

Environmental Performance of Electricity Generation Based on Resources: A Life Cycle Assessment Case Study in Turkey

Zerrin Günkaya, Alp Özdemir, Aysun Özkan and Müfide Banar

Table S1. Data used to model coal-fired TPPs in SimaPro (with calculation details).

Data Description	TPPs		
	Lignite	Hard Coal	Imported Coal
Calorific value of lignite (kJ/kg)	8360 ¹	12,958 ²	25,707 ³
Total coal consumption in 2012 (ton)	48,859,540 ¹	1,254,623 ¹	30,000,000 ⁴
Lignite consumption (kg/kWh)	1.43	0.63	1.1
Coal burning system	Pulverized coal burner (PCB) system		
Cooling system ⁵	Sea water cooled		
Cooling water consumption (m ³ /kWh) ⁵	0.096	0.16	0.01
Process water treatment ⁶	Chlorination-coagulation/flocculation demineralization		
Wastewater generation (lt/kWh) ⁷	0.25	0.42	0.27
The wastewater emissions of the TPPs (mg/kWh) ⁸			
Chemical Oxygen Demand (COD) (mg/kWh)	7.53	12.7	8.01
Suspended Solid Matter (SSM) (mg/kWh)	25.1	42.2	26.9
Oil and Grease (mg/kWh)	2.51	4.22	2.69
Total Cyanide (mg/kWh)	0.13	0.21	0.14
Flue gas treatment unit	Particle matter and DeSO _x removal systems		
Stack gas emissions (kg/MWh) ⁹			
SO ₂	41.07	4.76	4.76
NO _x	3.41	4.11	4.11
Dust	4.29	3.75	3.75
CO ₂ ¹⁰	819	767	767
Disposed ash (kg/kWh) ¹¹	0.29	0.48	0.31
Heat waste (MJ/kWh) ¹²	4.05	6.78	4.27
Transport (sea miles) ¹³	-	-	7058

¹ The calorific value of approximately 70% of Turkish lignite reserves is below this value [1]; ² Calorific value of hard coal fired in Çatalağzı TPP is 2700–3500 kcal/kg [2]; ³ Calorific value of imported coal fired in Su gözü TPP is 6150 kcal/kg is obtained from [3]; ⁴ Based on [4]; ⁵ In 2012, a total of 6,407,505,000 m³ water was used by thermal plants with 98% of this amount supplied from the sea. Ninety-nine percent of this amount was used for cooling purposes [5]; ⁶ Chlorinated raw water drawn from rivers in order to prevent the formation of algae on machines. Then, hydrated lime and iron (III) chloride was used as feed water, softened with a demineralization process. The treatment efficiencies of these units are 95%; ⁷ In 2012 year, 16,941,013 m³ of wastewater was treated by thermal plants [6]; ⁸ Wastewater discharge limits for thermal power plants were given by the Water Pollution Control Regulation [7] as COD 30 mg/L, SSM 100 mg/L, Oil and Grease 10 mg/L, Total Cyanide 0.5 mg/L, at a temperature of 35 °C; ⁹ Stack gas emissions of lignite and hard coal burned TPPs were obtained from Kincay and Ozturk [8]. Emissions generated from hard coal burning TPPs were also used for imported coal burning TPPs, since there is a lack of data; ¹⁰ Calculated from the average CO₂ emission factors given by [9]; ¹¹ In 2012 year, 19,262,185 tons of ash were generated from thermal plants. A total of 67.4% of this amount was disposed of at thermal power plants. In this study, only these disposed ash amounts are considered [6]; ¹² Heat waste to the sea was calculated using a heat equation as follows: $Q = m \cdot c \cdot (T_{outlet} - T_{inlet})$, where Q is the heat quantity generated by cooling, m is the amount of sea water used by thermal power plants, and c is the specific heat capacity for water (4.18 J·g⁻¹·°C⁻¹). It was assumed that the inlet temperature of the sea water was 15 °C, and that of the outlet sea water was 25 °C; ¹³ Transportation of the fuel was not considered for the lignite and hard coal-fired TPPs, since it was assumed that these TPPs are adjacent to the mine. The imported coal was mainly supplied from Russia, Colombia, the USA, and South Africa, with shares of 33.3%, 24.5%, 14.6%, and 11.2%, respectively [4]. Coal is shipped in by ocean freighter. It was assumed that the imported coal-fired TPPs in Zonguldak and Çanakkale were supplied fuel from Russia, since they are close to the Black Sea, whereas the TPP in Iskenderun imported coal from Colombia, since Iskenderun is close to the Mediterranean Sea. The ships' freight capacities were calculated as kg·km based on the distances [10] and coal consumption by the TPPs in direct proportion to their electricity generation.

Table S2. The data used to model the natural gas fired TPPs in SimaPro.

Data Description	Data
Total natural gas consumption in 2012 (m ³)	4,427,602,000 ¹
Energy obtained from natural gas (kJ/m ³)	34,585.67 ²
System in natural gas thermal power plants	Combined cycle ³
Cooling system	Air dried in turbine generator, cooling water from well for steam generator
Water consumption (m ³ /year)	120,000 ⁴
Wastewater generation (m ³ /year)	93,360 ⁴
Wastewater parameters (mg/kWh) ⁵	
COD	216
Chloride (Cl ⁻)	2160
Sulphate (SO ₄ ⁻²)	3240
Iron (Fe)	10.8
Power plant construction	ecoinvent
Air emissions (kg/MWh) ⁶	
SO ₂	0.043
NO _x	3.08
CO ₂	456.96
CO	0.16

¹ Based on [1]; ² Based on [8]; ³ A large amount of electricity is generated by combined cycle plants;

⁴ Based on [11]; ⁵ The wastewater emissions of the natural gas fired TPPs were calculated using the wastewater generation amount and wastewater discharge limits given by the Turkish Regulation on Water Pollution Control (Table 9.6: 10 mg/L oil and grease and 100 mg/L SSM) [7]; ⁶ Based on [8], and [12].

Table S3. Hydroelectric power plants operated in 2012.

Reservoir Basis	Installed Capacity (MW)	Electricity Generation (GWh)	River Basis	Installed Capacity (MW)	Electricity Generation (GWh)
Almus	27	99	Ceyhan	3.6	12
Altunkaya	700	1632	Çağçağ	14.4	42
Aslantaş	138	569	Defne	3	15
Atatürk	2400	8900	Doğankent-1	32.8	124
Berke	510	1668	Durucasu	0.8	3
Birecik	672	2518	Engil	4.6	14
Borçka	300	1039	Girlevik	3.04	17
Demirköprü	69	193	Hazar-1	20.12	128
Derbent	58	257	Hazar-2	10	64
Dicle	110	298	İkizdere	15.12	100
Gökçekaya	278	562	Kadıncık-1	70	345
Hasan Uğurlu	500	1217	Kayaköy	3.84	12
Hirfanlı	128	400	Kepez-1	26.4	169
Karakaya	1800	7534	Kernek	0.83	3
Karkamış	189	652	Kiti	2.76	6
Keban	1130	6000	Kovada-1	8.25	35
Kemer	48	143	Kovada-2	51.2	222
Kesikköprü	76	250	Sızır	6.77	35
Kiğı	140	423	Tortum-1	26.18	85
Kralkızı	94	146	Yerköprü	10.56	65
Muratlı	115	444			
Oymapınar	540	1620			
Sarıyar	160	400			
Seyhan	54	350			
Sır	284	725			
Suat Uğurlu	46	273			
Yamula	100	422			
Total	10,666	38,734	Total	314.27	1496

References

1. Elektrik Üretim A.Ş. EUAS, Turkish Electricity Generation Company—Annual Report. 2012. Available online: http://www.euas.gov.tr/Documents/YILLIK_RAPOR_2012.pdf (accessed on 17 October 2016).
2. Kızıl, H.; Tekin, E.; Erdoğan, B.; Topal, H.İ.; Topuz, A. The experimental analysis of cool drying in fluidized bed (in Turkish). In Proceedings of the 19th National Heat Science and Technique Congress, Samsun, Turkey, 9–12 September 2013; pp. 582–587.
3. Say, N.P. Lignite-fired thermal power plants and SO₂ pollution in Turkey. *Energy Policy* **2006**, *34*, 2690–2701.
4. Turkish Coal Enterprise. Coal Sectoral Report. 2012. Available online: <http://www.Tki.Gov.Tr/dosyalar/dosya/k%c3%b6m%c3%bcrsekt%c3%b6rraporu2012.Pdf> (accessed on 17 October 2016). (In Turkish)
5. Turkish Statistical Institute. 2014. Available online: <http://www.tuik.gov.tr/PreHaberBultenleri.do?sessionId=p2D5TdKcR6nlNn3KY2syfqhy67mGWhFL2DTcVPGJLQG1CgtLk83!-184462139?id=16164> (accessed on 17 October 2016)
6. Turkish Statistical Institute. 2012. Available online: <http://www.turkstat.gov.tr/PreHaberBultenleri.do?id=16164> (accessed on 17 October 2016).
7. Regulation on Water Pollution Control. Official Gazette Dated 09.04.1988—No. 19.999. Available online: <http://mevzuat.basbakanlik.gov.tr/Metin.Aspx?MevzuatKod=7.5.7221&sourceXmlSearch=&MevzuatIliski=0> (accessed on 17 October 2016). (In Turkish)
8. Kincay, O.; Öztürk, R. Thermal power plants in Turkey. *Energy Sources* **2003**, *25*, 135–153.
9. IPCC Guidelines for National Greenhouse Gas Inventories. Combustion. Available online: http://www.ipccngip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf (accessed on 17 October 2016).
10. National Geospatial (2001) Distances between Ports. Available online: http://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_pageLabel=msi_portal_page_62&pubCode=0005 (accessed on 17 October 2016).
11. Envy Energy. The Environmental Assessment Report of Hamitabat Natural Gas Combined Cycle Power Plant Renewal Project. Available online: http://www.csb.gov.tr/db/ced/editordosya/Limak_Hamitabat_CED.pdf (accessed on 17 October 2016). (In Turkish)
12. Sözen, A.; Alp, İ.; Özdemir, A. Assessment of operational and environmental performance of the thermal power plants in Turkey by using data envelopment analysis. *Energy Policy* **2010**, *38*, 6194–6203.