Techno-Economic Evaluation of Carbon Capture, Utilisation and Storage; Case Study of Scenarios in Western Macedonia, Greece

Nikolaos Koukouzas [1,], Rania Karametou [1], Dimitrios Karapanos [1], George S. Maraslidis [1], Pavlos Tyrologou [1], Paula Coussy [2], Anders Nermoen [3], Julio Carneiro [4], Paulo Mesquita [4] and Paula Canteli [5]*

https://doi.org/10.5281/zenodo.8108279

Over the previous decades, the region of Western Macedonia in Greece has become home to heavy industrial clusters. Carbon capture, utilisation, and storage (CCUS) is an essential technology for climate change mitigation that could deliver significant economic growth. As part of the EU-funded STRATEGY CCUS project (2019-2022), two scenarios were developed and economically evaluated for the deployment of CCUS technologies in Western Macedonia. These scenarios were created using a novel software tool to analyse the CCUS business model in the Greek region. For this, two suitable local onshore geological sites were utilised for storing captured CO_2. Five industries from different industrial sectors have been chosen for CO_2 utilisation. Key Performance Indicators (KPIs) were calculated to measure this project's long-term value and return on investment (ROI) while also measuring its short-term efficiency and profitability over the deployment process lifetime.

Au cours des décennies précédentes, la région de Macédoine occidentale en Grèce est devenue le foyer de pôles industriels importants. Le captage, l'utilisation et le stockage du carbone (CCUS) est une technologie essentielle pour l'atténuation du changement climatique qui pourrait générer une croissance économique significative. Dans le cadre du projet STRATEGY CCUS financé par l'UE (2019-2022), deux scénarios ont été développés et évalués économiquement pour le déploiement des technologies CCUS en Macédoine occidentale. Ces scénarios ont été créés à l'aide d'un nouvel outil logiciel pour analyser le modèle commercial CCUS dans la région grecque. Pour cela, deux sites géologiques terrestres locaux appropriés ont été utilisés pour stocker le CO_2 capturé. Cinq industries de différents secteurs industriels ont été choisies pour l'utilisation du CO_2. Des indicateurs de performance clés (KPI) ont été calculés pour mesurer la valeur à long terme et le retour sur investissement (ROI) de ce projet tout en mesurant son efficacité et sa rentabilité à court terme sur la durée de vie du processus de déploiement.

En las últimas décadas, la región de Macedonia Occidental en Grecia se ha convertido en un centro de desarrollo de la industria pesada. La captura, utilización y almacenamiento de carbono (CCUS), es una tecnología esencial para la mitigación del cambio climático, que podría aportar un crecimiento económico importante. Como parte del proyecto STRATEGY CCUS (2019-2022), financiado por la UE, se desarrollaron y evaluaron económicamente dos escenarios para la implementación de tecnologías CCUS en Macedonia Occidental. Estos escenarios fueron creados utilizando una nueva herramienta computacional para analizar el modelo económico de CCUS en dicha región de Grecia. Para esto, se eligieron dos sitios geológicos propicios para el almacenamiento de CO_2. Se seleccionaron cinco industrias de diferentes sectores productivos para la utilización del CO_2. Se calcularon indicadores claves de desempeño (KPI's), para medir el valor y retorno de largo plazo de la inversión (ROI), además de la eficiencia y rentabilidad de corto plazo, durante la duración del proceso.

1. Introduction

The latest Intergovernmental Panel on Climate Change (IPCC) report [1] provides further evidence that climate change is widespread, rapid, and intensifying with some trends now irreversible. Human-induced climate change is globally causing many weather and climate extremes. Persistent and sustained reductions in carbon dioxide (CO_2) emissions including other greenhouse gases, could reduce the greenhouse effect and improve air quality, with the expectation that global temperatures could stabilize over the next decades. In 2019, the concentration of atmospheric CO_2 reached a 2 million-year high. Furthermore, methane and nitrous oxide concentrations peaked at levels unseen in the last 800,000 years [1].

The 2015 Paris Agreement [2] aims to avoid the most devastating effects of climate change and limit global temperature increase to no more than 2°C above pre-industrial levels. The 2021 IPCC report [1] clarifies that the global surface temperature increased by 1.09°C over the decade between 2011 and 2020 compared to the period between 1850 and 1900. Additionally, the past five years were recorded to be the hottest since 1850.

Oil continues to hold the top position as the primary source of energy, accounting for 33% of the global energy mix. Moreover, fossil fuels represent 84% of the world's primary energy mix [3-4].

On July, 14, 2021, the European Commission adopted a series of legislative proposals to achieve climate neutrality in the EU by 2050. The proposals include an intermediate target of at least 55% net reduction in greenhouse gas emissions by 2030 [5]. This EU plan for a green transition, referred to as "fit for 55", consists of proposals aimed to revise and update EU legislation and is part of the European Green Deal, which outlines the EU's road-

[1] Centre for Research and Technology Hellas (CERTH), Chemical Process and Energy Resources Institute (CPERI), Egialias 52, 15125 Marousi, Attica, Greece
[2] IFP Energies nouvelles, 1-4 avenue de Bois-Préau, 92852 Rueil-Malmaison, France
[3] NORCE AS, Tullins gate 2, 0166 Oslo, Norway
[4] ICT, Instituto de Ciências da Terra, Universidade de Évora, Évora, Portugal
[5] Instituto Geológico y Minerode España IGME-CSIC, Ríos Rosas 23, 28003 Madrid, Spain
* koukouzas@certh.gr

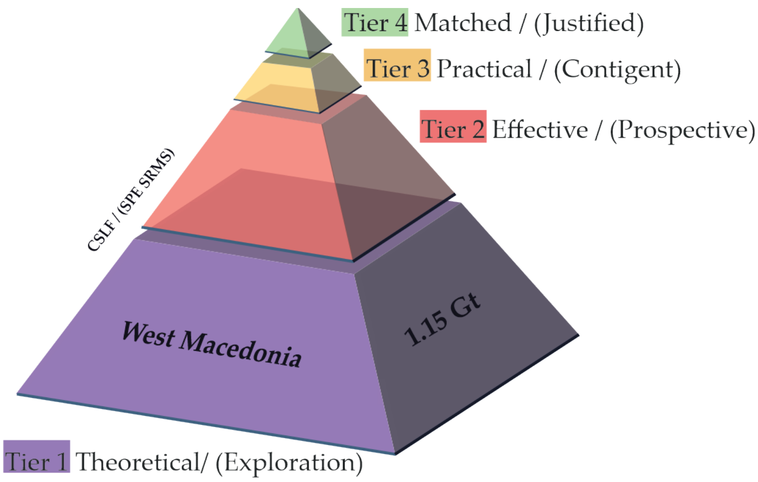

Figure 1: (A) Location of remote northern communities in Canada; (B) main geological regions; (C) climate zones; and (D) map of the studied area centered on the Arctic. YT – Yukon Territory, NWT – Northwest Territories, NU – Nunavut, NK – Nunavik, QC – Quebec and NL – Newfoundland and Labrador (Nunatsiavut).

map for a sustainable economy.

As part of its efforts, the European Union has implemented policymaking through initiatives like the Green Deal, REPowerEU and EU taxonomy. Greece, as an EU member, has committed itself to reducing CO_2 emissions to a minimum by phasing out its technologically outdated lignite-based power plants in Megalopolis and Western Macedonia.

The region of Western Macedonia is located in the northwest of Greece, adjacent to the regions of Central Macedonia (East), Thessaly (South), and Epirus (West). It shares its northern borders with the Republic of North Macedonia and Albania. The region covers a total area of 9,451 km^2, representing 7.2% of the country's total area and a population of 283,689 inhabitants, which is 2.6% of the country's total population.

The majority of the population (56%) lives in rural areas [6]. The capital of the region is the city of Kozani, with a population of 67,161. Other major towns include Ptolemaida with 32,142 inhabitants, Grevena with 21,440, Florina with 29,611 and Kastoria with 33,227 inhabitants [7].

The lignite industry preoccupied the workforce of these cities, causing many residents to renounce traditional activities such as farming, leading to rapid economic growth and prosperity and as a result, power plants had become the dominant sector of employment [8].

Since the early 1950s, the lignite industry has shaped the development course of Western Macedonia. The intensive exploitation of domestic lignite deposits contributed significantly to electrifying Greece and consistently supporting the security of the national energy supply. As a result, the region hosts the highest installed unit power of Greece, regarding thermal power plant units. Out of 13,077.9 MW of installed net power, the region has 3,945 MW based on lignite units and another 375 MW on hydroelectric power, covering 33% of the total capacity and 39.2% of thermal unit power. However, according to the new Greek National Energy and Climate Plan, all operating lignite-based power plants are scheduled to be retired by 2023, meaning that Western Macedonia is currently in its decarbonisation phase.

In the H2020 European Project STRATEGY CCUS ***(https://www.strategyccus.eu)***, two CCUS scenarios were formulated up to 2050 to evaluate the techno-economic feasibility of CCUS technologies in Western Macedonia, Greece. The main objective of this paper is to present these CCUS scenarios, the methodology used in their development, followed by a synthesis of the KPI evaluation and the main results. This techno-economic evaluation will be useful to compare the total costs, that Western Macedonia would incur by investing in CCUS technologies, to the costs incurred by the EU Emissions Trading System (ETS) in absence of CCUS projects, during the same period.

In the next subsection of this paper, an introduction to CCUS technologies is provided, followed by a description of the STRATEGY CCUS project. Section 2 includes a description of the software used and the scenario generation procedure, along with the presentation of medium-term and long-term scenarios that were developed for Western Macedonia. The third section, "Results", contains the techno-economic evaluation of both scenarios, along with pie charts depicting the benefits of CCUS adoption in the region. Finally, the concluding section presents the findings of this study on the implementation of CCUS technologies in Western Macedonia.

1.1 Carbon Capture, Utilisation and Storage technology

Currently there are only five large-scale carbon capture and storage (CCS) demonstration projects in Europe: Sleipner and Snøhvit in Norway, ROAD in the Netherlands, Iceland's Carbfix project and, Peterhead and White Rose in the United Kingdom. All these projects are offshore, storing CO_2 in deep geological formations [9].

CCUS refers to the process of capturing CO_2 and either storing it permanently or utilizing it by converting it into valuable products, such as fuels and chemicals. There are three main categories of capture technologies:

a. Post-combustion – In this method, waste gas produced by industrial combustion or power stations is captured and the CO_2 is separated.
b. Pre-combustion – This method involves pre-treatment of fuels, separating the carbon from the components that are ultimately burnt. For example, coal is first converted into a mixture of CO_2 and hydrogen by gasification, then the CO_2 is captured and only the hydrogen is burned.
c. Oxy-fuel combustion – This method involves, burning fuel with pure oxygen instead of regular air, resulting CO_2 to make up a larger fraction of the waste gas, making it easier to separate and store or repurpose the CO_2 [10].

The STRATEGY CCUS project aims to facilitate the implementation of carbon capture, utilisation, and storage (CCUS) in eight regions. These are identified as promising because they possess strategic elements, such as industrial clusters, potential CO_2 storage sites, opportunities for CO_2 utilisation and options for hydrogen production and use. The project also involves creating local development plans and business models for each region. This article expands on the previously published work "Carbon Capture, Utilisation, and Storage as a Defense Tool against Climate Change: Current Developments in Western Macedonia (Greece)" [11].

During the STRATEGY CCUS project, the potential for CO_2 storage in the Mesohellenic Trough was re-evaluated

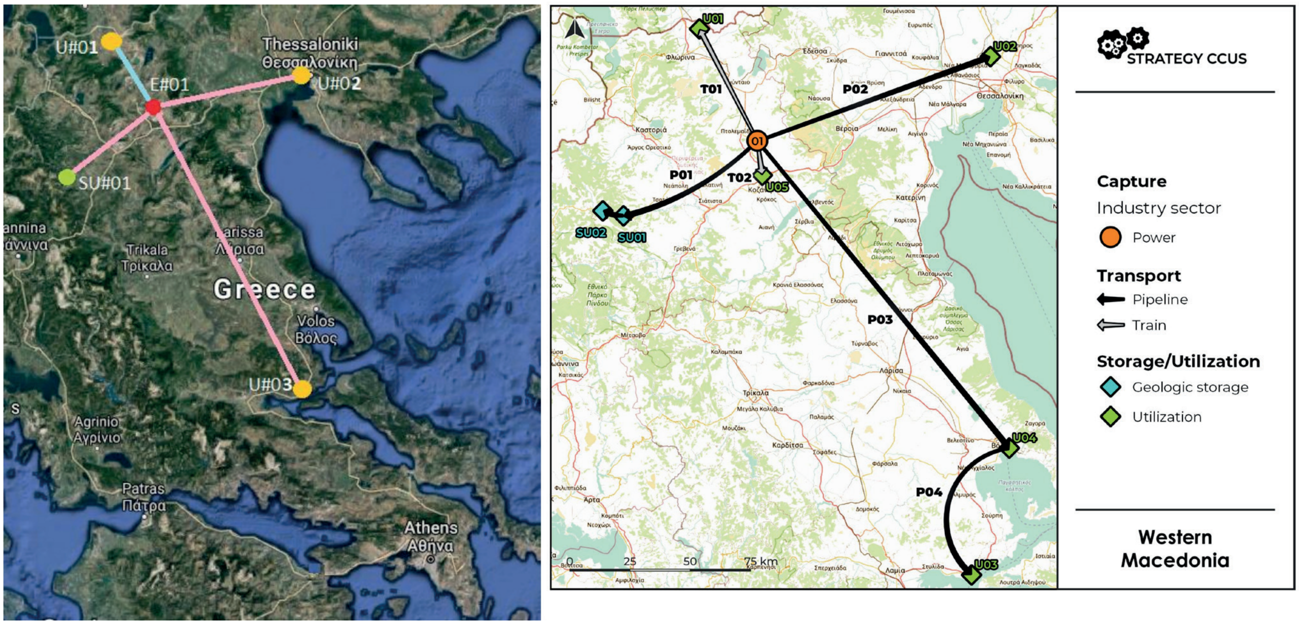

Figure 2: The transportation map for (a) the medium-term scenario and (b) the long-term scenario for Western Macedonia.

using available data whilst deploying the USDOE methodology. The Mesohellenic Trough contains the Pentalofos and Eptachori Formations, along with their corresponding daughter units. The Pentalofos Formation has an estimated CO_2 storage capacity of 1.02 Gt, whereas the Eptachori Formation can store 0.13 Gt.

Currently, CO_2 storage in Greece remains categorised with a Tier 1 status, as depicted in Figure 1. Therefore, a theoretical approach based on literature data and calculations was used to estimate the CO_2 storage capacity within sedimentary formations of the Mesohellenic Trough.

For estimating storage capacity, a four-tiered pyramid is proposed based on the North American CSLF approach [12]. The capacity quantification is based on the common P90-P50-P10 estimation (CO_2 Stored), which matures from generic formation level estimates to more detailed daughter prospects and candidate site estimates. The recommendations allow for outcomes to be transferred to an SRMS analysis.

As CCUS projects are driven by reducing global carbon emissions, the technologies employed in these projects have a critical role in achieving this goal.

2. Methods and Software (Tool)

During the STRATEGY CCUS project, a specialized software was developed to create local medium-term and long-term CCUS scenarios in each of the seven participating European countries and their eight regions. This software was developed by a core team composed of the STRATEGY CCUS project partners [13-14] using Microsoft Excel. The software is essentially an interconnected database with many different mathematical functions to describe the individual CCUS elements of Capture, Utilisation, and Storage. The software generates custom scenarios for different time horizons while performing extensive techno-economic analysis. By using this software, various economic Key Performance Indicators (KPIs) were generated, comparing the cost of implementing a CCUS project in the region of interest with the cost of paying CO_2 taxes in the same region if such a project were not implemented. For each region, two main scenarios were implemented: a medium-term scenario from 2030 to 2040, and a long-term scenario extending to 2050.

The data required for this software tool were gathered during a previous project and contain information about emitters, storage sites and industries that can utilise quantities of CO_2 in every participating country. This data created a database that was integrated into the tool, enabling the defining of business case scenarios, CO_2 hubs and clusters for each case. The basic starting point for the scenarios includes the publicly available data integrated into the tool, allowing the deployment of these scenarios.

One of the challenges facing CCUS technologies is the transport of significant volumes of CO_2 from point sources to sites established for large-scale storage. To address this issue, routing algorithms were applied with the help of GIS software to define feasible routes connecting sources, utilisation locations, and storage regions for captured CO_2. The transport routes and modes of transportation were designed and chosen accordingly to minimize the total cost. Solutions include, pipeline transportation, while train, truck or ship transportation were also available through the tool, depending on the transported volume of CO_2 and its probability of coming from dispersed sources. The study also evaluated the cost of pipeline transport, based on the quantity of CO_2 supplied and the distance, compared to CO_2 shipped by tanker vessels. The results show that the pipeline option is cheaper, but only for shorter distances. The costs for this implementation are evaluated in the CCUS scenarios below:

a. They are based on public data and directly related to stakeholders (Industry and Regional Committee).
b. They depend on the CO2 capture profile, transport options and storage capacity for Greece.
c. They involve financial assessment of each scenario by submitting Key Performance Indicators (KPIs).
d. They are harmonized with greenhouse gas reduction targets for each country.
e. They are expected to increase the likelihood of CCUS deployment in Greece, particularly Western Macedonia.

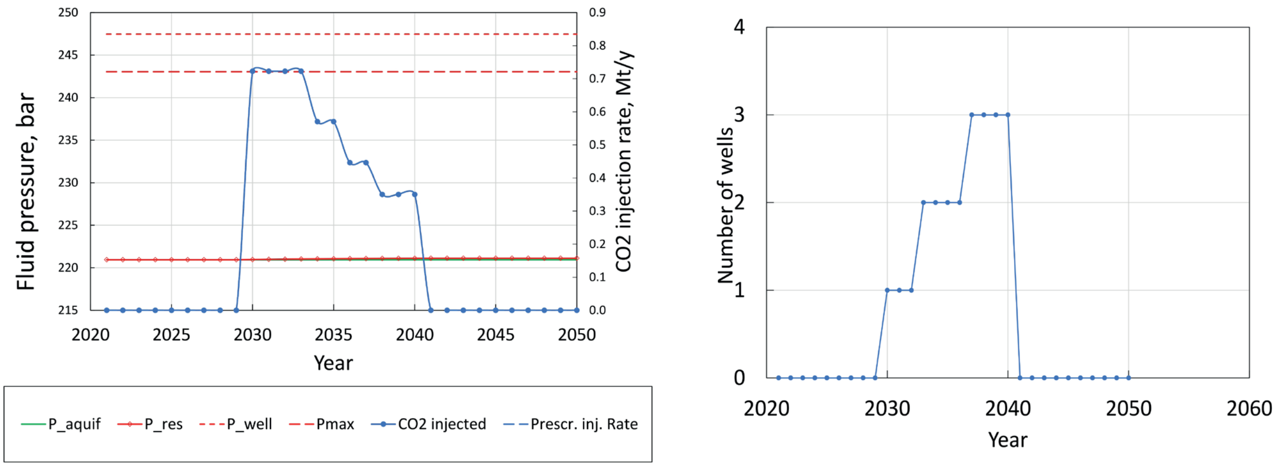

Figure 3: (a) Storage for the medium-term scenario in Western Macedonia; (b) The number of required wells in the medium-term scenario.

2.1. Description of the scenario generation procedure

The scenario creation tool identifies the linkages between emissions, transport modes, CO_2 reuse, and storage sites, to create local perspectives. It then checks the correlation between the different captured CO_2 flows, their transportation or utilisation. It also checks the potential for storage at the local level, form short-term to long-term.

For each selected regional scenario, a financial estimate has been made concerning the cost for each scenario and for each tonne of CO_2 avoided. Calculations were then made of Key Performance Indicators (KPIs) such as CAPEX / OPEX, additional energy costs, CO_2 avoidance and ETS savings. Moreover, the tool considered transport corridors on multiple time scales and then developed the most cost-effective transportation network.

The tool imported data on reservoir characteristics, as well as data on industries to be exploited for CO_2 reuse and the Ptolemaida V emitter unit. Data on interconnection points, such as spatial data, pipeline characteristics, gas temperature, and pressure were also imported by the tool.

2.2. The short/medium-term scenario for Western Macedonia

Adhering to the new Greek National Energy and Climate Plan, all currently operating lignite-based power plants will be retired by 2028. The only operational lignite power plant that will remain is the new Ptolemaida V power plant, located in North-Western Greece. The estimated CO_2 emissions available for CO_2 capture from the Ptolemaida V power plant are 4.5 Mt/y for a period of 30 years. The plant is designated as a CCS-ready facility.

The Ptolemaida V power plant will contribute to multiple levels. It will renew installed plants, owned by the Public Power Corporation, producing electricity at competitive costs by reducing lignite consumption and lowering CO_2 costs. It will significantly improve the environmental footprint and lower the cost of electricity generation. Overall, it will bring significant benefits to the Greek economy and reduce unemployment.

Four key advantages of this new power plant are the reductions of a) lignite consumption by 40%, b) greenhouse gas emissions by 40%, c) pollutant emissions by 60%, and d) particle emissions by 90%.

Due to the rapid decarbonisation phase in the last years, only one emitter, Ptolemaida V, was considered for the Greek medium-term scenario. The power plant is located approximately 8km southeast of the town (Figure 2) and the captured CO_2 will be transported via pipeline.

The selected Pentalofos Storage Unit for the medium-term scenario is located approximately 67 km west of Ptolemaida V. The first captured CO_2 utilisation site is located in Florina, a nearby city 68 km north of Ptolemaida V. The transportation of CO_2 to Florina will be done by train, using the existing railway network in this area. The second utilisation site is in Thessaloniki, the second-largest city in Greece, located 166 km from Ptolemaida V. Furthermore, the third utilisation site, chosen in this scenario, is located in Stylida, 260 km south of the Greek emitter. All transportation routes and their characteristics were generated using GIS software, with terrain factors and elevation profiles adequately considered for the pipelines. For the industries that require train transportation, the existing railroad network was utilised. Basic user input data for the tool includes the longitude and latitude of each location, the maximum CO_2 flow rate (Mt/year) and the starting/ending year of operation.

2.3. Basic design parameters and key KPIs

The basic design parameters of the three pipelines in this scenario all have the same values. However, there are differences in distance, elevation profiles and terrain factors considered for each route. The transportation of CO_2 by train, chosen for the first utilisation site (Florina), allows for the minimisation of the total transportation costs in this scenario. The wagon capacity of the train was calculated to be 240 tn. Therefore, a locomotive with three wagons is required, making a maximum of 679 trips per year to satisfy the needs of the first utilisation site. The total time required per trip, including loading and unloading of the captured CO_2 was calculated and found to be 1.12 hours per trip.

Basic design parameters for the pipelines and train transportation include Upstream pressure/temperature; Inlet pressure/transport temperature; Maximum/minimum pressure allowed; Pipeline length; Elevation difference; Start year/construction years; Discount rate; Desired outlet pressure; Wagon capacity; Number of wagons. Additionally, some of the key KPIs include Total undiscounted costs; Total CO_2 transported; CO_2 transport costs per tonne undiscounted/discounted; travel/total time per trip.

2.4. Short description of utilisation units and results

In the medium-term scenario, three utilisation units were selected. Two of which belong to the fuel category, while the other is in the pure CO_2 category. Each industry unit has Ptolemaida V (Emitter 1) as a CO_2 source, and their ramp-up percentage is based on their prospects for carbon dioxide use.

Utilisation Site No.1 (U#01):

The U#01 utilises pure CO_2 in various industrial sectors such as oil and gas, aeronautics, automotive, beverage, chemicals, waste and water management, metal, hospital care, laboratories, and research centres. In the medium-term scenario, U#01 is projected to consume 276,120 tonnes of CO_2 annually with a ramp-up rate of 45% in the first six years. Ptolemaida V, the main scenario emitter, will provide the required amount of CO_2 for this utilisation unit.

Utilisation Site No.2 (U#02):

The U#02 aims to reduce emissions from its processes with 50% by 2030, to address climate change and contribute to the energy transition. Its activities will include innovative technologies such as recycled CO_2 utilisation, renewable energy sources, hydrogen and new raw materials. Its main facilities are located in the city of Thessaloniki in Northern Greece. In the medium-term scenario, U#02 will use 543,750 tonnes of CO_2 annually, with a ramp-up rate of 28% in the first four years. Ptolemaida V, the main scenario emitter, will provide the required amount of CO_2 for this utilisation unit.

Utilisation Site No.3 (U#03):

The U#03 is a Greek industrial company with integrated operations in the agribusiness, bioenergy and food sectors. Its facilities are located in Stylida, Central Greece, which is approximately 255 km away from Western Macedonia. In the medium-term scenario, U#03 will use 309,214 tonnes of CO_2 annually, with a ramp-up rate of 31% in the year 2038. Ptolemaida V, the main scenario emitter, will provide the required amount of CO_2 for this utilisation unit.

Utilisation results and product KPIs were generated for the currently investigated medium-term scenario. From 2030 to 2040, 1.46 Mt CO_2 will be used in the pure CO_2 category and 6.45 Mt in e-fuels. The maximum amount of CO_2 will be utilised in the medium-term scenario from 2036 to 2040 due to a ramp-up in the utilisation process.

2.5. Storage

Greece offers opportunities for CO_2 storage, such as deep saline aquifers in the Greek Mesohellenic basin, as well as depleted hydrocarbon fields in the Tertiary sedimentary basins of Prinos [11]. The Mesohellenic basin and its Grevena sub-basin region offer CO_2 storage options for the Western Macedonian industrial cluster. The Grevena sub-basin, is approximately 50 km away and characterized by deep saline aquifers.

The Pentalofos Formation (Upper Oligocene-Lower Miocene epoch) which is part of the Mesohellenic basin has been selected as the storage site for the medium-term scenario. The Pentalofos Formation consists of conglomerates, followed by turbiditic sandstones and shales, with an average thickness of 2500 m and a maximum thickness of 4000 m. The formation is divided into two daughter units, Tsarnos and Kallon, which have a similar lithologic composition, comprising of conglomerates, turbiditic sandstones (occasionally coarse-grained), shales, and a porosity ranging from 7% to 25% [15]. During this project, the potential for CO_2 storage in the Mesohellenic Trough was re-evaluated deploying the USDOE methodology based on available historical data. The estimated CO_2 storage capacity of the Pentalofos Formation is 1.02 Gt.

In Figure 3a, the storage scenario for the Pentalofos Formation and the closed storage unit is presented. CO_2 injection will be at the maximum level for the first three years (2030-2033), and following these years, the amount of injected CO_2 will gradually be reduced. Additionally, in Figure 3b, the number of wells essential for the implementation of the medium-term scenario is shown.

Table 1 presents the key KPIs for the Pentalofos storage unit (GR.SU.001) in the medium-term scenario (2030-2040). Specifically, the total amount of net CO_2 that will be stored is 5.98 Megatonnes, while the total amount emitted is only 0.03 Megatonnes. The total undiscounted costs will be 25.5 million euros, while the undiscounted CO_2 cost per tonne will be up to 4.3 euros.

3. Results

3.1. Assessment for the medium-term scenario

The Western Macedonian CCUS KPIs of the medium-term scenario are presented in Table 2. This table includes the analysis of the CCS system, CO_2 volumes, and ETS allowances. In the medium-term scenario, 20 Mt of CO_2 are captured and transported, 14 Mt are utilised and 6 Mt are stored, resulting in the avoidance of 6 Mt of CO_2 emissions. The following graphs provide information about the CCUS chain regional benefits and costs for the medium-term scenario of Western Macedonia. It is clear that transportation accounts for the largest share of the total CCUS chain costs, while storage is the smallest (Figure 4a). Additionally, CO_2 sales and ETS savings generate regional revenues and significantly reduce the total costs (Figure 4b).

The application of CCUS technologies avoided about 5.9 Mt of CO_2 emissions in Western Macedonia, while the total CO_2 emitted by carbon capture is 2.3 Mt. The financial results of the medium-term scenario are presented in the figures below. Figure 5a shows the undiscounted CAPEX for Western Macedonia, which is 46.7 million euros in the capture stage, 78.1 million euros in the transport stage, and 21.2

Table 1: KPIs for the Pentalofos storage unit in the Greek medium-term scenario.

Key KPIs for GR.SU.001, Scenario ID: EC_Scenario_1		
	Closed	*Unit*
NPC in year 2021 (discounted)	*-8.8*	*M€*
Total undiscounted costs	*-25.6*	*M€*
Total CO_2 stored	*5.98*	*Megatonnes*
Total CO_2 emitted	*0.03*	*Megatonnes*
Net CO_2 stored	*5.94*	*Megatonnes*
CO_2 costs per tonne (undiscounted)	*4.3*	*€/tonnes*
CO_2 store cost per tonne (discounted)	*1.5*	*€/tonnes*
First year	*2030*	*yr*
Last year of full injection	*2040*	*yr*

Table 2: Region KPIs of the medium-term scenario.

Analysis of the CCS system		***Analysis of CO_2 volumes (Mt)***		***Analysis of ETS allowances***	
Total CCS value chain				*EU ETS parameters*	
CCS value chain (€/tonne CO_2 avoided)	*-25*	*Total CO_2 Captured*	*20.4*	*Price of allowances in 2025 (€/tonne CO_2)*	*70*
		CO_2 utilised	*14.4*	*Price of allowances in 2045 (€/tonne CO_2)*	*0*
Total CAPEX per block	*-12*	*CO_2 for mineralisation (perm. avoided)*	*0.0*		
Cost of Capture (€/tonne CO_2 avoided)	*-4*	*Stored*	*6.0*		
Cost of Transport (€/tonne CO_2 avoided)	*-7*	*Total emitted with CCS*	*2.3*	*Whole regional expense without CCUS*	
Cost of Storage (€/tonne CO_2 avoided)	*-2*	*Total avoided emission*	*5.9*	*ETS costs without CCUS (M€)*	*1802.8*
		BIO CO_2 captured, neg. Emissions	*0.0*		
OPEX per block	*-13*	*Total CO_2 fed into transport network*	*20.4*	*Whole region expense with CCUS*	
Cost of Capture (€/tonne CO_2 avoided)	*-5*	*CCUS national objectives*	*200.0*	*ETS costs with CCUS, remaining emissions (M€)*	*1423.4*
Cost of Transport (€/tonne CO_2 avoided)	*-8*	*Share in national objectives*	*3.0%*	*Cost of CCUS (M€)*	*150.6*
Cost of Storage (€/tonne CO_2 avoided)	*0*			*TOTAL costs with CCUS (M€)*	*1573.9*
Transport cost (€/tonne CO_2 transported)	*-4.3*	STRATEGY CCUS A viable solution for a sustainable future		*Cost difference, with minus without CCUS (M€)*	*-229.0*
Utilisation (income from CO_2 sales) (M€)	*1226.4*			*Average yearly energy need, TWh/year*	*0.71*
EUA/ETS credit savings in the region (M€)	*379.4*			*Peak energy need, TWh/year*	*1.29*
				Breakeven CO_2 price (€/tonne CO_2)	*31*
				First year of profit	*2030*

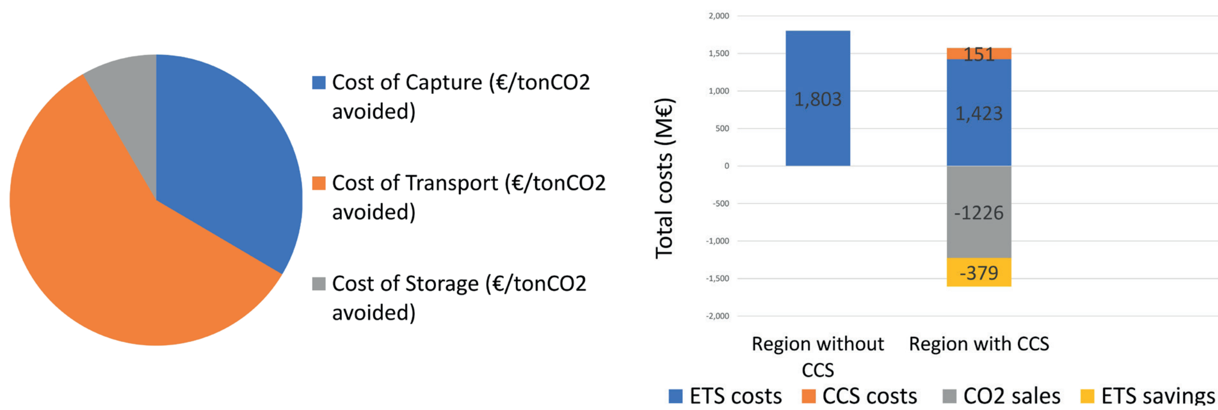

Figure 4: (a) Share of CCS total cost; (b) Total regional costs until 2040.

million euros in the storage stage. Utilisation has an undiscounted CAPEX of zero.

Regarding the undiscounted OPEX for the medium-term scenario, the utilisation procedure generates 2.71 billion euros in revenues from CO_2 sales (Figure 5b). Moreover, the total undiscounted OPEX is 162 million euros. The fraction of CAPEX (in euros) per tonne of avoided CO_2 is higher in the transport stage, whereas the utilisation stage has a value of zero (Figure 6a). The regional revenues from the CO_2 utilisation stage are unambiguous (Figure 6b). The highest fraction of OPEX (in euros) per tonne of avoided CO_2 appears in the utilisation procedure, which is due to generated revenues. On the other hand, the capture procedure incurs a higher cost per avoided tonne of CO_2.

Figure 7 displays both the project costs and income per year when implement-

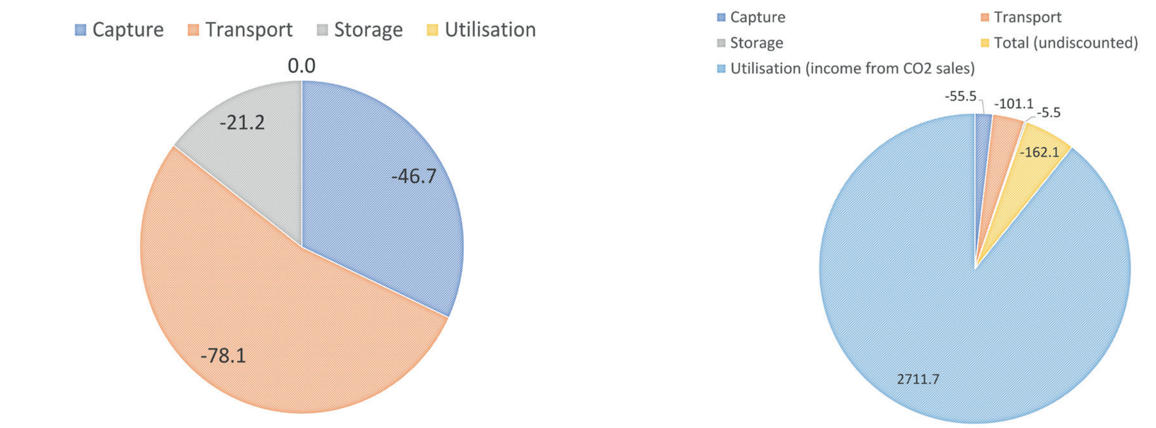

Figure 5: (a) Undiscounted CAPEX for the Greek medium-term scenario; (b) Undiscounted OPEX for the Greek medium-term scenario

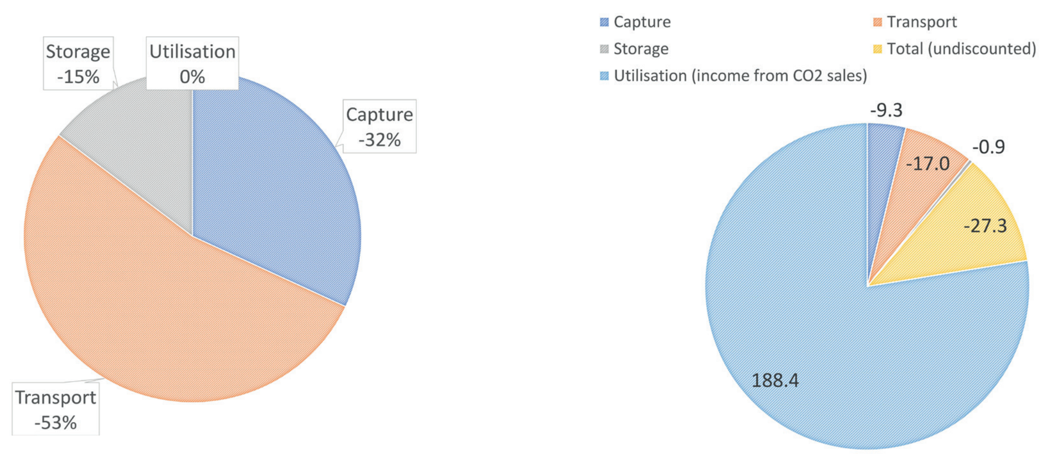

Figure 6: (a) CAPEX per avoided tonne of CO2 for the Greek medium-term scenario; (b) OPEX per avoided tonne of CO₂ for the Greek medium-term scenario.

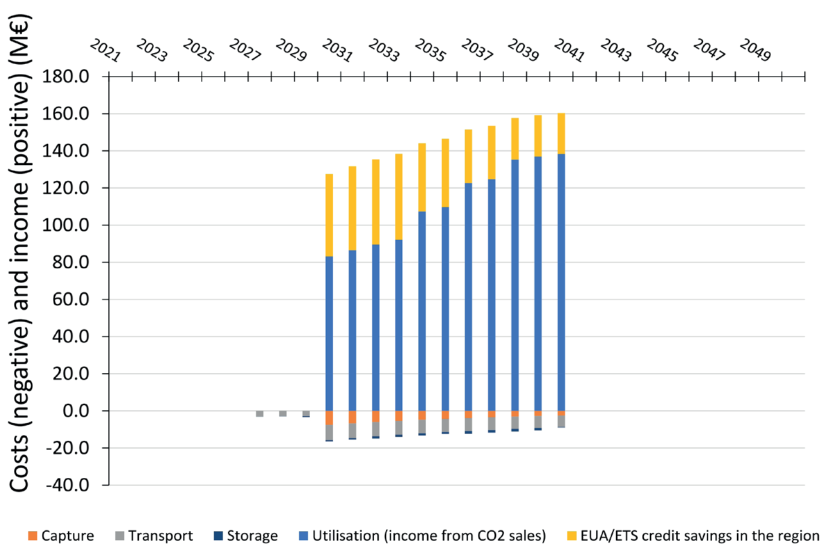

Figure 7: Regional costs and incomes for Western Macedonia in the medium-term scenario.

ing a medium-term scenario in Western Macedonia. Between 2027 and 2030, most costs will be incurred by the transport stage, followed by the storage stage. From 2030, the first year of the medium-term scenario, Western Macedonia will start earning incomes from EUA/ETS savings and CO_2 sales. Thus, the regional revenues will be significantly higher than the costs during the medium-term scenario. This indicates that the developed medium-term scenario is advantageous and profitable for Western Macedonia, both economically and environmentally.

3.2. Assessment for the long-term scenario

The primary difference between the medium-term and long-term scenarios is the duration of the latter, which is extends up to 2050. Furthermore, the long-term scenario includes five utilisation units, with the addition of one cement plant next to the Ptolemaida V unit, and another industrial company with integrated operations in fertilizers and the agribusiness. The long-term scenario also features an extra storage unit which is chosen as a second storage site, located in Eptachori village and also part of the Mesohellenic basin.

The KPIs for the long-term scenario of CCUS in Western Macedonia are presented in Table 3. This table includes the analysis of the CCS system, CO_2 volumes and ETS allowances. 39Mt of CO_2 are captured, 39Mt are transported, 32 Mt are utilised and 7 Mt are stored in the long-term scenario. The avoided emissions amount to approximately 17 Mt of CO_2.
The following graphs provide important

Table 3: KPIs for the long-term scenario in Western Macedonia.

Analysis of the CCS system		***Analysis of CO_2 volumes (Mt)***		***Analysis of ETS allowances***	
Total CCS value chain				***EU ETS parameters***	
CCS value chain (€/t CO_2 avoided)	*-36*	*Total CO_2 Captured*	*38.9*	*Price of allowances in 2025 (€/tonne CO_2)*	*70*
		CO_2 utilised	*31.7*	*Price of allowances in 2045 (€/tonne CO_2)*	*212*
Total CAPEX per block	***-17***	*CO_2 for mineralisation (perm. avoided)*	*10.0*		
Cost of Capture (€/tonne CO_2 avoided)	*-11*	*Stored*	*7.2*		
Cost of Transport (€/ tonne CO_2 avoided)	*-4*	*Total emitted with CCS*	*4.3*	*Total regional expense without CCUS:*	
Cost of Storage (€/tonne CO_2 avoided)	*-2*	*Total avoided emission*	*17.2*	*ETS costs without CCUS (M€)*	*2,672.7*
		BIO CO_2 captured, neg. Emissions	*0.0*		
OPEX per block	***-19***	***Total CO_2 fed into transport network***	***39***	***Total regional expense with CCUS***	
Cost of Capture (€/tonne CO_2 avoided)	*-13*	*CCUS national objectives*	*200*	*ETS costs with CCUS, remaining emissions (M€)*	*1,619.0*
Cost of Transport (€/ tonne CO_2 avoided)	*-6*	*Share in national objectives*	*8.6 %*	*Cost of CCUS (M€)*	*613.8*
Cost of Storage (€/tonne CO_2 avoided)	*0*			*TOTAL costs with CCUS (M€)*	*2,232.8*
Cost of Transport (€/ tonne CO_2 transported)	*-4.3*			***Cost difference, incl. minus excl. CCUS (M€)***	***-440.0***
Utilisation (income from CO_2 sales) (M€)	*2841.7*			***Average yearly energy need, TWh/year***	***0.91***
EUA/ETS credit savings in the region (M€)	*1053.8*			***Peak energy need, TWh/year***	***1.29***
				Breakeven CO_2 price (€/tonne CO_2)	*39*
				First year of profit	*2030*

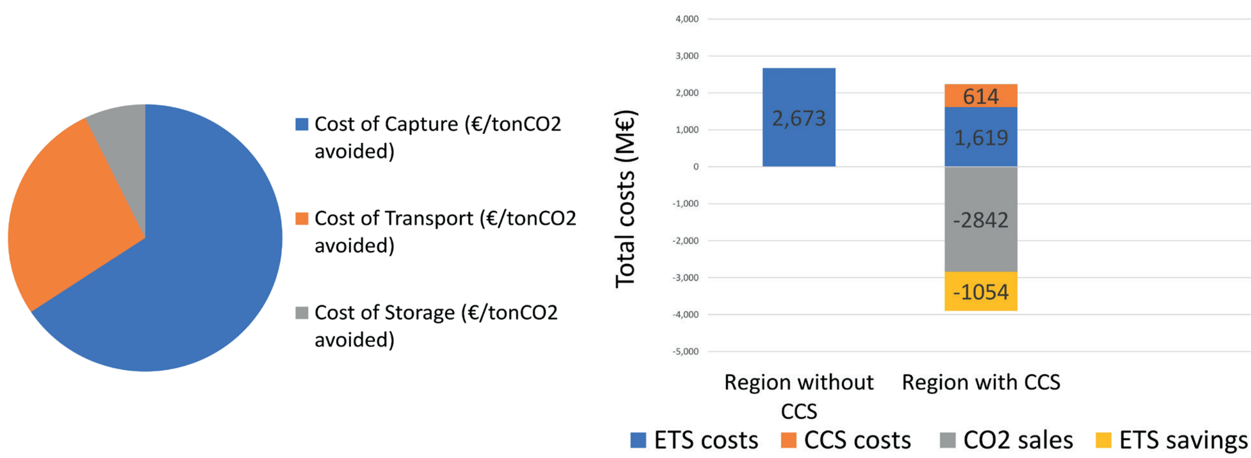

Figure 8: (a) Distribution of total cost among CCS stages; (b) Total regional costs until 2050.

information on the regional long-term scenario of Western Macedonia and are essential to evaluate. They specifically contain relevant details about regional benefits and costs of the CCUS chain. Clearly, costs of capture represent the largest share of the total costs in the CCUS chain, while costs of storage represent the smallest share (Figure 8a). Additionally, CO_2 sales and ETS savings generate regional revenues, which significantly reduce the total costs (Figure 8b). Therefore, the implementation of a long-term scenario will enable Western Macedonia to generate revenues of up to nearly 3.8 billion euros from CO_2 sales and ETS savings.

Emission benefits resulting from the application of CCUS technologies in Western Macedonia are presented in Figure 9a, showing an avoidance of approximately 17 Mt of CO_2 emissions. In contrast, only

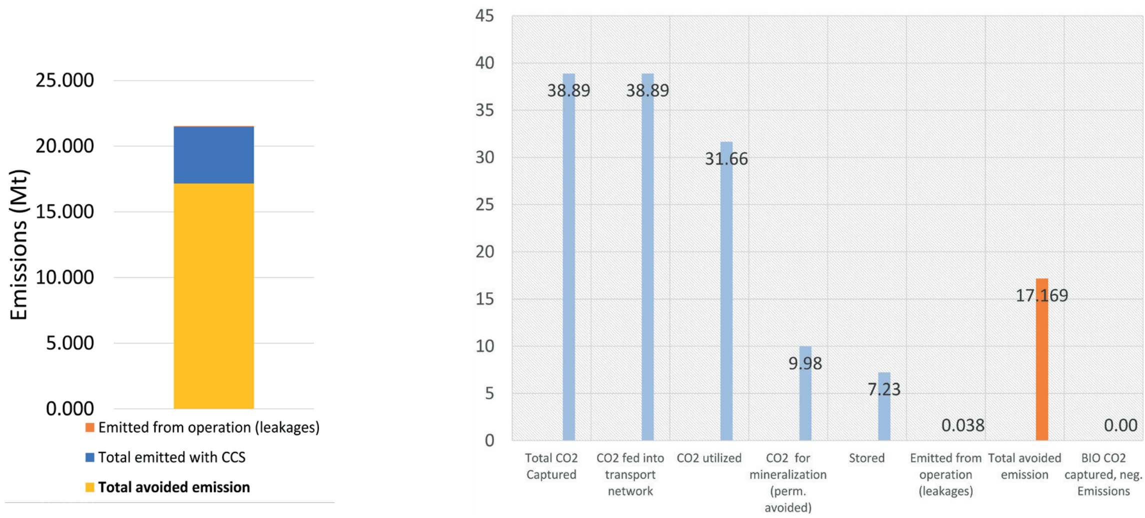

Figure 9: (a) Reduction of regional emissions until 2050; (b) CO2 flows in the long-term scenario for Western Macedonia.

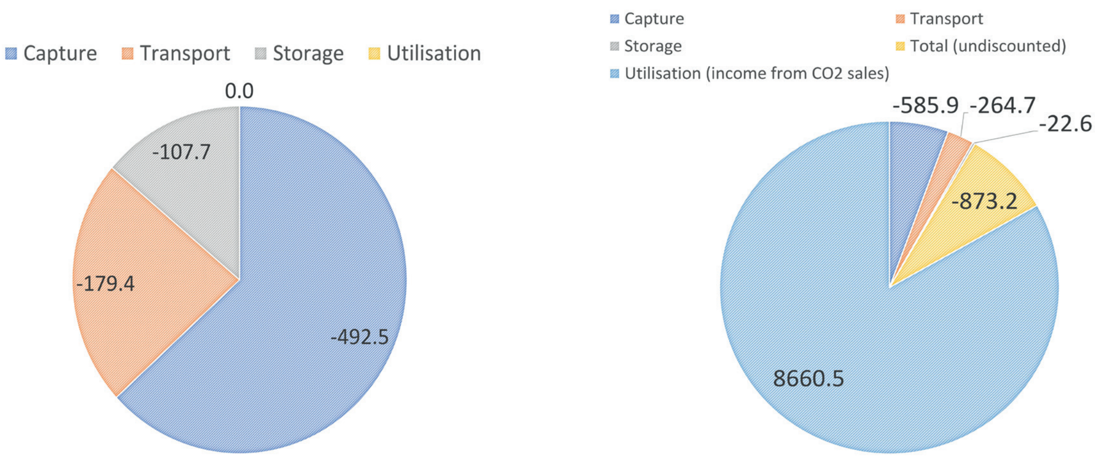

Figure 10: (a) Undiscounted CAPEX for the Greek long-term scenario; (b) Undiscounted OPEX for the Greek long-term scenario.

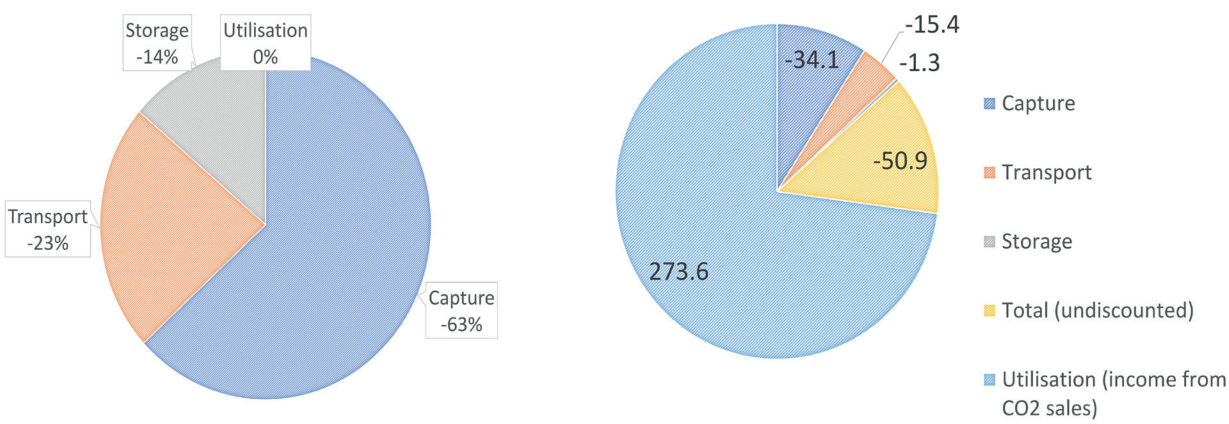

Figure 11: (a) CAPEX per avoided tonne of CO_2 for the Greek long-term scenario; (b) OPEX per avoided tonne of CO_2 for the Greek long-term scenario.

0.04 Mt is emitted by carbon capture. The results show evidence for the significant environmental benefits of CCUS technologies. Furthermore, Figure 11b provides detailed information on CO_2 flows.

The financial results of the long-term scenario are presented in the following figures. Figure 10a shows the undiscounted CAPEX for Western Macedonia's long-term scenario. The undiscounted CAPEX is 492 million euros in the capture stage, 108 million euros in the storage stage, 179 million euros in the transport stage and the utilisation has an undiscounted CAPEX of zero.

Regarding the undiscounted OPEX for the long-term scenario, Figure 10b shows that the utilisation procedure generates 8.6 billion euros in revenues from CO_2 sales. The total undiscounted OPEX is 873 million euros (586 M€ costs from capture, 265 M€ costs from transport, and 23 M€ costs from storage). The fraction of CAPEX (in euros) per tonne of avoided CO_2 is larger in the transport and capture stages, while for utilisation it appears to be zero (Figure 11a). The regional revenues from the CO_2 utilisation stage are significant (Figure 11b) and the fraction of OPEX (in euros) per tonne of avoided CO_2 is the highest in

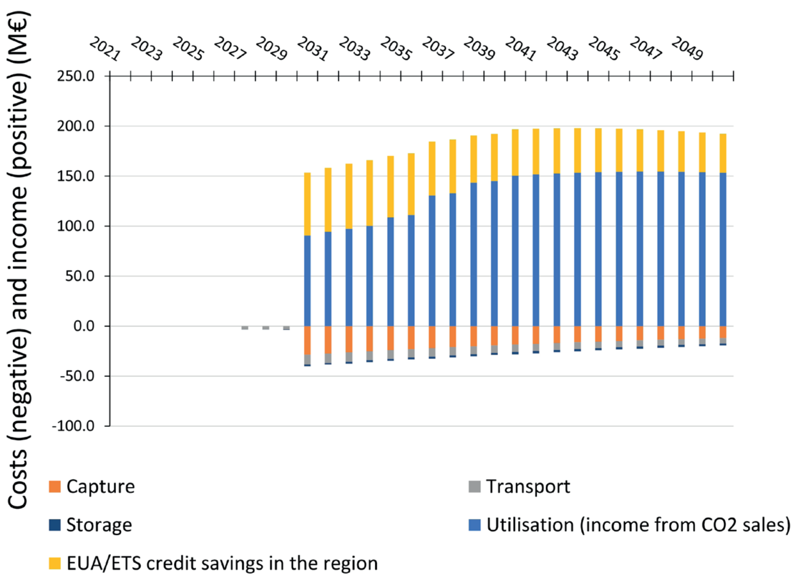

Figure 12: Regional costs and incomes for Western Macedonia in the long-term scenario.

the utilisation stage due to these revenues. In the Greek long-term scenario, the capture and transport stages are the most expensive per avoided tonne of CO_2.

Figure 12 presents the project costs and incomes for Western Macedonia per year when implementing the long-term scenario. From 2027 to 2030, the region will incur the most expenses in the transport stage, followed by the storage stage. However, from 2030, the first year of the long-term scenario, Western Macedonia will earn from EUA/ETS savings and CO_2 sales. Thus, the regional revenues will be much higher than the costs during the long-term scenario. This indicates that the developed long-term scenario is highly advantageous and profitable for Western Macedonia, both economically and environmentally.

4. Discussion - Conclusions

In the period from 2011 to 2019, the costs related to lignite activity in the lignite units of Western Macedonia decreased by about 10% per year [16]. The goal of a complete national lignite phase-out by 2028 is included in the National Plan for Energy and Climate. The commitment to phase-out lignite in power generation will lead to a radical transformation of the energy sector and achieve a climate-neutral economy. CCUS is an essential technology for climate change mitigation and can also deliver economic growth and employment. Industries such as cement, iron and steel, chemicals, natural gas, and electricity generation can benefit from the ability of CCUS to deep-cut industrial CO_2 emissions. The CCUS sector is growing at an unprecedented rate and this growth is accelerating. The economic performance of CCUS is becoming increasingly important for achieving reliant net-zero technologies. CCUS projects can stimulate the development of CCUS technologies to reach the EU's long-term climate targets at the lowest possible cost.

The development of CCUS technologies in Western Macedonia can provide a significant boost to the Greek region. The region has experienced major economic decline due the decarbonisation phase, resulting in business shutdowns and job losses. However, for both the medium-term and long-term scenarios, several benefits are brought to the region, both in economic and environmental terms. The deployment of CCUS technologies can create jobs in various sectors such as power, cement, steel, refinery, oil & gas, shipping, and the pipeline industry. For example, constructing CO_2 capture facilities, CO_2 transport pipelines, and geological storage sites can generate employment in construction, engineering, and manufacturing. Western Macedonia offers a high storage capacity, which is crucial for the development of CCUS technologies. In addition, the Ptolemaida V lignite unit, the only emitter for both scenarios, is CCUS ready, providing a significant advantage for CCUS projects. Although construction costs will be high in the first years of both scenarios, the regional revenues are expected to exceed the costs. In addition, the environmental benefits of the application of CCUS technologies in the region are clear, as a significant amount of carbon dioxide emissions would be avoided.

In addition, as part of the STRATEGY CCUS project, transnational scenarios were also developed beyond these two local scenarios. One scenario involved France, Spain, and Greece. In this transnational scenario, France and Spain participated with their carbon dioxide emitters and heavy industries for carbon capture, while storage took place in Greece due to its large geological reservoirs. Prior to storage, the CO_2 was transported by ship to the port of Thessaloniki and utilised the pipeline network of the medium and long-term scenarios. The benefits of such a process go beyond the national borders and lead to a collective approach towards the climate change problem. Countries with geological storage capacity can provide the storage aspect, while countries with large industries can cover the capture part. This interconnection between countries allows for a holistic solution to the problem and facilitates the effective adoption of CCUS technologies.

Author Contributions: Conceptualisation, N.K., R.K., D.K., G.S.M. and P.T. ; methodology, R.K., D.K., G.S.M. ; software, P.C., A.N., J.C. and P.M.; validation, N.K., and P.C; formal analysis, R.K., D.K. and G.S.M.; investigation, N.K., R.K., D.K. and G.S.M. ; resources, D.K.; data curation, R.K; writing—original draft preparation, R.K., D.K. and G.S.M.; writing—review and editing, N.K., R.K., and G.S.M.; visualisation, D.K., A.N. and P.M; supervision, N.K.; project administration, P.C., P.C. and N.K; funding acquisition, P.C., P.C. and N.K. All authors have read and agreed to the published version of the manuscript.

Funding: The STRATEGY CCUS project has received funding from the from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 837754.

Acknowledgments: During the work we got lots of support by the partners in the STRATEGY CCUS project. They are acknowledged for their continuous support and constructive criticism during the development of the scenarios.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

[1] IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

[2] UNFCCC. The Paris Agreement. in Paris Climate Change Conference. 2015. Paris, France: United Nations.

[3] Ritchie, H. (2019), Energy, Our World in Data, ***https://ourworldindata.org/***

[4] Griffiths, T., Pearson, R., Michael Bluck, M., and Takeda, S. (2022). The commercialisation of fusion for the energy market: a review of socio-economic studies. Progress in Energy, Volume 4, Number 4. ***https://doi.org/10.1088/2516-1083/ac84bf***

[5] IEA (2021), World Energy Outlook 2021, IEA, Paris ***https://www.iea.org/reports/world-energy-outlook-2021***

[6] Population Data of Western Macedonia. (2019). ***https://westernmacedonia.gr/pluthismiaka-stoixeia-dutikis-makedonias/*** (accessed on 14 December 2021)

[7] Hellenic Statistical Authority. (2022). 2021 Census Results of Population and Housing 2021.

[8] Vlassopoulos, C. (2020). Persistent lignite dependency: The Greek energy sector under pressure. Energy Policy, 147, 111825. ***https://doi.org/10.1016/j.enpol.2020.111825***

[9] Gastine, M., R. Berenblyum, R., Czernichowski-lauriol, I., de Dios, J.C., P. Audigane, P., Hladik, V., Poulsen, N., Vercelli, S., Vincent, C., Wildenborg, T. (2017). Enabling Onshore CO2 Storage in Europe: Fostering International Cooperation Around Pilot and Test Sites. Energy Procedia, 114, 5905-5915. ***https://doi.org/10.1016/j.egypro.2017.03.1728.***

[10] Kanniche, M., Gros-Bonnivard, R., Jaud, P., Valle-Marcos, J., Amann, J. M., & Bouallou, C. (2010). Pre-combustion, post-combustion and oxy-combustion in thermal power plant for CO2 capture. Applied Thermal Engineering, 30(1), 53-62. ***https://doi.org/10.1016/j.applthermaleng.2009.05.00***

[11] Koukouzas, N., Tyrologou, P., Karapanos, D., Carneiro, J., Pereira, P., de Mesquita Lobo Veloso, F., Koutsovitis, P., Karkalis, C., Manoukian, E., Karametou, R. Carbon Capture, Utilisation and Storage as a Defense Tool against Climate Change: Current Developments in West Macedonia (Greece). Energies. 2021. 14(11):3321. ***https://doi.org/10.3390/en14113321***

[12] Bachu, S., Didier Bonijoly, D., Bradshaw, J., Burruss, R., Holloway, S., Christensen, N.P., Mathiassen, O.M. CO2 storage capacity estimation: Methodology and gaps. International Journal of Greenhouse Gas Control. 2007. 1 (4), 430-443, ***https://doi.org/10.1016/S1750-5836(07)00086-2.***

[13] Nermoen, A., Berenblyum, R., Coussy, P., Guichet, X., Canteli, P., Mesquita, P., ... & Orio, R. M. (2022). A Techno-Economic Analysis Tool for Regional CO2 Capture, Transport, Use and Storage Scenarios. Transport, Use and Storage Scenarios (July 8, 2022). ***http://dx.doi.org/10.2139/ssrn.4271525***

[14] Coussy, P., Canteli, P., Dumas, C., Carneiro, J., Gravaud, I., Guichet, X., ... & Krawczyk, P. (2022). Economic Evaluation of Eight Regional Scenarios for the Deployment of Carbon Capture, Use and Storage in Southern and Eastern Europe to 2050. ***http://dx.doi.org/10.2139/ssrn.4205472***

[15] Zelilidis, A.; Piper, D.; Kontopoulos, N. Sedimentation and Basin Evolution of the Oligocene-Miocene Mesohellenic Basin, Greece. AAPG Bull. 2002, 86, 161–182. ***https://doi.org/10.1306/61EEDA6C-173E-11D7-8645000102C1865D***

[16] Ministry of the Environment and Energy. (2020). Just Transition Development Plan of lignite areas. ***https://www.sdam.gr/sites/default/files/consultation/Master_Plan_ Public_Consultation_ENG.pdf***