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Konstantinos Kavouridis, Christos Roumpos***, *Mihail Galetakis**

THE EFFECT OF POWER PLANT EFFICIENCY, LIGNITE QUALITY AND INORGANIC MATTER ON CO_2 EMISSIONS AND COMPETITIVENESS OF GREEK LIGNITE

1. Introduction

Domestic lignite with a share of 60.5% (2005) in power generation and accounting about 30% of primary energy consumption is currently the most important indigenous fuel of Greece. Lignite industry in Greece has more than 50 years in house experience in exploration and open-cast mining. Significant achievements and large experience has been gained during many years of mining operations place Greek lignite mining industry in the leading position in Europe. At present, Public Power Corporation SA (PPC), producing 97% of the lignite extracted in Greece, operates five open-cast lignite mines in Western Macedonia region, Northern Greece and in Peloponese region (Megalopolis), Southern Greece, together mining approximately 70 Mt of lignite per year. The four mines (Main field, South field, Kardia field and Amyndeon-Florina) constitute the lignite Center of Western Macedonia with an annual production of 55–57 Mt, while the mines in Peloponese region under the name of lignite Center of Megalopolis produces approximately 14 Mt per year. Five principle power plants supplied by lignite from Western Macedonia lignite Center are located within a radius of 12 km from the mines with a total installed capacity of 4395 MW (Power plants: Ptolemais 620 MW, Kardia 1250 MW, Agios Dimitrios 1595 MW, Amyndeon 600 MW and Meliti 330 MW). Lignite from Megalopolis mines is used to supply power plants located within a radius of 2 kilometers from the mines with a total installed capacity of 850 MW [4]. The contribution of lignite in the future energy mix of Greece will be crucially determined by environmentally compatible i.e. low CO_2 generation of electricity.

This work is divided into three parts. The first presents the methodology and a theoretical model of calculation of CO_2 emission from coal/lignite power plants. The second

* Technical University of Crete, Greece
** Public Power Corporation of Greece SA

investigates the effect of power plant efficiency and the lignite quality on CO_2 emissions and consequently on the cost of power generation from existing lignite units of Greece. The third part is focused on the contribution of carbonate minerals, which are common minerals in the inorganic matter of Greek lignite, to CO_2 emissions when they decompose during the combustion process.

2. Reserves and lignite quality

The total proven lignite reserves in Greece amount to approximately 5.8 billion tones. Today 3.1 billion tones of them are exploitable reserves suitable for electricity generation.

The following map (Fig. 1) shows the location of the main exploitable lignite reserves in Greece. Greek exploitable lignite reserves are fossil fuels of low calorific value and high ash content [5].

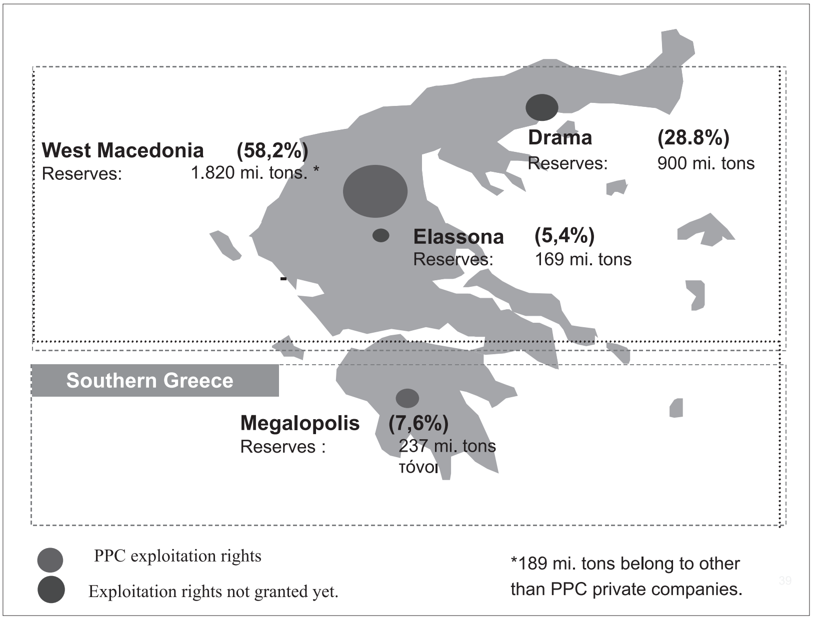


Fig. 1. Location of the main exploitable lignite reserves in Greece — 31.12.2005

The quality of the Greek lignite deposits under exploitation varies highly both within and across mines [1, 2].

Table 1 gives the daily range and monthly mean concentration of power heating value and ash content (dry basis) of the lignite produced from the Ptolemais mines in the years 2000–2005.

TABLE 1

Daily range and monthly mean concentration of LHV and ash content (dry basis) of lignite from Ptolemais — Amynteon mines in the period 2001–2005*

	Lower heating value — LHV, kcal/kg		Ash content (dry basis), %	
Mines	range	mean value	range	mean value
Main Field	1050–1600	1352	21.0–44.0	32.9
Kardia Field	1020–1605	1320	23.5–43.0	31.5
South Field	950–1505	1220	28.0–44.0	36.0
Amynteon Field	950–1620	1254	28.6–55.0	38.3

* the water content of the excavated lignite fluctuated in the range 48–55% in this period

3. The CO_2 Emission Trading System (ETS) and a cost efficient way of CO_2 reduction

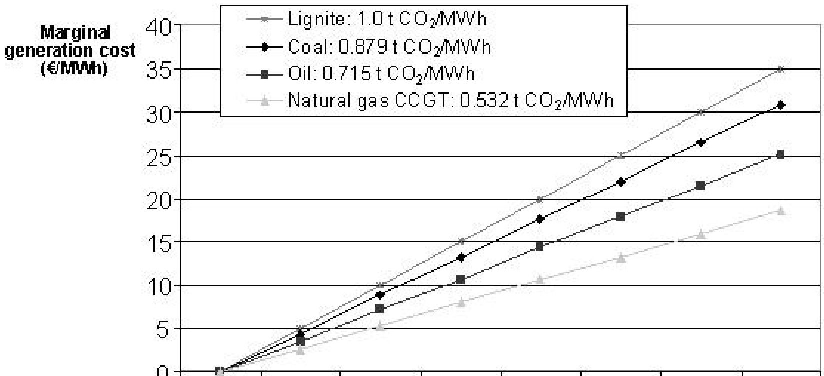
The application of Kyoto protocol, since February 2005, has created a new framework for the energy market and consequently for lignite activities in Europe. Key element to achieve Kyoto protocol target of GHh reduction for EU is the ETs.

Under the Emission Trading Directive EU member States are obliged to adopt National Allocation Plans (NAPs) aiming to cut CO_2 emissions where it proves cost effective. The Greek NAP for the first phase (2005–2007) includes 213.4 Mt CO_2.

The introduction of emission allowances will alter operating cost in the power generation sector and is expected to have an influence of existing generation capacity as well as the composition of the future investment. The CO_2 emission allowance will increase the variable costs of fossil-fuel power plants and thus its short-run marginal costs, since an emission allowance will be needed for each ton of CO_2 produced. Lignite produced electricity is affected much more than gas produced electricity, because of the higher (approximately double) CO_2 emission per unit of output. Figure 2 illustrates how allocation prices of CO_2 affect the marginal cost of power generation. For the Greek generation system the specific value of CO_2 emissions (t of CO_2/MWh), per fossil fuel, is given in Table 2. Therefore, the rising allocation prices for CO_2 has a higher effect on marginal cost of lignite fired power plants.

A further boost to efficiency of power plant is the right approach to tackle climate protection issues and also offer the possibility to continue using lignite in the future in quantity comparable to current. According to EU Coal Industry, the efficiency of power construction has been increased and remains increasing, by means of high investments in new and upgraded existing facilities, while emissions are decreasing at the same time. The construction of new lignite-fuelled power plants is the cost — efficient way of reducing CO_2

emission. Modern lignite-fuelled power plants achieve an efficiency of more than 40% approximately, 30% more than the facilities that were built in the 1960s and that now need to be replaced.



Price (€/t CO_2e)	0	5	10	15	20	25	30	35
Natural gas	0	2.66	5.32	7.97	10.63	13.29	15.95	18.61
Oil	0	3.58	7.15	10.73	14.31	17.88	21.46	25.04
Coal	0	4.39	8.79	13.18	17.57	21.96	26.36	30.75
Lignite	0	5	10	15	20	25	30	35

Fig. 2. Effect of CO_2 prices on the marginal generation costs from fossil fuels

TABLE 2

Specific emission factor (tonCO_2/MWh) per fuel type of Greek power generation system — PPC's power plants (2005)

Power plants	Specific emission factor, ton CO_2/MWh
1. Lignite	
1.1 Ptolemais — Amynteon	1.31
1.2 Florina	0.94
1.3 Megalopolis	1.49
2. Gas (average)	0.44
3. Oil (average)	0.75

Figure 3 shows the maximum CO_2 reduction, which can be achieved by building new modern lignite-fuelled power plants. A total reduction 2.5–3.0 million tons of CO_2 can be achieved by building a new 1000 MW unit operated under normal loading conditions.

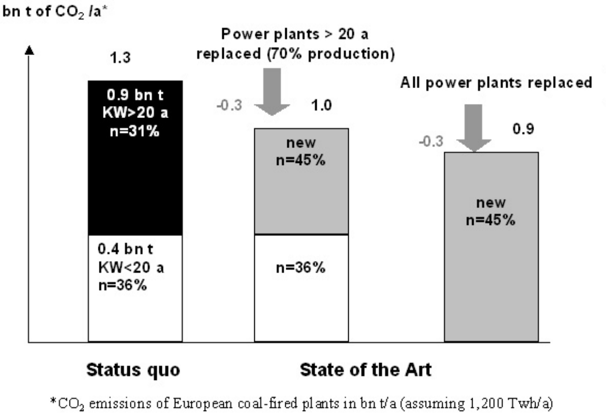


Fig. 3. Maximum CO_2 reduction by building new coal-fuelled power plants in Europe

4. Theoritical model of calculation of CO_2 emission from lignite (coal) power plants

According to Directive 2003/87 the general formula proposed for the calculation of CO_2 emissions is given below:

CO_2 emissions = Activity data × Emission factor × Oxidation factor

For a more accurate estimation of CO_2 emissions from lignite-fuelled power plant, a theoretical model was developed based on the mass balance of total carbon during the combustion process [2]. Figure 4 shows schematically the mass balance of total carbon in a lignite-fired power plant.

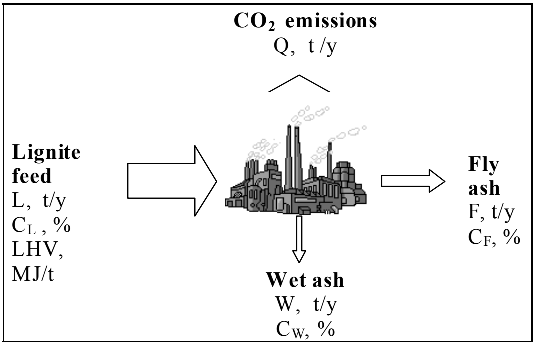


Fig. 4. Mass balance of total carbon, used for calculation of CO_2 emissions: *L* — annual lignite consumption, t/y; C_L — total carbon content of lignite in dry basis, %; *LHV* — lower heating value, kcal/kg or MJ/t; *Q* — annual carbon dioxide emission, t CO_2/y; *W* — annual production of bottom ash, t/y; C_W — total carbon content of bottom ash as received basis, %; *F* — annual production of fly ash, t/y; C_F — total carbon content of fly ash in as received basis, %

The mass balance of total carbon is given by the following equation:

$$L \cdot C_L = \frac{12}{44} \cdot Q + W \cdot C_W + F \cdot C_F$$

where Q represents annual carbon dioxide emissions (t/y).

Based on the actual data of the lignite quality analysis of the central part of the Ptolemais deposit (South Field and Sector 6 mines, which contribute to ~60% of the total lignite production of Greece), the relations between total carbon content (C_L), lower heating value (LHV) and moisture (Wt), were established via linear regression methods. Combining these relations with the above equation, the following equation for the specific emission factor t CO_2/MWh was derived:

$$Q_S\left(\frac{\mathrm{tCO_2}}{\mathrm{MWh}}\right) = \frac{3153.3}{LHV \cdot n}\left(0.0258\,LHV + 5.67\right)\left(\frac{100 - Wt}{100}\right) +$$

$$-0.04\frac{\left(33 - 0.21\,LHV\right)C_W}{100} - 0.96\frac{\left(33 - 0.012\,LHV\right)C_F}{100}$$

By substituting the nominal power plant efficiency, n, and the typical values of the lignite quality parameters in the above equation, the following simple equation between specific emission factor and LHV was derived (Fig. 5):

$$Q_S\left(\frac{\mathrm{tCO_2}}{\mathrm{MWh}}\right) = \frac{1600}{LHV}$$

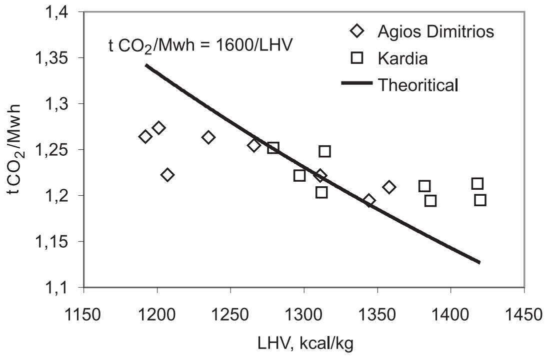


Fig. 5. Correlation between *LHV* and specific emission factor of Ptolemais lignite

5. Effect of power plant efficiency and lignite quality on carbon dioxide emissions and the cost of the electricity production

In Tables 3 and 4, operational data and quality parameters of lignite fed to Agios Dimitrios (1595 MW) and Kardia (1250 MW) power plants, located in Ptolemais lignite area, during 1998–2005, are shown.

TABLE 3

Quality data of lignite and operational data of Agios Dimitrios power plant during 1998–2005

Lignite quality parameters	1998	1999	2000	2001	2002	2003	2004	2005
Total moisture, %	51.19	51.13	50.23	49.66	50.27	49.89	49.64	50.00
Ash as received, %	15.55	15.89	17.31	17.98	17.08	18.15	18.56	18.77
Inorganic CO_2, %	5.11	3.68	4.09	4.31	4.90	5.10	4.70	3.83
Organic C, %	18.84	18.69	18.47	18.14	17.37	17.68	17.38	17.79
Total C, %	20.23	19.70	19.58	19.31	18.71	19.07	18.66	18.83
LHV, kcal/kg	1358	1344	1311	1266	1207	1192	1201	1235
Annual lignite consumption, t	18606697	18178920	21195077	21677541	21375508	22972765	22035402	22089375
Total C in wet ash, %	38.73	36.40	30.68	29.33	34.82	34.45	31.42	25.60
Total C in fly ash, %	2.18	2.35	2.42	2.65	3.11	0.69	0.75	0.59
Power plant efficiency (gross), %	37.00	37.50	37.50	37.00	37.40	37.40	37.30	37.35
Generated electricity, MWh	10862020	10641565	12103890	11807890	11239500	11921785	11481875	11634375
Annual CO_2 emission, t	13132638	12713614	14787589	14816169	13739903	15071342	14624457	14697281
Specific CO_2 emission, t/MWh	1.21	1.19	1.22	1.25	1.22	1.26	1.27	1.26

TABLE 4
Quality data of lignite and operational data of Kardia power plant during 1998–2005

Lignite quality parameters	1998	1999	2000	2001	2002	2003	2004	2005
Total moisture, %	53.07	52.72	52.03	52.59	51.77	51.46	50.69	50.25
Ash as received, %	14.16	14.47	14.92	13.85	15.7	15.61	15.54	16.53
Inorganic CO_2, %	2.44	2.59	2.5	2.51	1.99	2.73	4.05	5.26
Organic C, %	19.54	19.59	19.57	20.05	19.05	18.91	18.90	18.22
Total C, %	20.20	20.29	20.25	20.74	19.59	19.65	20.01	19.66
LHV, kcal/kg	1382	1386	1418	1420	1312	1297	1314	1279
Annual lignite consumption, t	14807569	14496416	14673342	14069475	15958565	14262070	16698945	15903692
Total C in wet ash, %	36.00	31.47	30.59	31.30	27.00	34.21	34.08	34.09
Total C in fly ash, %	1.80	2.20	2.40	2.30	3.10	1.77	1.81	1.73
Power plant efficiency (gross), %	35.59	36.27	36.14	36.25	36.68	36.74	36.5	36.84
Generated electricity, MWh	8500455	8546410	8662590	8,449,515	8960870	7292695	9107935	8612845
Annual CO_2 emission, t	10288147	10207421	10506262	10098511	10783514	8910494	11367001	10782908
Specific CO_2 emission, t/MWh	1.21	1.19	1.21	1.20	1.20	1.22	1.25	1.25

These power plants, which are the largest lignite power plant in Greece, produce about 60% of the total power generation of Greece by lignite.

For constant nominal power plant efficiency, the correlation between the lower heating value of lignite and the specific emission factor of CO_2, for Agios Dimitrios power plant, is shown in Figure 6. The increase in CO_2 emissions, as a function of power plant efficiency is shown in Figure 7. A decrease of power plant efficiency from 87% (nominal power plant efficiency) to 75%, results to CO_2 emissions increase by 13.8%.

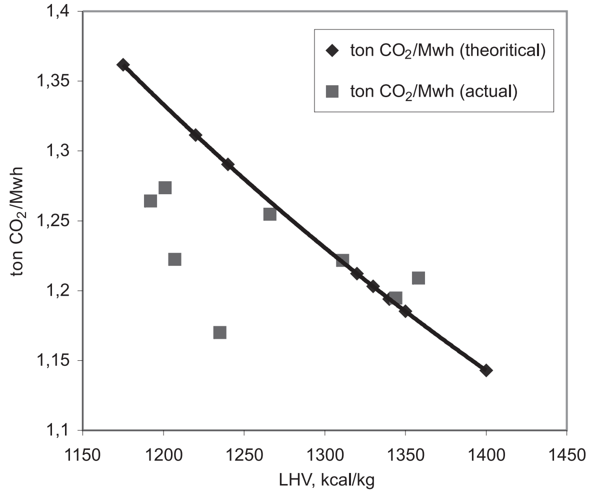


Fig. 6. Correlation of specific emission factor and *LHV* of lignite mined at South Field mine in the period 2001–2005

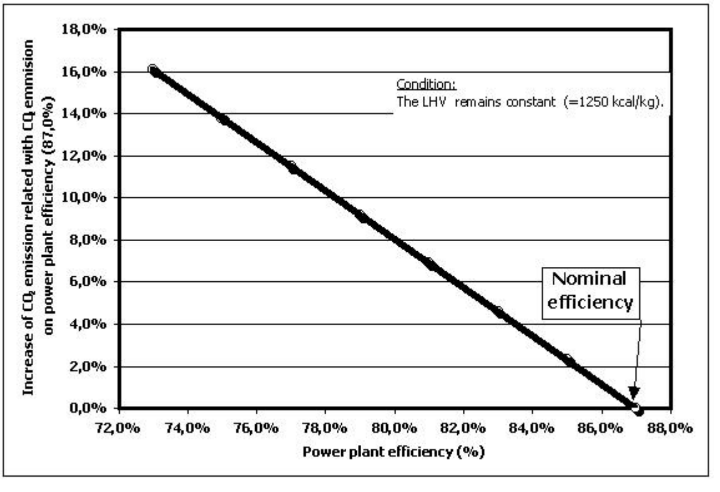


Fig. 7. Increase of CO_2 emission as a function of power plant efficiency

The effect of the power plant efficiency and lignite quality on electricity cost is shown in the Figure 8.

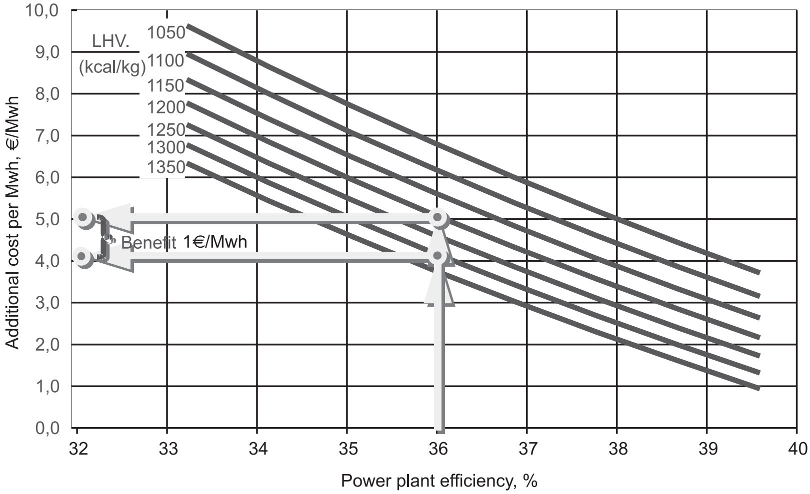


Fig. 8. The effect of power plant efficiency and *LHV* on the generation cost (€/MWh) of Agios Dimitrios power plant (Price of CO_2: 27€/ton, hours of operation per year: 7500 h, annual production: 11 962 500 MWh)

It is worth noticing that for Agios Dimitrios Power Plant, which produces about 12000 GWh annually, the price of 27 € per tone of CO_2 increase the cost of lignite produced MWh by 1 €, when the quality of the lignite deteriorates from 1300 kcal/kg (nominal fuel) to 1200 kcal/kg.

This additional cost represents about 3% of the lignite fired power plant generation cost. This additional cost is reduced to the half with CO_2 prices around 12–15 €/t, which are the current level prices of carbon market.

6. The effect of inorganic matter of lignite on the CO_2 emissions and on the cost of electricity production

The Greek lignite is fossil fuel of high ash content and low calorific value. For Agios Dimitrios and Kardia power plants the ash (as received) of lignite fed varied from 14.2% to 18.7% in the period 1998–2005, while for the same period the dry ash content varied from 30.2% to 37.5%. The CO_2 content of ash, which is originated from the carbonate minerals in ash, mainly from calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), affects considerably the CO_2 emissions. From Brandt formula, shown below, it is obvious that the presence of CO_2 decreases considerably the LHV of lignite.

$$LHV\,(\text{kcal/kg}) = 34.8\text{C} + 93.8\text{H} + 10.5\text{S} + 6.3\text{N} - 10.8\text{O} - 2,5Wt - 4.2\text{CO}_2$$

where C, H, S, N, O, Wt, CO_2 are the% concentration of coal in organic carbon, hydrogen, sulfur, nitrogen, oxygen, moisture and inorganic carbon dioxide respectively.

CO_2 not only is released directly during combustion, but also contributes to additional CO_2 production through the combustion of more organic coal for the production of 4.5 kcal/kg demanded for its decomposition. On the contrary, the presence of sulfur increases the heat released through the lignite combustion and consequently the high sulfur lignite emits less CO_2 in relation to lower sulfur lignite. In lignite-fired power plants with desulphurization processes in the produced gases, CO_2 emissions increase because of the added limestone. Calculations indicate 0.5 kg additional CO_2 for each kg of sulfur removed.

Based on a large number of mineralogical and chemical analysis data from Ptolemais lignite, it can be suggested that the main carbonate minerals is $CaCO_3$. During coal combustion, 0.44 kg of CO_2 are released for every kg of $CaCO_3$ that is contained in lignite ash (Quick and Glick, 2000). In Figure 9 the evolution of organic and inorganic carbon (expressed as% CO_2) of the lignite fed to Agios Dimitrios Power plant, for the decade 1995-2005, is shown. Figure 10 indicates the contribution of organic and inorganic carbon on the emission factor (kg of CO_2/GJ).

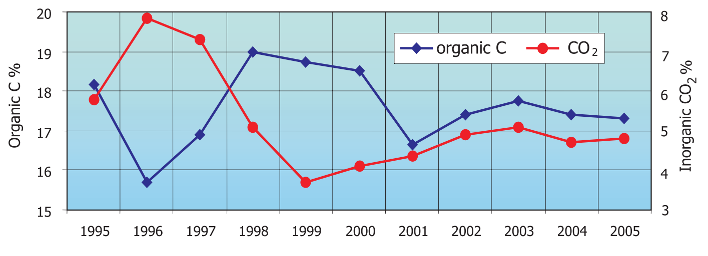


Fig. 9. Temporal fluctuation of % C (organic) and % CO_2 (from carbonate minerals) in lignite from South Field mine (Agios Dimitrios)

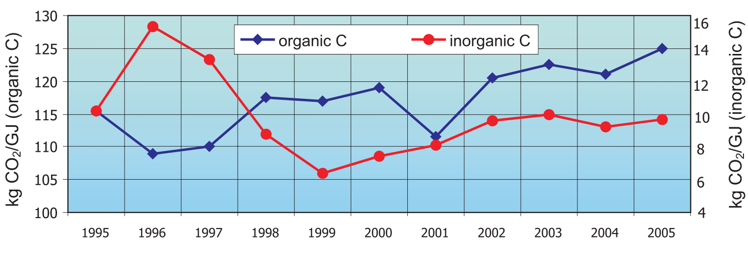


Fig. 10. Temporal variation of CO_2 emission factors (kg of CO_2/GJ) according to organic and inorganic carbon of lignite (South Field mine)

From the above actual data it comes out that the specific emission factor kg of CO_2/GJ from the decomposition of carbonate minerals varied from 6–15,8 kgCO_2/GJ while the corresponding specific emission factor from the combustion of organic carbon varied from

115–125 $kgCO_2/GJ$. In Figure 11, the additional cost of lignite produced kWh from Agios Dimitrios Power plant increasing the $CaCO_3$ content in the ash of lignite fed to the plant in the year 2005 is shown.

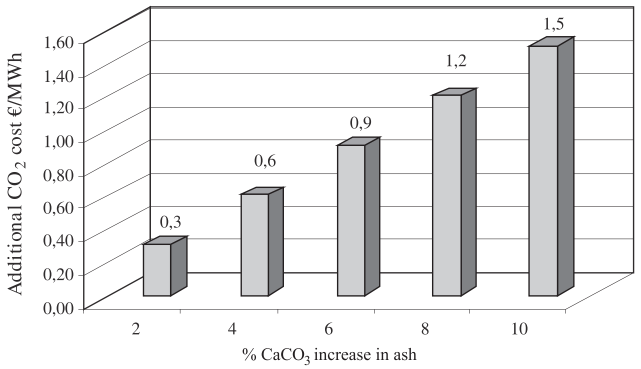


Fig. 11. Additional generation cost of Agios Dimitrios power plant as a function of $CaCO_3$ increase in ash content (CO_2 price: 13,5 □/ton)

From the above-presented results it can be concluded that in multi-seam lignite deposits, with small seam thickness, where lignite layers alter with marly layers, special excavation procedures should be considered in order to avoid the co-excavation of carbon layers along with the lignite.

7. CO_2 emissions and competitiveness of lignite

Lignite is strategic fossil fuel for Greece as well as the main part of electricity production energy mix. Figure 12 shows that, for the period 2000-2005, the generation costs based on lignite were about 40% below oil and gas costs in PPC power plants.

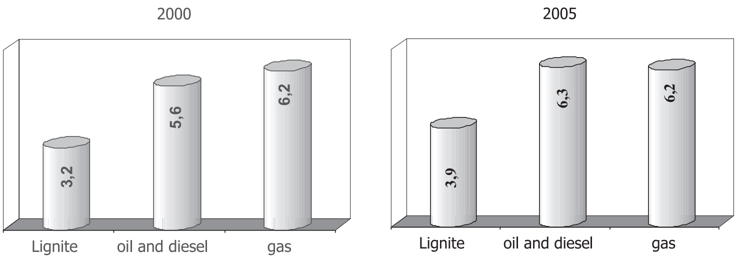


Fig. 12. Generation cost per fuel type (□c/kWh) in the years 2000 and 2005

With the incorporation of the CO_2 emission allowances cost, the cost of lignite-fired power plants that are in operation in Greece, in comparison to the corresponding cost of natural gas and oil-fired power plants is shown in the following Table 5.

TABLE 5

Comparison of variable cost generation per fuel type with the incorporation of CO_2 allowances

Lignite power plant	Variable cost of lignite			Specific CO_2 emission factor		CO_2 emission cost (15 /t)	Total variable cost of lignite	Total average variable cost of gas/oil power plant	Lignite cost advantage
	/tn	t/MWh	/MWh	t/MWh	t/t lignite	/MWh	/MWh	/MWh	/MWh
Ptolemais	3.63	2.16	7.84	1.40	0.71	20.93	28.76	56.40	27.64
Megalopolis	3.25	3.02	9.86	1.41	0.53	21.15	31.01	56.40	25.40
Kardia	3.29	2.04	6.71	1.32	0.71	19.76	26.48	56.40	29.93
Agios Dimitrios	4.24	2.16	9.12	1.34	0.67	20.07	29.19	56.40	27.21
Filotas	3.43	2.06	7.07	1.26	0.68	18.90	25.97	56.40	30.43
Meliti- Achlada	8.10	1.38	11.20	0.94	0.77	14.10	25.30	56.40	31.10

With the prices of natural gas and oil of the year 2005, and a price of CO_2 emission allowances 15 €/ton CO_2, the marginal cost of lignite–fired power plants varies from 25.4 to 31.1 €/MWh (Tab. 5).

8. Conclusions

The quality of the organic and inorganic matter of lignite and the efficiency of the lignite power plants, significantly affects the position of lignite in the future fuel mix of Greece.

To keep (over the next years) lignite's competitiveness in the strict EU environmental legislation framework, the lignite industry should undertake measures towards the development of quality innovative processes to be used in power plants and mines operation.

The expected results of the improvement of lignite's quality and power plant's efficiency are presented.

In order to improve the position of lignite, the following measures should be undertaken:

— Specific measures during the mining process:
1. avoidance of co-excavation interbedded material along with the lignite,
2. avoidance or minimizing the use of conventional equipment (shovels, loaders, etc.) during lignite mining,
3. quality control of the mined lignite at both the mine face and the stock yard,
4. improvement of the quality of lignite with the application of homogenization methods,
5. evaluation of mines' effectiveness, with the emphasis on the quality of the available lignite at the thermal power plants,
6. collaboration of mine operators and thermal power plants operators on issues related to the quality of lignite.

— Measures for the increase of the thermal power plants' efficiency:
- investments for the increase of the installed units efficiency,
- replacement of the old units with new using clean coal technologies providing high efficiency,
- optimization of the power generation management of the existing units in order to cover the needs in the electricity markets.

REFERENCES

[1] *Kavouridis K., Galetakis M.*: Determination of lignite quality produced in Ptolemais open cast mines for power generation. Mineral Wealth, 98/1999, 25–41

[2] *Kavouridis K., Pavloudakis F.*: Evaluation of an on-line analysis system for low grade and inhomogeneous Greek lignite. Proceedings 8th ISCSM 2006, Aachen — Germany, 24–27 September 2006, 281–291

[3] *Kavouridis K., Vamvuka, Galetakis M.*: The effect of lignite quality on CO_2 emissions and cost power production from Western Macedonia power plants. Proceeding 2nd Inter. Conference, AMIREC, Chania, 25–27 September 2006, 45–50

[4] *Kavouridis, K.*: Lignite Mining and Use in Greece. Energy supply and Environment. Inter. Journal of Mining, Reclamation and Environment, Canada, January 2007

[5] *Papanicolaou C., Galetakis M., Foscolos A.*: Quality characteristics of Greek brown coals and their relation to the applied exploitation and utilization methods, Energy & Fuels, 19, 2005, 230–239

[6] *Quick J.C., Glick D.C.*: Carbon dioxide from coal combustion: Variation with rank of US coal. Fuel 79, 2000, 803–812