CO_2 CAPTURE AND STORAGE IN GREECE: A CASE STUDY FROM KOMOTINI NGCC POWER PLANT

by

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The aim of this paper is to examine the possibilities for the abatement of CO_2 emissions in the Greek fossil fuel power generation sector. An overview of CO_2 capture, transportation, and storage concepts, on which the R&D community is focused, is presented. The implementation of post-combustion CO_2 capture options in an existing fossil fuel power plant is then examined and the consequences on the overall plant performance are determined. Finally, the possibilities of transportation and then underground storage of the pure CO_2 stream are analysed taking into account both technical and economical factors. The results of this analysis show that CO_2 sequestration is technically feasible for existing fossil fuel fired power plants in Greece. However, substantial reduction in plant efficiency is observed due to increased energy demand of the technologies used as well as in electricity production cost due to capital and operation costs of capture, transport, and storage of CO_2.

Key words: *carbon dioxide, sequestration, fossil fuel power plants*

Introduction

It's widely accepted that the main anthropogenic greenhouse gas is carbon dioxide, with substantial contribution to the anticipated change in the climate, and the main cause of its existence is the combustion of fossil fuels for power generation [1]. On the contrary, power generation will become more dependent on fossil fuels in the future. It is estimated that the share of power sector in total emissions will rise, from 40% in 2002 to 44% in 2030 [2].

CO_2 emissions in Greece

Fossil fuels are expected to dominate in power production in Greece. It is estimated that they will account for around 75% of total electricity produced in 2020 [3]. The contribution of the electricity sector to the total national CO_2 emissions in Greece was approximately 50% in 2003 as shown in fig. 1 [3]. The target set under the Kyoto Protocol for the greenhouse gases levels in Greece in the period 2008-2012 is a maximum of 25% raise compared to 1990 levels. However, the Greek National Allocation Plan foresees that greenhouse gases will increase by 39.2% in 2010 and by 57.2% in 2020 compared to 1990 level. Well established measures for emission avoidance are dealing with improving energy efficiency or shifting to non fossil energy sources, such as renewables. A new approach that is gaining significant interest worldwide is to control CO_2 emissions by sequestering CO_2 from fossil-fuel combustion sources in geological formations [4-6]. The complete process involves capturing and compressing CO_2 from the power plant, transporting CO_2 to an injection site and storing it in a reservoir.

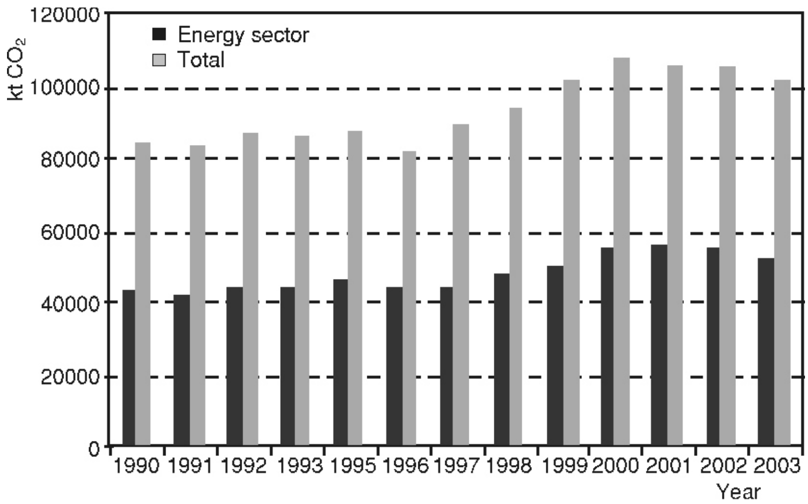

Figure 1. CO_2 emissions in Greece and the contribution of the energy sector [3]

CO_2 storage potential in Greece

In Greece, potential CO_2 storage sites were investigated through past R&D projects proving a limited storage capacity. The only proven hydrocarbon field is the oil field in Prinos with a storage capacity of 17 Mt. Additional storage capacity of 2.2 Gt is exhibited by saline aquifers, however further research must be carried out in order to validate their capability to store CO_2 [7]. Furthermore, a study has shown that the Mesohellenic basin constitutes excellent reservoir storage capability; therefore it can comprise a potential CO_2 storage site in the future [8]. Finally it is worth mentioning that Greece remains one of the most unexplored countries especially in depths below 3000 m. Therefore, the CO_2 storage capacity in Greece can substantially increase in the near future.

Capture and storage of CO_2

Technologies for CO_2 capture 9, 10

Within the R&D community there is significant interest in new carbon-capture concepts. Special focus has been given over the last decade in three specific concepts which are the following:

(a) *Post combustion capture*: CO_2 is captured from flue gases (3-20% vol. CO_2) in low pressure (1 bar). This technology is based on the separation of CO_2 from a gas mixture of nitrogen and oxygen. The most common practice is the amine scrubbing technology which can be implemented as a retrofit option in existing fossil fuel power plants. However this will result in a substantial cost which is currently estimated at 40-60 €/t of CO_2 avoided [11].

(b) *Pre-combustion capture*: CO_2 is separated from a high hidrogen content gas mixture, product of coal gasification or natural gas steam reforming in high pressure (15-40 bar). The most common practice is the absorption of CO_2 with Rectisol or Selexol.

(c) *Oxy-fuel combustion*: the target is to exclude nitrogen before or during the combustion process and to produce a concentrated stream of CO_2. In this concept the critical stage is the production of oxygen from air. Cryogenic separation is the leading option.

Options for CO_2 storage

Following the capture process, CO_2 needs to be stored, in order not to be emitted to the atmosphere. The main storage options are:

(a) *Storage in active oil reservoirs (enhanced oil recovery)*: enhanced oil recovery (EOR) is a technique that allows increased recovery of oil in depleted or high viscosity oil fields but also sequestered CO_2 that would normally be released to the atmosphere. In general terms, CO_2 is flooded into an oil-field through a number of injection wells mixed with the crude oil, causing it to swell and thereby reduce its viscosity. This also helps to maintain or increase the pressure in the reservoir. These processes allow more of the crude oil to flow to the production wells while an amount of the CO_2 remains in the reservoir [12].

(b) *Storage in coal beds (Enhanced coalbed methane recovery)*: in this process the CO_2 is injected into deep, unmineable coal seams. It is adsorbed at the expense of coal bed methane, which can then be recovered as free gas while the CO_2 remains stored within the seam. A particular advantage of this technique is that coal seams can store several times more CO_2 than the equivalent volume of a conventional oil or gas reservoir because coal has a large surface area [13].

(c) *Storage in deep saline aquifers*: CO_2 is injected in reservoirs, at depths greater than 800 m, which contain salt water. CO_2 will dissolve in it and become widely dispersed in the reservoir. It can also react with the minerals within the aquifer and remain fixed there [14].

(d) *Storage via mineralization*: a new method that CO_2 reacts with minerals (magnesium – calcium oxide) to form solid carbonates that are thermodynamically stable and cannot release significant volumes of CO_2. There is an argumentation that CO_2 storage in minerals is likely to be safer than other underground sequestration options [15].

Options for transport

There are four different transportation systems suitable for CO_2 captured from the fossil-fuelled power industry: (a) *motor carriers (trucks)*, option with high transportation costs and low capacity, (b) *railway*, a competitive means of transportation but needs appropriate rail infrastructure and transportation equipment, (c) *water carriers (vessels)*, very cost-effective means of transportation for CO_2 off-shore due to the large loading capacity, and (d) *pipeline*, already applied to many CO_2 storage and CO_2 EOR projects [16].

CO_2 sequestration in an existing natural gas fired power plant in Greece

In Greece the most promising suitable field for CO_2 sequestration is the off-shore oil reservoirs located at the area of Prinos in North Greece, which is estimated to be of a storage capacity of approximately 17 Gt. Furthermore, this aspect is gaining more interest by the fact that a natural gas fired power plant exists in a feasible distance for CO_2 transport and the CO_2 stream can be utilised for recovering additional quantities of oil (CO_2 EOR option).

At the first stage of this study, the feasibility of post combustion CO_2 capture with chemical absorption is examined in an existing natural gas combine cycle power plant in Greece. Then a possible option for CO_2 transport and storage to an oil reservoir under operation is proposed and analysed both from technical and economical point of view.

Post combustion CO_2 capture in a natural gas combined cycle – Case study results

Amine scrubbing technology description

Amine scrubbing is a well established technology for capturing CO_2 while it is widely used in food industry and in the Sleipner plant in North Sea to remove CO_2 from natural gas [13]. Applying this technology to a gas turbine power plants involves separation of CO_2 from the exhaust gases coming after the heat recovery steam generator (HRSG) using chemical absorption with amine based (*e. g*. monoethanolamine – MEA) aqueous solutions [17-19]. In this method, MEA absorbs CO_2 through chemical reaction in an absorber column. Because the reaction is reversible, the CO_2 can be collected by heating the CO_2-rich amine solution in a separate stripper column. The MEA may then be recycled through the process. Amine scrubbing systems require large amount of heat in order to regenerate the CO_2-rich solvent. This heat is typically drawn from the steam cycle and significantly reduces the net efficiency of the power plant shown later. Additional mechanical work is required in order to overcome pressure drop in the absorber column and for auxiliary pumping systems.

Power plant performance evaluation

Post combustion capture with amine scrubbing technology was applied in one of the four natural gas-powered thermoelectric power stations currently in operation in Greece which located near the city of Komotini. The Komotini natural gas combined-cycle (NGCC) power plant consists of two gas turbines (ABB GT3E2 50 Hz model) and one steam turbine, resulting in a total net power output of 476 MW_e. A similar gas turbine combine cycle was simulated with the Gatecycle software package [20] in order to evaluate the performance of the plant assuming the above-mentioned post-combustion CO_2 capture scenario.

The flue gas exiting the HRSG enters the amine plant, as shown in fig. 2 to produce a CO_2 rich-stream. The separated CO_2 is compressed and cooled in order to meet the storage and transport over supercritical conditions (140 bar, 32 °C). CO_2 compression can be realised using a three stage compressor with equal pressure ratios up to 80 bar and intercooling at 25 °C and pumping to the final pressure (140 bar). The overall system was simulated assuming a 90% CO_2 capture and an energy input for the reboiler in the amine plant of 3.5 MJ/kg CO_2 recovered [19]. This energy requirement is met by low pressuresteam (1.4 bar) which is extracted from the steam cycle from the low pressure steam turbine and accounts for 80 kg/s. This results in a substantial loss of power in the

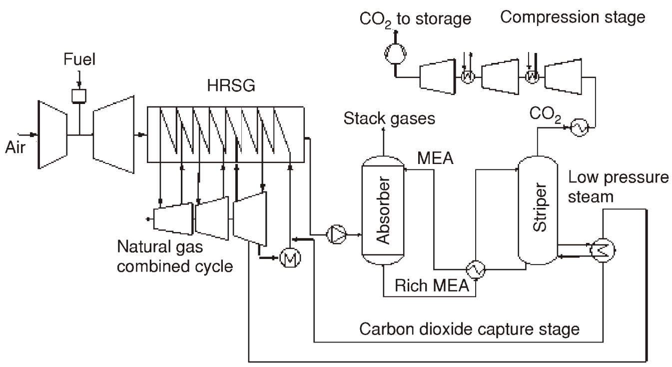

Figure 2. Flow sheet diagram of the CO_2 capture process with amine scrubbing in a NGCC power plant

steam cycle and when combined with the compression power requirement results in a significant power penalty for CO_2 capture.

In tab. 1 it is shown that the net power produced decreases to 395 MW_e from 476 MW_e and the overall efficiency decreases to 43% from 52%. Substantial electrical energy also is needed to compress the captured CO_2 for pipeline transport to a storage site The calculated results is in good agreement with other similar studies in the literature [19, 21, 22].

Table 1. Calculated results for a NGCC with and without CO_2 capture

	NGCC without CO_2 capture	NGCC with CO_2 capture
Net power output, [MW_e]	476	395
Gas turbine 1	156.5	156.5
Gas turbine 2	156.5	156.5
HP steam turbine	37	37
IP steam turbine	70	70
LP steam turbine	56	25.5
Mechanical work CO_2 for compresion	–	23.3
Mechanical work in amine plant		
– Exhaust gas fan	–	22.6
– Auxiliary pumps	–	3.3
Net plant efficiency (HLV), [%]	52	43
CO_2 to atmosphere, [kg/MWh]	504	50.4
CO_2 captured, [kg/MWh]	–	453.6

CO_2 transport and storage in an oil field

A suitable location to store the captured CO_2 from the power plant in Komotini is the oil field in Prinos. It covers an extent of 4 km^2 roughly and it is found 8 km western of island Thasos and 18 km southern of the seacoast. The oil field is found at depth of 2500 m and it is extended up to 2850 m, while the depth of the sea in the region is 30 to 35 m roughly [23]. The first two deposits of Prinos (oil) and S. Kavala (natural gas) are already depleted and they can be used as CO_2 storage sites. The deposit in North Prinos (oil) from the second exploitation sections is still in operation and is a potential site for CO_2 EOR.

In this case study the transportation via pipeline is chosen due to the fact that pipelines can deliver large amounts of CO_2, continuously when it is delivered in its liquid or supercritical/dense phase. In these phases the pressurized CO_2 has higher density and therefore the maximum throughput can be transported. For the final storage, the conditions will be similar to transportation conditions, due to high hydrostatic pressure which occurs in the underground porous rock formations at these depths.

Cost of transport

The possible route of the pipeline, as shown in fig. 3, is a 120 km line comprising an on-shore and off-shore segment. The on-shore part is extended from the power plant in Komotini to land installations of the S. Kavala. A while the off-shore part ends to the injection point. For the design of the pipeline, it is assumed that the terrain (tab. 2) is normal (flat). The pipeline diameter is assumed at 8" capable to transport an annual capacity of 1.2 Mt similar to the calculated amount from the selected power plant [24]. A probable lifetime for a pipeline is 25 years and this number is used in the following calculations together with an assumed interest of 5% [25].

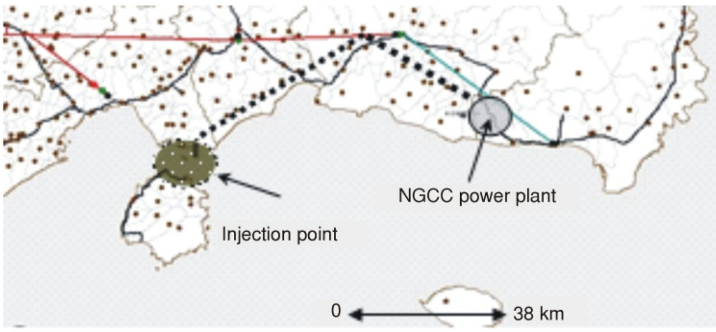

Figure 3. Prinos oil reservoir and NGCC power plant location and probable pipeline layout

Table 2. Pipeline technical specifications

Pipeline length on-shore	100 km	ANSI Class 900# (140 bar)
Pipeline length off-shore	20 km	ANSI Class 1500# (220 bar)
Pipeline diameter (in)	8"	
Terrain	flat	

The investment and operational and maintenance costs for constructing and operating the on-shore and off-shore pipeline are calculated according to the methodology proposed by the IEAGHG [26]. In this case study, the injection wells and platforms already exist therefore they are not considered in the total storage cost. The investment cost of the 100 km on-shore pipeline is 9.88 M$, while for the 20 km off-shore segment it is estimated at 13.3 M$. The operational cost of a 120 km pipeline with 8" diameter is calculated at 0.29 M$ as shown in fig. 4. Cost estimates of sequestration in depleted oil/gas fields range from 1 to 8 €/t CO_2 injected depending on the depth of the reservoir, re-use of facilities and on- or off-shore location [27, 28]. Cost of EOR are estimated to range from –10 to 10 €/t CO_2 injected on-shore and –10 to 20 €/t CO_2 injected off-shore [30]. Therefore an additional reduction in the overall costs can be achieved if the EOR option is used.

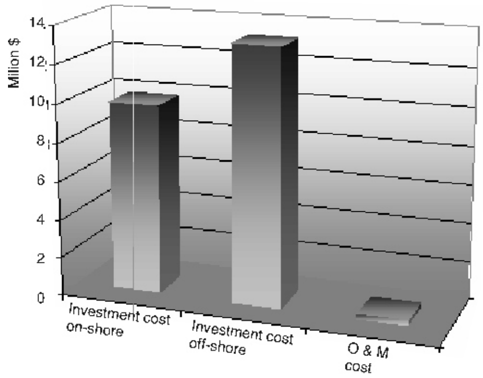

Figure 4. Calculated costs of CO_2 transport by pipeline

Environmental issues

The potential impacts associated with CO_2 in geological formations are largely associated with the possibility of leakage. The potential for such leakage will depend upon cap rock integrity and the security of well capping methods in the longer term together with the degree to which the CO_2 is eventually "trapped" through solubility in *e. g.* residual oil, formation waters or by reaction with minerals to form carbonates. Other major environmental issues may be associated with pipeline leakage and the release of other impurities presented in the CO_2 stream, such as, toxic compounds (H_2S, HCN, COS, CO, SO_2), acidic compounds (NO_x) *etc*. The existing statistics from the EOR industry show that the risks for pipeline leakage are lower than for natural gas or other hazardous pipelines [30], but to minimize risks, transportation of CO_2 should be carried out away from populated areas. Another issue, which can indirectly affect the transportation, is the public opinion concerning storage of CO_2. Therefore, the probability of a pipeline leakage and its consequence either on the population area or on marine life and ecosystem needs to be carefully evaluated.

Conclusions

CO_2 sequestration is technically feasible for existing fossil fuel fired power plants in Greece. However, substantial reduction in plant efficiency and in output power is observed due to increased energy demand for CO_2 capture using the amine scrubbing technology. An equivalent energy penalty is observed due to mechanical work for CO_2 compression to its supercritical phase. Assuming 90% carbon capture efficiency the thermal efficiency of the plant is by nine percentage points lower by lower than in the plant without CO_2 capture. Transport and storage of the captured CO_2 seems to be feasible for the case examined while the calculated capital and operational costs are estimated at reasonable level. This is attributed mainly to the relative small distance between the power plant and the injection point. Potential profit from the enhanced oil recovery option can be further decrease the total cost of sequestration. However, the major barrier for the implementation of CO_2 sequestration remains the high cost of capture which is approximately 40-60 €/t CO_2 avoided.

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