ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 4 (2011) 2978–2983
Energy Procedia
www.elsevier.com/locate/procedia

GHGT-10

Cost of pipeline-based CO_2 transport and geological storage in saline aquifers in Greece

N. Koukouzas[a]*, F. Ziogou[b], V. Gemeni[a]

[a] *Centre for Research & Technology Hellas/Institute for Solid Fuel Technology & Applications, Mesogeion Ave. 357-359, GR-15231, Halandri, Athens, Greece*

[b] *Centre for Research & Technology Hellas/Institute for Solid Fuel Technology & Applications, 6th km. Harilaou, Thermi Road, P.O. Box 361, GR-570 01, Thermi, Thessaloniki, Greece*

Abstract

This work aims to provide an insight of the cost estimation for large scale CCS application in the Greek thermal power plants given the high dependency on fossil fuels for the bulk of the national electricity generation and the aim to fulfil Greece's share of the overall European energy policy targets. Greece generates almost 92% of its electrical power requirements from fossil fuels, with lignite accounting for about 63% of the total while the share of liquid fuels and natural gas is 14% and 22% respectively (2007). Total CO_2 emissions increased from 83.15 Mt in 1990 to 113.56 Mt in 2007. This increase of 36.57% from 1990 to 2007 is mainly attributed to the increased electricity production (average annual rate of 3.6% for the period). Taking into consideration the forecasts for increase in the electricity demand over the coming years and the old and low-efficiency units that should be either renovated or replaced by new units, the capture and geological storage of CO_2 is considered as a critical climate change mitigation option at national level.

In particular, the cost calculations are focused on CO_2 transport from a new capture-ready 650 MWe coal fired power plant using supercritical steam cycle, to be erected in the Region of Western Macedonia, to potential geological formations via pipeline and the subsequent storage in deep saline aquifers. The cost estimations are based on a pipeline transport infrastructure linking one large CO_2 source with individual storage sites. The results from the geological characterisation and the storage capacity of the identified Prinos, West Thessaloniki, and Messohellenic Trough - Pentalophos saline formations in the Tertiary sedimentary rocks of Greece will be presented.

To conclude, the geological properties of the sedimentary basins in Greece appear to to have the potential to sequester billions of tons of CO_2 for CCS implementation. The identified geological reservoirs occur within approximately 100-200 km of the majority of stationary CO_2 emissions in Greece, which is favourable in terms of infrastructure costs for the development of a CO_2 pipeline transport network. However a range of R&D activities is required in order to assess the effective CO_2 storage potential of saline aquifers in Greece like a more detailed site –specific geological analysis, stratigraphic mapping and correlation, petrophysical property characterization, generation of quantitative and dynamic 3-D geological models, geochemical simulations etc.

Keywords: Prinos saline aquifer; Mesohellenic Trough; Greece; coal-fired power plant;, Western Macedonia

doi:10.1016/j.egypro.2011.02.207

1. Introduction

CCS is a key component of the greenhouse gas (GHG) mitigation portfolio of technologies [1]; [2]. Together with renewable energy technologies, nuclear energy and greater energy efficiency, CCS contributes significantly to the least cost route of reducing and stabilising CO_2 emissions in the atmosphere. It has been estimated that, without CCS in the technology mix, the cost of climate stabilisation would increase by 70% [2].Taking into account the high fossil fuel dependency of the Greek power sector as well as the expected increase in the electricity demand over the coming years, the capture and geological storage of CO_2 is considered as a critical climate change mitigation option at national level.

The goal of this work is to provide a first-order cost assessment for the transport of CO_2 emissions from a proposed new capture-ready 650 MWe coal fired power plant using supercritical steam (SC) cycle, to be erected in the Region of Western Macedonia, to potential geological formations via pipeline and the subsequent storage in deep saline aquifers. The cost estimations are based on a pipeline transport infrastructure linking the new capture-ready 650 MWe coal fired power plant with individual storage sites in the proximity of the point source (within area of radius less than 200 km) . Flue gas rate from the new supercritical coal fired power plant at full load of 650 MWe is estimated at 140 kg/s CO_2 and assuming an average capture rate of 90% through chemical absorption with amines (post combustion capture) around 3,5 Mt CO_2/y will be available for geological storage.

According to previous work in the GESTCO (Geological storage of CO_2 from fossil fuel combustion) Project [3] and the results of a preliminary assessment of the suitability of Tertiary sedimentary basins in Greece [4] CO_2 storage options in Greece fulfilling the following criteria: (a) Adequate capacity and injectivity, (b) A satisfactory sealing caprock or confining unit and (c) A sufficiently stable geological environment to avoid compromising the integrity of the storage site [1], exist in deep saline watersaturated reservoir rocks of the Mesohellenic Trough (MHT), the Thessaloniki Basin and the Prinos Basin Miocene sediments (Figure 1). The computation of cost estimation for CO_2 transport and storage in the identified saline aquifers was performed following the methodology adopted by the **IEA Greenhouse Gas R&D Programme, Report Number: 2005/2** (Building the cost curves for CO_2 storage: European Sector) [5], excluding the cost for CO_2 capture and compression.

2. Geological setting of deep saline aquifers in Greece

The reservoir properties and the storage capacity estimations of the identified Prinos, West Thessaloniki, and Messohellenic Trough - Pentalophos saline formations (Figure 1) in the Tertiary sedimentary rocks of Greece are presented in Table 1 [3], [4]

2.1. Prinos Basin

The Prinos Miocene sedimentary basin in the North Aegean Sea covers an area of 800 km2. The thickness of sediments within it exceeds 6 km. The Prinos Basin is a fault controlled rift basin, trending NE–SW. The reservoirs in the basin consist of sandstones and some siltstones with an aggregate thickness of around 260 m. Containment is provided by salt and evaporite deposits and overlying clastic unconsolidated sediments, which cover the whole basin and are up to 2300 m thick [3], [4]. The depth to the top of the Prinos saline aquifer is about 2 km assuring the supercritical state of CO_2 for such a warm basin [6]. The average thickness of the reservoir is estimated to be 260 m with a net/gross of 0.8 resulting in approximately 208 m of net sand. The reservoir intervals have an average permeability of 50 mD and porosity ranging from 15% to 20% indicating fair injectivity potential [4]. The storage capacity of the saline water-bearing reservoir rocks in the offshore Prinos Basin has been estimated at 1350 Mt CO_2 [3].

2.2. Thessaloniki basin

The Thessaloniki Basin is located to the west of the city of Thessaloniki covering an area of 4200 km^2 onshore and 4000 km^2 offshore. The Thessaloniki Basin has a NNW–SSE trend and constitutes a complicated tectonic graben [4]. The sediments comprise mainly clastic units (conglomerates, sands, clays) and locally calcareous sediments (limestones, marls) [4]. The basement below the basin contains high grade metamorphic rocks mainly of the Axios geotectonic zone. The thickness of the saline sandstone aquifers of the Western Thessaloniki Basin reservoir formations exceeds 500 m [4], providing opportunities for CO_2 storage. The overlying sediments comprise primarily Oligocene flysch with a thickness of around 1200 m forming a major cap rock [4].

Figure 1 Proposed pipeline route from the new capture-ready 650 MWe coal fired power plant to the candidate saline formations

The sand/clay ratio in the aquifer formation ranges between 40% and 90% sand and is strongly affected by the formation of the salt structures. The depth to the top of the saline formations varies from 900 to 2400 m (West Thessaloniki), respectively, meeting the optimum depth that maximizes the CO2 storage capacity in cold basins [6]. The injectivity varies from very poor to poor, with porosity ranging from 5% to 20% and permeability ranging from a few mD to 120 mD [3], [4].The total storage capacity of volumetric traps in the onshore Thessaloniki Basin is estimated at 605 Mt CO_2 [3].

	Location	Depth (m)	Thickness (m)	Porosity (%)	Storage capacity (Mt CO2)
Prinos	Offshore	2.400	260	Average 18	1350
West Thessaloniki	Onshore	900 - 2.400	100	Average 10	605
Messohellenic Trough (Pentalophos)	Onshore	1.000	Variable	10	216

Table 1 Reservoir properties and CO2 storage capacities of saline aquifers in the Tertiary sedimentary rocks of Greece

2.3. The Mesohellenic Trough

The Messohellenic Trough, the largest and most important ‘molasse-type’ basin of the Hellenides, located on the western border of the central Hellenic thrust belt. It is 40 km wide and 300 km long, extending from Albania to Thessalia in a NNW–SSE direction. This Tertiary basin hosts thick sequences of conglomerates and sandstones, which seem to provide the necessary space and seal in order to store significant quantities of CO2 [3].

Potential CO_2 storage opportunities exist in the Eptahori and Pentalophos saline formations of the Mesohellenic Trough and specifically, between the east margin of the Trough and the Theotokos-Theopetra uplifted structure. In that area, the formations are in the adequate depth and there is no risk of lateral migration of the CO2 as they come in contact with impermeable rocks (ophiolites and schists) [4].

The Eptahori Formation, with an estimated thickness of 1200 m, consists of conglomerates and sandstones while the seal is provided by marine turbiditic shales (thickness about 250 m). The base of the Pentalophos Formation consists of conglomerates, followed by alternating turbiditic sandstones and shales. The estimated thickness is 2500 m [4]. The porosity of the turbidite sandstones of the Eptahori and Pentalophos Formations varies between 15% and 25% while the average permeability is estimated to be low indicating poor to moderate injectivity potential [4]. The depth to the top of the geological structures varies from 1 to more than 2 km, which is adequate to maintain CO2 in a supercritical state [4].The CO_2 storage capacity of the Pentalophos Formation was estimated to be around 216 Mt CO_2 [3].

3. Cost of pipeline-based CO2 transport in Greece

The schematic pipeline route from the new capture-ready 650 MWe supercritical coal fired power plant to the candidate saline formations, as CO_2 storage reservoirs with sufficient available CO_2 storage capacity for the assumed lifetime of the storage facility (20 years), is illustrated in Figure 1. The resulting transport cost (euro/t CO_2) is indicated in Table 2, following the steps and the equations of the IEA Greenhouse Gas R&D Programme methodology [5]:

- Determination of pipeline diameter
- Determination of pipeline investment costs (the investment costs for booster stations are not considered as no booster stations are required for the defined transport distances)
- Determination of annual transport costs, as an addition of the annualised investment costs (using a discount rate of 10%/y) and the annual Operation & Maintenance costs (as 3% of investment costs for pipelines)
- Computation of specific transport costs (euro/t CO_2)

The schematic pipeline route from the new capture-ready 650 MWe supercritical coal power plant to the proposed offshore Prinos saline aquifer would involve an onshore leg of around 165 km and 45 km offshore (Figure 1).

	Messohellenic Trough (Pentalophos saline formation)	West Thessaloniki saline formation	Prinos saline formation
Distance (km)	120	150	190
Storage capacity (Mt CO2)	216	605	1.350
Flow rate (kg/s)	126	126	126
Pipeline diameter (in)	12,5	12,5	12,5
Terrain factor	1,5	1,3	1,2
Pipeline investment costs (M€)	29,6	31,5	52,3
Annual transport costs (M€/y)	3,6	3,8	7,7
Specific transport costs (€/t CO2)	1,00	1,06	2,15
Specific transport costs (€/t CO2/100 km)	0,8	0,7	1,13

Table 2 Estimated cost of CO_2 pipeline transport from the new 650 MW coal power plant to saline aquifers in North Greece

4. Cost for CO2 storage in saline aquifers in North Greece

The storage cost calculations include capital investment costs (CAPEX) divided in: a) site development costs; b)drilling costs; c) surface facilities and d)monitoring costs and operational expenditures (OPEX) related to the daily operational costs of a storage facility and the maintenance costs which include operational and maintenance items as well as costs of monitoring the storage facility for safety. These operational as well as maintenance costs are generally taken as a certain percentage of the investment cost [5].

The estimated CO_2 storage cost for each candidate saline aquifer in North Greece is given in Table 3 based on the following assumptions [5]:

- The calculations are partly based on figures converted from former European currencies to euro. The baseline for the cost calculations is the year 2000. 1 US$ = 1 € is taken as the currency exchange rate.
- Each storage structure is filled within 20 years, the assumed lifetime of the storage facility and assuming that sufficient CO_2 is available.
- The cost calculations are based on the levelised costs, assuming a discount factor of 10%.
- CO_2 is delivered by pipeline at the storage facilities pressurized at 8 MPa.

	Drilling Costs (M€)	Capital Investment costs (CAPEX) (M€)	Operational costs (OPEX) (M€/y)	Levelized annual storage cost (M€/y)	Storage cost (€/tCO2)
Prinos	11,6	38,4	3	7,5	2,1
West Thessaloniki	7,1	11,1	0,7	2	0,6
Messohellenic Trough (Pentalophos)	7,5	11,5	0,8	2,1	0,6

Table 3 Estimated cost for CO_2 storage in deep saline aquifers in North Greece

5. Conclusions

The preliminary cost analysis suggests that the emissions from the new capture-ready 650 MWe coal fired power plant can be stored in the onshore saline formations (West Thessaloniki, and Messohellenic Trough – Pentalophos) and the offshore Prinos saline aquifer at estimated transport and storage costs of less than **$10/t** CO2. The cost for CO_2 transport is **1 €/t** CO_2 for the onshore saline aquifers and around **2 €/t** CO_2 for Prinos saline aquifer showing that the offshore storage location as well as the greater length of the CO_2 pipeline have a significant impact on transport cost. These preliminary cost estimates (0,7 – 1,13 €/t CO_2/100 km) in line with the ranges reported in other studies (0,3 – 2,4 € / t CO_2 / 100 km, [5], [1], [7]).

Similarly, the total storage cost depends on onshore versus offshore storage formations. The total onshore storage cost is estimated at around **1€/t** CO_2 for onshore saline aquifers and increases sharply to **2 €/t** CO_2 for the offshore option. The results are in agreement with other studies' estimates [5], [8], [9].The increased storage costs of the offshore Prinos saline aquifer could be countered by the well established infrastructure framework within 30–40 km of the coast (pipelines, wells and platforms for oil and gas production). In addition, CO_2 transport and storage in the Prinos saline aquifer would be more cost effective in the case that a backbone transport infrastructure could be developed clustering several capture points [5], [7].

It is worth noting that the CO_2 storage capacity of saline aquifers in Greece in the Tertiary sedimentary basins was estimated for the whole basin storage capacity based on bulk volume of the aquifers using a storage efficiency factor of 6% [4]. Therefore, a range of R&D activities is required in order to determine the storage efficiency factor, as site specific value, through numerical simulations and field work.

To conclude, the presented calculations represent a rough idea of the CO_2 transport and storage costs at national level. A more specific case-by-case cost evaluation is required through the development of an updated engineering and economic models of CO_2 transport via pipelines, and geological storage of CO_2 in deep saline aquifers of North Greece taking into account the significant escalation (by over 100%) in fuel and steel costs over the last five years compared to earlier estimates [10].

References

[1] IPCC. Carbon Dioxide Capture and Storage, edited by Bert Metz, Ogunlade Davidson, Heleen de Coninck, Manuela Loos and Leo Meyer, Cambridge University Press, Cambridge, UK; 2005

[2] IEA (International Energy Agency). Energy Technology Perspectives 2008, OECD/IEA, Paris; 2008a

[3] GESTCO Project: Geological Storage of CO_2 from Combustion of Fossil Fuel. European Union Fifth Framework Programme for Research & Development, second ed. Project No. ENK–CT-1999-00010. Summary Report; 2004

[4] Koukouzas N, Ziogou F, Gemeni V.Preliminary assessment of CO_2 geological storage opportunities in Greece, Int. J. of Greenhouse Gas Control 2009; 3(4):502-513

[5] IEA (International Energy Agency) Greenhouse Gas R&D Programme Report Number 2005/2: Building the cost curves for CO_2 storage: European Sector; 2005

[6] Bachu, S. Screening and ranking of sedimentary basins for sequestration of CO2 in geological media in response to climate change. Environ. Geol. 2003; 44:277– 289

[7] McKinsey & Company. Carbon Capture & Storage: Assessing the Economics; 2008

[8] European Technology Platform for Zero Emission Fossil Fuel Power Plants: Analysis of funding options for CCS demonstration plants, Climate Change Capital; 2007

[9] European Technology Platform for Zero Emission Fossil Fuel Power Plants, Working Group 4 Subgroup on « Markets, Policy and Regulation », 2006

[10] IEA (International Energy Agency) (2008), Energy Technology Analysis: CO_2 capture and storage, A key carbon abatement option, OECD/IEA, Paris.