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A Concise Review of Carbon Dioxide Storage in Depleted Oil Fields of Prinos in Northern Greece †

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Abstract: This paper examines the prospects of carbon dioxide capture and storage in depleted oil wells in Prinos in Kavala, Northern Greece. The need to store this gas arises from measures to minimize carbon emissions into the atmosphere to be climate-neutral by 2050 and establish an economy with net-zero greenhouse gas emissions. Greece, as part of the European Green Deal, has adopted the EU's strategy in line with its commitment to global climate action under the Paris Agreement. The possibility of reusing the produced carbon dioxide through the oil industry is being investigated, a method that has been the subject of studies worldwide in recent decades. Incorporating evidence from studies, scientific research, and publications, the paper demonstrates that CO_2 storage is an affordable and technologically compatible method with existing gas storage methods. The resulting economic and environmental benefits are highlighted, and reference is also made to the possibility of exploiting similar reservoirs in the wider area. In brief, the greenhouse effect will be reduced, and oil fields "Epsilon" and "Ammodis" are going to be extracted; hence, the financial gain should be increased. The importance of making such an investment at this particular period and the environmental and economic benefits for Greece and the EU are pointed out.

Keywords: CO_2 emissions; carbon storage; depleted oil fields; Prinos; hydrogen

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1. Introduction

The main objective of this research, compiled as a bibliographic work based on scientific articles that mainly originated from databases such us sciencedirect.com and researchgate.com, is to inform the general public about Greece's ability to limit carbon dioxide emissions into the atmosphere. The research methodology emerged based on the data of the country's carbon dioxide emitters, their European restrictions, and the most likely solution to the problem. Keywords used for the accurate completion of the research in this case are CO_2 emissions of Greece, carbon capture storage technologies, depleted oil field of Prinos, and blue hydrogen production.

Carbon dioxide (CO_2) is defined as a natural substance consisting of carbon and oxygen. Under normal atmospheric conditions, it is considered a gas, and it is characterized as a greenhouse gas due to its ability to capture heat energy from the sun, while it can be frozen into a solid, compressed into a liquid, or dissolved in water. The environment, human communities, and natural resources worldwide are subjected to a wide range of significant impacts due to the continued increase in atmospheric CO_2 levels [1].

Although Greece, between 2005 and 2019, reduced the intensity of CO_2 emissions per unit of GDP by 23%, at the end of the last decade was the seventh economy of carbon dioxide emissions in the European Union. The average reduction of EU member states reached 33%, with Greece's equivalents increasing by 203 gCO_2 [2]. Fifty percent of fixed CO_2 emissions in Greece come from the area of Western Macedonia, specifically from the coal basin of

Kozani–Ptolemais–Florina, where the largest lignite power plants are located, as also shown in the figure below. The development of CO_2 capture and storage technologies (carbon capture storage, CCS) is considered the most likely option for stabilizing and reducing atmospheric concentrations of greenhouse gases [3].

Figure 1 shows the places in Greece with the highest carbon dioxide emissions. It is seen that (as mentioned above) the region of Western Macedonia produces the most emissions, while a significant percentage of the carbon dioxide produced comes from metal industries, cement factories, and other chemical industries. The amount of carbon dioxide varies by region and industry and ranges from 100 thousand tons per year to over 10 million tons per year.

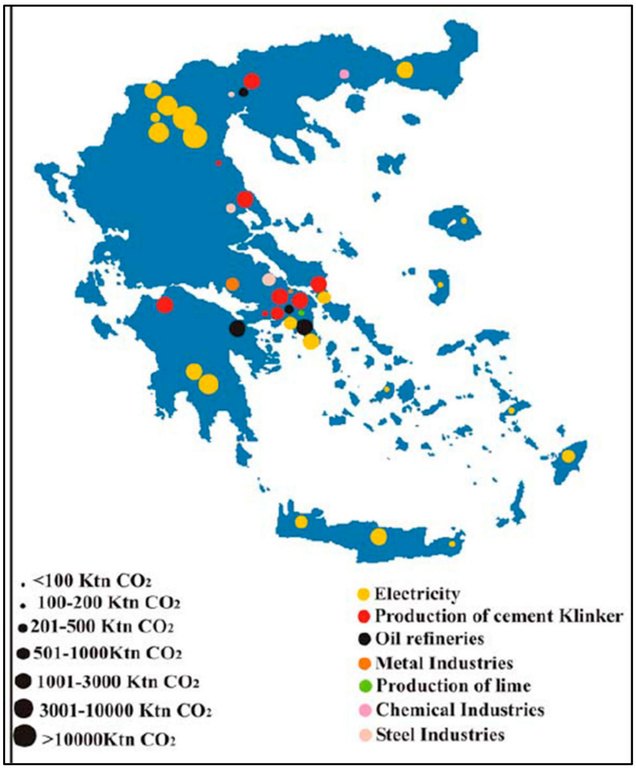

Figure 1. Emissions of CO_2 in Greece. Adapted with permission from Ref. [4]. 2009, Nikolaos Koukouzas, Ioannis Typou.

2. Carbon Capture Storage in Prinos, Greece

For the long-term sequestration and storage of CO_2 emissions from both remote emissions and local industries, it has been proposed to utilize the oil extraction facilities of Prinos in the sea bay of Kavala [5]. The most common way to store carbon dioxide (CO_2) underground is as a supercritical fluid. As supercritical, we characterize CO_2 whose temperature and pressure define its critical point, which is formed at 31.1 °C and pressure above 72.9 atm, respectively. Under these conditions, CO_2 has some properties like a gas and some properties like a liquid [6].

CCS Technology Steps

The CCS technologies consist of the following three steps: i. capture, ii. transfer, and iii. storage [7]. Three main CO_2 capture technologies can influence CO_2 emissions: post-combustion CO_2 capture, pre-combustion CO_2 capture, and oxy–fuel combustion [8]. Two of the three basic CO_2 capture techniques can be applied to the power plants under study, and these are post-combustion capture and oxy-combustion [9]. The post-combustion carbon capture process begins by scrubbing the flue gas in the vessel containing the absorber; then, the CO_2-containing solvent is transferred to another vessel where the CO_2

is released, and the solvent used can be recycled into the process. The released CO_2 is then compressed and transported [10]. Oxy–fuel combustion involves the process of burning the fuel with nearly pure oxygen instead of air. In order to control the flame temperature, some parts of the flue gas are recycled back into the furnace/boiler [11].

There are three types of CO_2 separation: separation with solvents, membrane separation, and separation by cooling. Separation with solvents occurs when the gas containing CO_2 comes into close contact with a liquid or solid absorbent capable of sequestering the CO_2. Membrane separation is the penetration of gas through specially constructed materials whose binding capacity is related to the nature of the material. Separation by cooling can exist while converting a gas to a liquid through compression, cooling, and expansion, after which the gas components can be separated in a distillation column [12].

3. Necessary Characteristics of the Candidate Tank

The characteristics that a storage space must have to be considered suitable are injectivity, capacity, storage security, and accessibility [1].

- Injection. A storage system can potentially include more than one reservoir of rocks characterized by different physicochemical properties. The content of a reservoir rock can be estimated through direct or indirect techniques [13]. The majority of Prinos, Epsilon, and Ammodis traps are bound in a densely faulted region as overturning anticlines. The Prinos basin, i.e., the northern part of all the traps, is 38 km long and about 20 km wide, while the southern part, which is deeper, forms the Prinos sub-basin [14]. The above basin includes three main filling series with very distinct boundaries between them: the pre-evaporative, evaporative, and post-evaporative series [15]. The mineralogical composition of the reservoirs in the basin consists of sandstones and some claystones. The inert thickness reaches about 260 m, while the depth from the surface to the top of the reservoir varies from 1 to 3.5 km. The ability to inject and maintain CO_2 in its supercritical state is supported by the average permeability of the reservoir intervals reaching 50 mD and porosity ranging from 15% to 20% [3];
- Capacity. It has been calculated that the sequestration capacity in the Prinos oil zones amounts to 14.3 billion m^3 and in the aquifers to 18 billion m^3, shaping the total CO_2 sequestration capacity of the Prinos reservoirs to 32.3 billion m^3. The development of the Epsilon and Eastern Thassos deposits will increase more than double the storage capacity, resulting in an increase in the CO_2 sequestration capacity of Greek greenhouse emissions to 31% [16];
- Safety. The anticlines that comprise the Prinos basin are covered with salt deposits and overlying clastic unconsolidated sediments with a thickness of 2300 m, offering excellent sealing and, by extension, security in CO_2 storage [3]. To ensure proper transfer and detect potential leaks during injection, developing a subsea CO_2 detection sensor for a novel use of existing data to reduce requirements for seismic data acquisition is required [17];
- Accessibility. CO_2 can be transported via pipelines, ships, trains, and trucks. Due to economies of scale, pipelines and ships are expected to be much more cost-effective in transporting megatons of CO2 per year (Mtpa) [18]. In the case of storage in the facilities of Prinos, the transport through pipelines is chosen due to their ability to transport large quantities of CO_2 in its liquefied or extremely critical/dense phase. Under these conditions, CO_2 has a higher density, while final storage conditions will be similar to those of transport due to the high hydrostatic pressure in the underground porous rock formations [19].

4. Total Cost and Alternative Perspectives

The CO_2 emissions from the power plants of Kardia and Agios Dimitrios (located in the wider area of Western Macedonia, Greece) will be transferred to the storage area of Prinos via pipelines, while the transport of CO_2 from Komotini is being considered to be performed in the same way. The total cost of the three booster stations needed, each with an installed capacity of 0.75 mW, is USD 18.9 million [4]. The following table and figure list the cost of each connection pipeline in detail and indicate the specific position of each booster station, respectively.

Table 1 shows the distances that pipelines would cover to transport the carbon dioxide to its final destination for storage. The table shows the kilometers and the diameter of the pipelines, the total cost of their installation, and the operating cost.

Table 1. Cost of connection pipelines [4].

Pipeline	Length (km)	Diameter (inch)	Investment Cost ($)	Operation Cost ($)
Kardia–Agios Dimitrios	15	24	4.8 million	7.66 million
Agios Dimitrios–Nea Karvali	350	30	128.8 million	1.6 million
Nea Karvali–Prinos	20	34	24.2 million	1.2 million
Komotini–Nea Karvali	150	16	24.4 million	667 thousand

Figure 2 indicates the exact route of the pipelines that will be used for the transportation of carbon dioxide. Also, the three boost stations that will be installed near Ptolemaida, Lagadas of Thessaloniki, and next to Energean's onshore facilities in the city of Kavala are presented. The operation of push stations lies in the need to eliminate the reduction in pressure due to the distance that the product must travel to be stored.

Figure 2. Transportation routes from the power plants to Prinos. Adapted with permission from Ref. [4]. 2009, Nikolaos Koukouzas, Ioannis Typou.

Energean Plc, the company that exploits the Prinos field, plans to utilize the technology "carbon capture utilization and storage, CCUS" processes in combination with the production of blue hydrogen, i.e., hydrogen produced from natural gas and supported by carbon capture and storage [20]. In the first half of 2021, the project in question joined the Resilience and Recovery Fund, and in the second half of the same year, the pre-FEED (front-end engineering and design) was started by Energean Plc. As a result, a service contract was signed between the field operator and Halliburton in March 2022 [21].

5. Conclusions

With the greenhouse effect affecting life on our planet, human energy needs to constantly increase, and with the Paris Agreement being in force, Greece is trying to limit the escape of carbon dioxide into the atmosphere by adopting methods that are already in place in other countries. The storage of carbon dioxide in the facilities of Prinos can be the key move to achieve the agreed conditions in the European Union and the transition to a more ecological environment, while at the same time, by exploiting the hydrogen production method, the overall process will emerge as a profitable investment. The total investment cost of the transport way, which is estimated to be approximately USD 200 million, as well as the major capacity of the storage reservoirs reaching the amount of 32.3 billion m^3, indicate the importance of the project coming to its completion. Energean Plc's collaboration with Halliburton provides the impetus for the inclusion of our country in a new cycle of energy investments and consolidating its position among the main pillars of Europe's development.

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References

1. Price, J.; Smith, B. *Geological Storage of Carbon Dioxide: Staying Safe Underground*; IEA: Paris, France, 2008; pp. 1–12.
2. Simões, H. Climate Action in Greece European Parliament. 2021. Available online: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/690685/EPRS_BRI(2021)690685_EN.pdf (accessed on 3 July 2023).
3. Koukouzas, N.; Ziogou, F.; Gemeni, V. Preliminary assessment of CO_2 geological storage opportunities in Greece. *Int. J. Greenh. Gas Control* **2009**, *3*, 502–513. [CrossRef]
4. Koukouzas, N.; Typou, I. An assessment of CO_2 transportation cost from the power plants to geological formations suitable for storage in North Greece. *Energy Procedia* **2009**, *1*, 1657–1663. [CrossRef]
5. HEREMA. Building a Bridge to a Carbon Free Future. 2023. Available online: https://herema.gr/wp-content/uploads/2023/01/Final-herema.companyprofile-digital.17a-EN-1.pdf (accessed on 28 June 2023).
6. National Energy Technology Laboratory. Carbon Storage, Faqs. Available online: https://www.netl.doe.gov/carbon-management/carbon-storage/faqs/carbon-storage-faqs (accessed on 27 June 2023).
7. Ktenas, D.; Kosmidou, V.; Spinos, S. Underground Geological Storage of CO_2 and Natural Gas in Greece, HEREMA. 6–8. 2020. Available online: https://www.greekhydrocarbons.gr/news_files/Technical_report_CCS_June_2020.pdf (accessed on 13 August 2023).
8. Czarnota, R.; Knapik, E.; Wojnarowski, P.; Janiga, D.; Stopa, J. Carbon Dioxide Separation Technologies. *Arch. Min. Sci.* **2019**, *64*, 487–488. [CrossRef]
9. Karakas, E.; Doukelis, A.; Koukouzas, N. CO_2 Capture and Storage in the Electricity Generation Sector, Institute of Energy (IENE). 12–13. 2011. Available online: https://www.iene.gr/articlefiles/eniaio_kakaras_04022011.pdf (accessed on 27 June 2023).
10. Allangawi, A.; Alzaimoor, E.; Shanaah, H. Carbon Capture Materials in Post-Combustion: Adsorption and Absorption-Based Processes. 2023. Available online: https://www.mdpi.com/2311-5629/9/1/17 (accessed on 1 July 2023).
11. Stanger, R.; Wall, T.; Sporl, R.; Paneru, M. Oxy–fuel combustion for CO_2 capture in power plants. *Int. J. Greenh. Gas Control* **2015**, *40*, 55–125. Available online: https://www.sciencedirect.com/science/article/pii/S1750583615002637 (accessed on 29 June 2023). [CrossRef]
12. Metz, B.; Davidson, O.; Coninck, H.; Loos, M.; Meyer, L. *Carbon Dioxide Capture and Storage*; Cambridge University Press: Cambridge, UK, 2005; pp. 105–179. Available online: https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport.pdf (accessed on 25 June 2023).
13. Arvanitis, A.; Koutsovitis, P.; Koukouzas, N.; Tyrologou, P.; Karapanos, D.; Karkalis, C.; Pomonis, P. Potential Sites for Underground Energy and CO_2 Storage in Greece: A Geological and Petrological Approach. *Energies* **2020**, *13*, 2707. [CrossRef]

14. Proedrou, P.; Papaconstantinou, C.M. Prinos Basin—A Model for Oil Exploration. In Proceedings of the 10th International Congress of Geological Society of Greece. Bulletin of the Geological Society of Greece, Thessaloniki, Greece, 15–17 July 2004; pp. 327–328. [CrossRef]
15. Mertzanides, Y.; Kargiotis, E.; Mitropoulos, A. Geological and Geophysical Data of "Epsilon" Field in Prinos Oil Basin. In Proceedings of the 12th International Congress of Geological Society of Greece, Patras, Greece, 19–22 May 2010; pp. 2257–2264. [CrossRef]
16. Tingas, J.; Logothetis, S.; Tingas, A. Synergies and Environmental Benefits of Lignite Gasification in Ptolemais with Combined CO_2 Sequestration and Enhanced Oil Recovery in the Prinos Oil Fields in Macedonia-Greece. In Proceedings of the Canadian International Petroleum Conference, Petroleum Society, Calgary, AB, Canada, 17–19 June 2008.
17. Danish Offshore Technology Center. CO_2 Storage in Depleted Oil and Gas Fields. Available online: https://offshore.dtu.dk/english/research/research-programmes/co2-storage (accessed on 24 June 2023).
18. Smith, E.; Morris, J.; Kheshgi, H.; Teletzke, G.; Herzog, H.; Paltsev, S. The Cost of CO_2 Transport and Storage in Global Integrated Assessment Modeling. *Int. J. Greenh. Gas Control* **2021**, *109*, 103367. [CrossRef]
19. Koukouzas, N.; Klimantos, P.; Stogiannis, P.; Karakas, E. CO_2 capture and storage in Greece: A case study from komotini ngcc power plant. *Therm. Sci.* **2006**, *10*, 71–80. [CrossRef]
20. Energean PLC. Sustainability Report 2021, Uniting Diverse Cultures for a Sustainable Energy Transition. Available online: https://www.energean.com/media/5201/2021-sustainability-report.pdf (accessed on 14 August 2023).
21. Offshore Engineer. Energean Hires Halliburton for Carbon Storage Project Offshore Greece. 2022. Available online: https://www.oedigital.com/news/495321-energean-hires-halliburton-for-carbon-storage-project-offshore-greece (accessed on 22 July 2023).