agreements on CO2 exports (London Protocol).</p>

The previous table is a mirror of the following SWOT analysis:

Greece's key advantage is the combination of "Natural Resources" (Prinos) and "Business Resources" (Shipping). Unlike projects in aquifers that start from scratch, Prinos offers 40 years of historical data, eliminating geological risk. In addition, Greek merchant shipping can operate as a vertically integrated service provider, controlling the entire value chain (Virtual Pipeline), something that few countries can achieve (Energean, 2022).

The weak spot of the system is the operating costs (OPEX). The need to liquefy CO2 for maritime transport introduces an energy penalty that does not exist in the pipeline networks of Northern Europe. Furthermore, the lack of a national pipeline network means that each industry must develop its own port facilities, increasing the complexity of logistics in the early stages (ZEP, 2011).

The greatest opportunity is geopolitical. The Mediterranean has no other mature storage facilities (apart from the planned Ravenna facility). Greece can capitalize on its "First

Mover Advantage" by attracting industrial customers from Bulgaria, Croatia, and Southern Italy before competitive schemes have a chance to develop. At the same time, the transition to the Hydrogen Economy offers Greek refineries a "second life" through Blue Hydrogen (Eni, 2023).

The main threat is economic/regulatory. The business model is based on the assumption that the price of CO₂ will remain high (>€80/t). An EU policy decision that would lead to a relaxation of targets or an economic downturn that would drive down the price of the pollutant would jeopardize the viability of the project. Equally important is the NIMBY threat: poor communication management of a minor accident or leak could turn public opinion against the technology, leading to the revocation of permits (Tcvetkov et al., 2019).

Based on the analysis, four strategic lines of action emerge:

- **Expansion Strategy:** Leveraging shipping power to dominate the Mediterranean market. Creation of joint ventures between Energean and shipping companies to offer a "Transport + Storage" package at a competitive price.
- **Investment Strategy:** Use of European funds to subsidize the high cost of liquefaction and create shared port infrastructure. The goal is to reduce marginal costs through economies of scale.
- **Shielding Strategy:** Use of long-term Take-or-Pay contracts and government contracts for difference (CCfDs) to exploit the uniqueness of Prinos and protect against the volatility of pollutant prices.
- **Legitimization Strategy:** Minimizing accident risk and addressing NIMBY through strict safety protocols, transparency (real-time monitoring data for the public), and highlighting the jobs created.

The cost-benefit analysis and strategic assessment conclude that the balance for the development of the CCS supply chain in Greece is positive, but conditional.

The technological and geological foundations are strong and the social benefits (job preservation, climate) are undeniable. However, economic sustainability remains fragile and dependent on external factors (energy/pollutant prices). The success of the venture requires a transition from the "stand-alone project" model to the "International Hub" model, so that through increased CO₂ volumes, the economies of scale required to offset the high operating costs of maritime transport can be achieved.

5.6 Conclusions and Detailed Evaluation

This thesis was written at a historic juncture for the global and national energy sector. The transition to climate neutrality (Net Zero) by 2050 is no longer an abstract environmental ambition, but a binding legal and economic one-way street dictated by the European Green Deal. Within this pressing context, Carbon Capture and Storage (CCS) technology emerged, through our bibliographic and analytical research, as the critical "missing link" for the sustainability of heavy industry.

The research focused on the case study of "Prinos CCS" and the development of an integrated Greek supply chain. The main conclusion is that the development of CCS in Greece is not simply an isolated technical infrastructure project. It involves the creation of a complex, multi-level logistics ecosystem, which requires the perfect synchronization of four pillars: technological maturity, shipping capacity, regulatory framework, and social acceptance. Greece, taking advantage of the unique geological resource of Prinos and the business resource of deep-sea shipping, has the potential to become a strategic regional hub for carbon management in the southeastern Mediterranean.

On a technical level, the research confirmed the high maturity (High Technology Readiness Level - TRL 9) of storage technology in depleted oil reservoirs. Prinos presents minimal geological risk due to the proven integrity of the caprock, which has retained hydrocarbons under high pressure for millions of years. The estimated capacity of 100 million tons of CO₂ more than covers national needs, creating a surplus for commercial exploitation.

However, the biggest technical finding concerns the challenges of the supply chain. The choice of the "Virtual Pipeline" model (maritime transport), although necessary due to the island's geography, introduces a significant "Energy Penalty." As highlighted in the Technical Analysis, the liquefaction process requires approximately 90-120 kWh per ton of CO₂, while the overall energy efficiency of the capture units is reduced by 8-12%. This finding leads to the conclusion that the environmental success of CCS is inextricably linked to the simultaneous development of Renewable Energy Sources (RES) to power the facilities. Without "green" energy, the carbon footprint of the logistics chain itself reduces the final net benefit in a small percentage, but it is a fact.

The cost-benefit analysis showed that the project's viability is marginal and highly sensitive to external factors. The total weighted cost (Levelized Cost of Storage - LCOS), which was calculated in our research to range between €65 and €120 per ton, is often above or close to the current price of emission allowances (EU ETS ~€80/t).

The critical conclusion here is that there is a clear "Viability Gap," especially for industries with low CO₂ concentrations. The economic equation cannot be solved solely in terms of the free market in the early stages. Success depends on achieving economies of scale. The analysis showed that the transition from the 1 Mtpa pilot phase to full development of 3+ Mtpa is necessary to reduce the marginal cost of maritime transport by approximately 30-40% and make the service competitive with carbon penalties.

In the social sphere, the study highlighted the dual nature of public opinion. On the one hand, there is the risk of the NIMBY ("Not In My Backyard") phenomenon, which stems from a lack of information and fear of leaks. The research concluded that the offshore nature of Prinos is the strongest "resistance point" against these reactions, eliminating visual disturbance.

On the other hand, the most important positive finding concerns the project's contribution to the "Just Transition." CCS acts as a job retention mechanism. As mentioned in the Social Analysis, every €1 billion invested in CCS infrastructure can maintain or create up to 15,000 jobs. For the region of Eastern Macedonia and Thrace, which has been hit hard by deindustrialization, the project is not just environmental, but deeply social and developmental.

Also it is necessary to mention about the Detailed Strategic Recommendations. Based on the SWOT analysis and the conclusions above, this thesis formulates a comprehensive framework of recommendations for the agencies involved.

There are three suggestions to the Greek State about the Institutional Protection:

1. **Implementation of Carbon Contracts for Difference (CCfDs):** The state must immediately proceed with the establishment of CCfD mechanisms. Through these, the state will guarantee a fixed price ("Strike Price") for each ton of stored CO₂. If the ETS price is lower than the operating cost, the state will cover the difference. This mechanism is necessary to reduce investment risk (de-risking) and make projects attractive for bank lending, following the successful example of the Netherlands (SDE++ scheme).
2. **Diplomatic Activation for Cross-Border Transport:** In order for Greece to function as a hub, legal barriers must be removed. The Ministry of Foreign Affairs and the Ministry of Environment and Energy must expedite the ratification of bilateral agreements with countries such as Bulgaria, Italy, and Egypt, within the framework of the amendment to the London Protocol. Without these intergovernmental agreements, CO₂ imports remain legally uncertain and the vision of a "Mediterranean Hub" unattainable.
3. **Integration into Higher Education:** One gap that has been identified is the lack of specialized personnel. It is proposed that postgraduate programs be created at Greek polytechnics (NTUA, Technical University of Crete, Democritus University of Thrace) specializing in Carbon Capture Engineering. The creation of a new generation of engineers is a prerequisite for national self-sufficiency in technical expertise.

However, there are also three suggestions for the for Industry and Shipping:

1. **Creation of Vertical Joint Ventures (Vertical JVs):** It is proposed that joint ventures be established between major polluters (cement, refineries), the storage operator (Energean), and shipping companies. Instead of fragmented contracts, a single scheme offering "Transport & Storage as a Service"

(T&SaaS) could reduce the profit margins of intermediaries and offer more competitive prices to end users.

2. **LCO₂ Fleet Standardization (Ship Standardization):** Greek shipping is called upon to lead the global effort to standardize CO₂ transport ship specifications. The analysis showed that the industry is leaning towards the "Low Pressure" solution (7 bar, -50°C), which allows for the construction of larger ships (over 20,000 cubic meters). Timely investment in this standard will give Greek shipyards and shipowners the "First Mover" advantage.
3. **Employee Reskilling Programs:** The oil and gas industries must immediately launch mass retraining programs for their personnel. The skills required for CCS (geology, high-pressure management, process safety) are 80% common with those of Oil & Gas. Certification of these skills will ensure a smooth transition of the workforce into the new era.

Despite the systematic approach, this study is subject to limitations that must be acknowledged. Firstly, the lack of primary operating data (as the project is still in the planning stage) means that the economic analysis was based on estimates rather than actual cost data. Furthermore, the EU regulatory framework (e.g., Net Zero Industry Act) is extremely fluid, and changes in subsidies may alter the economic data in the near future.

In summary, the development of the CCS chain in Greece is a high-risk but also high-return national challenge. It is not simply an environmental obligation, but a unique opportunity for industrial transformation. Greece is called upon to turn its geographical disadvantage (insularity, lack of pipelines) into a strategic advantage by developing a flexible maritime logistics model that can serve the entire Eastern Mediterranean. The success of the Prinos project will mark the country's entry into the era of the "New Carbon Economy," ensuring the sustainability of its industry, protecting thousands of jobs, and strengthening its geopolitical role in Europe's energy map.

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