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Coals of Greece: a review of properties, uses and future perspectives

C. Papanicolaou[a], T. Kotis[a], A. Foscolos[b,*], F. Goodarzi[b]

[a] Institute of Geology and Mineral Exploration, Messoghion 70, Athens 11527, Greece
[b] Geologiocal Survey of Canada, 3303-33rd Street NW, Calgary, Canada T2L 2A7

Abstract

Greece relies heavily on lignites to satisfy its domestic needs for power generation and produces some of the cheapest and most cost effective KWh within the European Community. Currently, it mines 70 tons/year of soft brown coal to cover over 70% of the country's domestic power needs.

Brown coal in Greece is found in 68 coal basins of various sizes. Generally, it is of poor quality that is of low calorific values and relatively high ash content. Henceforth, a detailed knowledge of maceral and ash composition is essential to appropriately construct boilers to avoid abrasion of mechanical parts, fouling and corrosion of boilers, and to take appropriate environmental measures.

Though the % composition of the maceral groups is relatively the same in almost all Greek coal basins, the % composition of maceral subgroups, especially that of huminite, varies substantially. This variation affects boiler's performance since the maximum heat release takes place at various heights inside the boiler. Humotelinitic brown coals rich in resinite release their thermal energy at lower temperatures than humocollinitic coals, which have low resinite contents. Furthermore, coal ash rich in gypsum, anhydrite and other minerals with hardness less than 3 do not affect the mechanical parts of the boiler whereas coal ash rich in quartz, feldspars and pyrites do.

Finally, Greek brown coals have variable trace elemental composition. Coals from basins surrounded by carbonate rocks (Western Greece) do not exhibit high concentrations of heavy elements, whereas coals from basins surrounded by mafic rocks (North-Central Greece) are rich in Cr, Ni, Cu and Zn, while coal basins surrounded by igneous rocks (North-Eastern Greece) are rich in Pb, Zn, Co, Hg, As and U.
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1. Introduction

Power utilities are continually striving to produce electricity at the lowest possible cost. Since coal mining and preparation of feedcoals represents 60–80% of power plant's operating costs one way of reducing the costs is to increase effectiveness of the coal burning process (Carpenter, 1998). Such an approach is of primary importance in Greece, where coal is the only abundant domestic energy source.

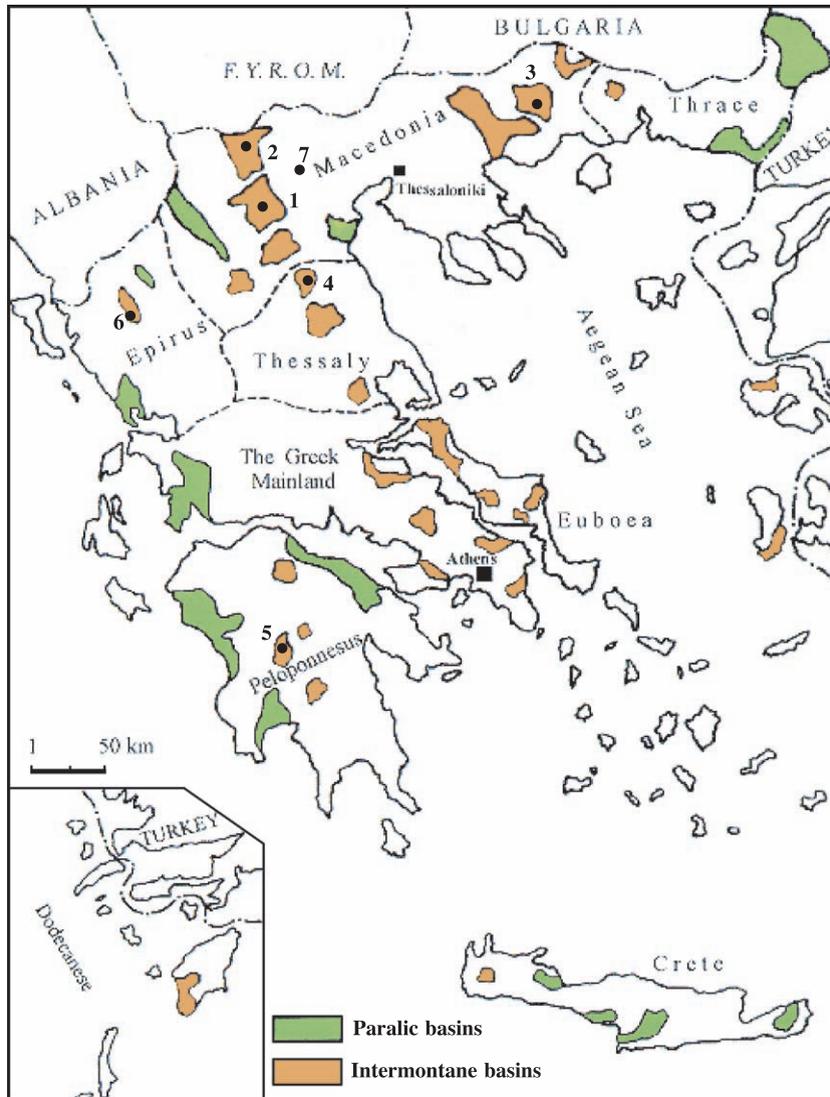Brown coal in Greece occurs in 68 coal basins of various sizes (Koukouzas, 1998). The most important

Fig. 1. Lignite-bearing basins of Greece. Major coal basins are: (1) Ptolemais, (2) Florina, (3) Drama, (4) Elassona, (5) Megalopolis, (6) Ioannina, and (7) Komnina (Papanicolaou et al., 2000).

deposits (Papanicolaou, 2001) are presented in Fig. 1. The relative amounts of various types of brown coal deposits and their classification based upon the age and the mineable reserves are presented in Fig. 2a–c.

Geologically proven brown coal reserves are estimated at 7.5 billion tons, whereas the economically mineable reserves amount to 4.1 billion tons; indicated reserves are estimated at 1.1 billion tons and inferred are valued at 2.3 billion tons (Papanicolaou, 2001). Brown coal deposits are exclusively exploited by the Public Power Corporation (PPC) of Greece and cover over 70% of Greece's power needs (Table 1). The annual consumption of brown coal currently stands at 66.5 million tons feeding a total of 4898 MWe power plants. The production will increase to 72.5 million tons by the end of 2003 when an additional 365 MWe power plant using 2.5 million tons of xylite as feedcoal will become operational. This output ranks Greece as one of the largest brown coal producers in the world and the
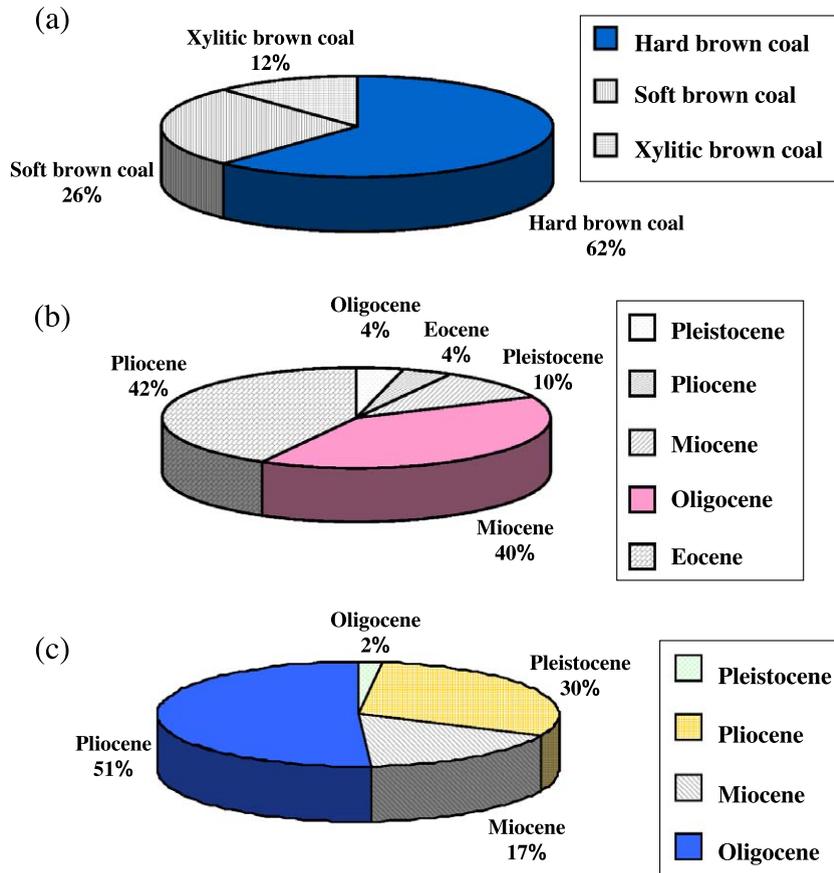
Fig. 2. (a) Distribution of Greek coal types based upon the mineable reserves. (b) Distribution of Greek brown coal bearing basins based upon the geological age. (c) Distribution of mineable Greek brown coal reserves based upon the geological age, (Koukouzas, 1998).

second as power producer using lignites (World Coal Institute, 2001).

Exploitation of coal in Greece is anticipated to continue because it is the only abundant indigenous resource which produces the cheapest and most cost effective KWh, within the European Community (Eurostat, 2002). It is obvious that in Greece inexpensive energy, which is a prerequisite for a sustainable economic growth and development, can be produced only from coal. However, using Greek lignites/xylites

Table 1
Per Cent Electricity Generation, in Greece, by Fuel (Foscolos et al., 2003)

YEAR	LIGNITE		OIL		GAS		HYDRO		TOTAL	
	GWh	%	GWh	%	GWh	%	GWh	%	GWh	%
1997	27751	76.7	4976	11.3	285[1]	0.8	4048	11.2	36160	100.0
1998	29231	75.8	3852	10.0	1616	4.2	3841	10.0	38540	100.0
1999	29276	70.9	3528	8.5	3700	9.0	4781	11.6	41285	100.0
2000	31058	69.2	4141	9.2	5596	12.5	4062	9.1	44856	100.0
2001	32106	72.4	3551	8.0	5801	13.1	2668	6.0	44373	99.5[2]
2002	31242	69.8	3391	7.6	6730	15.0	3381	7.6	44744	100.0

[1] Imported from Yugoslavia.
[2] Wind power 0.5%.

Table 2
Mean average concentration of moisture, ash, proximate and ultimate analyses and calorific values on as received basis from representative coal basins of Greece (Foscolos et al., 1989, 1998; Gentzis et al., 1996, 1997; Papanicolaou, 2001)

Coal Basins	Age	Moisture %	Volatile %	Fixed C %	Ash %	C %	H %	N %	S_T %	O %	Calorific Values Kcal/Kg	VR_o
Thrace												
Alexandroupolis	Up. Oligoc.	9	24.4	24.7	41.9	26.2	3.2	0.7	4.3	14.7	3108	0.42
Orestiada	Up. Oligoc.	26	19.7	16.6	37.7	22.8	2.0	0.4	1.9	9.2	1800	0.39
Eastern Greek Macedonia												
Drama	Pleistocene	59	16.4	8.2	16.4	16.1	1.4	0.4	0.1	6.5	1015	0.25
Western Greek Macedonia												
Florina	L. Pliocene	40	26.0	17.2	16.8	27.1	2.2	0.2	0.7	13.0	2200	0.28
Ptolemais	Up. Pliocene	56	17.2	14.0	12.8	18.7	1.6	0.2	0.4	10.3	1400	0.32
Kozani	Pliocene	54	19.2	14.9	11.9	22.2	1.9	0.5	0.4	9.1	950	0.33
Moschopotamos	Up. Miocene	18	27.1	27.7	27.2	40.2	3.0	1.0	1.4	9.3	3580	0.41
Epirus												
Ioannina	Pleistocene	66	16.2	8.0	9.8	14.1	1.1	0.4	1.4	7.2	930	0.21
Central Greece												
Zeli	Pliocene	29	26.6	21.3	23.1	29.4	2.3	0.8	0.7	14.6	2591	0.39
Peloponnesus												
Kalavryta	Pliocene	21	32.9	19.1	27.0	32.0	2.4	0.9	1.5	14.7	2655	0.30
Megalopolis	Pleistocene	60	16.1	9.0	14.9	15.2	1.2	0.3	1.2	7.1	950	0.26
Olympia	Pleistocene	46	22.9	15.1	16.0	24.7	2.8	0.3	1.6	8.6	1750	0.28
Koroni	Up. Miocene	32	31.1	19.5	17.4	31.6	2.5	0.3	1.1	15.1	3000	0.35
Crete												
Plakias	Mid. Mioc.	15	20.1	21.6	43.3	28.8	2.3	0.3	0.4	9.9	2480	0.42

presents a technologically and environmentally challenging undertaking (Carpenter, 1998; Skorpuska, 1993; Gerouki et al., 1996). Some of the challenges are: the wide variation of its maceral composition, the highly variable ash concentration along with the very different mineral and chemical composition and, finally, the wide range of volatile and non-volatile trace element composition and concentration. Therefore, an integral study of coal properties is essential to assist mechanical and electrical engineers in designing more efficient boilers, mining engineers to exploit more wisely coal seams and environmental engineers to reduce pollution problems and plan land reclamation. The present paper is a review of several major studies, along with unpublished data, as well as results from the ongoing research on fly ashes from the power stations located in the wider area of Ptolemais/Amynteon, the coal mining centre of Greece for the last 45 years.

2. Results and discussion

2.1. Properties of Greek brown coals

2.1.1. Proximate and ultimate analyses

The results concerning the properties of the organic portion of the Greek lignites are based on the following literature: Anastopoulos and Koukouzas (1972), Broussoulis and Yakkoupis (1977), Broussoulis et al. (1991), Cameron et al. (1984), Foscolos et al. (1989, 1998), Georgakopoulos and Valceva (2000), Gentzis et al. (1996, 1997), Kalkreuth et al. (1991), Kavouridis (1995), Kotis et al. (1992), Koukouzas and Koukouzas (1995), Papanicolaou et al. (2000), Papanicolaou (1994, 2001), and Papanicolaou and Demetriou (2002).

The results of proximate and ultimate analyses on as received coal samples of the 14 most important and representative coal basins of Greece are presented in Table 2. Moisture content ranges from 9% to 66%, ash concentration varies from 9.8% to 43.3%, volatile matter fluctuates between 16.1% and 32.9% and fixed carbon from 8.0% to 27.7%. Results from the ultimate analysis indicate that total carbon ranges from 14.1% to 40.2%, total hydrogen varies from 1.1% to 3.2%, total nitrogen fluctuates between 0.2% and 3.2%, total sulphur oscillates between 0.1% and 4.3% and, finally, total oxygen varies between 6.5% and 15.1%. The

relatively large variations are attributed to the age, nature of lignite, environment of deposition and the geological setting. Data from Foscolos et al. (1989) show that total sulphur content on dry and ash free basis vary from 1% in the coals from Lava basin, to 6.4% in the coals from the Ioannina basin. High values of volatile sulphur (organic and pyritic sulphur), ranging from 86% to 100% of the total sulphur content, are encountered in the coal basin of Megalopolis and all the Oligocenic coal basins of Alexandroupoli and Orestiada, Thrace, north-eastern Greece. The lowest percentage of volatile sulphur content (12%) is found in the coals from the Ptolemais/Amynteon basin.

An average typical coal composition which includes water, ash, volatile matter, fixed carbon and total C, H, O, N and S of the feedcoals from the Megalopolis power station and the coals from Florina basin which will be used as feedcoals for the new 365 MWe power station in 2003 presented in Fig. 3a and b.

2.1.2. Calorific values

Calorific values are quite variable (Table 2). The lowest values of 930 kcal/kg are observed in Ioannina basin coals. Mid-range values of 1400 and 2300 kcal/kg are determined for Ptolemais and Florina coals, respectively, while the Moschopotamos basin coals show the highest values of 3580 kcal/kg. The distribution of calorific values for the mineable coal deposits is shown in Fig. 4. The comparison of % moisture, ash and calorific values of the mineable Greek brown coals to other mineable brown coals in the world is presented in Fig. 5.

2.1.3. Organic petrology

The differences in calorific values are reflected by the variable rank of the Greek coals. Reflectance values, determined on eu-ulminite B, range from VR_o 0.21%, for the coals from the Ioanninna basin to VR_o 0.42% for the subbituminous coals from the Alexandroupolis basin. Corresponding calorific values are 930 kcal/kg (3894 kJ/kg) for the coals of the Ioannina basin and 3108 kcal/kg (13,007 kJ/kg) for the coals from the Alexandroupolis basin. Hence, the differences in rank follow the variability in calorific values.

Substantial differences in the Greek lignites are also encountered in the maceral composition (Papanicolaou, 2001) (refer to Figs. 6 and 8). These variations
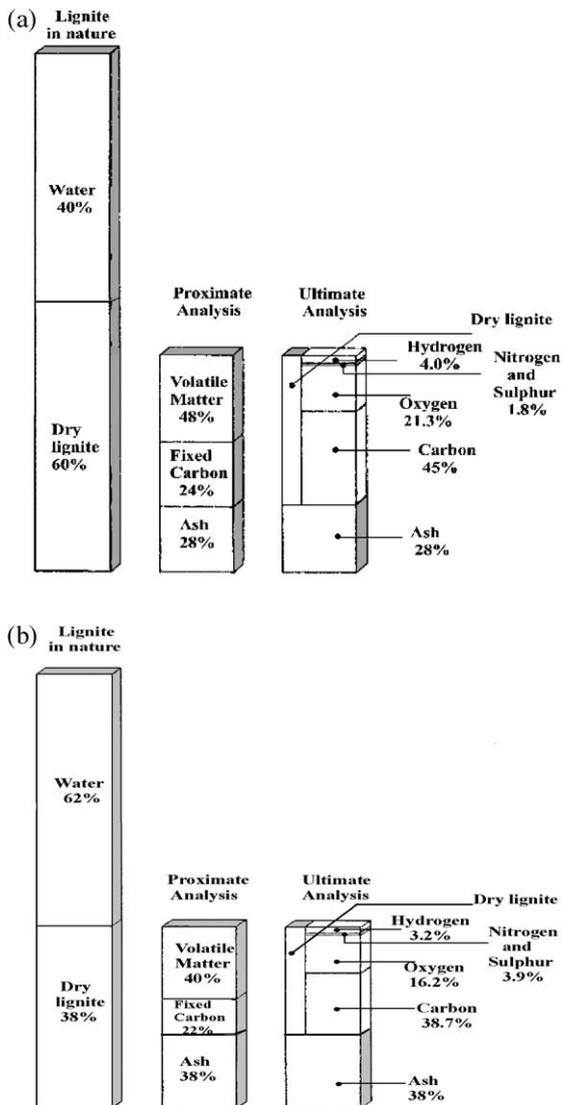
Fig. 3. Average percentage of moisture, coal, ash, proximate and ultimate analysis of the feedcoals from (a) Florina and (b) Megalopolis.

are exemplified in the composition of the feedcoals from the coals basins of Ptolemais/Amynteon and Megalopolis as well as the coals from the Florina and Elassona basins, which will supply feedcoal for two new 365 MWe power plants (Table 3). Huminite content varies from 74 vol.% in the coals from the coal basin of Florina to 90 vol.% for the feedcoals from the Megalopolis basin. The average liptinite concentration ranges from 3 vol.% in the feedcoals

produced from the Ptolemais/Amynteon coal basins to 24 vol.% for the coals from the Florina basin. The average inertinite content varies from 2 vol.% in the feedcoals from the Megalopolis basin to 17 vol.% in the feedcoals from the Ptolemais/Amynteon basins. Another important petrographic variation is found in the composition of the huminite subgroup (Table 3). Humotelinite concentration ranges between 20 vol.% in the feedcoals from the Ptolemais/Amynteon basins, to 51 vol.% in the xylites from the Elassona coal basin. Humodetrinite varies from 18 vol.% in the coals from the Florina basin to 52 vol.% in the feedcoals from the Ptolemais/Amynteon basin. Finally, humocollinite ranges between 6 vol.% for the xylites from the Elassona coal basin to 8 vol.% for the feedcoals from the Ptolemais/Amynteon basin. An additional factor, which differentiates the Greek brown coals, is the presence and amount of fluorescent tissues, that is the concentrations of liptinites and resinous textinites and textoulminites of the coals (Fig. 6a and b; Figs. 7 and 8). The concentration of the fluorescent tissues in the Greek brown coals ranges from 3 vol.% for the feedcoals from Ptolemais/Amynteon basins, to 66 vol.% for the xylitic coals from the Florina basin. Liptinites along with resinous textinites and textoulminites influence the amount and type of volatile matters since it includes not only the sum of H_2O and CO_2 but also the highly flammable compounds. The latter influences the heat flux profile of the combustible material, a property that affects boilers' design. Finally, the concentration of the inertinite is another important factor affecting not only the quality of the ash but also the efficient operation of the boiler. Brown coals from Ptolemais/Amynteon have an average concentration of inertinite of 17 vol.%, and since the combustion temperature is around 855 °C, inertinite is not burnt. As a result, inertinite either concentrates in the fly ash or it can be entrapped with SO_2 in the flue gases and when combined with alkalis, which are vaporized upon burning the coal, forms an insulating sleeve around the boiler tube surfaces. This lowers the thermal conductivity and therefore the heat transfer. In certain coal, samples obtained from borehole of the Ptolemais/Amynteon basins, inertinite concentration reaches as high as 50 vol.% (Papanicolaou, 2001). On the other hand, fly ashes rich in inertinites can be considered an excellent material for landfills since they contain substantial amounts of organic matter.
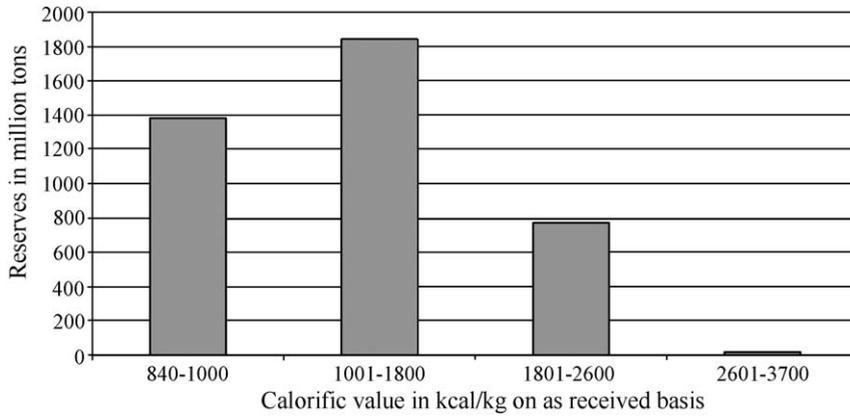
Fig. 4. Distribution of economically recoverable lignite reserves based upon their calorific value (Koukouzas, 1998).

2.1.4. Mineralogy

The mineralogy of Greek brown coals have been studied by Foscolos et al. (1989, 1998), Foscolos and Kostakis (1990), Filippidis and Georgakopoulos (1992), Filippidis et. al. (1992), Georgakopoulos et al. (1992), Gentzis et al. (1996, 1997), Papagianakis and Vallindras (1997), and Sakorafa et al. (1996). Mineral composition of coals is important because of its impact on boiler's performance and the environment. Minerals with Mohs scale of hardness over 6 are abrasive destroying the metallic parts of the boiler (Raask, 1988; Scott, 1995; Sligar, 1996). In addition,
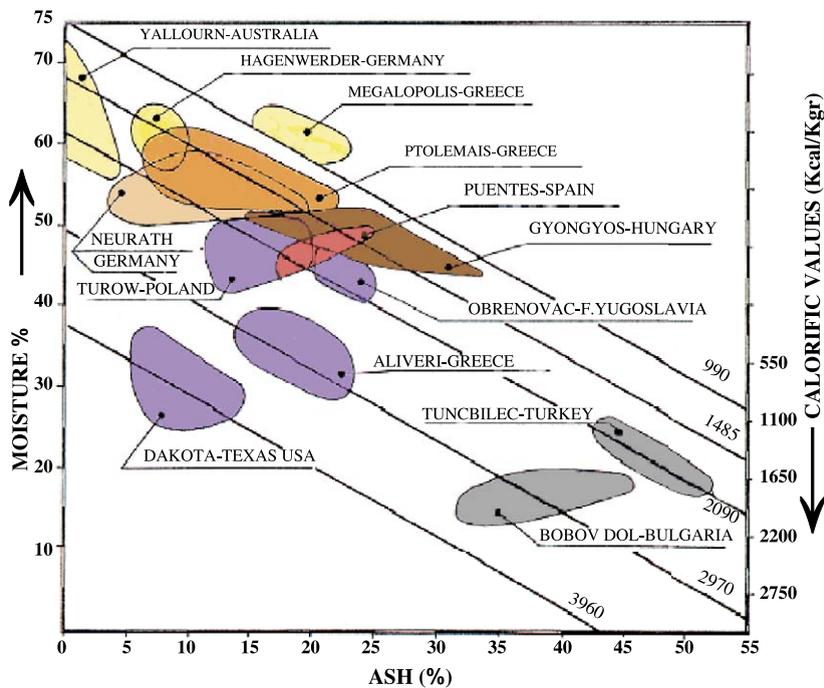

Fig. 5. Relation of percent moisture to percent ash and calorific values, on as received basis, from various lignite basins in the world (Kavouridis et al., 1991).
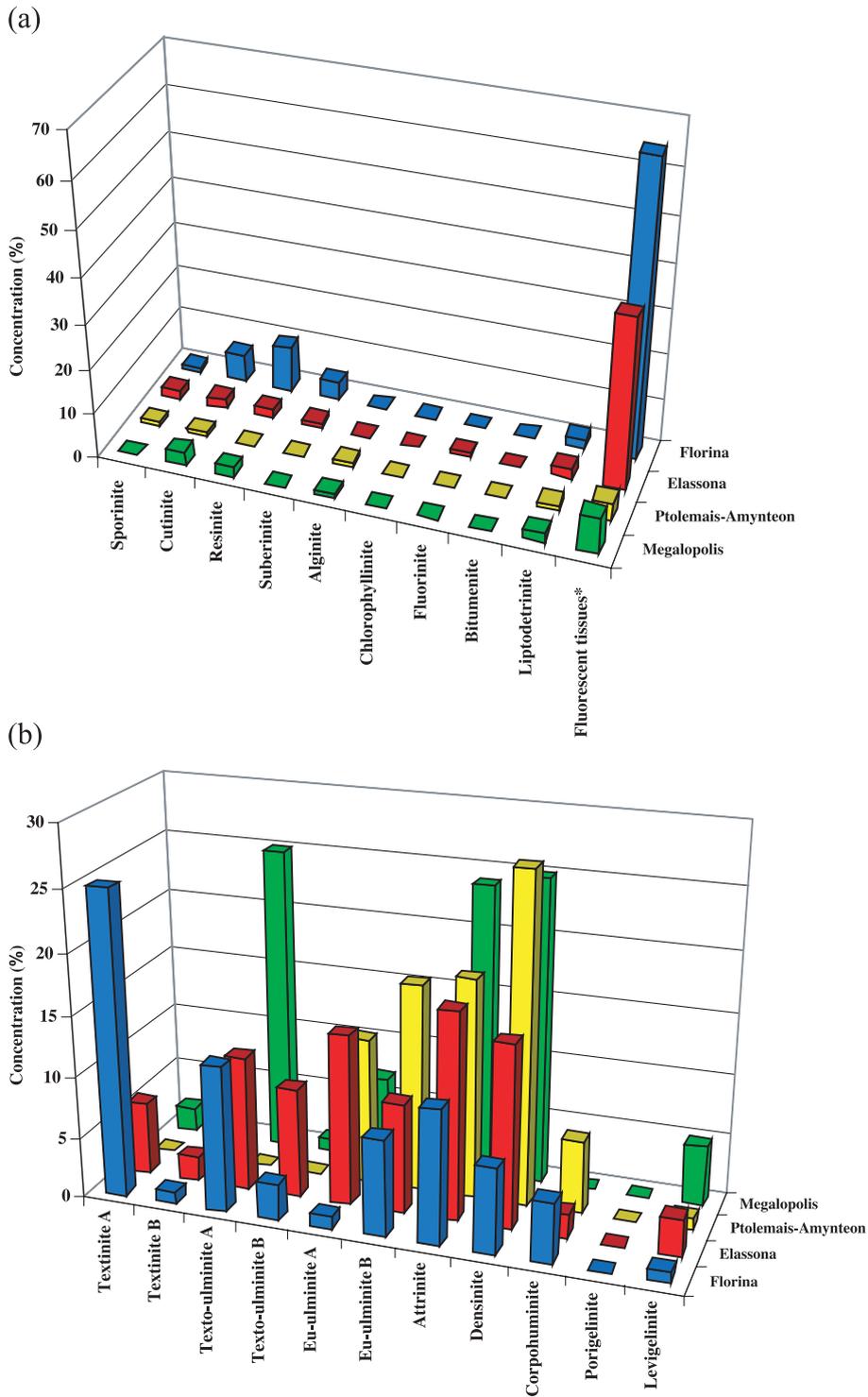
Fig. 6. Average (a) huminite and (b) liptinite composition of Greek coal samples from the coal basins of Megalopoli, Ptolemais/Amynteon, Florina and Elassona.
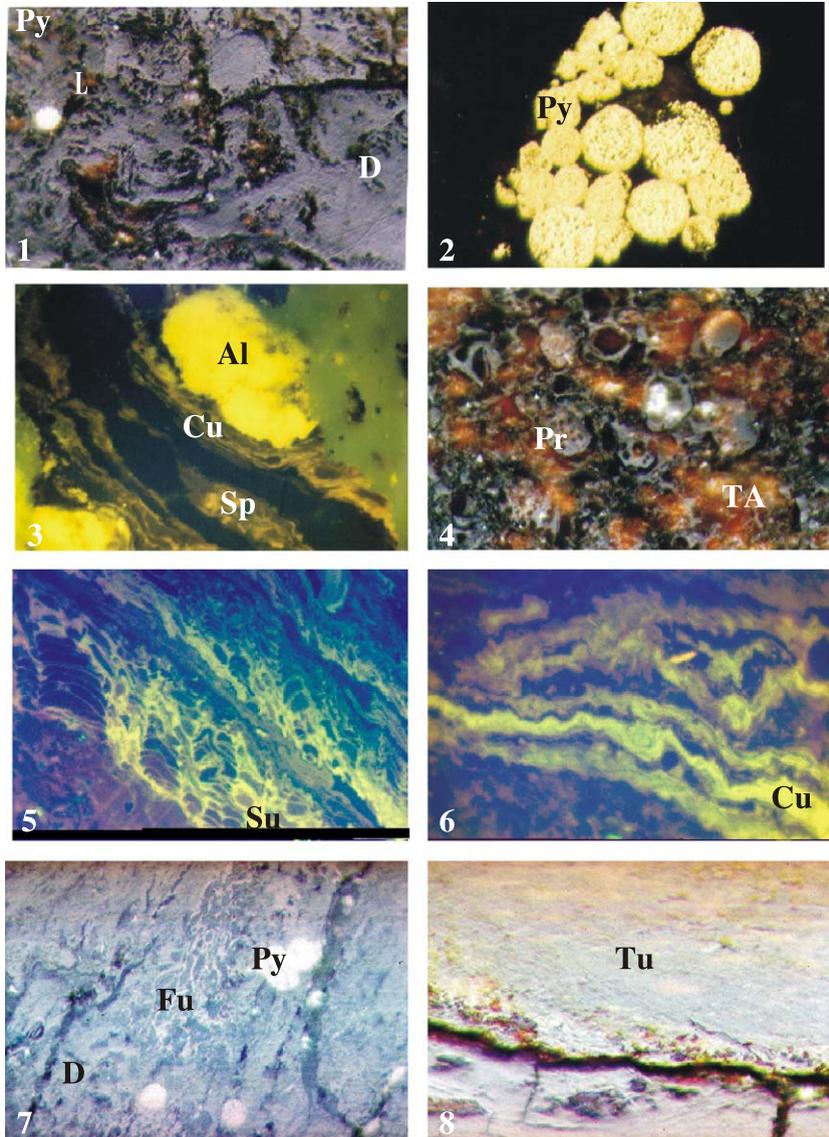
Fig. 7. Photomicrographs of macerals from Megalopolis and Komnina, Ptolemais coal basins. (1) Densinite groundmass (D) hosting dark liptinites (L) and framboids of pyrite (Py); Pleistocene brown coals (R_or 0.28%), from Megalopolis basin (white incident light and oil immersion objectives, 500 ×). (2) Clusters of pyrite framboids (Py) in Pleistocene brown coals (R_or 0.28%), from Megalopolis basin (white incident light and oil immersion objectives, 500 ×). (3) Alginite (Al) exhibiting high intensity and lighter yellow colours than cutinite (Cu) and sporinite (Sp) under blue light irradiation; Pleistocene brown coals (R_or 0.28%), from Megalopolis basin (white incident light and oil immersion objectives, 500 ×). (4) Textinite (TA) with internal reflectance. Porigelinite (Pr) in cell lumen; Pleistocene brown coals (R_or 0.28%) from Megalopolis basin (white incident light and oil immersion objectives, 500 ×). (5) Highly fluorescent suberinite (Su); Miocene brown coals (xylite) (R_or 0.32%) from Komnina, Ptolemais basin (blue incident light and oil immersion objectives, 500 ×). (6) Cutinites (Cu) viewed in fluorescent light; Miocene brown coals (xylite) (R_or 0.32%) from Komnina, Ptolemais basin (blue incident light and oil immersion objectives, 500 ×). (7) Fusinitized tissues (Fu) and pyrite framboids (Py) in a densinite matrix (D); Pliocene brown coals (R_or 0.31%) from Amynteon, Ptolemais basin (white incident light and oil immersion objectives, 500 ×). (8) Textoulminite B (TU) with internal reflectance; Pliocene brown coals (R_or 0.31%) from Amynteon, Ptolemais basin (white incident light and oil immersion objectives, 500 ×).
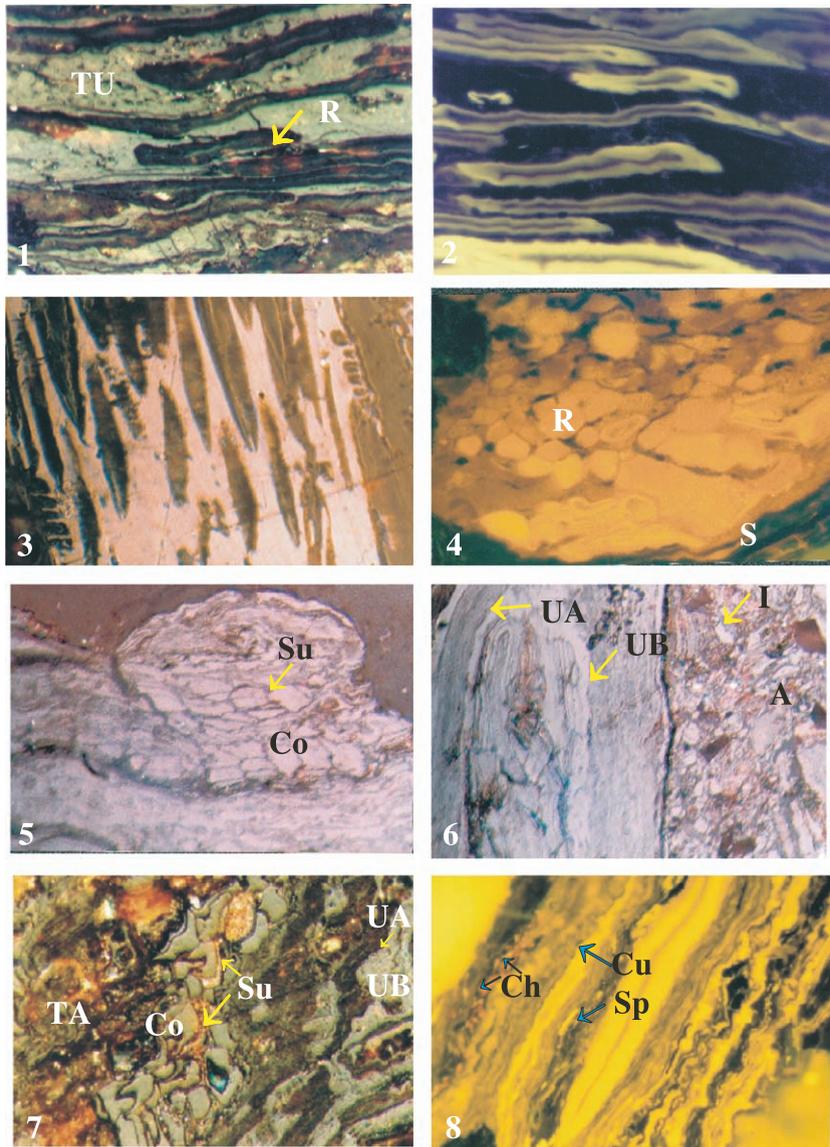
Fig. 8. Photomicrographs of macerals from Vevi, Lofi and Achlada coal Fields, Florina basin. (1) Elongated resinite (R) bodies included in textoulminite B (TU); Miocene brown coals ($R_o r$ 0.30%) from Vevi coal field, Florina basin (white incident light and oil immersion objectives, 500 ×). (2) Same field as (1), fluorescent light; note the intense fluorescence of resinite. (3) Textoulminite B (TU) with well preserved cell structures; Miocene brown coals (xylititic) ($R_o r$ 0.32%), from Lofi coal field, Florina basin (white incident light and oil immersion objectives, 500 ×). (4) Clusters of intense fluorescent resinites (R) sporinites (S); Miocene brown coals ($R_o r$ 0.32%), from Lofi coal field, Florina basin (blue incident light and oil immersion objectives, 500 ×). (5) Corpohuminite (var. phlobaphenite) (Co) infilling suberinite (Su) in rootlet; Miocene brown coals ($R_o r$ 0.32%), from Lofi coal field, Florina basin (white incident light and oil immersion objectives, 500 ×). (6) Concentric layers of eu-ulminite A (UA) and B (UB) (left side). Attrinite (A) with inertodetrinite (I) (right side); Miocene brown coals ($R_o r$ 0.32%), from Lofi coal field, Florina basin (white incident light and oil immersion objectives, 500 ×). (7) Eu-ulminite B (UB) with dark eu-ulminite A (UA) from sclereids. In the middle corpohuminite (var. phlobaphinite) (Co) infilling suberinite (Su). Textinite A (TA) with internal reflectance (left side); Miocene brown coals (xylitic) ($R_o r$ 0.32%), from Achlada coal field, Florina basin (white incident light and oil immersion objectives, 500 ×). (8) Densely packed cutinites (Cu) and sporinites (Sp) with intense yellow fluorescence. Orangish colour of Chlorophylinite (Ch); Miocene brown coals ($R_o r$ 0.32%), from Achlada coal field, Florina basin (blue incident light and oil immersion objectives, 500 ×).

Table 3

Maceral composition (percentage by volume) of Greek coals from Ptolemais/Amynteon, Megalopolis, Florina and Elassona coal basins, (Papanicolaou, 2001)

Macerals	Ptolemais/ Amynteon	Megalopolis	Florina	Elassona
Textinite A		2	25	6
Textinite B			1	2
Textoulminite A		25	12	11
Textoulminite B		1	3	9
Eulminite A		7	1	14
Eulminite B	20	1	8	9
Humotelinite	20	36	50	51
Attrinite	25	24	11	17
Densinite	27	25	7	15
Humodrinite	52	49	18	32
Corpohuminite	7		5	2
Porigelinite			0	0
Levigelinite	1	5	1	3
Humocollinite	8	5	6	5
Total Huminite	80	90	74	88
Sporinite	1		1	2
Cutinite		3	6	2
Resinite		2	10	2
Suberinite			5	1
Alginite	1	1		
Chlorophullinite				
Flourinite				
Bitumenite				
Liptodetrinite	1	2	2	2
Total Liptinite	3	8	24	10
Semifusinite				
Fusinite	13	1	2	1
Macrinite				
Micrinite				
Inertodetrinite	3			1
Sclerotinite	1	1		
Total Inertinite	17	2	2	2
Total Organic Matter	100	100	100	100
V_{ro}%	0.32	0.28	0.32	0.31

since fly ashes are used in various industrial products, it is important to know their mineral compositions and their concentration.

2.1.4.1. Mineral matter in low temperature coal ash. Several minerals have been identified in the low temperature ashes. Ubiquitous are quartz, feldspar, mixed layer silicates, illite, kaolinite, chlorite, calcite, gypsum, anhydrite, bassanite and pyrite (Table 4). Less common minerals are dolomite, siderite, meta-aluminite and amphiboles whereas epsomite,

jaroisite anatase, hercynite, jacobsite and witherite are rare (Table 4).

2.1.4.2. Newly formed minerals in fly ash. During the combustion of calcium-rich feedcoals new minerals are created. The type of the newly created minerals depend on the original mineral content and composition and the temperature of the combustion that in the Greek power stations does not exceed 855 °C. While newly formed gehlenite, lime, portlandite, calcite, ettringite, thaumasite aphithitalite, wollastonite and Ca_2SiO_4 are encountered in fly ashes derived from calcium rich feedcoals, hematite and anhydrite are ubiquitos (Table 4).

2.2. Elemental composition of coals

2.2.1. Elemental concentration of volatile elements

The concentration range of As, B, Br, Cl, F, Hg, I, Se and U encountered in 13 coal basins of Greece is presented in Table 5.

Arsenic (As) concentration is high in Miocene and Oligocene coal samples from Serres and Drama basins ranging from 22 to 138 ppm, respectively, whereas in some Pliocene coals from Lava, Kozani, northern Greece, concentrations up to 207 ppm have been reported (Foscolos et al., 1989). High fluorine (F) values, ranging from 132 to 258 ppm, are reported in the coals from the western Peloponesse basins indicating the influence of paralic environment or an environment with high salinity (Krejci-Graf, 1983). In the same coals, bromine (Br) concentrations vary from 9 to 172 ppm with an average value of 50 ppm indicating a paralic environment (Goodarzi, 1987a,b). High boron (B) concentrations, ranging from 22 to 167 ppm, have been identified in the coals from the Orestiada basin, Thrace, north-eastern Greece, indicating brackish influenced environment (Degens et al., 1958; Couch, 1971; Gluscoter et al., 1977; Lindahl and Finkelman, 1986; Goodarzi, 1987a,b; Swaine, 1990; Swaine and Goodarzi, 1995). In the remaining Greek coal basins boron concentration is less than 100 ppm pointing to slightly brackish or freshwater environment (Swaine and Goodarzi, 1995). However, boron (B) can be associated with either concomitant 2:1 layer silicates (Dewis et al., 1972), or it can be the result of secondary enrichment derived from evaporation or it can be attributed to the presence of tourmaline or even

Table 4
Minerals encountered in low temperature ashes and fly ashes of Greek brown coals

Low temperature ashes			Fly ashes		
Ubiquitos[a]		Rare[a]	Ubiquitos[a]		Rare[a]
Quartz	Illite	Diaspore	Quartz	Anhydrite	Diaspore
Felspars	Kaolinite	Amphiboles	Feldspar	Lime[b]	Amphiboles
Pyrite	Chlorite	Anatase		Gehlenite[b]	Anatase
	2:1 Layer	Amonium		Portlandite[b]	Rutile
	Silicate	Iron Sulfate			
	Gypsum	Jarosite		Ettringite[b]	Illmenite
	Anhydrite	Jacobsite		Thaumasite[b]	Magnetite
	Bassanite	Meta-aliminit		Aphithitalite[b]	Maghemite
	Calcite	Epsomite		Hematitite	Apatite
	Dolomite	Illmenite		Calcite	Barite
	Magnesite	Rutile		Wollastonite	Witherite
	Siderite	Hexahydrite			
		Barite			
		Apatite			
		Witherite			
		Kiezerite			
		Stromayerite			
		Hercynite			

(Foscolos et al., 1989, 1998; Filippidis and Georgakopoulos, 1992; Filippidis et al., 1992; Georgakopoulos et al., 1992; Gentzis et al., 1996, 1997; Papagianakis and Vallindras, 1997; Sakorafa et al., 1996).
[a] Semiquantitative X-ray diffraction.
[b] In calcium rich lignites upon combusing to 855 °C.

volcanic and geothermal activities which were abundant in this area of north-eastern Greece, during Upper Eocene to Oligocene (Fytikas et al., 1984). As a result, boron concentrations should be used cautiously for paleosalinity indicators.

In the coal basins of Megalopolis and Olympia, Peloponnesus, the concentrations of Br, Cl and I are high reaching the values of 172, 166 and 9 ppm, respectively, indicating a paralic environment (Goodarzi, 1987a,b). Hg is encountered in high concentrations (4 ppm) in the Oligocene coals from the Serres basin. This is attributed to its mobilization and transportation by surficial waters from the adjacent Serbomacedonian Massif which has abnormally high Hg concentrations, (Foscolos et al., 1998), or it might attributed to the presence of arsenopyrites, since Hg can be incorporated in their crystal lattice (Finkelman, 1995). The Serbomacedonian (Rhodope) Massif is very rich in sulfides minerals, especially arsenopyrites (Eliopoulos, 2000).

2.2.2. Major elements in coal ash

Data for the concentrations of major elements in coal ash have been obtained from Foscolos et al. (1989, 1998), Foscolos and Kostakis (1990), Filippidis and Georgakopoulos (1992), Filippidis et al. (1997), Georgakopoulos et al. (1992, 1995), Gentzis et al. (1996, 1997), and Sakorafa et al. (1996). The range of elemental concentrations encountered in the coal ashes of 15 coal basins of Greece is presented in Table 6.

The results show wide variation of values reflecting the geological setting of the coal deposits. SiO_2 concentrations are high in the Megalopolis coal basin ranging from 51.8% to 57.5%. These values are attributed to high concentrations of quartz, clay and probably feldspars. Low SiO_2 concentrations are reported in the Serres coal basin ranging from 11.9% to 32.8%. Al_2O_3 concentrations are high in the Megalopolis coal basin, ranging between 20.8% and 23.4%, and the Plakia coal basin in Crete ranging from 20.0% to 25.9%. These values are attributed to the presence of feldspars and clays as indicated also by the relatively high K_2O and Na_2O concentrations, respectively. In contrast, low Al_2O_3 concentrations fluctuating between 7.1% and 19.3% are found in the Serres coal basin. Fe_2O_3 concentrations are high in the coal ash from the Orestiada

Table 5

Range of volatile trace element concentrations, in ppm, in coals from 13 coal basins of Greece (Foscolos et al., 1989, 1998; Gentzis et al., 1996, 1997)

Coal Basins	As	B	Br	Cl	F	Hg	I	Se	U
Thrace									
Orestiada	20.7–57.1	22–167	5–6	38.7–234	78–159	<0.1–0.3	<0.6–1.3	<0.9–5.9	1–19
Eastern Geek Macedonia									
Drama	22–138	8–25	16–37	46–371	35–138	0.01–0.06	<0.6	1.8–9.4	8–97
Serres	34–124	10–21	1–4	31–65	40–60	0.09–4.06	0.7–0.9	1.0–5.2	13–34
Western Greek Macedonia									
Florine	6–20	12–47	5–21	51–74	22–32	0.07–0.15	<0.6–8.0	<0.9–1.3	1–11
Ptolemais	6–22	11–95	11–19	49–121	79–135	0.3–0.130	2.4–5.6	1.1–1.8	4–17
Kozani	7–207	12–22	2–16	38–58	78–100	0.06–0.13	0.6–8.1	<0.6–1.7	1–7
Moschopotamos	24–30	22–43	3–4	38–39	118–217	<0.01	<0.6–4.0	4.1–5.9	17–19
Epirus									
IoannIna	3–63	16–20	8–31	61–278	80–99	0.03–0.07	4.1–5.8	1.6–9.4	13–14
Central Greece									
Elassona	3–6	N.D.	5–17	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Peloponese									
Kalavryta	6–17	20–41	9–25	30–57	154–203	0.05	<0.6–6.0	3.1–6.0	3
Megalopolis	7–14	20–73	9–55	21–106	154–258	0.01–0.05	1.2–2.4	1.1–1.8	4–17
Olympia	6–7	45–75	9–172	21–166	132–218	<0.1–0.06	<0.6–9	2.1–8.8	3–5
Crete									
Plakias	14–18	N.D.	3–6	70–879	N.D.	N.D.	N.D.	2.0–6.0	10–65

basin, ranging between 18.2% and 39.7%, due to the presence of pyrite whereas low concentrations, ranging from 5.8% to 6.4%, are detected in the coal basin of Zeli, central Greece. High TiO_2 concentrations ranging from 0.5% to 1.5% are reported in the Elassona coal basin and low values in the coal basin of Orestiada, Thrace. High concentrations of CaO, ranging between 20.1% and 56.4%, are reported in the Ptolemais coal basin due to the absence of calcium bearing minerals such as calcite and gypsum, while low concentrations, ranging between 4.8% and 4.9%, are reported in the coal basin of Zeli. High MgO concentration ranging from 6.4% to 9.7% are encountered in the coal ashes from the Moschopotamos basin due to the presence of serpentinites, which are a weathering by-product of the surrounding ophiolites, whereas low values, ranging from 0.8% to 2.1%, are found in the Ioannina coal basin. High values of Na_2O ranging from 2.2% to 4.6% are reported in the Plakias coal basin, Crete,

due to the presence of feldspars, whereas low values ranging from <0.1% to 0.1% are encountered in the Ioannina coal basin. Elevated K_2O concentration ranging from 2.1% till 3.6% are found again in the Plakia coal basin due to the presence of feldspars while low concentrations ranging from 0.1% to 1.7% are reported in the coal ashes from the Elassona basin. Relatively high concentrations of P_2O_5 ranging between 0.1% and 2.6% are encountered in the Kozani coal basin due to the presence of apatites, whereas low concentrations, <0.1%, are reported for the Orestiada coal basin. Finally, high SO_3 values ranging from 13.5% to 32.7% are found in the Serres coal basin, due to the occurrence of sulphide and sulphate minerals, whereas low concentrations fluctuating between 0.1% and 0.3% are found in the coal basin of Zeli.

The average chemical composition of major elements in the fly ashes from the five main power stations in Greece and the coal ashes from the Florina

Table 6
Concentration range of major elements, in per cent[1], encountered in coal ash from fifteen representative coal basins of Greece (Foscolos et al., 1989, 1998; Filippidis et al., 1997; Georgakopoulos et al., 1992, 1995; Gentzis et al., 1996, 1997; Sakorafa et al., 1996)

Coal Basins	Age	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	SO_3
Thrace											
Alexandroupoli	Upper Oligocene	32.8–51.9	12.3–24.1	0.1–0.6	11.5–14.5	0.7–19.4	1.9–5.6	0.3–3.3	1.0–2.9	0.1–0.2	3.6–19.3
Orestiada	Upper Oligocene	31.2–32.0	16.2–23.0	0.1	18.2–39.7	4.2–5.4	2.9	0.1–2.2	0.9–1.5	<0.1	0.3–3.5
Eastern Greek Macedonia											
Drama	Pleistocene	19.6–55.4	6.8–24.3	0.2–0.9	2.5–13.0	7.4–63.4	2.2–4.1	0.6–1.3	0.5–2.8	0.2–0.5	0.8–29.0
Serres	Miocene	11.9–32.8	7.1–19.3	0.1–0.8	14.1–26.8	12.6–27.5	2.0–6.1	0.3–1.2	0.8–1.0	<0.1–0.3	13.5–32.7
Western Greek Macedonia											
Florina	Lower Pliocene	26.0–48.2	12.5–26.1	0.6–1.1	10.0–11.1	6.9–32.6	2.8–3.2	<0.1–0.1	0.3–0.6	0.3–0.6	2.9–12.9
Ptolemais	Upper Pliocene	9.1–55.3	8.1–24.3	0.4–1.1	5.3–10.1	20.1–56.4	2.2–8.8	0.0–0.7	0.8–1.9	<0.1–0.6	0.8–21.4
Kozani	Pliocene	15.4–24.5	11.2–14.2	0.4–0.5	6.4–10.7	25.3–27.5	3.7–4.4	0.0–0.1	0.1–2.7	0.1–2.6	19.2–22.8
Moschopotamos	Upper Miocene	32.0–52.7	16.9–23.2	0.1–0.6	9.3–15.6	1.6–14.4	6.4–9.7	0.0–0.2	1.1–1.3	0.1–1.4	0.3–10.4
Epirus											
Ioannina	Pleistocene	11.6–56.0	6.3–23.7	0.2–0.9	3.1–12.9	3.8–45.4	0.8–2.1	<0.1–0.1	0.8–1.6	<0.3–0.5	2.0–38.5
Central Greece											
Elassona	Upper Miocene	30.4–51.4	8.6–24.9	0.5–1.5	6.1–16.7	6.9–17.9	3.7–5.9	0.0–0.3	0.1–1.7	<0.1–0.7	4.2–14.6
Zeli	Pliocene	47.3–57.4	19.7–22.3	0.0–0.7	5.8–6.4	4.9–4.8	4.1–6.7	0.0–0.2	1.5–1.6	<0.1–0.1	0.1–0.3
Peloponnesus											
Kalavryta	Pliocene	42.1–50.9	17.8–19.6	0.7–0.9	10.7–15.0	8.7–8.9	3.5–4.5	0.0–0.2	2.2–2.7	0.1–0.2	2.6–6.0
Megalopolis	Pleistocene	51.8–57.5	20.8–23.4	Traces	7.2–10.8	5.5–8.5	2.0–2.4	0.2–0.4	2.0–2.5	0.2–0.4	0.7–3.4
Olympia	Pleistocene	49.3–50.9	16.8–19.6	0.1–0.7	8.4–9.7	9.2–9.6	4.0–4.2	0.0–0.4	2.4–2.6	0.3	3.8–7.7
Crete											
Plakias	Middle Miocene	33.4–46.5	20.0–25.9	0.9–1.2	9.5–21.5	1.8–6.8	3.2–6.1	2.2–4.6	2.1–3.6	0.1–0.2	0.4–2.5

[1] L.O.I. is difference of the sum of oxides minus 100 per cent.

Table 7
Average composition, in percent, of major elements in the fly ashes of Megalopolis, Amynteon, Ptolemais, Kardia, Aghios Demetrios power stations and the coal ash from the Florina coal basin

Elements	Megalopolis	Amynteon	Ptolemais	Kardia	Aghios Demetrios	Florina
SiO_2	50.79	42.36	33.47	29.17	30.86	41.81
Al_2O_3	20.41	15.79	14.08	13.27	13.76	17.53
TiO_2	0.82	0.74	0.60	0.51	0.70	1.00
Fe_2O_3	9.03	7.71	5.32	4.94	6.35	6.71
CaO	10.20	21.17	33.14	40.97	32.65	14.80
MgO	3.47	3.14	3.34	3.86	6.32	3.44
Na_2O	0.38	0.64	0.29	0.50	0.77	0.20
K_2O	1.95	0.96	0.97	0.72	0.77	1.43
P_2O_5	0.31	0.23	0.34	0.40	0.37	0.22
SO_3	2.58	7.28	8.46	5.52	7.48	12.87
BaO	——	0.04	0.02	0.02	0.02	——
MnO	0.04	0.07	0.03	0.03	0.03	0.14
Total	99.98	100.13	100.06	99.91	100.08	99.93

coal basin, where a new 365 MWe power plant in Greece is about to operate, is presented in Table 7.

2.2.3. Concentration of trace elements in coal ash and fly ash

The range of concentrations of trace elements in ppm, in coal ash from the basins of Ptolemais/Amynteon Megalopolis, Florina, Drama and Ioannina basins, where different geological settings are encountered, is presented in Table 8.

High concentrations of Cr and Ni, ranging from 234 to 591 ppm and from 229 to 651 ppm, respectively, are found in the ashes from the Ptolemais/Amynteon basin. Even higher values for these two elements are reported in the Miocene coal ashes from Moschopotamos basin (Foscolos et al., 1989). Cr concentrations range between 1863 and 3444 ppm while Ni ranges from 1472 to 3046 ppm. These high concentration values are attributed to their mobilization by ground waters from the surrounding peridotites and serpentinites which host nickel and chromite deposits (Koukouzas and Kouvelos, 1973; Kotis, 1997).

High concentrations of As, Mo, Pb, U, V and Y are reported in the coal ashes from the Drama basin (Table 8). Arsenic (As) concentrations range between 102 and 606 ppm, Mo between 46 and 712 ppm, Pb between 50 and 119 ppm, U between 33 and 313 ppm, V from 116 ppm to 737 ppm, W between 26 and 155 ppm and Y from 28 to 298 ppm. In the Serres coal basin, which is adjacent to the Drama coal basin, extremely high values for As, Pb, U, V and W are reported by Foscolos et al. (1989). Here also arsenic (As) concentration ranges from 856 to 1131 ppm, Pb fluctuates between 76 and 548 ppm, U fluctuates from 98 to 563 ppm, V oscillates between 215 and 1900 ppm and Zn ranges from 208 to 2991 ppm. The reasons for the high As, Mo, Pb and Zn concentration are the occurrence of sulfides such as arsenopyrite, molybdenite, galena and sphalerite in the Western Rhodope Massif (Nesbitt et al., 1988; Eliopoulos, 2000). The concomitant presence of high Y with U leads to the possible presence of the mineral samarskite (combination of rare earths and uranium elements), in traces, something highly possible in this area. The simultaneous presence of high U and V leads to the possibility of having carnotite and/or roscoelite and/or vivianite minerals. This is plausible in this area since during the Upper Eocene to Oligocene intense volcanic activities along with magmatism and geothermal fluid circulation were recorded (Ashworth et al., 1985; Fytikas et al., 1984). For comparison, the concentrations of trace elements in fly ash encountered in the four power stations located in the wider area of Ptolemais/Amynteon, Kardia and Aghios Demetrios) are presented in Table 9.

2.3. Effects of lignites properties of coal fired power plant performance

Greek lignites coals clearly show quite variable chemical characteristics and physical properties. The

Table 8

Range of concentrations of trace elements, in ppm, in coal ashes from the coal basins of Ptolemais/Amynteon, Megalopolis, Florina, Drama and Ioannina

Elements	Ptolemais/Amynteon	Megalopolis	Florina	Drama	Ioannina
Ag	<4.0	<3.6	<3.4	<5.2	<3.3
As	23.5−1.04	20−30	22−252	102−606	105−225
Au (ppb)	5−68	15−28	11−22	32−46	39−51
Ba	616−852	487−700	192−805	425−132.3	147−740
Cd	<3.3	<1.8	<3.3	<2.1	<3.2
Ce	64−122	87−92	71−244	32−129	35−121
Co	18−35	25−53	15−53	9−25	13−48
Cr	234−591	236−351	84−211	50−290	92−343
Cs	5−8	10−13	0−13	14−41	4−24
Cu	140−220	165−194	68−200	25−110	191−355
Dy	5−8	7−9	4−9	3−10	2−13
Eu	1.2−1.8	1.6−2.1	1.3−5.7	0.5−1.9	1.2−4.1
Hf	2.2−4.2	4.8−5.6	0.4−5.7	1.7−5.7	1.7−6.6
Ho	1.2−1.7	2.0−3.2	2.0−7.8	1.2−7.1	1.3−3.4
La	31−46	50−61	34−124	5−50	21−100
Lu	0.7−1.4	0.9−1.2	0.6−1.9	0.3−1.5	0.5−2.5
Mo	18−29	10−33	38−73	46−712	6−182
Mn	304−1172	319−531	611−2206	168−1273	881−1284
Nd	26−43	39−43	30−64	7−50	11−68
Ni	229−651	215−226	54−198	57−246	155−227
Pb	50−67	56−66	16−128	50−119	31−35
Rb	33−101	121−434	56−181	52−193	34−141
Sb	4.1−5.7	5.2=6.3	0.0−14.0	6.6−30.7	6.9−10.5
Sc	15−24	20−25	12−38	10−22	6.−30
Se	<3.0	<3.0	<3.0	<3.0	<3.0
Sm	5.0−9.4	7.6−9.2	6.1−14.5	3.2−12.0	–
Sr	239−705	239−549	423−485	90−332	843−155
Ta	1.6−1.7	1.8−2.0	2.0−2.8	0.1−1.9	0.6−2.6
Tb	0.7−22	1.3−1.5	0.6−2.6	0.7−5.9	0.8−1.4
Tm	<0.4−0.7	0.6−0.7	<0.3−0.9	0.5−0.9	1.0−1.5
Th	12−17	14−16	10−40	7−27	6−20
U	21−97	12−13	9−19	33−313	9−77
V	267−348	227−282	85−257	116−737	252−327
W	3−7	<2−3	12−37	26−155	<2.6−3
Y	24−26	35−47	23−57	28−298	28−41
Yb	2.4−5.4	3.6−4.4	2.4−16.3	3.0−4.1	2.7−3.8
Zn	57−98	110−185	50−547	50−242	130−151
Zr	143−227	215−231	174−212	93−253	244−276

(Foscolos et al., 1989, 1998; Gentzis et al., 1996, 1997; Pentari, 2002; Sakorafa et al., 1996).

impact of the feedcoal properties on boiler design and efficient operation in power plants located in megalopolis, Ptolemais/Amynteon and Florina is discussed in detail below.

2.3.1. Megalopolis coal basin

Megalopolis coal basin has provided feedcoal over the past 40 years for the 850 MWe power plant. These feedcoals are characterized by a very high moisture content, 60%, high ash content and very low calorific value (Table 2). These properties promote the building of very large boilers to accommodate large quantities of feedcoals. Moreover, the low calorific value affects steam generation since the coal flow rate will increase. In addition, the mineralogical composition of the ash in these feedcoals contains large concentrations of quartz and pyrite which promotes abrasive wear of

Table 9

Concentration of trace elements in ppm of the ashes from the Ptolemais, Amynteon, Kardia and Aghios Demetrios power stations. Enrichment factor (EF), in relation to: A, earth crust concentrations, B, granite concentration, and C, to shale concentrations. Concentrations after Krauskopf and Bird, 1995

Element	Ptolemais	Amynteon	Kardia	Aghios Demetrios	Average	E.F. to Earth's Crust	E.F. to Granite	E.F. to Shale
Ag*	0.8	1.0	0.7	1.1	0.9	12.9	18.0	12.9
As	19	28	28	19	24	13.3	48.0	1.8
Au	3	3	3	<2	<3	——	——	——
B	90	30	86	90	74	7.4	43.5	0.7
Ba	648	598	647	380	568	0.4	0.5	1.0
Be	1.8	1.2	2.2	0.9	1.0	0.4	0.3	0.3
Bi*	0.4	0.5	0.4	0.5	0.5	2.5	7.1	1.3
Cd	1.9	0.4	0.8	0.4	0.8	4.0	26.7	2.7
Ce	87	72	59	81	75	1.3	0.4	1.5
Co	20	27	22	17	22	0.9	7.6	0.3
Cr	285	231	342	317	294	2.9	14.7	3.3
Cs	5.8	4.9	4.7	4.3	4.9	1.6	3.3	1.0
Cu	65	61	32	24	45	0.8	3.5	1.0
Dy	5.8	4.7	4.8	5.9	5.3	1.8	2.2	1.2
Er	2.6	2.9	2.0	2.7	2.6	0.9	2.2	1.0
Eu	1.3	1.1	1.0	0.9	1.1	0.9	0.8	1.0
Ga	18	16	13	13	15	1.0	0.7	1.3
Gd*	5.2	6.7	4.6	6.2	5.7	1.1	1.1	1.1
Ge	<10	<10	<10	<10	<10	8.7	——	——
Hf	3.8	2.8	3.8	2.7	3.2	1.1	0.6	1.1
Hg	<0.2	<0.2	<0.2	<0.2	<0.2	——	——	——
Ho	0.9	1.1	0.7	1.0	0.9	0.7	2.6	0.7
La	43	32	29	26	32	1.1	0.3	1.3
Li	32	28	34	32	31	1.5	1.4	0.5
Lu	0.6	0.4	0.4	0.3	0.4	0.5	2.1	0.7
Mo	12	12	13	11	12	8.0	0.2	4.6
Nb	32	29	33	28	30	1.5	1.2	2.7
Nd	33	27	23	19	25	0.9	0.4	1.0
Ni	160	131	225	218	183	2.45	183	2.7
Pb	28	32	31	29	30	2.3	0.6	2.0
Pr*	6.4	8.2	6.0	7.2	7.0	0.9	0.4	1.1
Rb	68	68	63	48	62	0.7	0.3	0.5
Sb*	0.7	1.8	1.4	1.1	1.3	6.5	4.2	0.9
Sc	15	14	12	11	13	0.6	4.5	1.0
Se	4.7	3.1	4.1	2.9	3.7	70.3	528.6	6.2
Sm	6.8	5.7	4.9	4.1	5.4	0.9	0.6	0.9
Sn*	1.5	1.8	1.6	1.3	1.6	0.8	0.5	0.3
Sr	296	318	345	379	334	0.9	1.3	1.1
Ta	1.3	1.0	1.0	0.8	1.0	0.5	0.7	1.2
Tb	0.8	0.7	0.6	0.6	0.7	0.8	1.3	0.3
Th	17.2	12.3	10.7	8.8	12.2	1.7	0.02	1.0
Tl*	0.6	0.9	0.6	0.9	0.8	1.6	5.3	0.8
U	32	28	34	32	32	17.8	9.4	8.6
V	131	110	141	96	120	0.9	7.1	0.9
W	4.0	2.1	8.7	4.1	4.7	3.1	11.8	2.6
Y*	23	26	17	24	23	0.7	1.8	0.9
Yb	3.0	2.7	2.0	1.9	2.4	0.7	2.2	1.1
Zn	91	73	65	41	68	1.0	1.5	0.7
Zr	51	62	68	61	61	0.4	0.3	0.4

* After Filippidis et al., 1997.

the pulverizer grinding system and erosion due to their impact on tube surfaces, coal air-pipes and burners (Raask, 1988; Skorpuska, 1993; Carpenter, 1995; Scott, 1995; Sligar, 1996). The high ash concentration of these feedcoals results in high fly ash concentrations, which also affects the performance of electrostatic feedcoals has a medium value of 1.05, low value of fouling index, 0.13, and very low alkali index, 0.06.

Based on the petrographic data the burnout performance of these feedcoals is considered satisfactory due to high attrinitic rich huminites (80%) and the low concentration of non-reactive inertinites (Table 3).

2.3.2. Ptolemais/Amynteon coal basin

The coals from the Ptolemais/Amynteon basin provide feedcoals for Aghios Demetrios (1550 MWe), Kardia (1220 MWe), Ptolemais (620 MWe) and Amynteon (600 MWe) power plants. These feedcoals have on average moisture content of 56% and calorific value, on an as received basis, of 1400 kcal/kg (5.9 MJ/kg) (Table 2). The average ash content in the feedcoals in these four power plants ranges from 20% to 31%. The mineralogy of the coals is quite variable due to different depositional environment (Anastopoulos and Koukouzas, 1972; Koukouzas et al., 1979, 1984; Kotis et al., 1992). Sediments of the Amynteon Basin were deposited along the shorelines of the Ptolemais/Amynteon intermontaine lake, whereas sediments of the Ptolemais Basin were developed in the center of the lake. As a result, feedcoals from Amynteon basin have more hard minerals such as quartz and feldspars whereas Ptolemais feedcoals contain soft minerals such as gypsum, calcite, bassanite and anhydrite. Consequently, though the quality of the combustible material is the same as it is in the remaining coals of Ptolemais area, the mineralogical differences are substantially different, a factor that was not considered when the Amynteon power station was designed. This created problems in the efficient operation of the power plant station due to the rapid wear and tear of the grinding mills, and tube ruptures of the boiler. To overcome this problem, ceramics linings were used to protect the metallic surfaces. The slagging index of these feedcoals is high (1.10), the fouling index is medium (0.57) and the total alkali content is low (0.04).

Feedcoals from the wider Ptolemais/Amynteon area have unexpectedly low burnout properties. This is attributed to the relatively high concentrations of inertinite, ranging from as low as 7% to as high as 50% in certain coals seams (Papanicolaou, 2001). Association of less reactive inertinite with reactive vitrinite/huminite might explain why coals which are acceptable and even desirable as feedcoals, based upon the results of proximate and ultimate analysis, have different burnout performances. It is within this context that petrographic characteristics are also important to know beforehand to design, accordingly, boilers. Unfortunately, during the construction of all the power stations in the area of Ptolemais/Amynteon the burnout index (Yamada and Kambara, 1995) was not considered.

2.3.3. Florina coal basin

The Florina coal basin consists of five subbasins (Vevi, Achlada-Meliti, Meliti-Lofi and Klidi) with geologically proven reserves of 362 millions tons of xylitic coals (Papanicolaou, 2001). The mineable reserves are estimated at 147 million tons. Xylites from this basins have on average water content of 40%, which is 15–20% less than the feedcoals used in Megalopolis and Ptolemais/Amynteon power stations. The average calorific values of the Florina lignites, on as received basis (Fig. 3a), is 2200 kcal/kg (9.2 MJ/kg), which is higher than the Megalopolis and Ptolemais/Amynteon feedcoals (Table 2). The % ash concentration though relatively low has substantial concentration of quartz and pyrites, which, as mentioned previously, should be taken into consideration in the construction of the boiler for the new 365 MWe power plant. Slagging index has the medium value of 0.79, the fouling index is low at 0.09 and the alkali metal content also low at 0.04.

Maceral composition of the Florina ignites is quite different than that of the Megalopolis and Ptolemais/Amynteon lignites (Table 3). Florina coals contain 74% huminites out of which 50% is humotelinitic in nature, saturated with resinous material. Liptinitic components are also quite high, 24%, while inertinitic components are very low, 2% (Table 3). The presence of resinous material textnites and textoulminites is equally important for the boiler design, because it affects the heat flux profile of the combustible material, hence the height of the burners, the location of the heaters and the reheaters

(Stultz and Kitto, 1992). Also, such composition affects the nature of the volatile matter, the stability of the flame and the heat release profile inside the boiler. The effects of high heat volatiles (HHV) on unburnt carbon levels are discussed by Hurt et al. (1995). Moreover, the presence of textinite affects the degree of granularity that can be achieved through milling and pulverization processes because fibrous textinites are difficult to mill. Inadequate pulverization affects combustion efficiency.

2.4. Environmental impact of coal power generation and coal exploitation

Production of feedcoal and its usage in coal-fired plants for power generation results in two environmental issues. These are the emission of gases and particles and secondarily the land reclamation and revegetation of depleted coal mines. Results of the ongoing environmental studies in the wider Ptolemais/Amynteon area with an annual production of 54 million tons of brown coal, the excavation and removal of 350 million tons of overburden and interbedded rocks and the operation of four power stations with 4000 MWe generating capacity, indicate the following.

2.4.1. Emission of NO_x, SO_2 and particulates

The amount of pollutant emissions of SO_2, NO_x and particulates in $\mu g/m^3$ are below the guidelines set by the European Community Council Directive (2001/80/EC) (Table 10). Moreover, the emission of acid gases, which are responsible for generating the acid rain in northern Europe, does not have any negative effect on soils, lakes and rivers in Greece since the concomitant and abundant CaO present in the suspended particles co-precipitates during the rain, thus neutralizing the acid effect. In addition, due to overabundance of limestones and dolomites in Greece, soils, rivers and lakes are also alkaline, thus neutralizing further any excess acidity.

2.4.2. CO_2 emissions

CO_2 is considered a major factor for the greenhouse effect. Based upon data provided by the International Energy Agency (2002), Greece annually emits 88 million tons of CO_2 into the atmosphere, which on a global scale represents 0.30% of the

Table 10
Emissions of SO_x, NO_x and particulates ($\mu g/m^3$) from lignite-fired power plants (April 2001 to March 2002). Data from the Division of Environment, Public Power Corporation of Greece, 2002

Plant	Capacity in MWe	SO_2[1] in $\mu g/m^3$	NO_x[2] in $\mu g/m^3$	Particulates[3] in $\mu g/m^3$
Aghios Dimitrios	1585	256	184	101
Kardia	1200	192	78	86
Ptolemais	620	65	101	94
Amynteon	600	61	182	52
Megalopolis	850	71	N.A.	97

[1] Upper limit 200 $\mu g/Nm^3$.
[2] Upper limit 600 $\mu g/Nm^3$.
[3] Upper limit 300 $\mu g/Nm^3$.

worldwide, or 2.60% of the total, CO_2 emitted by the EC countries. However, Greece is allowed to increase its CO_2 emissions by 20% (International Energy Administration, 2003).

2.4.3. Particles and elements emissions and deposits

(i) The concentration of suspended fly ash particles vary between 52 to 101 $\mu g/Nm^3$ of air well below the 150 $\mu g/Nm^3$ limit set by the European Community Council Directive (2001/80EC).

(ii) The amount of fly ash falling on cultivated soils around the areas surrounding by the power stations is 50 g/month/m^3 (Kallithrakas-Kontos et al., 1998).

(iii) The concentration of heavy metals and toxic elements in the highly calcareous aerosol particles according to Kallithrakas-Kontos et al. (1998) is: for Mo less than 10 ng/Nm^3 for Cd, Hg, and less than 20 ng/Nm^3 for Pb, As and V, while the concentration of Cu ranges from 83 to 285 ng/Nm^3, Cr from 52 to 75 ng/Nm^3 and Ni from 11 to 22 ng/Nm^3.

2.4.4. Fly ash disposal

Fly ash is highly alkaline due to high CaO concentrations ranging from 10.20% to 40.97% (Table 7). Analyses of heavy metals and elements of environmental concern in fly ash from Amynteon, Ptolemais, Kardia and Aghios Demetrios power stations are presented in Table 10. In general, the concentrations of As range between 19 and 28 ppm

Cd values fluctuate between 0.4 and 1.9 ppm, Hg is less than 0.2 ppm, Pb ranges between 28 and 32 ppm, Cu between 24 and 65 ppm and Zn between 41 and 91 ppm. For the remaining 43 elements the range of values encountered in the fly ash is presented in Table 10. Since the pH of water extracts from the fly ashes is well over 12, the solubility of these elements is extremely low. Water concentrations of Hg and As are less than 0.01 ppm, while Pb, Ni, Cd and Co have been recorded at less than 0.1 ppm, which are low and below the European Community Guidelines (91/69/EC, 1994) (Gerouki et al., 1996). Also, the concentrations of other elements are very low. As a result, Ptolemais/Amynteon brown coal fly ashes are classified as inert material, European Community Council Directive (91/684/EC).

2.4.5. Use of bottom and fly ash for land reclamation

For land reclamation bottom and fly ashes are mixed with overburden and interbedded sediments at a ratio of roughly 1:33. The obtained material is suitably landscaped and subsequently used for farming or as forestland serving as wildlife habitat. The concentration of heavy and toxic elements in the rehabilitated soils is very low (Gerouki and Vassiliadis, 2001), while the concentration of the same elements in the water extracts of the soils with pH ranging from 8.0 to 8.2 is extremely low (Gerouki et al., 1996). Hg concentration is <0.005 ppm, V and Cd are <0.01 ppm, and Pb, Mo and As are <0.02 ppm.

The above results indicate that brown coals mined from the wider Ptolemais/Amynteon Basin can be used for power generation, provided its environmental impact is regularly monitored.

2.5. Future uses of lignites and its perspectives

Until now, lignites in Greece have been used exclusively for power generation whereas the by-products of this process, that is fly ash and hot water derived from the power stations, have a variety of uses. Fly ash is used as additive by the cement industry in construction of dams and road pavement, whereas hot water is currently used to heat 15,000 residential homes in the cities of Kozani and Ptolemais, thus reducing the use of more expensive heating oil. The net environmental result is a reduction of emitted SO_2, NO_x and aerosol particles derived from the use of oil fired heating installations.

Further research is underway to investigate the use of Greek lignites coals for briquetting (already 34,000 tons/year are used by the nickel, iron and steel industry as coke in the Former Yugoslavic Republic of Macedonia), bio-filters for cleaning industrial waste disposals, toxic gas absorbents, soil conditioners, fertilizers and soil stabilizers to fight desertification after forest fires. However, the future perspective for the Greek lignites coals still lies in their use as feedcoals for power generation. According to Koukouzas et al. (1997), if we assume an annual increase of power demand by 3% and that 70% of all country's power demands will be met by coal, then the existing recoverable brown coal deposits in Greece will last for the next 60 years assuming that the current efficiency of the coal fired plants remains at 32%.

3. Conclusions

The properties of Greek lignites have been presented and discussed in detail and in relation to their impact on power station operation and the environment.

It is concluded that low calorific value coals, such as the Greek lignites, can produce a very competitive and cost effective KWh, and their exploitation and use will have very little environmental impact when appropriate measures are taken.

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