Carbon Capture, Utilisation and Storage as a Defense Tool against Climate Change: Current Developments in West Macedonia (Greece)

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Abstract: In West Macedonia (Greece), CO_2 accounts as one of the largest contributors of greenhouse gas emissions related to the activity of the regional coal power plants located in Ptolemaida. The necessity to mitigate CO_2 emissions to prevent climate change under the Paris Agreement's framework remains an ongoing and demanding challenge. It requires implementing crucial environmentally sustainable technologies to provide balanced solutions between the short-term needs for dependency on fossil fuels and the requirements to move towards the energy transition era. The challenge to utilise and store CO_2 emissions will require actions aiming to contribute to a Europe-wide CCUS infrastructure. The Horizon 2020 European Project "STRATEGY CCUS" examines the potential for CO_2 storage in the Mesohellenic Trough from past available data deploying the USDOE methodology. Research results show that CO_2 storage capacities for the Pentalofos and Eptachori geological formations of the Mesohellenic Trough are estimated at 1.02 and 0.13 Gt, respectively, thus providing the potential for the implementation of a promising method for reducing CO_2 emissions in Greece. A certain storage potential also applies to the Grevena sub-basin, offering the opportunity to store any captured CO_2 in the area, including other remote regions.

Keywords: carbon capture utilisation and storage; climate change; mesohellenic basin; carbon emissions

1. Introduction

The global economy is highly dependent on electrical energy to meet current and future demands on food, water sanitation, higher living standards and any other daily activity. Water, energy and food are important natural resources that influence the human health, quality of life, as well as the economic growth and social progress at the national and global levels. These three factors should be examined within a systematic and holistic framework and they cannot be considered separately [1]. Climate change is a global phenomenon that further affects and complicates the interrelationships between water, food and energy. In this context, the water-food-energy-climate nexus is one of the most important challenges to achieve sustainable development. Due to the emerging developing countries and global economic growth, the energy demand is steadily increasing, albeit slower than in previous decades, with an average of about 0.7% per year through 2050 compared to a more than 2% average from 2000 to 2015 [2,3]. The reduction in the growth rate is due to increased efficiency resulting from industrial digitisation, structured economic growth that has led to

a decline in European and North American demand, and the global economic shift towards less demanding energy services.

Industry is an essential economic growth source and a critical factor in our modern society that creates wealth while it is also responsible for nearly one-third of global greenhouse gas emissions. Tables 1 and 2 show details on the electrical energy forecast requirements from the present to 2040. Primary energy consumption measures total energy consumption and losses during the electrical energy transformation process. Total final energy consumption estimates the energy demand requirements of customers.

Table 1. Total primary and final energy consumption requirements for Europe in Mtoe unit [4].

	2020	2021	2022	2023	2024	2025	2030	2035	2040
Primary	1858	1852	1842	1831	1818	1800	1712	1658	1650
Final	1354	1357	1357	1354	1346	1334	1261	1211	1193

Table 2. Forecast for Europe's total energy demand from 2020 to 2040 including the categories of the energy sector [4]).

Category	Unit	2020	2025	2030	2035	2040
Demand for electricity consumption	TWh	3398	3528	3648	3793	3985
Total electrical capacity installed	GW	1331	1430	1488	1556	1617
Renewables % in the generation of electricity	%	39.9	45.6	49.0	51.9	53.8
Consumption of natural gas	bcm	339	328	292	259	241
Inputs for natural gas for power plants	Mtoe	130	141	142	148	156
Total emissions of CO_2, including industrial processes	$MtCO_2$	3959	3670	3313	3075	2940
CO_2 intensity for electricity generation	gCO_2/kWh	268	230	198	180	168

In 2018 figures, 81% of the electrical energy is produced via burning fossil fuels that convert chemical energy to electricity [5]. To sustain economic growth at the current increasing population rates, many scenarios were established based on a mix of fossil fuels and renewables, with a progressively increasing share of renewables at the expense of fossil fuels [6,7].

The above follows the European Council objectives to achieve the current 2030 targets for GHG emissions, renewable energy and energy efficiency. These targets for the EU-27 are: (a) at least a 40% reduction in the domestic GHG emissions (compared with 1990 levels), (b) an increase in the energy derived from renewable sources to at least 32% of gross final energy consumption by 2030 and (c) at least a 32.5% improvement in energy efficiency by 2030 [8].

Current economic and social issues continue to hamper the development of renewable energy sources [6,9]. Burning fossil fuels emits greenhouse gases such as CO_2 and nitrous oxide (N_2O) that contribute significantly to climate change and global warming [10]. Reducing emissions in industry is one of the most significant challenges for reaching net-zero emissions. Combustion of natural gas emits 50–60% less CO_2 with respect to combustion of coal. As a result, the use of natural gas is expected to increase by 40% by 2021 [4], while burning coal and oil will be significantly reduced but still will claim a significant proportion of the energy conversion [10].

The atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have all increased since 1750 due to human activity [11]. In 2011 the total concentration of these greenhouse gases was 391 ppm. The annual CO_2 emissions production

from fossil fuel combustion and cement production during 2002–2011 was on average 8.3 [range 7.6 to 9.0] gigatonnes of carbon/yr while in 2011 reached 9.5 [8.7 to 10.3] gigatonnes of carbon/yr in 2011, 54% above the 1990 level [11]. Over the past decade, carbon dioxide (CO_2) emissions have seen a 2.7% annual increase globally directly related to increased energy demands.

Floods, droughts and wildfires have increased in frequency and intensity due to the greenhouse effect caused by the elevated CO_2 emissions [10,12]. Changes in climate can be attributed to natural processes (such as volcanic eruptions and solar variations) or they can have an anthropogenic origin, which is linked with deforestation, urban development and greenhouse gas emissions. CO_2 is one of the most common greenhouse gases that is substantially associated with human activities. In particular, countries with lower development degrees, which are based on the use of fossil fuels for their energy demands present higher CO_2 emissions compared to the most developed countries, which are characterised by higher consumption of renewable resources [1,13]. Climate change has profound consequences on societal resilience. An example of this is food security. Crop productivity is directly affected by temperature variation, amount of rainfall, radiation, humidity on crop development and growth [14,15], and damages caused by extreme heatwaves, hail, and flooding [14]. While increased CO_2 atmospheric emissions is expected to benefit crop productivity at lower temperatures, it may reduce nutritional quality [11]. It is forecasted that in 2050, due to climate change, a cereal price increase of up to 29% would impact consumers globally through higher food prices.

The Paris Agreement aims to reduce CO_2 emissions by 60% [16]. Such reductions will be possible only by decoupling economic growth and CO_2 emissions [15]. Improving efficiency in both the energy demand and supply sector, implementing low-carbon energy sources and capturing CO_2 from fossil fuel combustion are critical strategies for reducing CO_2 emissions.

2. Current State of the Art

Carbon Capture, Utilisation, and Storage (CCUS) is widely recognised as a vital technology required to meet the Paris Agreement's goals. CCUS technology (Figure 1) involves capturing CO_2 from industrial flue gases, pipelines for transportation, utilisation sites, and finally injecting the surplus into secure geological reservoirs [17–20]. This paper presents a review on potential CCUS clusters and transport systems and then provides a CO_2 storage resource assessment.

Capture technologies include post-combustion capture, pre-combustion capture [21,22], oxy-fuel combustion [22,23], and chemical looping combustion [24]. After being captured, CO_2 could be converted into products and services such as fuels, chemicals, building materials from minerals, building materials from waste, and CO_2 used to enhance the yields of biological processes. Although a market exists already for these technologies, it is expected to remain relatively small in the short term; each of the cited mature technologies of CO_2 uses would be scaled-up to a market size of at least 10 Mt/yr [25]. CO_2 uses have a limited impact on climate change, as current technologies are not able to sequester permanently large quantities of CO_2. Indeed, CO_2 utilisation is not considered as CO_2 avoidance.

Geological CO_2 storage provides the potential for storing permanently large quantities of CO_2 through various options mitigating the effects of climate change [26]. These options include deep saline aquifers [27], salt caverns [28], coal seams [29], abandoned coal mines [30] and depleted hydrocarbon fields [31]. Enhanced oil and/or gas recovery (CO_2-EOR and CO_2-EGR respectively) are processes that combine the extraction of crude oil and/or natural gas with simultaneous CO_2-storage [32]. CO_2-mineralisation is an additional option for CO_2-storage that involves the chemical reaction of several rock-types (such as basalts, sandstones and serpentinites) with supercritical CO_2, resulting in formation of carbonate minerals, and the subsequent CO_2-sequestration in the form of thus formed carbonate minerals [33–39].

CO$_2$ captured via:
1. Pre-combustion
2. Post-combustion
3. Oxy-fuel combustion
at plants, no emissions
into the atmosphere

Utilisation

1. Chemical products
2. Liquid fuels
3. Bio-energy (algae)
4. Enhanced Oil Recovery (EOR)
5. Concrete building materials
6. Polymers
7. Urea

Storage: excess
carbon is stored in
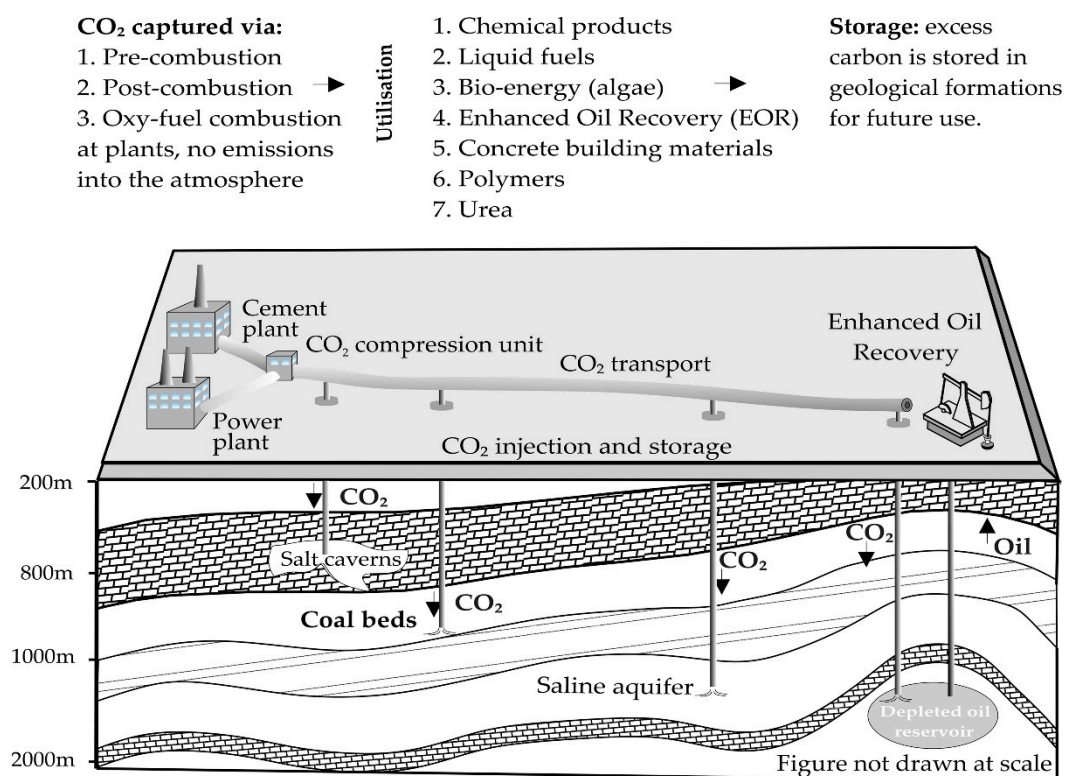geological formations
for future use.

Figure 1. Depiction of CCUS technology.

CCUS could reduce ~19% of CO$_2$ emissions until 2050 [7]. This corresponds to a rapid increase in CCUS growth from the current amounts of captured CO$_2$ (~30 million tonnes) to 4000 Mt of captured CO$_2$ until 2040 [40,41].

Current fossil-fuel based power plants can be modified and use various capture technologies to capture CO$_2$. Certain technologies have been implemented commercially for some industrial process and needs (production of urea and methanol, EOR) while others are found in the pilot or the demonstration stage (oxy-fuel) [42].

The high cost of capturing CO$_2$ can be offset by the higher carbon tax and positive value applications that will utilise CO$_2$ [40]. The CO$_2$ price on the EU Emissions Trading System (EU ETS), well below 10 €/tCO$_2$ from 2012 to 2017, is increasing since 2018, reaching the highest ETS price of 51.40 €/tCO$_2$ on 24 May 2021 [43]. Still, emerging capture technologies are even more promising, with a 40% energy reduction compared to the current ones [44].

Industry and government have proven first-generation CCUS technologies with large-scale projects that are operating globally. These projects have a CO$_2$ capture capacity of 37 million tonnes per annum (Mtpa)—the equivalent of eight million cars removed from the road each year [45]. The Sleipner and Snovit projects in Norway contribute valuable experience lessons for CCS in Europe. Since 1996, both projects have captured and securely stored 20 million tonnes of CO$_2$ into deep offshore saline formations [46].

The research presented is part of the STRATEGY CCUS project, funded under the Horizon 2020 program. STRATEGY CCUS aims to elaborate economic scenarios at short (2030) and long-term (2050) time-scale of carbon capture, utilisation and storage (CCUS) in eight European Union regions identified as promising since they feature strategic elements, such as clusters of industry, potential CO$_2$ storage sites, opportunities for CO$_2$ usage, and options for hydrogen production and use. Each of these is situated in Portugal, Spain, Croatia, Greece, Romania, and France, with two regions.

The scenarios identify CO$_2$ transport corridors between local CCUS clusters of industry, including the possibility of connecting to the North Sea CCUS infrastructure, reducing costs, and contributing to a Europe-wide CCUS infrastructure. Greece and especially West

Macedonia is part of the project and are being investigated for the potential to deploy CCUS technologies to reduce carbon emissions during its energy transition from a high to a low carbon energy production system.

Data regarding carbon emissions, related industrial infrastructure, potential industrial carbon utilisation, geological storage potential was collected from: (a) Public Power Corporation, (b) Greek Ministry of Energy, (c) available databases of the European Environment Agency (d) published scientific literature and (e) field research. Data collected, where possible, were cross-correlated before being reported.

2.1. Current Energy Reforms in Greece

Greece is currently implementing comprehensive energy sector reforms to advance competitive energy markets. By increasing the share of natural gas and renewables in the energy mix, Greece can achieve longer-term reduction emissions outcomes.

To meet the current and future energy demand, burning fossil fuels (coal and natural gas) will be part of the energy mix during the transition time to renewable energy. Mitigating the emissions by fossil fuels burning can only be achieved by carbon capture and storage [47]. The 3,9 MtCO$_2$e (CO$_2$ makes up approximately 80% of total greenhouse gas emissions) offered for capture can be either utilised as raw material for product development or stored safely in reservoir rocks at depths > 800 m [48].

Despite the fact that Greece is the one of the largest lignite producers in the EU (after Germany, Poland and Czech Republic), it has achieved the national target to reduce 20% of the greenhouse gas emissions compared to those of 1990. In this context, generation of electricity from coal and oil in Greece, presented a remarkable reduction of ~50% for the time period between 2006 and 2016 (Figure 2). However, natural gas and oil present an increasing trend between 2016 and 2019 (reaching up to 4.3 and 10.3 Mtoe of energy supply respectively), whereas the coal use presents a continuously decreasing trend for the same time period that reaches up to 3 Mtoe.
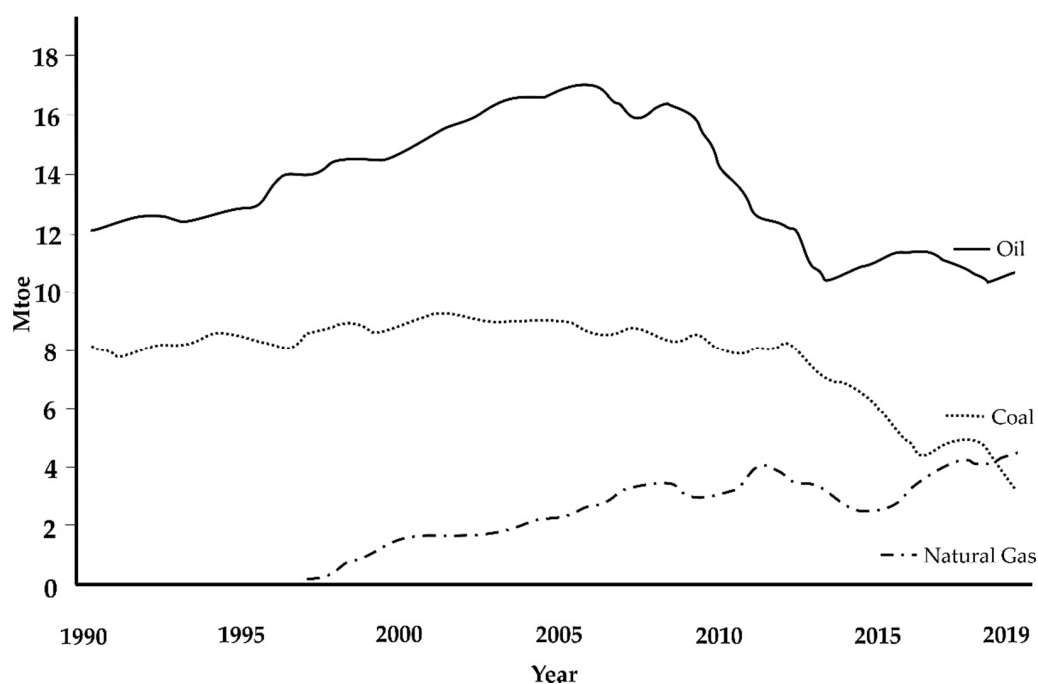

Figure 2. Total energy supply by source, Greece 1990–2019 (source: IEA, World Energy Balances 2020).

During the same period, power generated from renewable sources has almost doubled [49]. Based upon the Greek National Energy and Climate Plan for 2030, the greenhouse gas emissions (GHGs) will be reduced 55% compared to those of 2005 [50].

Oil consumption reached a peak at 16.393 ktoe in 2008. After this point, a downward trend concluded at 11.357 ktoe in 2016. Furthermore, coal's primary energy supply increased until 2007 (8.8ktoe) and from 2007 to 2019 declined by around 66% (~3 ktoe). Natural gas became the primary electrical energy supply throughout this 16-year period. In Greece, the total carbon footprint is measured at 6.26 tons per capita, while the EU measures 5.39 tons per capita. The total CO_2 emissions in Greece correspond to the consumption of: (a) diesel and gasoline (49%), (b) natural gas (8%), (c) coal (39%) and (d) other sources (4%) [49]. Natural gas is the only source of energy in which Greece outperforms the EU in per capita levels.

2.2. Industrial Cluster in Western Macedonia for Carbon Emission Capture

Western Macedonia is a heavily industrialised area of northern Greece with three active power plants based on lignite extraction that emit CO_2. One new power plant (Ptolemaida 5) is currently under construction, with an estimated operational date of 2022. The industrialisation of the area was achieved due to large domestic lignite resources available in Western Macedonia. The 2017 year was the last one with simultaneous operation of all the power plants and the quicklime and lime industry. Table 3 presents information regarding the industrial plants in Western Macedonia and their annual CO_2 emissions for 2017 year. CO_2 emissions from the industrial plants range between 40,150 and 8,940,000 tonnes per year. Most of these emissions are associated with coal (lignite) power plants, whereas a small amount of the total CO_2 emissions is attributed to the quicklime and lime industry.

Table 3. Information on industrial plants in Western Macedonia and their annual CO_2 emissions up to year 2017.

Facility Name	Sector [1]	City	Emissions (tCO$_2$/y) [2]	Main Fuel
Agios Dimitrios	Power 1587 MW	Kozani	8,940,000	Lignite
Amyntaio	Power 600 MW	Amyntaio	2,760,000	Lignite
Kardia	Power 1200	Ptolemaida	6,400,000	Lignite
Meliti	Power 330 MW	Florina	2,270,000	Lignite
Ptolemaida	Power 620 MW	Ptolemaida	2540,000	Lignite
Liptol	Power 43 MW	Ptolemaida	118,000	Lignite
Ptolemaida V	Power 660 MW	Ptolemaida	4,500,000 (estimated)	Lignite
Amyntaio	Quicklime	Amyntaio	40,150 (estimated)	No Data

Sources: [1] Greek Regulatory Authority for Energy, [2] European Environment Agency, Industrial reporting database, https://prtr.eea.europa.eu/#/pollutantreleases (accessed on 3 June 2021)

Figure 3 presents past, current and future operational powerplants in Western Macedonia that convert energy from lignite to electricity.

At the current stage there are three operational power plants in Western Macedonia namely A. Dimitrios, Kardia and Meliti (Table 4) and refer to the year of 2019. The A. Dimitrios power plant has five operating generators while Kardia one has currently two operating generators and two inactive. Both power plants are much older than Meliti's power plant which was built in 2003 and has one operating generator. These differences are the cause of the inequalities between the data shown below. A. Dimitrios power plant carried out desulphurization in 2020, in order to reduce SO emissions. Based on Public Power Corporation S.A data (2021), SO ranges from 1,120 to 11,400 tonnes, followed by NO_2, which ranges between 893 and 41,400 tonnes in 2019. Carbon monoxide (CO) emissions (54.5–2180 tonnes) are substantially lower than those of SO and NO_2.
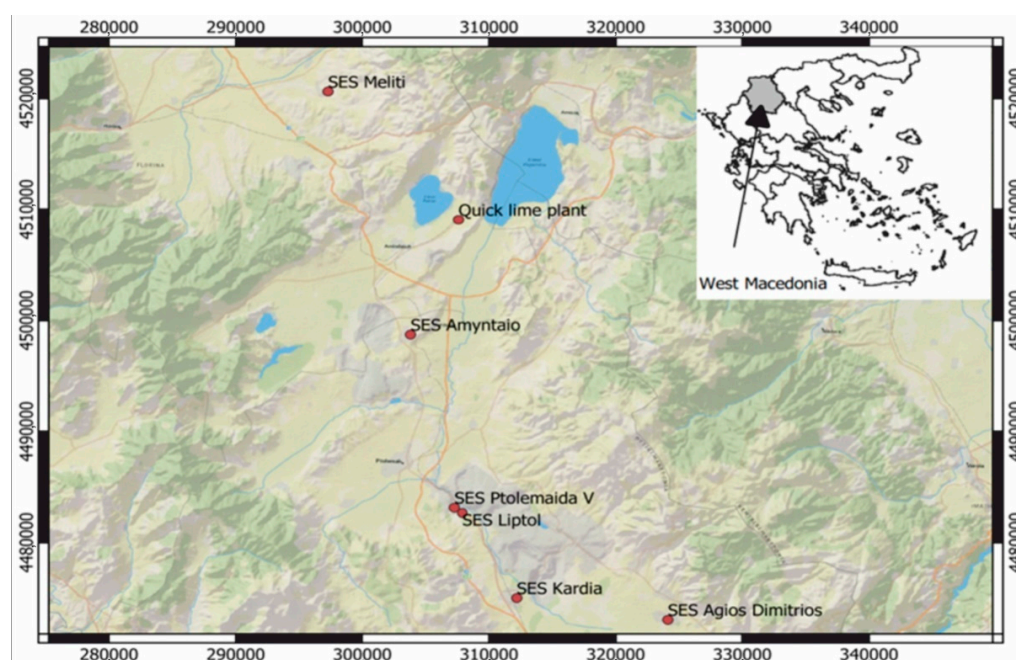
Figure 3. Locations of power and lime plants in the Western Macedonia.

Table 4. Data on the emissions from the operational power plants of the West Macedonia in 2019. (Source: Public Power Corporation S.A, 2021).

SES	Emissions (tCO$_2$/y)	CO$_2$ (% *v/v*)	T ($^\circ$C)	Flow Rate [1] (Nm^3/h)	CO (tn)	SO$_2$ (tn)	NO$_2$ (tn)
A. Dimitrios	6,840,000	12	151	571,8311.00	2180	11,400	4140
Kardia	2,870,000	10,375	147.52	756,324.67	2000	2960	2260
Meliti	1,410,000	12–14	65–69	786,133.61	54.5	1120	893

[1] Impurities observed: As, Cd, Cr, Hg, Ni, Pb, PM$_{10}$, NO$_x$/NO$_2$, SO$_x$/SO$_2$, CO, tn stands for tonne, average volume flow rate of flue gas.

Based on the new Greek National Energy and Climate Plan, all operating power plants will be retired by 2023, whereas Kardia is due for retirement in 2021. The only remaining operational lignite power plant will be the Ptolemaida V from 2022 to 2052, although the plan may still be revised, leaving other plants operational. The CO$_2$ emissions available for CO$_2$ capture will be Ptolemaida V powerplant, estimated at 4.5 Mt/y for 30 years. The plant is designed as a CCS-ready facility.

2.3. Potential for Carbon Utilisation in the Greek Industry

Captured CO$_2$ is delivered in high purity, allowing for potential utilisation in various applications such as fuel, chemical products, and concrete building materials [21]. Currently, Western Macedonia has limited potential to utilise the CO$_2$ produced. Other industrial users are located in other parts of Greece (Table 5).

The region of Prinos (South Kavala, Northern Greece) can serve as a potential site for high capacity and cost-effective CO$_2$-storage. Estimations indicate that the off-shore Prinos basin has a storage capacity of 30 Mt CO$_2$ within the oil reservoirs and 1350 Mt CO$_2$ within the 2.4 km depth saline aquifers [51]. In the same region, the Miocene sandstones, which are located at ~1600 m depth provide an additional option for the implementation of CO$_2$-storage technologies with a capacity of 35 Mt CO$_2$. The Prinos oil and gas field holds the potential to combine CO$_2$-stoarge with underground gas storage (UGS) technologies. Research studies suggest that the Prinos oil-field is amongst the most promising sites for UGS in Greece, presenting a total gas volume and energy storage capacity of

2280 mm^3 and 4,826,105 MWh[e] respectively [52]. The Prinos oil fields can provide secure and cost-effective site for CO_2-EOR due to its-reservoir properties, the short distance from the mainland, as well as the presence of existing infrastructures. The aforementioned indicate that the region of Prinos provides significant advantages for safe long-term and cost-effective storage scenarios.

Table 5. Potential Greek industries available for CO_2 utilisation.

Industrial Sector for CO₂ Utilisation	Number of Industries in Greece			
	North	Central	South	Total
Building materials	7	7	-	14
Refineries (synthetic fuels)	1	3	-	4
Yield boosting (greenhouses, urea, fertilisers)	1	-	1	2
Chemicals industry (plastic, resins, foams)	5	-	1	6
Other (e.g., ink, aluminum)	1	2	-	3

The EU strategy for reduction of the industrial energy consumption attempts to achieve sustainable development by combining high energy efficiency with environmental protection and decarbonisation. In this context, the Clean Energy Package (CEP) attempts to reduce the energy consumption by at least 32.5% until 2030 [53,54]. EU is highly depended on oil and natural gas energy imports, which create further concerns regarding the energy policy that should be followed [53]. The increasing demand for clean energy, has led to the exploitation of alternative energy resources, such as hydrogen, wind, solar and hydro power. Several technological processes have been developed for the production of pure hydrogen [55]. At the current stage, the increasing hydrogen demands are covered by fossil fuels such as coal, oi and natural gas, through technological processes, namely regarded as "hydrogen pathways". Combination of these processes with CCUS, provides the opportunity to integrate the mitigation of CO_2 emissions into the hydrogen production, giving rise to the blue hydrogen pathways [55]. Financial estimations on the future cost trends of blue hydrogen indicate that the total cost in terms of blue hydrogen mass are expected to be within the range of 1.20–3.00 USD/kg of produced hydrogen by 2050 [55,56]. In Greece, Energian Plc plans to develop the first CO_2-storage/small-scale hydrogen plant in Mediterranean close to the Prinos oil-field, with a capital expenditure of ~500 million USD [57].

2.4. CCUS Corridors and Transport Routes

Transport of CO_2 for either utilisation or storage can be achieved via road transport and shipping similar to the North Sea CO_2 development, using pipelines or combining the aforementioned. Western Macedonia is connected via the national roadway network to the rest of Europe through the Balkan countries. The same road network provides access to the rest of Greece and seaports. The nearest ports from the Western Macedonia industrial hub to the east (Aegean Sea) are Thessaloniki (140 km), Kavala (291 km) and Alexandroupolis (450 km), whereas Igoumenitsa (230 km) to the west provides access to the Ionian Sea. The ports of Alexandroupolis and Thessaloniki have oil and gas terminals with the potential to host CO_2 related infrastructure in the future. Larger-scale CO_2 cargo in the range of 10,000 to 40,000 m^3 shares similar characteristics with the shipment of liquefied petroleum gas (LPG).

Other means of CO_2 transportation can be offered through the Southern Gas Corridor by the 878km-long Transadriatic pipeline that currently transfers natural gas from the Caspian region to Europe through Greece, Albania, and Italy. The initial pipeline's capacity is ten bcm/y to be expanded at 20 bcm/y. Technologies are currently under development for the simultaneous transfer of CO_2 and natural gas [58].

2.5. Estimation of Carbon Geological Storage in Mesohellenic Trough

Greece offers opportunities for CO_2 storage such as deep saline aquifers in the Greek Mesohellenic basin and existing depleted hydrocarbon fields in the Tertiary sedimentary basins of Prinos. The Mesohellenic basin and its Grevena sub-basin area offer CO_2 storage for the Western Macedonia industrial cluster due to its 50 km proximity and the deep saline aquifers.

Koukouzas et al., 2016 [59], based on initial assumptions, estimated the CO_2 storage in the Grevena area at 5.8 gigatonnes for Pentalofos formation and 722 gigatonnes for the Eptachori formation.

The maturity level and the confidence of storage resource capacity appraisal was re-evaluated in STRATEGY CCUS. The classification of storage resources followed a two-fold approach. The first one provided a qualitative assessment of suitability to enhance the capacity estimate. Suitability covers all technical aspects of storage from reservoir capacity and quality to seals, faults and wells. The appraisal consisted of a Boston Square Analysis (BSA) score for both attribute suitability and data quality.

The second fold provides a classification based on a pyramid approach. Capacity estimates were ranked using a quantitative resource pyramid approach consisting of four tiers that reflect the increasing maturity of data and understanding related to potential storage capacity from regional first approximations to targeted storage sites candidates. The requirements for each tier reflect this maturation [60].

A tiered approach is a risk assessment progressing from relatively simple to more complex systems, reducing the evaluation's uncertainty when moving to higher tiers [61]. The first tier provides a theoretical estimate of the storage capacity. [62].

The Mesohellenic basin has a 150 km length and 30 km width. It is partly located in Northern Greece and partly in Albania and was developed from Middle Eocene to Upper Miocene. The Grevena sub-basin area is suitable for CO_2 storage [40] and comprises five molassic-type geological formations in a gently-stipping syncline setting (Figure 4). From top to down, these are:

1) Ondria Formation (Early-Middle Miocene epoch), partly eroded, consists of sandstones and marls with a maximum estimated thickness of about 350 m [63].
2) Tsotyli Formation (Lower-Middle Miocene epoch) with a thickness of about 1500 m to 2000 m [64,65]. The Tsotyli Formation consists of ophiolite-derived conglomerates and it has been characterised as an effective cap rock [66]. In the southern part of the basin, the Tsotyli Formation overlies the Pentalofos Formation unconformably.
3) Pentalofos Formation (Upper Oligocene-Lower Miocene epoch) consists of conglomerates, followed by turbiditic sandstones and shales. The formation has an average 2500 m thickness. The maximum thickness of 4000 m is observed in the centre [63,65].
4) Eptachori Formation (Uppermost Eocene—Lower Oligocene epoch) consists of conglomerates and sandstones overlain by marine turbiditic shales. Structurally, they have a thickness of about 1100 m [65] with a dipping 60–70° to the east [67].
5) Krania Formation (Middle-Upper Eocene epoch) is characterised by various facies, including coarse breccias, olistolithic blocks, turbiditic siltstones, fine-grained sandstones [67]. The formation has an estimated thickness of 1500 m [63,65,68].

Two formations provide the storage capacity in Grevena sub-basin (i) the Pentalofos Formation, with Tsarnos and Kalloni daughter units of similar lithologic composition, comprising conglomerates, turbiditic sandstones (occasionally coarse-grained) and shales, with a porosity ranging from 7% to 25% and (ii) the Eptachori formation (undivided) comprising conglomerates and sandstones that are overlain by marine turbiditic shales. Its porosity ranges around 12% [65].
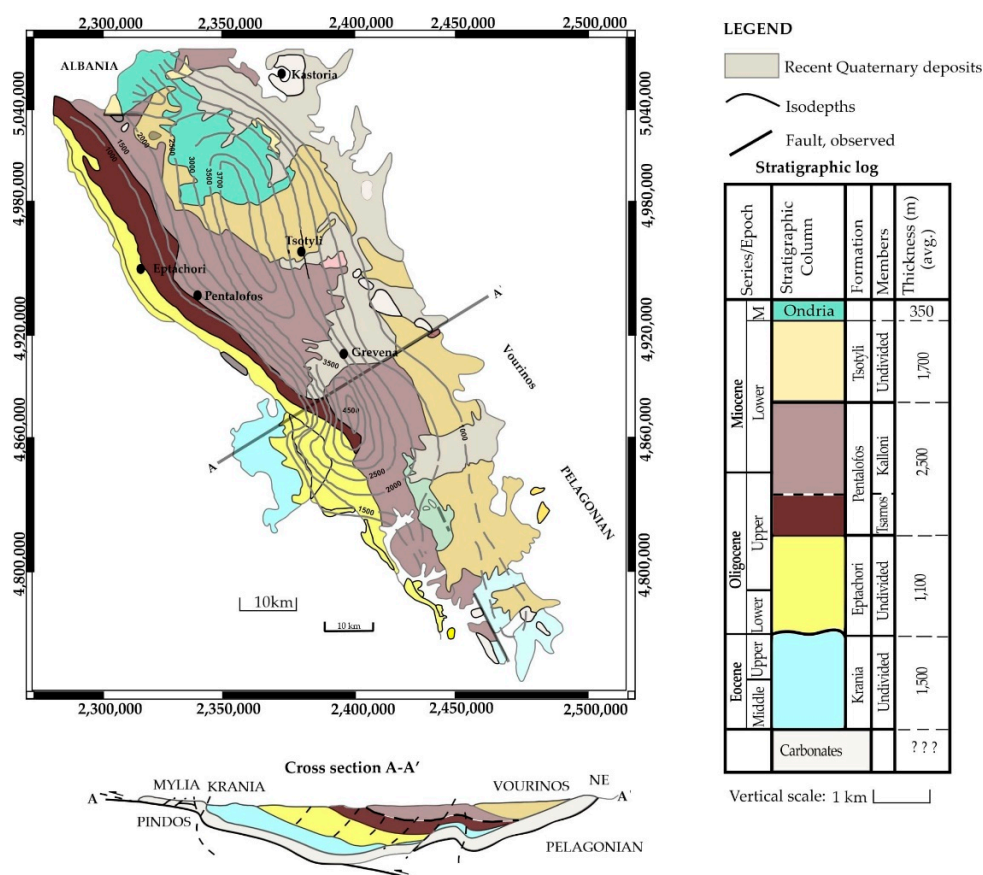
Figure 4. Geological Map and stratigraphic column adapted from Ferriere et al., 2004, of the proposed CO_2 Storage basins in Grevena area depicting Pentalofos and Eptachori formations, scale 1:1,000,000. Cross-sections of the Mesohellenic Trough. Lithological formations: Krania Turbidites, Eptachori, Taliaros, Pentalofos, Tsotyli. M stands for Middle Miocene, scale 1:500,000.

The CO_2 storage capacity was estimated using the United States Department of Energy—National Energy Technology Laboratory (US-DOE-NETL) methodology based on data availability [3,45,69] as adopted in the STRATEGY CCUS project [70,71]. This method applies to a region when subsurface geologic data are sparse and limited.

The volume of CO_2 storage is estimated using a stochastic modelling procedure taking into account the variation in the geologic parameters such as total formation area, gross thickness, and total porosity. Regional geothermal gradient obtained from previously published data for an average depth of 2500 m [72]. Equation (1) describes the estimation of CO_2 storage capacity:

$$G_{CO2} = A \times hg \times f_{tot} \times \rho_{res} \times E_{saline} \times NG \tag{1}$$

where G_{CO2} is the CO_2 storage capacity of a prospect field as a mass (kg), A is the total area of the prospect reservoir (m^2), hg is the gross reservoir thickness (m), f_{tot} is the average total porosity (ratio), ρ_{res} is the CO_2 density at reservoir storage conditions (kg/m^3), NG is the net-to-gross factor and E_{saline} the storage efficiency factor (ratio).

The total area (A) of the prospect reservoirs for the Pentalofos and Eptachori was obtained from Koukouzas et al. 2019 [73]. The gross reservoir thickness was estimated from Feriere et al., [63] (Figure 4).

The Pentalofos Formation storage unit is subdivided into two daughter units, Tsarnos overlain by Kalloni. The daughter units consist of turbidite sandstones, shale and conglomerates [74] with a bibliographic derived f_{tot} porosity of 0.15 [52]. The base of the Tsarnos member at 2544 m is the deepest point that CO_2 can be stored. The Eptachori formation is not divided into daughter

units and is dominated by thick conglomerates and sandstones with an estimated f_{tot} porosity of 0.12 (Figure 4). Both porosities were calculated based on the formations' geological history (burial, uplifting) [75]. It is noted that the obtained porosities represent a crude estimation based on mechanical particle sorting and compaction without considering chemical dissolution, recrystallisation and cementation [75,76]. To account for the aforementioned, the porosity values that were selected and presented above belong to the conservative spectrum of porosity values, i.e., P90 (90% of reservoir have porosity greater than this value).

The CO_2 density at reservoir storage conditions ρ_{res} is calculated using temperature and pressure variables. The temperature at 1500 m and 2000 m depth was estimated from available geothermal gradients for Greece [72]. Pressure was calculated by multiplying the average overburden density of the overlying rocks with depth. This conservative approach was adopted, as a first estimation, due to the fact that current data of seal fraction pressure is not as yet available. Using the previously mentioned parameters, the ρ_{res} was determined using the Online Calculation Carbon dioxide (peacesoftware.de) software [77]. Table 6 summarises the characteristics of potential onshore storage units' features in West Macedonia for a conservative scenario of a 0.01 storage efficiency factor (E_{saline}) [78–80].

Table 6. Geological properties for the Pentalofos and Eptachori formations.

Formations	Geological Properties						
	Lithology	Average Depth (m)	A (m^2)	hg (m)	f_{tot}	ρ_{res} (kg/m^3)	E_{saline}
Pentalofos	Conglomerates, turbiditic sandstones and shales	1500	1147	2500	0.15	594	1
Eptachori	Conglomerates, sandstones, marine turbiditic shales with lignitic horizon, marine sandstones and some pebbly conglomerates	2000	400	1100	0.12	603	1

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For each input parameter that compose the Equation (1), the intrinsic uncertainty for both potential reservoir formations needs to be considered. The degree of uncertainty associated with the storage capacity of these formations is high, mainly when selecting a single value of Esaline and for each petrophysical property, since these storage resources are classified at the lowest maturity level, i.e., the saline aquifers are still theoretical storage resources. For this reason, it is noteworthy that the uncertainty should not be neglected; instead it must be considered and carried out in the calculation of storage capacity of potential reservoirs.

To overcome this deterministic approach for storage capacity estimates, a stochastic modelling approach, based on the Monte Carlo method and using probability distribution functions (PDF's), was conducted enabling to integrate uncertainty degrees associated to the parameters of Equation (1).

The stochastic modelling approach was performed based on simulations using the probabilistic method of Monte Carlo to randomly generate and sample an ensemble of values for each reservoir parameter, conditioned to prior PDF's types and conditions firstly assigned, resulting in a final distribution. This approach allows for a better understanding of parameters variation and the integration of different degrees of uncertainty, according to the prior knowledge about each reservoir formation. In addition, a sensitivity analysis of the reservoir properties was also performed, enabling to identify which input parameters are more uncertain and, consequently, have a higher impact in the inferred storage capacity values for both geological formations.

Hence, probability distribution functions (PDFs) were assigned, based on the mean values of each reservoir parameter (Table 6) to incorporate the variability and intrinsic uncertainty of these parameters in the stochastic modelling.

To integrate the uncertainty associated with the storage efficiency factor, the storage capacity values were computed varying the E_{saline} according to the notation proposed in [71], which considers the maturity level of storage resources. Instead of using a deterministic value, storage efficiency factors of 0.75%, 1.5% and 3% were assigned to the potential storage units of maturity level Tier 1 for clastic reservoirs of semi-closed saline aquifers. These storage efficiency factors were used to integrate the uncertainty of this parameter when inferring the storage capacity of each geological formation, assigning a triangular distribution with an expected value of 1.5% and extreme values of 0.75% and 3% corresponding to the minimum and maximum values of the prior PDF's, respectively.

Besides the uncertainty associated with the storage efficiency factor (E_{saline}), the uncertainty of petrophysical reservoir properties, composing the Equation (1), was also incorporated, overcoming the previous deterministic estimates indicated in Table 6, to achieve more realistic values of storage capacity. The selection of PDF's type was conducted according to the prior knowledge of reservoir properties: Normal PDFs, with user-defined standard deviations, were assigned to the reservoir area and net-to-gross as the expected values were only available; and Pert PDFs were assigned for the reservoir thickness and porosity, as the expected boundary values (i.e., minimum and maximum) were also available. The ρ_{res} was the only input parameter that was set constant in this stochastic modelling approach. The same parameterization of these prior PDFs was kept for both geological formations under study as listed in Tables 7 and 8.
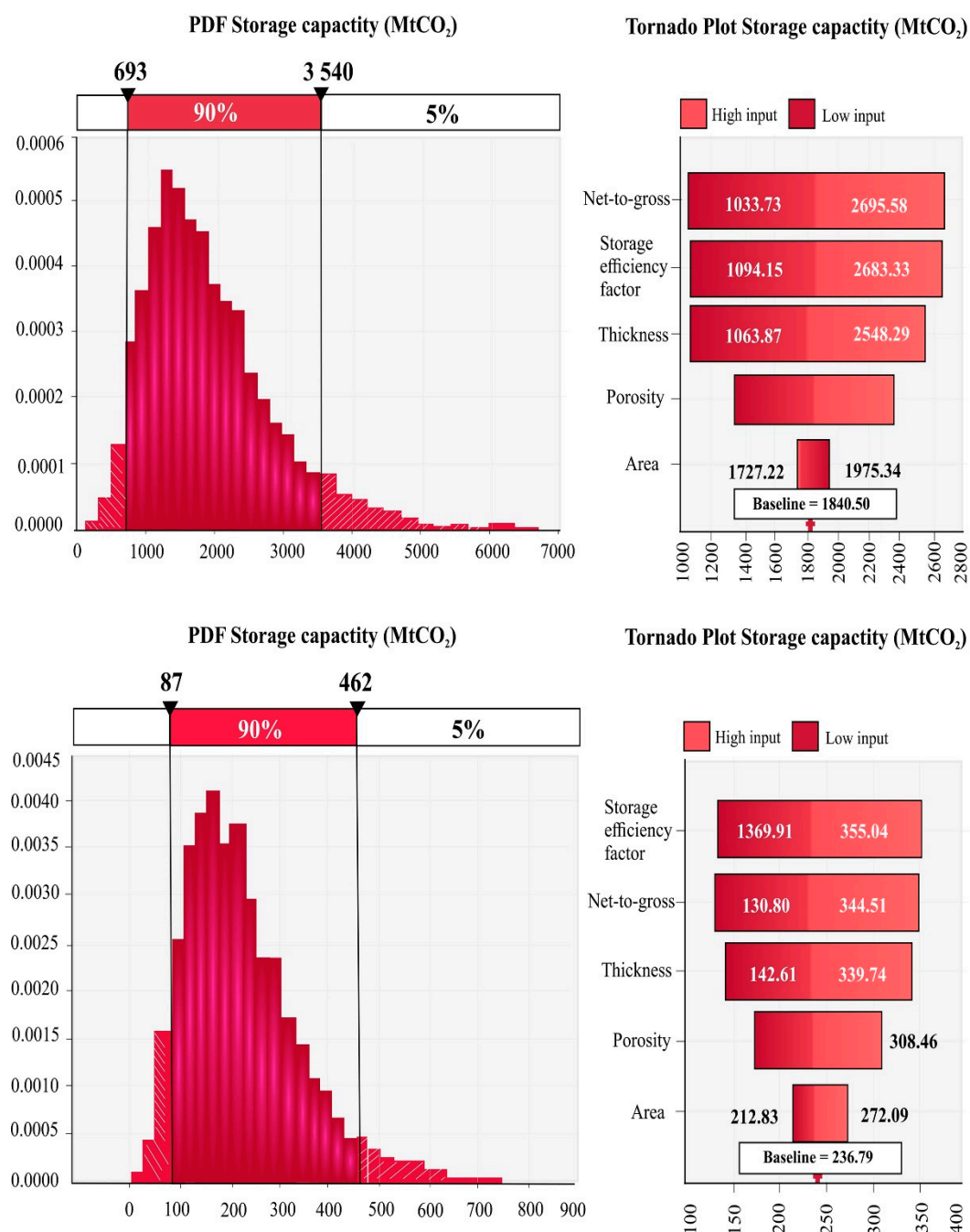
Table 7. Parameter distribution for the Pentalofos Formation.

Parameter	Units	Min	Most Likely	Max	Mean	Std	Distribution
Reservoir Area (A)	km^2	-	1147	-	1147	50	normal
Reservoir Thickness (h)	m	800	2500	4000	-	-	pert
ftot Porosity (Ø)	-	0.1	0.15	0.24	-	-	pert
Net-to-gross (NG)	-	-	0.4	-	0.4	0.1	normal
CO$_2$ density	kg/m^3	-	594	-	-	-	constant
Storage Efficiency Factor	-	0.0075	0.015	0.03			triangular

Table 8. Parameter distribution for the Eptachori Formation.

Parameter	Units	Min	Most Likely	Max	Mean	Std	Distribution
Reservoir Area (A)	km^2	-	400	-	400	50	normal
Reservoir Thickness (h)	m	500	1100	2000	-	-	pert
ftot Porosity (Ø)	-	0.07	0.12	0.18	-	-	pert
Net-to-gross (NG)	-	-	0.4	-	0.4	0.1	normal
CO$_2$ density	kg/m^3	-	603	-	-	-	constant
Storage Efficiency Factor	-	0.0075	0.015	0.03	-	-	triangular

In this work, 5000 Monte Carlo simulations were performed and applied to the storage capacity model (i.e., Equation (1)), corresponding the a posteriori PDFs of storage capacity values to the distribution of output estimates. The output PDF's of storage capacity and sensitivity analyses are illustrated in Figure 5 for Pentafolos and Eptachori Formations, represented by the histograms and the Tornado plots, respectively. The Tornado plots reveal that the storage efficiency factor and the net-to-gross are the most uncertain input parameters in the storage capacity models and, consequently, impact significantly the final estimates of storage capacity.

Figure 5. Histograms of storage capacity for the Pentafolos (**top**) and Epatchori Fm (**bottom**), resulting from 5000 Monte Carlo runs of Equation (1) using the probability density distributions (PDF's) of parameters in Tables 7 and 8, and the corresponding Tornado plots for each geological formation.

From the histograms of Figure 5, the final storage capacity values for each geological formation were extracted according to the 10, 50 and 90 percentiles, which corresponded to the low, best and high estimates, respectively. As we are dealing with storage capacity values, these final values must be associated with the uncertainty scenarios, i.e., P90, P50 and P10, considering the Proven, Likely and Possible scenarios of storage capacity, respectively. Thus, the final value for the P90 scenario was extracted from the 10 percentile value of the histograms illustrated in Figure 5, meaning that the 90% of inferred storage capacity estimates were equal or exceeded this value (Proven scenario). Contrarily, the P10 scenario corresponded to the extracted value of 90 percentile, meaning that only 10% of

final values from the storage capacity PDF's were equal or exceeded this value (Possible scenario). Finally, for the P50 scenario (i.e., the best estimate or the expected value) the 50 percentile value was extracted from the final PDF of storage capacity corresponding to the Likely scenario. As these final PDF's have skewed shape trends, i.e., they are not symmetrical, the extraction of the 50 percentile was preferred instead of the mean value of the distribution. The final values of storage capacity associated with the P90, P50 and P10 scenarios, for both geological formations, are indicated in Table 9.

Table 9. Summary of CO_2 storage capacity for potential reservoirs in West Macedonia.

Storage Capacity (Mt)	Tier 1	
	Pentalofos	Eptachori
P90	854	125
P50	1680	215
P10	3051	394

Based on the quality of the data available and the results, the CSLF pyramid was used as an indicator for the maturation capacity estimate. This quantitative tiered approach is divided into four levels based on the accuracy of the estimations. West Macedonia is currently classified as Tier 1 with an estimated theoretical CO_2 storage potential of 1.15 Gt. The information is presented graphically in Figure 6a.

(a)   (b)
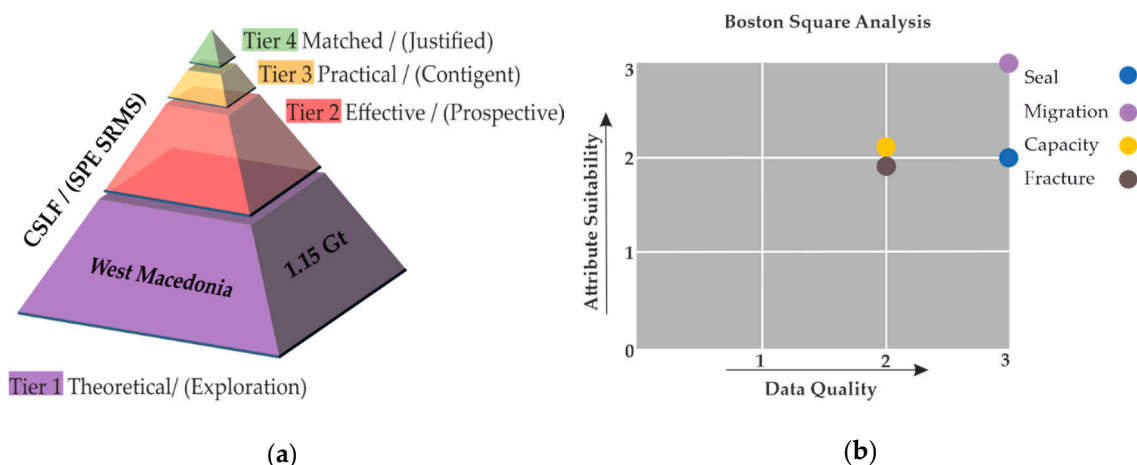
Figure 6. (**a**) CSLF four-tier capacity pyramid presenting the relationship between Theoretical, Effective, Practical and Matched capacities (**b**) Boston Square analysis for West Macedonia, Grevena sub-basin.

The Boston Square Analysis (BSA, Figure 6b) represents the broader assessment for data quality (x-axis) and suitability of attributes (y-axis). This approach allows for a qualitative analysis for data suitability and data quality (both evaluated as an index 1, 2 and 3) of a suite of parameters (see Appendix A) from reservoir capacity and seal quality to injectivity and the presence of faults. Attributes leading to high and low scores in data quality describe the type of data (seismic, core, logging, and literature), their quantity and uncertainty. Suitability is scored by expert judgement. High values indicate good attributes such as high capacity, high reservoir porosity and permeability, an effective seal, an absence of problematic faulting, fracturing or well issues; low scores flag a prospect for review. Data quality (Figures A1 and A2) indicates strengths and gaps in the evidence base [71].

It was possible to classify attributes such as storage capacity, migration risk, level of fracturing and seal quality, which are in the medium to high suitability (index 2 and 3), and medium to high data quality (1–3) (Figure 6b). Nevertheless, there is a lack of information to apply the BSA on some critical attributes, such as injectivity, number and conditions of existing wells, location and conditions for monitoring or intervention in case of leak-

age. Fieldwork, drilling and seismic data interpretation will be essential steps to upgrade the CLSF pyramid rank and to improve the BSA classification, and its use for comparison between storage supporting decision-making.

4. Summary and Conclusions

CO_2 is one of the most common GHGs emissions in West Macedonia (11–14% v/v of the total GHGs emissions). These emissions are mostly associated with the activity of coal power plants located in the region of Ptolemaida. The national strategy for a phase-out of coal power plants envisages that a single coal power plant will be operational by 2028. Future operation will depend on the utilisation of biomass as a renewable source of energy. In either case, CO_2 emissions will need to be captured and either utilised or stored. Currently (2021), under the Green Deal regime and the European energy transition fund there is an accelerated decarbonisation of the Greek electrical energy mix with the country's power plans being revised.

During the H 2020 European Project "STRATEGY CCUS", the potential for CO_2 storage in the Mesohellenic Trough was re-evaluated from past available data deploying the USDOE methodology. Based on the BSA analysis reflecting a low confidence of the storage resources estimates, a stochastic modelling was performed to define a range for each variable of the analytic capacity estimates at different level of probability (P10, P50 and P90).

The Mesohellenic Trough contains Pentalofos and Eptachori Formations with its 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 at P50.

It can be safely concluded that CCUS technology offers a promising option for CO_2 emission reduction in Greece. The storage potential existing in the Grevena sub-basin provides the opportunity to store any captured CO_2 in the area, including other remote regions, should the transport cost be acceptable.

The Greek plan for the development of CCS technologies is getting more mature. Still, there are gaps in knowledge of the cost of capture, transport and storage capacity processes, indicating the discrepancy between top-down and bottom-up approaches. Realistically, the conversion from theoretical to practical or matched storage requires a further scientific effort. Notwithstanding the defined methodologies suggested for estimating CO_2 storage capacity, significant challenges lie ahead due to lack of data, particularly for the storage reservoirs and the main trapping mechanisms. Previous attempts to assess CO_2 storage capacity used various approaches and methodologies, resulting in a range of estimates. Based on the currently presented tiered approach results, a sound scientific basis is provided for further research on confident storage capacity estimates for the Grevena sub-basin. Addressing these gaps should be based on laboratory experiments, numerical simulations and field measurements.

At the current stage, CO_2 storage in Greece remains in Tier 1 status. The current study provides a theoretical approach based on literature data and calculations regarding the CO_2 storage capacity within sedimentary formations of the Mesohellenic Trough (Western Macedonia, Greece). In this context, research uncertainties, such as porosimetry, depth estimations and storage capacity calculations are assigned to the lack of primary experimental data. The assessed storage is not matured sufficiently to meet this demand and need to be reappraised to deliver sufficient storage in the coming years and fulfill the country's net zero ambitions. Further research is going to be deployed in order to provide detailed mineralogical, petrological, geochemical, petrophysical and geological data. These data will be combined with experimental results (such as CO_2 storage experiments) in order to propose comprehensive CO_2 storage scenarios. Based on the IEA Energy Technology Perspectives forecast [81] for CCUS contributions to mitigation, Europe requires injection rates of 52 million tonnes per year from 2025 to 96 million tonnes by 2030 to meet established targets. In the region of West Macedonia, further research will be held in order to provide matured results from theoretical to matched level regarding the CSLF

pyramid. This will lead itself to an accurate Boston Square Analysis for data suitability and data quality across a range of aspects of seal quality and reservoir injectivity.

Funding for future research has been secured via the H 2020 Programme (Pilot Strategy, grant agreement No. 101022664) to provide reliable results on CO_2 capacity. This research will take into consideration several parameters such as geological aspects, physicochemical features, geomechanical considerations and experimental results. It is anticipated that this new project will bring CO_2 storage capacity estimation at the Technical Readiness Level (TRL) 5 forecasted to reach TRL 9 over the next decade.

Appendix A

Definitions Table

Attribute	Criteria	Score	Comments
Storage Suitability	Capacity	3	Large volume, dominant high scores in checklist
		2	Medium - low volume, low score in some factors
		1	Dominant low values, or scores close to unacceptable
	Injectivity	3	High value for permeability * thickness (k*h)
		2	Medium k*h
		1	Low k*h
Seal Suitability	Seal	3	Good sealing shale, dominant high scores in checklist
		2	At least one sealing layer with acceptable properties
		1	Seal with uncertain properties, low scores in checklist
	Fracture	3	Dominant high scores in checklist
		2	Insignificant fractures, either natural or wells
		1	Low scores in checklist
	Wells	3	No previous drilling in reservoir, safe plugging of wells
		2	Wells penetrating seal, no leakage documented
		1	Possible leaking wells, need for evaluation
Other Suitability Attributes	CO_2 Density	3 / 2 / 1	Supercrtical, high density gas, or low density gas
	CO_2 Migration	3 / 2 / 1	Low migration risk, moderate risk
	Location	3 / 2 / 1	Location suitability relative to other sinks and sources
	Monitoring	3 / 2 / 1	Suitability of site for performance monitoring
	Intervention	3 / 2 / 1	Suitability of site for remedial interventions
	Upside	3 / 2 / 1	Sutiability of site for growth as a storage hub
Data Quality	All Criteria	3	High quality data with good coverage and density
		2	Adequate data with some gaps in coverage
		1	Low quality and/or sparse data with known gaps

Figure A1. Guide ranges for principle attribute quality [71,82].

Reservoir Assessment

Reservoir Properties	High	Low
Traps	Defined sealed structures	Poor definition of traps
Pore pressure	Hydrostatic or lower	Overpressure
Depth	800- 2500 m	< 800 m or > 2500 m
Reservoir	Homogeneous	Heterogeneous
Net thickness	> 50 m	< 15 m
Average net porosity	> 25 %	< 15 %
Permeability	> 500 mD	< 10 mD

Seal Assessment

Sealing Properties	High	Low
Sealing layer	More than one seal	One seal only
Properties	Proven barrier > 100 m thickness	Thickness < 50 m
Composition	High clay content, homogeneous	Silty, or silt layers
Faults	No faulting of the seal	Big throw through seal
Fractures	No fracture	sand injections, slumps
Wells	No drilling through seal	High well count

Figure A2. Attribute list for Boston square analysis [71,82].

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