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Life cycle environmental impacts of electricity from fossil fuels in Turkey

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ABSTRACT

This paper presents for the first time the life cycle environmental impacts of electricity generation from fossil fuel power plants in Turkey which supply three quarters of national demand. There are 16 lignite, eight hard coal and 187 gas power plants in Turkey, all of which are considered in the study. The results suggest that electricity generation from gas has the lowest impacts for 10 out of 11 impacts considered. However, its ozone layer depletion is 48 times higher than for lignite and 12 times greater than for hard coal electricity. Lignite is the worst option overall, with eight impacts higher than for hard coal, ranging from 11% higher fossil fuel depletion to six times greater fresh water ecotoxicity. Conversely, its depletion of elements and ozone layer are four times lower than for hard coal; global warming is 6% lower. Most impacts are mainly caused by the operation of power plants and transportation of imported fuels. Annually, electricity generation from fossil fuels emits 109 Mt CO_2-eq. and depletes 1660 PJ of primary fossil energy. These and the majority of other impacts are from lignite and hard coal power, despite the gas plants generating almost three and five times more electricity, respectively. Therefore, reducing the share of lignite and hard coal power and expanding the contribution of natural gas would lead to significant reductions of environmental impacts from the electricity sector in Turkey, including greenhouse gas emissions; however, ozone layer depletion would increase substantially.

1. Introduction

Turkey is one of the MINT (Mexico, Indonesia, Nigeria, and Turkey) countries projected to grow rapidly (REPRISK, 2014). Like many other countries, it already has difficulties in meeting energy demand as the endogenous fossil energy resources are insufficient, the problem that will only be exacerbated by the growing economy and population. On the other hand, although there is a large potential of renewable energy resources, their current utilisation is low (MENR, 2012). In 2010, the primary energy generation in Turkey was 377,894 GWh while the primary consumption amounted to 1,270,764 GWh, more than three times higher than the country's generation capacity. This has led to Turkey's dependency on energy imports from other countries so that nearly 70% of the national demand is being met by imported fossil fuels and their share continues to increase each year (MENR, 2011; TUIK, 2011b).

Turkey's largest domestic energy source is coal, which was the main energy source until the 1970s. Overall, Turkey has 1.5% of the world's coal reserves. The large majority of this is lignite, with the reserves of 11.8 billion tonnes; this represents 6% of the global lignite deposits (TKI, 2012). However, most of Turkish lignite is of low quality, with low calorific value and high sulphur and ash content. The second most important coal type is hard coal with the reserves of about 1.3 billion tonnes; like lignite, it is of low grade but of cokeable or semi-cokeable quality (TTKI, 2011). Other types of coal found in Turkey are asphaltite, bituminous shale and peat, but their reserves are much smaller. In 2010, total coal production reached 73.4 Mt of which 69.7 Mt was lignite, 2.5 Mt hard coal and 1.2 Mt asphaltite (TKI, 2012). By comparison, 24.3 (MENR, 2011) Mt were imported, of which 60% from Russia and Colombia and 40% from the USA and South Africa (TKI, 2012).

In the mid-1980s, natural gas overtook coal to become the main energy source and, despite the low domestic production (Ozturk et al., 2011), its consumption has been growing rapidly since, increasing from 0.74 billion m^3 in 1987 to 38.13 billion m^3 in 2010 (EIA, 2011; MENR, 2011). With the gas reserves estimated at 6.2 billion m^3 in 2010 and at the current production levels, the

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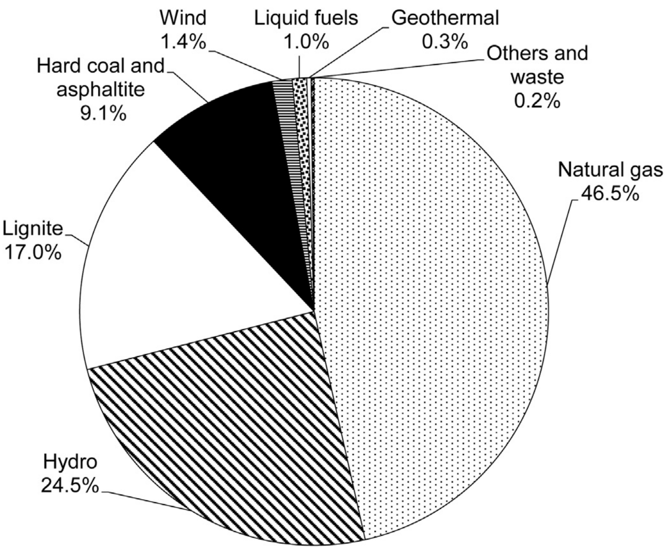

Fig. 1. Turkey's electricity mix in 2010 (EUAS, 2011).

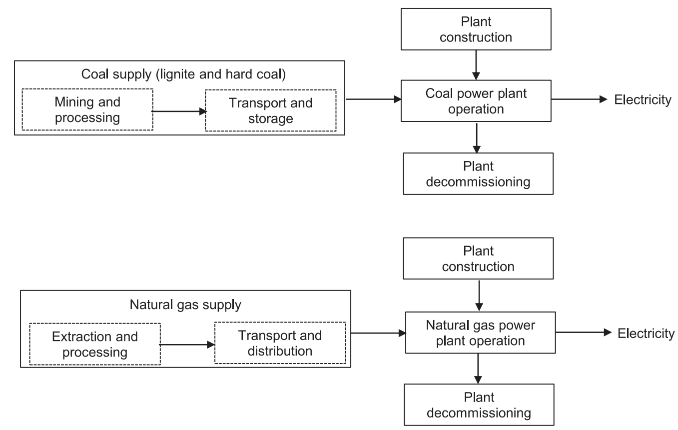

Fig. 3. The life cycle of lignite, hard coal and gas electricity from cradle to grave.

reserve-to-production ratio of domestic gas is around nine years (BOTAS, 2011; EIA, 2011; TPAO, 2011). Thus, the majority of gas is imported, with Russia being the main supplier, providing 17.5 billion m^3 (BOTAS, 2011; EMRA, 2011).

Both coal and natural gas are still the dominant sources of electricity in Turkey. In 2010 they generated 153,190 GWh, contributing 72.5% to the total generation of 211,208 GWh (TEIAS, 2011), of which 46.5% was supplied by gas and 26.1% by coal power plants (see Fig. 1). The next largest contribution is from hydropower (24.5% in 2010). Fig. 2 shows that the generation by coal and gas power plants has grown rapidly since the mid-80s to help meet the fast growing national demand, with the gas electricity supply increasing 1700 times and the coal around four times.

In total, there are 16 lignite and eight hard coal power plants with the total installed capacity of 11,891 MW that in 2010 generated over 55,046 GWh (Fig. 2). The majority (85%) of the plants are pulverised coal (PC) and the rest are circulating fluidised bed (CFB) plants. By comparison, 187 gas power plants with 18,213 MW of installed capacity generated 98,144 GWh in the same year (Fig. 2). More than 90% of this are combined cycle gas turbines (CCGT), including the oil power plants, most of which have been converted to gas so that Turkey has almost no oil installations left.

The high share of fossil fuels in Turkey's electricity mix, together with the increasing demand, has led to a steady increase in greenhouse gas (GHG) emissions, reaching 99 Mt CO_2 eq. in 2010 (FutureCamp, 2011), a quarter of the total national emissions of 403.5 Mt in the same year (EEA, 2012). While Turkey still has the lowest GHG emission per capita in Europe – 5.6 t CO_2-eq. compared to 9.4 t in the EU28 countries (EEA, 2012; TUIK, 2011a) – they are set to increase owing to the growing energy demand. At the same time, being a party to both the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, government is keen to reduce the GHG and other emissions (MoEU, 2007). It is, therefore, important that Turkey identifies and deploys sustainable energy technologies suitable for the country, if climate change and other environmental impacts are to be curbed.

However, the environmental impacts of energy generation in Turkey are largely unknown so that it is not possible to identify sustainable or otherwise options for the country. In an attempt to contribute towards this goal, this paper presents for the first time the life cycle environmental impacts of electricity generation in Turkey. Given their current dominance, the focus is on generation from fossil fuels: lignite, hard coal and gas. The impacts have been estimated using life cycle assessment (LCA) as detailed in the rest of the paper.

2. Methodology

The LCA has been carried out following the ISO 14040/14044 guidelines (ISO, 2006a,b). GEMIS 4.8 (Öko Institute, 2012) and GaBi v.6 (PE International, 2013) software packages have been used for

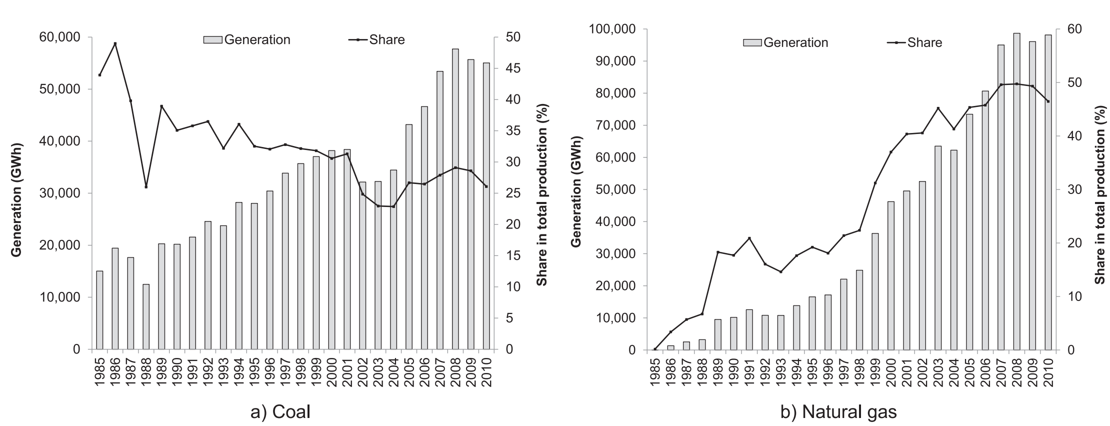

Fig. 2. Electricity generation from coal and natural gas in Turkey and their share in total electricity generation from 1985 to 2010 (TEIAS, 2012).

Table 1
Lignite power plants in Turkey in 2010.[a]

	Power plant	Location	Type	Installed capacity (MW)	Annual generation in 2010 (GWh)	Contribution to total generation (%)	Efficiency (%)	Secondary fuel oil (t)
1.	Afsin Elbistan A	K. Maras	PC[b]	1355	2042	5.8	29	5500
2.	Afsin Elbistan B	K. Maras	PC + FDG[c]	1440	7694	21.7	35	8286
3.	Mart Can	Canakkale	CFB[d]	320	2141	6.0	40	1450
4.	Kangal	Sivas	PC + FDG[e]	457	2313	6.5	34	950
5.	Orhaneli	Bursa	PC + FDG	210	1174	3.3	35	28
6.	Seyitomer	Kutahya	PC	600	3623	10.2	33	2174
7.	Tuncbilek	Kutahya	PC	365	1659	4.7	33	320
8.	Kemerkoy	Mugla	PC + FDG	630	2720	7.7	34	0
9.	Soma A	Manisa	PC	44	29	0.1	31	34
10.	Soma B	Manisa	PC	990	3868	10.9	31	19
11.	Yatagan	Mugla	PC + FDG	630	2599	7.3	31	–
12.	Yenikoy	Mugla	PC + FDG	420	1308	3.7	34	–
13.	Cayirhan Park	Beypazarı	PC + FDG	620	4324	12.2	38	–
			Total	**8081** **(8140[f])**	**35,494** **(35,942[f])**			

[a] The 13 plants listed in the table are connected to the grid. The remaining three plants (not listed) are autoproducers which are not connected to the grid.
[b] PC: pulverised coal.
[c] FGD: flue gas desulphurisation.
[d] CFB: circulating fluidised bed.
[e] FGD installed on one unit of 157 MW.
[f] The total lignite installed capacity in 2010 was 8140 MW and the generation was 35,942 GWh. The difference from the installed capacity and the generation shown in the table is due to a lack of data for the three autoproducer plants not included in the table. However, the total actual electricity generation has been used to estimate the impacts from lignite plants.

LCA modelling and estimation of the impacts. The goal of the study, data and the assumptions are discussed below.

2.1. Goal and scope definition

The goal of the study is to estimate the life cycle environmental impacts of electricity generation from the fossil fuel power plants in Turkey, using 2010 as the base year. Two functional units are considered:

i) generation of 1 kWh of electricity by lignite, hard coal and gas power plants; and
ii) annual generation of electricity from these plants (153,190 GWh).

The scope of the study is from cradle to grave, comprising extraction, processing, and transportation of the fuels, their combustion to generate electricity in power plants and plant construction and decommissioning at the end of their lifetime (see Fig. 3). Since the functional units are related to the generation rather than supply of electricity, its distribution and consumption are outside the system boundary.

2.2. Data and assumptions

As mentioned previously, there are 16 lignite, eight hard coal and 187 gas plants in Turkey all of which are considered in this study. Primary data have been obtained from the Turkish Petroleum Pipeline Corporation (BOTAS), Turkish Ministry of Energy and Natural Resources (MENR), Turkish Electricity Generation Corporation (EUAS), Turkish Electricity Transmission Company (TEIAS) and Energy Market Regulatory Authority (EMRA). Additional information was collected from government and industrial reports as well as academic literature as detailed further below. Detailed data have been available for all the lignite and hard coal plants (Tables 1 and 2); however, for the gas plants, the data are more scant (Table 3). For this reason, an average efficiency of 55% has been assumed for all the gas plants; this matches the average efficiency for the CCGT plants for which the data have been available (Table 3) but also the efficiency of the plants in Turkey reported by the International Energy Agency (IEA) and Nuclear Energy Agency (IEA/NEA, 2005) as well as others (Aslanoglu and Koksal, 2012). Note that the power plants listed in Tables 1–3 are those that are connected to the grid and for which the data were available. Specific data were not available for autoproducer plants which are not connected to the grid but generate

Table 2
Hard coal power plants in Turkey in 2010.[a]

	Power plant	Location	Type	Installed capacity (MW)	Annual generation in 2010 (GWh)	Contribution to total generation (%)	Efficiency (%)
1.	Catalagzi	Zonguldak	Hard coal, PC	300	1883	11.7	31
2.	Karabiga	Canakkale	Imported coal, CFB	405	3132	19.5	40
3.	Isken Sugozu	Adana	Imported coal, PC + FGD	1320	9302	57.8	38
4.	Silopi/Sirnak	Silopi	Asphaltite, CFB	135	984	6.1	40
5.	Eren Catalagzi	Zonguldak	Imported coal, SC[b] + CFB	1360[c]	798	5.0	40
			Total	**3520** **(3751[d])**	**16,099** **(19,104[d])**		

[a] The five plants listed in the table are connected to the grid. The remaining three plants (not listed) are autoproducers which are not connected to the grid.
[b] SC: supercritical coal.
[c] 1230 MW of supercritical coal and 160 MW of circulating fluidised bed.
[d] The total installed capacity in 2010 was 3751 MW and the generation was 19,104 GWh. The difference from the installed capacity and generation shown in the table is due to a lack of specific data for some of the three autoproducer plants not included in the table. However, the total actual electricity generation has been used to estimate the impacts from hard coal plants.

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Table 3
Natural gas power plants in Turkey in 2010.[a]

	Gas plant	Location	Installed capacity (MW)	Annual generation in 2010 (GWh)	Contribution to total generation (%)	Efficiency (%)
1	Ambarli	Istanbul	1350.9	7941	8.09	51
2	Bursa	Bursa	1432	7098	7.23	55
3	Hamitabat	Luleburgaz	1120	5750	5.86	47
4	Aliaga	Izmir	180	251	0.26	42
5	Adapazari-1	Adapazari	1595.4	12,147	12.38	
6	Adapazari-2	Adapazari	797.7	6097	6.21	
7	Baymina	Ankara	798	5579	5.68	
8	Izmir	Izmir	1590.7	12,093	12.32	
9	Enron Trakya	Tekirdag	498.7	3387	3.45	
10	Esenyurt	Istanbul	188.5	1353	1.38	55
11	Colakoglu Dilovasi	Kocaeli	258.4	1882	1.92	48
12	Uni Mar IPR	Tekirdag	504	3429	3.49	
13	Aksa Antalya	Antalya	850	2226	2.27	59
14	Aksa Manisa	Manisa	115.3	663	0.68	
15	Alarko Altek	Kirklareli	164	481	0.49	
16	Cakmaktepe	Izmir	104.7	178	0.18	
17	Antalya	Antalya	94.2	386	0.39	
18	Arenko	Denizli	12	54	0.06	
19	Ayen OSTIM	Ankara	41	197	0.2	
20	Berk	Istanbul	14.8	75	0.08	
21	Binatom	Emet	2	4	0	
22	BIS	Bursa	410	1712	1.74	
23	BOSEN	Bursa	142.8	698	0.71	
24	Burgaz	Luleburgaz	6.9	0	0	
25	Can Enerji	Tekirdag	56.3	291	0.3	
26	Can	Tekirdag	29.1	48	0.05	
27	Camis	Mersin	252.2	1887	1.92	
28	Cengiz	Samsun	203.9	460	0.47	
29	Cebi		64.4	302	0.31	
30	Celik Uzunciftlik		2.4	11	0.01	
31	Cerkezkoy	Tekirdag	49.2	213	0.22	
32	Delta		60	227	0.23	
33	Enerji SA	Bandirma	930.8	743	0.76	59
34	Entek Koc	Istanbul	2.3	18	0.02	
35	Entek	Kosekoy	157.2	987	1.01	
36	Falez		11.7	57	0.06	
37	Global Pelitlik		23.8	93	0.09	
38	Hacisirahmet		7.8	36	0.04	
39	HABAS	Izmir	224.5	1451	1.48	
40	Hayat Kagit		7.5	24	0.02	
41	Karege Arges	Kemalpasa	43.7	171	0.17	
42	Modern		96.8	402	0.41	
43	Noren		8.7	33	0.03	
44	RASA	Van	114.9	593	0.6	
45	Sayenerji	Kayseri	5.9	0	0	
46	Sonmez	Usak	70.7	161	0.16	
47	Sahinler Corlu	Tekirdag	26	65	0.07	
48	T Enerji		1.6	0	0	
49	Ugur	Tekirdag	60.2	136	0.14	
50	Zorlu (B. Karistiran)	Luleburgaz	115.3	513	0.52	
51	Zorlu (Bursa)	Bursa	90	514	0.52	
52	Zorlu (Sincan)	Ankara	50.3	228	0.23	
53	Zorlu (Kayseri)	Kayseri	188.5	754	0.77	
54	Zorlu (Yalova)	Yalova	15.9	104	0.11	
55	AK (K.Pasa)	Kemalpasa	127.2	564	0.57	
56	AK (Bozuyuk)	Bozuyuk	126.6	513	0.52	
57	AK (C.Koy)	Cerkezkoy	98	427	0.44	
58	AKSA	Yalova	70	427	0.43	
59	ATAER		119.2	520	0.53	
60	Baticim		45	277	0.28	
61	Bil Balgat	Ankara	36.6	123	0.13	
62	Camis	Trakya	32.9	194	0.2	
63	DESA		9.8	70	0.07	
64	Gul		24.3	1	0	
65	Ege Birlesik	Izmir	12.8	80	0.08	
66	Enerji-SA	Kosekoy	120	581	0.59	
67	Enerji-SA	Canakkale	64.1	378	0.39	
68	Enerji-SA	Adana	130.2	703	0.72	
69	Enerji-SA	Mersin	64.5	385	0.39	
70	Entek	Demirtas	145.9	805	0.82	
71	Eskisehir 2	Eskisehir	59	276	0.28	
72	KEN Kipas Karen	K. Maras	41.8	73	0.07	
73	MOSB	Manisa	84.8	541	0.55	

Table 3 (*continued*)

	Gas plant	Location	Installed capacity (MW)	Annual generation in 2010 (GWh)	Contribution to total generation (%)	Efficiency (%)
74	Maksi		7.7	49	0.05	
75	Nuh		38	125	0.13	
76	Yurtbay	Eskisehir	6.9	53	0.05	
		Total	**16,709 (18,213[b])**	**91,369 (98,144[b])**		

Blank spaces in the table indicate no data availability.
[a] The plants listed in the table are connected to the grid. The remaining 111 plants are autoproducers which are not connected to the grid.
[b] The total installed capacity in 2010 was 18,213 MW and the generation was 98,144 GWh. The difference from the installed capacity and generation shown in the table is due to a lack of data for the autoproducer plants not included in the table. However, total actual electricity generation has been used to estimate the impacts from gas plants.

electricity for own consumption. However, total generation from these plants has been considered (see notes to the tables), although specific data for each plant were not available.

The power plant and generation data have been used together with the fuel composition data in Table 4 and the amount of fuels used for electricity generation in Table 5 to estimate the emissions from the individual plants using GEMIS 4.8 (Öko Institute, 2012). The results are summarised in Table 6. The emissions calculated in GEMIS have then been imported into Gabi v.6 to estimate the life cycle impacts of electricity generated by lignite, hard coal and gas plants, using the inventory data and the assumptions in Table 4. The background life cycle inventory data have been sourced from Ecoinvent (Ecoinvent, 2010) but have been adapted as far as possible to Turkey's conditions.

3. Results and discussion

The environmental impacts have been estimated following the CML 2001 impact assessment method (Guinée et al., 2002). The following impacts are considered: abiotic depletion potential (ADP elements and fossil), acidification potential (AP), eutrophication potential (EP), fresh water aquatic ecotoxicity potential (FAETP), global warming potential (GWP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), ozone layer depletion potential (ODP), photochemical ozone creation potential (POCP) and terrestrial ecotoxicity potential (TETP). The results for each impact are discussed in the following sections, first for the functional unit related to the generation of 1 kWh of electricity and then for the annual generation of electricity from fossil fuels in 2010.

3.1. Environmental impacts per kWh of electricity generated

The results in Fig. 4 suggest that electricity from gas has the lowest impacts for all the categories except for ODP which is 48 times higher than for lignite and 12 times greater than for hard coal. Lignite is the worst option overall, with eight out of 11 impacts higher than for hard coal, ranging from 11% higher ADP fossil to

Table 4
Assumptions and summary of inventory data.

Life cycle stage	Lignite	Hard coal	Natural gas
Mining and processing	• Domestic • Open pit and underground mining • Composition (% w/w): ○ Sulphur: 0.8–4.5% ○ Ash: 19–40% ○ Water: 20–50% • Net heating value: 7.2–13.9 MJ/kg	• Domestic and imported • Open pit and underground mining • Composition (% w/w): ○ Sulphur: 0.5–0.9% ○ Ash: 7–11% ○ Water: 4–7% • Net heating value: 27–27.5 MJ/kg	• Composition (% vol.): ○ C_1: 94.7–97.3% ○ C_2: 1–3.4% ○ C_3: 0.3–0.6% ○ C_4: 0.1–0.4% ○ C_{5+}: 0.02–0.1% ○ CO_2:0.06–0.6% ○ N_2: 0.1–4.6% • Net heating value: 36.5–40.4 MJ/kg • Leakage during extraction: 0.38% • Leakage in production: 0.12%
Transport	• Power plants adjacent to the mine	• Shipping and rail transport; see Table 5 for details	• Pipeline; see Table 5 for details • Leakage from pipeline: 0.023% per 100 km • Energy use by compressor stations: 0.27% per 100 km
Electricity generation	• See Table 1 for details • Average water use: 37.3 kg/kWh	• See Table 2 for details • Average water use: 32.7 kg/kWh	• All plants assumed to be CCGT with efficiency of 55% • Average water use: 3.4 kg/kWh
Plant construction	• Lifetime: 30 years[a] • Data from Ecoinvent based on average size of the plant of 380 MW (a mix of 500 MW and 100 MW plants in a 70:30 ratio)	• Lifetime: 30 years[a] • Data from Ecoinvent based on average size of the plant of 460 MW (a mix of 500 MW and 100 MW plants at 90:10 ratio)	• Lifetime : 25 years[a] • Data from Ecoinvent assuming 400 MW plant
Plant decommissioning[b]	• Metals and concrete: 50% recycled, 50% landfilled • Plastics: 20% recycled, 80% landfilled	• Metals and concrete: 50% recycled, 50% landfilled • Plastics: 20% recycled, 80% landfilled	• Metals and concrete: 50% recycled, 50% landfilled • Plastics: 20% recycled, 80% landfilled

[a] Source: TEIAS (2013).
[b] The system has been credited for recycling.

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Table 5
The amount of fuels used for electricity generation in 2010 and transport distances for imported fuels.

	Natural gas (million m^3)	Hard coal (million tonnes)	Lignite (million tonnes)	Transport distances (km)	
				Gas[a]	Hard coal[b]
Domestic fuel	–	0.20	55.89	–	–
Imported fuel					
Russia	9921	4.45[c]	–	5750	5000
Iran	4383	–	–	2700	–
Azerbaijan	2551	–	–	1150	–
Algeria	2205	–	–	4000	–
Nigeria	671	–	–	4500	–
USA	–	1.48	–	–	10,500
South Africa	–	1.48	–	–	13,000
Other	1738	–	–	1750	–
Total	**21,469**	**7.61**	**55.89**	**19,850**	**28,500**

[a] Transport by pipeline. Total weighted average distance of 4000 km used for LCA modelling, taking into account the amounts of gas imported from each country as listed in the table.
[b] Russia: 4500 km by rail, 500 km by shipping; USA: 1000 km by rail, 9500 km by shipping; South Africa: 500 km by rail, 12,500 km by shipping.
[c] This includes the amount of hard coal imported from Colombia but as there are no LCA data for the Colombian coal, the LCA impacts from the Russian coal have been used instead.

almost six times greater FAETP. On the other hand, the ADP elements and ODP are four times lower from lignite power than from hard coal; the GWP is 6% lower.

Most of the impacts are mainly caused by the operation of power plants and transportation of fuels. Construction and decommissioning of the plants have negligible impacts, with the credits for recycling of materials after decommissioning having a marginal effect on reducing the overall impacts (by <1%); the only exception to this is depletion of elements which is reduced by around 35% through recycling (based on the assumptions made in this study). These results are discussed in more detail below. Note that all the results incorporate the credits for material recycling.

3.1.1. Abiotic depletion potential (ADP elements)

The depletion of elements for lignite and gas power are estimated at 20 and 24 μg Sb-eq./kWh, respectively (Fig. 4). The value for hard coal power is equivalent to 81 μg Sb-eq./kWh, around four times higher than for lignite power. The main reason for this is the long-distance transport of hard coal (see Table 5) which contributes 63% to the total impact (Fig. 4), with mining adding a further 25% and plant construction 10%. By contrast, most of the ADP elements for electricity from lignite occurs during mining (81%) as lignite is not imported so there is no transport; the rest is from plant operation (11%) and construction (8%). For gas plants, fuel distribution is also a significant contributor (20%) but still much lower than its extraction (45%) and plant construction (33%).

Table 6
Air emissions from coal and gas power plants.[a]

	Lignite (g/kWh)[a]	Hard coal (g/kWh)[b]	Natural gas (g/kWh)[c]
CO_2	1020	923	364
CO	0.67	0.23	0.27
NO_x	2.11	0.65	0.41
N_2O	0.03	0.04	0.016
SO_2	7.84	3.88	0.003
CH_4	0.02	0.02	0.02
Particles (>PM10)	0.11	0.06	–
Particles (PM2.5–PM10)	0.11	0.03	–
Particles (PM2.5)	0.94	0.24	0.003

[a] The emissions calculated using GEMIS 4.8 and GaBi v.6 software packages.
[b] Weighted average taking into account the contribution of each power plant to the total mix.
[c] Average values for all gas plants.

3.1.2. Abiotic depletion potential (ADP fossil)

Fossil resource depletion associated with power generation from hard coal is equivalent to 13.5 MJ/kWh and from lignite to 15.1 MJ/kWh. The impact from gas power is nearly two times lower (8.8 MJ/kWh) owing to the lower efficiency of coal-based plants compared to those using natural gas as well as the lower heating value of lignite and hard coal compared to gas (see Tables 1–4). Fuel extraction is the single largest contributor to the ADP fossil from hard coal (92%) and gas (90%) electricity with the transport contributing the rest. Fuel extraction accounts for all of this impact for the lignite plants as there is no fuel transportation.

3.1.3. Acidification potential (AP)

Lignite electricity has the AP of 10.8 g SO_2-eq./kWh. The single biggest contributor (87%) is the emission of SO_2 from lignite combustion. This is primarily due to the high sulphur content in the lignite and a lack of desulphurisation at some power plants (see Table 1). Estimated at 6 g SO_2-eq./kWh, the impact from hard coal power is 1.8 times lower than for lignite. The majority of the AP for hard coal is due to the emissions of SO_2 (86%) and NO_x (12%), generated largely during the operation of power plants. At 0.8 g SO_2-eq./kWh, the AP from gas is around 13 times lower than from lignite. The majority of the impact comes from gas extraction (57%) and its combustion to generate electricity (26%); gas distribution makes up the rest (17%). The emissions of SO_2 and NO_x contribute respectively 57% and 40% to the total AP of gas plants, with the majority of SO_2 (88%) emitted during gas extraction and NO_x during gas combustion (64%) as well as gas transportation (26%).

3.1.4. Eutrophication potential (EP)

The EP for electricity generation from lignite is equal to 11.9 g PO_4-eq./kWh. Nearly 85% of this impact is due to the emissions of phosphates to fresh water, occurring primarily in the mining stage. The EP for hard coal is around five times lower (2.3 g PO_4-eq./kWh) and for gas two orders of magnitude smaller (0.1 g PO_4-eq./kWh) than for lignite. Like lignite, the emissions of phosphates during mining are the biggest contributor (73%) for hard coal power while for natural gas, NO_x emissions from fuel combustion (64%) and transportation (26%) contribute the majority of this impact.

3.1.5. Fresh water aquatic ecotoxicity potential (FAETP)

Lignite power has an estimated FAETP of 2.1 kg dichlorobenzene (DCB)-eq./kWh. The value for FAETP for hard coal power is 0.4 kg DCB-eq./kWh, around five times lower than for lignite power. Both values are still several orders of magnitude higher than for gas power which is estimated at 3.5 g DCB-eq./kWh. Mining is the single largest contributor to the FAETP (>80%) for both lignite and hard coal, while for gas, 40% is from gas extraction, 31% from its transportation and 20% from plant construction. The majority of the impact for all three options is due to the emissions of metals to fresh water during mining, including nickel, beryllium, cobalt, vanadium, copper and barium.

3.1.6. Global warming potential (GWP)

As can be seen in Fig. 4, this impact is highest for hard coal at 1126 g CO_2-eq./kWh, followed by lignite with 1062 g CO_2-eq./kWh and gas with less than half of that (499 g CO_2-eq./kWh). For all three options, the majority of the GWP is from fuel combustion, ranging from 97% for lignite to 83% for hard coal and 74% for gas.

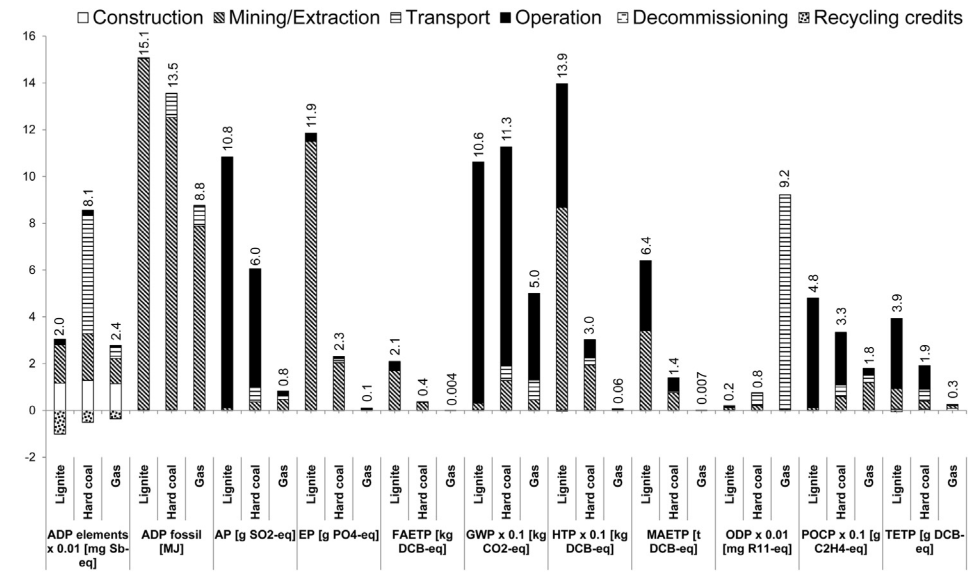

Fig. 4. Environmental impacts per kWh of electricity. [The values shown on top of each bar represent the total impact after the recycling credits for the plant construction materials have been taken into account. Some values have been rounded off and may not correspond exactly to those quoted in the text. ADP elements: Abiotic depletion of elements; ADP fossil: Abiotic depletion of fossil; AP: Acidification potential; EP: Eutrophication potential; FAETP: Fresh water aquatic ecotoxicity potential; GWP: Global warming potential; HTP: Human toxicity potential; MAETP: Marine aquatic ecotoxicity potential; ODP: Ozone layer depletion potential; POCP: Photochemical ozone creation potential; TETP: Terrestrial ecotoxicity potential.]

The second largest contributor for the latter is gas distribution (17%) because of its leakage during the long-distance pipeline transport. The CO_2 emissions account for 98% of the total GWP for lignite and around 90% for both hard coal and gas power.

3.1.7. *Human toxicity potential (HTP)*

The HTP for electricity from lignite is estimated at 1393 g DCB-eq./kWh, nearly five times higher than for hard coal (301 g DCB-eq./kWh) and 232 times greater than for gas electricity (6 g DCB-eq./kWh). This is largely due to the impact from lignite mining (62%) and particularly as a result of emissions of selenium, molybdenum, beryllium and barium. The rest of the impact is associated with the emissions generated during fuel combustion to generate electricity. Similar contribution is found for hard coal electricity, except that, in addition to mining (64%) and plant operation (25%), coal transport is also a contributor (10%). Gas power shows a different trend, with plant construction contributing nearly half of the HTP (46%) owing to the emissions of heavy metals to air, including chromium, arsenic and nickel. The next largest contributor is gas extraction (26%), with the rest being from transport (17%) and plant operation (11%).

3.1.8. *Marine aquatic ecotoxicity potential (MAETP)*

Electricity from lignite emits 6.4 t DCB-eq./kWh, nearly five times more than hard coal (1.4 t DCB-eq./kWh) and three orders of magnitude more than gas power (6.9 kg DCB-eq./kWh). For all three types of technologies, mining is the main source of this impact (Fig. 4), mainly because of the emissions of heavy metals to water.

3.1.9. *Ozone layer depletion potential (ODP)*

The ODP of lignite is estimated at 1.9 μg R11-eq./kWh, 60% of which is from mining and the rest from plant operation. The impact from hard coal is four times higher (7.6 μg R11-eq./kWh) and that

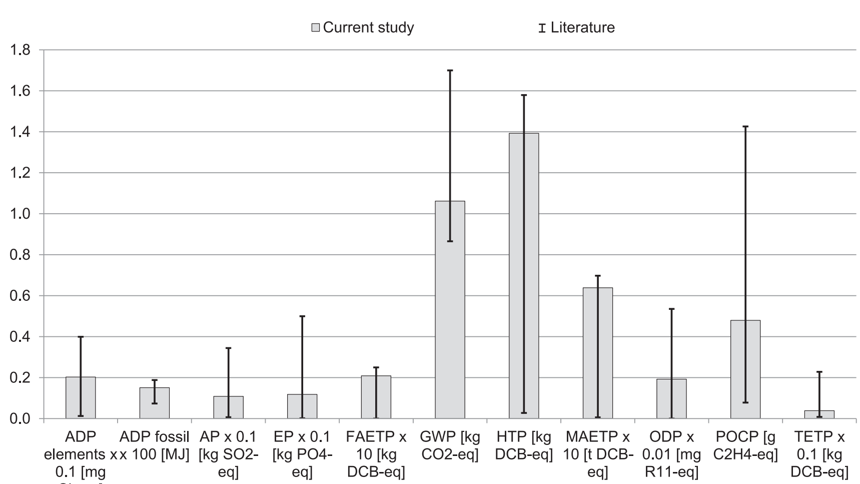

Fig. 5. Comparison of the results from current study with the literature for lignite power. [All impacts expressed per kWh of electricity generated, estimated using the CML 2001 method. Literature data from Weisser (2007), Pehnt and Henkel (2009), Ecoinvent (2010), PE International (2013), Pehnt and Henkel (2009) and Weisser (2007). For impacts nomenclature, see Fig. 4.]

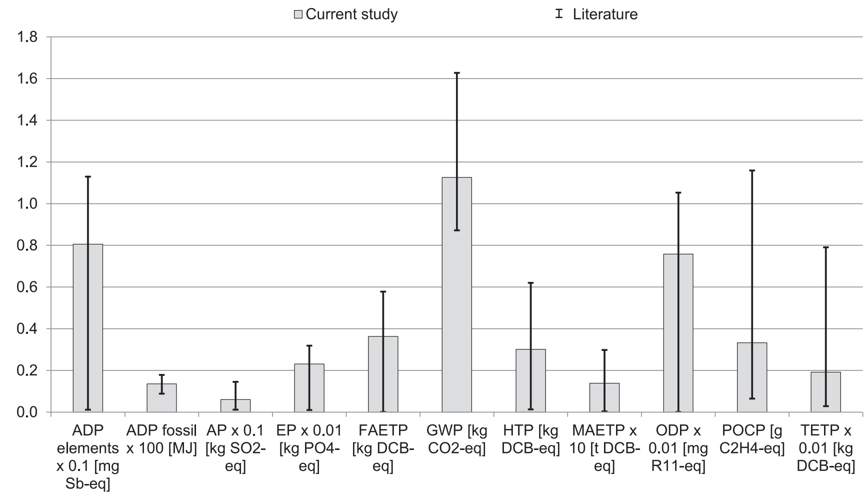

Fig. 6. Comparison of the results from current study with the literature for hard coal power. [All impacts expressed per kWh of electricity generated, estimated using the CML 2001 method. Literature data from Ecoinvent (2010), PE International (2013) and Stamford and Azapagic (2012). For impacts nomenclature, see Fig. 4.]

from gas 48 times higher (92 μg R11-eq./kWh), largely from transport of fuels and in particular the emissions of halons 1211 and 1301 used as fire suppressants and coolants in the gas pipeline distribution system.

3.1.10. Photochemical oxidant creation potential (POCP)

Lignite and hard coal-based power have the POCP of 0.48 g C_2H_4-eq./kWh and 0.33 g C_2H_4-eq./kWh, respectively. The large majority of this impact is due to the emissions of SO_2, NO_x and CO from coal combustion (see Fig. 4). By contrast, the main source of the POCP estimated at 180 mg C_2H_4-eq./kWh for gas electricity is fuel extraction (66%) because of the emissions of non-methane volatile organic compounds, N_2O and SO_2.

3.1.11. Terrestrial ecotoxicity potential (TETP)

The TETP of the lignite power life cycle is equivalent to 3.9 g DCB-eq./kWh and that of hard coal to 1.9 g DCB-eq./kWh; the impact from gas power is one order of magnitude lower (0.3 g DCB-eq./kWh). Emissions to air and soil of mercury, chromium, vanadium and arsenic are the main cause of this impact for all three options.

3.2. Comparison of results with literature

As far as we are aware, there are no other LCA studies of electricity generation from fossil fuels in Turkey so comparison of the results with other studies is not possible. However, similar studies for other countries abound in LCA databases (Ecoinvent, 2010; PE International, 2013) and academic literature (e.g. Kannan et al., 2005; Pehnt and Henkel, 2009; Santoyo Castelazo, 2011; Stamford and Azapagic, 2012; Weisser, 2007) so that the current results are compared to these sources in Figs. 5–7. As can be seen, a wide range of values has been reported for each impact across different studies. This is primarily due to different technological assumptions, such as plant efficiency, fuel origin and pollution control measures as well as the background data used to estimate the impacts.

As can be seen from the figures, all the impacts per kWh of generated electricity estimated in this study are well within the ranges reported in the literature. For example, for lignite power the GWP falls between 866 and 1700 g CO_2-eq./kWh, which compares well with the estimate in this study of 1062 g CO_2-eq./kWh. For hard coal electricity, the GWP in the literature ranges between 872 and 1628 g CO_2-eq./kWh so that the value of 1126 g CO_2-eq./kWh

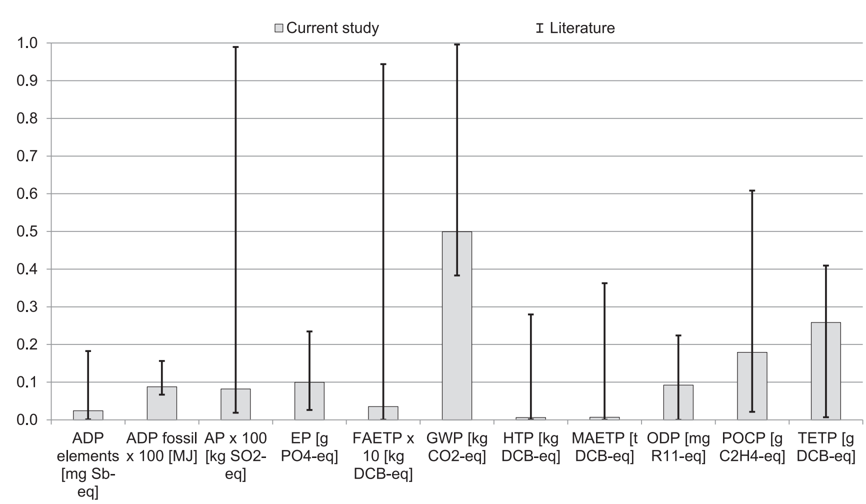

Fig. 7. Comparison of the results from current study with the literature for gas power. [All impacts expressed per kWh of electricity generated, estimated using the CML 2001 method. Literature data from Ecoinvent (2010), Kannan et al. (2005), PE International (2013), Santoyo Castelazo (2011), Stamford and Azapagic (2012) and Weisser (2007). For impacts nomenclature, see Fig. 4.]

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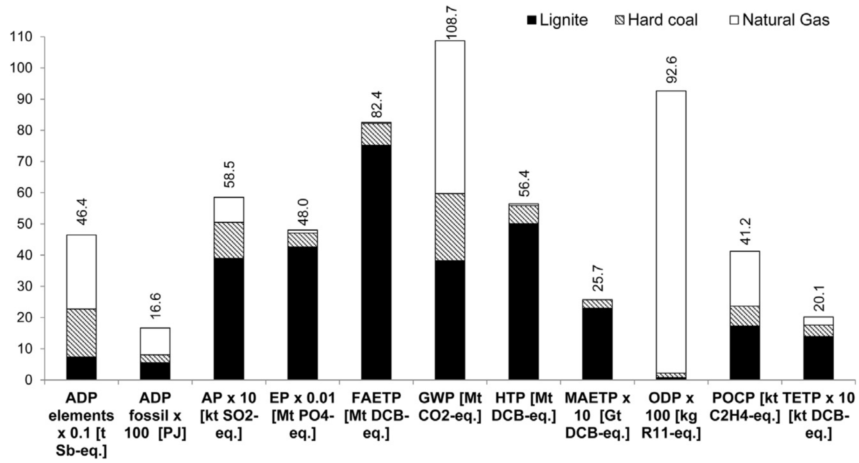

Fig. 8. Annual environmental impacts from fossil-fuel electricity generated in Turkey in 2010. [For impacts nomenclature, see Fig. 4.]

obtained in the current study sits well within the range. The GWP for gas power reported in the literature ranges between 383 and 996 g CO_2-eq./kWh, compared to the value of 499 g CO_2-eq./kWh obtained in the current study.

3.3. Annual environmental impacts

The annual environmental impacts from fossil-based electricity generated in Turkey in 2010 have been estimated using the impacts per kWh discussed in the previous section and the total fossil-fuel electricity generated that year (153,190 GWh); the results are shown in Fig. 8. For example, the annual GWP is estimated at 109 Mt CO_2-eq., of which gas power contributes 45%, lignite 35% and hard coal 20%. The direct emissions are equivalent to 91.2 Mt CO_2-eq. which compares well to the direct emissions of 95.8 Mt CO_2-eq. from coal and gas electricity estimated by FutureCamp (2011). The difference (4.8%) between the two estimates stems from different assumptions, including the efficiency of the power plants and the amount of fuel used in different power plants.

As can also been seen from Fig. 8, the majority of the impacts are from lignite and hard coal. This is despite the fact that the amount of electricity generated by the gas power plants is 2.7 and 5.1 times higher than that of lignite and hard coal, respectively (see Tables 1–3). The notable exception to this is the ODP, which is almost entirely (98%) from gas electricity because of the fire suppressants and coolants mentioned in the previous section.

4. Conclusions

This study has estimated for the first time the life cycle environmental impacts of fossil-fuel electricity in Turkey. The results suggest that electricity from gas has the lowest impacts than power from lignite and hard coal for ten out of 11 categories considered, including GWP. The latter is estimated at 499 g CO_2-eq./kWh for gas, which is less than half the value for lignite (1062 g CO_2-eq./kWh) and hard coal power plants (1126 g CO_2-eq./kWh). However, the ODP from gas electricity is 48 times higher for gas than for lignite and 12 times greater than for hard coal. Power from lignite is the worst option overall, with eight impacts higher than for hard coal, ranging from 11% higher ADP fossil to almost six times greater FAETP. On the other hand, the ADP elements and ODP are around four times lower from lignite power than from hard coal; the GWP is 6% lower.

The impacts are caused mainly during the operation of power plants and transportation of fuels. Construction and decommissioning of the plants have negligible impacts. The credits for recycling of materials after decommissioning reduce the impacts by less than 1%; the only exception to this is depletion of elements which is reduced by around 35%.

Annually, electricity generation from fossil fuels emits 109 Mt CO_2-eq. on a life cycle basis, of which the majority is from lignite and hard coal power, despite the gas plants generating 2.7 and 5.1 more electricity, respectively.

These results highlight the importance of reducing the share of lignite and hard coal power in the electricity mix of Turkey which would lead to significant reductions in environmental impacts from the electricity sector, including GHG emissions. In the short term, this could be achieved by expanding the use of natural gas; however, ozone layer depletion would increase significantly compared to electricity from lignite and hard coal. Further short-term measures to reduce emissions include energy efficiency improvements to the current plants and wider adoption of pollution control technologies; the latter should be legislated more tightly. In the medium to long term, expansion of renewable electricity generation should be considered, including wind and sun energy which are abundant in Turkey. The role of carbon capture and storage as well as nuclear power in country's future electricity mix should also be investigated. A sustainability assessment considering life cycle environmental impacts, economic costs and social aspects of these options would help the industry and policy makers in Turkey to identify and implement most sustainable electricity options for the future. This is the subject of ongoing research by the authors.

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