Proceeding Paper

Assessing Natural Gas Versus CO$_2$ Potential Underground Storage Sites in Greece: A Pragmatic Approach [†]

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Abstract: Although subsurface traps have been regularly explored for hydrocarbon exploration, natural gas and CO$_2$ storage has drawn industrial attention over the past few decades, thanks to the increasing demand for energy resources and the need for greenhouse gas mitigation. With only one depleted hydrocarbon field in Greece, saline aquifers, salt caverns and sedimentary basins ought to be evaluated in furtherance of the latter. Within this study the potential of the Greek subsurface for underground storage is discussed. An overview and re-evaluation of the so-far studied areas is implemented based on the available data. Lastly, a pragmatic approach for the storage potential in Greece was created, delineating gaps and risks in the already proposed sites. Based on the above details, a case study for CO$_2$ storage is presented, which is relevant to the West Katakolo field saline aquifer.

Keywords: underground storage; natural gas; CO$_2$ storage; Greece; sustainability

1. Introduction

Since IPCC's special report [1], significant work has been carried out on carbon dioxide (CO$_2$) capture and storage (CCS). This aims to mitigate and control the greenhouse effect by isolating part of the anthropogenically produced greenhouse gas emissions. Subsurface formations of adequate storage capacity and sealing such as depleted hydrocarbon reservoirs and saline aquifers can be used for such storage.

The case of underground natural gas (NG) storage has also been considered lately as it perfectly anticipates the seasonality issues related to shipping or to pipeline transportation. NG storage acts as a buffer which can offer additional gas volumes when required on a seasonal basis. Such a PCI project (project of common interest) has already been under development in South Kavala, Greece.

Contributing to a sustainable future, we discuss the potential of underground NG and CO$_2$ storage in Greece by analyzing the available information on various locations, with a focus on the widely studied Neogene and Mesozoic sedimentary basins.

2. Method of Evaluation

Each location has been assessed based on the characteristics listed in Table 1 with each class marked as green, yellow, and red to represent a low, medium and high risk, respectively. As data deficiency complicates such an assessment, the risking thresholds were introduced based on characteristics of successful storage sites, sedimentological facts and geotectonics for a solid evaluation. Although rock properties are of prime importance, sedimentary facies are also discussed as they are the driving factors of their values.

Table 1. Reservoir, seal, and trap risks related to storage efficiency. Porosity and permeability were set according to [2,3]. Aquifer type is based on [4], and seal type is based on [5].

Risk	High	Medium	Low
1-4 Reservoir facies adequacy	Low N:G clastics or with low fracture connectivity	Medium N:G clastics, fractured carbonates	High N:G clastics, fractured carbonates with joint fractures
1-4 Diagenetic effect	High (e.g., Illite bridging, cementation)	Affected to some extent	None/Solution diagenesis/Low diagenetic impact
1-4 Reservoir Porosity	<5%	5–10%	>10%
1-4 Reservoir permeability (mD)	<0.001	0.001–0.01	>0.01
1-4 Wettability	-	Oil wet	Water Wet
1-4 Aquifer type	Shallow and/or Open	Deep and Open or Closed	Deep and Semi-Confined
1-4 Seal facies	Absent, All except non-fractured evaporites and shales	Shales, Low N:G clastics, intraformational	Non-fractured evaporites (i.e., Messinian) and shales
1-4 Trapping mechanism	None	Residual entrapment	Structural, Well-confined stratigraphic
1-4 Fault Seal (if applicable)	Yes but no seal juxtaposition	-	Yes and seal juxtaposition

3. Examined Cases

Potential sites for geological storage of either CO_2 or NG, apart from the well-known Prinos oil and gas field, include but are not restricted to the following:

1. Salt diapirs in Western Greece;
2. West Katakolo field;
3. Eocene–Miocene Mesohellenic Trough;
4. Cenozoic extensional basins such as the Florina basin.

3.1. Salt Caverns

Salt structures have been widely used as storage sites; the U.S. Gulf Coast has been using them for hydrogen storage for decades. Salt caverns created from water injection [6], diapirs, thick evaporite layers and underground salt mines are ideal for such a project. This is due to their storage capacity for a given cavity volume, which could be high enough depending on the depth and thus on the maximum injection pressure.

In the Fold and Thrust belt (FTB) of Greece, Triassic evaporites [7] develop interesting structural closures through low-to-medium angle thrusting surfaces of the belt. Although underground mines are not available, promising salt layers and diapirs could be identified along the FTB. Alternatively, subsurface salt caverns could act as short-term storage sites for NG. This is based on their relatively lower volume compared to an aquifer, yet of higher deliverability and sealing efficiency due to related pressure regimes.

Thus, evaporitic layers and diapirs could provide prospective sites in Greece for both storage types. Yet, seismicity and regional tectonics should be carefully examined in advance, considering their extensive effect on the area. Given the plasticity of the evaporites, a low-medium risk was assigned to all parameters, while depth was assigned medium-high risk. Potential sites are shown in Figure 1. As specific data are not available, such structures are generally considered to have medium risk, with further exploration based on existent seismic and hydrocarbon wells being vital to verify our risk evaluation.
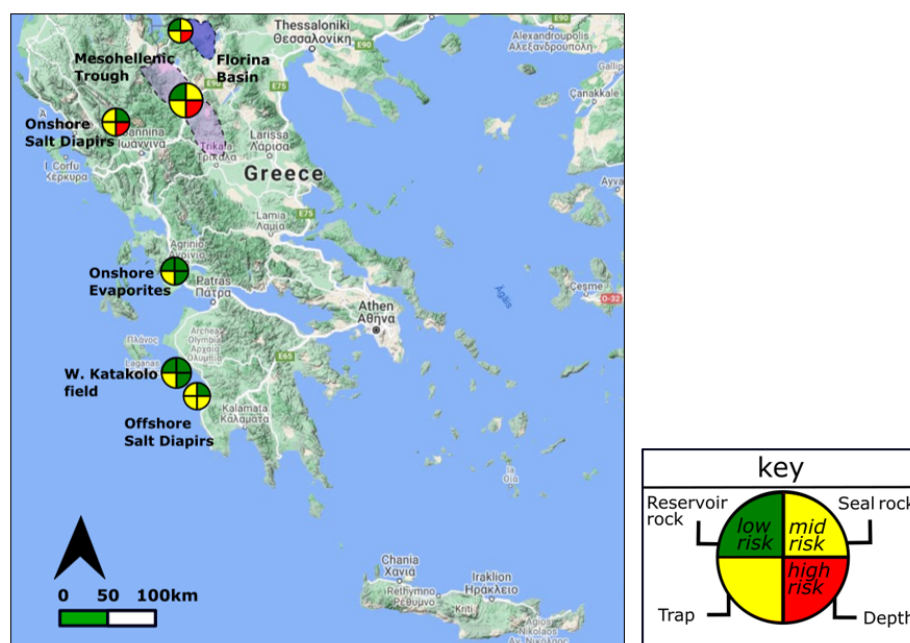
Figure 1. Risking map of the assessed potential storage locations in Greece, based on the traffic light system.

3.2. Mesohellenic Trough

The Mesohellenic Trough (MHT) is an elongated, NNW–SSE trending sedimentary basin, located between the Pelagonian and the Apulian geotectonic zones of Greece [8]. Its structural history is still controversial, yet most authors, such as those of [9,10], have agreed to a piggy-back type of basin with a lithostratigraphy dominated by turbiditic deposits, covered by Paleogene- to Neogene-aged, shallow-to-deep water molassic sediments [11–14].

Many studies [15,16] have examined the MHT for its CO_2 storage potential. Pressure and temperature data, as well as formation depths, were provided in these studies, suggesting an area with high CO_2 storage potential. The pressure gradient appears to have a value of 57 MPa at 2 km with a temperature of 80 °C.

Although the Pentalofos and Eptahori formations are considered as reservoirs and the overlying Tsotyli formation as a seal rock based on their characteristics [16], important downsides do exist. According to [17] these reservoir formations are turbidite fan delta deposits, with a net to gross (N/G) reaching 40% [18]. Top-sealed by Tsotyli formation (Figure 2) and juxtaposed by the Pelagonian basement to the East, the storage potential focus should be given there. Yet, sedimentary drawbacks such as potential connectivity to the sediment source in the west [14] might provide ideal migration pathways and should be thoroughly investigated. Additionally, even disregarding the supercritical phase of the fluid, the basin's sedimentary formations do not reach adequate depths for safe storage, imposing a high risk of potential geo-hazards, should such a project be implemented.

Therefore, the reservoir seems adequate for such a project (low risk), but only for one of low capacity as the best-case scenario is isolated and stacked sand bodies with reduced connectivity. Also, considering the present-day depth and N/G of these formations, the local seal, depth and trap are assigned medium, high and medium risk, respectively. Thus, the basin is of medium-high risk (Figure 1) considering both types of storage.

3.3. Florina Basin

The CO_2 storage potential of this Cenozoic extensional basin has been discussed by [19] regarding its fluvial and alluvial fan deposits. While natural CO_2 accumulations have been detected at less than 550 m depth within Mesozoic limestones to Neogene fluvial sandstones, these formations seem to crop out laterally. The latter has a high risk for such

a project even when stratigraphic trapping is considered, a fact further supported by the local natural CO_2 leakage.
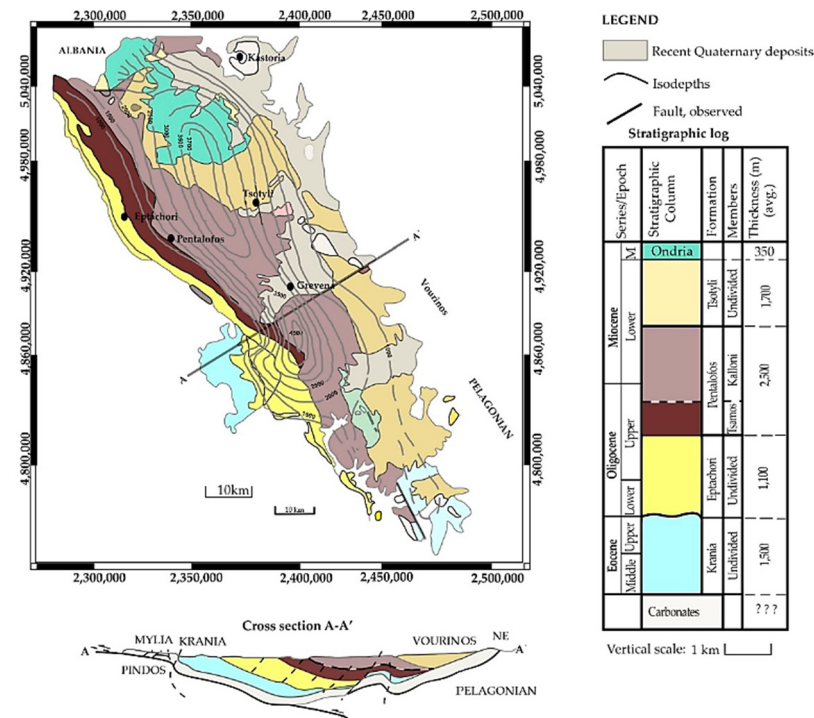

Figure 2. Geological map and stratigraphic column of the Mesohellenic trough from [18].

The basin seems to lack robust sealing as well as burial depth, very similarly to the MHT. Although stratigraphic trapping could have been adequate for an oil reservoir, in such shallow depths, a thorough examination of the sealing rock properties should be performed as several risks related to high pressures in such depths might be triggered with time. Consequently, although the reservoir seems to be of low risk, the sealing and trapping mechanisms have medium risk, while the depth attains a high risk in this case (Figure 2).

4. West Katakolo Field—Case Study

4.1. Conceptual Modeling of Production and Injection Processes

The Katakolo area has been under study since the early 1980s when the first exploration wells were drilled, followed by pressure tests (RFT, DST), to verify the presence of a saturated reservoir with a gas cap and the open bottom drive aquifer within a carbonate sequence trapped by a Miocene pseudo-anticline. To investigate its potential for NG or CO_2 storage a conceptual model was developed to describe the storage process. For the case of NG, it is envisaged that the reservoir will firstly undergo primary and secondary recovery before NG storage is initiated. It is customary not to produce the primary gas cap to maintain pressure and facilitate production. Gas injection will run at the crest of the structure, thus acting as a gas flood, which will further add to the oil production as long as the production wells are in operation. When the ever-increasing gas recycling becomes non-viable, the production wells will shut, only allowing for gas storage thereafter. Oil and water saturation are expected to reduce to close-to-critical values (connate water and residual oil level). From this point on, further gas injection will push the free water level downwards, resulting in OWC (Oil–Water Contact), achieving further gas storage. Gas injection will be terminated by the time the free-water level (hence, the gas plume bottom) arrives at a depth below which the seal integrity is not guaranteed. Note that if the assumption that the aquifer is fully open is not verified, gas injection will be terminated earlier, before pressure approaches cap-rock-fracture levels.

The conceptual model for the CO_2 storage case is similar, and the main difference lies in the tertiary production envisaged due to the beneficial nature of the injected gas in miscible gas injection schemes. CO_2 is expected to mobilize more oil which otherwise would have been trapped by high capillary and viscous forces, reducing the residual oil volume, and increasing CO_2 storage. Possible mixing of the gas cap to the injected CO_2 does not pose severe problems as the latter is injected for permanent storage. In both cases, the injected gas will float above reservoir water and the final position of the NG, or the CO_2 plume will be determined by gravity and by capillary forces.

4.2. Gross Rock Volume (GRV)

To proceed with calculations, the *GRV* needs to be estimated down to the spill depth. To estimate the *GRV* from the crest down to the OWC, the contour map shown in Figure 3 was utilized. This map was digitized with each square accounting to 0.25 km^2, and their values versus depth are shown in Figure 4. For the uncertainty in the column height, a probabilistic area distribution factor was incorporated, leading to three column height values h, each taken as equal to the one at which the contour area is 21%, 37% and 64% of the maximum (P_{max}). The values obtained (85 m, 120 m and 198 m) correspond to three scenarios (optimistic, expected, pessimistic) known as P10, P50 and P90. In this case, the base area (P_{max}) at the OWC is estimated at 3.5 km; hence, the gross volumes are estimated at 0.062, 0.155 and 0.444 km^3, respectively.
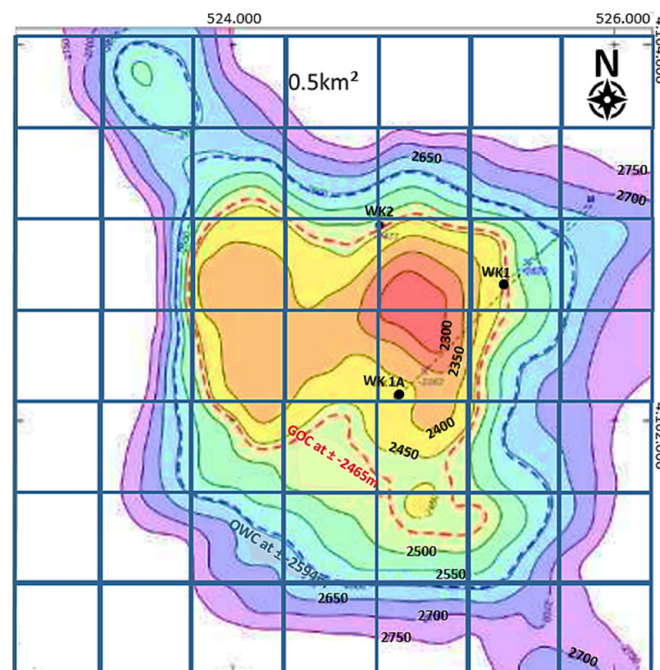
Figure 3. Depth–contour map of the West Katakolo field, modified after [20].

Lastly, to account for the non-cuboidal shape of the reservoir, a correction is needed, and this is the geometric factor (*GF*). Further reducing the rock volume according to the ratio r between the gross thickness and the obtained column height, *GF* equals 6.2%, 15.5% and 44.4% for the examined scenarios, as obtained from its model $GF = 1.0 \exp(-0.695\,r)$. Ultimately, both factors are combined to create the following equation:

$$GRV = P_{max} \cdot h(P_{max}) \cdot GF \tag{1}$$

to provide gross rock volume estimates of 0.012, 0.039 and 0.155 km^3, respectively. The same process is repeated for any possible spill depths below the OWC.

4.3. Available Pore Volume (PV)

To convert the *GRV* to the *PV* available for NG and CO_2 storage, estimations of porosity and connate water level are required. Based on the experience obtained in carbonate fields and on the evidence received from the exploration drilling program, porosity is expected to be governed by a triangular distribution with boundary values equal to 8% and 15% and a mode of 10%. Initial water saturation above the OWC is estimated based on analogs and is expected to vary uniformly in (20%, 40%), whereas below the OWC it will be 100%. Finally, the residual oil saturation after water flooding and miscible CO_2 injection for such systems is expected to vary, normally settling at around 40% and 20%, respectively.
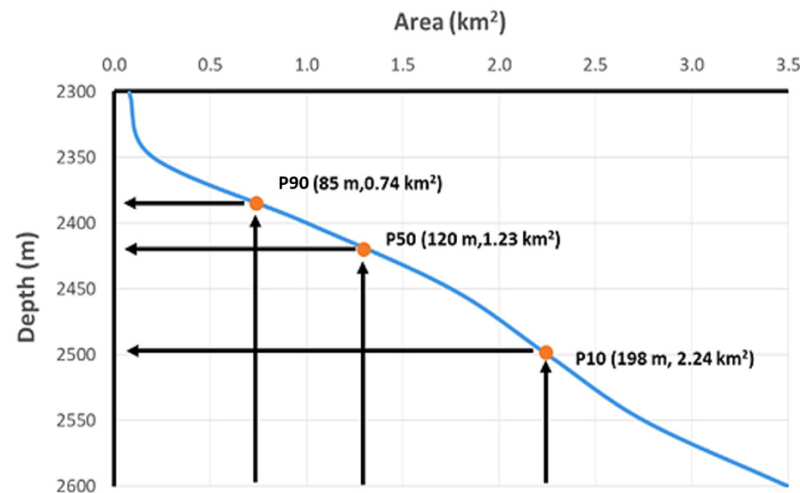
Figure 4. P10, P50 and P90 estimates of the rock volume area and column height above the OWC.

4.4. PVT Values

To estimate oil and gas volumetric factors black oil correlations were adopted utilizing reservoir temperature and traditional field data input, i.e., tank oil API, tank gas gravity and *GOR*, out of which only tank oil density is known to be equal to 27 API. To handle uncertainty, three values were realized for each of the unknown parameters. Reservoir temperature was estimated using various geothermal gradients equaling 160, 180 and 210 °F, and gas specific gravity is expected to exhibit values equal to 0.8, 0.9 and 0.95, with the highest value corresponding to the possibility of high H_2S content.

As *GOR* is not known, the pressure at the GOC was used to correlate since that value is equal to the oil and gas saturation pressure. P_b varies and is estimated to be equal to 3700, 3750 or 3800 psi due to the uncertainty in the DST measurements. By combining the above to the standing correlation, *GOR* is estimated to vary between 830 and 900 scf/stb. By further incorporating the latter in the standing correlation for B_o, its values are expected to vary between 1.43, 1.53 and 1.57 rb/stb. Of course, pore volume below the OWC only needs a B_w value, typically set at 1.05 as it is fully filled by water. NG volume factor, B_g, is estimated by considering its relationship to the compressibility factor, i.e.,:

$$B_g = Z \frac{p_{atm}}{p_{res}} \frac{T_{res}}{T_{amb}} \tag{2}$$

which is a function of the gas gravity varying between 0.55 (for pure methane) to 0.87 (in the presence of heavier components) with the range between 0.6 and 0.7 being the most common. Under those assumptions and combining pressure and temperature uncertainty, Z is expected to vary normally between 0.86 and 0.93; therefore, B_g is expected to vary between 0.0040 and 0.0047 cf/scf. For the case of CO_2, the injected gas will appear in a supercritical state in the reservoir with a density of approximately 900 kg/m^3.

4.5. Injected Gas Storage Capacity

Although the uncertainty incorporated into each variable has been recognized and described numerically, the combination of all those sources needs to be evaluated by means of a Monte Carlo simulation. The results obtained indicate that the pore volume above the OWC available to be filled with NG corresponds to 2.1%, 3.5% and 5.3% of the *GRV*, for P90, P50 and P10, respectively. For the CO_2 case, those figures increase slightly to 3.6%, 5.5% and 8.4%. Similarly, the available pore volume below the OWC corresponds to 8.3%, 11.1% and 14.6% of the *GRV* for both injected fluids.

Using the above results, a chart of the expected stored gas volume for NG and CO_2 was constructed (Figure 5). At the maximum studied depth (3700 m), the average scenario, as far as both rock volume and fluid phase behavior are concerned, leads to a NG and CO_2 storage of 32 bcm and 123 MMtn. Even if the spill depth proves to be shallower (i.e., 3000 m), expectations are restricted to 9 bcm and 34 MMtn, respectively, which are still excellent, even if some of the NG would be permanently trapped as cushion gas. Yet, it seems that the storage capacity of gas above the OWC is very low, which is in line with the rather small size of what is today considered as the Katakolo hydrocarbon prospect.
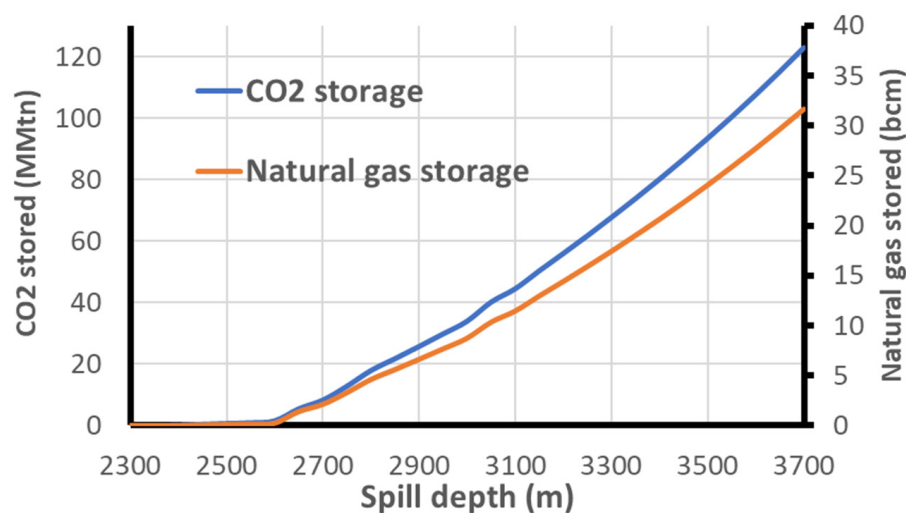

Figure 5. Estimated storage capability of the mid-case scenario (P50) as a function of depth.

5. Discussion and Conclusions

The overview and re-evaluation of already suggested prospective storage sites in Greece and a few new ones has revealed some key risks and drawbacks of the cases examined. With both reviewed Cenozoic basins having shallow present-day depths, the primary risk would be the potential geo-hazards caused over time by such implementations, mainly due to the induced pressures. Additionally, although the reservoir facies in these basins would have been excellent as oil reservoirs, they are neither likely able to provide adequate capacities nor sealing efficiency from a storage perspective. On the other hand, the scenario of salt caverns could be very promising; yet several parameters should be examined alongside regional stresses, such as the actual volume of the diapir structures.

Considering the Katakolo case study, its structure clearly offers a great capability to store either NG or CO_2. Although the reservoir of the West Katakolo field must firstly undergo primary and secondary production for such a scenario to be implemented, its potential needs to be further investigated. It is evident from the above evaluation that one of the dominant questions which needs to be answered thus concerns the openness of the system and its ability to allow water escape and as such, the related spill depth.

Lastly, a serious drawback in such scenarios is transportation infrastructures. NG ought to be transported to such sites in a raw state and be injected after treatment. Yet, neither such transportation nor treatment sites are available in Greece, complicating the overall

evaluation. A potential plan for transporting NG from a producing field, either within (i.e., offshore blocks W and SW of Crete) or outside Greece, could provide a plausible scenario.

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