DEVELOPMENT OF ELECTRICITY PRODUCTION FROM LIGNITE AND HARD COAL LCA PROCESSES FOR FUTURE NATIONAL DATABASE OF TURKEY

by
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ABSTRACT

DEVELOPMENT OF ELECTRICITY PRODUCTION FROM LIGNITE AND HARD COAL LCA PROCESSES FOR FUTURE NATIONAL DATABASE OF TURKEY

The reliability of life cycle assessment (LCA) studies is determined by the quality of the inventory data used in the analysis and the degree to which the processes reflect the true production conditions of the country. The goal of this study is to develop country-average LCA processes for electricity production from lignite and hard coal of Turkey. Air emissions for 15 lignite and 8 hard coal power plants operating in Turkey were estimated based on coal combustion and emission control technologies and the properties of coal utilized at the plants using the emission factors of the United States Environmental Protection Agency (US EPA) WebFIRE database. The calculated emission values were then used to developed the country average electricity production processes from lignite and hard coal using Ecoinvent template datasets. The environmental impacts of the newly developed and the original Ecoinvent processes were compared for consistency using LCA methodology. The air emission calculations for CO_2, CO, N_2O, NO_x and SO_x have yielded values that are close to the values in Ecoinvent datasets, with most accurate results obtained for CO and SOx emissions in lignite and CO_2 and NO_x emissions in hard coal processes. LCA comparison has revealed the environmental impacts of the newly developed processes to be comparable with their Ecoinvent counterparts, where difference in total normalized environmental impacts are less than 2% for lignite and 21% for hard coal processes. In overall, the obtained results demonstrate the adequacy of the approach utilized in the study for developing the LCA energy processes.

ÖZET

TÜRKİYE’NİN GELECEK ULUSAL VERİ TABANI İÇİN LİNYİT VE TAŞKÖMÜRÜNDEN ELEKTRİK ÜRETİMİ YDD PROSESLERİNİN GELİŞTİRİLMESİ

Yaşam döngüsü değerlendirmesi (YDD) çalışmalarının güvenirliğini, analizde kullanılan envanter verilerinin kalitesi ve kullanılan proseslerin ülkenin gerçek üretim değerlerini ne derece yansıttığı belirlemektedir. Bu çalışmanın amacı Türkiye için ortalama linyit ve taşkömüründen elektrik üretimi YDD proseslerini geliştirmektir. Türkiye’de çalışan 15 linyit ve 8 taşkömürü termik santrali için, bu santrallerin yakma ve emisyon kontrol teknolojileri ve yakılan kömürün özellikleri baz alınarak ve Birleşik Devletleri Çevre Koruma Kurumu’na (US EPA) ait WebFIRE veri tabanındaki emisyon faktörleri kullanılarak ortalama hava emisyonları hesaplanmıştır. Hesaplanan emisyon değerleri daha sonra şablon Ecoinvent veri setleri kullanılarak, ülke ortalaması linyit ve taşkömüründen elektrik üretim prosesleri geliştirilmiştir. Son olarak, yeni geliştirilen proseslerin çevresel etkileri tutarlılık açısından Ecoinvent veri tabanındaki karşılıklarıyla YDD yöntemi ile kıyaslanmıştır. CO_2, CO, N_2O, NO_x ve SO_x için gerçekleştirilen hava emisyon hesapları Ecoinvent veri setlerindeki değerlerle tutarlı sonuçlar vermiş olup, Ecoinvent değerlerine en yakın sonuçlar linyit prosesinde CO ve SO_x, taşkömürü prosesinde ise CO_2 ve NO_x emisyonları için elde edilmiştir. Aynı zamanda, YDD karşılaştırması, yeni geliştirilen prosesler ile Ecoinvent proseslerinin bir birine yakın çevresel etkiye sahip olduğunu, ikisi arasında normalize toplam çevresel etki farkının linyit için %2, taşkömürü için ise %21 olduğu gözlemlenmiştir. Böylece, elde edilen sonuçlar çalışmada YDD enerji proseslerinin geliştirilmesi için kullanılan yöntemin uygun olduğunu sergilemiştir.

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LIST OF SYMBOLS/ABBREVIATIONS

Symbol	**Explanation**	**Unit**
°C	Celsius	°C
A	Ash Weight Percentage of Coal	-
AP	Acidification Potential	kg SO_2 eq.
$Ca(OH)_2$	Calcium Hydroxide	-
$CaCO_3$	Calcium Carbonate	-
$CaSO_3$	Calcium Sulfite	-
CO	Carbon Monoxide	-
CO_2	Carbon Dioxide	-
$EF_{in,p,f,ct}$	Uncontrolled EF of Pollutant p for EGUs Burning Fuel Type f using Combustion Technology ct	g/ton coal
$EF_{out,p,f,ct}$	EF of Pollutant p for EGUs Burning Fuel Type f using Combustion Technology ct	g/kWh
$EF_{p,f,ct}$	Averaged EF of a Pollutant p Emitted by Power Plants Burning Fuel f using Combustion Technology ct	g/kWh
$elec.gen_{f,ct}$	Net Electricity Generation by Fuel Type and Combustion Technology ct	kWh
$Emission_{p,f,ct,i}$	Emissions of a Pollutant p from Power Power Plant i Burning Fuel f using Combustion Technology ct	g
EP	Eutrophication Potential	kg PO_4 eq.
$ER_{p,\mathrm{ec}}$	Emission Reduction Efficiency of Pollutant p Using Control Technology ec	-
GWP	Global Warming Potential	kg CO_2 eq.
$heatinput_{f,ct}$	Heat Input by Fuel Type f and Combustion Technology ct	mmBtu
HHV_f	HHV of fuel type f	mmBtu
$HI_{f,ct,i}$	Net Annual Heat Input to Plant i from the Burning of Fuel Type f using Combustion Technology ct	mmBtu

LHV_f	LHV of fuel type f	mmBtu
N_2	Nitrogen	-
N_2O	Nitrous Oxide	-
$NEG_{f,ct,i}$	Net Electricity Generated by Power Plant i Burning Fuel f using Combustion Technology ct	kWh
NH_3	Ammonia	-
NO	Nitrogen Monoxide	-
NO_2	Nitrogen Dioxide	-
NO_x	Nitrogen Oxides	-
PM_{10}	Particulate Matter Less Than 10 Micrometers in Size	-
$PM_{2.5}$	Particulate Matter Less Than 2.5 Micrometers in Size	-
PO_4	Phosphate	-
$POCP$	Photochemical Ozone Creation Potential	kg Ethene eq.
S	Sulfur weight percentage of coal	-
SO_2	Sulfur Dioxide	-
SO_3	Sulfur Trioxide	-
SO_x	Sulfur Oxides	-
$\eta_{LHV,ct}$	LHV-based Energy Conversion Efficiency of Combustion Technology ct	-
μm	Micrometer	µm
Σ	Summation	-

Abbreviation	**Explanation**
AFBC	Atmospheric Fluidized Bed Combustion
AP-42	US EPA Compilation of Air Pollutant Emission Factors
ASTM	American Society for Testing and Materials
BAT	Best Available Techniques
BFBC	Bubbling Fluidized Bed Combustion
BREF	Best Available Techniques Reference Document
CCS	Carbon Capture and Storage
CFBC	Circulating Fluidized Bed Combustion
CHP	Combined Heat and Power

CPM	Condensable Particulate Matter
$DeNO_x$	Denitrification
EF	Emission Factor
eGRID	Emissions Generation Resource Integrated Database
EGU	Electric Generating Unit
ELCD	European Reference Life Cycle Database
EPLCA	European Platform on Life Cycle Assessment
ESP	Electrostatic Precipitator
ETKB	Ministry of Energy and Natural Resources of Turkey
EU	European Union
EÜAŞ	Electricity Generation Company
FBC	Fluidized Bed Combustion
FGD	Flue Gas Desulfurization
FPM	Filterable Particulate Matter
g	Gram
GHG	Greenhouse Gas
GJ	Gigajoule
GLAD	Global LCA Data Access Network
GWh	Gigawatt Hour
HHV	Higher Heating Value
IGCC	Integrated Gasification Combined Cycle
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
JRC	Joint Research Centre
kcal	Kilocalorie
kg	Kilogram
kWh	Kilowatt hour
lb	Pound
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LHV	Lower Heating Value
LNB	Low NO_x burner
m	Meter
m^3	Cubic meter
mg	Milligram

MIT	Massachusetts Institute of Technology
mmBTU	Million British Thermal Units
MMO	Chamber of Mechanical Engineers
MPa	Megapascal
Mtoe	Million Tons of Oil Equivalent
MW	Megawatt
MWh	Megawatt Hour
NMVOC	Non-Methane Volatile Organic Compound
OFA	Overfire Air System
OS	Overfeed Stoker
PC	Pulverized Coal
PFBC	Pressurized Fluidized Bed Combustion
PM	Particulate Matter
R/P	Reserves to Production
SCR	Selective Catalytic Reduction
SETAC	Society of Environmental Toxicology and Chemistry
TEP	Tons of Oil Equivalent
TKİ	Turkey Directorate General of Coal Enterprises
TTK	Turkish Hard Coal Enterprise
TÜİK	Turkish Statistical Institute
UNEP	United Nations Environment Programme
US EPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound
WebFIRE	Factor Information Retrieval Data System
YDD	Yaşam Döngüsü Değerlendirmesi

1. INTRODUCTION

Achieving sustainable consumption and production in the country requires a holistic approach towards increasing energy and resource efficiency and reducing greenhouse gas (GHG) and other emissions not only in the manufacturing phase of the products but throughout their entire life cycle. In this regard, life cycle assessment (LCA) approach allows for evaluation of environmental performance of various industrial sectors as a whole and on product or service basis and development of improvement strategies and preventive measures based on those results.

The currently practiced four-stage LCA methodology was first defined by the Society of Environmental Toxicology and Chemistry (SETAC) in 1991 and its principles and framework were standardized in ISO 14040:1997, ISO 14041:1999, ISO 14042:2000, ISO 14043:2000 which were later amended with ISO 14040:2006 and ISO 14044:2006 (ISO, 2006a; ISO, 2006b; SETAC, 1991). As a data-intensive methodology, the quality of an LCA study and reliability of its results strongly depend on the quality of the inventory data used in the analysis. Since the entire life cycle of even the simplest products include a large number of processes and sub-processes, numerous national, private and sector-based life cycle inventory (LCI) databases have been developed around the world to support LCA practitioners. These databases provide required background processes for the product system under analysis, while practitioners focus on development of core processes of their studies.

Up until now, LCA studies conducted in Turkey relied on foreign databases that did not accurately reflect production conditions of the country, leading to high levels of uncertainty in the results. The primary barrier in developing country-specific LCA datasets is the insufficiency of consistent inventory data needed for generating the processes. In the past decade, this issue has become particularly acute in the energy sector as more and more companies had been privatized and obtaining process data has become problematic. Since, energy processes are directly or indirectly utilized in almost all industry sectors and constitute the major portion of products' environmental impact, developing accurate country-average energy datasets is essential and will serve as a foundation of the future national LCI database of Turkey.

In this study, an alternative approach is employed to develop electricity production from lignite and electricity production from hard coal LCA processes for Turkey, without using directly measured power plant emission data. The amounts of key air pollutants required for developing the processes are instead calculated theoretically, using the emission factors (EF) of the United States

Environmental Protection Agency (US EPA) and the information gathered on the coal combustion and emission control technologies utilized in individual lignite and hard coal power plants as well as the properties of fuel used at each plant. The calculated emission values are then used to develop the average lignite and hard coal electricity production processes of Turkey, using corresponding datasets from the Ecoinvent database as templates. The developed processes are then compared with their Ecoinvent counterparts using LCA methodology in order to test whether the processes generated based on theoretically calculated values are close to the processes currently available in Ecoinvent database.

2. BACKGROUND AND LITERATURE REVIEW

In this chapter, the energy outlook of Turkey is first discussed, with particular emphasis on hard coal and lignite reserves of the country. Further, coal combustion and emission control technologies that are relevant to the study are reviewed. Finally, life cycle inventory (LCI) databases are addressed in detail by providing examples from prominent LCI databases from around the world to support the discussion.

2.1. Energy Outlook of Turkey

According to the Statistical Review of World Energy Report published by British Petroleum, the primary energy consumption of Turkey has increased by 9.5% in the year 2017, while the average growth in the past decade had been 4.4% (British Petroleum, 2018). Meanwhile, according to 2016 data released by the General Directorate of Energy Affairs under the Ministry of Energy and Natural Resources of Turkey (ETKB), 88% of primary energy supply is obtained from fossil fuels while 12% comes from renewable resources. As a net energy importer, 83% of primary energy supply of Turkey is met through imports, of which 45% is petroleum, 34% is natural gas and 21% is hard coal. The graph depicting primary energy supply by source, prepared based on 2016 National Energy Balance Table published by ETKB is given in Figure 2.1.

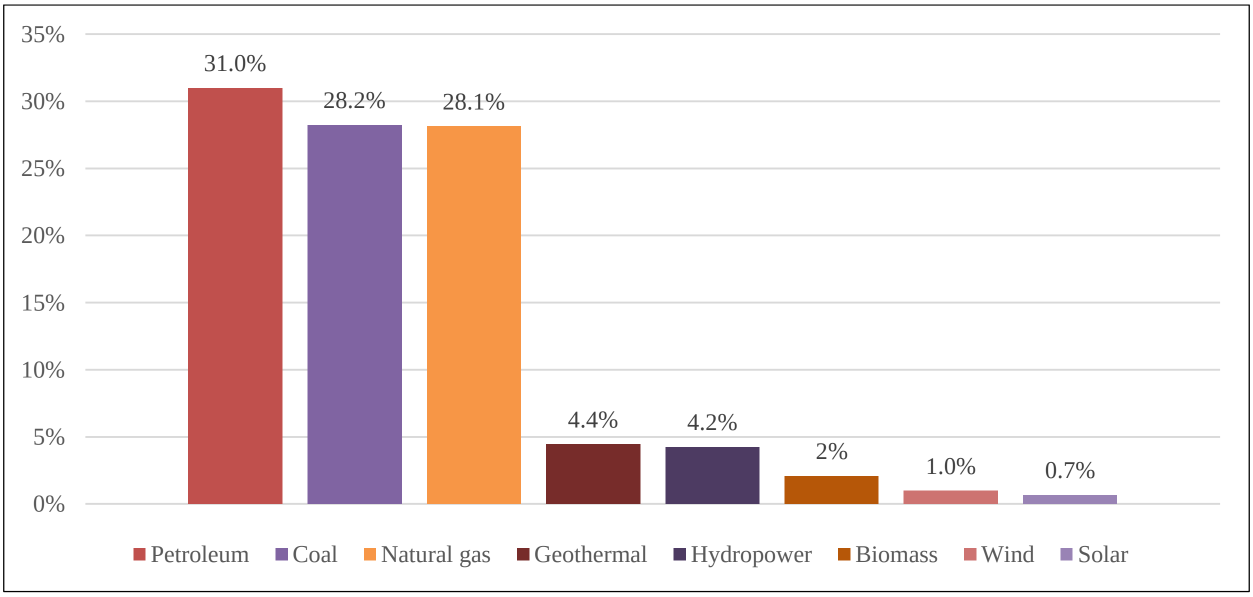

Figure 2.1. Percent distribution of energy sources in primary energy supply (EİGM, 2016).

In terms of electricity production, the total installed capacity of the country had reached 85,200 MW by the end of 2017, which corresponded to 110% increase compared to the year 2006. Thermal power plants constitute more than half of the installed capacity (54%) while hydropower and other renewable resources (wind, solar and geothermal) constitute 32 and 14% of the total, respectively (EPDK, 2017). Detailed source-based distribution of installed capacity is given in Figure 2.2.

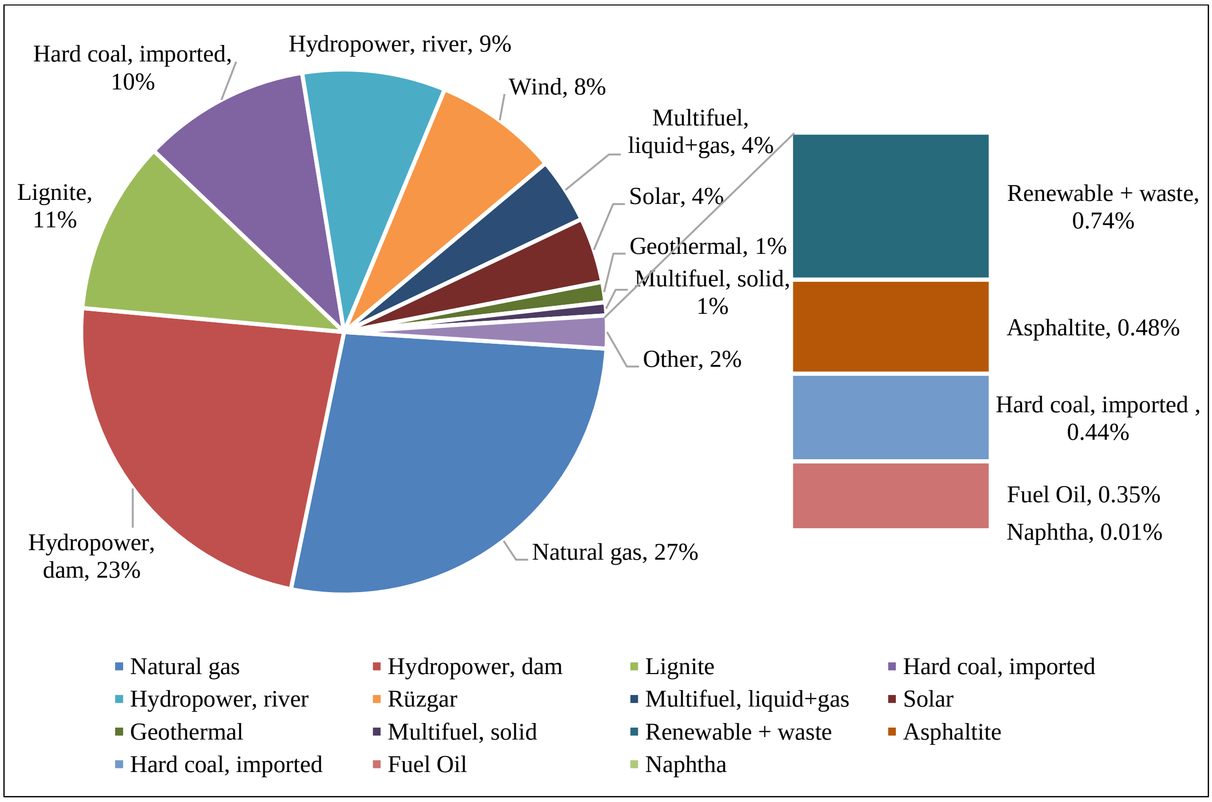

Figure 2.2. Installed power capacity by source (EPİAŞ, 2016; TEİAŞ, 2017a).

Meanwhile, the share of private sector in the total installed capacity of Turkey has increased drastically in the past decade, reaching 75% in 2017 (Figure 2.3), which might pose additional challenges in obtaining inventory data for energy production processes (EPİAŞ, 2016; TEİAŞ, 2017a).

Electricity production and consumption in Turkey had reached 295,606 GWh and 292,004 GWh, respectively (EPİAŞ, 2016). At the same time, the Electrical Energy Demand Projection Report prepared by the Ministry of Natural Resources of Turkey, predicts between 24 to 37% increase in demand for electrical power from the year 2017 to 2023 (TEİAŞ, 2017b). Turkey also imports electricity directly, depending on the annual demand and energy prices. In 2017, the total of 2,729,060 MWh electric power was imported from Bulgaria, Georgia, Iran and Greece with 76.02%, 18.08%, 5.88% and 0.02% from each, respectively. (EPDK, 2017). The losses during transmission were estimated to be approximately 2-2.5% according to 2016 data released by the Turkish Electricity Transmission Corporation.

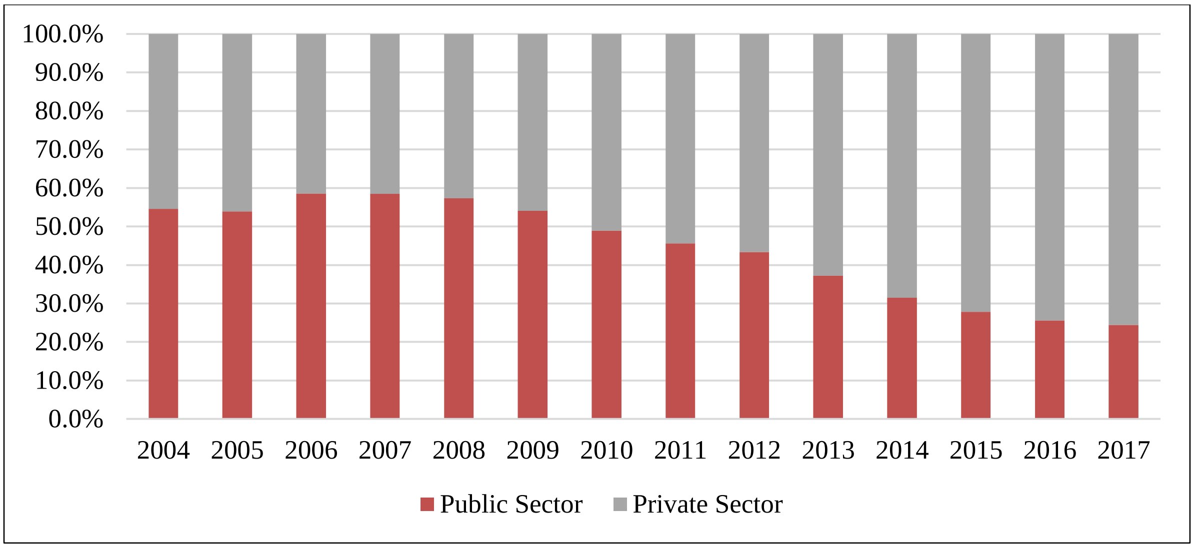

Figure 2.3. Distribution of installed capacity ownership in Turkey (TEİAŞ, 2017c).

2.2. Energy Production from Coal in the World and in Turkey

Coal is on the of the most abundant fossil fuels used around the world and in Turkey containing 90% of the fossil fuel energy, globally (Thakur, 2017). It is also one the most polluting energy feedstock, resulting in not only emission of GHGs but, also significant amounts of sulfur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter (PM) (Energy Information Administration, 2019). The following two sections take a closer look at the energy production from coal in the World and in Turkey.

2.2.1. Energy Production from Coal in the World

The current annual world coal consumption is 7,800 million tons, which is primarily utilized in power generation, iron and steel production and cement manufacturing industries. The coal that currently supplies roughly 40% of the world's electricity is projected to remain the primary source for electric power generation for the next 30 years (World Energy Council, 2016). The figure provided by the International Energy Agency also illustrates that the dominating share of coal in electric power generation has essentially remained unchanged in the past 40 years (Figure 2.4). The current coal reserves of the world are enough to meet 150 years of the total global production with approximately three times the reserves to production (R/P) ratio of gas and oil. In terms of regional abundance, Asia Pacific has the largest available reserves (46.5% of global reserves).

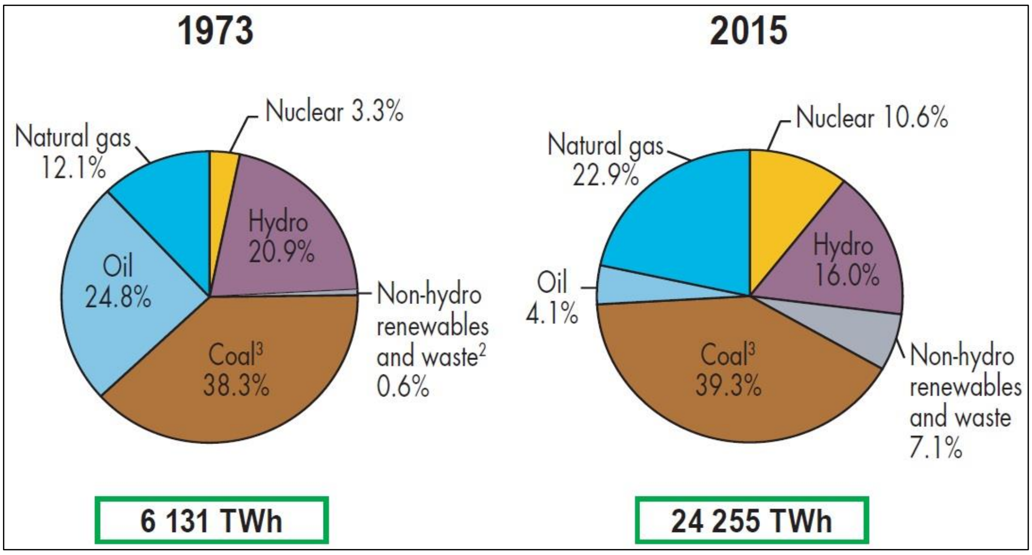

Figure 2.4. 1973 and 2015 source shares of electricity generation (IEA, 2017).

The United States (US) is the largest holder of coal reserves in the world (22.1%), followed closely by China (21.4%). However, in terms of annual consumption values, China is by far the largest consumer of coal, followed by India and US, as seen in Figure 2.5.

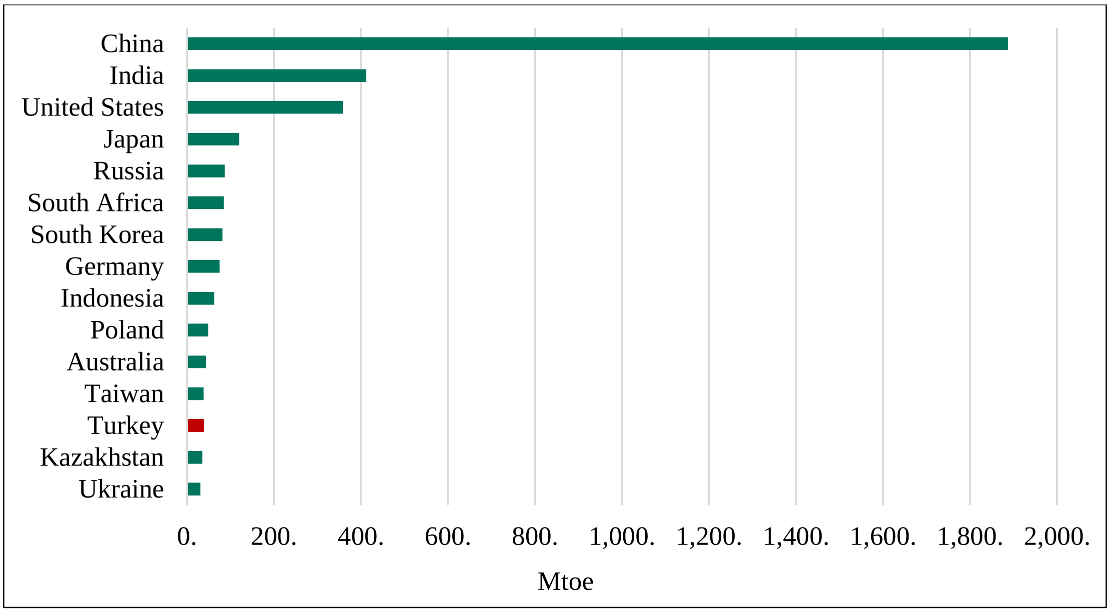

Figure 2.5. Worldwide coal consumption by countries in 2016 (BP, 2018).

2.2.2. Energy Production from Coal in the World

Lignite coal with relatively low calorific value formed during the third geological period constitute the major portion of Turkey's fossil fuel reserves, with much lower amount of hard coal, primarily found in Zonguldak basin of Carboniferous age (Ediger et al., 2014). This section reviews the lignite and hard coal reserves and energy production from these sources in Turkey as well as the hard coal imported into the country.

2.2.2.1. Lignite Resources of Turkey. The main lignite reserves of Turkey are Elbistan, Soma (Manisa), Tunçbilek, Seyitömer, Tavşanlı (Kütahya), Yatağan (Muğla) and Çan (Çanakkale). Due to its low calorific value, high ash and moisture content it is mostly utilized as fuel in thermal power plants. Roughly 70 million tons of lignite with total energy value of 14 million TEP was produced in Turkey in 2016, over 85% of which was utilized for electricity production (EİGM, 2016; ETKB, 2019). The calorific value of lignite found in the country ranges between 1,000 and 5,000 kcal/kg and more than half of the total reserves has a calorific value below 2,000 kcal/kg), as seen in Figure 2.6**.** Distribution of coal reserves and corresponding power plants in Turkey are shown in Figure 2.7.

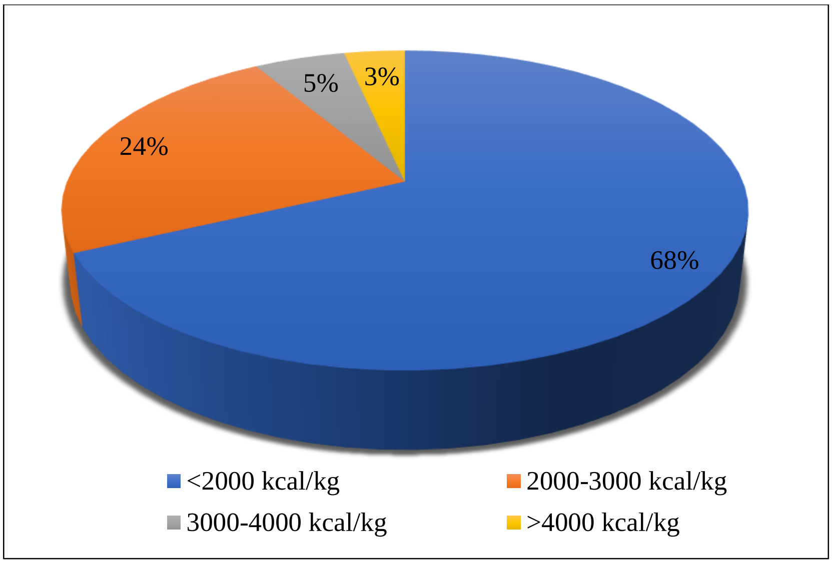

Figure 2.6. Calorific value of lignite reserves in Turkey (ETKB, 2019).

According to the General Directorate of Energy Affairs of Turkey, 88% of lignite was utilized for electricity production in the year 2016, while 5% was used in various industries, another 5% for residences and services and the remaining 2% was used for heat production (EİGM, 2016).

In terms of ownership, Turkey Directorate General of Coal Enterprises (TKİ) and Electricity Generation Company (EÜAŞ) had 31% and 17% share in lignite production, respectively, while private sector possessed the 52% by the year 2016 (ETKB, 2019). The percentage of state ownership in the sector has dropped significantly in the past two decades; TKİ’s share dropped from 85% to 31% in the last 20 years while EÜAŞ’s share dropped from 50% to below 20%. The change in percent share of lignite production among organizations between 2011 and 2016 is given in Figure 2.8.

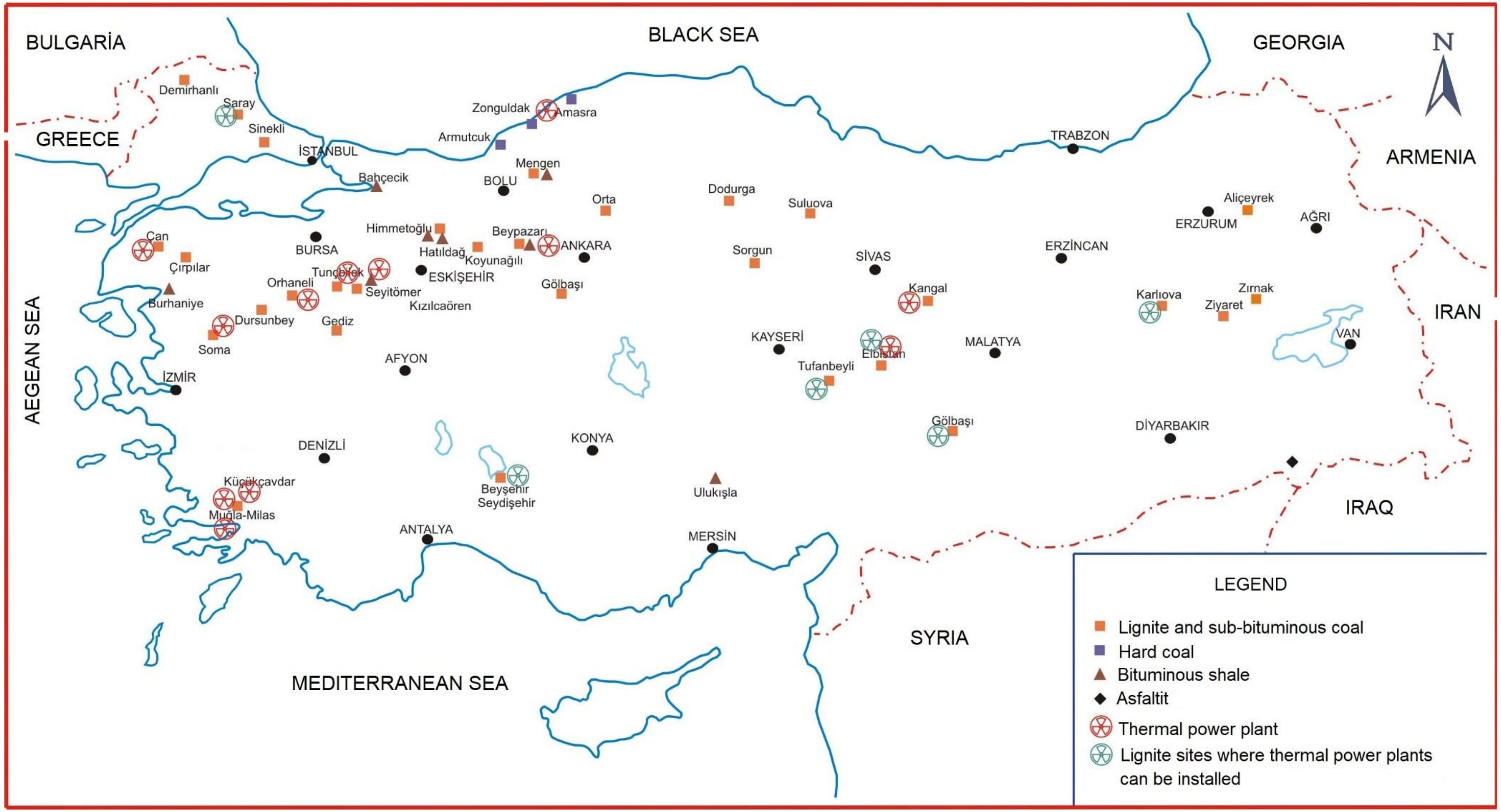

Figure 2.7. Coal reserves of Turkey (MTA, 2019).

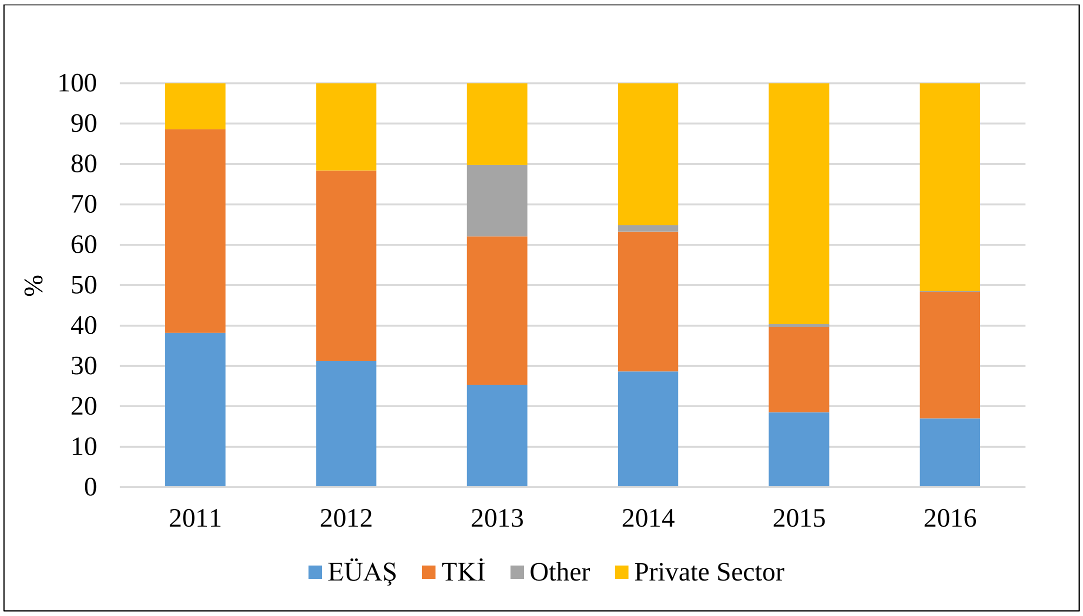

Figure 2.8. Distribution of lignite producers by total production volume (ETKB, 2019).

2.2.2.2. Hard Coal Resources of Turkey. The most significant hard coal reserves of Turkey are in the Zonguldak coal field. Field explorations performed in the region up to 1,200 m depth has revealed 1.5 billion tons of geological coal reserves, roughly half of which is considered to be visible reserves. The hard coal reserves of Turkey are given in Table 2.1. The coking coal constitutes 57% of the total reserves (TTK, 2018).

Table 2.1. Hard coal reserves of Turkey by region (thousand tons) (TTK, 2018).

Reserves	**Armutçuk**	**Kozlu**	**Üzülmez**	**Karadon**	**Amasra**		**Total**
					A	**B**	
Ready	1,909	3,321	3,321	1,849	440	-	7,901
Visible	6,175	63,053	133,756	130,855	4,160	395,955	733,954
Probable	15,860	40,539	94,342	159,162	3,694	151,162	464,758
Possible	7,883	47,975	74,020	117,034	7,758	58,813	313,483
Total	31,827	154,888	302,501	408,900	16,051	605,929	152,010

Hard coal in Turkey is primarily utilized for electricity production and it's share in total electricity production has been increasing in the past five years. In 2016, 49% of all hard coal consumed in the country was used for electricity production, while the remaining 16% and 15% were used in industry and coke ovens, respectively (TTK, 2018).

Turkey is a net importer of hard coal. Only 3.29% of the 37,475,000 tons of hard coal consumed in 2017 was met by domestic resources and the rest was imported mainly from Russia and Columbia and several other countries. The only thermal power plant running on domestic hard coal is Çatalağzı power plant with 315 MW installed capacity. Additionally, Silopi power plant with 405 MW installed capacity located in Şırnak is using domestic asphaltite as fuel. Combined together, the two power plants accounted for 2% of total electricity production of the country in 2016 (TEİAŞ, 2017b; TTK, 2018). In 2017, the total installed capacity of power plants running on imported hard coal has reached 8,794 MW which constituted 10.5% of total installed capacity. The share of power plants using imported hard coal in terms of installed capacity and electricity production in the past ten years is illustrated in Figure 2.9.

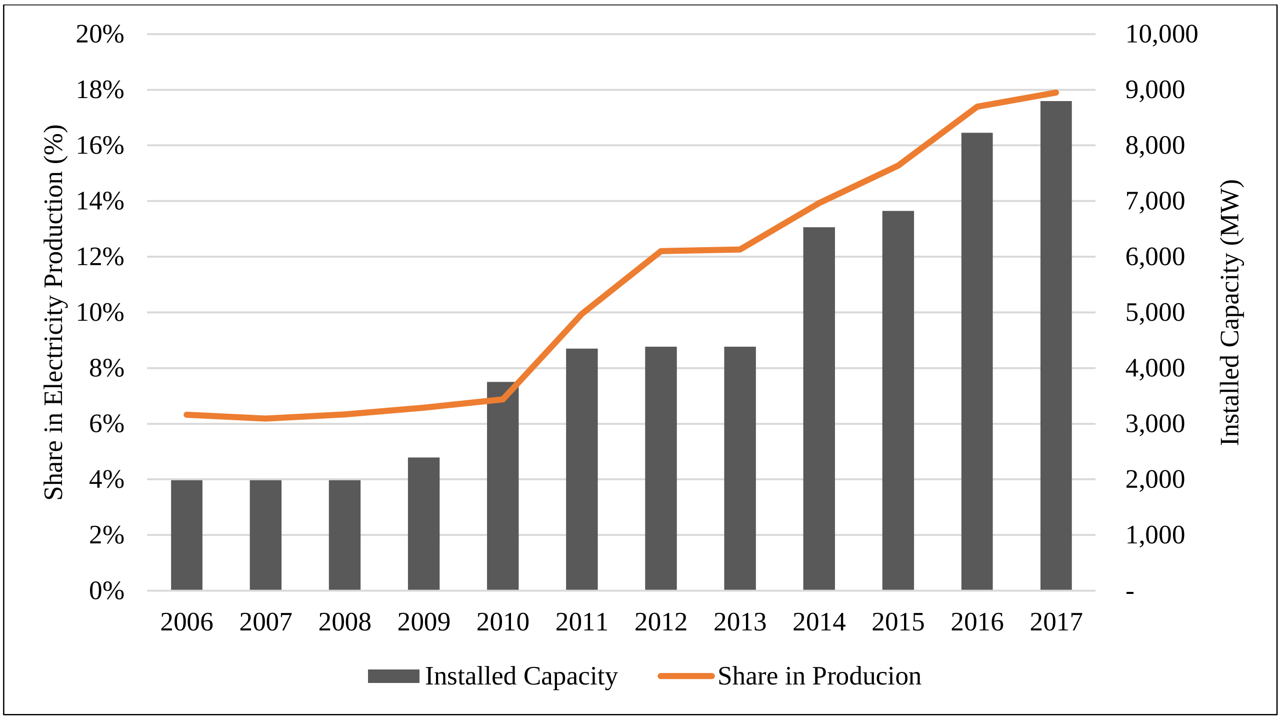

Figure 2.9. Thermal power plants utilizing imported hard coal in Turkey. (EPDK 2017; TEİAŞ, 2017b).

In terms of ownership of domestic hard coal reserves, unlike for lignite, the state-owned Turkish Hard Coal Enterprise (TTK) accounts for the majority of production. Despite the increase in coal production by private companies and parallel decrease in TTK's production between 2000 and 2008, the public sector's share was 67% in 2017 and the remaining third was owned by the private companies (Figure 2.10).

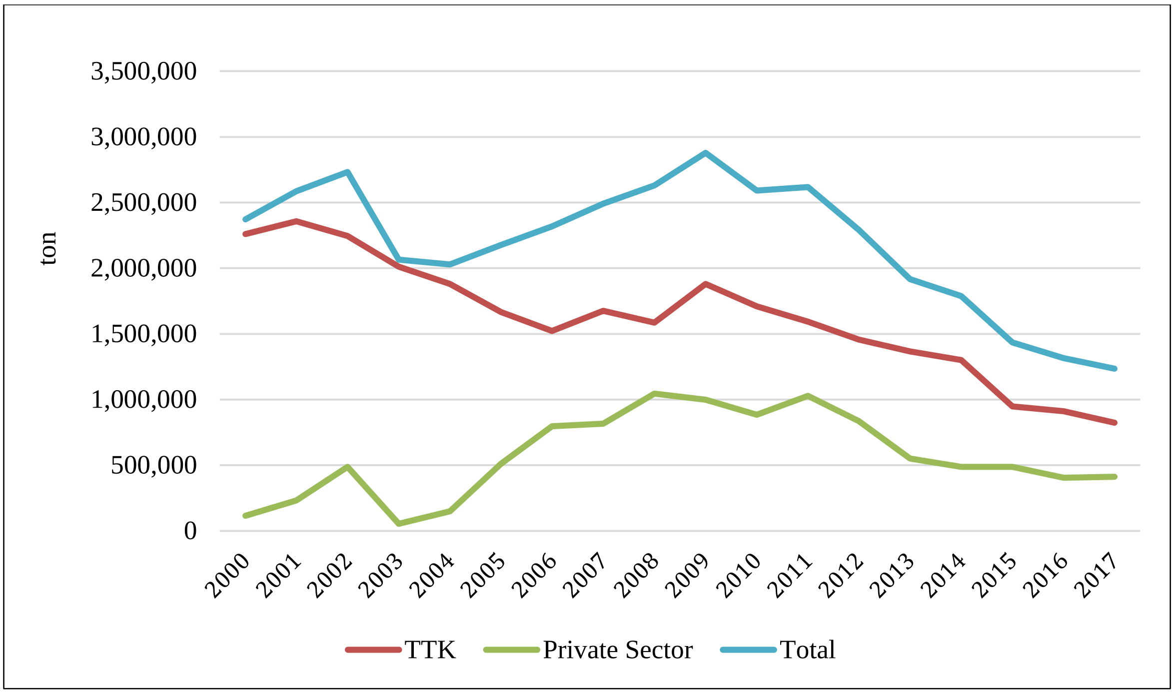

Figure 2.10. Domestic hard coal production by public and private sectors

2.3. Electricity Production and Emission Control Technologies

The coal types, coal combustion technologies and associated boiler types used in electricity production and emission control technologies applied at thermal power plants that are utilized in Turkey and are relevant to the conducted study are discussed in this section.

2.3.1. Types of Coal

Coal is a black/brownish-black sedimentary rock composed primarily of carbon and hydrocarbons that can be utilized to produce electricity. It is found in all continents across the globe in underground formations called “coal beds” that can be up to 30 m thick and stretch for 1,500 km (Energy Information Administration, 2018). The coal is ranked based on its carbon content and calorific value, and therefore on the amount of heat it produces, from lignite to anthracite (Laney and Attfield, 2014). The main properties of each coal types are explained below:

- Lignite: Also knowns as brown coal, is the lowest ranked coal in terms of energy value with carbon content of 25-35% and obtained from younger coal deposits (~250 million years old). It’s primarily used to generate electricity.

- Subbituminous coal: Has higher calorific value than lignite with carbon content of roughly 35-45%. It is obtained from 100-million-year old coal deposits and primarily used in electricity production
- Bituminous coal: Formed between 100 to 300 million years ago under higher temperature and pressure compared to lignite and subbituminous with carbon content ranging from 45 to 85%. It’s used both in electricity production and steel and iron industries.
- Anthracite: Formed under high temperature and pressure, with oldest deposits dating back 400 million years, anthracite has the highest calorific value among coal types with carbon content of up to 97%. Due to its high value it is rarely utilized for electricity production and instead used house heating in stoves, industrial furnaces and in steel and iron production (Energy Information Administration, 2018; Mulvaney, 2010; USGS, 2019).

2.3.2. Electricity Production from Coal

Electricity production technologies from coal can broadly divided into two group; conventional methods that use pulverized coal (PC) as a feedstock and advanced methods that include a wide range of methods such as Integrated Gasification Combined Cycle (IGCC), cogeneration, also known as combined heat and power (CHP), underground coal gasification and other clean coal technologies. This section will deal only with conventional methods since only these technologies are currently being applied in thermal coal power plants in Turkey.

In conventional PC combustion systems, the coal is first grinded into small powder in order to increase the surface are of the fuel and therefore the burning efficiency. The fine powdered coal is then blown into the combustion chamber where it’s burnt at high temperature, resulting in production of high-energy gases and heat. These heat up the water running through pipes within the boiler, turning it into high-pressure steam. The steam is then used to propel the turbine attached to generator at high speeds which produces electricity. The cooled down steam is converted back to water and returns to boiler pipes to continue the cycle. The main components of a conventional PC combustion system are shown in Figure 2.11. PC combustion technologies can be divided into subcritical, supercritical and ultra-supercritical systems. These technologies differ in terms of operating steam pressure within the boiler which affects the efficiency of the power plants and associated air emissions. Additionally, fluidized bed combustion (FBC) technology where fuel particles are suspended in upward moving fluid stream is also widely applied in coal power plants. The details of these technologies are described in the following subsections.

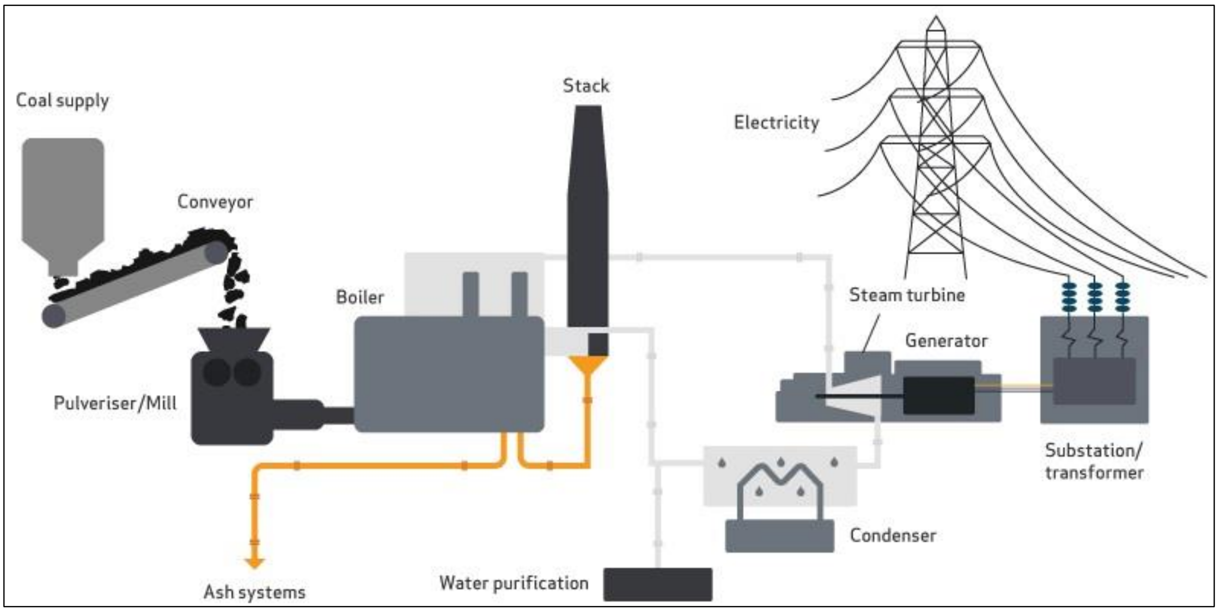

Figure 2.11. Conventional PC combustion system (World Coal Association, 2013).

2.3.2.1. Subcritical, Supercritical and Ultra-Supercritical Combustion. Higher thermal efficiency and lower emissions per unit of electric power generated can be achieved through supercritical and ultra-supercritical coal combustion technologies compared to conventional subcritical technology. This is achieved through higher operational temperature and pressure, which allows the water to remain in supercritical state within boilers and thus eliminating the need for water-steam separation (Susta and Seong, 2004). The operational conditions and efficiencies of subcritical, supercritical and ultra-supercritical power plants are summarized in Table 2.2. Korea and Japan lead in application of supercritical technology which constitute roughly 70% of coal-fired power plants in terms of total electricity generated. Ultra-supercritical technology is being applied in Denmark, Germany, Italy and Japan but it’s share in total production remains low (Burnard and Bhattacharya, 2011).

Table 2.2. Properties of subcritical, supercritical, and ultra-supercritical technologies (Nalbandian, 2008).

PC unit	**Main steam temperature (°C)**	**Main steam Pressure (MPa)**	**Reheat steam temperature (°C)**	**Net efficiency (%, LHV base)**
Subcritical	Up to 565	<22.1	Up to 565	35-41
Supercritical	540-580	22.1-25	540-580	38-44
USC	>580	>25	>580	>44

2.3.2.2. Fluidized Bed Combustion (FBC). In FBC boiler technology, the coal is scattered and burned in a fluidized bed of inert particles such as sand or limestone. The solid coal particles are suspended in upwards moving currents of air throughout the combustion process, increasing the efficiency of the reaction. The operational temperature of the bed is most commonly maintained between 750 °C to 1000 °C in order to drive the reaction to completion (Dryden, 1982). There are two main types of FBC, atmospheric fluidized bed combustion (AFBC) and pressurized fluidized bed combustion (PFBC), which are further classified into bubbling fluidized bed combustion (BFBC) and circulating fluidized bed combustion (CFBC) (Sarkar, 2015). Among these, atmospheric CFBC is by far the most widely utilized technology in the world because it can be applied to wide range of fuel categories (Burnard and Bhattacharya, 2011). FBC technologies offer several environmental advantages compared to standard PC technologies. This includes lower SO_x emissions since those can be captured using sulfur-absorbing chemicals such as limestone or dolomite (a double carbonate of calcium and magnesium) within the boiler (Miller, 2005). Additionally, since coal is burned at temperatures below the threshold temperature at which NO_x (~1,370 °C) are formed, NO_x emissions are also lower (Hardy et al., 2007).

2.3.3. Emission Control Technologies

Environmental impacts associated with combustion of coal are primarily associated with CO_2 and other GHGs, SO_x, NO_x and PM emissions. Different emission control technologies directed at reducing these emissions have been developed and are being implemented in coal power plants. The main technologies are flue gas desulfurization (FGD) for SO_x, denitrification ($DeNO_x$) for NO_x, electrostatic precipitator (ESP) and baghouse for PM and carbon capture and storage (CCS) technologies for CO_2 emissions.

2.3.3.1. Flue Gas Desulfurization (FGD). FGD, also known as scrubbing, is a technology utilized at thermal power plants to remove the SO_x emissions from flue gas formed as a result of combustion. FGD is a highly efficient and economic method of removing SO_2 and other oxides of sulfur from flue gas using high-calcium based sorbents such as lime or limestone. Alternative reagents such as magnesium oxides, manganese oxides, ammonia, sodium, sea water and others are also being researched, tested and applied (Salehi et al., 2019; Sun et al., 2008; Ye et al, 2013). The subtypes of FGD technology include wet, semi-dry and dry systems. Wet lime or limestone FGD installations are by far the most widely applied desulfurization technology in the world representing roughly 80% of all units, based on total installed capacity (Nolan, 2000). The main reason behind wide-spread application of wet scrubbers is the high SO_x removal efficiency (up to 99%) (National Lime

Association, 2019). Wet systems are typically applied in large and medium-scale power plants whereas semi-dry and dry systems are mostly used in medial to small-scale plants. The reactions for wet lime and limestone scrubbing are shown in Equations 2.1 and 2.2, respectively (Pimenta, 2010).

$$Ca(OH)_2\ (s) + SO_2\ (g) \Rightarrow CaSO_3\ (s) + H_2O\ (l) \tag{2.1}$$

$$CaCO_3\ (s) + SO_2\ (g) \Rightarrow CaSO_3\ (s) + CO_2\ (g) \tag{2.2}$$

It has to be noted that in addition to SO_2 and other SO_x emissions, FGD systems are also responsible for removal of condensable portion of PM emissions as well as HCl and mercury (Cai et al., 2012; Diao et al., 2018; Li et al, 2017).

2.3.3.2. Denitrification (DeNO$_x$) and Low NO$_x$ Burner (LNB). Burning of coal in the boiler produces NO, NO_2 and other oxides of nitrogen, collectively referred to as NO_x. These emissions cause a wide range of negative environmental impacts, including acid rain, eutrophication of water bodies and formation of photochemical smog in the troposphere. The most commonly applied technology at coal power plants for reducing these emissions selective catalytic reduction (SCR) process that catalytically converts NO_x to N_2 and water in presence of NH_3 (Mladenović et al., 2018). Thy system typically consists of ammonia storage, evaporation, injection and distribution units and SCR catalytic reactor. Ammonia is either fed as evaporated NH_3/air mixture or in aqueous form. The temperature in the catalytic reactor is maintained in 300-400 ^oC range since NH_3 reacts with SO_2 and SO_3 at lower temperatures, forming ammonium sulfate and bisulfate which can plug the equipment (Indreco, 2019). The DeNO$_x$ unit can be installed upstream of ESP in “high-dust” configuration, downstream of ESP in “low-dust” configuration or further downstream of FGD unit in “tail-end” configuration. The reduction of NO_x gases in SCR unit occurs through the following reactions, described in Equations 2.3, 2.4 and 2.5 (Schreifels et al., 2012). Efficiency of DeNO$_x$ units vary but was reported to be in 80-90% range by Institute of Clean Air Companies (ICAC, 2009).

$$4NO + 4NH_3 + O_2 \Rightarrow 4N_2 + 6H_2O \tag{2.3}$$

$$NO + NO_2 + 2NH_3 \Rightarrow 2N_2 + 3H_2O \tag{2.4}$$

$$2NO_2 + 4NH_3 + O_2 \Rightarrow 3N_2 + 6H_2O \tag{2.5}$$

Additionally, LNBs are utilized in coal power plants to reduce the NO_x emissions at source. Since, thermal NO_x is the result of high-temperature combustion, this task is achieved by creating bigger and more branched flames at each burner by controlling the fuel and air mixing process which reduces the availability of oxygen at the hottest parts of the flame (IEA Clean Coal Centre, 2019). LNBs are most commonly adopted with air staged combustion in the main combustion zone in order to prevent fuel-NO_x conversion and to reduce the release of NO_x in flame (Zhou et al., 2019).

2.3.3.3. Electrostatic precipitator (ESP) and baghouse. ESP and baghouse are the two most commonly used technologies for removal of dust in coal-fired power plants. ESP is a type of dry scrubber that utilizes static electricity to remove PM from flue gas. The flue gas is passed through two electrodes in the shape of wires, plates or bars depending on specific installation. One of the plates charges the particles with high negative charge and the other one, that possesses net positive charge, attracts these particles, removing them from flue gas. Since, coal burned in different regions vary in terms of their ash content and other key properties, different variations of ESP have been developed to meet the specific needs of the power plants. The modern ESP installations are highly efficient, removing up to 99.9% of PM, depending on particulate size. In general, both large (>1 μm) and ultrafine particles (<0.1 μm) can be efficiently removed by EPS but, intermediate-sized particles ($PM_{2.5}$) are most problematic to charge and hence have lower removal efficiency (Pui et al., 2014).

A baghouse, also known as fabric filter is an emission control device that removes PM from flue gas stream. In this system, the gas is directed into baghouse that consists of series of porous textile fabric that retain and collect the particles. The trapped PM forms a layer over the filters known as dust cake. The filters are cleaned periodically with self-cleaning mechanism such as pulse-jet, reverse air or shaker (Industrial Accessories Company, 2019). With 99.7% removal efficiency, baghouses are more effective in eliminating $PM_{2.5}$ emissions than ESP systems (Pui et al., 2014).

2.3.3.4. Carbon Capture and Storage (CCS). CCS is an umbrella term that refers to a group of technologies that are used to capture the CO_2 emitted from large point-sources, such as thermal power plants. A CCS system consists of three main stages, namely, capture, transportation and storage of captured carbon dioxide underground The capture technologies can be further divided into pre-combustion capture, post-combustion capture and oxyfuel com-bustion method (Carbon Capture and Storage Association, 2019). While these technologies help reduce the carbon footprint of power plants, this reduction comes at a cost; the efficiency of the power plant is also reduced due to loss of energy at various stages of CCS. This loss in efficiency is primarily associates with energy spent to recover CO_2 from the solution and energy required to compress the CO_2 for storage (Cebrucean et al., 2014; MIT, 2007).

2.4. Life Cycle Inventory (LCI) Databases

An LCI database is defined by the United Nations Environment Programme (UNEP) as a system intended to organize, store, and retrieve large amounts of digital LCI datasets that fully or partially conforms to a common set of criteria, including methodology, format, review, and nomenclature that can be accessed to perform LCA studies (UNEP, 2011). These datasets represent unit or aggregated processes from wide range of industries and energy sector and contain quantitative input/output and impact assessment data, along with descriptive metadata. This section describes the importance of country-specific datasets and development of a national LCI database and elaborates on currently available international databases in the world.

2.4.1. Significance of Developing a National LCI Database

LCA approach allows for evaluation of environmental performance of various industrial sectors as a whole and on product or service basis, expression of obtained results in terms of national or international performance indicators and development of improvement strategies and preventive measures based on those results. However, such evaluation via LCA requires inventory information from many sources that is laborious to obtain for most practitioners and along with current data gaps and bureaucratic barriers associated with obtaining the data, poses a significant impairment for these efforts. Moreover, in most cases, inventory data required for LCA studies on national scale come from different governmental, non-governmental and private sources, which vary in terms of data quality, level of detail as well as temporal and spatial parameters. Establishing a national database helps overcome the abovementioned obstacles by a providing an accurate, up-to-date, expert-reviewed, consistent process inventory data in a standard format that accurately reflect real production conditions of the country. Providing systematically stored and consistent inventory data from a single source to LCA practitioners is expected to significantly cut down on time and labor spent in inventory analysis phase of the studies and reduce the uncertainty level of the final results (UNEP, 2011).

Energy production processes constitute the core of almost all LCI databases for two main reasons. First, electricity production and primary energy carrier processes (natural gas, hard coal, lignite, petroleum and petroleum derivatives) are directly or indirectly utilized in almost all industry sectors. Hence, assessing environmental burdens of chemicals, automotive, cement, textile and other significant industries of the country, as well as expanding the database in the future to encompass those sectors require the availability of energy processes as a minimum. The second reason for prioritizing energy processes is associated with the fact that the results of most LCA studies conduct for a diverse range of products and services around the world, point to energy processes as the main source of environmental burdens across all impact categories, with climate change prominent among them. Since, fossil fuels are the primary cause of climate change and other significant environmental impacts and since coal is the main domestic fossil fuel of Turkey, starting with development of coal processes is logical.

2.4.2. LCI Databases Around the World

Development of LCI databases was first initiated in Europe in 1980s, primarily by universities and research centers that focused on specific product groups and industrial sectors. The initial databases were disconnected, fragmented and not well organized. As the number of databases increase around the world, the need for common standards and guidelines have arisen (Jolliet et al., 2016). The first national LCI databases became available in early 2000s, with Switzerland, Germany and US databases considered the first ones among them. Since then, many more countries have developed their national databases and both the number of datasets within those database and diversity of sectors and products they cover have been increasing (Wolf, 2014). Currently, the most advanced national databases in terms of the number and quality of available datasets and data flow management are in Italy, Switzerland, Sweden, Australia, Canada, Taiwan, Japan, South Korea and US (Ali et al., 2014). The map developed by GreenDelta illustrating the state of dataset availability for individual countries is given in Figure 2.12. Regions with a darker shade have a higher number of processes, with Germany currently leading with over 45,000 processes.

Figure 2.12. Map of LCI databases in the world (Life Cycle Initiative, 2019a).

LCA network and database development and management efforts have been internationally endorsed and facilitated in the leadership of the UNEP and SETAC through International Life Cycle Partnership launched in 2002, known as Life Cycle Initiative. The "Global Guidance Principles for Life Cycle Assessment Databases" document released by the Initiative in 2011 provides guidelines on how to develop and manage LCI databases (Jolliet et al., 2016). Most recently, in 2008, the Initiative has launched the Global LCA Data Access Network (GLAD) comprised of independently-operated LCA databases which will improve the data accessibility and interoperability among databases (Life Cycle Initiative, 2019b). In addition to national and industry-specific databases, there are three most prominent international LCI databases with datasets from diverse group of sectors and countries, as discussed in the next subsections.

2.4.2.1. Ecoinvent Database. Ecoinvent database developed and operated by Ecoinvent Center, a Switzerland-based nonprofit organization. The latest version of the database (Ecoinvent 3.5) contains over 14,700 LCI datasets from wide range of products and industrial sectors including energy, transportation, agriculture, biofuels, chemicals, construction materials, wood, and waste treatment (Ecoinvent Association, 2019). Individual LCI datasets constitute the basic building blocks of Ecoinvent database, which are interlinked in a way that intermediate good inputs to processes (e.g. electricity consumption) are linked to other unit processes that supply these intermediate goods. The basic structure of the database is shown in Figure 2.13.

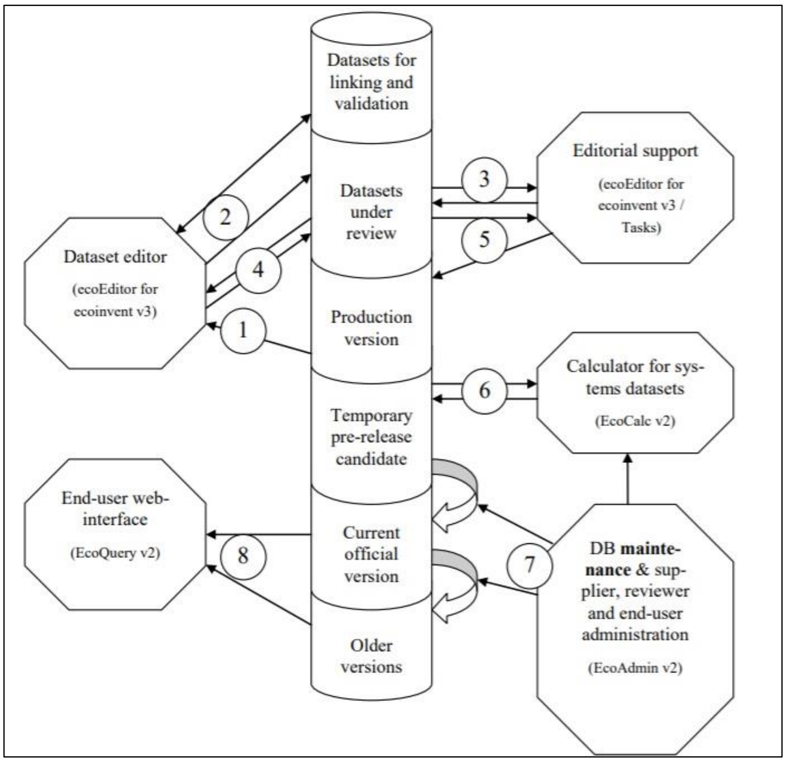

Figure 2.13. The basic structure of Ecoinvent database system (Weidema et al., 2011).

2.4.2.2. GaBi Databases. GaBi databases, developed by Thinkstep AG, collectively contain over 30,000 unit processes which have been interlinked to produce over 12,500 plans and LCI datasets available to users. The bulk of the datasets are in the GaBi Professional database which currently contains 3,888 processes and 95 plans, that are primarily either cradle-to-gate aggregated processes or parameterized unit processes. The sectors covered in the Professional database are the following:

- Organic and inorganic chemicals
- Metals
- Plastics
- Wood and wood products
- Power generation
- Transport
- Production techniques
- End of life processes (waste treatment)

In addition to Professional database, industry-specific databases including organic and inorganic intermediates, energy, steel, construction materials, electronics, plastics and bioplastics, textile, food and renewable raw materials are available. The Professional and additional databases are integrated to GaBi LCA software (Kupfer et al., 2019; Thinkstep, 2019).

2.4.2.3. European Reference Life Cycle Database (ELCD). ELCD was developed by the Joint Research Centre (JRC) of the European Commission. The latest version of the database (v.3) contains over 500 datasets from various industries including chemical and metal industries, energy production, transport and end-of-life processes. The entry-level data quality requirements for the ELCD database are laid out in the International Reference Life Cycle Data System (ILCD) Handbook published by the European Platform on Life Cycle Assessment (EPLCA) (SimaPro, 2019).

3. PURPOSE

The goal of the study is to create the “Electricity production from hard coal” and “Electricity production from lignite” LCA processes for Turkey and contrasting them with their counterparts in Ecoinvent database by conducting a comparative LCA analysis. Gate-to-gate processes will be created for hard coal and lignite that would represent the average electricity production conditions in Turkey from respective feedstock. The motivation behind developing these processes is threefold:

I. Verifying whether the novel approach utilized in the study, yields LCA processes that are comparable with corresponding processes currently available in Ecoinvent database and comparing their environmental impacts using LCA methodology.
II. Calculating the environmental burdens associated with electricity production from coal in Turkey using LCA methodology
III. Serving as an input for developing “Power grid mix” LCA process for Turkey, once processes for other energy sources, namely natural gas, hydropower, fuel oil, wind, solar, geothermal and biogas have also been developed

The most challenging aspect of developing country-specific LCA datasets is obtaining inventory data, which requires extensive emission data collection for each life cycle phase of the product or service. This problem is particularly acute in energy sector of Turkey; collecting emission data on power plant level needed for creating the datasets is problematic, especially for ones operated by private companies. Obtaining emission data from relevant government bodies such as the Ministry of Environment and Urbanization that collect controlled emissions from power plant operators is equally challenging due to confidentiality issues. On the other hand, general emission data reported by Turkish Statistical Institute (TÜİK) on national level lacks the essential details, transparency and flexibility required for generating useful LCA datasets.

The novel approach proposed in this study attempts to overcome the abovementioned challenges associated with data collection by estimating the key emissions for each coal-fired power plant in Turkey based on the fuel properties, combustion technology and emission control technologies applied at the plant, instead of collecting or measuring emissions directly. For this purpose, EFs for air pollutants from industrial processes in US EPA’s Web-based Factor Information Retrieval (WebFIRE) database are adopted for Turkish conditions by taking into account local fuel properties and fuel combustion and emission control technologies applied in hard coal and lignite power plants in Turkey.

Calculated key emissions are then used to develop electricity production from lignite and hard coal processes using corresponding processes in Ecoinvent 3.3 database as a template. Finally, created processes are used to calculate the environmental impacts of electricity production from coal in Turkey using LCA methodology and the results are compared with the ones obtained for corresponding processes in Ecoinvent database. The general procedure followed in the study is summarized in Figure 3.1.

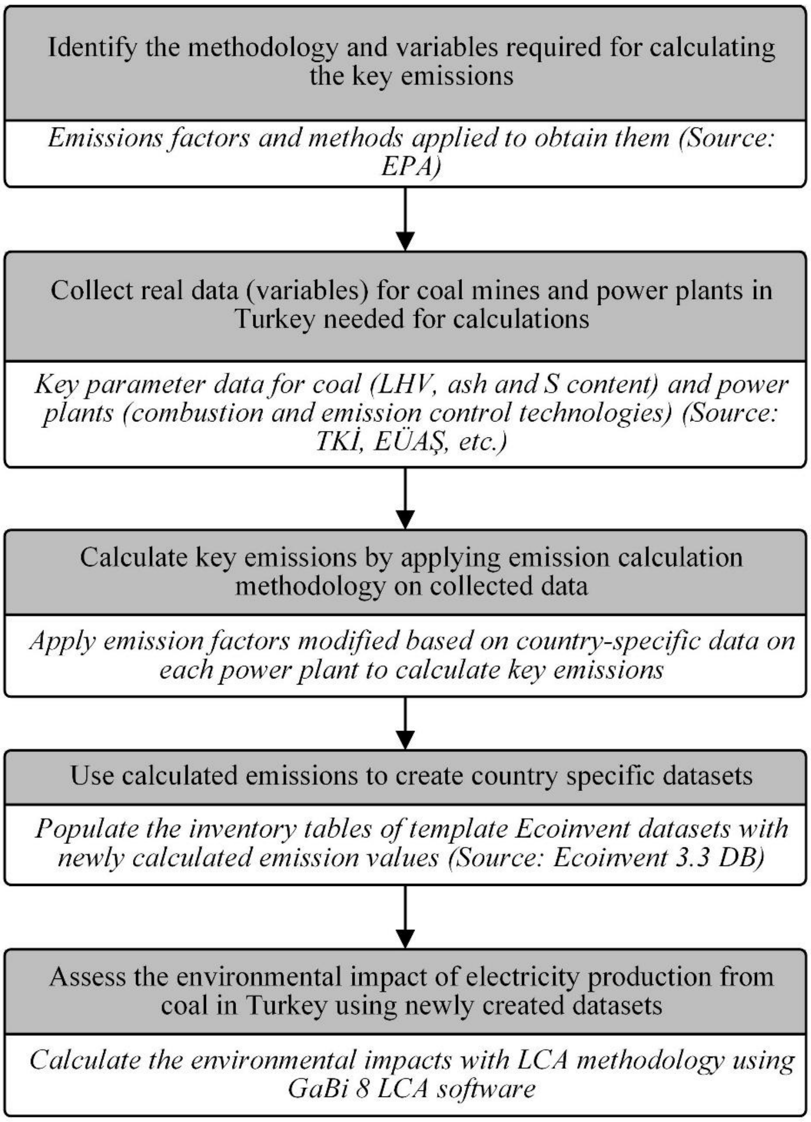

Figure 3.1. General procedure of the study.

4. MATERIALS AND METHODS

In this chapter, the procedures and calculations used for estimating key air emissions from coal power plants in Turkey and the methodology utilized for developing LCI processes using the estimated emission values are discussed in detail along with key assumptions and approximations applied in the study.

4.1. Terminology and Key Concepts

This section defines and clarifies the terminology and key concepts used throughout the document in order to facilitate the easier understanding of the manuscript and prevent confusion of the concepts.

4.1.1. Feedstock Classification

Two distinct processes for electricity production from coal feedstock will be developed within the scope of the study; “Electricity production from lignite” and “Electricity production from hard coal”, which is how these processes are classified in current LCI databases, including Ecoinvent database. The hard coal is further classified into anthracite, bituminous and sub-bituminous coal categories for choosing appropriate EFs from US EPA’s WebFIRE database, in accordance with ASTM D388-18 (ASTM, 2012). The list of terms used for feedstock classification is given in Table 4.1.

Table 4.1. Feedstock classification used in the study.

Term	**Description**
Coal	A general term, refers to all coal species including lignite, hard coal and hard coal subcategories. Within text, a "coal dataset" is a collective term describing both lignite and hard coal LCA datasets
Lignite	Refers to all lignite coal species, including Lignite A and B
Hard Coal	Refers to all hard coal species, including anthracitic, bituminous and subbituminous and their subcategories

4.1.2. Key LCA Terms and Concepts

The terms “LCA process”, “LCA dataset” and “unit/aggregated process or dataset” used throughout the study refer to a set of well-defined input/output tables, parameters and metadata that collectively describe a products or service. While in many instances these terms are used interchangeably, there are some key differences. Table 4.2. presents the current definitions of these and other key LCA terms as described in the “Global Guidance Principles for Life Cycle Assessment Databases” document (UNEP, 2011).

The scope of an LCA dataset varies based on life cycle phases that the given dataset covers. The most common types include:

- Cradle-to-grave; covers the whole life cycle of a product, from extraction of resources to end of use and disposal
- Cradle-to-gate; covers all stages from extraction of resources to manufacturing of product at plant/factory
- Gate-to-gate; covers only one value-added process in the product’s life cycle

These concepts are illustrated in Figure 4.1 (Simonen, 2014).

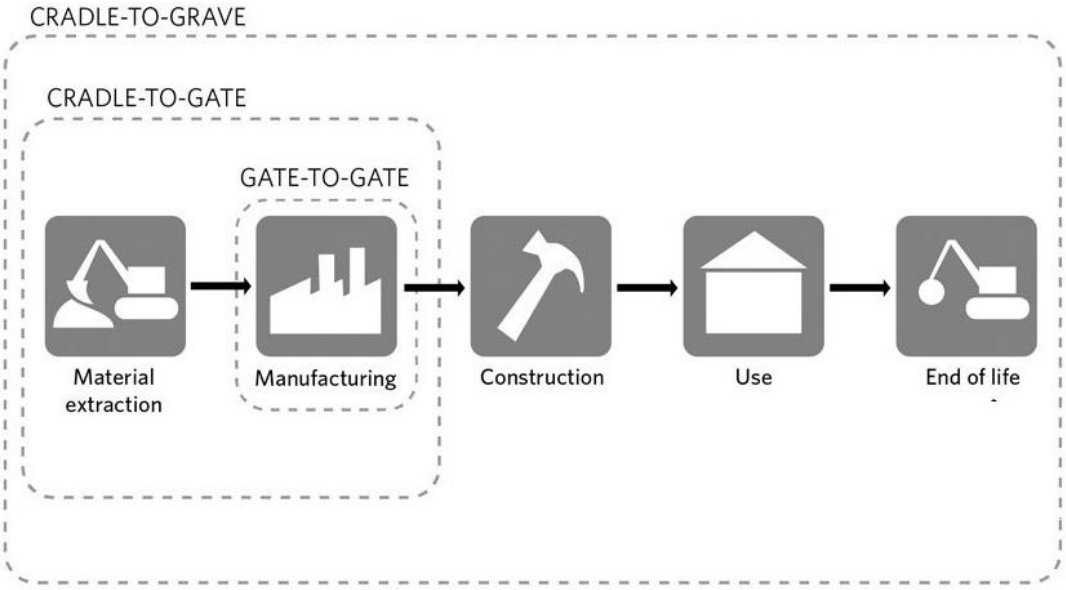

Figure 4.1. LCA variants based on covered life cycle phases.

Table 4.2. Key LCA terms.

Term	Definition	Reference
LCA process	Set of interrelated or interacting activities that transforms inputs into outputs.	ISO, 2005
LCA dataset	A document or file with life cycle information of a specified product or other reference (e.g. site, process), covering descriptive metadata and quantitative life cycle inventory and/or life cycle impact assessment data	European Commission, 2009
Unit process	Smallest element considered in the life cycle inventory analysis for which input and output data are quantified.	ISO, 2006b
Aggregated process	An activity dataset showing the aggregated environmental exchanges and impacts of the product system related to one specific product from the activity.	Weidema et. al., 2011
Background system/process	The background system consists of processes on which no or, at best, indirect influence may be exercised by the decision-maker for which an LCA is carried out. Such processes are called "background processes."	Frischknecht, 1998
Functional unit	Quantified performance of a product system for use as a reference unit	ISO, 2006b
Reference flow	Measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit.	ISO, 2006b
Power grid mix process	A country-specific aggregated process that represents an average electricity production in the country and consists of electricity production processes from different resources, averaged based on relative contribution to national power grid	Kupfer et al., 2019

4.2. Emission Calculations for Coal Power Plants in Turkey

The following key emissions are calculated for coal-fired power plants in Turkey within the scope of the study and then used to construct LCA processes for energy production processes from coal and lignite:

- CO_2
- CO
- NO_x
- N_2O
- SO_2
- PM_{10}
- $PM_{2.5}$

All abovementioned emissions except for the CO_2 were calculated by first adopting EFs published in WebFIRE database by US EPA to Turkey's conditions based on domestic fuel properties and utilized combustion and emission control technologies and applying those EFs to coal-fired power plants in Turkey. The WebFIRE database contains US EPA's recommended EFs for air emissions from industrial and non-industrial processes. The database is both comprehensive and transparent, and includes individual data values used in development of the EFs as well as data submitted to US EPA by federal, state and local agencies industry representatives. Additionally, the database contains descriptive information such as industry and source category type, control technology and supporting documentation used for the EFs (US Environmental Protection Agency, 2016).

4.2.1. WebFIRE Emission Factors

EFs in the US EPA's WebFIRE database are representative values that relate the quantity of pollutant released to the atmosphere with the activity that resulted in release of that pollutant. As such, Equation (4.1) represents the most general expression for calculating an average EF for a given pollutant from a defined type of electricity production facility and fuel (Cai et al., 2012):

$$\mathrm{EF}_{p,f,ct} = \frac{\sum_{\mathrm{i}} \mathrm{Emission}_{p,f,ct,i}}{\sum_{\mathrm{i}} \mathrm{NEG}_{f,ct,i}} \tag{4.1}$$

where

$EF_{p,f,ct}$: averaged EF of a pollutant p emitted by all power plants burning fuel f using combustion technology ct [g/kWh]

$Emission_{p,f,ct,i}$: emissions of a pollutant p from power plant i burning fuel f using combustion technology ct [g]

$NEG_{f,ct,i}$: net electricity generated by power plant i burning fuel f using combustion technology ct [kWh]

In cases where a power plant utilizes more than one type of fuel, the fuel with the highest utilization ratio in terms of power production is considered as a primary fuel type and emission calculations are based on this fuel. Similarly, many power plants have multiple generators that utilize different types of prime mover technologies. In this case, prime mover technology with the biggest share in total electric power generation capacity of the plant is considered as the representative prime mover type of the plant. While both approaches result in small error due to differences in fuel properties and combustion efficiency, they assist in practical application of the formula and calculations, as recommended by the Argonne National Laboratory of the U.S. Department of Energy and thus were adopted in this study (Cai et al., 2012).

In order to account for the emission reductions associated with various emission control technologies utilized at power plants, Equation (4.1) is expanded to include the emission reduction efficiencies of those technologies and the contribution of each technology is calculated based on annual heat input of each power plant employing the particular technology, as described in Equation (4.2) (Cai et al., 2012):

$$\mathrm{EF}_{p,f,ct} = \frac{\sum_{\mathrm{i}} \mathrm{Emission}_{p,f,ct,i}}{\sum_{\mathrm{i}} \mathrm{NEG}_{f,ct,i}} \tag{4.2}$$

where

$EF_{out,p,f,ct}$: EF of pollutant p for EGUs burning fuel type f using combustion technology ct [g/kWh]

$EF_{in,f,ct,p}$: uncontrolled EF of pollutant p for EGUs burning fuel type f using combustion technology ct [g/ton coal]

$HI_{f,ct,i}$: net annual heat input to plant i from the burning of fuel type f using combustion technology ct [mmBtu]

HHV_f: HHV of fuel type f [mmBtu]

$ER_{p,ec}$: emission reduction efficiency of pollutant *p* using control technology *ec*

$NEG_{f,ct,i}$: net electricity generated by power plant *i* burning fuel *f* using combustion technology *ct* [kWh]

The combustion technology and emission control technology categories available for coal species in WebFIRE database are given in Tables 4.3.

Table 4.3. Combustion and emission control technologies in WebFIRE database.

Combustion Technologies	Emission Control Technologies
• Fluidized bed combustion (FBC) ○ Bubbling bed ○ Circulating bed • Cell burner • Cyclone furnace • Overfeed stoker (OS) ○ Spreader stoker ○ Traveling grate stoker • Pulverized coal (PC) ○ Dry bottom ○ Wet bottom	• Baghouse • Electrostatic precipitator (ESP) • Low NO_x burner (LNB) • Multiple cyclones ○ Fly ash reinjection ○ No fly ash reinjection • Scrubber • Overfire air system (OFA) • Thermal oxidizer (TO) • Uncontrolled

4.2.1.1. CO, N_2O and NO_x Emission Factors. EFs for CO, N_2O and NO_x emissions from coal and lignite power plants are given in the following tables (Table 4.4 – Table 4.6). EFs for bituminous and subbituminous coal are given together when the values for the two subtypes are identical. The units were converted from the original lb/ton coal to kg/ton coal. Bituminous and Subbituminous coal are designated as BIT and SUB, respectively, in all relevant tables throughout the document.

Table 4.4. CO emission factors for coal and lignite power plants (kg/ton coal).

Fuel	Combustion Technology	Emission Control Technologies		
		Uncontrolled	OFA	LNB
Anthracite Coal	PC	0.27216		
Anthracite Coal	OS, traveling grate	0.27216		
BIT Coal	FBC, circulating bed	8.16466		
BIT/SUB Coal	FBC, bubbling bed	8.16466		
BIT/SUB Coal	Cell burner	0.22680		

Table 4.4. CO emission factors for coal and lignite power plants (kg/ton coal) (continued).

Fuel	**Combustion Technology**	**Emission Control Technologies**		
		Uncontrolled	**OFA**	**LNB**
BIT/SUB Coal	Cyclone furnace	0.22680		
BIT/SUB Coal	PC, dry bottom	0.22680		0.22680
BIT/SUB Coal	PC, wet bottom	0.22680		
BIT/SUB Coal	OS, spreader stoker	2.26796		
BIT/SUB Coal	OS, traveling grate	2.72155		
Lignite	FBC, bubbling bed	0.06804		
Lignite	FBC, circulating bed	0.06804		
Lignite	Cyclone furnace	0.27216		
Lignite	PC, dry bottom, tangential fired	0.27216	0.04536	
Lignite	PC, dry bottom, wall fired	0.11340	0.21772	0.21772
Lignite	OS, spreader stoker	2.26796		
Lignite	OS, traveling grate	2.72155		

Table 4.5. N_2O emission factors for coal and lignite power plants (kg/ton coal).

Fuel	**Combustion Technology**	**Emission Control Technologies**	
		Uncontrolled	**Multiple Cyclones**
BIT/SUB Coal	OS, spreader stoker	0.01814	0.01814
BIT/SUB Coal	OS, traveling grate	0.01814	0.01814
BIT/SUB Coal	PC, dry bottom	0.01361	
BIT/SUB Coal	PC, wet bottom	0.03629	
BIT/SUB Coal	PC, dry bottom, tangential fired	0.03629	
BIT/SUB Coal	Cyclone furnace	0.04082	
BIT/SUB Coal	FBC, bubbling bed	1.58757	
BIT/SUB Coal	FBC, circulating bed	1.58757	
Lignite	FBC	1.13398	
Lignite	FBC, bubbling bed	1.13398	
Lignite	FBC, circulating bed	1.13398	

Table 4.6. NO_x emission factors for coal and lignite power (kg/ton coal).

Fuel	Combustion Technology	Emission Control Technologies		
		Uncontrolled	LNB	OFA
Anthracite Coal	PC	8.16466		
Anthracite Coal	OS, traveling grate	4.08233		
BIT	PC, dry bottom	5.44310	4.98951	
BIT	PC, wet bottom	14.06135		
BIT	Cyclone furnace	14.96854		
BIT Coal	OS, spreader stoker	4.98951		
BIT/SUB Coal	OS, traveling grate	3.40194		
BIT Coal	PC, dry bottom, tangential fired	4.53592	4.39984	
BIT Coal	Cell burner	14.06135		
BIT/SUB Coal	FBC, bubbling bed	6.89460		
BIT/SUB Coal	FBC, circulating bed	2.26796		
SUB Coal	PC, dry bottom	3.35658		
SUB Coal	PC, wet bottom	10.88621		
SUB Coal	Cyclone furnace	7.71106		
SUB Coal	OS, spreader stoker	3.99161		
SUB Coal	PC, dry bottom, tangential fired	3.26586		
SUB Coal	Cell burner	6.35029		
Lignite	PC, dry bottom, wall fired	2.85763	2.08652	2.08652
Lignite	PC, dry bottom, tangential fired	3.22050		2.72155
Lignite	Cyclone furnace	6.80388		
Lignite	OS, traveling grate	2.72155		
Lignite	OS, spreader stoker	2.63083		
Lignite	FBC, bubbling bed	1.63293		
Lignite	FBC, circulating bed	1.63293		

4.2.1.2. SO_x Emission Factors. SO_x EFs for coal and lignite power plants are given in Table 4.7. SO_x here collectively refers to various oxides of sulfur that result from combustion of coal (SO_2, SO_3, SO_3^{2-} and H_2SO_4), with SO_2 prominent among them (Munawer, 2018). Hence, the SO_x the EFs are expressed as SO_2 in the WebFIRE database, per US EPA's recommendation and they are also expressed as such in the Ecoinvent's template coal dataset. Since, the amount of SO_x emissions from a coal power plant is correlated with the amount of sulfur contained within the coal, the EFs for SO_x are expressed as formulas that incorporate the weight percent of sulfur in the feedstock, rather than constant numeric values.

Table 4.7. SO_x emission factors for coal and lignite power plants (kg/ton coal).

Fuel	**Combustion Technology**	**Emission Control Technologies**	
		Uncontrolled	**LNB**
Anthracite Coal	PC	17.69*S	
Anthracite Coal	OS, traveling grate	17.69*S	
BIT	PC, dry bottom	17.24*S	17.24*S
BIT	PC, wet bottom	17.24*S	
BIT	Cyclone furnace	17.24*S	
BIT	OS, spreader stoker	17.24*S	
BIT	OS, traveling grate	17.24*S	
BIT	PC, wet bottom, tangential fired	17.24*S	
BIT	PC, dry bottom, tangential fired	17.24*S	17.24*S
BIT	Cell burner	17.24*S	
BIT/SUB Coal	FBC, bubbling bed*	17.96(S)(Ca/S)^-1.9	
BIT/SUB Coal	FBC, circulating bed*	17.96(S)(Ca/S)^-1.9	
SUB Coal	PC, dry bottom	15.88*S	
SUB Coal	PC, wet bottom	15.88*S	
SUB Coal	Cyclone furnace	15.88*S	
SUB Coal	OS, spreader stoker	15.88*S	
SUB Coal	OS, traveling grate	15.88*S	
SUB Coal	PC, dry bottom, tangential fired	15.88*S	
SUB Coal	Cell burner	15.88*S	
Lignite	Cyclone furnace	13.61*S	

Table 4.7. SO_x emission factors for coal and lignite power plants (kg/ton coal) (continued).

Fuel	**Combustion Technology**	**Emission Control Technologies**	
		Uncontrolled	**LNB**
Lignite	PC, dry bottom, wall fired	13.61*S	
Lignite	PC, dry bottom, tangential fired	13.61*S	
Lignite	OS, traveling grate	13.61*S	
Lignite	OS, spreader stoker	13.61*S	
Lignite	FBC	4.54*S	
Lignite	FBC, circulating bed	4.54*S	

S: Sulfur weight percentage (%) of coal

*: This equation can be used when the Ca/S is known and is within the 1.5-7 range. Here, S is the weight percent sulfur in the fuel and Ca/S is the molar calcium-to-sulfur ratio in the bed.

Since SO_x EFs for plants with FGD were not available in the WebFIRE database, the reduction efficiencies were obtained from the literature and applied to the EFs in Table 4.7 when calculating the SO_2 emissions for coal power plants. While exact figures for SO_2 removal efficiency vary depending on specific reaction conditions and applied technology, the efficiencies up to 97% (EPPSA, 2015), 90% (limestone) and 95% (lime) (US Environmental Protection Agency, 2003) and 95-99% (National Lime Association, 2019; Romanik, 2016) have been reported for wet lime FGD and up to %85 (lime) and %75 (limestone) (Çift and Okutan, 2010), below 80% (US Environmental Protection Agency, 2003), 70-90% (İlhan, 2012) and above 80% (if baghouse is used) (Sargent & Lundy, 2007) have been reported for dry lime FGD. Based on these data, 95% and 80% SO_2 emission removal rates for wet lime and dry lime FGD, respectively, were used in calculations in this study.

4.2.1.3. PM_{10} and $PM_{2.5}$ Emission Factors. PM_{10} and $PM_{2.5}$ EFs for coal and lignite power plants are given in Table 4.8 and Table 4.9, respectively. The EFs in the tables are expressed as lb/ton and will be converted to kg/ton unit by multiplying with 0.453592 before being used in calculation of emissions from coal power plants in Turkey. The PM_{10} and $PM_{2.5}$ EFs in Table 4.8 and Table 4.9 are expressed as the sum of two terms which correspond to filterable particulate matter (FPM) and condensable particulate matter (CPM) fractions of the emitted PM that depend on the ash and sulfur contents of coal, respectively. Since, only CPM EFs were available in the WebFIRE database, the missing EFs were adopted from the Argonne National Laboratory Report (U.S. Department of Energy laboratory) that used WebFIRE EFs along with data from literature and Emissions & Generation Resource Integrated Database (eGRID) to estimate the PM_{10} and $PM_{2.5}$ EFs (Cai et al., 2012).

Table 4.8. PM$_{10}$ emission factors for coal and lignite power plants (lb/ton coal).

Fuel	Combustion technology	Emission control technologies					
		Uncontrolled	ESP	Baghouse	Multiple Cyclones		Scrubber
					No Fly Ash Reinjection	Fly Ash Reinjection	
Anthracite Coal	OS, traveling grate	4.8+(0.08*A)	1.48	1.11	8.84	13.04	
BIT Coal	OS, spreader stoker	14.24	1.48	1.11	10.9		
BIT Coal	OS, traveling grate	7.04			6.04		
BIT Coal	FBC, bubbling bed	12.90					
BIT Coal	FBC, circulating bed	12.90					
BIT Coal	PC, dry bottom, FGD	2.3*A+0.469	0.054*A+0.469	0.02*A+0.469	0.58*A+0.469		0.42*A+0.469
BIT Coal	PC, dry bottom, no FGD	2.3*A+(0.1*S-0.03)*23.44	0.054*A+(0.1*S-0.03)*23.44	0.02*A+(0.1*S-0.03)*23.44	0.58*A+(0.1*S-0.03)*23.44		0.42*A+(0.1*S-0.03)*23.44
BIT Coal	PC, wet bottom, FGD	2.6*A+0.469	0.042*A+0.469		1.3*A+0.469		
BIT Coal	PC, wet bottom, no FGD	2.6*A+(0.1*S-0.03)*23.44	0.042*A+(0.1*S-0.03)*23.44		1.3*A+(0.1*S-0.03)*23.44		
BIT Coal	PC, tangential fired, FGD	2.3*A+0.469	0.054*A+0.469	0.02*A+0.469	0.58*A+0.469		0.42*A+0.469
BIT Coal	PC, tangential fired, no FGD	2.3*A+(0.1*S-0.03)*23.44	0.054*A+(0.1*S-0.03)*23.44	0.02*A+(0.1*S-0.03)*23.44	0.58*A+(0.1*S-0.03)*23.44		0.42*A+(0.1*S-0.03)*23.44
BIT Coal	Cyclone furnace	0.26*A+(0.1*S-0.03)*23.44	0.011*A+(0.1*S-0.03)*23.44		0.112*A+(0.1*S-0.03)*23.44		
SUB Coal	PC, dry bottom, FGD	2.3*A+0.4	(0.01)*2.3*A+0.4	(0.001)*2.3*A+0.4	(0.075)*2.3*A+0.4		(0.03)*2.3*A+0.4

Table 4.8. PM_{10} emission factors for coal and lignite power plants (lb/ton coal) (continued).

Fuel	**Combustion technology**	**Emission control technologies**					
		Uncontrolled	**ESP**	**Baghouse**	**Multiple Cyclones**		**Scrubber**
					No Fly Ash Reinjection	**Fly Ash Reinjection**	
SUB Coal	PC, dry bottom, no FGD	2.3*A+(0.1*S-0.03)*20	(0.01)*2.3*A+(0.1*S-0.03)*20	(0.001)*2.3*A+(0.1*S-0.03)*20	(0.075)*2.3*A+(0.1*S-0.03)*20		(0.03)*2.3*A+(0.1*S-0.03)*20
SUB Coal	PC, wet bottom	2.6*A+(0.1*S-0.03)*20					
SUB Coal	PC, tangential fired	2.3*A+(0.1*S-0.03)*20					
SUB Coal	OS, spreader stoker	14.00			8.60	13.20	
SUB Coal	OS, traveling grate	6.80			5.80		
SUB Coal	FBC, bubbling bed	16.60					
SUB Coal	Cyclone furnace	0.26*A+(0.1*S-0.03)*20					
Lignite	PC, dry bottom, FGD	0.79*2.3*A+0.29		0.00018*A+0.29	0.79*0.88*A+0.29		0.000945*A+0.29
Lignite	PC, dry bottom, no FGD	0.79*2.3*A+(0.1*S-0.03)*14.5		0.00018*A+(0.1*S-0.03)*14.5	0.79*0.88*A+(0.1*S-0.03)*14.5		0.000945*A+(0.1*S-0.03)*14.5
Lignite	PC, tangential fired, FGD	2.3*A+0.29		0.00018*A+0.29	0.88*A+0.29		0.000945*A+0.29
Lignite	PC, tangential fired, no FGD	2.3*A+(0.1*S-0.03)*14.5		0.00018*A+(0.1*S-0.03)*14.5	0.88*A+(0.1*S-0.03)*14.5		0.000945*A+(0.1*S-0.03)*14.5
Lignite	OS, traveling grate	(1.07*A)+0.64					
Lignite	OS, spreader stoker	(1.6*A)+0.64			(0.66*A)+0.64		

S: Sulfur weight percentage (%) of coal

A: Ash weight percentage (%) of coal

Table 4.9. PM$_{2.5}$ emission factors for coal and lignite power plants (lb/ton coal).

Fuel	**Combustion technology**	**Emission control technologies**					
		Uncontrolled	**ESP**	**Baghouse**	**Multiple Cyclones**		**Scrubber**
					No Fly Ash Reinjection	**Fly Ash Reinjection**	
Anthracite Coal	OS, traveling grate	2.5+(0.08*A)					
BIT Coal	OS, spreader stoker	5.64	1.34	1.07	4.24	2.44	
BIT Coal	OS, traveling grate	3.24			4.84		
BIT Coal	FBC, bubbling bed	1.88					
BIT Coal	FBC, circulating bed	1.88					
BIT Coal	PC, dry bottom, FGD	0.6*A+0.469	0.024*A+0.469	0.01*A+0.469	0.06*A+0.469		0.3*A+0.469
BIT Coal	PC, dry bottom, no FGD	0.6*A+(0.1*S–0.03)*23.44	0.024*A+(0.1*S–0.03)*23.44	0.01*A+(0.1*S–0.03)*23.44	0.06*A+(0.1*S–0.03)*23.44		0.3*A+(0.1*S–0.03)*23.44
BIT Coal	PC, wet bottom, FGD	1.48*A+0.469	0.022*A+0.469		0.86*A+0.469		
BIT Coal	PC, wet bottom, no FGD	1.48*A+(0.1*S–0.03)*23.44	0.022*A+(0.1*S–0.03)*23.44		0.86*A+(0.1*S–0.03)*23.44		
BIT Coal	PC, tangential fired, FGD	0.6*A+0.469	0.024*A+0.469	0.01*A+0.469	0.06*A+0.469		0.3*A+0.469
BIT Coal	PC, tangential fired, no FGD	0.6*A+(0.1*S–0.03)*23.44	0.024*A+(0.1*S–0.03)*23.44	0.01*A+(0.1*S–0.03)*23.44	0.06*A+(0.1*S–0.03)*23.44		0.3*A+(0.1*S–0.03)*23.44
BIT Coal	Cyclone furnace	0.11*A+(0.1*S–0.03)*23.44	0.0006*A+(0.1*S–0.03)*23.44		0.11*A+(0.1*S–0.03)*23.44		
SUB Coal	PC, dry bottom, FGD	0.6*A+0.4	(0.01)*0.6*A+0.4	(0.001)*0.6*A+0.4	(0.075)*0.6*A+0.4		(0.03)*0.6*A+0.4
SUB Coal	PC, dry bottom, no FGD	0.6*A+(0.1*S–0.03)*20	(0.01)*0.6*A+(0.1*S–0.03)*20	(0.001)*0.6*A+(0.1*S–0.03)*20	(0.075)*0.6*A+(0.1*S–0.03)*20		(0.03)*0.6*A+(0.1*S–0.03)*20

Table 4.9. PM$_{2.5}$ emission factors for coal and lignite power plants (lb/ton coal) (continued).

Fuel	**Combustion technology**	**Emission control technologies**					
		Uncontrolled	**ESP**	**Baghouse**	**Multiple Cyclones**		**Scrubber**
					No Fly Ash Reinjection	**Fly Ash Reinjection**	
SUB Coal	PC, wet bottom	1.48*A+(0.1*S–0.03)*20					
SUB Coal	PC, tangential fired	0.6*A+(0.1*S–0.03)*20					
SUB Coal	OS, spreader stoker	5.40			4.00	2.20	
SUB Coal	OS, traveling grate	3.00			4.60		
SUB Coal	FBC, bubbling bed	1.88					
SUB Coal	Cyclone furnace	0.11*A+(0.1*S–0.03)*20					
Lignite	PC, dry bottom, FGD	0.79*0.66*A+0.29		0.00008*A+0.29	0.79*0.36*A+0.29		0.0005*A+0.29
Lignite	PC, dry bottom, no FGD	0.79*0.66*A+(0.1*S–0.03)*14.5		0.00008*A+(0.1*S–0.03)*14.5	0.79*0.36*A+(0.1*S-0.03)*14.5		0.0005*A+(0.1*S–0.03)*14.5
Lignite	PC, tangential fired, FGD						
Lignite	PC, tangential fired, no FGD						
Lignite	OS, traveling grate	(0.4066*A)+0.64					
Lignite	OS, spreader stoker	(0.56*A)+0.64			(0.42*A)+0.64		

S: Sulfur weight percentage (%) of coal

A: Ash weight percentage (%) of coal

4.2.1.4. CO_2 Emission Factors. Since CO_2 EFs were not available in WebFIRE database additional resources were surveyed to locate the EFs for this important GHG and were adopted from the “The Future of Coal” report published by the Massachusetts Institute of Technology (MIT). The report presents CO_2 EFs for several boiler types and operating conditions, with and without carbon capture options but, does not differentiate between lignite and other hard coal subtypes (MIT, 2007). The CO_2 EFs adopted from this report and used in calculations in this study are given in Table 4.10.

Table 4.10. CO_2 emission factors for coal power plants (kg/kWh).

CO_2 Emission Factors	**Pulverized Coal**			**FBC (Subcritical)**
	Subcritical	**Supercritical**	**Ultra-Supercritical**	
Without carbon capture	0.931	0.830	0.738	1.030
With carbon capture	0.127	0.109	0.094	0.141

Since no carbon capture technology related information was available for coal power plants in Turkey, CO_2 EFs without carbon capture were used in calculations.

4.2.2. Calculation of Emissions for Coal Power Plants in Turkey

The EFs presented in the previous section and technical information gathered about coal power plants operating in Turkey and fuel properties utilized in those plants were used in order to calculate the emissions from each plant on annual basis. Those emissions were proportioned based on annual net electricity generated from those plants to calculate average emissions on kg/kWh basis which were then used to develop coal and lignite LCA processes for Turkey.

The coal power plants operating in Turkey with installed capacity of 100 MW and above were included in the study while small-scale plants and autoproducers designed to supply electricity to specific industrial establishments rather than national electricity grid were excluded. The complete list of power plants is listed in Table 4.11. İskenderun Demir Çelik and Çolakoğlu power plants were also excluded from the study due to lack of data on coal combustion and emission control technologies. Additionally, Cenal Karabiga, Çan 2 and Soma Kolin power plants that were put into operation after 2016 were not included in the study due to lack of reliable annual electricity production figures.

Table 4.11. Coal power plants included in the study.

Code	Power Plant	Location (Province)	Installed Capacity (MW)	Fuel
PP1	Afsin-Elbistan A	Kahramanmaras	1,355	Lignite
PP2	Afsin-Elbistan B	Kahramanmaras	1,440	Lignite
PP3	Soma B	Manisa	990	Lignite
PP4	Kemerköy	Muğla	630	Lignite
PP5	Yatagan	Muğla	630	Lignite
PP6	Çayırhan	Ankara	620	Lignite
PP7	Seyitömer	Kütahya	600	Lignite
PP8	Kangal	Sivas	457	Lignite
PP9	Tufanbeyli	Adana	450	Lignite
PP10	Yeniköy	Muğla	420	Lignite
PP11	Tunçbilek	Kütahya	365	Lignite
PP12	18 Mart Çan	Çanakkale	320	Lignite
PP13	Aksa Bolu Göynük	Bolu	270	Lignite
PP14	Orhaneli	Bursa	210	Lignite
PP15	Yunus Emre	Eskişehir	290	Lignite
PP16	Silopi	Şırnak	405	Asphaltite
PP17	Çatalağzı	Zonguldak	315	Hard coal (domestic)
PP18	Zonguldak Eren	Zonguldak	2,790	Hard coal (imported)
PP19	İSKEN Sugözü	Adana	1,210	Hard coal (imported)
PP20	İçdaş Bekirli	Çanakkale	1,200	Hard coal (imported)
PP21	Atlas İskenderun	Hatay	1,200	Hard coal (imported)
PP22	İçdaş Biga	Çanakkale	405	Hard coal (imported)
PP23	İzdemir Enerji Aliağa	İzmir	350	Hard coal (imported)

The coal combustion technologies (boiler types and subtypes) and emission control technologies employed at the power plants and the type of fuel utilized are listed in Table 4.12. Information regarding combustion and emission control technologies used in the plants were collected from technical reports published by the Chamber of Mechanical Engineers (MMO) (MMO, 2017; MMO, 2010), Global Energy Observatory database (GEO, 2019) and the websites of individual companies operating the power plants. Coal classification is based on ASTM D388-18 standard (ASTM, 2012).

Table 4.12. Coal combustion and emission control technologies and fuel types utilized in the power plants.

Power Plant	**Fuel**	**Combustion Technology**	**Emission Control Technology**	**Source**
PP1	Lignite	PC, subcritical	FGD	GEO (2019)
PP2	Lignite	PC, supercritical	Dry lime FGD, ESP	MMO (2017), EÜAŞ (2019), GEO (2019)
PP3	Lignite	PC, subcritical	FGD, ESP	Soma (2019), MMO (2010)
PP4	Lignite	PC, subcritical	Wet lime FGD	GEO (2019)
PP5	Lignite	PC, subcritical	Wet lime FGD, ESP	MMO (2017), Yatağan (2019)
PP6	Lignite	PC, subcritical	Wet lime FGD	GEO (2019)
PP7	Lignite	PC, subcritical	ESP	GEO (2019), MMO (2010)
PP8	Lignite	PC, subcritical	Wet lime FGD	GEO (2019)
PP9	Lignite	FBC	Wet lime FGD	EnerjiSA (2019)
PP10	Lignite	PC, subcritical	Wet lime FGD	GEO (2019)
PP11	Lignite	PC, subcritical	-	GEO (2019)
PP12	Lignite	FBC, circulating bed	-	MMO (2017)
PP13	Lignite	FBC (with sulfur removal)	Wet lime FGD, LNB	Aksa (2019)
PP14	Lignite	PC, subcritical	Wet lime FGD	GEO (2019)
PP15	Lignite	FBC, circulating bed	Semi-dry FGD, ESP	Adularya (2019), MMO (2017)
PP16	Asphaltite (SUB)*	FBC (with sulfur removal)**	ESP	Ciner (2019), ÇED (2010)
PP17	SUB coal	PC, subcritical	FGD, ESP	Çatalağzı (2019)
PP18	BIT Coal	FBC, circulating bed (160 MW) and PC, supercritical (2,630 MW)	-	Eren Enerji (2019)

Table 4.12. Coal combustion and emission control technologies and fuel types utilized in the power plants (continued).

Power Plant	Fuel	Combustion Technology	Emission Control Technology	Source
PP19	BIT Coal	PC, dry bottom, supercritical	Wet lime FGD, LNB, ESP	İsken (2019)
PP20	BIT Coal	PC, supercritical	Wet lime FGD, $DeNO_x$	İçdaş (2019)
PP21	BIT Coal	PC, supercritical	Wet lime FGD, $DeNO_x$, Baghouse	Diler (2019)
PP22	BIT Coal	FBC, circulating bed	Wet lime FGD, LNB, ESP	GEO (2019)
PP23	BIT Coal	PC, supercritical	FGD, $DeNO_x$, ESP	İzdemir (2019)

*: The asphaltite fuel is classified as subbituminous coal within the scope of this study based on its calorific value

**: The Ca/S in the boiler bed is 2.4 (ÇED, 2010)

The combustion technology of the PP18 is considered as “PC, supercritical” within the scope of the study since the summed capacities of the supercritical PC boilers (two 615 MW and two 700 MW units) represent the largest fraction of the power plant’s total capacity. The EFs for wet lime FGD emission control technology is used for PP16 since high-efficiency (above 95%) sulfur removal is utilized within the FBC boiler (ÇED, 2010). The EFs for LNB emission control technology is used for plants utilizing $DeNO_x$ technologies (PP20, PP21 and PP23).

The lower heating value (LHV), sulfur and ash content of coal utilized in the power plants are listed in Table 4.13. Most of the LHV and ash content data for domestic coal is obtained from MMO 2017 report and the missing data is supplemented from literature. Most of the sulfur content data for domestic coal is obtained from Say (2006) and the rest is gathered from other academic publications. websites of individual companies operating the power plants. Since no reliable data on fuel properties were available for power plants operating with imported hard coal, the limit value requirements in the Circular on Imported Solid Fuels published by the Ministry of Environment and Urban Planning were used instead (CŞB, 2011). The average LHV for imported hard coal was adopted as 6,200 kcal/kg based on 6,400 kcal/kg (-200 kcal/kg tolerance) limit value in the Circular, 6,000 kcal/kg value reported for hard coal imported from Russian (Argus Media, 2017) and Columbia (TTK, 2018) and 6,000-6,500 kcal/kg range value reported in MMO 2017 report for imported hard coal utilized in İSKEN Sugözü. The 0.9% sulfur content is consistent with the fact that over 80% of hard coal for thermal power plants traded internationally have sulfur content below 1% and only 10% has sulfur content below 0.7% (ILO, 1995).

Table 4.13. LHV, ash and sulfur content of coal utilized in the power plants.

Power Plant	Fuel	LHV (kcal/kg)	Sulfur Content (%)	Ash Content (%)	Source
PP1	Lignite	1,050	1.4	18	MMO (2010), Say (2006)
PP2	Lignite	1,225	1.5	15	MMO (2017), Say (2006)
PP3	Lignite	1,975	1.5	46	MMO (2017), Say (2006)
PP4	Lignite	1,750	3.2	33	MMO (2017), Say (2006)
PP5	Lignite	2,100	2.7	20	MMO (2017), Say (2006)
PP6	Lignite	2,500	4.7	34	MMO (2017), Say (2006), Karaca et al. (2009)
PP7	Lignite	1,700	2	40	MMO (2017), Say (2006)
PP8	Lignite	1,100	2	25	Kangal (2019), Say (2006), MMO (2017)
PP9	Lignite	1,332	2.26	27	Erdoğan et al. (2001)
PP10	Lignite	1,750	4	31	MMO (2017), Say (2006)
PP11	Lignite	2,710	1.88	40	MMO (2017), Direskeneli (2014)
PP12	Lignite	2,600	4	32	MMO (2017)
PP13	Lignite	2,450	1.37	35	Aksa (2019), Ünlü et al. (1986)
PP14	Lignite	2,170	1.9	31	MMO (2017), Say (2006)
PP15	Lignite	2,539	2.51	31	MTA (2010)
PP16	Asphaltite (SUB)*	5,511	8.17	36	Demirci et al. (2019), Ciner (2019)
PP17	SUB coal	3,300	0.8	45	Çatalağzı (2019), Say (2006)
PP18	BIT Coal	6,200	0.9	16	ÇŞB (2011), Argus Media (2017), MMO (2017), TTK (2018)
PP19	BIT Coal	6,200	0.9	16	
PP20	BIT Coal	6,200	0.9	16	
PP21	BIT Coal	6,200	0.9	16	
PP22	BIT Coal	6,200	0.9	16	
PP23	BIT Coal	6,200	0.9	16	

*: The LHV, ash and sulfur content data indicated for asphaltite utilized in PP16 are the average values for the asphaltite obtained from Harbul and Silip veins, as reported by Demirci et al. (2019), that are used in the power plant (Ciner, 2019).

The annual net electricity production values, percent contribution to the total electricity produced by the plants and amount of fuel consumed per kWh of electricity produced for lignite and hard coal power plants are given in Table 4.14 and Table 4.15, respectively. Annual production values were obtained from the web-based Energy Atlas of Turkey and represent production values of the year 2016 (Enerji Atlası, 2016). Although more recent data was available for several power plants, the 2016 values were selected for consistency. For the power plants for which the 2016 data was not available, an average annual production value leading up to 2016 was selected. Fuel consumption data of the power plants P1-P5, P7-P12, P14 and P17 were obtained from the MMO reports (MMO, 2017 and MMO, 2010). Fuel consumption data of PP18 and PP19 were not available in the MMO report and were calculated by diving their reported annual coal consumption by net annual electricity production values (Eren Enerji, 2019; MMO, 2017).

Table 4.14. Electricity production and fuel consumption of lignite power plants.

Power Plant	Annual Production (GWh)	Percent Contribution (%)	Fuel Consumption (kg/kWh)	Source
PP1	2,440	7.58	2.500	(MMO (2010)
PP2	428	1.33	2.250	(MMO 2017)
PP3	4,505	13.99	1.467	(MMO 2017)
PP4	2,642	8.20	1.462	(MMO 2017)
PP5	2,759	8.57	1.099	(MMO 2017)
PP6	2,698	8.38	1.101	Calculated
PP7	3,380	10.49	1.546	(MMO 2017)
PP8	2,489	7.73	2.190	(MMO 2017)
PP9	1,138	3.53	2.000	(MMO 2017)
PP10	2,593	8.05	1.352	(MMO 2017)
PP11	1,605	4.98	1.125	(MMO 2017)
PP12	1,959	6.08	0.850	(MMO 2017)
PP13	1,523	4.73	1.107	Calculated
PP14	1,003	3.11	0.996	(MMO 2017)
PP15	1,050	3.26	1.068	Calculated

Table 4.15. Electricity production and fuel consumption of hard coal power plants.

Power Plant	Annual Production (GWh)	Percent Contribution (%)	Fuel Consumption (kg/kWh)	Source
PP16	2,872	6.02	0.482	Calculated
PP17	1,862	3.90	0.827	(MMO 2017)
PP18	10,560	22.13	0.796	Calculated
PP19	9,527	19.96	0.346	Calculated
PP20	8,360	17.52	0.378	Calculated
PP21	9,174	19.22	0.378	Calculated
PP22	2,885	6.04	0.418	Calculated
PP23	2,486	5.21	0.378	Calculated

The fuel consumption of the power plants for which annual coal consumption values were not available (PP6, PP13, PP15, PP16 and PP20-PP23), was calculated based on the average efficiency of the combustion technology employed at the power plant and its annual electricity generation using Equation (4.3) (Cai et al., 2012):

$$\eta_{LHV,\,ct} = \frac{elec.gen_{f,ct}}{heatimput_{f,ct} \times \frac{\mathrm{LHV}_f}{\mathrm{HHV}_f}} \times 100\% \tag{4.3}$$

where

$\eta_{\mathrm{LHV,ct}}$: LHV-based energy conversion efficiency of combustion technology ct

elec.gen$_{f,ct}$: net electricity generation by fuel type and combustion technology ct

heatinput$_{f,ct}$: heat input by fuel type f and combustion technology ct

LHV$_f$ and HHV$_f$: LHV and HHV, respectively, of the fuel type

The energy efficiency values of combustion technologies were adopted from the “The Future of Coal” report of the MIT as 34.3% for subcritical PC (PP6), 38.5% for supercritical PC (PP20, PP21 and PP23) and 34.8% for FBC (PP13, PP15, PP16 and PP22) (MIT, 2007). The $\mathrm{LHV_f}$ / $\mathrm{HHV_f}$ ratios for lignite, subbituminous and bituminous coal were adopted as 0.91138, 0.93036 and 0.95332, respectively, based on the ultimate analysis of coal properties (US Environmental Protection Agency, 2006). Once the heat input was calculated, the annual coal consumption was estimated based on the calorific value of the coal utilized at the power plant.

Finally, the EFs for CO, N_2O, NO_x, SO_x, PM_{10}, $PM_{2.5}$ and CO_2 emissions given in Tables 4.4 to 4.10 were assigned to the lignite and hard coal power plants based on the combustion and emission control technologies and fuel properties utilized in those plants given in Table 4.12 and Table 4.13. The EFs assigned to lignite and hard coal power plants are given in Table 4.16 and Table 4.17, respectively. The numeric EFs for SO_x, PM_{10}, and $PM_{2.5}$ were calculated based ash and sulfur content of coal used in the power plants. As more commonly utilized options, circulating bed was assumed for FBC and dry bottom was assumed for PC combustion technologies in cases where information on boiler subtype was not available for the power plant (IEA Clean Coal Centre, 2019). Since, further, more detailed, classification of the combustion technologies was not available for the analyzed power plants, the average of the EFs for boiler subtypes were calculated and assigned to the plants, when more than one EFs was available for the particular boiler type (e.g. an average of "PC, dry bottom, wall fired" and "PC, dry bottom, tangential fired" EFs were used). Since, PM_{10} EFs for FBC technology were not available for subbituminous coal and lignite, the EF of bituminous coal was used for both fuels instead. Similarly, N_2O EF for PC combustion technology was not available for lignite and was replaced with EF of subbituminous coal. Also, PM_{10} EFs were not available for lignite power plants with ESP emission control technology EFs for baghouse technology were used instead. However, since ESP EFs are larger than that of baghouse EFs, PM_{10} emissions might be under-represented for lignite powered plants employing this emission control technology. The EFs in Table 4.16 and Table 4.17 were then multiplied with annual coal consumption and divided by net annual electricity production values of the respective power plants indicated in Table 4.14 to calculate average kg/kWh emissions of each power plant. Since, two distinct LCA processes, namely "Electricity production from lignite in Turkey" and "Electricity production from hard coal in Turkey" will be generated using these emissions, calculations were performed separately for lignite and hard coal power plants. Lastly, the weighted average for each emission was calculated based on percent contribution of the respective power plants to total net electricity production from lignite and hard coal and these final emission values, representing national averages were then used to develop the LCA processes.

In addition to air emissions, average fuel consumption values per kWh net electricity produced from lignite and hard coal were also calculated by taking weighted average of fuel consumed by individual power plants. The amount of lignite/hard coal consumed per kWh electricity generated, in turn, determines all uphill environmental impacts associated with mining and preparation of the fuel. For this reason, the LCA conducted within the scope of the study comparing "electricity production from lignite/hard coal in Turkey" processes from the Ecoinvent 3.3 database and the ones generated in this study include the raw material acquisition phase.

Table 4.16. Emission factors of the lignite power plants.

Power Plant	**Emission Factors**									
	CO_2 (kg/kWh)	**CO (kg/ton coal)**	**N_2O (kg/ton coal)**	**NO_x (kg/ton coal)**	**SO_x**		**PM_{10}**		**$PM_{2.5}$**	
					Formula (kg/ton coal)	**Numeric (kg/ton coal)**	**Formula (lb/ton coal)**	**Numeric (kg/ton coal)**	**Formula (lb/ton coal)**	**Numeric (kg/ton coal)**
PP1	0.931	0.192777	0.024948	3.039066	(13.61*S)*0.05	0.952700	0.79*2.3*A+0.29	14.966722	0.79*0.66*A+0.29	4.388593
PP2	0.830	0.192777	0.024948	3.039066	(13.61*S)*0.2	4.083000	0.00018*A+0.29	0.132766	0.00008*A+0.29	0.132086
PP3	0.931	0.192777	0.024948	3.039066	(13.61*S)*0.05	1.020750	0.00018*A+0.29	0.135297	0.00008*A+0.29	0.133211
PP4	0.931	0.192777	0.024948	3.039066	(13.61*S)*0.05	2.177600	0.79*2.3*A+0.29	27.329372	0.79*0.66*A+0.29	7.936136
PP5	0.931	0.192777	0.024948	3.039066	(13.61*S)*0.05	1.837350	0.00018*A+0.29	0.133175	0.00008*A+0.29	0.132267
PP6	0.931	0.192777	0.024948	3.039066	(13.61*S)*0.05	3.198350	0.79*2.3*A+0.29	28.153548	0.79*0.66*A+0.29	8.172639
PP7	0.931	0.192777	0.024948	3.039066	13.61*S	27.220000	0.00018*A+(0.1*S-0.03)*14.5	1.121370	0.00008*A+(0.1*S-0.03)*14.5	1.119556
PP8	0.931	0.192777	0.024948	3.039066	(13.61*S)*0.05	1.361000	0.79*2.3*A+0.29	20.735958	0.79*0.66*A+0.29	6.044113

Table 4.16. Emission factors of the lignite power plants (continued).

Power Plant	**Emission Factors**									
	CO_2 (kg/kWh)	**CO (kg/ton coal)**	**N_2O (kg/ton coal)**	**NO_x (kg/ton coal)**	**SO_x**		**PM_{10}**		**$PM_{2.5}$**	
					Formula (kg/ton coal)	**Numeric (kg/ton coal)**	**Formula (lb/ton coal)**	**Numeric (kg/ton coal)**	**Formula (lb/ton coal)**	**Numeric (kg/ton coal)**
PP9	1.030	0.068039	1.133980	1.632931	(4.54*S)*0.05	0.513020	12.90	5.851337	1.88	0.852753
PP10	0.931	0.192777	0.024948	3.039066	(13.61*S)*0.05	2.722000	0.79*2.3*A+0.29	25.681018	0.79*0.66*A+ 0.29	7.463131
PP11	0.931	0.192777	0.024948	3.039066	13.61*S	25.586800	0.79*2.3*A+(0.1* S-0.03)*14.5	34.006246	0.79*0.66*A+ (0.1* S-0.03)*14.5	10.499294
PP12	1.030	0.068039	1.133980	1.632931	4.54*S	18.160000	12.90	5.851337	1.88	0.852753
PP13	1.030	0.068039	1.133980	1.632931	(4.54*S)*0.05	0.310990	12.90	5.851337	1.88	0.852753
PP14	0.931	0.192777	0.024948	3.039066	(13.61*S)*0.05	1.292950	0.79*2.3*A+0.29	25.681018	0.79*0.66*A+ 0.29	7.463131
PP15	1.030	0.068039	1.133980	1.632931	(4.54*S)*0.2	2.279080	12.90	5.851337	1.88	0.852753

Table 4.17. Emission factors of the hard coal power plants.

Power Plant	**Emission Factors**									
					SO_x		**PM_{10}**		**$PM_{2.5}$**	
	CO_2 (kg/kWh)	**CO (kg/ton coal)**	**N_2O (kg/ton coal)**	**NO_x (kg/ton coal)**	**Formula (kg/ton coal)**	**Numeric (kg/ton coal)**	**Formula (lb/ton coal)**	**Numeric (kg/ton coal)**	**Formula (lb/ton coal)**	**Numeric (kg/ton coal)**
PP16	1.030	8.164656	1.587572	2.267960	17.96(S)(Ca/S)^-1.9	27.805264	12.90	5.851337	1.88	0.852753
PP17	0.931	0.226796	0.024948	3.311222	(15.88*S)*0.05	0.635200	(0.01)*2.3*A+0.4	0.650905	(0.01)*0.6*A+0.4	0.303907
PP18	0.830	0.226796	0.024948	4.989512	17.24*S	15.516000	2.3*A+(0.1*S-0.03)*23.44	17.330117	0.6*A+(0.1*S-0.03)*23.44	4.992415
PP19	0.830	0.226796	0.024948	4.694677	(17.24*S)*0.05	0.775800	0.054*A+0.469	0.604638	0.022*A+0.469	0.372399
PP20	0.830	0.226796	0.024948	4.694677	(17.24*S)*0.05	0.775800	2.3*A+0.469	16.904920	1.48*A+0.469	10.953793
PP21	0.830	0.226796	0.024948	4.694677	(17.24*S)*0.05	0.775800	0.02*A+0.469	0.357884	0.022*A+0.469	0.372399
PP22	1.030	8.164656	1.587572	2.267960	[(17.96(S)(Ca/S)^-1.9]*0.05	0.153150	12.90	5.851337	1.88	0.852753
PP23	0.830	0.226796	0.024948	4.694677	(17.24*S)*0.05	0.775800	0.054*A+0.469	0.604638	0.024*A+0.469	0.386914

4.3. Development of Electricity Production LCA Processes

"Electricity production from lignite in Turkey" and "Electricity production from hard coal in Turkey" LCA processes were generated by using the corresponding LCA processes in the Ecoinvent 3.3 database as a template. The CO_2, CO, N_2O, NO_x and SO_x, emission values in the original Ecoinvent datasets were replaced with the Turkey's national average values calculated for these emissions in the previous section. PM10 and PM2.5 emissions were not replaced because, the values calculated for these pollutants were deemed unreliable and inaccurate, as explained in the Results and Discussion section.

The remaining secondary data that include air emissions of halogens, heavy metals, radioactive elements and other rare materials have much lower values both in terms of the emission amounts and their share in the overall environmental impact associated with the power generation activity, compared to the main emissions calculated within the scope of this study. Hence, these secondary emissions required for development of the processes were adopted as is from the Ecoinvent database. As with the original Ecoinvent processes, the activities included in the developed processes start from the constructed lignite/hard coal power plant ready to produce electricity with reception of lignite and operating materials at power plant gate and end with 1 kWh of high voltage electricity produced at the power plant and arrived at the busbar.

4.3.1. Life Cycle Impact Comparison of the Developed and Ecoinvent Processes

The electricity production from hard coal and electricity production from lignite LCA processes developed within the scope of this study were compared with their Ecoinvent counterparts in terms of their environmental impacts. GaBi LCA software (version: 8.2.0.55) was used to conduct the LCA analysis. The CML is a midpoint oriented environmental impact assessment method that was developed by the Institute of Environmental Sciences, Leiden University, Netherlands. The methodology contains characterization factors for over 1,700 material flows, including all air emissions relevant to this study (Menoufi, 2011). The baseline midpoint environmental impact categories of the CML method used in the analysis are given in Table 4.18, along with CML 2001 - Jan. 2016, EU 25+3 normalization factors that were used to compare the relative magnitudes of the different impact categories (adopted from GaBi 8 software). Ozone Layer Depletion Potential and Eco-toxicity related environmental impact categories were not included because the emissions calculated within the scope of this study have no impact on those categories.

Table 4.18. Baseline impact categories of CML methodology.

Impact category	Unit	Normalization Factor
CML2001 - Jan. 2016, Acidification Potential (AP)	kg SO_2 eq	5.95E-11
CML2001 - Jan. 2016, Photochemical Ozone Creation Potential (POCP)	kg Ethene eq	5.41E-11
CML2001 - Jan. 2016, Global Warming Potential (GWP 100)	kg CO_2 eq	1.92E-13
CML2001 - Jan. 2016, Eutrophication Potential (EP)	kg PO_4 eq	5.78E-10

The functional unit of the LCA analysis was chosen as “1 kWh electricity production from coal in Turkey” since the power generation from lignite and hard coal processes developed in the study represent the country average values. The scope of the analysis includes both “gate-to-gate” and partial “cradle-to-gate” comparison of the developed and Ecoinvent processes. The gate-to-gate analysis compares individual Ecoinvent and newly developed electricity production processes for lignite and hard coal whereas “cradle-to-gate” analysis compares the overall impact and includes the raw material acquisition phase, that is, coal mining activities. The purpose of the latter comparison is to reveal the differences in environmental impacts associated with coal mining phase, which arises due to difference in the average coal consumption of the power plant in Ecoinvent and developed processes. The relative share of the countries from which the hard coal is imported was taken into account based on 2016 import statistics reported by Turkish Hard Coal Authority and the appropriate coal mining processes were selected from the Ecoinvent database (Table 4.19). These relative shares were observed while connecting the imported hard coal mining processes in the GaBi plans.

Table 4.19. Hard coal imports by country and corresponding Ecoinvent processes.

Country	2016 Imports (thousand tons)	% Share	Corresponding Ecoinvent Process
Poland	196	0.65	PL - Hard coal mine operation
US	184	0.61	RNA - Hard coal mine operation
Other OECD	358	1.18	WEU - Hard coal mine operation
Columbia	15182	50.11	RLA - Hard coal mine operation
South Africa	2317	7.65	ZA - Hard coal mine operation
Russia	11779	38.88	RU - Hard coal mine operation
Others	279	0.92	RoW - Hard coal mine operation

RNA: North America; WEU: Western Europe; RLA: Latin America and the Caribbean; RoW: Rest of the World

5. RESULTS AND DISCUSSIONS

"Electricity production from hard coal in Turkey" and "Electricity production from lignite in Turkey" LCA processes have been developed within the scope of this study to represent the country-average electricity production processes of Turkey from the respective fuel types. The processes were developed by first estimating the key air emissions associated with electricity production at hard coal and lignite power plants in Turkey based on combustion and emission control technologies and fuel properties utilized at those power plants and then replacing the emissions values of the key air pollutants in template Ecoinvent processes with the newly calculated ones (with the exception of calculated PM_{10}, and $PM_{2.5}$ values, which were deemed inaccurate upon evaluation). Additionally, an LCA analysis was conducted in order to compare the environmental impacts of the original Ecoinvent processes and the one developed in this study. The results of emission calculations are presented and discussed in Section 5.1 and LCA results are given in Section 5.2.

5.1. Calculation of Key Air Emissions and Development of LCA Processes

Emission values of CO_2, CO, N_2O, NO_x, SO_x, PM_{10}, and $PM_{2.5}$ have been estimated for lignite and hard coal power plants within the scope of the study. Calculated emissions for individual power plants and their weighted average values that represent country-averages for lignite and hard coal power plants of Turkey are given in Table 5.1 and Table 5.2, respectively. The calculated national average values of the emissions and values of those emissions in current Ecoinvent 3.3 database are compared in Table 5.3 and represent the main findings of this study.

The following subsections are dedicated to explaining the discrepancies between the calculated and Ecoinvent emission values for the air pollutants considered within the scope of the study. It has to be noted that according to Ecoinvent's process documentation for lignite and hard coal electricity production processes, all emissions in the dataset with the exception of SO_2, NO_x and PM emissions are adopted from the global dataset, which in turn is a weighted-average process of ten datasets within the database, corresponding to electricity production processes of Austria, Belgium, Czech Republic, Germany, Spain, France, Hungary, Poland, Slovakia and Slovenia. Hence, the emission values of the Ecoinvent processes are not necessarily the ultimate, most accurate figures and the calculated emissions may in fact be closer to real values.

Table 5.1. Calculated emissions of lignite power plants in Turkey (kg/kWh).

Power Plant	**CO_2**	**CO**	**N_2O**	**NO_x**	**SO_x**	**PM_{10}**	**$PM_{2.5}$**
PP1	0.931000	0.000482	0.000062	0.007598	0.002382	0.037417	0.010971
PP2	0.830000	0.000434	0.000056	0.006838	0.009187	0.000299	0.000297
PP3	0.931000	0.000283	0.000037	0.004458	0.001497	0.000198	0.000195
PP4	0.931000	0.000282	0.000036	0.004443	0.003184	0.039956	0.011603
PP5	0.931000	0.000212	0.000027	0.003340	0.002019	0.000146	0.000145
PP6	0.931000	0.000212	0.000027	0.003346	0.003521	0.030996	0.008998
PP7	0.931000	0.000298	0.000039	0.004698	0.042082	0.001734	0.001731
PP8	0.931000	0.000422	0.000055	0.006656	0.002981	0.045412	0.013237
PP9	1.030000	0.000136	0.002268	0.003266	0.001026	0.011703	0.001706
PP10	0.931000	0.000261	0.000034	0.004109	0.003680	0.034721	0.010090
PP11	0.931000	0.000217	0.000028	0.003419	0.028785	0.038257	0.011812
PP12	1.030000	0.000058	0.000964	0.001388	0.015436	0.004974	0.000725
PP13	1.030000	0.000075	0.001256	0.001808	0.000344	0.006479	0.000944
PP14	0.931000	0.000192	0.000025	0.003027	0.001288	0.025578	0.007433
PP15	1.030000	0.000073	0.001212	0.001745	0.002435	0.006252	0.000911
Weighted Average	**0.947083**	**0.000257**	**0.000269**	**0.004165**	**0.008728**	**0.019166**	**0.005595**

Table 5.2. Calculated emissions of hard coal power plants (kg/kWh).

Power Plant	**CO_2**	**CO**	**N_2O**	**NO_x**	**SO_x**	**PM_{10}**	**$PM_{2.5}$**
PP16	1.030000	0.003937	0.000766	0.001094	0.013408	0.002822	0.000411
PP17	0.931000	0.000188	0.000021	0.002738	0.000525	0.000538	0.000251
PP18	0.830000	0.000181	0.000020	0.003972	0.012351	0.013795	0.003974
PP19	0.830000	0.000078	0.000009	0.001624	0.000268	0.000209	0.000129
PP20	0.830000	0.000086	0.000009	0.001775	0.000293	0.006392	0.004142
PP21	0.830000	0.000086	0.000009	0.001775	0.000293	0.000135	0.000141
PP22	1.030000	0.003415	0.000664	0.000949	0.000064	0.002448	0.000357
PP23	0.830000	0.000086	0.000009	0.001775	0.000293	0.000229	0.000146
Weighted Average	**0.858066**	**0.000542**	**0.000097**	**0.002178**	**0.003741**	**0.004590**	**0.001721**

Table 5.3. Calculated and Ecoinvent emissions of lignite and hard coal power plants (kg/kWh).

Power Plant	**CO_2**	**CO**	**N_2O**	**NO_x**	**SO_x**	**PM_{10}**	**$PM_{2.5}$**
Lignite (Calculated)	**0.947083**	**0.000257**	**0.000269**	**0.004165**	**0.008728**	**0.019166**	**0.005595**
Lignite (Ecoinvent)	1.230671	0.000230	0.000017	0.002810	0.009280	0.025590	0.022900
Hard coal (Calculated)	**0.858066**	**0.000542**	**0.000097**	**0.002178**	**0.003741**	**0.004590**	**0.001721**
Hard coal (Ecoinvent)	0.949724	0.000088	0.000013	0.002960	0.001810	0.000038	0.000034

Additionally, weighted average coal inputs were calculated for lignite and hard coal electricity production processes as 1.468 and 0.490 respectively, based on net annual electricity production and specific fuel consumption values of the power plants given in Tables 4.14 and 4.15. Since, hard coal power plants in Turkey utilize both domestic and imported hard coal, the hard coal inputs were further divided among different countries of origin based on data in Table 4.19.

Finally, the country-average electricity production of from lignite and hard coal processes were created by substituting the calculated emission and coal consumption values in the corresponding Ecoinvent processes. The developed processes with complete input and output tables for lignite and hard coal are given in Appendix A.

5.1.1. CO_2 Emissions

The calculated CO_2 emissions were lower for both lignite (0.947083 kg/kWh vs. 1.230671 kg/kWh) and hard coal (0.858066 kg/kWh vs. 0.949724 kg/kWh) processes compared to Ecoinvent values. CO_2 is the only emission that was not calculated based on US EPA’s WebFIRE database but rather on CO_2 emission values reported on g/kWh basis in MIT’s “The Future of Coal” report. Unlike CO_2 EFs of WebFIRE database, the emission values reported in MIT’s report took into account the operational conditions of the boilers (subcritical, supercritical and ultra-supercritical). Hence, lower emission values associated with increased thermodynamic efficiency of supercritical boilers were taken into account. Since, 5 out of 8 hard coal power plants operate with supercritical PC or FBC boilers, the resulting calculated emission values were lower compared to Ecoinvent values. On the other hand, according to Ecoinvent process documentation, CO_2 emission values are calculated via bottom-up approach by collection information about single plants in European counties. However, no information is provided on sampling approach or the number of power plants that have been assessed. The only visible shortcoming of MIT EFs is that no distinction is made between hard coal and lignite fuel and the focus is instead on specific combustion conditions. Finally, the Report also provides distinct CO_2 EFs for coal power plants with installed carbon capture technologies as seen in Table 4.10. This gives an opportunity for easily updating the processes by substituting the current CO_2 EFs with the ones specific to carbon capture technologies when such installations are made in the power plants.

5.1.2. CO Emissions

The calculated CO emissions very close to and Ecoinvent values for lignite processes (calculated: 0.000257 kg/kWh vs. Ecoinvent: 0.000230 kg/kWh) and higher for hard coal processes (calculated: 0.000542 kg/kWh vs. Ecoinvent: 0.000088 kg/kWh). The high emission value for hard coal process arises from much higher EF for FBC technology (8.16466 kg/ton coal) compared to its lignite counterpart (0.06804 kg/ton coal) in the WebFIRE database, as indicated in Table 4.4. Since the ratio of hard coal power plants utilizing FBC boilers (PP16, and PP22) on net annual electricity production basis is comparable to lignite power plants (PP9, PP12, PP13 and PP15), which are 17.6% and 12.1% for hard coal and lignite power plants, respectively, the difference in emissions is solely due to differences in WebFIRE EFs. The emission values in Ecoinvent datasets are derived from literature and are average values of 14 different countries. Considering the fact that CO is a product of incomplete combustion of fuel and hence depends on the fuel oxidation efficiency of boilers, the CO emissions from hard coal power plants in Turkey with boilers operating under supercritical conditions (5 out of 8 power plants), would be expected to be lower compared to lignite power plants, as it is a case in Ecoinvent datasets. Therefore, it is concluded that the CO emission value indicated in the original Ecoinvent process for hard coal is likely to be closer to real emission value that the calculated one. The calculated CO emission can be improved in the future upon update of the WebFIRE EF for FBC boilers.

5.1.3. N_2O Emissions

The calculated N_2O emissions for both lignite (0.000269 kg/kWh) and coal (0.000097 kg/kWh) processes were higher than their Ecoinvent counterparts, which were 0.000017 and 0.000013 for lignite and hard coal, respectively. The main reason behind higher calculated N_2O emissions is the fact that only “Uncontrolled” EFs were available for N_2O gas emitted from coal power plants in the WebFIRE. Both LNB and $DeNO_x$ reduce the amount of N_2O emissions as part of the NO_x group but no EFs were available for these technologies in the database. Although the information on LNB and $DeNO_x$ applications were available for the power plants (Table 4.12), no information could be gathered regarding the efficiency of these technologies from the power plant operators and the values reported in the literature were inconsistent. Therefore, the EFs could not be modified to account for the installed emission control technologies. According to Ecoinvent process documentation, the N_2O emissions in the lignite and hard coal datasets are the averages of 10 and 14 European countries, respectively, but the individual country-specific N_2O emissions are calculated by taking into account the share of $DeNO_x$ installation among the coal power plants in the country. Therefore, despite the fact the Ecoinvent emission values are based on calculated emission values of European countries, the values are probably closer to real figures than the ones calculated in this study.

5.1.4. NO_x Emissions

The NO_x emissions calculated for lignite (0.004165 kg/kWh) and hard coal (0.002178 kg/kWh) processes were in agreement with their Ecoinvent counterparts (lignite: 0.002810 kg/kWh and hard coal: 0.002960 kg/kWh), up to third decimal point for hard coal processes. NO_x removal was accounted for by applying WebFIRE EFs for LNB control technology to lignite and hard coal power plants with nitrogen removal control technologies. EFs for LNB were also applied to power plants with $DeNO_x$ installations since no separate EFs were available for this nitrogen removal technology.

According to Ecoinvent process documentation, the amount of NO_x in the flue gas (mg/m^3) and a factor for the amount of flue gas (m^3/GJ burned) were adopted from the “Air pollution from electricity-generating large combustion plants: an assessment of the theoretical emission reduction of SO_2 and NO_x through implementation of BAT as set in the BREFs” Report published by the European Environmental Agency (EEA, 2008). Additionally, the share of lignite and hard coal power plants with installed $DeNO_x$ technology which lowers NO_x emissions were adopted as 66% and 19% based on total installed capacity, respectively. The efficiency of the technology was accepted as 60% based on Dones et al. (2007). In this study, the collective share of $DeNO_x$ and LNB technologies for lignite and hard coal power plants were 3% (PP13) and 55% (PP19-23), respectively (based on Table 4.11 and Table 4.12). On the other hand, the difference in WebFIRE EFs for uncontrolled and LNB installed power plants were 27% for lignite and only 3-9% for hard coal power plants (depending on combustion technology). Hence, due to lower share of power plants with installed $DeNO_x$ technology and lower emission reduction efficiency, the calculated NO_x emissions were higher for lignite processes compared to its Ecoinvent counterpart. On the other hand, calculated NO_x emissions for hard coal process was comparable to its Ecoinvent counterpart because, even though higher percentage of plants had DeNO$_x$ technology, the accepted reduction efficiency was much lower.

5.1.5. SO$_x$ Emissions

The calculated SO$_x$ emissions for both lignite (0.008728 kg/kWh) and hard coal (0.003741 kg/kWh) processes were comparable with their Ecoinvent counterparts (lignite: 0.009280 kg/kWh and hard coal: 0.001810 kg/kWh). Since, only uncontrolled EFs were available for SO$_x$ emissions in the WebFIRE database, these EFs were modified with a coefficient corresponding to sulfur reduction efficiency of FGD technologies, based on literature data (unlike in the case of DeNO$_x$ control technology, the emission reduction efficiency values for FGD technologies were available and within close range in the literature). Hence, 95% and 80% SO$_2$ emission removal efficiency were adopted for wet lime and dry lime FGD, respectively.

Similar to NO$_x$ emissions, the amount of SO$_x$ in the flue gas (mg/m^3) and a factor for the amount of flue gas (m^3/GJ burned) were adopted from the “Air pollution from electricity-generating large combustion plants: an assessment of the theoretical emission reduction of SO$_2$ and NO$_x$ through implementation of BAT as set in the BREFs” Report published by the European Environmental Agency (EEA, 2008). The share of lignite and hard coal power plants with installed FGD technology were adopted as 36% and 81% based on total installed capacity, respectively. The efficiency of the technology was estimated as 95% for lignite and 92% for hard coal power plants based on Dones et al. (2007). In this study, the share of lignite and hard coal power plants with installed FGD emission control technologies were 78% and 72% based on net annual production values. Very close accepted emission reduction efficiencies (only two power plants had dry-lime based FGD with 80% efficiency and the rest were wet-lime based FGD with 95% efficiency) and comparable FGD installation shares among power plants resulted in similar SO$_x$ emissions in both processes.

5.1.6. PM$_{10}$ and PM$_{2.5}$ Emissions

The calculated PM emissions proved to be the most inaccurate, particularly for hard coal processes where the calculated values were orders of magnitude higher compared to their Ecoinvent counterparts (0.004590 kg/kWh vs. 0.000038 kg/kWh for PM$_{10}$ and 0.001721 kg/kWh vs 0.000034 kg/kWh for PM$_{2.5}$). Only PM$_{10}$ emission values for lignite processes were agreeable with Ecoinvent values with 0.019166 kg/kWh for calculated and 0.025590 kg/kWh for Ecoinvent processes. The calculated PM$_{10}$ and PM$_{2.5}$ emissions were therefore not used in development of the lignite and hard coal electricity production processes. There are multiple factors that collectively have contributed to the large discrepancy in PM emission values between calculated and existing Ecoinvent processes, as explained further:

- Unlike the EFs of the other air pollutants calculated in this study, the EFs for PM are complex functions of boiler type and configuration, pollution control equipment, and fuel properties that include ash and sulfur content, as seen in Tables 4.8 and 4.9. Here, each extra term introduces additional uncertainty into the equation, contributing to error.
- While ash and sulfur content of lignite utilized in individual lignite power plants were obtained from MMO reports and other scientific literature, these data were not available for hard coal power plants operating with imported coal, which constitute the majority of hard coal power plants in Turkey. Hence, due to lack of data, the upper limit values for ash and sulfur content of hard coal imposed by the Ministry of Environment and Urban Planning were adopted in place of actual measured values. Therefore, these values are likely overrepresented, leading to higher calculated EFs and consequently higher calculated emission values.
- Both PM_{10} and $PM_{2.5}$ emissions are divided into FPM and CPM. According to AP-42 document, the PM EFs available in WebFIRE database include only the filterable portion of the total PM emissions and data on condensable particulate emissions must collected or calculated separately. Therefore, since total PM_{10} and $PM_{2.5}$ EFs were revoked in the WebFIRE database, these EFs were adopted from Argonne National Laboratory of the U.S. Department of Energy Report, leading to further uncertainty (Cai et al., 2012).
- Even if PM emissions could be reliably estimated, the calculated PM_{10} and $PM_{2.5}$ emissions would not have been sufficient to fully replace the emissions in Ecoinvent datasets because PM emissions here are presented as (a) particulates below 2.5 μm, (b) particulates above 10 μm and (c) particulates between 2.5 μm and 10 μm, because $PM_{2.5}$ is in fact the subset of PM_{10} emissions (PM_{10} emission values given for Ecoinvent processes in Table 5.3 are the summed values of “a” and “c”).

5.1.7. Final Remarks on Calculated Emissions

In overall, with the exception of PM emissions, the results of the calculations were successful when all aspects of the study are taken into consideration, namely the number of different independent data sources, assumptions, approximations that were utilized and the uncertainty that has been introduced into calculations with each additional factor:

- The calculations are based on US EPA's EFs rather than directly measured values reported by the power plants operators
- The combustion technology subtypes (boiler details) were not available for most power plants and the averages of the EFs for each individual subtype had to be used
- Multiple parameters required for calculations including power plant fuel consumption values and fuel properties such as ash and sulfur content and LHV of lignite and hard coal were obtained by different means and from multiple sources rather than a single, unified study;
    - Part of the fuel consumption values of individual power plants were obtained from MMO Report (MMO, 2017) while others had to be calculated based on either total annual coal consumption and electricity production values reported by the operators or based on calorific values of the coal (which in turn, we also collected from multiple sources) utilized at the plants. Incidentally, the consumption values reported by the MMO were based on plant design parameters
    - The sulfur and ash content and LHV of lignite used in calculations were obtained from multiple literature sources, reports and websites of the power plant operators. The information on sulfur and ash content and LHV of imported hard coal was not available and had to be approximated by the limits set on imported coal by the Ministry of Environment and Urbanization
- The efficiencies of emission control technologies were not available on individual power plant basis and had to be approximated based on literature values as it was the case for wet lime and dry lime desulfurization
- EFs for lignite and hard coal had to be used interchangeably in several occasions when EFs were not available for particular fuel combustion technology
- Power plants for which emission control technologies were not reported by the power plant operators or in the literature, were assumed to not possess those technologies and suitable EFs were selected based on this assumption. However, theoretically, those technologies could still be utilized by the power plants but simply not reported.

Despite the abovementioned list of error and uncertainty sources, the calculated emission values, with the exception of PM emissions, were comparable with the values available within the corresponding Ecoinvent processes. In overall, the most accurate results were obtained for CO and SO_x emissions in lignite process and CO_2 and NO_x emissions in hard coal process.

5.2. LCA Comparison of Developed and Ecoinvent Processes

LCA was conducted within the scope of the study to compare the environmental impacts of the developed electricity production processes from lignite and Ecoinvent with their Ecoinvent counterparts. Section 5.2.1 presents the “gate-to-gate” LCA comparison results of individual electricity production processes. Section 5.2.2 presents “cradle-to-gate” LCA results which also include raw material acquisition phase (i.e. coal mining operations) in order to analyze the environmental consequences of consuming different amounts of fuel per kWh net electricity generated.

5.2.1. “Gate-to-gate” LCA Comparison of Developed and Ecoinvent Processes

The results of LCA comparison of the electricity production from lignite and hard coal processes developed within the scope of the study with corresponding Ecoinvent processes are presented in this section. The processes are compared across four environmental impact categories: Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and photochemical ozone creation potential (POCP) as well as in terms of total environmental impact through normalization.

5.2.1.1. Global Warming Potential (GWP). GWP is a quantitative measure of how much a given amount of a chemical substance contributes to global warming, i.e. long-term trend of increasing average global temperature throughout a set period of time, which in this study was selected to be 100-year time horizon. The GWP of individual substances are defined as the ratio of the warming caused by the given substance to the ration of warming caused by equivalent mass of CO_2 and expressed in carbon dioxide equivalent (CO_2 eq).

The results of LCA comparison of the developed and Ecoinvent electricity production processes from lignite and hard coal are given in Figure 5.1. As expected, CO_2 is the predominant emission contributing to GWP for all examined processes. Since, calculated CO_2 outputs are lower for both developed processes compared to Ecoinvent processes, the overall GWP potential is lower for both newly developed processes. Since this difference in CO_2 emission is higher for lignite processes (0.283588 kg CO_2/kWh) than for hard coal processes (0.091658 kg CO_2/kWh), the difference in GWP is similarly reflected in the graph. However, the calculated emission values for N_2O, which is a potent GHG with GWP 265 times greater than that of CO_2, are higher for both calculated lignite and hard coal processes, which slightly lowers the difference in GWP of calculated and Ecoinvent processes, as seen in Figure 5.1.

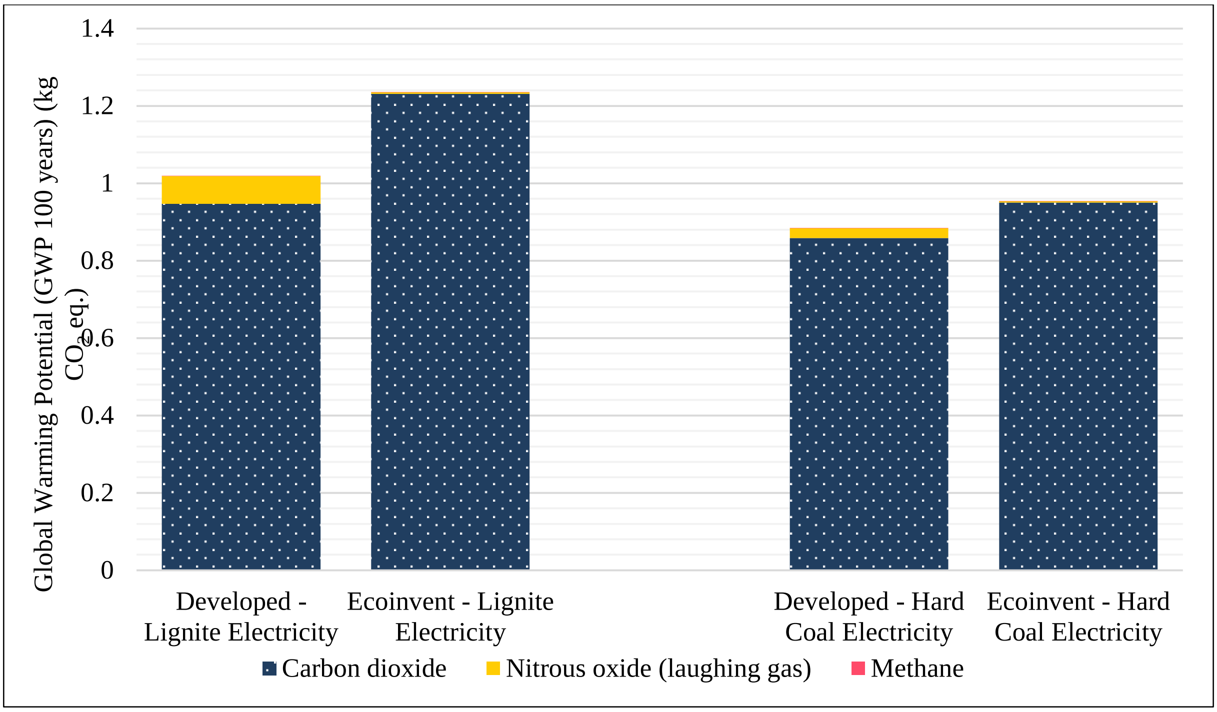

Figure 5.1. Global warming potential (GWP) of developed and Ecoinvent processes.

5.2.1.2. Acidification Potential (AP). AP is a measure of substance's capacity to lower the pH value of its environment by increasing the concentration of hydrogen ions in the presence of water, resulting in damage of vegetation, declining fish populations and deterioration of buildings and other construction structures. AP is expressed in sulfur dioxide equivalent (SO_2 eq).

The AP of developed and Ecoinvent electricity production processes from lignite and hard coal are given in Figure 5.2. The primary source of AP in all processes is SO_x emissions followed by NO_x and minor contributions from hydrogen chloride and hydrogen fluoride. Interestingly, despite the fact that calculated SO_x emissions for the developed lignite process are slightly lower compared to Ecoinvent process, the calculated NO_x emission value is almost double the amount in Ecoinvent process and since NO_x has a twice higher AP compared to SO_x, the total AP of the developed and Ecoinvent processes have been equalized (0.0126 SO_2 eq for both processes). For hard coal processes, both SO_x and NO_x emissions are higher in the developed processes compared to their Ecoinvent counterparts, resulting in having 50% higher overall AP.

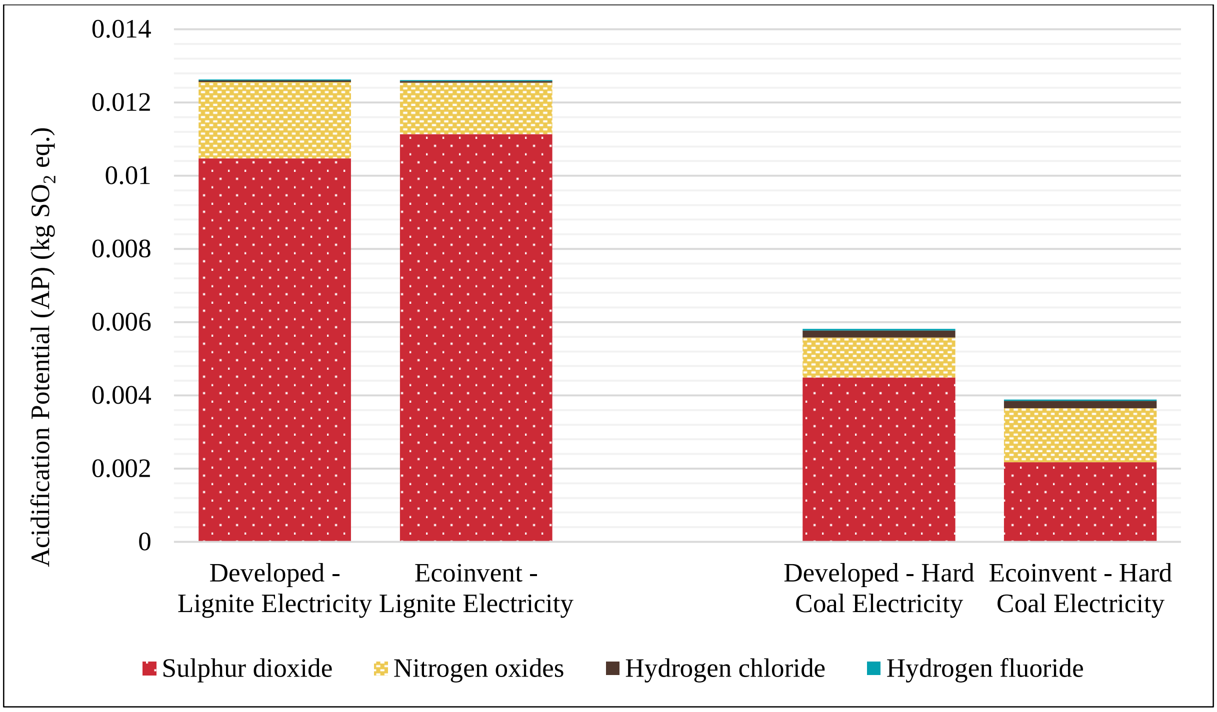

Figure 5.2. Acidification potential (AP) of developed and Ecoinvent processes.

5.2.1.3. Eutrophication Potential (EP). EP is a reflection of amount of nutrients (phosphorus and nitrogen), that can leach into aquatic environments resulting in overgrowth of algae and leading to reduction of available oxygen in water. In the CML methodology the EP is expressed in terms of phosphate equivalent (PO_4 eq) although alternative units are also used in other methodologies such as nitrogen equivalent (N eq) in TRACI impact assessment methodology.

The EP of developed and Ecoinvent electricity production processes from lignite and hard coal are given in Figure 5.3. The only two emissions contributing to EP of electricity production processes from lignite and hard coal are NO_x and N_2O, with NO_x being the primary contributor. The values of both emissions are higher in calculated lignite process compared to its Ecoinvent counterpart, resulting in 40% higher overall EP than Ecoinvent process. The calculated NO_x emissions for developed hard coal process is higher compared to its Ecoinvent counterpart, while N_2O emissions are lower, leading to 20% lower EP than Ecoinvent process.

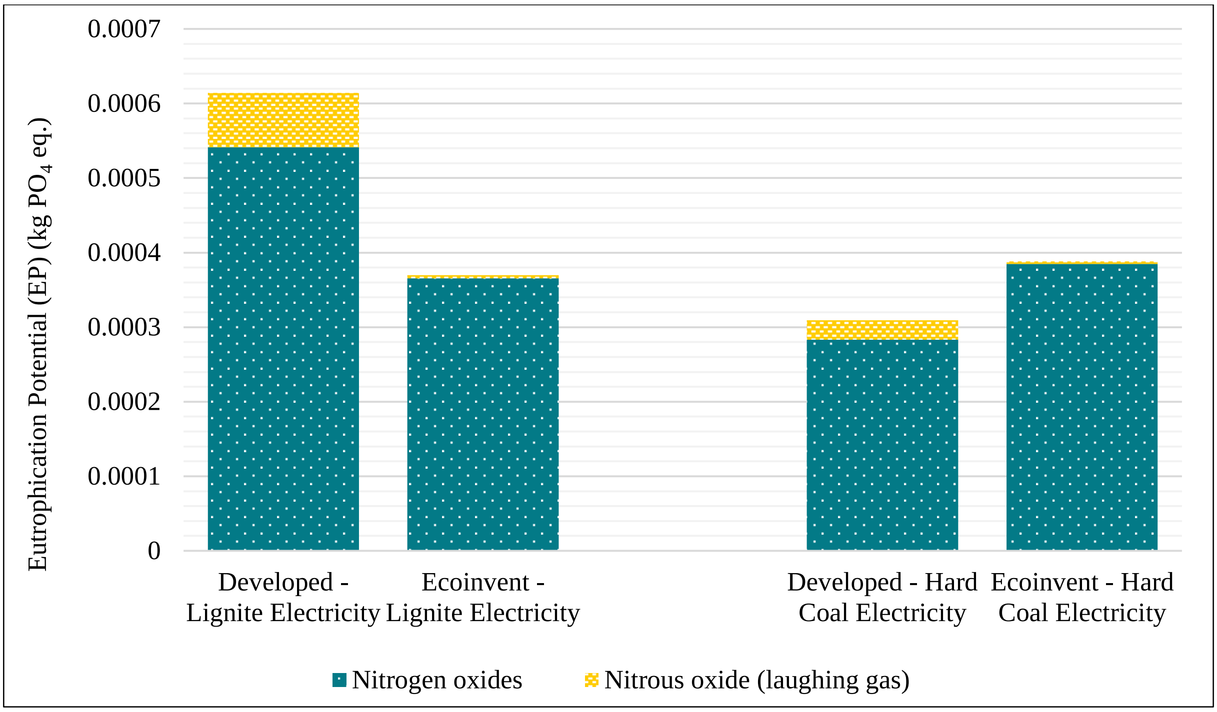

Figure 5.3. Eutrophication potential (EP) of developed and Ecoinvent processes.

5.2.1.4. Photochemical Ozone Creation Potential (POCP). POCP, also known as summer smog, forms in the troposphere as a result of degradation of volatile organic compounds (VOCs) and nitrogen under high temperature and sunlight conditions through complex photochemical reactions and is a type of severe air pollution. POCP is expressed in terms of ethene equivalent (ethene eq).

The POCP of developed and Ecoinvent electricity production processes from lignite and hard coal are given in Figure 5.4. The main contributor to POCP in all processes is SO_x, followed by NO_x emissions, while CO and other organic air emissions have minor contributions. The “organic emissions to air” category seen in the graph is a collection of organic compounds, including halogenated organic emissions, a diverse group of hydrocarbons, benzene derivatives and methane. Due to the fact that the calculated lignite process has slightly lower SO_x emission and twice the amount of NO_x emission values compared to values in the corresponding Ecoinvent process and with NO_x having almost two times higher POCP than SO_x, the resulting overall POCP of two processes are very close to each other. For hard coal process, the calculated SO_x emission value is twice as high as its Ecoinvent counterpart while NO_x emissions are slightly lower, resulting in 31% higher overall POCP for calculated hard coal electricity production process.

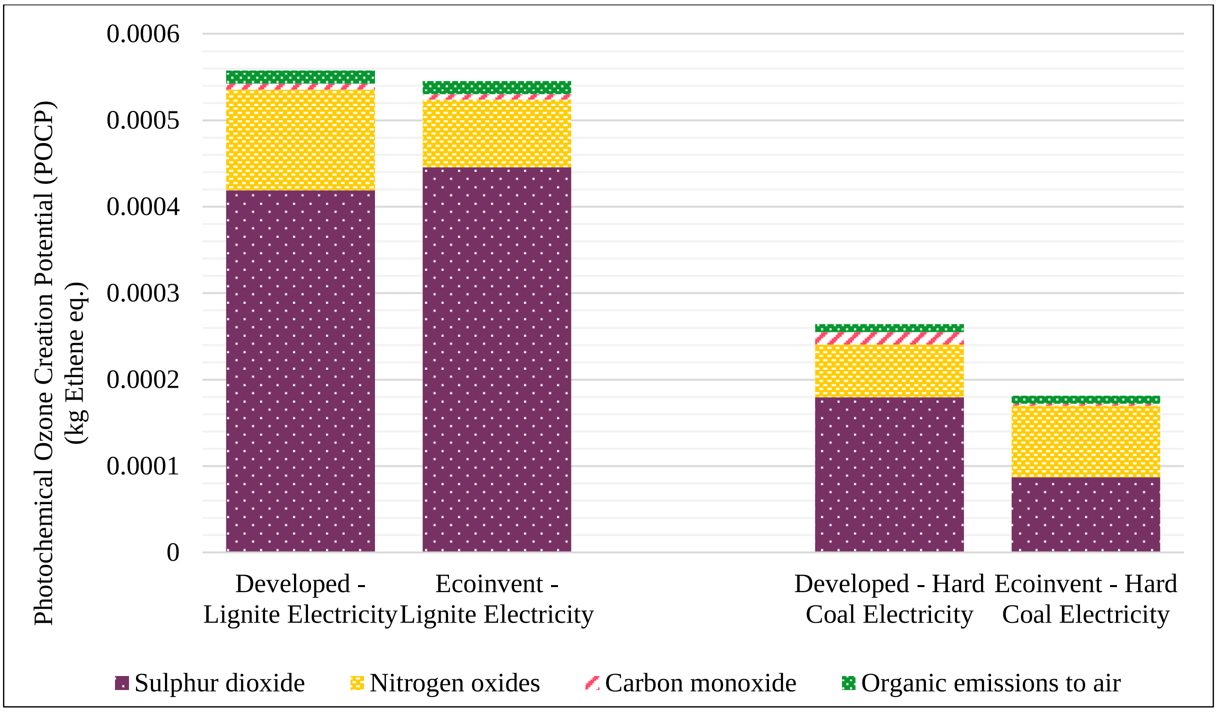

Figure 5.4. Photochemical Ozone Creation Potential (POCP) of developed and Ecoinvent processes.

5.2.1.5. Normalization. Normalization is an optional step of LCA defined as calculating the magnitude of category indicator results relative to reference information in ISO 14044:2006 document, and allows for comparison of the magnitude of individual environmental impact potentials covered within the scope of the study and calculating the total environmental impact (ISO, 2006). CML 2001 - Jan. 2016, EU 25+3 normalization method based on reference values of 25+3 EU countries was used in the study and the results are given in Figure 5.5.

AP is by far the highest environmental impact for all compared processes, constituting more than half of the total impact. The other half is divided between POCP and GWP, with only minor share of from EP. In overall, the best result is obtained for lignite processes, for which the difference in total normalized environmental impact between the developed and Ecoinvent processes is less than 2%. For hard coal processes, the total normalized impact of the calculated process is 21% higher compared to Ecoinvent process.

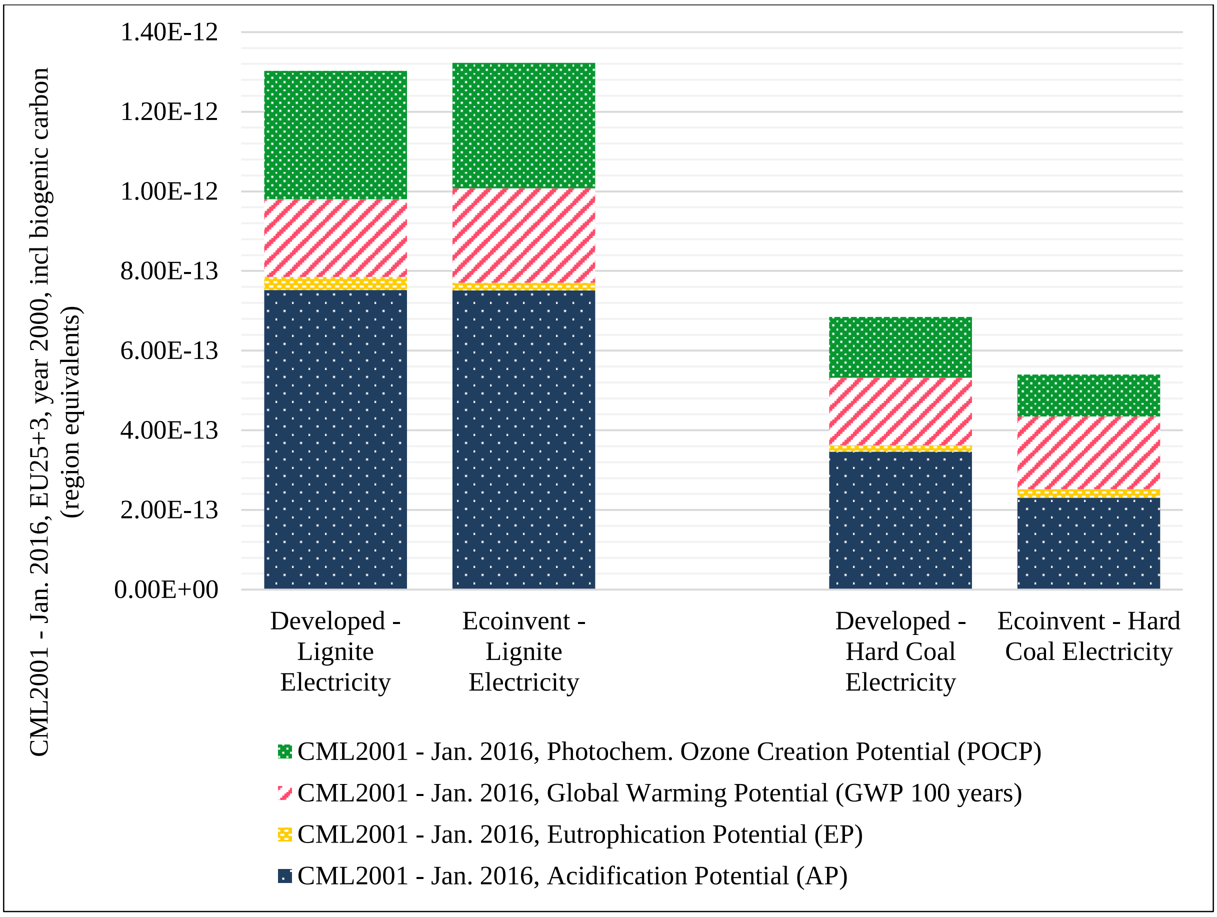

Figure 5.5. Normalization results of developed and Ecoinvent processes.

5.2.2. “Cradle-to-gate” LCA Comparison of Developed and Ecoinvent Processes

This section presents the results of “cradle-to-gate” comparison of the developed and Ecoinvent processes and includes coal mining operations in addition to electricity production processes from hard coal and lignite compared in the previous section. The fuel input values in developed lignite and hard coal electricity production processes vary from the ones in the corresponding Ecoinvent processes and the goal of the “cradle-to-gate” analysis was to measure the differences in upstream environmental impacts stemming from differences in fuel input amounts of electricity production processes. The coal mining processes themselves are procured from Ecoinvent 3.3 database and are not newly developed processes; the goal of the analysis is to measure the differences in environmental impacts solely due to differences in lignite and coal consumption of the power plants per kWh of net electricity generated. The results of the comparison for lignite and hard coal are given in Sections 5.2.2.1 and 5.2.2.2, respectively.

5.2.2.1. "Cradle-to-gate" LCA Comparison of Lignite Processes. The results of "cradle-to-gate" LCA comparison of the developed and Ecoinvent lignite processes in terms of GWP, AP, EP and POCP are given in Figures 5.6 to 5.9. The graphs include separate coal mining and electricity production processes and their combined impacts. The results reveal that the major portion of GWP, AP and POCP result from the electricity production processes for both the developed and Ecoinvent processes. The electricity production phase accounts for 97%, 99% and 98% of total GWP, AP and POCP, respectively.

On the other hand, the major portion of EP come from the coal mining phase with 95% and 96% of the total impact for lignite and Ecoinvent processes, respectively. The high EP of the mining phase is primarily due to phosphate emissions to freshwater resulting from mining operations, with 0.0092 kg PO_4 eq. for the developed and 0.0078 kg PO_4 eq for Ecoinvent processes. Phosphate emissions constitute roughly 87% of total EP from the mining phase for both developed and Ecoinvent processes. Hence, it can be concluded that while the difference in lignite consumption by the power plant has minimal impact in terms of GWP, AP and POCP, it has the major impact on EP associated with the mining phase and hence the total EP across lignite's life cycle.

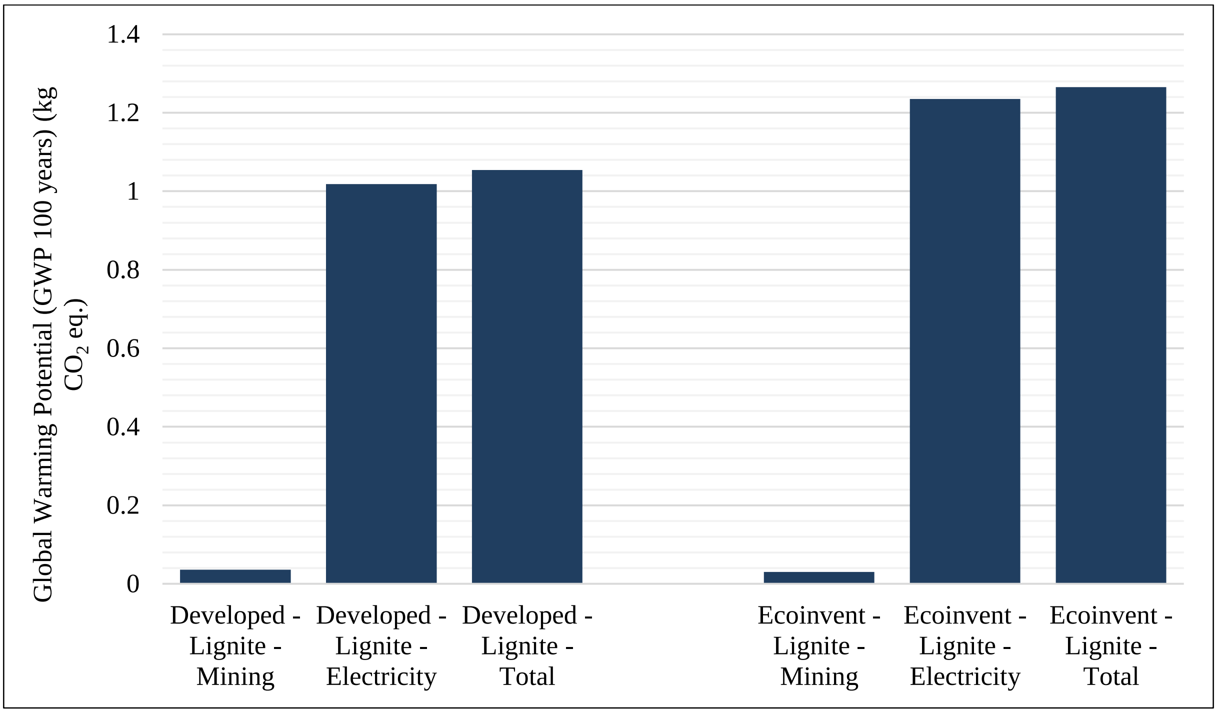

Figure 5.6. Cradle-to-gate global warming potential (GWP) of developed and Ecoinvent lignite processes.

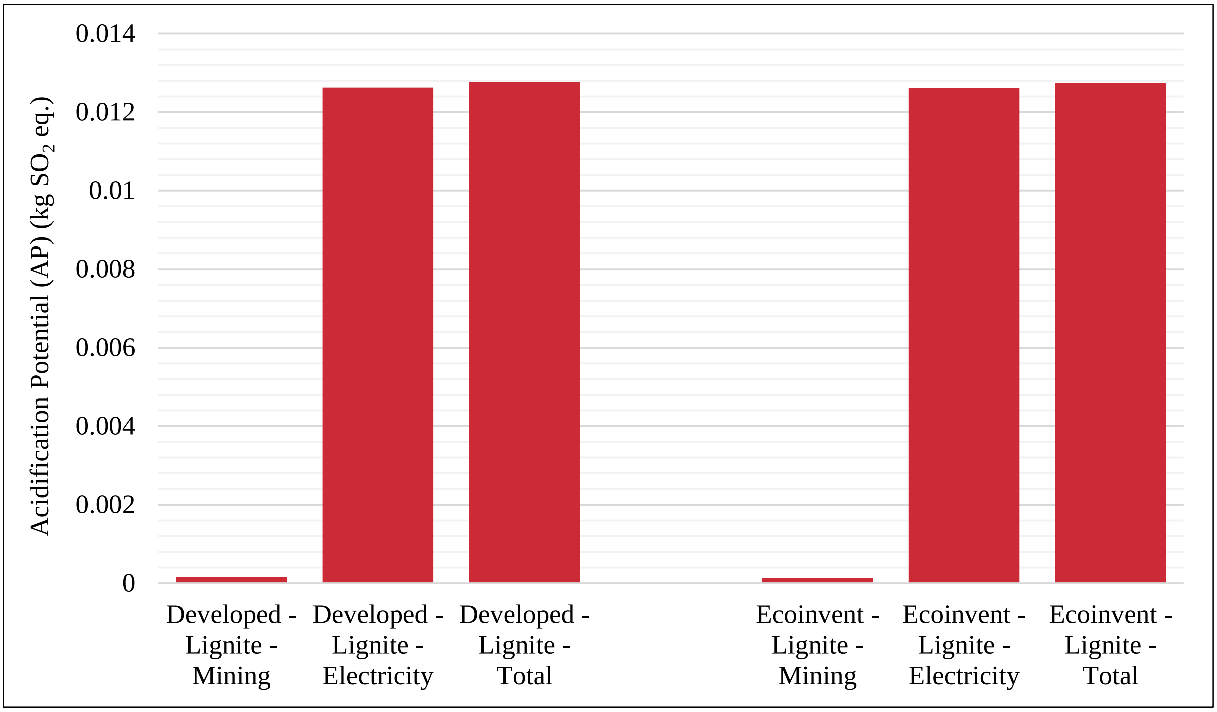

Figure 5.7. Cradle-to-gate acidification potential (AP) of developed and Ecoinvent lignite processes.

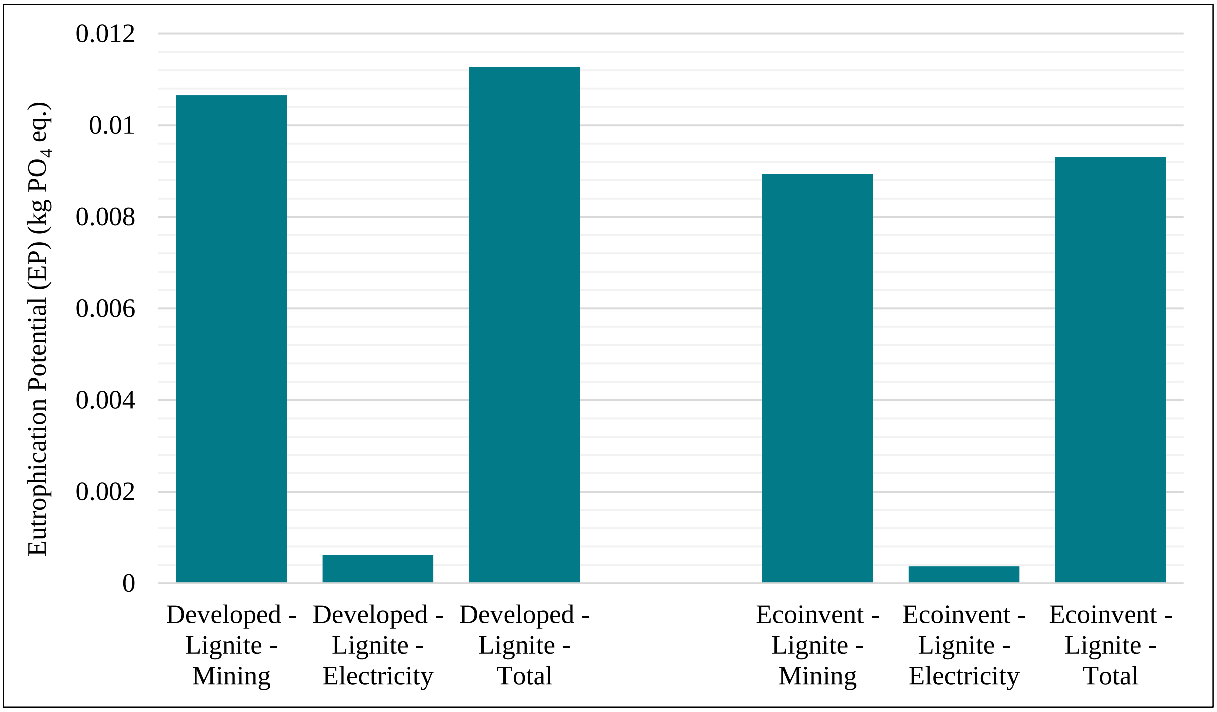

Figure 5.8. Cradle-to-gate eutrophication potential (EP) of developed and Ecoinvent lignite processes.

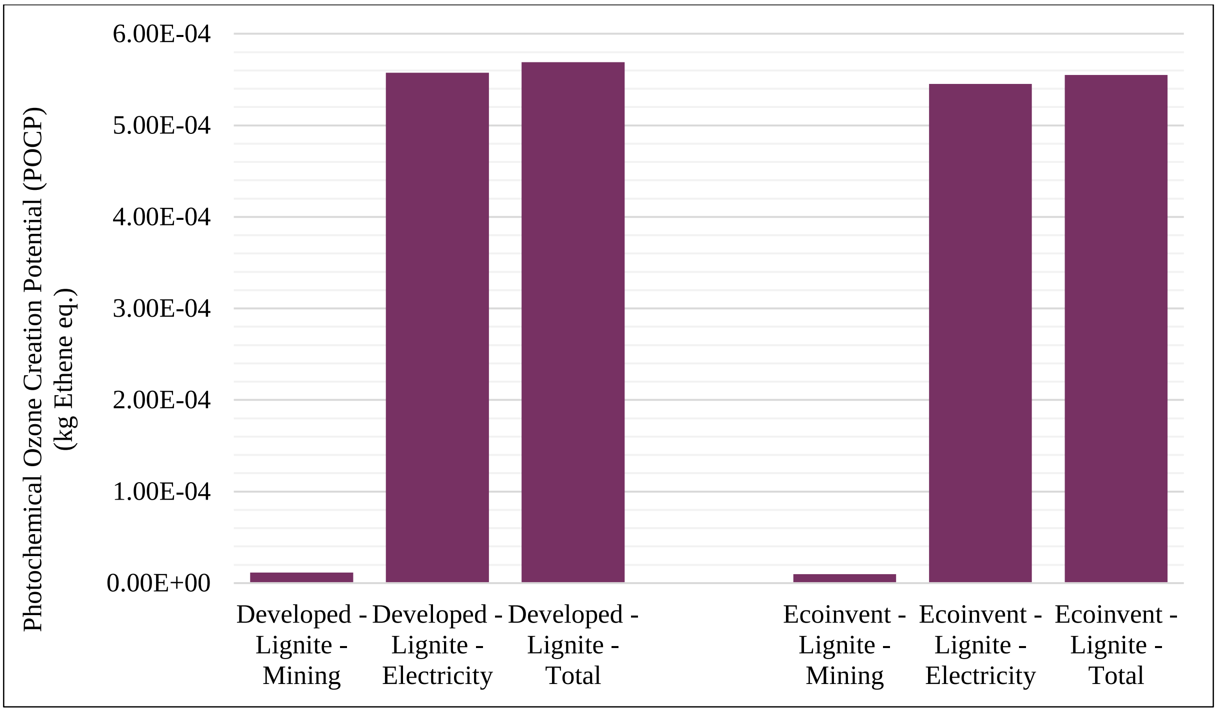

Figure 5.9. Cradle-to-gate photochemical ozone creation potential (POCP) of developed and Ecoinvent lignite processes.

5.2.2.2. “Cradle-to-gate” LCA Comparison of Hard Coal Processes. Since most hard coal power plants in Turkey operate on imported hard coal, the appropriate country-specific coal mining processes were selected from the Ecoinvent database and the amounts were adjusted based on coal import statistics of Turkey. The values in the developed processes are based on hard coal import statistics for the year 2016 as reported by the Turkish Hard Coal Authority, whereas the Ecoinvent dataset values are based on 2010 import statistics reported by EUROCOAL in 2012, according to Ecoinvent process documentation. Moreover, the import figures used in Ecoinvent dataset are for total hard coal imports into the country and does not differentiate between hard coal for thermal power plants, steel production, industry or domestic heating purposes, whereas import values used in the developed process are specifically for the hard coal imported to be utilized in thermal power plants. The GaBi plans created based on the available information for the developed and Ecoinvent processes are shown in Figure 5.10 and Figure 5.11, respectively.

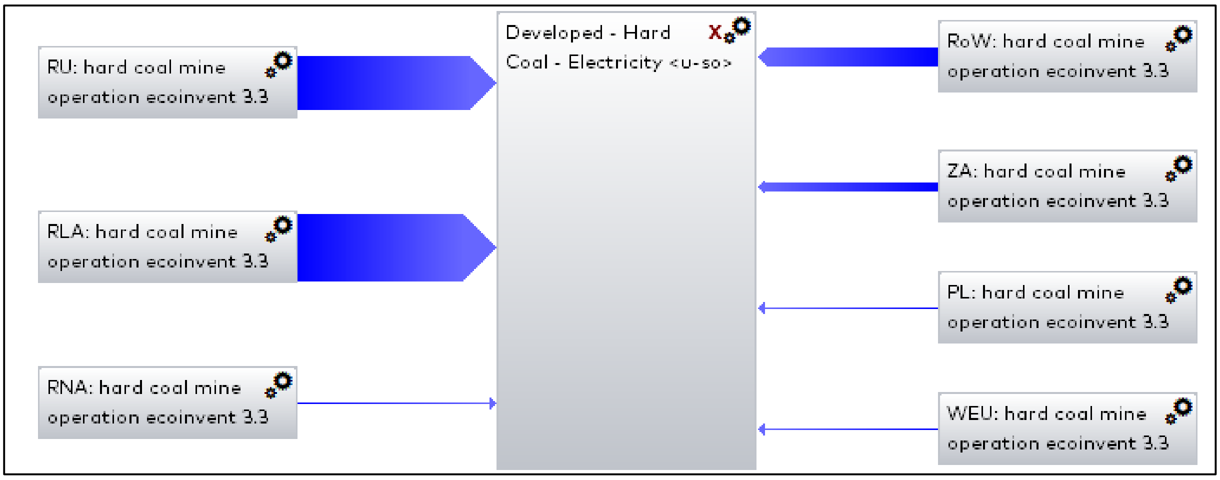

Figure 5.10. Cradle-to-gate GaBi plan of the developed hard coal process.

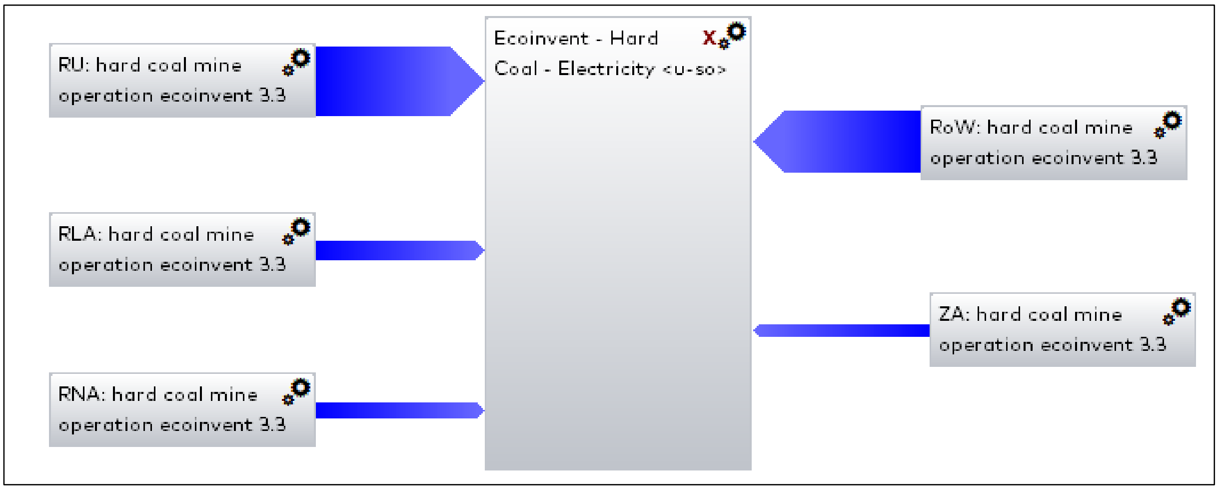

Figure 5.11. Cradle-to-gate GaBi plan of the Ecoinvent hard coal process.

The results of “cradle-to-gate” LCA comparison of the developed and Ecoinvent hard coal processes in terms of GWP, AP, EP and POCP are given in Figures 5.12 to 5.15. The same trends and patterns were observed for the hard coal processes as for the lignite processes. However, since the difference in average hard coal consumption of the calculated and Ecoinvent processes were smaller (developed: 0.490 kg/kWh; Ecoinvent: 0.437 kg/kWh) compared to lignite processes (developed: 1.463 kg/kWh; Ecoinvent: 1.231 kg/kWh), the difference in upstream environmental impacts were also less pronounced. Similar to lignite, the difference in power plant’s fuel consumption has the major impact in total EP of the hard coal and minimal impact on GWP, AP and POCP.

On the other hand, the contribution of the mining phase to total environmental impact across all impact categories is higher for both developed and Ecoinvent processes, compared to lignite processes despite the fact that less hard coal is utilized per kWh electricity produced. The reason for this is twofold. Firstly, the environmental impacts associated with electricity production from hard coal is lower compared to that of lignite, which lowers its relative contribution to total environmental impact. Secondly, the emissions associated with coal mining phase are higher for hard coal LCA processes compared to lignite processes, in terms of absolute numbers, which in turn could be multiple reasons including the differences in mining equipment and technology, additional pretreatment applications, the type of mining practices employed (e.g. open pit vs. underground).

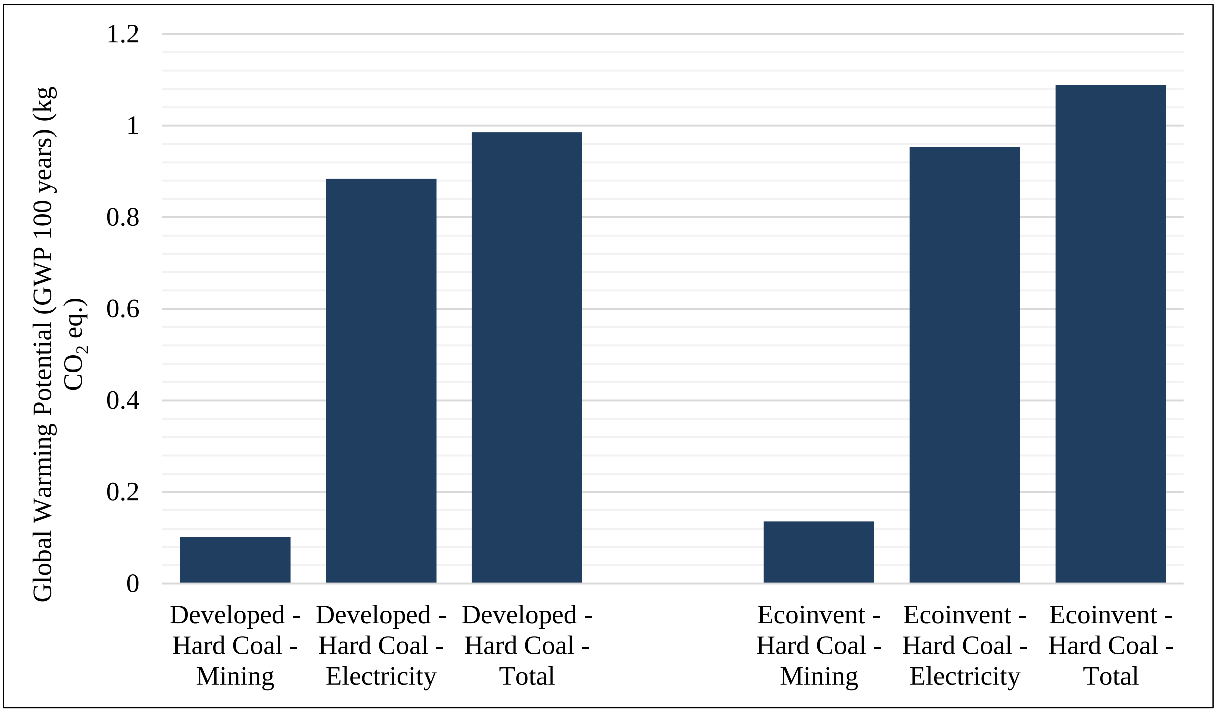

Figure 5.12. Cradle-to-gate global warming potential (GWP) of developed and Ecoinvent hard coal processes.

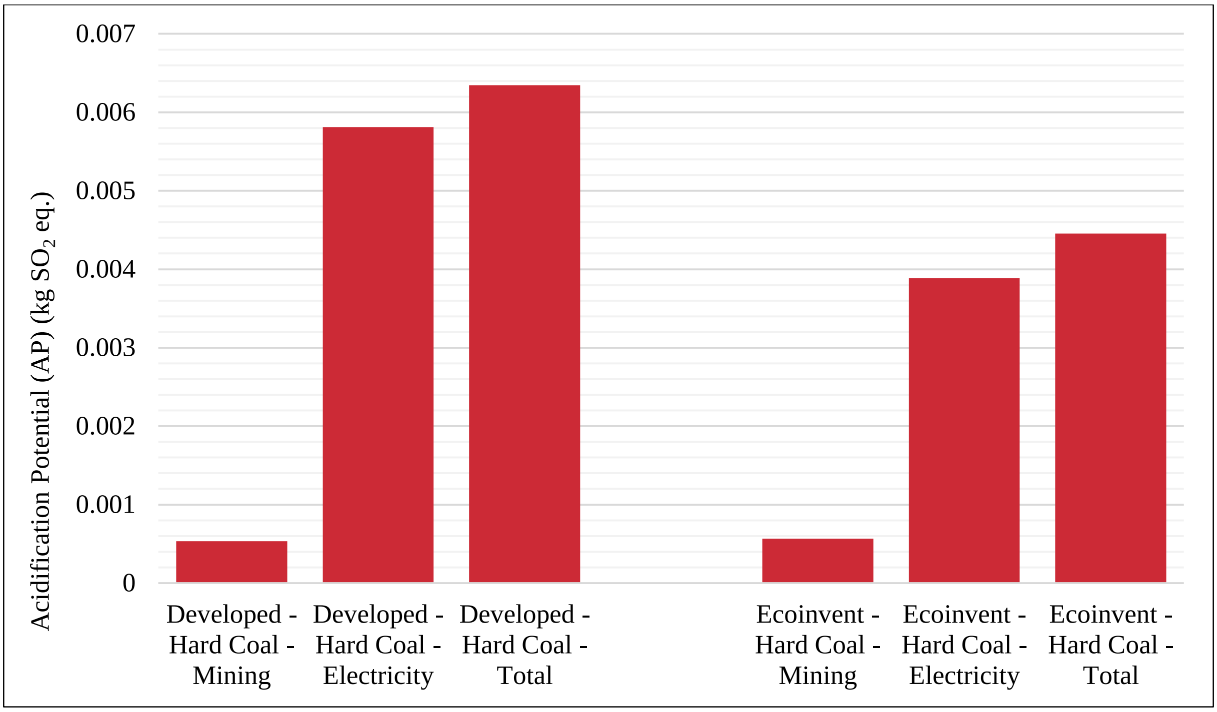

Figure 5.13. Cradle-to-gate acidification potential (AP) of developed and Ecoinvent hard coal processes.

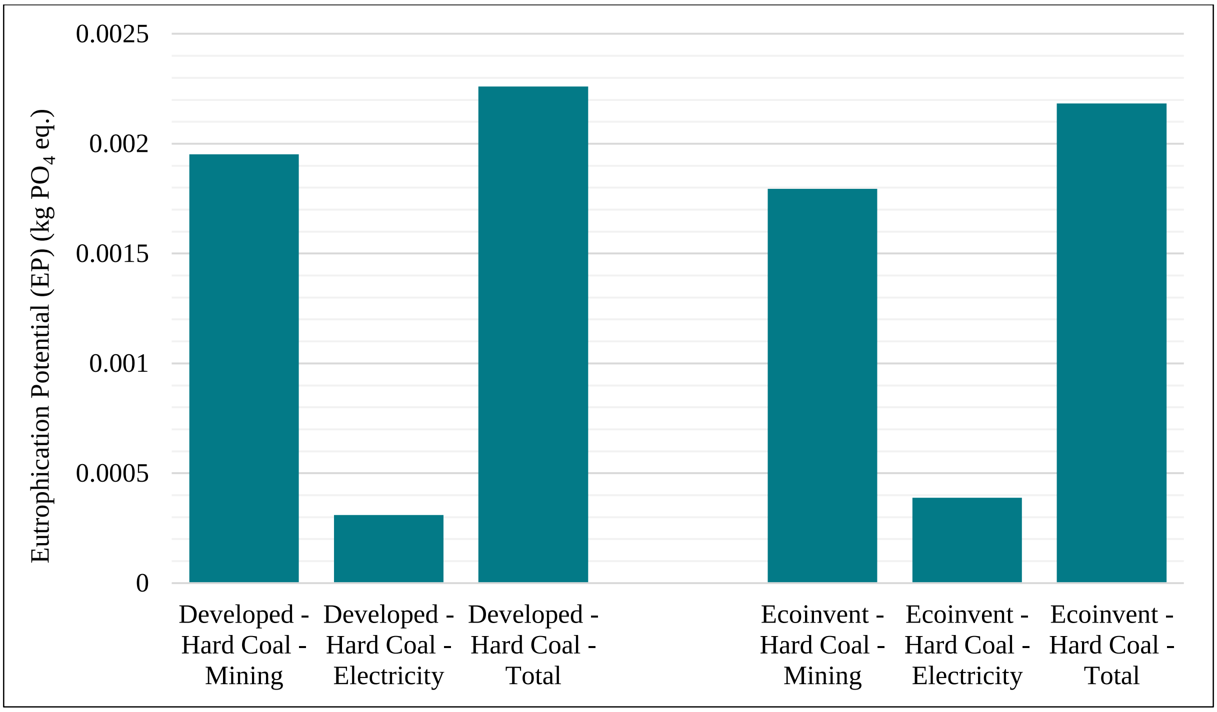

Figure 5.14. Cradle-to-gate eutrophication potential (EP) of developed and Ecoinvent hard coal processes.

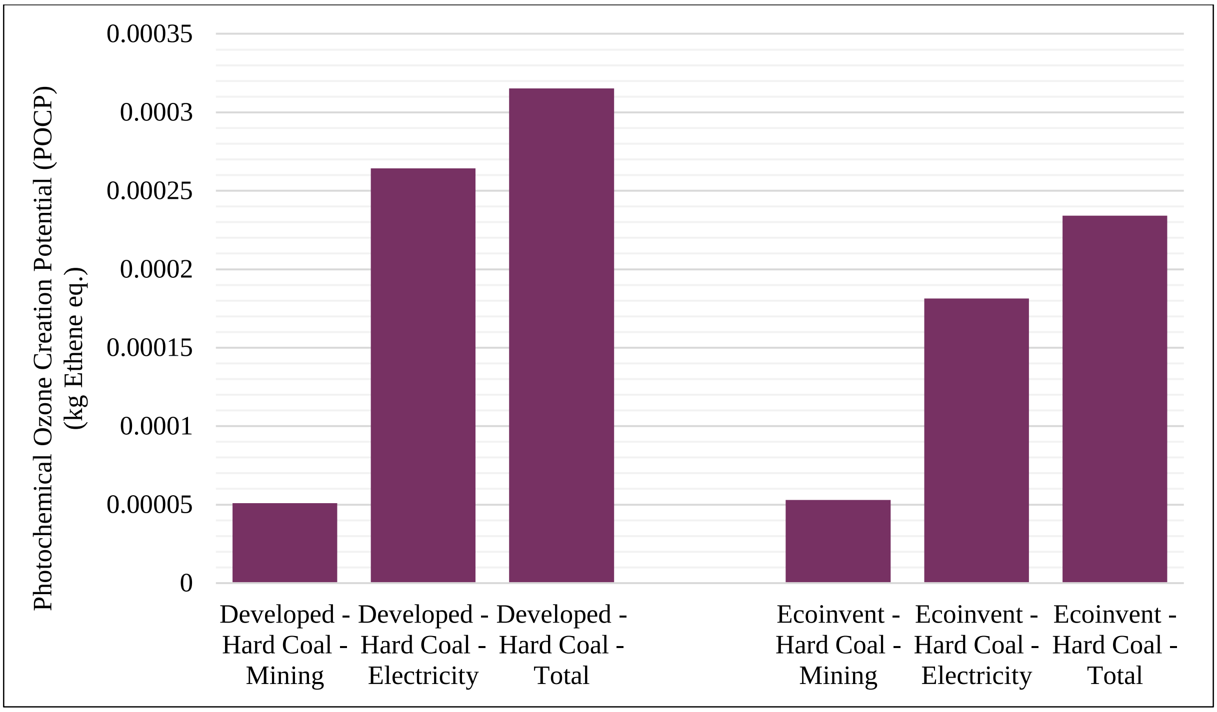

Figure 5.15. Cradle-to-gate photochemical ozone creation potential (POCP) of developed and Ecoinvent hard coal processes.

5.2.2.3. "Cradle-to-gate" Normalization Results. The total normalized environmental impacts of the developed and Ecoinvent lignite and hard coal processes are given in Figure 5.16. The difference in total impact between the developed and Ecoinvent processes is only 4% for lignite and 17% for hard coal.

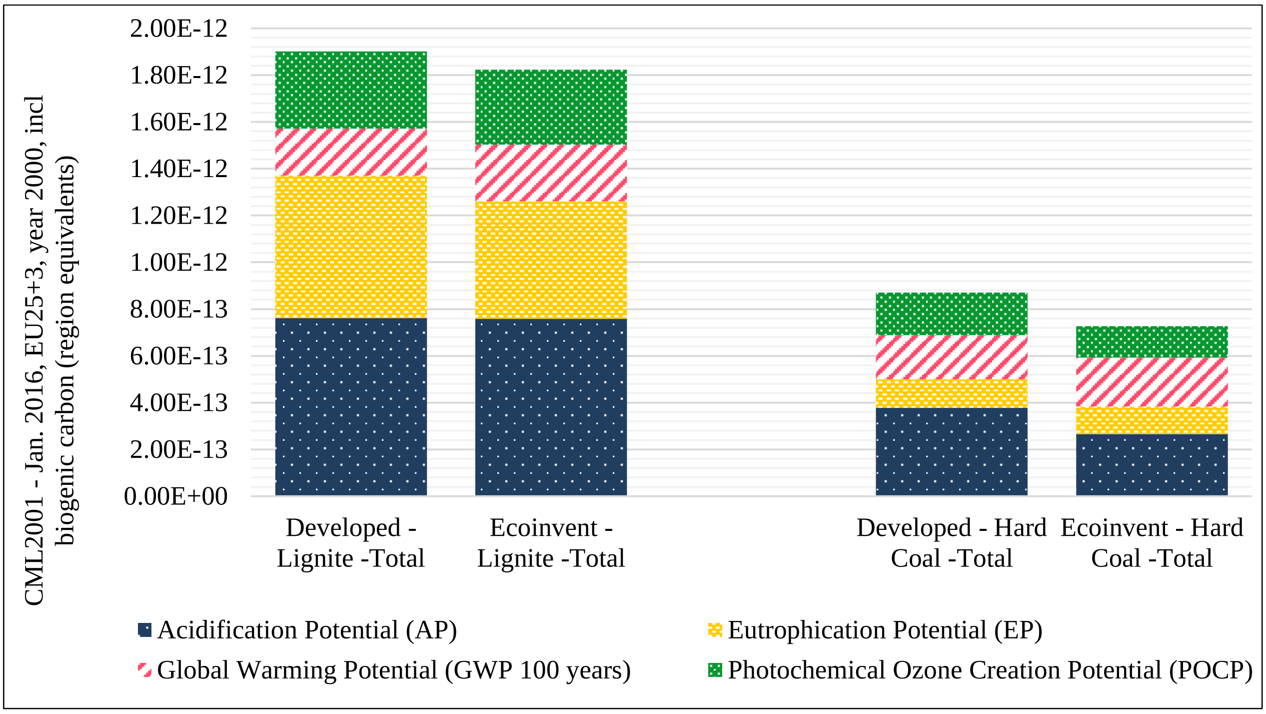

Figure 5.16. Cradle-to-gate normalization results of developed and Ecoinvent processes.

6. CONCLUSIONS

LCA is a data-intensive methodology and depends on accurate, well-documented and up-to-date inventory data to produce reliable results. Developing country-specific energy processes that accurately reflect the energy production conditions in the country is a key step in that direction. The difficulty of obtaining emission and fuel consumption data for the power plants in Turkey is a major barrier for developing the energy processes. This problem has been exacerbated as the energy sector of Turkey became increasingly privatized in the past decade since, there is no incentive for private energy companies to share their emission data publicly. Meanwhile, the energy processes of Turkey currently available in international LCI databases such as Ecoinvent are primarily based on average world or European inventory data and outdated information and do not reflect the true conditions of the country. The research study presented in this thesis overcomes these barriers by first calculating the key emissions and fuel consumption values of lignite and hard coal power plants of Turkey on theoretical basis and then using their weighted averages to build the electricity production from lignite and hard coal processes.

In this study, the emission values of CO_2, CO, N_2O, NO_x, SO_x, PM_{10} and $PM_{2.5}$ were first calculated for lignite and hard coal power plants operating in Turkey based on coal combustion and emission control technologies and the ash, sulfur, energy content and subtype (bituminous, subbituminous and lignite) of utilized coal, using the US EPA’s EFs specific to abovementioned parameters and the CO_2 EFs published by MIT. Plant-specific coal consumption values were partly gathered from literature and the rest was calculated using annual electricity production values, plant efficiency and the LHV of coal utilized in respective power plants. The calculated values were then inserted into template lignite and hard coal datasets from Ecoinvent 3.3 database to develop the country-average electricity production processes for lignite and hard coal. Finally, the developed processes were compared with their original Ecoinvent counterparts in terms of their environmental impacts using GaBi 8 LCA software and CML 2001 - Jan. 2016 impact assessment methodology. The environmental parameters considered in the comparison are global warming, acidification, eutrophication, and photochemical ozone creation potentials. Additionally, a “cradle-to-gate” LCA was conducted involving the coal mining phase as well, in order to measure the differences in upstream environmental impacts due to differences in coal consumption values.

The calculated values for CO_2, CO, N_2O, NO_x and SO_x emissions were close to their counterparts in Ecoinvent database for both lignite and hard coal electricity production processes. In terms of closeness to Ecoinvent dataset values, the most accurate results were obtained for CO (calculated: 0.000257 kg/kWh; Ecoinvent: 0.000230 kg/kWh) and SO_x (calculated: 0.008728 kg/kWh; Ecoinvent: 0.009280 kg/kWh) emissions in lignite and CO_2 (calculated: 0.858066 kg/kWh; Ecoinvent: 0.949724 kg/kWh) and NO_x (calculated: 0.002178 kg/kWh; Ecoinvent: 0.002960 kg/kWh) emissions in hard coal processes. On the contrary, with the exception of PM_{10} emission value calculated for lignite process, that was comparable with its Ecoinvent counterpart (calculated: 0.019166 kg/kWh; Ecoinvent: 0.025590 kg/kWh), PM emissions for both lignite and hard coal processes were highly inaccurate, particularly for hard coal process, with calculated PM_{10} and $PM_{2.5}$ values being orders of magnitude greater compared to Ecoinvent values. The most likely contributors to this discrepancy are the inadequacy of the PM EFs in the WebFIRE database, since only filterable portion of PMs could be reliably represented in the EF formulae, as stated in "Compilation of Air Pollutant Emission Factors" document (AP-42) of the US EPA and the unreliability of the ash and sulfur content data of imported hard coal, which are approximated based on limit values set on imported coal by the Ministry of Environment and Urbanization. For this reason, the calculated PM_{10} and $PM_{2.5}$ values were deemed unreliable and therefore were not used in development of lignite and hard coal processes. The values can be recalculated with updated EFs and more accurate hard coal data and integrated into the developed processes in the future. However, since PM emissions only have impact in human toxicity category in CML 2001 - Jan. 2016 and other impact assessment methods, the lack of PM emission values did not have any effect on the results of the LCA comparison between developed and Ecoinvent processes, where global warming, acidification, eutrophication, and photochemical ozone creation potentials were considered.

Gate-to-gate LCA comparison of the developed and Ecoinvent processes has revealed comparable results for both lignite and hard coal processes. The closest results for lignite processes were obtained in AP (99.9% identical) and POCP categories (98.1% identical) that primarily depend on SO_x emissions. The closest results for hard coal processes were obtained in GWP (92.7% identical) category that mainly depends on CO_2 emissions and EP (79.6%) category that depends primarily on NO_x emissions. In terms of total normalized impacts, the difference between the developed and Ecoinvent processes was 1.6% and 21.1% for lignite and hard coal processes, respectively. The results demonstrate that more accurate results were obtained for lignite process compared to hard coal process. This can be partially attributed to less reliable sulfur content data for hard coal, that was based on limit values imposed on imported hard coal, which determines the SO_x emissions, which in turn is the primary emission that determines the AP that constitutes more than half of total environmental impact, as evident from normalization results. The cradle-to-gate LCA comparison that includes the mining operations of lignite and hard coal life cycles has revealed that the mining phase constitutes the major portion of the total EP, which is 94.5% and 86.3% for the developed lignite and hard coal process life cycles. Therefore, the average coal input of the lignite and hard coal electricity production processes is a much more significant determinant of the total EP than NO_x and N_2O emission values.

The results obtained for air pollutant calculations and LCA comparison studies described above have demonstrated the adequacy of the approach employed in the study in gathering the necessary inventory data, emission calculations and process development procedures. Despite the key data used in calculations including ash and sulfur content and LHV of coal, combustion and emission control technologies employed at power plants, annual net electricity production and power plant fuel consumption values being gathered from different sources, the multiple assumptions and approximations including efficiencies of emission control technologies and key properties of imported hard coal and gaps in data including lack of EFs and emission control technology information for several power plants, the results of emission calculations and LCA comparison study have proven to be comparable with the corresponding datasets in Ecoinvent database. This shows that not only the electricity production from lignite and hard coal processes developed in this study can be used in future LCA studies in Turkey but that the same approach can be attempted to develop the processes for other energy carriers such as natural gas and fuel oil.

It is important to note that although the values obtained in the study are comparable with ones in the corresponding Ecoinvent datasets, these Ecoinvent datasets are not necessarily the most accurate representations of the real energy production conditions and are also base on multiple assumptions and approximations. However, the fact that Ecoinvent datasets are subjected to both internal and third-party review process and data quality evaluation, lends credibility to the information contained within these datasets. Additionally, in the future studies, the LCA comparison of the developed processes can be expanded to include datasets from other reputable databases such as GaBi Professional. The ultimate verification of the accuracy of these calculations and the degree to which the processes developed within the scope of the study reflect the real conditions will only be possible once emission and fuel consumption data is measured and made available for each power plant in the country. Meanwhile, the current results can be further improved by gathering a more detailed and accurate information on coal combustion and emission control technologies as fuel properties.

The sheer number of data sources and modeling assumptions used in the calculations may have resulted in accumulation of uncertainties. In order to ensure the reliability of the results, a quantified uncertainty analysis can be conducted in the future for the developed processes and compared with that of Ecoinvent datasets. Special care must be taken while handling emission control technologies and their reduction efficiencies since these have the highest impact on the final calculated emission values. It's worth noting that the study was performed for a small sample size, that is, 23 thermal power plants. A statistical analysis can hence be performed to define the confidence range in which the calculated values fall within a probability of 95%. The obtained emission values can be further validated by verifying whether they fall within the boundaries defined by the European Union and other reputable agencies and governmental bodies.

The main advantage of the LCA processes developed in this study is the ease with which they can be updated and improved in the future. Since, all inventory data, assumptions and calculation procedures are presented in a transparent manner, the future LCA practitioners can update the processes using new data as it becomes available. The parameterized and modular nature of the approach simplifies this task since the processes can be updated easily by tweaking individual parameters such as the sulfur content of fuel or net electricity produced by individual power plants.

The lignite and hard coal electricity production processes developed within the scope of this study can be integrated into international LCI databases such as Ecoinvent and GaBi Professional as well as the future national LCI database of Turkey when it is established. They can be integrated as individual processes and also serve as inputs for generating the average national electricity production dataset (power grid mix) when other power production processes such as hydropower, wind, geothermal etc. have also been developed. These processes, developed based on energy production data specific to Turkey will increase the reliability of LCA studies conducted in the country by suppling accurate inventory data for the analysis.

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APPENDIX A: DEVELOPED LCA PROCESSES

Electricity production from lignite and hard coal LCA processes are given in Table A.1 and Table A.2, respectively.

Table A.1. Electricity production from lignite in Turkey.

Flow	Quantity	Amount	Unit
Inputs			
GLO: lignite ash [Waste]	Mass	0.16907	kg
GLO: lignite power plant [allocatable product]	Number of pieces	1.00E-11	pcs.
GLO: petroleum coke [allocatable product]	Mass	0.001599	kg
GLO: residue from cooling tower [Waste]	Mass	5.75E-05	kg
GLO: water, completely softened, from decarbonised water, at user [allocatable product]	Mass	0.06901	kg
GLO: water, decarbonised, at user [allocatable product]	Mass	2.300319	kg
RoW: lignite [allocatable product]	**Mass**	**1.467577**	**kg**
Water, cooling, unspecified natural origin [Water]	Volume	0.059966	m3
Outputs			
Electricity, high voltage [allocatable product]	**Energy**	**1**	**kWh**
Alkane (unspecified) [Group NMVOC to air]	Mass	2.52E-06	kg
Alkene (unspecified) [Group NMVOC to air]	Mass	2.48E-06	kg
Antimony [Heavy metals to air]	Mass	6.00E-09	kg
Arsenic [Heavy metals to air]	Mass	3.40E-08	kg
Barium [Inorganic emissions to air]	Mass	1.78E-07	kg
Benzene [Group NMVOC to air]	Mass	2.50E-06	kg
Benzo{a}pyrene [Group PAH to air]	Mass	2.30E-12	kg
Boron [Inorganic emissions to air]	Mass	2.15E-05	kg
Bromine [Inorganic emissions to air]	Mass	7.60E-07	kg
Butane [Group NMVOC to air]	Mass	2.19E-07	kg
Cadmium [Heavy metals to air]	Mass	7.73E-09	kg
Carbon dioxide [Inorganic emissions to air]	**Mass**	**0.947083**	**kg**
Carbon monoxide [Inorganic emissions to air]	**Mass**	**0.000257**	**kg**
Chromium [Heavy metals to air]	Mass	3.06E-08	kg
Chromium (+VI) [Heavy metals to air]	Mass	3.69E-09	kg
Cobalt [Heavy metals to air]	Mass	6.19E-09	kg
Copper [Heavy metals to air]	Mass	8.51E-08	kg
Dust (> PM10) [Particles to air]	Mass	0.00135	kg
Dust (PM2,5 - PM10) [Particles to air]	Mass	0.00269	kg
Dust (PM2.5) [Particles to air]	Mass	0.0229	kg
Ethane [Group NMVOC to air]	Mass	4.72E-07	kg
Formaldehyde (methanal) [Group NMVOC to air]	Mass	6.67E-07	kg

Table A.1. Electricity production from lignite in Turkey (continued).

Flow	**Quantity**	**Amount**	**Unit**
Outputs			
Hydrogen chloride [Inorganic emissions to air]	Mass	6.50E-05	kg
Hydrogen fluoride [Inorganic emissions to air]	Mass	1.55E-05	kg
Iodine [Inorganic emissions to air]	Mass	5.52E-07	kg
Lead [Heavy metals to air]	Mass	2.99E-08	kg
Lead (Pb210) [Radioactive emissions to air]	Activity	0.096268	Bq
Manganese [Heavy metals to air]	Mass	9.73E-08	kg
Mercury [Heavy metals to air]	Mass	6.22E-08	kg
Methane [Organic emissions to air (group VOC)]	Mass	1.15E-05	kg
Molybdenum [Heavy metals to air]	Mass	1.85E-08	kg
Nickel [Heavy metals to air]	Mass	1.17E-07	kg
Nitrogen oxides [Inorganic emissions to air]	**Mass**	**0.004165**	**kg**
Nitrous oxide (laughing gas) [Inorganic emissions to air]	**Mass**	**0.000269**	**kg**
Pentane (n-pentane) [Group NMVOC to air]	Mass	1.69E-06	kg
Polonium (Po210) [Radioactive emissions to air]	Activity	0.175974	Bq
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD) [Halogenated organic emissions to air]	Mass	8.05E-14	kg
Polycyclic aromatic hydrocarbons (PAH, unspec.) [Group PAH to air]	Mass	1.15E-08	kg
Potassium (K40) [Radioactive emissions to air]	Activity	0.033355	Bq
Propane [Group NMVOC to air]	Mass	4.03E-07	kg
Propene (propylene) [Group NMVOC to air]	Mass	1.84E-07	kg
Radium (Ra226) [Radioactive emissions to air]	Activity	0.024843	Bq
Radium (Ra228) [Radioactive emissions to air]	Activity	0.014837	Bq
Radon (Rn220) [Radioactive emissions to air]	Activity	1.460703	Bq
Radon (Rn222) [Radioactive emissions to air]	Activity	2.587859	Bq
Selenium [Heavy metals to air]	Mass	1.41E-07	kg
Strontium [Inorganic emissions to air]	Mass	1.58E-07	kg
Sulfur dioxide [Inorganic emissions to air]	**Mass**	**0.008728**	**kg**
Thorium (Th228) [Radioactive emissions to air]	Activity	0.008017	Bq
Thorium (Th232) [Radioactive emissions to air]	Activity	0.012652	Bq
Toluene (methyl benzene) [Group NMVOC to air]	Mass	1.25E-06	kg
Uranium (U238) [Radioactive emissions to air]	Activity	0.020703	Bq
Vanadium [Heavy metals to air]	Mass	3.88E-08	kg
Water [Other emissions to fresh water]	Volume	0.060762	m3
Water vapour [Inorganic emissions to air]	Mass	0.001574	kg
Xylene (dimethyl benzene) [Group NMVOC to air]	Mass	1.06E-05	kg
Zinc [Heavy metals to air]	Mass	2.00E-07	kg

Table A.2. Electricity production from hard coal in Turkey.

Flow	Quantity	Amount	Unit
Inputs			
GLO: hard coal ash [Waste]	Mass	0.07439	kg
GLO: hard coal power plant [allocatable product]	Number of pieces	1.33E-11	pcs.
GLO: residue from cooling tower [Waste]	Mass	5.47E-05	kg
GLO: water, completely softened, from decarbonised water, at user [allocatable product]	Mass	0.059669	kg
GLO: water, decarbonised, at user [allocatable product]	Mass	1.98895	kg
PL: hard coal [allocatable product]	**Mass**	**0.002776**	**kg**
RLA: hard coal [allocatable product]	**Mass**	**0.215033**	**kg**
RNA: hard coal [allocatable product]	**Mass**	**0.002606**	**kg**
RoW: hard coal [allocatable product]	**Mass**	**0.065235**	**kg**
RoW: light fuel oil [allocatable product]	Mass	0.000169	kg
RU: hard coal [allocatable product]	**Mass**	**0.166834**	**kg**
WEU: hard coal [allocatable product]	**Mass**	**0.005071**	**kg**
ZA: hard coal [allocatable product]	**Mass**	**0.032817**	**kg**
Water, cooling, unspecified natural origin [Water]	Volume	0.045481	m3
Outputs			
Electricity, high voltage [allocatable product]	Energy	1	kWh
1,1,1-Trichloroethane [Halogenated organic emissions to air]	Mass	1.64E-09	kg
Acenaphthene [Group NMVOC to air]	Mass	4.18E-11	kg
Acrolein [Group NMVOC to air]	Mass	2.38E-08	kg
Aktinide (general) [Radioactive emissions to air]	Activity	0.170055	Bq
Aldehyde (unspecified) [Group NMVOC to air]	Mass	7.79E-08	kg
Alkane (unspecified) [Group NMVOC to air]	Mass	1.34E-06	kg
Alkene (unspecified) [Group NMVOC to air]	Mass	1.27E-06	kg
Antimony [Heavy metals to air]	Mass	1.19E-08	kg
Arsenic [Heavy metals to air]	Mass	9.91E-08	kg
Barium [Inorganic emissions to air]	Mass	6.45E-07	kg
Benzene [Group NMVOC to air]	Mass	1.38E-06	kg
Benzo{a}pyrene [Group PAH to air]	Mass	4.29E-12	kg
Beryllium [Inorganic emissions to air]	Mass	1.72E-09	kg
Boron [Inorganic emissions to air]	Mass	3.81E-06	kg
Bromine [Inorganic emissions to air]	Mass	3.11E-06	kg
Butane [Group NMVOC to air]	Mass	1.11E-07	kg
Cadmium [Heavy metals to air]	Mass	1.03E-08	kg
Carbon dioxide [Inorganic emissions to air]	**Mass**	**0.858066**	**kg**
Carbon disulphide [Inorganic emissions to air]	Mass	1.06E-08	kg
Carbon monoxide [Inorganic emissions to air]	**Mass**	**0.000542**	**kg**
Chlorinated hydrocarbons (unspecified) [Halogenated organic emissions to air]	Mass	1.66E-08	kg
Chloromethane (methyl chloride) [Halogenated organic emissions to air]	Mass	4.35E-08	kg
Chromium [Heavy metals to air]	Mass	8.15E-08	kg

Table 2.A. Electricity production from hard coal in Turkey (continued).

Flow	**Quantity**	**Amount**	**Unit**
Outputs			
Chromium (+VI) [Heavy metals to air]	Mass	1.39E-08	kg
Cobalt [Heavy metals to air]	Mass	3.32E-08	kg
Copper [Heavy metals to air]	Mass	8.16E-08	kg
Cumene (isopropylbenzene) [Group NMVOC to air]	Mass	4.47E-10	kg
Cyanide (unspecified) [Inorganic emissions to air]	Mass	2.05E-07	kg
Cycloalkanes (unspec.) [Group NMVOC to air]	Mass	4.74E-08	kg
Dichloroethane (ethylene dichloride) [Halogenated organic emissions to air]	Mass	3.27E-09	kg
Dichloromethane (methylene chloride) [Halogenated organic emissions to air]	Mass	2.38E-08	kg
Dust (> PM10) [Particles to air]	Mass	2.01E-06	kg
Dust (PM2,5 - PM10) [Particles to air]	Mass	4.02E-06	kg
Dust (PM2.5) [Particles to air]	Mass	3.42E-05	kg
Ethane [Group NMVOC to air]	Mass	2.42E-07	kg
Ethyl benzene [Group NMVOC to air]	Mass	7.71E-09	kg
Formaldehyde (methanal) [Group NMVOC to air]	Mass	3.61E-07	kg
Furan [Group NMVOC to air]	Mass	4.10E-13	kg
Hexane (isomers) [Group NMVOC to air]	Mass	5.52E-09	kg
Hydrogen chloride [Inorganic emissions to air]	Mass	0.000264	kg
Hydrogen fluoride [Inorganic emissions to air]	Mass	2.81E-05	kg
Iodine [Inorganic emissions to air]	Mass	1.58E-06	kg
Lead [Heavy metals to air]	Mass	3.69E-07	kg
Lead (Pb210) [Radioactive emissions to air]	Activity	0.689171	Bq
Magnesium [Inorganic emissions to air]	Mass	9.01E-07	kg
Manganese [Heavy metals to air]	Mass	3.56E-07	kg
Mercury [Heavy metals to air]	Mass	2.69E-08	kg
Methane [Organic emissions to air (group VOC)]	Mass	8.97E-06	kg
Molybdenum [Heavy metals to air]	Mass	1.14E-08	kg
Nickel [Heavy metals to air]	Mass	1.99E-07	kg
Nitrogen oxides [Inorganic emissions to air]	**Mass**	**0.002178**	**kg**
Nitrous oxide (laughing gas) [Inorganic emissions to air]	**Mass**	**9.71E-05**	**kg**
NMVOC (unspecified) [Group NMVOC to air]	Mass	9.25E-06	kg
Pentane (n-pentane) [Group NMVOC to air]	Mass	8.65E-07	kg
Phenol (hydroxy benzene) [Group NMVOC to air]	Mass	1.31E-09	kg
Polonium (Po210) [Radioactive emissions to air]	Activity	1.223204	Bq
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD) [Halogenated organic emissions to air]	Mass	1.05E-13	kg
Polycyclic aromatic hydrocarbons (PAH, unspec.) [Group PAH to air]	Mass	7.45E-08	kg
Potassium (K40) [Radioactive emissions to air]	Activity	0.228729	Bq
Propane [Group NMVOC to air]	Mass	2.06E-07	kg
Propene (propylene) [Group NMVOC to air]	Mass	9.42E-08	kg
Protactinium (Pa234m) [Radioactive emissions to air]	Activity	0.010243	Bq
Radium (Ra226) [Radioactive emissions to air]	Activity	0.181989	Bq

Table 2.A. Electricity production from hard coal in Turkey (continued).

Flow	**Quantity**	**Amount**	**Unit**
Outputs			
Radium (Ra228) [Radioactive emissions to air]	Activity	0.058773	Bq
Radon (Rn220) [Radioactive emissions to air]	Activity	5.041989	Bq
Radon (Rn222) [Radioactive emissions to air]	Activity	4.952486	Bq
Selenium [Heavy metals to air]	Mass	1.64E-07	kg
Strontium [Inorganic emissions to air]	Mass	5.89E-07	kg
Styrene [Group NMVOC to air]	Mass	2.03E-09	kg
Sulphate [Inorganic emissions to air]	Mass	3.92E-09	kg
Sulfur dioxide [Inorganic emissions to air]	**Mass**	**0.003741**	**kg**
Tetrachloroethene (perchloroethylene) [Halogenated organic emissions to air]	Mass	3.52E-09	kg
Thorium (Th228) [Radioactive emissions to air]	Activity	0.032818	Bq
Thorium (Th230) [Radioactive emissions to air]	Activity	0.010243	Bq
Thorium (Th232) [Radioactive emissions to air]	Activity	0.048033	Bq
Thorium (Th234) [Radioactive emissions to air]	Activity	0.010243	Bq
Toluene (methyl benzene) [Group NMVOC to air]	Mass	6.61E-07	kg
Trichloromethane (chloroform) [Halogenated organic emissions to air]	Mass	8.04E-09	kg
Uranium (U234) [Radioactive emissions to air]	Activity	0.020088	Bq
Uranium (U238) [Radioactive emissions to air]	Activity	0.158122	Bq
Vanadium [Heavy metals to air]	Mass	1.47E-07	kg
Water [Other emissions to fresh water]	Volume	0.046098	m3
Water vapour [Inorganic emissions to air]	Mass	0.001431	kg
Xylene (dimethyl benzene) [Group NMVOC to air]	Mass	5.43E-06	kg
Zinc [Heavy metals to air]	Mass	4.14E-07	kg