DETERMINATION OF TÜRKİYE’S NATIONAL EMISSION FACTORS FOR ELECTRICITY AND CEMENT SECTORS

TÜRKİYE’NİN ELEKTRİK VE ÇİMENTO SEKTÖRLERİ İÇİN ULUSAL EMİSYON FAKTÖRLERİNİN BELİRLENMESİ

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ABSTRACT

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Air pollution is a major problem associated with fossil fuel consumption. The primary air pollutants are carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), total organic carbon (TOC), and particulate matter <10 μm size (PM_{10}). Two main sectors, electricity production and cement production, play a critical role in emitting these pollutants. Estimating emissions from these sectors most accurately is crucial to taking precautions against air pollution and determining the right policies. Three methods for forecasting emission levels are direct sampling measurements, mass balance, and emission factors. Emission factors are one of the most practical methods for performing estimation. Therefore, national (Tier 2) emission factors were determined as controlled and uncontrolled for each technology of these two sectors in the scope of this study for Türkiye. Moreover, five processes (fluidized bed, pulverized, natural gas combined cycle, and open-cycle gas turbines) are used in the electricity and cement sectors of Türkiye. Four pollutants (CO, NO_x, SO_2, PM_{10}) were selected to calculate national emission factors (Tier 2) for the electricity sector, whereas five pollutants (CO, NO_x, SO_2, PM_{10}, and TOC) were chosen to compute these emission factors for the cement sector within the scope of the thesis.

These calculated emission factors were compared with the values from three databases (AP42, EMEP/EEA, and NPI). Except for two values, all the computed emission factors for these sectors are similar to those presented in three databases: the NO_x emission factor for the hard coal-fuelled pulverized electricity plants and the TOC emission factor for the cement sector. The reason is that the reduction percentage is higher in selective catalytic reduction for NO_x in the electricity sector and the utilization of different fuels during cement production. Statgraphics 18 was used for the calculations of emission factors in the thesis. For the electricity sector, the national emission factors of Türkiye for four pollutants (CO, NO_x, SO_2, and PM_{10}) were computed as 0.552 kg/ton, 1.776 kg/ton, 2.918 kg/ton, and 2.404 kg/ton for hard coal respectively. In addition, the national emission factors of Türkiye for the same pollutants can be listed as 0.143 kg/ton, 1.072 kg/ton, 2.216 kg/ton, 14.016 kg/ton, and 0.205 kg/ton for lignite. For natural gas, the calculated Tier 2 emission factors of CO were computed as 31.095 g/GJ, while the NOx emission factor was 42.609 g/GJ. Lastly, the Tier 2 emission factors of CO, NO_x, SO_2, PM_{10}, and TOC are 1596.167 g/ton, 1277.235 g/ton, 251.299 g/ton, 26.436 g/ton, and 29.841 for the cement sector, respectively in the thesis.

Keywords: Air pollution, electricity, cement, Tier 2 emission factor, national emission factors

ÖZET

TÜRKİYE'NİN ELEKTRİK VE ÇİMENTO SEKTÖRLERİ İÇİN ULUSAL EMİSYON FAKTÖRLERİNİN BELİRLENMESİ

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Hava kirliliği son dönemde tüm dünyada gözlemlenen temel sorunlardan biridir. Sorunun temel nedeni, atmosfere giren karbon monoksit (CO), nitrojen oksitler (NO_x), kükürt dioksit (SO_2), toplam organik karbon (TOC) ve <10 µm boyutundaki partikül madde (PM_{10}) gibi kirleticilerdir. Enerji üretimi ve endüstriyel süreçler gibi çeşitli faaliyetlerde fosil yakıtların kullanılması nedeniyle iki ana sektör olan elektrik üretimi ve çimento üretimi bu kirleticilerin salınımında kritik rol oynamaktadır. Bu kirliliğe karşı önlem almak ve doğru politikaları belirlemek için emisyonların en doğru şekilde tahmin edilmesi büyük önem taşımaktadır. Emisyon seviyelerini tahmin etmek için üç yöntem vardır: doğrudan örnekleme ölçümleri, kütle dengesi ve emisyon faktörleri. Emisyon faktörleri, emisyon tahminin gerçekleştirilmesinde en pratik yöntemlerden biridir. Bu nedenle Türkiye için bu çalışma kapsamında bu iki sektörün her teknolojisi için ulusal (Kademe 2) emisyon faktörleri kontrollü ve kontrolsüz olarak belirlenmiştir. Ayrıca Türkiye'nin elektrik ve çimento sektörlerinde beş teknoloji (akışkan yataklı, pulverize, doğal gaz kombine çevrimi ve açık çevrimli gaz türbinleri) kullanılmaktadır. Elektrik sektörü için ulusal emisyon faktörlerini (Kademe 2) hesaplamakamacıyla dört kirletici (CO, NO_x, SO_2, PM_{10}) seçilirken, çimento sektörü için bu emisyon faktörlerini hesaplamak üzere beş kirletici (CO, NO_x, SO_2, PM_{10} ve TOC) seçilmiştir.

Hesaplanan bu emisyon faktörleri üç veri tabanından (AP42, EMEP/EEA ve NPI) alınan değerlerle karşılaştırılmıştır. Bu sektörlerde hesaplanan emisyon faktörlerinin tamamı iki değer dışında kabul edilebilir aralıktadır. Bunlar, elektrik sektörünün taşkömürü kısmı için NOx emisyon faktörü, çimento sektörü için ise PM_{10} emisyon faktörüdür. Bunun nedeni elektrik sektöründe seçici katalitik indirgemenin azaltım oranının yüksek olması ve çimento sektöründe farklı yakıtların kullanılmasıdır. Hesaplanan kabul edilebilir aralık, tezdeki her kirletici ve sektör için farklıdır. Tezde emisyon faktörlerinin hesaplanmasında Statgraphics 18 kullanılmıştır. Elektrik sektörü için Türkiye'nin dört kirleticiye (CO, NO_x, SO_2 ve PM_{10}) yönelik ulusal emisyon faktörleri, taşkömürü için sırasıyla 0.552 kg/ton, 1.776 kg/ton, 2.918 kg/ton ve 2.404 kg/ton olarak hesaplanmıştır. Ayrıca aynı kirleticiler için Türkiye'nin ulusal emisyon faktörleri ise linyit için 0.143 kg/ton, 1.072 kg/ton, 2.216 kg/ton, 14.016 kg/ton ve 0.205 kg/ton olarak sıralanabilir. Doğal gaz için hesaplanan Tier 2 CO emisyon faktörleri 31.095 g/GJ, NO_x emisyon faktörü ise 42.609 g/GJ olarak hesaplanmıştır. Son olarak tezde yer alan çimento sektörü için Tier 2 emisyon faktörleri sırasıyla CO, NO_x, SO_2, PM_{10} ve TOC 1596.167 g/ton, 1277.235 g/ton, 251.299 g/ton, 26.436 g/ton ve 29.841'dir.

Anahtar kelimeler: Hava kirliliği, elektrik, çimento, Tier 2 emisyon faktörleri, ulusal emisyon faktörleri

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Onur SALMAN

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ABBREVIATIONS

CO	Carbon monoxide
CEMS	Continuous Emission Monitoring System
CO_2	Carbon dioxide
EEA	European Environmental Agency
ESP	Electrostatic precipitator
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
NO	Nitric oxide
NO_2	Nitrogen dioxide
N_2O	Nitrous oxide
SO_2	Sulfur dioxide
SO_x	Sulfur oxides
SO_3	Sulphur trioxide
PM	Particulate matter
FGD	Flue gas desulphurization
VOCs	Volatile organic carbons (VOCs)
WHO	World Health Organization
NGCC	Natural gas combined cycle
OCGT	Open-cycle gas turbines
SCR	Selective catalytic reduction
SNCR	Selective non-catalytic reduction techniques
SCMs	Supplementary Cementitious Material

1. INTRODUCTION

1.1. General Overview

Pollutant emissions from two industries, cement and power, threaten the atmosphere. This is due to the release of many pollutants into the atmosphere during industrial activities, including carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic carbons (VOC_s), and particulate matter <10 μm size (PM_{10}) [1].

Air pollution is one of the major global problems impacting social, environmental, and economic values. In other words, it is one of the biggest environmental challenges causing environmental calamities. Moreover, the phenomenon, a process, has accelerated its pace and has severely threatened natural resource sustainability and global biodiversity for the future of humanity due to anthropogenic facilities. The phenomenon is detected because of several sectors. This phenomenon occurs due to pollutants produced as a result of production in many sectors. Electricity and cement sectors can be given as examples of these sectors. [2].

The electricity sector is one of the indispensable sectors because of several targets, such as industry, vehicles, and street lighting. The utilization of electricity is crucial for the development of nations. Fossil fuels are used mostly during electricity production. The pollutants detected in the sector are CO, NO_x, SO_2, and PM_{10} [3].

The cement sector is the other sector analyzed in this study. It is utilized for goals such as civil infrastructure and building construction materials. The industry is one of the fundamental contributors to anthropogenic gas emissions. Emissions from the sector are detrimental to humanity and the world's ecosystem. These emissions into the environment cause several health problems like bronchitis, heart failure, and asthma. Moreover, they threaten the diversity of living things and cause many creatures to become extinct. The pollutants specified in the sector are CO, NO_x, SO_2, PM_{10}, and total organic carbon (TOC) [3].

In addition, an emissions factor is a value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. There are three types of emission factors: Tier 1 (default approach), Tier 2 (technology-specific approach), and Tier 3 (facility-specific approach).

1.2. Problem Statement

The utilization of fossil fuels is very high in the cement and electricity sectors. Sector-specific emission factors should be utilized in calculations to evaluate accurate emission levels.

Several countries like Australia, the United States, and Germany have determined sector-specific (Tier 2) emission factors to estimate the emission levels for various pollutants like CO, NO_x, and SO_2 for many sectors. However, Türkiye has no sector-specific emission factors. The level of emissions is different for each country. Therefore, the sector-specific emission factors for Türkiye are required to calculate the exact solutions for the emission estimation.

In addition, emission factors are utilized mostly in air quality models such as The Community Multiscale Air Quality Modeling System (CMAQ). Country-specific emission factors are significant in obtaining certain model results.

For this reason, sector-specific emission factors will be determined by utilizing monitored pollutant data provided by the Ministry of Environment, Urbanization, and Climate Change for Türkiye within the scope of the thesis to fill this gap in the literature. Thus, valid emission estimates can be obtained owing to the country-specific emission factors. Also, consistent air quality model results may be determined using these emission factors for Türkiye.

1.3. Aim and Objective of the Thesis

The study aims to calculate sector-specific emission factors for the electricity and cement sectors and compare these emission factors with selected databases (i.e., AP-42 provided by the US EPA, EMEP/EEA guidebook, and NPI technique manual). Türkiye's Tier 2 sector-specific emission factors will be determined using monitored pollutant data for the cement and electricity sectors.

In this context, the objectives of this thesis are stated as follows:

- To obtain monitored pollutant data and plant data for two sectors;
- To analyze these data for two sectors;
- To specify the technology used for production in these sectors;
- To attain the emission factors written on databases that are EPA Emission Factor Documentation for AP-42, EMEP/EEA Air Pollutant Emission Inventory Guidebook, and NPI - Emission Estimation Technique Manual for each pollutant and technology;
- To calculate Tier 2 sector-specific emission factors for Türkiye for the production technology of these sectors;
- To compare the calculated Tier 2 emission factors with those taken from three selected databases.

1.4. Scope of the Thesis

This study is carried out using the data of sixty-eight power plants in the electricity sector and fifty-five cement plants. Mass flow data are taken from three hundred forty-two chimneys monitored in the Continuous Emission Monitoring System (CEMS) created by the Republic of Türkiye, Ministry of Environment, Urbanization and Climate Change for 2021.

Operational data of the power plants and cement factories, like fuel type, installed capacity (MW), and electricity production data (MWh), are taken from the website named “Enerji Atlası” for each facility for 2021. The capacity of cement production, working hours, and fuel types for cement factories are obtained from activity reports of each plant. The total amount of cement production is computed as ton/yr. The total cement production (ton/yr) is taken from the TURKCEMENT report for the same year [15].

Various technologies in the electricity sector are considered in the study: fluidized bed, pulverized (subcritical, supercritical, and ultra-supercritical), and natural gas combined cycle (NGCC). Three fuel types (hard coal, lignite, and natural gas) are determined for the electricity sector. The dry process is obtained for the cement sector as well. A Tier 2 emission factor is calculated for each technology and fuel type of both sectors. Tier 2 emission factors are taken from selected three databases (AP42, EMEP/EEA, and NPI) for these technologies. Tier 2 emission factors computed for these sectors are compared with database emission factors.

1.5. Structure of the Thesis

The thesis includes six chapters. Chapter 1 presents an overall review of the research. Chapter 2 procures general background information associated with the emission problem, two sectors in the scope of the thesis, emission estimation methods, and the emission factor calculation. Chapter 3 displays previous studies on the emission factor calculation and emission estimation. Chapter 4 presents steps of collecting monitored and plant data and analyzing data, calculating Tier 2 emission factors, and analyzing emission factor databases. Chapter 5 contains the number of plants and chimneys and the results of Tier 2 and database emission factors. Chapter 6 shows the major outcomes of this study as well as several suggestions for future studies.

2. BACKGROUND INFORMATION

2.1. Emission Problem

The problem of air pollution is one of the major troubles that people worldwide have faced in recent years. Intergovernmental Panel on Climate Change (IPCC) defines air pollution as "*The contamination of the indoor or outdoor environment by any chemical, a physical or biological agent that modifies the natural characteristics of the atmosphere*”. The effect of the problem has become apparent because of the increment in the number of air pollution sources like industrial facilities, household combustion devices, transport vehicles, and fires in forests nowadays. Air pollution induces several health problems, such as respiratory and cancer- the crucial source of morbidity as well as mortality. Moreover, air pollution is one of the factors that greatly harms humanity's health. According to data published by the World Health Organization (WHO), nearly all of the population living around the world breathes air that exceeds guideline limits specified by WHO and includes high amounts of pollutants, with poor countries suffering from the highest exposures at a rate of 99% [4].

Emissions from two sectors (electricity and cement) are a crucial problem for the world's air quality. Therefore, a variety of pollutants, such as CO, SO_2, NO, NO_2, N_2O, VOCs, and dust, spread into the atmosphere through industrial processes [5].

2.2. Selected Sectors and Their Processes

This part explains the processes of two selected sectors, electricity and cement. These sectors are crucial because they cause most of the pollutants occurring from industrial processes. The air pollutants emitted from these two sectors, electricity and cement, can be listed as follows [6]:

- Carbon monoxide (CO)
- Nitrogen oxides (NO_x)
- Sulfur dioxide (SO_2)
- Total organic carbons (TOCs)
- Particulate matter (PM)

2.2.1. Electricity Sector and Its Process

The electricity sector is one of the crucial sectors. It is utilized for various purposes: in the industry, in buildings, in vehicles, in street lighting, and in working devices. Electricity production is fundamental to the development and growth of nations. Fossil fuels utilized during electricity production have been determined to be the major contributor to air pollution in the atmosphere in the electricity sector [7].

Several applications like planning adaptation or preventive measures can be influential in improving the future environment. In addition, there has been a shift from the utilization of fossil fuels to the increment in the amount of renewable energy usage to curb environmental issues [8]. Yet, the majority of electricity production is still produced using fossil fuels. Today, 85% of the world's total energy needs are satisfied by burning fossil fuels. Using non-renewable energy sources, mainly fossil fuels, Türkiye generated 75% of its electrical needs [9].

The majority of the electricity is produced at coal and natural gas-fuelled power plants. Types of pollutants are listed in Table 1:

Table 1. Pollutants emitted from coal-fuelled and natural gas-fuelled power plants

Coal-Fuelled Power Plants	**Natural Gas-Fuelled Power Plants**
CO	CO
NO_x	
SO_2	NO_x
PM	

Moreover, emissions from combustion plants are known as point sources. This activity generally addresses emissions from larger combustion plants (>50MWth). The emissions of electricity production are generated by controlled combustion processes such as boiler emissions, furnace emissions, and emissions from gas turbines or stationary engines. These emissions are mainly characterized by the types of fuels utilized [8].

An industrial or utility boiler that uses pulverized coal—also referred to as powdered coal or coal dust since it's as fine as face powder in makeup—is blown into the firebox to produce thermal energy. Using the entire furnace volume to burn solid fuels is the fundamental concept behind a firing system that uses pulverized fuel. When coal is burned, its mineral substance is turned to ash. Fly ash and bottom ash are extracted from the ash. At the bottom of the furnace, the bottom ash is removed. Large turbines are powered by steam produced by this boiler, which is prevalent in coal-fired power plants [8].

Fuel is burned in fluidized bed combustion (FBC), which includes injecting combustion air into a turbulent bed through the boiler's bottom. Low combustion temperatures between 750 °C and 950 °C, limestone addition, and air staging all contribute to the normal relatively low emissions. FBC is especially well-suited to coals with a lot of ash. Only a small number of sizable combustion facilities use the FBC technique; most of them fall into the category of thermal capacity under 300 MW, where circulating fluidized bed combustion (CFBC) is used [10].

Gas turbines are commonly utilized in co-generation plants. The gas turbine is connected directly to an electricity generator. The energy supplied by hot exhaust gases is recovered in a boiler or used directly. Co-burners are commonly utilized to provide additional heat input to the exhaust gases in the electricity plant. Both types represent relevant emission sources [8].

The simple diagram of electricity production is displayed in Figure 1.

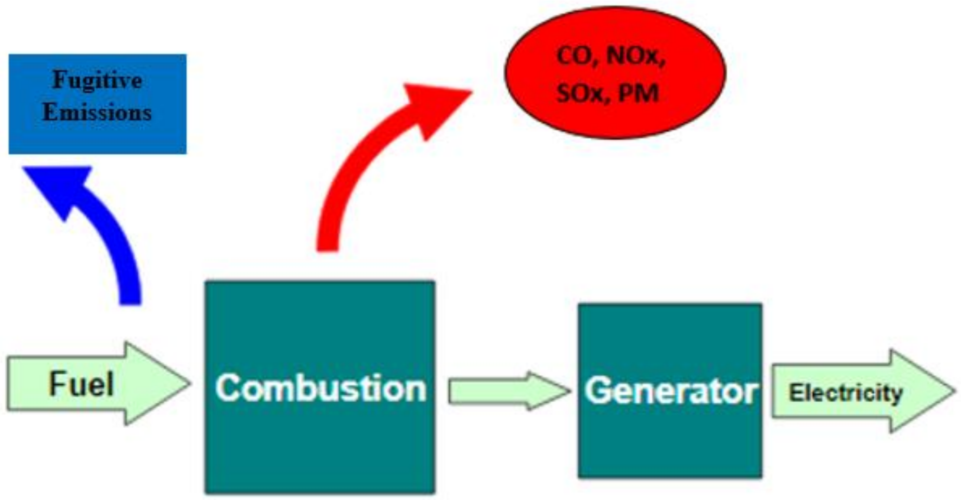


Figure 1. Simple diagram of power plant [10]

Several pollutants are examined in the production of electricity. These substances are Sulphur oxides (SO_x), Nitrogen oxides (NO_x), Carbon monoxide (CO), particulate matter, and fugitive emissions [10].

2.2.1.1. Sulphur Oxides (SO_x)

The emissions of sulfur oxides (SO_x) are directly associated with the sulfur content in the fuel controlled by the technology named flue gas desulphurization (FGD). In addition, the sulfur content of refined natural gas is omissible. The majority of SO_x is detected as sulfur dioxide (SO_2). Yet, small proportions of sulfur trioxide (SO_3) may arise. Coal is a complex mixture of biological and inorganic mineral particles created over ages by successive layers of fallen vegetation. Coals can be classified by rank based on their progression through the pure metamorphosis process from lignite to anthracite. The content of coal, consisting of volatile parts of matter, fixed carbon, moisture, and oxygen, determines its rank, although no one measure defines it. [10].

2.2.1.2. Nitrogen oxides (NO_x)

Emissions of nitrogen oxides (NO_x) containing nitric oxide and nitrogen dioxide are detected from nitrogen in the fuels and the reaction of atmospheric nitrogen. Emission control can be provided effectively thanks to NO_x emission control technologies like low NOx burner, selective catalytic reduction (SCR) as well as selective non-catalytic reduction techniques (SNCR) [10].

2.2.1.3. Carbon monoxide (CO)

Carbon monoxide (CO) always appears as a mid-output of the combustion process, particularly under partial stoichiometric combustion situations. When the circumstances of combustion are insufficient, substantial emissions of CO are detected. In addition, higher CO emissions are prospective in the event of flue gas recirculation as a significant criterion for NO_x reduction [10].

2.2.1.4. Particulate matter (PM)

Particulate matter (PM) emissions arising out of large combustion installations (>50MW) burning solid fuels are often lower than emissions from smaller plants. The physical and chemical characteristics of the PM vary because of the practice of different combustion and abatement techniques [10]. When burned, fuels can produce solid residues that may be deposited in various parts of the combustion system. These residues might include furnace bottom ash, fly ash on boiler surfaces or ducting, and soot and fly ash on heat exchanger surfaces. Both coal and other fuels with high ash content have the greatest potential to spread PM. Ash material suspended in exhaust gases can be captured by particulate abatement or other emission control devices, resulting in abatement residues. Nonetheless, any material that remains in the flue gases after passing through the abatement equipment and is released into the atmosphere is considered primary PM. [10].

2.2.2. Cement Sector and Its Process

The cement sector is one of the indispensable sectors. It is utilized for various purposes, such as building construction materials and civil infrastructure. The cement industry is an important contributor to anthropogenic gas emissions. As a result, the industry is crucial for development in terms of urbanization. Emissions occurring from the sector are harmful to the ecosystem and inhabitants of the world [8].

Moreover, the industry is one of the crucial subscribers to pollutant emissions worldwide. Also, alternative low-carbon cement types can promote important emission reduction in the cement industry [3]. The basic flow diagram of cement production is shown in Figure 2.

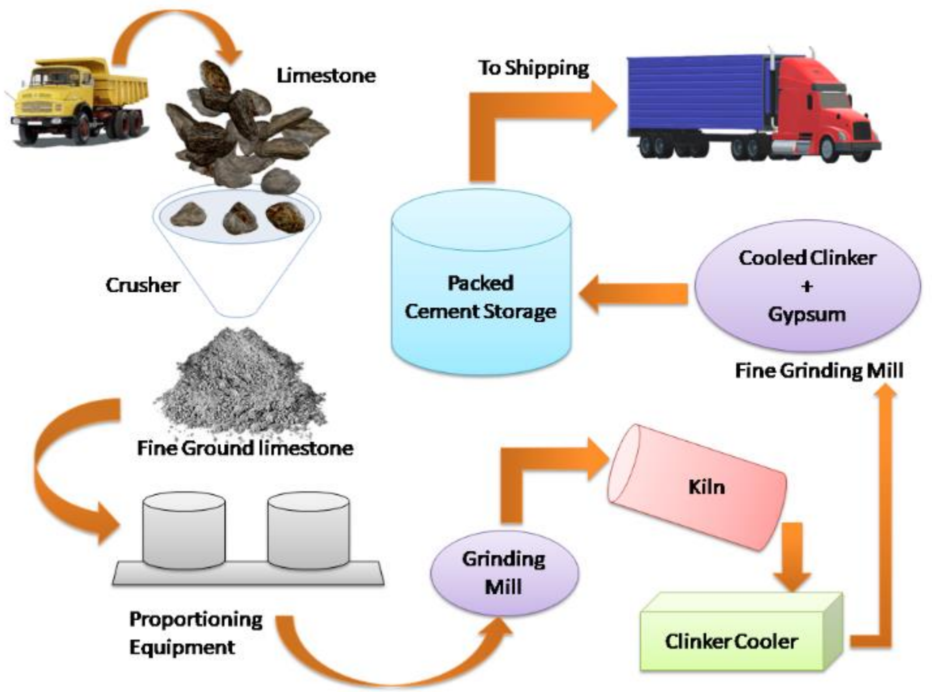


Figure 2. Flow diagram of cement production [3]

Cement production includes several processes: crushing, proportioning, grinding, and kiln. Additives like Gypsum / Anhydrite and Supplementary Cementitious Materials (SCMs) are utilized to produce packed cement for shipping [3].

Two processes, dry and wet, produce cement in cement plants. The dry process is utilized in plants located in Türkiye. The production steps of cement are displayed in detail in Figure 3. In Figure 3, cement plants include several parts. Raw material preparation (quarrying, primary and secondary crushing, proportioning, grinding), rotary kiln, clinker cooler, clinker storage, finish grinding mill, product storage, shipment, and air separator. In addition, the wet process and dry process include different pathways. The wet process has a unit called slurry mixing and blending, whereas the dry one can have three extra units: dry mixing and blending, optional preheater, and optional pre-calciner [8].

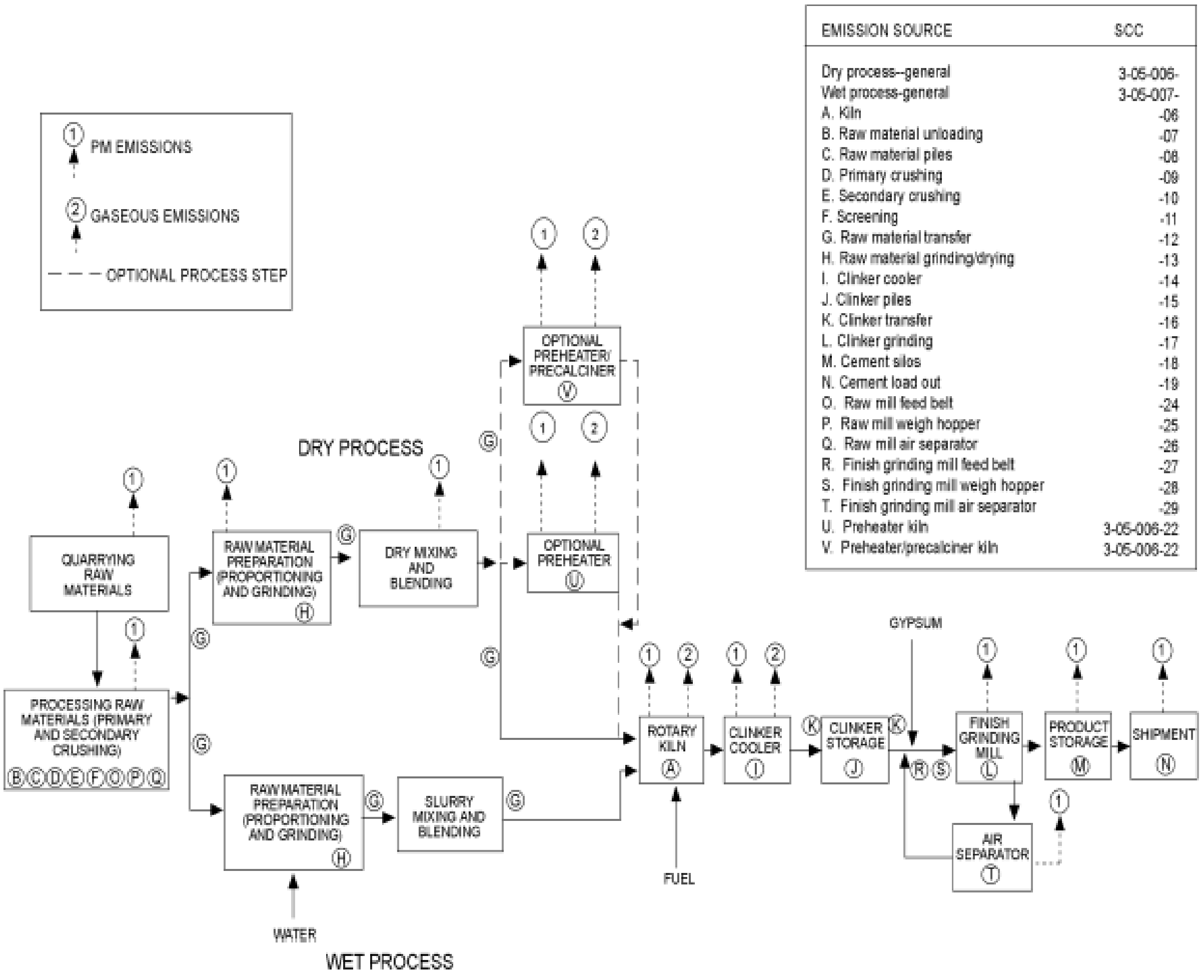


Figure 3. Flow diagram of processing portland cement plant [8]

2.2.2.1. Gaseous Emissions

Gaseous emissions, which are CO, NO, NO_2, and SO_2, are established in several units that are preheater, pre-calciner, rotary kiln, and cooler in cement production [10].

2.2.2.2. PM Emissions

PM emissions are detected in many units, which are quarrying raw materials, raw material unloading, raw materials piles, primary and secondary crushing, screening, raw mill feed belt, weigh hopper, air separator, raw material partitioning, and grinding, preheater, pre-calciner, rotary kiln, clinker cooler, grinding mill, product storage as well as shipment in cement production [10].

2.2.2.3. VOC Emissions

VOC emissions can be detected in several units: optional preheater, precalciner, and rotary kiln [8].

Several fuels utilized widely in the cement production are written as follows:

- Lignite
- Petroleum coke
- Natural gas
- Fuel oil
- Waste tires
- Waste oils
- Refuse-Derived Fuels (RDFs)
- Contaminated wastes

2.3. Emission Estimation

There are various techniques to estimate the amount of emissions. These techniques can be listed as follows [11]:

- sampling or direct measurement
- mass balance
- emission factors

2.3.1. Sampling or Direct Measurement

The sampling strategy is dependent on a number of variables written on the following [12]:

- resources available
- number of data points
- degree of uniformity between samples
- geographic distribution of data points
- the convenience of data collection
- a suitable period of time

There are three types of sampling methods: random, systematic, and stratified [12].

Continuous Emission Monitoring System (CEMS) is used as a direct measurement approach for emission estimation. CEMS is a system that measures the amount and composition of gases from large industrial sources. These systems ensure the environmental compatibility of industrial facilities by continuously measuring the emissions of pollutants released into the environment [13].

CEMS covers common systems for individual industrial chimneys across various industries, such as cement, metallurgy, chemicals, and energy generation. These parameters are recorded as raw data continuously for every minute in the system. The variety of data obtained owing to CEMS can be listed in Table 2:

Table 2. Data types obtained from CEMS

Data type	**Unit**
Concentrations of pollutants	mg/m^3
Temperature of the flue gas	°C
Speed of the flue gas	m/s
Flow rate of the flue gas	m^3/h
The pressure of the flue gas	atm or hpa
Humidity of the flue gas	% Vol

Then, normalized concentration values (mg/Nm^3) and mass flow (kg/h) are calculated using data obtained by CEMS for each facility.

2.3.2. Mass Balance

Mass balance is a technique that utilizes the conservation of mass to define physical systems. The mass flows are determined by computing the quantity of material entering and leaving the system [14]. The emission rate can be calculated based on the pollutants in the raw materials. If no accumulated substance exists, the input matter equals the output matter in the mass balance [15].

Moreover, fuel analysis can be used to predict several substances, like PM, SO_2, and other pollutants associated with applying mass conservation laws. The presence of specific elements such as sulfur in fuels can be used to estimate their presence in emission streams. Thus, it might be converted into other compounds during combustion [11].

2.3.3. Emission Factors

An emissions factor is a representative value that attempts to relate the amount of a pollutant emitted to the atmosphere to an activity connected with the discharge of that pollutant [10].

The general equation for emissions estimation is defined as follows [10]:

$$E = A \times EF \times (1-ER/100) \qquad \text{(Eq. 1)}$$

where:

E = emissions, kg Pollutant
A = activity rate, ton or PJ of fuel consumed
EF = emission factor, kg Pollutant/ton or PJ of fuel consumed
ER =overall emission reduction efficiency, %

There are various databases used for emission factors all over the world. Yet, three databases are utilized commonly. They are listed as follows:

- US EPA[1] Emission Factor Documentation for AP-42
- EMEP/EEA[2] Air Pollutant Emission Inventory Guidebook
- NPI[3] - Emission Estimation Technique Manual

Emission factors commonly display the amount of emitted substances from a source to some common activity related to those emissions. Emission factors are commonly gathered from databases created by the United States, Europe, and Australia. These factors are typically defined as the weight of a substance emitted per unit mass, volume, length, or

[1] U.S. Environmental Protection Agency
[2] European Monitoring and Evaluation Programme / European Environmental Agency
[3] National Pollutant Inventory

time period of the activity emitting the matter (e.g., kilograms of sulfur dioxide emitted per tonne of coal consumed). When possible, it is best to use facility-specific information (e.g. monitoring data) for forecasting emissions [10].

Emission factors contain three methods listed as follows:

Tier 1 (default approach): It is readily available for national or international factors supplied by several organizations such as the Intergovernmental Panel on Climate Change (IPCC). There are two requirements in Tier 1. These requirements are data on the amount of fuel combusted and a default emission factor provided by the IPCC [1].

Tier 2 (technology-specific approach): It is an intermediate stage of complexity and locally specific data. It requires data on the amount of fuel combusted and country-specific emission factors for each pollutant [1].

Tier 3 (use of facility-specific data): It is very complex and demands the most specific data. There are many requirements for Tier 3, such as the data on the amount of fuel combusted, operating conditions, combustion technology, abatement technology, an emission factor for each pollutant (country-specific), the quality of maintenance, and the age of the equipment utilized to burn the fuel [1].

Tier 2 and Tier 3 are more accurate than Tier 1 since they are more specific to the area in which they are used. Tier 2 and Tier 3 methodology adopts a more site-specific and detailed assessment of factors influencing emissions [7].

2.4. Closing Remarks

Air pollution has become a major problem due to recent developments in some facilities, such as industrial facilities, combustion activities, transportation, and forest fires. Moreover, two sectors (electricity and cement) are crucial because they cause most pollutants due to industrial processes. Five pollutants, CO, NO_x, SO_2, VOCs, and PM_{10}, are detected in these sectors. Several emission estimation methods include sampling or direct measurement, mass balance, and emission factors.

3. PREVIOUS STUDIES

In this part of the thesis, several studies related to the subjects of the thesis are explained, such as emission estimation and calculation of emission factors.

3.1. Summary of Previous Studies

The study conducted by Zeydan et al. explained the emissions of power plants in the Çatalağzı Energy Basin. The electricity generation in this basin is nearly 3% of the installed capacity of Türkiye. The study analyzed three power plants in the basin for four pollutants (NO_x, SO_2, and PM_{10}). Emission estimation of these pollutants was performed in the study. Also, the SO_2 emission was obtained as 22282.9 tons/year, while that of NO_x was determined as 31703.6 tons/year. The emission of PM_{10} was calculated as 1583.3 tons/year [16].

The study, performed by Canpolat et al., clarified the calculation of emission factors of cement plants in Türkiye for four pollutants (PM, SO_2, NO_2, and CO). The emission measurements performed by the Turkish Cement Manufacturers' Association (TCMA) were utilized to calculate the emission factors in the study. Twenty-eight cement plant data were used for the calculation. National emission factors as uncontrolled were obtained to be 0.190 kg/t cement for PM, 1.861 kg/t cement for CO, 1.390 kg/t cement for NO_2, and 0.053 kg/t cement for SO_2. The emission factors calculated in the study were compared with databases from several countries, such as Austria and the Netherlands. In addition, SO_2 emission factors are lower than the database values, whereas PM emission factors are larger than these databases for cement sectors. CO and NO_2 emission factors are similar to these emission factor database values. The results of the study are shown in Table 3 [17]. When Table 3 is examined, Tier 1 emission factor values were calculated in the studies for three countries.

Table 3. Calculated emission factors of Türkiye, Austria, and Netherlands [17]

Country	CO (kg/t)	NO_2 (kg/t)	SO_2 (kg/t)	PM (kg/t)
Türkiye	1.861	1.390	0.053	0.190
Austria	2.209	1.296	0.191	0.029
Netherlands	0.400	1.400	0.258	0.100

The study performed by Zhao et al. includes an improved database of emission factors combining the latest domestic area measurements with a bottom-up methodology, and it is advanced to forecast the emissions of anthropogenic CO from China at national and provincial stages. The uncertainties of national Chinese CO emissions are determined by statistical analysis at - 20% and + 45%, with a 95% confidence interval in several sectors, including the electricity and cement sectors. Also, the largest uncertainties were detected for emissions from these sectors because of a poor understanding of emission factors as well as activity levels for the combustion of solid fuels [18].

Furthermore, the study conducted by Ali et al. demonstrates that the cement sector consumes nearly 12–15% of the usage of total industrial energy. According to the study, the fundamental techniques are capturing and storing gas emissions by diminishing the ratio of clinker/cement by moving clinker with distinct additives and utilizing alternative fuels rather than fossil fuels. Lastly, a reduction in indirect emissions emitted to the atmosphere is expected owing to process remediations providing several energy savings in cement industries [19].

The study, performed by Zhao et al., explains a database that includes the emission factors of three pollutants (NO_x, SO_2, and PM) from coal-fired power plants in China. Two devices (a gas analyzer and an electric low-pressure impactor were used to measure the number of pollutants in the study. Ten units of eight power plants were analyzed in the scope of the study. Emission factors were computed by controlling to boiler types, fuel quality, and emission control devices with a 95% confidence level. The emission factor of NO_x for hard coal and lignite was calculated as 4.0 kg/ton and 5.2 kg/ton lignite, respectively. The value for SO_2 was calculated as 15.0S. The emission factor of PM_{10} was computed as 0.291A in the study as well [20].

In the study conducted by Dios et al., emission factors of a 300 MW coal-fired power plant were calculated by using continuous monitoring data. Emission factors were developed in the study as follows:

- Collection and evaluation of emission data from databases
- Statistical analysis of the data
- Evaluation of emission factor data

- Determination of fuel types and burning technology
- Calculation of emission factors for each fuel and technology
- Identification of variability of emission factors

Emission factors were computed for dry bottom tangentially fired boiler and two types of coal (sub-bituminous and lignite). Statistical analyses were performed using IBM SPSS software in the study. Emission factors of NO_x were computed as 0.332 kg/ton and 3.4 kg/ton, respectively. Additionally, the emission factor of SO_2 was calculated as 41.7 kg/ton for sub-bituminous, while the value was computed as 33.5 kg/ton for lignite [21].

A study performed by Li et al. explains emission factors of three pollutants (NO_x, SO_2, and PM) calculated for several sectors such as heating, power generation, and cement industries. Small-scale boilers with various fuels like coal, coal gas, and natural gas were utilized in the study. Seventeen small-scale boilers and 15 power plants were examined to calculate emission factors for these fuels. Install capacities of the plants change from 330 MW to 600 MW. The emission factor was 2.00 kg/t for NO_x, while the emission factor was 5.41 kg/t for SO_2. The sulfur content was expressed as 0.8% in the calculation. In addition, the emission factor was determined as 23.9 for PM. Moreover, eight cement plants were examined in the study. Emission factors of NO_x, SO_2, and PM are 708 g/ton, 97.4 g/ton, and 289 g/ton, respectively, for the cement sector in the study [22].

A study performed by Tang et al. explains the Continuous Emission Monitoring System (CEMS) in China. The China Emissions Accounts for Power Plants (CEAP) database consists of an inventory of emissions caused by power plants in China. The concentration of three pollutants (NO_x, SO_2, PM) and stack knowledge falls within the database. CEAP dataset includes plants and 6267 units from 26 provinces in China. Fuel types in the system are coal, gas, oil, biomass, and others [23].

The study conducted by Nazari et al. obtained emission factors of three pollutants (NO_x and SO_2) and analyzed these emission factors for fifty thermal power plants in Iran. Several properties of power plants include boiler types, chamber characteristics, combustion systems, and pollution control. Emission values were obtained by continuous emission monitoring systems utilized in the study. The total install capacities of them have been calculated as 34,863 MW in the study. The total emission is 552,000 tons for SO_2, whereas the value is 465,000 tons for NO_x in Iran's thermal plants. Emission factors of these pollutants have been computed for various systems such as steam cycle, gas turbine, and combined cycle for natural gas and heavy oil in these plants. Emission factors were calculated using the average weight determined from the electricity generation of each plant. The emission factor of NO_x is calculated as 2.694 -/+ 0.038 g/kWh for natural gas. In addition, the emission factor of NO_x is computed as 2.519 -/+ 0.036 g/kWh for natural gas, while the value is calculated as 15.276 -/+ 0.227 g/kWh for heavy oil [24].

Moreover, the emission factor development of the AP42 emission factor database is explained for the electricity sector and cement sector with several steps. First, emission data is collected from test reports from several organizations and universities in the United States. Sampling is realized three times for each pollutant. Next, their average is utilized to calculate the emission factor. The quality rating is performed using EPA-approved methods for each piece of data. Then, uncontrolled emission factor calculations are performed for each technology and each fuel. Control technologies are determined for them. The percent of abatement is specified for each technology. Then, controlled emission factors are calculated using these percentages and uncontrolled emission factors [25].

According to NPI, the development of emission factors created by the Australian Government is done with several steps. First, production processes are appointed for the electricity and cement sectors. Then, emission sources like fuel combustion products, raw material storage, and grinding are detected for each process for these sectors. Emission estimation techniques like sampling measurement and mass balance are determined for both sectors. Continuous emission monitoring system (CEMS) data is utilized to calculate emission factors. The CEMS data is provided for several pollutants such as SO_2, NO_x, and CO hourly and automatically for the database. Uncontrolled emission factors are calculated by using these data. Also, control technologies are obtained for each pollutant in the two sectors. Then, emission factors, as controlled and uncontrolled, are computed for each substance and each process in the database [6].

EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019 includes several parts, which are production techniques, emission sources, description of abatement technologies used in BREF notes, methods for estimating process emissions, and emission factor calculations for two sectors. The Tier 1 emission factors are computed as uncontrolled for each fuel type in the document. In addition, the Tier 2 strategy is comparable to the Tier 1 approach. To implement the Tier 2 strategy, a country's fuel usage and combustion technology affect activity data and emission variables. According to the document, these strategies may involve a combination of fuels and various types of combustion plants [26].

3.2. Closing Remarks

This section presents studies on emission estimation using continuous monitoring systems, the development of emission inventories, the development of emission factors, and calculation steps for the emission factors in the literature. There are numerous publications available on the calculation of emission factors for various countries, but there is a lack of literature specifically focused on calculating emission factors for each fuel type process for Turkish electricity and cement sectors. In addition, sector-specific emission factors are vital in estimating the emissions of major air pollutants for Türkiye.

4. METHODOLOGY AND DATA SOURCES

The methodology includes data gathering, data analysis, sector-specific emission factor identification, and comparison with other databases.

The methodology of the study is displayed in Figure 4.

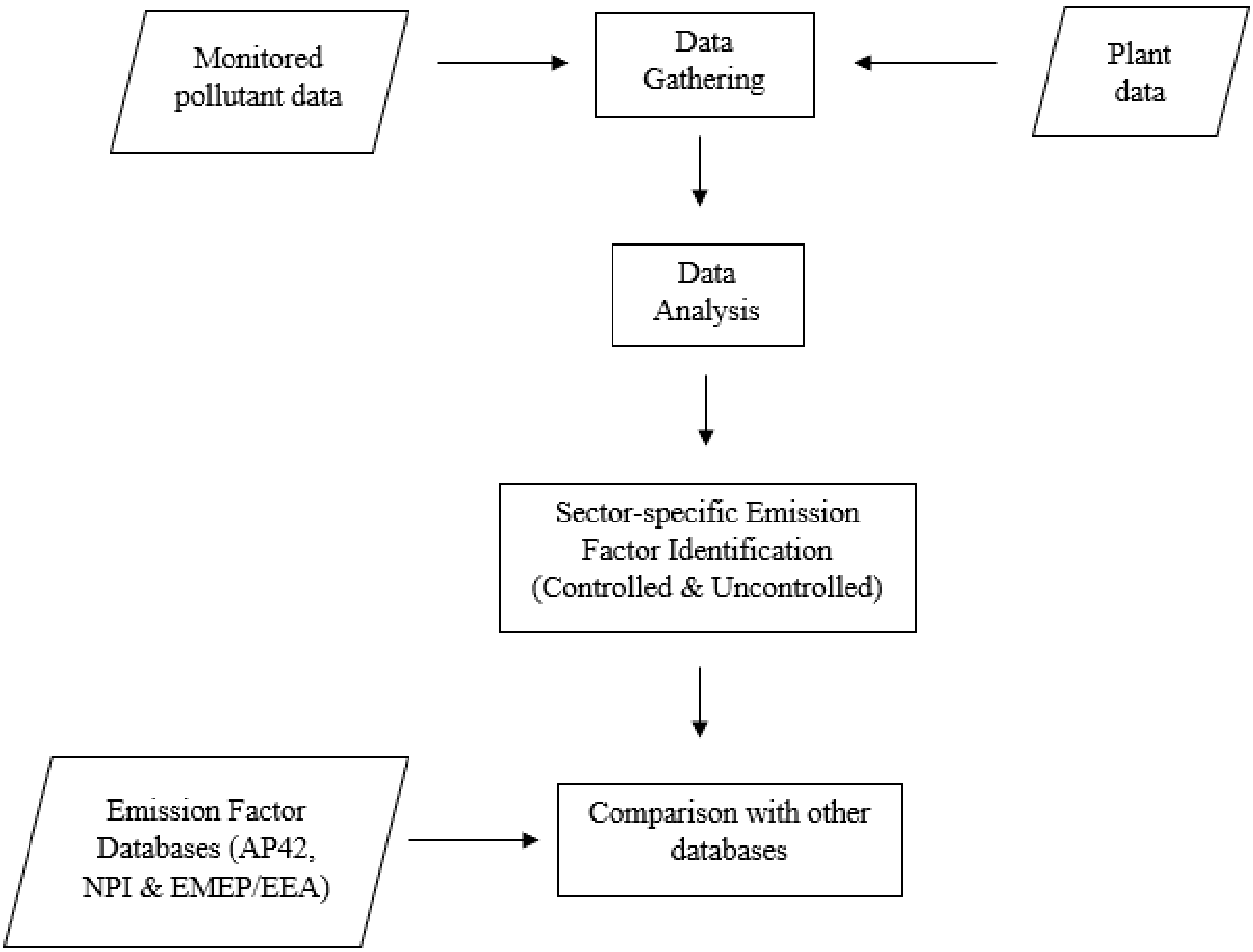


Figure 4. Methodology of the study

4.1. Data Gathering

This section presents detailed information on plant data, such as process and fuel data, monitored pollutant data, and emission factor databases for the electricity and cement sectors.

4.1.1. Plant Data

The plant data utilized is explained below for two separate sectors.

4.1.1.1. Electricity Sector

Power plants are listed as name, location, fuel type, and technology. In addition, installed capacity (MW) and electricity production data (MWh) are taken from the "Enerji Atlası" website for each facility. [27].

The amount of coal (tonne) is estimated using heating value and the amount of electricity production (MWh) at hard coal and lignite power plants. Similarly, the volume of natural gas (m^3) is estimated using the same method. Then, the mass of natural gas (kg) is computed with the density and volume of natural gas (m^3). Working hours are obtained from electricity production (MWh) and installed capacity (MW). The total energy input (TJ and toe) is also calculated for each facility. Then, their capacity is computed using these data. Efficiency (%) is selected for each technology.

The type of technologies is obtained from power plant reports for each facility. These technologies for each fuel type can be listed as follows:

Hard Coal:

- Fluidized Bed
- Pulverized (Subcritical, Supercritical, Ultra-supercritical)

Lignite

- Fluidized Bed
- Pulverized (Subcritical)

Natural Gas

- Natural Gas Combined Cycle (NGCC)
- Open Cycle Gas Turbines (OCGT)

4.1.1.2. Cement Sector

Cement factories are listed as name, location, fuel, and process. Working hours and fuel types for cement factories are obtained from activity reports of each plant. The capacity of cement production (ton/yr) is taken annually from the activity reports for each cement plant. The total amount of cement production is computed as ton/yr. The total cement production (ton/yr) is taken from the TURKCEMENT report. A proportion is calculated by using these values. Lastly, the adjusted cement production value is estimated based on the proportion [28].

4.1.2. Monitored Pollutant Data

Monitored pollutant data is taken from the Continuous Emission Monitoring System (CEMS) via the Air Emission Management Portal for both sectors [29]. In this part, systems used as data sources and the type of data utilized are explained step by step. The Air Emission Management Portal has been used by the Ministry of Environment, Urbanization, and Climate Change since 2017. Emission reports are recorded in the Air Emission Management Portal [30].

In the Air Emission Management Portal, data is collected from sources that produce pollution. Emission amounts are calculated, and maps are created by running an air quality model remotely with a temporal and spatial resolution of 1 km by 1 km. Additionally, the portal includes several modules, such as the Emission Measurement Module, Modelling Module, Solid Fuel Module, and the CEMS Module Knowledge on the emissions of facilities, such as concentration, mass flow rate, and fuel data, is recorded in this system [30].

CEMS is a system developed by the Republic of Türkiye, Ministry of Environment, Urbanization and Climate Change. The system is utilized in various sectors, such as electricity and cement, where strict regulations on air pollution control exist. These systems continuously monitor emissions from facilities in Türkiye, measuring and recording the amount of pollutants released into the environment [31].

CEMS is commonly placed on the facility's chimneys. The system utilizes a variety of technologies to obtain the chemical composition and quantity of pollutants. For example, it uses several technologies, such as infrared spectrometers that analyze the composition of gases with the help of a filter through which the gases are collected or several sensors, such as electrochemical and ultraviolet to detect the concentration of gases. CEMS is crucial to ensure the facility's environmental compliance. Facilities can keep emissions under control by receiving warnings, maintaining the facility, or changing their processes in case of any increase in waste gas emissions or exceeding the limit values. Additionally, CEMS data helps industrial facilities track trends in waste gas emissions and helps determine actions needed to improve environmental compliance [13].

Various types of data can be obtained owing to the CEMS database. They are listed as follows:

- Raw concentrations of pollutants (mg/m^3)
- Flue Gas Temperature (°C)
- Speed (m/s)
- Flow rate (m^3/h)
- Chimney Pressure (ATM) (hpa)
- O_2 (% Vol)
- Humidity (% Vol)
- Normalized concentrations of pollutants (mgN/m^3)
- Mass flow of pollutants (kg/h)

Within the scope of the CEMS Regulation, measurement and calibration operations such as the Quality and Assurance System and Annual Validity Test are carried out by authorized institutions under the legislation and standards within the scope of the procedures and principles that must be followed regarding the establishment and operation of continuous emission measurement systems and the establishment of the quality assurance system [31].

Monitored pollutant data are evaluated for two sectors: the electricity sector and the cement sector.

4.1.2.1. Electricity Sector

Power plants placed in CEMS systems are examined in the study. The mass flow data (kg/h) is taken from CEMS hourly for each factory. They are grouped according to the type of fuels (hard coal, lignite, and natural gas) utilized to produce electricity.

Mass flow data of each facility is taken for five pollutants from the CEMS Database displayed in Table 4:

Table 4. Pollutant types for three fuels in the electricity sector

Hard Coal	**Lignite**	**Natural Gas**
CO (kg/h)	CO (kg/h)	CO (kg/h)
NO_x (kg/h)	NO_x (kg/h)	
SO_2 (kg/h)	SO_2 (kg/h)	NO_x (kg/h)
PM (kg/h)	PM (kg/h)	

4.1.2.2. Cement Sector

The mass flow data (kg/h) is taken from CEMS hourly for each factory in the cement sector. Mass flow data is taken for five pollutants from the CEMS Database:

- CO (kg/h)
- NO_x (kg/h)
- SO_2 (kg/h)
- PM (kg/h)
- TOC (kg/h)

4.1.3. Emission Factor Databases

There are three databases used commonly for emission factors all over the world. Values utilized for calculations from these databases are displayed in Appendix 1. Several examples taken from them can be shown as follows:

4.1.3.1. EPA Emission Factor Documentation for AP-42

The US EPA provides the documentation named AP42. It can be utilized to estimate emissions from sources of various air pollutants. The database does not contain recommended emission limits or standards. Emission factors (EF) are categorized based on pollutant types, fuels, control technologies, and processes [8]. An example table from AP42 is displayed in Figure 5.

Firing Configuration	SCC	SO_x [b]		NO_x [c]		CO [d,e]	
		Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
PC, dry bottom, tangentially fired, bituminous, Pre-NSPS[g]	1-01-002-12 1-02-002-12 1-03-002-16	38S	A	15	A	0.5	A
PC, dry bottom, tangentially fired, bituminous, Pre-NSPS[g] with low-NO_x burner	1-01-002-12 1-02-002-12 1-03-002-16	38S	A	9.7	A	0.5	A
PC, dry bottom, tangentially fired, bituminous, NSPS[g]	1-01-002-12 1-02-002-12 1-03-002-16	38S		10	A	0.5	A
PC, dry bottom, tangentially fired, sub-bituminous, Pre-NSPS[g]	1-01-002-26 1-02-002-26 1-03-002-26	35S	A	8.4	A	0.5	A
PC, dry bottom, tangentially fired, sub-bituminous, NSPS[g]	1-01-002-26 1-02-002-26 1-03-002-26	35S	A	7.2	A	0.5	A
PC, wet bottom, wall-fired[f], bituminous, Pre-NSPS[g]	1-01-002-01 1-02-002-01 1-03-002-05	38S	A	31	D	0.5	A
PC, wet bottom, tangentially fired, bituminous, NSPS[g]	1-01-002-11	38S	A	14	E	0.5	A
PC, wet bottom, wall-fired sub-bituminous	1-01-002-21 1-02-002-21 1-03-002-21	35S	A	24	E	0.5	A

Figure 5. Emission Factor for SO_x, NO_x, and CO for coal combustion [8]

4.1.3.2. EMEP/EEA Air Pollutant Emission Inventory Guidebook

The "Air Pollutant Emission Inventory Guidebook" documentation is supplied by the European Environmental Agency (EEA). It is used to prepare emissions inventories for various air pollutants like CO, NO_x, and PM [10]. A sample table from the European Monitoring and Evaluation Programme (EMEP) Guidebook is shown in Figure 6.

Tier 2 emission factors					
	Code	Name			
NFR Source Category	1.A.1.a	Public electricity and heat production			
Fuel	Coking Coal, Steam Coal & Sub-Bituminous Coal				
SNAP (if applicable)	010101 010102	Public power - Combustion plants >= 300 MW (boilers) Public power - Combustion plants >= 50 and < 300 MW (boilers)			
Technologies/Practices	Dry Bottom Boilers				
Region or regional conditions	NA				
Abatement technologies	Abatement assumed except for SO_2 EF				
Not applicable					
Not estimated	NH_3				
Pollutant	**Value**	**Unit**	**95% confidence interval**		**Reference**
			Lower	**Upper**	
NOx	209	g/GJ	200	350	US EPA (1998), chapter 1.1
CO	8.7	g/GJ	6.15	15	US EPA (1998), chapter 1.1
NMVOC	1.0	g/GJ	0.6	2.4	US EPA (1998), chapter 1.1
SOx	820	g/GJ	330	5000	See Note
TSP	11.4	g/GJ	3	300	US EPA (1998), chapter 1.1
PM_{10}	7.7	g/GJ	2	200	US EPA (1998), chapter 1.1
$PM_{2.5}$	3.4	g/GJ	0.9	90	US EPA (1998), chapter 1.1
BC	2.2	% of $PM_{2.5}$	0.27	8.08	See Note
Pb	7.3	mg/GJ	5.16	12	US EPA (1998), chapter 1.1
Cd	0.9	mg/GJ	0.627	1.46	US EPA (1998), chapter 1.1
Hg	1.4	mg/GJ	1.02	2.38	US EPA (1998), chapter 1.1
As	7.1	mg/GJ	5.04	11.8	US EPA (1998), chapter 1.1
Cr	4.5	mg/GJ	3.2	7.46	US EPA (1998), chapter 1.1
Cu	7.8	mg/GJ	0.233	15.5	Expert judgement derived from EMEP/EEA (2006)
Ni	4.9	mg/GJ	3.44	8.03	US EPA (1998), chapter 1.1
Se	23	mg/GJ	16	37.3	US EPA (1998), chapter 1.1
Zn	19	mg/GJ	7.75	155	Expert judgement derived from EMEP/EEA (2006)
PCB	3.3	ng WHO-TEG/GJ	1.1	9.9	Grochowalski & Konieczyński, 2008
PCDD/F	10	ng I-TEQ/GJ	5	15	UNEP (2005); Coal fired power boilers
Benzo(a)pyrene	0.7	µg/GJ	0.245	2.21	US EPA (1998), chapter 1.1
Benzo(b)fluoranthene	37	µg/GJ	3.7	370	Wenborn et al., 1999
Benzo(k)fluoranthene	29	µg/GJ	2.9	290	Wenborn et al., 1999
Indeno(1,2,3-cd)pyrene	1.1	µg/GJ	0.591	2.36	US EPA (1998), chapter 1.1
HCB	6.7	µg/GJ	2.2	20.1	Grochowalski & Konieczyński, 2008

Figure 6. Tier 2 emission factors for source category 1.A.1.a, dry bottom boilers using coking coal, steam coal, and sub-bituminous coal [10]

4.1.3.3. NPI - Emission Estimation Technique Manual

The database named NPI - Emission Estimation Technique Manual is supplied by the Australian Government. It can be utilized to forecast emissions from sources for several air pollutants [11]. There is a sample table from the NPI - Emission Estimation Technique Manual is displayed in Figure 7:

Appendix A – Emission factors

ESP = Electrostatic precipitator
FF = Fabric filter

Process	Fuel	Control	Substance	Emission factor	Emission factor scientific notation	Rating
Precalciner kilns	Coal	ESP	Acetone	0.00019	1.90E-04	U
Precalciner kilns	Coal	ESP	Ammonia (total)	0.00083	8.30E-04	D
Precalciner kilns	Coal	ESP	Arsenic & compounds	0.0000013	1.30E-06	U
Precalciner kilns	Coal	ESP	Benzene	0.004	4.00E-03	C
Precalciner kilns	Coal	ESP	Biphenyl	0.0000031	3.10E-06	U
Precalciner kilns	Coal	ESP	Cadmium & compounds	0.0000042	4.20E-06	U
Precalciner kilns	Coal	ESP	Carbon disulfide	0.000055	5.50E-05	D
Precalciner kilns	Coal	ESP	Carbon monoxide	0.5	5.00E-01	C
Precalciner kilns	Coal	ESP	Chromium (III) & compounds	0.0000039	3.90E-06	U

Figure 7. Emission factors of precalciner kills in the cement sector [11]

4.2. Data Analysis

This section explains the analyses performed for the data obtained for the electricity and cement sectors. The procedure described below is applied to each piece of data.

- Mass flow data for pollutants (CO, NO_x, SO_2, PM, TOC) is taken from the CEMS module that is placed on the Air Emission Management Portal. The part is explained in detail in the previous section.
- A spreadsheet including hourly mass flow values is prepared for each facility's chimney.
- Mass flow values are examined for all chimneys. Values less than zero are cleared from the spreadsheet.
- Using a statistical program called Statgraphics 18, statistical analyses are performed for all chimneys specific to each facility.
- Statistical analyses are performed with a 95% confidence interval.
- Time series, cluster, and quantitative data analyses are performed to analyze the chimney data.
- The statistical analyses obtained with the statistical program are listed below:

- Average
- Standard deviation
- Coefficient of variation
- Minimum and maximum values
- Maximum value
- Range
- Standard skewness
- Standard kurtosis

- Three types of graphs are obtained as a result of statistical analyses. These graphs are listed as follows:
  - Scatter plot
  - Box and Whisker plot
  - Histogram plot

- The average mass flows obtained for each chimney are summed as a consequence of statistical analyses.
- The total mass flows are obtained for each facility.
- The same process is performed for all pollutants.

4.3. Sector-specific Emission Factor Determination

In this part, sector-specific emission factor development is explained for two sectors. The procedure described below is applied for the type of emission factor data.

4.3.1. Methodology for Electricity Sector

- Plants are divided according to the three types of fuel used (hard coal, lignite, and natural gas).
- The following information is prepared for each facility [27]:
  - Install capacity
  - Technology
  - Plant efficiency
  - Annual production
  - Heating value
  - Density

- Ash percent
- Sulfur percent
- Humidity
- Annual coal demand
- Working hour

- Total mass flow rate is calculated by summing the pollutants from each chimney for each facility.
- The annual amount of pollutants is determined by multiplying the mass flow rate and plant operating hours. This value is found for each pollutant.
- Coal masses are calculated using heating value and efficiency percent for each facility utilizing hard coal and lignite.
- The volume of gas is calculated by utilizing the plant capacity, efficiency, and heating value in facilities using natural gas.
- Average ash, sulfur, and humidity content is calculated for each fuel type and technology.
- The mass of natural gas is computed owing to the volume of gas and its density.
- The amount of produced energy is calculated using the heating value and the fuel mass in each facility.
- The emission factor is calculated by dividing the annual total amount of pollutants by the annual amount of fuel used. Emission factors are calculated for each pollutant.
- The facilities are divided into groups according to the technology utilized for each fuel type.
- Facilities are grouped separately according to controlled and uncontrolled processes.
- The emission factor's average is calculated using the emission factor for each facility. This value is found for each pollutant.
- Graphs are prepared for each pollutant based on the emission factor calculated for the facilities.
- These emission factors are known as uncontrolled for CO in the CEMS Module because of no control devices in the chimneys of plants for the pollutant. However, they are known to be controlled for other pollutants (NO_x, SO_2, and PM_{10}). The reason is that control devices such as SCR, low NO_x, and ESP are utilized for these pollutants.
- Thus, emission factors are calculated based on technology.
- Tier 2 emission factors are obtained for the electricity sector.

4.3.2. Methodology for Cement Sector

- The following information is prepared for each facility [15]:
  - The type of fuel
  - The processes used in each facility
  - Working hours
  - Total cement production capacity
  - Technology
- Total mass flow rate is calculated by summing the pollutants from each chimney for each facility.
- The annual amount of pollutants is determined by multiplying the mass flow rate and plant operating hours. This value is found for each pollutant.
- Total cement production is estimated using cement production capacity for each facility.
- The emission factor is calculated by dividing the annual total amount of pollutants by the annual cement production. Emission factors are calculated for each pollutant.
- The emission factor's average is calculated using the emission factor for each facility. This value is found for each pollutant.
- Graphs are prepared for each pollutant based on the emission factor calculated for the facilities.
- These emission factors are known as uncontrolled for four pollutants, CO, NO_x, SO_2, and TOC, in the CEMS Module, whereas they are known as controlled with ESP for PM_{10}.
- Tier 2 emission factors are obtained for the cement sector.

4.4. Comparison with Other Databases

In this section, the Tier 2 emission factors calculated for each technology are compared with the emission factor values contained in the selected databases (AP42, EMEP/EEA, and NPI).

4.4.1. Comparison for the Electricity Sector

The following steps are applied to compare emission factor values in the electricity sector:

- The emission factor value is taken from these databases as follows:
  - AP-42 (Ib/ton, Ib/10^6 scf)

  - EMEP/EEA (g/GJ)
  - NPI /kg/ton, kg/PJ)
- AP42 and NPI emission factors are controlled and uncontrolled, whereas EMEP/EEA emission factors are uncontrolled for each technology and fuel. These emission factors are shown in Appendix 2.
- Assumptions of collecting efficiency can be listed for each technology as follows:
  - The collecting efficiency with SCR is assumed to be 95% to convert uncontrolled to controlled NO_x emissions [32].
  - The collecting efficiency with low NO_x is assumed to be 65% to convert uncontrolled to controlled NO_x emissions [33].
  - The collecting efficiency of the wet subrubber is assumed to be 90% to convert uncontrolled to controlled SO_2 emissions [34].
  - The collecting efficiency of ESP is assumed to be 99% to convert uncontrolled to controlled PM_{10} emissions [18].
  - The collecting efficiency of the bag filter is assumed to be 98% to convert uncontrolled to controlled for PM_{10} [18].
- The emission factor values are converted to kg/ton for hard coal and lignite.
  - Constants taken in the EMEP/EEA database, which are heating values, SO_2/coal value, MMBTU/ton value, converting factor (GJ/m^3), and Ca/S value, are utilized to convert the EMEP/EEA emission factors from g/GJ to kg/ton.
  - Average ash and sulfur content evaluated for each fuel type are used to convert AP42 emission factors from Ib/ton to kg/ton [8].
  - NPI emission factors are utilized directly as kg/ton.
- The emission factor values are converted to g/GJ for natural gas.
  - Ib/kg constant and conversion factor are used to convert AP42 emission factors from Ib/10^6 scf to g/GJ [8].
  - NPI emission factors are converted from kg/PJ to g/GJ.
  - EMEP/EEA emission factors are utilized directly as g/GJ.
- An Excel sheet is prepared to compare these values with the calculated Tier 2 emission factors.
- Then, they are compared with the Tier 2 emission factors calculated for each pollutant and each technology.

4.4.2. Comparison for the Cement Sector

The following steps are applied to compare emission factor values:

- The emission factor values are gathered from the EMEP/EEA database as g/ton as uncontrolled.
- The PM_{10} emission factor value is converted from uncontrolled to controlled using proposed abatement percentages. Other pollutants are not converted, and uncontrolled values are used for comparison.
- Assumptions of collecting efficiency can be listed for each technology as follows:
  - The collecting efficiency of ESP is assumed to be 99% to convert uncontrolled to controlled PM_{10} emissions [18].
  - The collecting efficiency of the bag filter is assumed to be 98% to convert uncontrolled to controlled PM_{10} emissions [18].
- The calculated Tier 2 emission factor values are compared with EMEP/EEA databases for each pollutant.

4.5. Closing Remarks

The thesis methodology comprises four main parts: data gathering, data analysis, sector-specific emission factor determination, and comparison with three selected databases (AP42, EMEP/EEA Guidebook, NPI). Sector-specific emission factors are calculated as controlled and uncontrolled for the electricity and cement sectors within the scope of this thesis. In addition, the next chapter includes the comparison of these calculated sector-specific emission factors with database values. Also, several statistical analyses, such as standard deviation, coefficient of variation, and skewness, are performed with a 95% confidence interval. As a result of these analyses, some graphs are achieved, like scatter plots, box-whicker plots, and histogram plots.

5. RESULTS AND DISCUSSION

The methodology outlined in Chapter 4 is applied, and sector-specific (Tier 2) emission factors calculated for various pollutants such as CO, NOx, SO_2, PM_{10}, and TOC for Türkiye's electricity and cement sector are presented in this chapter.

5.1. Overview of the Gathered Data for the Study

This part represents detailed information on the data gathered for the study. The data on power plant operations monitored pollutant emissions and emission factors are presented here. Several pieces of information about plants, such as plant names and plant-specific pollutant emissions, cannot be given here individually due to the non-disclosure agreement signed with the Ministry of Environment Urbanization and Climate Change.

5.1.1. Plant Data

There are 57 coal-fuelled and 280 natural gas fuıeled power plants with the license to operate in Türkiye [30]. However, when the ones with low installed capacity and those not operating are eliminated, 12 lignite, 15 hard coal, and 41 natural gas power plants with monitored pollutant data are used in this study, as presented in Figure 8.

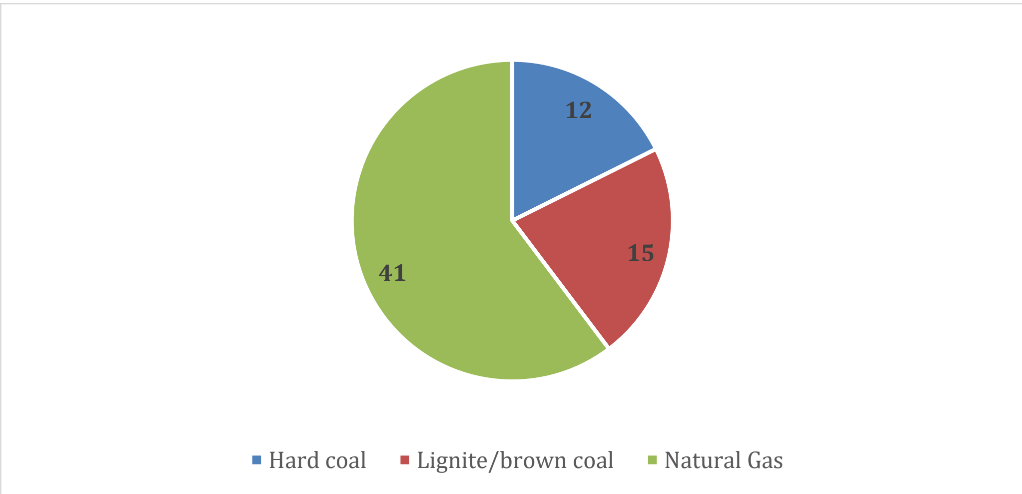


Figure 8. Power plants within the scope of this study

When the graph is analyzed, the number of power plants that utilize natural gas to produce electricity is higher than others.

Hard Coal: This study analyzes twelve power plants utilizing hard coal as fuel. There are four types of technologies in these plants. They can be listed as follows [30]:

- Fluidized bed – 2 power plants
- Pulverized -10 power plants
    - Subcritical pulverized -5 power plants
    - Supercritical pulverized – 4 power plants
    - Ultra supercritical pulverized – 1 power plant

The range of install capacities of power plants with hard coal can be displayed in Figure 9 [27]:

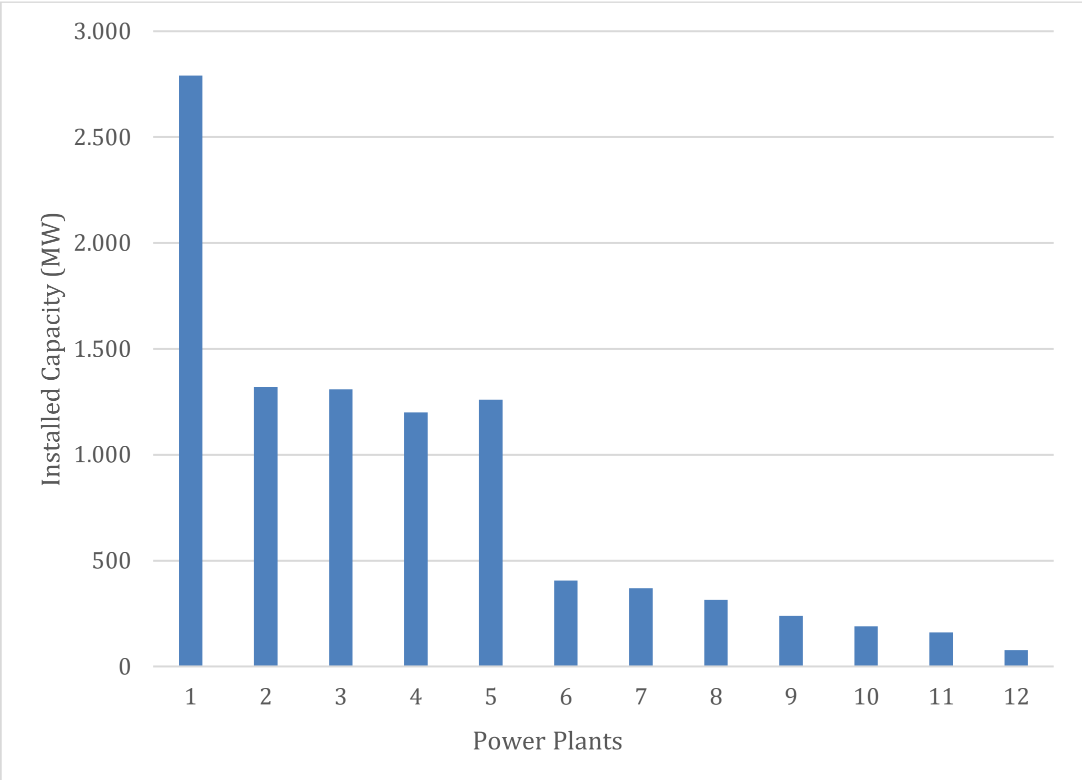


Figure 9. Install capacities of power plants with hard coal [27]

Lignite: This study analyses fifteen power plants that utilize lignite coal as fuel. There are two types of technologies in these plants. They can be listed as follows [30]:

- Fluidized bed – 3 power plants
- Pulverized -12 power plants

The range of install capacities of power plants with lignite/brown coal is shown in Figure 10.

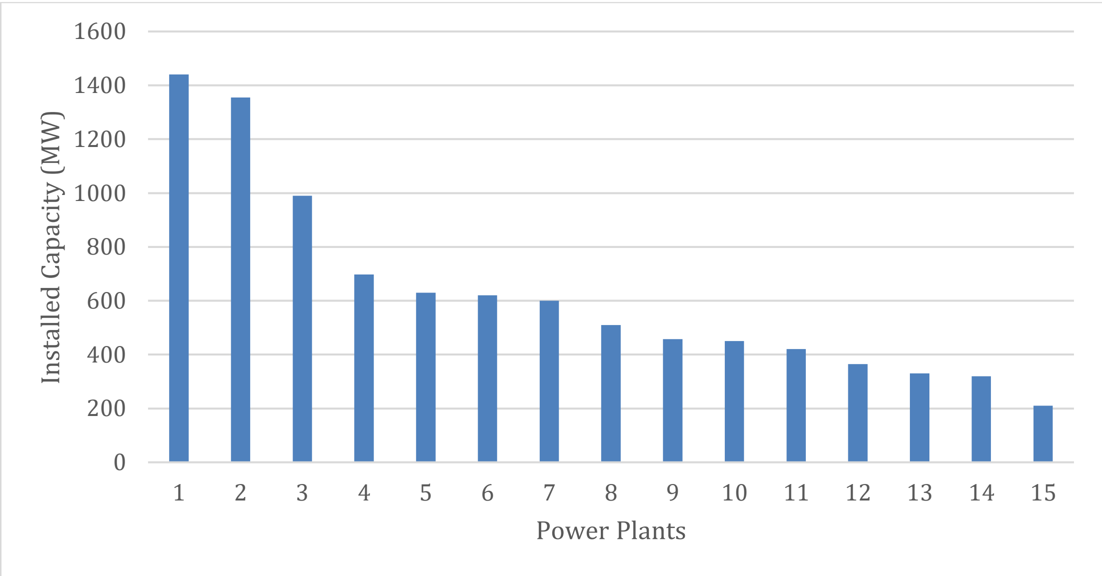


Figure 10. Install capacities of power plant with lignite [27]

According to Figure 10, the highest installation capacity is approximately 1450 MW, while the lowest is 200 MW.

Natural Gas: Natural gas-fuelled power plants use two technologies: natural gas combined cycle (NGCC) and open-cycle gas turbines (OCGT). According to the Regulation on Control of Industrial Air Pollution arranged by the Ministry of Environment, Urbanization, and Climate Change, facilities with an installed power greater than 50 MW are defined as large combustion facilities. Within the scope of this thesis, large combustion plants were analyzed. Yet, 41 plants were selected from these plants to calculate the emission factor [35].

The range of power plant installation capacities with natural gas is shown in Figure 11.

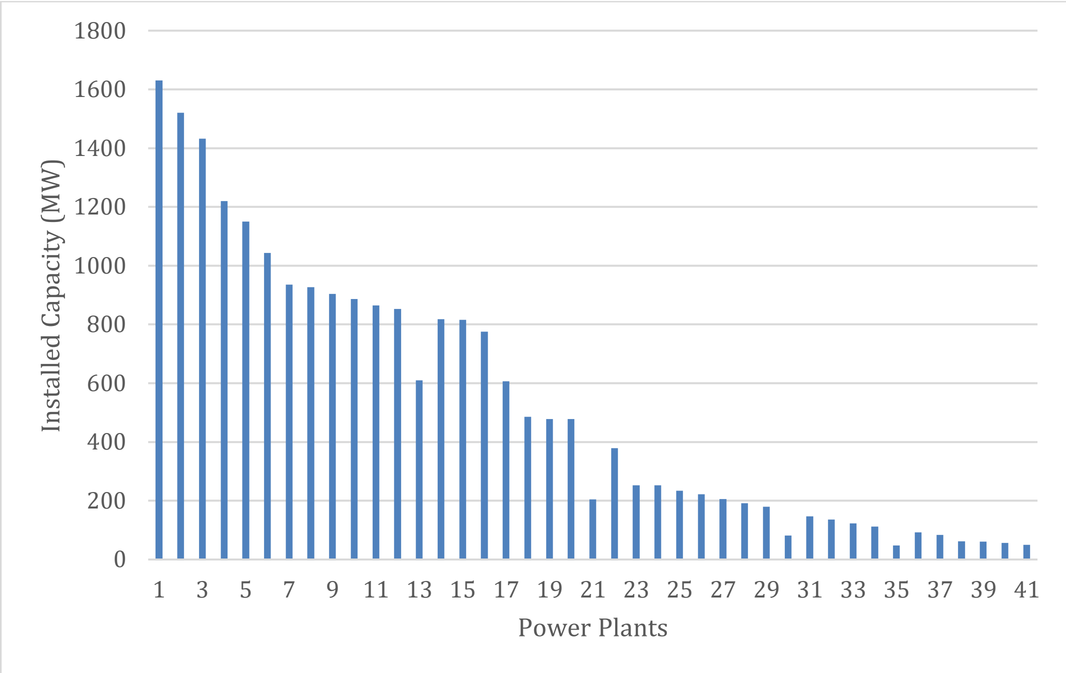


Figure 11. Install capacities of power plants with natural gas [27]

According to Figure 11, the largest installation capacity is about 1650 MW, whereas the minimum is 50 MW.

The amount of electricity (MWh) produced by plants within the scope of this study in 2021 is shown in Table 5.

Table 5. Electricity production by plants within the scope of this study in 2021 (MWh) [22]

Fuel Type	Electricity Production in 2021 [MWh]
Hard Coal	59,181,032.47
Lignite	44,351,094.46
Natural Gas	87,402,604.99
Total	190,934,731.92

When examining Table 5, it is evident that the largest electricity production by plants in this study in 2021 was achieved using natural gas, with 87,402,604.99 MW. Then, hard coal generated 59,181,032.47 MWh, and lignite produced 44,351,094.46 MWh in 2021. It is worth noting that the number of power plants using natural gas exceeds those using other sources. [27].

The second sector analyzed within the scope of this study is the cement sector. The dry process is merely used in Türkiye in the cement sector. There are 55 plants that produce cement in Türkiye. These cement plants are shown in the Figure 12:

Figure 12. Cement plants in Türkiye [36]

The amount of cement production taken from activity reports of plants in 2021 is shown in Figure 13:

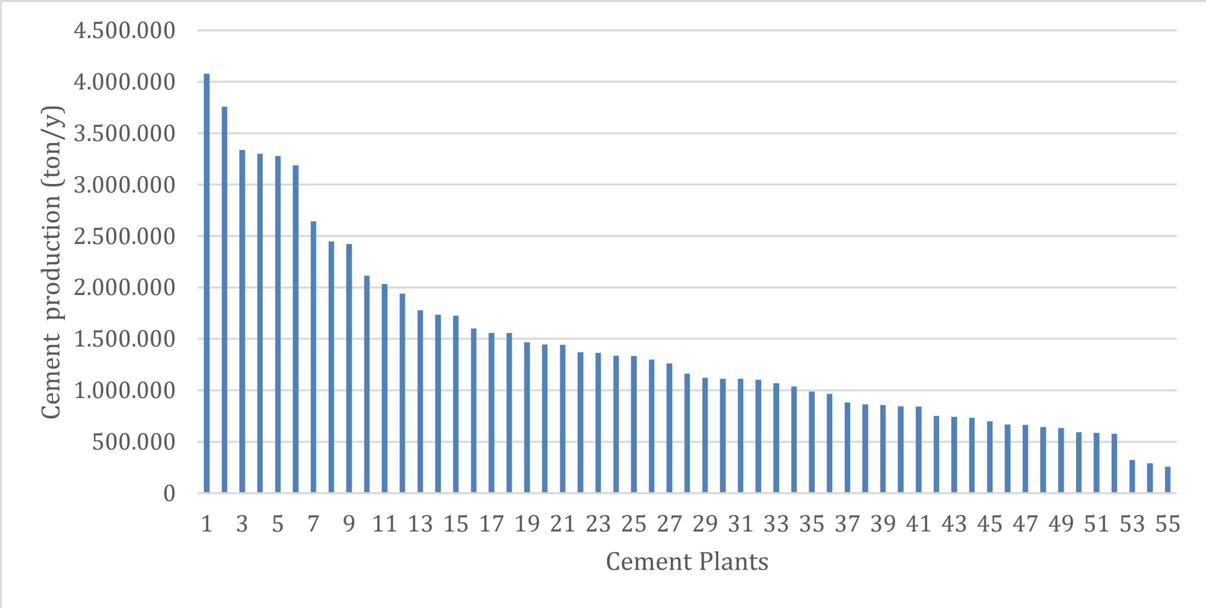


Figure 13. Cement production in 2021 [15]

When examining the graph, the production range varied from 4,000,000 tons/year to 250,000 tons/year. The total cement production in 2021 was 78,945,029 tons [15].

5.1.2. Monitored Pollutant Data

Data on pollutant levels from the plant was obtained from the Continuous Emission Monitoring System (CEMS) through the Air Emission Management Portal for the electricity and cement sectors in 2021. A total of 342 chimneys from both sectors were analyzed. The distribution of the chimneys analysed in this study is illustrated in Figure 14 [18].

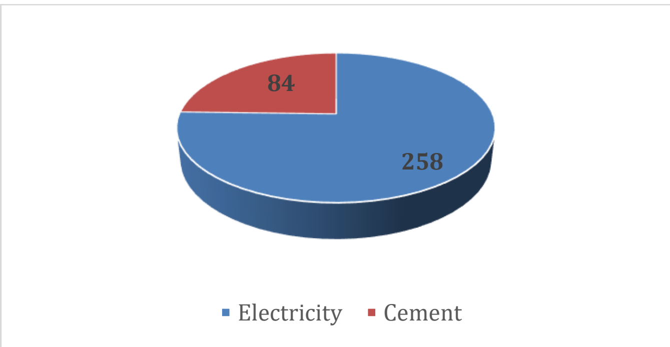


Figure 14. The number of analysed chimney

Looking at Figure 14, the number of analyzed chimneys in the electricity sector is higher than in the cement sector.

The chimney data was taken hourly for five pollutants (CO, NO_x, SO_2, PM_{10}, TOC) for each sector. 8760 hours of mass flow data from each chimney were analyzed for each sector pollutant. The total number of analyzed data is about 2,996,000 for these sectors in the thesis.

Nonetheless, several information about plants, like the chimney knowledge, concentration of pollutants from chimneys, and their mass flow rates, could not be presented because of the non-disclosure agreement signed with the Ministry of Environment Urbanization and Climate Change.

5.1.3. Emission Factor Databases

Emission factor databases utilized for calculations of the study from these databases are displayed in Appendix 1.

Also, emission factors are converted to a single unit for comparison with the calculated sector-specific (Tier 2) emission factor. The unit is kg/ton for hard coal and lignite, while it is g/GJ in natural gas in the electricity sector. Also, the unit is g/ton in the cement sector. These emission factors are displayed as controlled and uncontrolled for each fuel for both sectors in Appendix 2.

5.2. Analysis of the Data Gathered

The chimney data was collected hourly for several pollutants from each sector, including CO, NO_x, SO_2, PM_{10}, and TOC. Statistical analysis was conducted on 8760 hours of mass flow data from each chimney for each industry pollutant.

In addition, detailed operational information about plants could not be explained because of the non-disclosure agreement signed with the Ministry of Environment, Urbanization, and Climate Change. However, an example of statistical analysis is provided for a pollutant without mentioning the plant's name.

The statistical analysis of a plant

First, a statistical table was created for each pollutant emitted from the plant's chimney. The table includes the count, average, standard deviation, coefficient of variation, minimum value, maximum value, skewness, and kurtosis. This information is shown in Table 6.

Statistical analyses were performed using statistical software called Statgraphics[4].

Table 6. Summary statistics of NO_x (kg/h) for Plant A

Count	8647
Average	712.538
Standard deviation	263.049
Coeff. of variation	36.92%
Minimum	0.22 kg/h
Maximum	1420.29 kg/h
Range	1420.07 kg/h
Stnd. skewness	-12.4735
Stnd. kurtosis	-19.9354

Next, the confidence interval was calculated for each pollutant. It is displayed as follows:

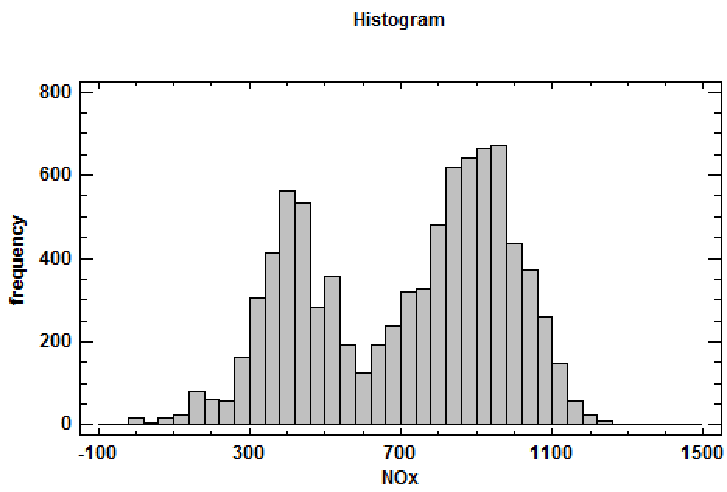
Confidence Intervals for NO_x

95% confidence interval for mean: 712.538 +/- 5.54437 [706.993; 718.082]

95% confidence interval for standard deviation: [259.186; 267.029]

Later, the histogram graph was drawn for each pollutant for the plant. A sample is displayed in Figure 15.

[4] Statgraphics is a statistics software used to make and describe fundamental and complex statistical operations.

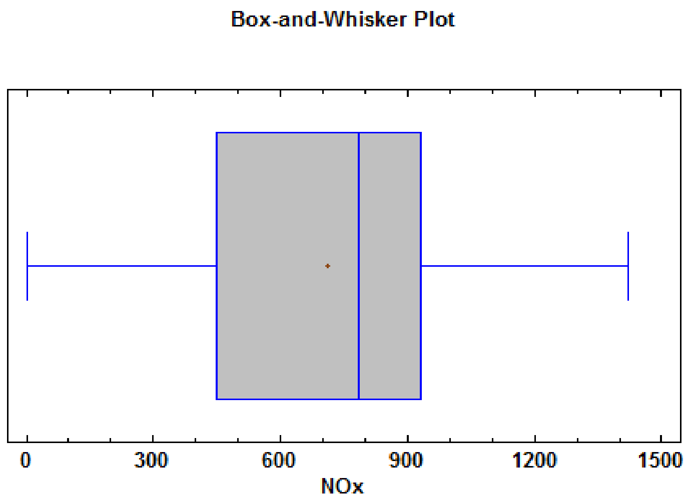


(kg/ton)

Figure 15. Histogram of NO_x for plant A

Later, the box-whisker plot is shown for each pollutant of plants. A sample is displayed in Figure 16.

The box plot contains five parts: the minimum value, the second quartile (the lower 25% of the data are contained), the median, the third quartile (the upper 25% of the data are contained), and the maximum value.



(kg/ton)

Figure 16. Box and whisker plot for NO_x for plant A

Lastly, a scatter plot was created to visualize the plant's pollutant levels. An example is shown in Figure 17.

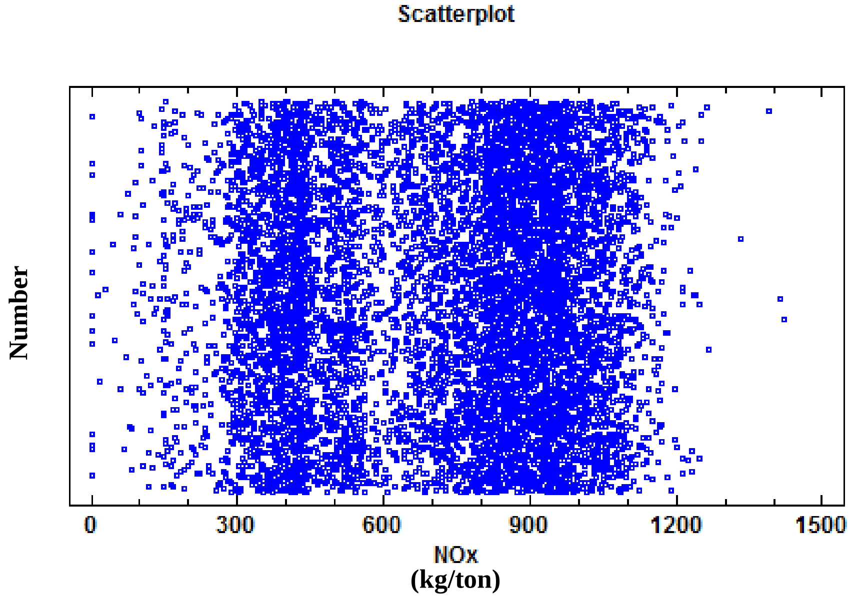


Figure 17. Scatterplot of NO_x for plant A

The statistical analysis steps described in the previous section were applied to each pollutant emitted by plants in the electricity and cement sectors.

5.3. Determined Sector-Specific (Tier 2) Emission Factors

According to the plant's fuel type and technology utilization, emission factor values were determined as controlled and uncontrolled and compared with those from three databases (AP 42, EMEP/EEA, and NPI). These results are shown with tables for each fuel and technology.

5.3.1. Sector Specific (Tier 2) Emission Factors for Electricity Sector

This part presents the calculated Tier 2 emission factors for each technology and fuel used in the electricity sector. These emission factors are calculated for CO, NO_x, SO_2, and PM_{10}.

Emission factors were calculated as uncontrolled for CO, while they were calculated as controlled for other pollutants such as NO_x, SO_2, and PM_{10}. CO emission factors remain uncontrolled due to the absence of control technology in power plants for this pollutant.

5.3.1.1. Hard Coal

In the section, the Tier 2 emission factors for hard coal are explained for two types of processes: fluidized bed and pulverized.

The number of plants that used their data in the calculations is shown for hard coal in Table 7.

Table 7. The number of plants that used their data for hard coal

Pollutant	Control Technology	Fluidized Bed	Pulverized
CO	-	2	10
NO_x	Low NO_x	1	-
	SCR	1	10
SO_2	Wet scrubbing	2	10
PM_{10}	Bag Filter	-	2
	ESP	2	8

According to Table 20, 2 plants used the fluidized bed process, while 10 plants utilized the pulverized process.

Emission factors calculated for each pollutant are listed with three database values as in the following:

5.3.1.1.1. Fluidized Bed

CO

Table 8. Calculated Tier 2 CO emission factor for hard coal (2 plants)

Calculated Tier 2 EF	Databases
0.552 +/- 5.546 kg/ton	AP42: 0.816 kg/ton
	EMEP/EEA: 0.816 kg/ton
	NPI: 0.815 kg/ton

The calculated emission factor for CO with 0.552 kg/ton is lower than the selected uncontrolled database values. The uncontrolled emission factor was computed because there is no control technology for CO in hard coal-fuelled power plants in Türkiye [37]. The reason is that there were not enough facilities (2 plants) in this section. Therefore, comprehensive statistical analysis could not be performed.

According to the result of the statistical analysis, the acceptable range is between 0 kg/ton and 6.098 kg/ton. The range does not provide an accurate value as only two plants can be utilized for statistical analysis. The emission factor in Table 8 was calculated as uncontrolled.

NO_x

Table 9. Calculated Tier 2 NO_x emission factors for hard coal (One plant each)

Control Technology	Calculated Tier 2 EF	Databases
SCR	1.776 kg/ton	AP42: 1.474 kg/ton
		EMEP/EEA: 1.471 kg/ton
		NPI: 1.625 kg/ton
Low NO_x	2.918 kg /ton	AP42: 1.968 kg/ton
		EMEP/EEA: 2.263 kg/ton
		NPI: 2.500 kg/ton

Two emission factors are computed for NO_x because power plants utilize two types of control technologies: low NO_x and Selective Catalytic Reduction (SCR) for the pollutant. The calculated emission factors are higher than the selected database values when Table 9 is examined. The emission factor for the low NO_x technology is higher than the others because the reduction percentage is higher in SCR. SCR is a newer and more advanced technology than low NO_x. The acceptable range for NO_x could not be calculated due to the unique facility of each control technology used in a hard coal-fueled power plant with a fluidized bed.

SO_2

Table 10. Calculated Tier 2 SO_2 emission factors for hard coal (2 plants)

Control Technology	Calculated Tier 2 EF	Databases
Wet scrubbing	2.404 +/- 20.482 kg/ton	AP42: 1.587 kg/ton
		EMEP/EEA: 2.249 kg/ton
		NPI: 1.750 kg/ton

According to Table 10, the calculated emission factor is higher than the selected database values due to the heating value and sulfur percent. The emission factors obtained from the databases are based on the fuel heating value of 6367 kcal/kg and fuel sulfur content of 1.4%. According to the result of the statistical analysis, the acceptable range is between 0 kg/ton and 22.886 kg/ton. The range does not provide a certain result as only two plants can be used for statistical analysis.

PM_{10}

Table 11. Calculated Tier 2 PM_{10} emission factors for hard coal (2 plants)

Control Technology	Calculated Tier 2 EF	Databases
ESP	0.281 +/- 0.540 kg/ton	AP42: No Data
		EMEP/EEA: 0.211 kg/ton
		NPI: 0.276 kg/ton

According to Table 11, the calculated emission factor for PM_{10} is nearly the same as the values in the selected databases. Plants that utilize hard coal prefer electrostatic precipitators (ESP) to control PM_{10} emissions because ESP technology has a high collection efficiency for hard coal [37]. The ash content is 8.2% for hard-fueled power plants with fluidized beds. When the result of the statistical analysis is examined, the acceptable range is between 0 kg/ton and 0.821 kg/ton.

5.3.1.1.2. Pulverized

CO

Table 12. Calculated Tier2 CO emission factors for hard coal (10 plants)

Calculated Tier 2 EF	Databases
0.255 +/- 0.105 kg/ton	AP42: 0.227 kg/ton
	EMEP/EEA: 0.227 kg/ton
	NPI: 0.250 kg/ton

According to Table 12, the calculated emission factor for CO is nearly the same as the values in the selected databases. The value was calculated as uncontrolled. According to the result of the statistical analysis, the acceptable range is between 0.150 kg/ton and 0.360 kg/ton. The calculated CO emission factor can be acceptable in Türkiye.

Also, the pulverized Tier 2 emission factor in Table 12 is presented for the average of three types of pulverized emission factors shown in Table 13 for CO.

Table 13. Emission Factors of CO for pulverized (10 plants)

Technology	Calculated Tier 2 EF
Subcritical pulverized	0.363 +/- 0.158 kg/ton (5 plants)
Supercritical pulverized	0.139 +/- 0.108 kg/ton (4 plants)
Ultra-supercritical pulverized	0.255 kg/ton (one plant)

The calculated emission factors for pulverized types change based on operating temperatures and pressures. When examining Table 13, the emission factor for ultra-supercritical pulverized is high as there were not enough facilities (1 plant) with this process to analyze. Apart from the process, the values for the other two processes (subcritical and supercritical) are acceptable because there were enough facilities (9 plants). The permissible range for subcritical pulverized is from 0.205 kg/ton to 0.521 kg/ton. In addition, the acceptable range for supercritical-pulverized is between 0.031

kg/ton and 0.247 kg/ton. The acceptable range for ultra-supercritical could not be calculated due to the unique facility of the process.

NOx

Table 14. Calculated Tier 2 NO_x emission factors for hard coal (10 plants)

Control Technology	Calculated Tier 2 EF	Databases
SCR	1.072 +/- 0.404 kg/ton	AP42: 4.740 kg/ton
		EMEP/EEA: 5.447 kg/ton
		NPI: 5.550 kg/ton

SCR is used as a control technology for NO_x emissions in pulverized coal combustion using hard coal. According to Table 14, the calculated emission factor for NO_x is lower than the ones presented in the selected databases. This is because combustion conditions can be better in the analyzed facilities using hard coal. SCR is a newer and more advanced technology than low NO_x technology for the NOx collection [37]. The acceptable range is between 0.668 kg/ton and 1.476 kg/ton.

Also, the pulverized Tier 2 emission factor in Table 14 consists of the average of three types of pulverized emission factors shown in Table 15 for NO_x.

The steam pressure within the boiler determines whether pulverized coal combustion technology is subcritical, supercritical, or ultra-supercritical. It affects the efficiency of the technology used in plants. The efficiency of subcritical, supercritical, and ultra-supercritical power plants is approximately 35%, 38.5%, and 43%, respectively. [39].

Table 15. Emission factors of NO_x for pulverized (10 plants)

Technology	Calculated Tier 2 EF
Subcritical pulverized	1.089 +/- 0.599 kg/ton (5 plants)
Supercritical pulverized	0.979 +/- 1.149 kg/ton (4 plants)
Ultra supercritical pulverized	0.924 kg/ton (one plant)

The acceptable range for ultra super pulverized could not be computed because of only one facility used in a hard coal-fueled power plant with a fluidized bed. However, the acceptable range for subcritical pulverized is from 0.490 kg/ton to 1.688 kg/ton. Moreover, the permissible range for supercritical-pulverized is between 0 kg/ton and 2.128 kg/ton.

SO_2

Table 16. Calculated Tier 2 SO_2 emission factors for hard coal (10 plants)

Control Technology	Calculated Tier 2 EF	Databases
Wet Scrubbing	4.016 +/- 2.482 kg/ton	AP42: 5.171 kg/ton
		EMEP/EEA: 6.748 kg/ton
		NPI: 5.700 kg/ton

Wet scrubbing is used as a control technology for SO_2 in the part. According to Table 16, the calculated emission factor is lower than the ones presented in the selected databases with 4.106 kg/ton. Combustion conditions in the analyzed facilities may be optimal, and the sulfur percentage can be low. It influences the quantity of emissions and the determined emission factors. The emission factors obtained from the databases are based on the fuel heating value of 6367 kcal/kg and fuel sulfur content of 0.8%. In addition, the permissible range for supercritical-pulverized is from 0 kg/ton and 2.128 kg/ton. The calculated SO_2 emission factor can be acceptable for Türkiye. Also, the pulverized Tier 2 emission factor in Table 16 consists of the average of three types of pulverized emission factors shown in Table 17 for SO_2.

Table 17. Emission factors of SO_2 for pulverized (10 plants)

Technology	Calculated Tier 2 EF
Subcritical pulverized	4.439 +/- 1.382 kg/ton (5 plants)
Supercritical pulverized	2.168 +/- 0.552 kg/ton (4 plants)
Ultra-supercritical pulverized	1.085 kg/ton (1 plants)

The steam pressure within the boiler determines whether pulverized coal combustion technology is subcritical, supercritical, or ultra-supercritical. The efficiency varies for each type of technology. The permissible range for subcritical pulverized is from 3.057 kg/ton to 5.821 kg/ton. In addition, the acceptable range for supercritical-pulverized is between 1.616 kg/ton and 2.720 kg/ton. The acceptable range for ultra-supercritical could not be calculated due to the unique facility of the process.

PM_{10}

Table 18. Emission factors of PM_{10} for emission factors for hard coal (10 plants)

Control Technology	Calculated Tier 2 EF	Databases
ESP	0.095 +/- 0.051 kg/ton (8 plants)	AP42: 0.205 kg/ton
		EMEP/EEA: 0.211 kg/ton
		NPI: 0.276 kg/ton
Bag filter	0.075 +/- 0.298 kg/ton (2 plants)	AP42: 0.192 kg/ton
		EMEP/EEA: 0.211 kg/ton
		NPI: 0.257 kg/ton

Two emission factors are computed for PM_{10} since power plants in Türkiye utilize two types of control technologies (ESP and bag filter) for the pollutant. The calculated emission factors are lower than the selected database values when Table 18 is examined.

The emission factor for the bag filter technology is lower than the others because the efficiency of a bag filter can reach up to 99.9%, whereas an ESP has an efficiency of 98-99% [37]. The acceptable range of PM_{10} for ESP is from 0.044 kg/ton whereas the range is between 0 kg/ton to 0.373 kg/ton for bag filters.

Also, the pulverized Tier 2 emission factor in Table 18 consists of the average of three types of pulverized emission factors shown in Table 19 for PM_{10}.

Table 19. Emission factors of PM_{10} for pulverized (10 plants)

Technology	Calculated Tier 2 EF
Subcritical pulverized	1.850 +/- 0.087 kg/ton (5 plants)
Supercritical pulverized	0.749 +/- 0.075 kg/ton (4 plants)
Ultra-supercritical pulverized	0.619 kg/ton (one plant)

The emission factors shown in Table 19 are different for each technology, which is low due to their low thermal power and low fuel consumption because thermal power requirement, efficiency, and fuel usage are different for each technology.

The acceptable range for subcritical pulverized is from 1.763 kg/ton to 1.937 kg/ton. In addition, the permissible range for supercritical pulverized is between 0.674 kg/ton and 0.824 kg/ton. The acceptable range for ultra-supercritical could not be calculated because of the unique facility of the process.

5.3.1.2. Lignite / Brown Coal

In this part, the Tier 2 emission factors for lignite are expressed for two types of processes: fluidized bed and pulverized.

The number of plants that utilized their data in the calculations is indicated for lignite in Table 20.

Table 20. The number of plants that used their data for lignite

Pollutant	Control Technology	Fluidized Bed	Pulverized
CO	-	4	11
NO_x	SCR	4	11
SO_2	Wet Scrubbing	4	11
PM_{10}	ESP	4	11

According to Table 20, 4 plants used the fluidized bed process, while 11 plants utilized the pulverized process.

Emission factors computed for each pollutant are listed with three database values as follows:

5.3.1.2.1. Fluidized Bed

CO

Table 21. Calculated Tier 2 CO emission factor for lignite (4 plants)

Calculated Tier 2 EF	Databases
0.104 +/- 0.046 kg/ton	AP42: 0.068 kg/ton
	EMEP/EEA: 0.089 kg/ton
	NPI: 0.080 kg/ton

The emission factor for CO in Table 21 is higher than the selected database values in the plants using lignite, and the value was calculated as uncontrolled. The situation can be seen because of the content of lignite utilized as fuel [37]. According to the result of the statistical analysis, the acceptable range is between 0.058 kg/ton and 0.150 kg/ton. The CO emission factor is within acceptable range for a lignite-fueled power plant utilizing a fluidized bed in Türkiye.

NO_x

Table 22. Calculated Tier 2 NO_x emission factor for lignite (4 plants)

Control Technology	Calculated Tier 2 EF	Databases
SCR	1.768 +/- 0.214 kg/ton	AP42: 1.633 kg/ton
		EMEP/EEA: 1.564 kg/ton
		NPI: 1.800 kg/ton

SCR is a technology that controls NO_x emissions in lignite-fired facilities in Türkiye. According to Table 22, The calculated emission factor of 1.768 kg/ton is almost the same as the selected database values. SCR is utilized for plants with lignite because the control system is useful and effective for NO_x collection. Additionally, SCR is a more advanced abatement technology than low NO_x. According to the result of the statistical analysis, the permissible range is from 1.554 kg/ton to 1.982 kg/ton. The NO_x emission factor can be an acceptable range for a lignite-fueled power plant utilizing a fluidized bed in Türkiye.

SO_2

Table 23. Calculated Tier 2 SO_2 emission factor for lignite (4 plants)

Control Technology	Calculated Tier 2 EF	Databases
Wet scrubbing	4.001 +/- 2.434 kg/ton	AP42: 4.536 kg/ton
		EMEP/EEA: 4.608 kg/ton
		NPI: 5.000 kg/ton

Wet scrubbing is utilized as a control technology for SO_2 in lignite-fired facilities in Türkiye. When reviewing Table 23, the calculated emission factor of 4.001 kg/ton is lower than the values in the selected database. The reason is that the analyzed plants have different sulfur percentages (3%) in lignite-fired facilities in Türkiye from three selected database values. The permissible range is from 1.567 kg/ton to 6.435 kg/ton. The emission factor for SO_2 may be acceptable for a lignite-fueled power plant utilizing a fluidized bed in Türkiye.

PM_{10}

Table 24. Calculated Tier 2 PM_{10} emission factor for lignite (4 plants)

Control Technology	Calculated Tier 2 EF	Databases
ESP	0.192 +/- 0.126 kg/ton	AP42: 0.180 kg/ton
		EMEP/EEA: 0.278 kg/ton
		NPI: 0.392 kg/ton

In Table 24, the calculated emission factor of 0.192 kg/ton exceeds the AP42 value but falls below the EMEP/EEA and NPI values. Plants that utilize lignite prefer electrostatic precipitators (ESP) to control PM_{10} emissions in Türkiye [37]. According to the result of the statistical analysis, the permissible range is between 0.066 kg/ton and 0.318 kg/ton for PM_{10}. The PM_{10} emission factor calculated may be acceptable for PM_{10} in a lignite-fueled power plant with a fluidized bed in Türkiye.

5.3.1.2.2. Subcritical Pulverized

CO

Table 25. Calculated Tier 2 CO emission factor for lignite (11 plants)

Calculated Tier 2 EF	Databases
0.143 +/- 0.058 kg/ton	AP42: 0.113 kg/ton
	EMEP/EEA: 0.227 kg/ton
	NPI: 0.130 kg/ton

According to Table 25, the calculated emission factor is higher than the AP42 and NPI values but lower than the EMEP/EEA value. Additionally, these values were calculated as uncontrolled for CO. Moreover, the permissible range for the emission factor of CO is from 0.085 kg/ton to 0.201 kg/ton in lignite-fueled power plants with pulverized in Türkiye. The calculated emission factor for CO can be considered acceptable as a Tier 2 emission factor in Türkiye.

NO_x

Table 26. Calculated Tier 2 NO_x emission factor for lignite (11 plants)

Control Technology	Calculated Tier 2 EF	Databases
Low NO_x	2.216 +/- 0.875 kg/ton	AP42: 2.715 kg/ton
		EMEP/EEA: 2.033 kg/ton
		NPI: 2.300 kg/ton

Low NO_x is used as a control technology for NO_x in lignite-fired facilities in Türkiye. According to Table 26, the calculated emission factor for NO_x is lower than the selected database values because combustion conditions may diverge in the analyzed facilities using lignite [37]. According to the result of the statistical analysis, the acceptable range is from 1.341 kg/ton and 3.091 kg/ton for NO_x. The calculated emission factor of NO_x can be accepted as 2.216 kg/ton for Türkiye. More reliable results are obtained when more facilities are included in the calculation.

SO_2

Table 27. Calculated Tier 2 SO_2 emission factor for lignite (11 plants)

Control Technology	**Calculated Tier 2 EF**	**Databases**
Wet scrubbing	14.016 +/- 7.731 kg/ton	AP42: 13.608 kg/ton
		EMEP/EEA: 13.825 kg/ton
		NPI: 15.000 kg/ton

Wet scrubbing is used as a control technology for SO_2 in lignite-fired facilities in Türkiye. According to Table 27, the calculated emission factor of 14.016 kg/ton is nearly the same as the selected database values. Combustion conditions in the analyzed facilities are optimal, and the sulfur percentage is low [37]. In addition, the acceptable range is from 6.285 kg/ton and 21.747 kg/ton for NO_x. The calculated emission factor of SO_2 may be accepted as 14.016 kg/ton for Türkiye.

PM_{10}

Table 28. Calculated Tier 2 PM_{10} Emission factor for lignite (11 plants)

Control Technology	**Calculated Tier 2 EF**	**Databases**
ESP	0.205 +/-0.062 kg/ton	AP42: 0.278 kg/ton
		EMEP/EEA: 0.206 kg/ton
		NPI: 0.403 kg/ton

According to Table 28, the calculated emission factor of 0.205 kg/ton for PM_{10} is nearly the same as the value in the EMEP/EEA database. However, the emission factor is lower than the other two database values. Plants that utilize hard coal prefer ESP to control PM_{10} emissions in Türkiye [37]. According to the result of the statistical analysis, the permissible range is between 0.143 kg/ton and 0.267 kg/ton for PM_{10}. The calculated PM_{10} emission factor can be acceptable in a lignite-fueled power plant with a pulverized in Türkiye.

5.3.1.3. Natural Gas

The following section explains the Tier 2 emission factors for natural gas for the NGCC process. The calculation did not include facilities using the OCGT process because there was insufficient data. In other words, the OCGT process is utilized in four plants. Emission factors calculated for each pollutant are listed with three database values as in the following:

CO

Table 29. Calculated Tier 2 CO emission factor for natural gas (28 plants)

Calculated Tier 2 EF	Databases
31.095 +/- 10.233 g/GJ	AP42: 35.471 g/GJ
	EMEP/EEA: 39.000 g/GJ
	NPI: 41.000 g/GJ

Based on Table 29, the calculated Tier 2 emission factor of 31.095 g/GJ is lower than the values from the selected databases (AP42, EMEP/EEA, and NPI). According to the result of the statistical analysis, the acceptable range is between 20.862 g/GJ and 41.328 g/GJ for CO. The emission factor calculated for CO may be acceptable for a power plant using natural gas in Türkiye.

NGCC is the most commonly used process in natural gas-fired facilities in Türkiye. Additionally, these values were calculated as uncontrolled for CO.

NO_x

Table 30. Calculated Tier 2 NO_x emission factor for natural gas (28 plants)

Control Technology	Calculated Tier 2 EF	Databases
Low NO_x	42.609 +/- 10.923 g/GJ	AP42: 38.981 g/GJ
		EMEP/EEA: 48.000 g/GJ
		NPI: 42.000 g/GJ

According to Table 30, the calculated emission factor is higher than the AP42 and NPI values but lower than the EMEP/EEA value. Low NO_x is selected as a control technology for NO_x in the part. The technology is more suitable than the other technology for NO_x reduction for plants using natural gas because it provides a reduction in environmental pollution and air quality problems [16]. Moreover, the permissible range is from 31.686 g/GJ to 53.532 g/GJ for NO_x. The emission factor calculated for NO_x may be acceptable for a power plant using natural gas in Türkiye.

5.3.2. Sector Specific (Tier 2) Emission Factors for Cement Sector

This part explains the calculated Tier 2 emission factors for the cement sector. These emission factors are calculated for CO, NO_x, SO_2, PM_{10}, and TOC. Emission factors were calculated as uncontrolled for CO, NO_x, SO_2, and TOC, whereas the other pollutant, PM_{10}, was computed as controlled. Emission factors are controlled for PM_{10} since ESP is utilized as a control technology for the pollutant in cement plants.

CO

Table 31. Calculated Tier 2 CO emission factor for cement plants (55 plants)

Calculated Tier 2 EF	EMEP/ EEA Emission Factor
1596.167 +/- 417.343 g/ton	1455.000 g/ton

According to Table 31, the calculated emission factor of CO is higher than the EMEP/EEA emission factor for the cement sector. The difference in these values may be detected due to different technologies utilized by plants in Türkiye and Europe. In addition, these values were calculated as uncontrolled for the pollutant. According to the result of the statistical analysis, the acceptable range is between 1178.824 g/ton and 2013.51 g/ton for CO. The calculated CO emission factor may be acceptable in the cement plants in Türkiye. The emission factor of CO in Table 3 is 1861 g/ton for Türkiye. This value is close to the calculated value for Türkiye in the thesis, but it is classified as a Tier 1 value in Table 3.

NO_x

Table 32. Calculated Tier 2 NO_x emission factor for cement plants (55 plants)

Calculated Tier 2 EF	EMEP/ EEA Emission Factor
1277.235 +/- 214.363 g/ton	1241.000 g/ton

Based on Table 32, the calculated emission factor of NO_x is higher than the EMEP/EEA emission factor. Yet, the difference is acceptable. Moreover, these values were calculated as uncontrolled for the pollutant. Moreover, the acceptable range is between 1062.872 g/ton and 1491.598 g/ton for NO_x. The calculated NO_x emission factor may be acceptable in the cement plants in Türkiye. The emission factor of NO_x in Table 3 is 1390 g/ton for Türkiye. This value is close to the calculated value for Türkiye in the thesis. Yet, the value was calculated as a Tier 1 in Table 3.

SO_2

Table 33. Calculated Tier 2 SO_2 emission factor for cement plants (55 plants)

Calculated Tier 2 EF	EMEP/ EEA Emission Factor
251.299 +/- 79.418 g/ton	374.000 g/ton

Based on Table 33, the calculated emission factor of SO_2 is lower than the EMEP/EEA emission factor. According to the interval specified in the EMEP/EEA database, the difference in SO_2 emissions for the cement sector is within an acceptable range. Upon examination of the EMEP/EEA database, the interval changes between 20 g/ton and 11120 g/ton. Moreover, these values were calculated as uncontrolled for the pollutant [10]. According to the result of the statistical analysis, the acceptable range is between 171.881 kg/ton and 330.717 kg/ton for SO_2. The emission factor calculated for SO_2 can be accepted for cement plants in Türkiye. The emission factor of SO_2 in Table 3 is 53 g/ton for Türkiye. This value is lower than the calculated value for Türkiye in the thesis. This is because the calculated value is categorized as Tier 2 in the thesis.

PM_{10}

Table 34. Calculated Tier 2 PM_{10} emission factor for cement plants (55 plants)

Control Technology	Calculated Tier 2 EF	EMEP/ EEA Emission Factor
Bag filter	26.436 +/- 8.025 g/ton	23.400 g/ton

The bag filter is utilized as a control technology for PM_{10} for the cement plant. The calculated emission factor of PM_{10} is close to the EMEP/EEA emission factor when examining Table 34. According to the result of the statistical analysis, the permissible range is from 18.411 kg/ton to 34.461 kg/ton for PM_{10}. The emission factor calculated for PM_{10} may be accepted for cement plants in Türkiye. The emission factor of PM_{10} in Table 3 is 190 g/ton for Türkiye. This value is higher than the calculated value for Türkiye in the thesis, but it is classified as a Tier 1 value in Table 3. The value was computed as the uncontrolled emission factor in Table 3.

TOC

Table 35. Calculated Tier 2 TOC Emission Factor for Cement Plants (55 plants)

Calculated Tier 2 EF	EMEP/ EEA Emission Factor
29.841+/- 10.472 g/ton	18.000 g/ton

The calculated TOC emission factor exceeds the EMEP/EEA emission factor based on Table 35. Yet, the difference is acceptable for TOC in the cement sector since the upper limit of emission factor for the pollutant is detected as 138.000 g/ton from the EMEP/EEA database. Moreover, these values were calculated as uncontrolled for the pollutant [10]. In addition, the permissible range is from 19.369 kg/ton to 40.313 kg/ton for TOC. The emission factor calculated for TOC may not be acceptable for cement plants in Türkiye.

5.4. Closing Remarks

This section of the thesis presents the gathered plant data and monitored pollutant data first. An example of different types of statistical analyses is also provided. Results of calculated sector-specific emission factors are expressed for each fuel type in the electricity and cement sectors. These calculated values are compared for several pollutants (CO, NO_x, SO_2, PM_{10}, and TOC) with three database values (AP42, EMEP/EEA, and NPI). Although some calculated sector-specific (Tier 2) emission factors may differ from the three databases selected for comparison, most of the calculated values are within an acceptable range for the two selected sectors. These values can be accepted as reliable for use in emission estimation for these sectors of Türkiye.

6. CONCLUSIONS

6.1. Conclusions and Major Outcomes of the Study

Air pollution is a serious problem that has been identified around the world. The main reason for this problem are emissions of various pollutants such as carbon monoxide (CO), sulfur dioxide (SO_2), nitric oxides (NO_x), and PM_{10} into the atmosphere during industrial activities.

The electricity and cement sectors selected within the scope of this thesis are the two sectors where these emissions are observed intensively. The reason is that non-renewable energy sources, mainly fossil fuels, are utilized as energy sources mostly for production in these sectors. In other words, more than 80% of the world's total energy needs are met due to these fuels. Türkiye meets approximately two-thirds of its electricity production from fossil fuels in the electricity sector. Although alternative fuels such as refuse-derived fuel (RDF) and end-of-life (EoL) tires are used in cement production, fossil fuels such as imported coal and brown coal/lignite are predominantly utilized in the cement sector.

Various estimation techniques include sampling or direct measurement, mass balance, and emission factors. Continuous Emission Monitoring System (CEMS) is utilized mostly as a direct measurement approach for emission estimation. Emission factor values from three databases (AP42, EMEP/EEA, and NPI) are used to compare the results of calculated Tier 2 emission factors. Emission factors were calculated for the electricity sector's four pollutants (CO, NO_x, SO_2, and PM_{10}). In addition to these four pollutants in the cement sector, an emission factor for TOC has also been calculated.

Using emission factors to forecast emissions is the most commonly used emission estimation technique. Also, using emission factors helps estimate emissions correctly and develop appropriate strategies to tackle the pollution in the atmosphere. Estimating the emissions using the emission factors is classified into several types: Tier 1, Tier 2, and Tier 3. In this study for Türkiye, sector-specific emission factors (Tier 2) were developed for each technology in these two sectors as part of the scope of the study.

In the electricity sector, uncontrolled Tier 2 emission factors for CO and controlled emission factors for the remaining pollutants were calculated. However, controlled Tier 2 emission factors for PM_{10} only and controlled emission factors for the remaining pollutants were calculated in the cement sector. Electrostatic precipitator (ESP), bag filter, wet scrubber, selective catalytic reduction (SCR), and low NO_x are utilized as control technologies.

Fluidized bed and pulverized technologies are utilized for hard coal and lignite, while natural gas combined cycle (NGCC) and open-cycle gas turbines (OCGT) are used for natural gas in the electricity sector. Yet, the utilization of pulverized and NGCC technologies in facilities is more common than the other two technologies in the electricity sector in Türkiye. In the cement sector, the dry process is used exclusively in Türkiye. As a result, calculated sector-specific (Tier 2) emission factors may differ from the three databases used for comparison.

For electricity sectors, the Tier 2 emission factors of CO, NO_x, SO_2, and PM_{10} are 0.552 kg/ton, 1.776 kg/ton, 2.918 kg/ton, and 2.404 kg/ton for hard coal, respectively. In addition, these values can be listed as 0.143 kg/ton, 1.072 kg/ton, 2.216 kg/ton, 14.016 kg/ton, and 0.205 kg/ton for lignite, respectively. For natural gas, the calculated Tier 2 emission factors of CO and NOx are 31.095 g/GJ and 42.609 g/GJ, respectively. Lastly, the Tier 2 emission factors of CO, NO_x, SO_2, $PM_{10,}$ and TOC are 1596.167 g/ton, 1277.235 g/ton, 251.299 g/ton, 26.436 g/ton, and 29.841 for the cement sector, respectively.

All calculated emission factors are within the acceptable range in the two sectors, except for the NO_x emission factor of 1.072 kg/ton for hard coal and the TOC emission factor of 29.841 kg/ton for the cement sector. In addition, the computed Tier 2 emission factors of NO_x for pulverized are one-fifth lower than those in the three databases (AP42, EMEP/EEA, and NPI) for power plants using hard coal in the electricity sector. In addition, the calculated Tier 2 emission factors for TOC are higher than the values with 29.841 kg/ton in these databases in the cement sector.

There are several limitations to the study. First, the number of plants evaluated for some technologies, such as fluidized bed for hard coal and ultra-supercritical pulverized for hard coal, is very limited. Thus, more data is required to estimate reliable emission factors. Another limitation is the amount of fuel used. The exact amount of fuel used for production at the facilities could not be obtained. Thus, the amount of fuel is estimated using plant operation data, such as installed capacity and the number of hours of power plant operation. The last limitation is the reliability of the monitored data. There might be some monitoring problems due to the CEMS measurement device or the CEMS systems.

6.2. Recommendations for Future Studies

The following recommendations for future investigations are based on the findings of this study.

- The more CEMS data used to calculate the emission factor, the more reliable results are obtained.
- Tier 3 approach can be utilized to obtain more precise emissions estimates by collecting specific data for each plant in two sectors.
- Tier 2 sector-specific emission factor calculations can be determined for various other sectors, such as the metal and agriculture sectors, with the exception of two specific sectors.

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APPENDICES

APPENDIX 1 – Emission Factor Databases Data

In this section, emission factors taken from selected databases are shown for the electricity sector and the cement sector.

A. Electricity Sector

AP 42, Fifth Edition, Volume I Chapter 1: External Combustion Sources

Tier 2 Emission factors placed on the AP42 Database are displayed for each fuel type as follows :

1.1 Bituminous and Subbituminous Coal Combustion (Hard Coal)

Table 1.1-3. EMISSION FACTORS FOR SO_x, NO_x, AND CO FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION[a]

Firing Configuration	SCC	SO_x [b]		NO_x [c]		CO[d,e]	
		Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
PC, dry bottom, wall-fired[f], bituminous Pre-NSPS[g]	1-01-002-02 1-02-002-02 1-03-002-06	38S	A	22	A	0.5	A
PC, dry bottom, wall-fired[f], bituminous Pre-NSPS[g] with low-NO_x burner	1-01-002-02 1-02-002-02 1-03-002-06	38S	A	11	A	0.5	A
PC, dry bottom, wall-fired[f], bituminous NSPS[g]	1-01-002-02 1-02-002-02 1-03-002-06	38S	A	12	A	0.5	A
PC, dry bottom, wall-fired[f], sub-bituminous Pre-NSPS[g]	1-01-002-22 1-02-002-22 1-03-002-22	35S	A	12	C	0.5	A
PC, dry bottom, wall fired[f], sub-bituminous NSPS[g]	1-01-002-22 1-02-002-22 1-03-002-22	35S	A	7.4	A	0.5	A
PC, dry bottom, cell burner[h] fired, bituminous	1-01-002-15	38S	A	31	A	0.5	A
PC, dry bottom, cell burner fired, sub-bituminous	1-01-002-35	35S	A	14	E	0.5	A

Figure 18. Fluidized bed bituminous and subbituminous coal combustion AP42 (1) [8]

Table 1.1-3 (cont.).

Firing Configuration	SCC	SO_x [b]		NO_x [c]		CO [d,e]	
		Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
PC, dry bottom, tangentially fired, bituminous, Pre-NSPS[g]	1-01-002-12 1-02-002-12 1-03-002-16	38S	A	15	A	0.5	A
PC, dry bottom, tangentially fired, bituminous, Pre-NSPS[g] with low-NO_x burner	1-01-002-12 1-02-002-12 1-03-002-16	38S	A	9.7	A	0.5	A
PC, dry bottom, tangentially fired, bituminous, NSPS[g]	1-01-002-12 1-02-002-12 1-03-002-16	38S		10	A	0.5	A
PC, dry bottom, tangentially fired, sub-bituminous, Pre-NSPS[g]	1-01-002-26 1-02-002-26 1-03-002-26	35S	A	8.4	A	0.5	A
PC, dry bottom, tangentially fired, sub-bituminous, NSPS[g]	1-01-002-26 1-02-002-26 1-03-002-26	35S	A	7.2	A	0.5	A
PC, wet bottom, wall-fired[f], bituminous, Pre-NSPS[g]	1-01-002-01 1-02-002-01 1-03-002-05	38S	A	31	D	0.5	A
PC, wet bottom, tangentially fired, bituminous, NSPS[g]	1-01-002-11	38S	A	14	E	0.5	A
PC, wet bottom, wall-fired sub-bituminous	1-01-002-21 1-02-002-21 1-03-002-21	35S	A	24	E	0.5	A

Figure 19. Fluidized bed bituminous and subbituminous coal combustion AP42 (2) [8]

Table 1.1-3 (cont.).

Firing Configuration	SCC	SO_x [b]		NO_x [c]		CO [d,e]	
		Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
Cyclone Furnace, bituminous	1-01-002-03 1-02-002-03 1-03-002-03	38S	A	33	A	0.5	A
Cyclone Furnance, sub-bituminous	1-01-002-23 1-02-002-23 1-03-002-23	35S	A	17	C	0.5	A
Spreader stoker, bituminous	1-01-002-04 1-02-002-04 1-03-002-09	38S	B	11	B	5	A
Spreader Stoker, sub-bituminous	1-01-002-24 1-02-002-24 1-03-002-24	35S	B	8.8	B	5	A
Overfeed stoker[i]	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	38S (35S)	B	7.5	A	6	B
Underfeed stoker	1-02-002-06 1-03-002-08	31S	B	9.5	A	11	B
Hand-fed units	1-03-002-14	31S	D	9.1	E	275	E

Figure 20. Fluidized bed bituminous and subbituminous coal combustion AP42 (3) [8]

Table 1.1-3 (cont.).

Firing Configuration	SCC	SO_x[b]		NO_x[c]		CO[d,e]	
		Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
FBC, circulating bed	1-01-002-18 1-02-002-18 1-03-002-18	—[j]	E	5.0	D	18	E
FBC, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	—[j]	E	15.2	D	18	D

Figure 21. Fluidized bed bituminous and subbituminous coal combustion AP42 (4) [8]

Table 1.1-4. UNCONTROLLED EMISSION FACTORS FOR PM AND PM-10
FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION[a]

Firing Configuration	SCC	Filterable PM[b]		Filterable PM-10	
		Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
PC-fired, dry bottom, wall-fired	1-01-002-02/22 1-02-002-02/22 1-03-002-06/22	10A	A	2.3A	E
PC-fired, dry bottom, tangentially fired	1-01-002-12/26 1-02-002-12/26 1-03-002-16/26	10A	B	2.3A[c]	E
PC-fired, wet bottom	1-01-002-01/21 1-02-002-01/21 1-03-002-05/21	7A[d]	D	2.6A	E
Cyclone furnace	1-01-002-03/23 1-02-002-03/23 1-03-002-03/23	2A[d]	E	0.26A	E
Spreader stoker	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	66[e]	B	13.2	E
Spreader stoker, with multiple cyclones, and reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	17	B	12.4	E
Spreader stoker, with multiple cyclones, no reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	12	A	7.8	E

Figure 22. Pulverized bituminous and subbituminous coal combustion AP42 (1) [8]

Table 1.1-4 (cont.).

Firing Configuration	SCC	Filterable PM[b]		Filterable PM-10	
		Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
Overfeed stoker[f]	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	16[g]	C	6.0	E
Overfeed stoker, with multiple cyclones[f]	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	9[h]	C	5.0	E
Underfeed stoker	1-02-002-06 1-03-002-08	15[j]	D	6.2	E
Underfeed stoker, with multiple cyclone	1-02-002-06 1-03-002-08	11[h]	D	6.2[j]	E
Hand-fed units	1-03-002-14	15	E	6.2[k]	E
FBC, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	[m]	E	[m]	E
FBC, circulating bed	1-01-002-18 1-02-002-18 1-03-002-18	[m]	E	[m]	E

[a] Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired. To convert from lb/ton to kg/Mg, multiply by 0.5. SCC = Source Classification Code.

Figure 23. Pulverized lignite combustion AP42 (1) [8]

Natural Gas Combustion

Table 1.4-1. EMISSION FACTORS FOR NITROGEN OXIDES (NO_x) AND CARBON MONOXIDE (CO) FROM NATURAL GAS COMBUSTION[a]

Combustor Type (MMBtu/hr Heat Input) [SCC]	NO_x[b]		CO	
	Emission Factor ($lb/10^6$ scf)	Emission Factor Rating	Emission Factor ($lb/10^6$ scf)	Emission Factor Rating
Large Wall-Fired Boilers (>100) [1-01-006-01, 1-02-006-01, 1-03-006-01]				
Uncontrolled (Pre-NSPS)[c]	280	A	84	B
Uncontrolled (Post-NSPS)[c]	190	A	84	B
Controlled - Low NO_x burners	140	A	84	B
Controlled - Flue gas recirculation	100	D	84	B
Small Boilers (<100) [1-01-006-02, 1-02-006-02, 1-03-006-02, 1-03-006-03]				
Uncontrolled	100	B	84	B
Controlled - Low NO_x burners	50	D	84	B
Controlled - Low NO_x burners/Flue gas recirculation	32	C	84	B
Tangential-Fired Boilers (All Sizes) [1-01-006-04]				
Uncontrolled	170	A	24	C
Controlled - Flue gas recirculation	76	D	98	D
Residential Furnaces (<0.3) [No SCC]				
Uncontrolled	94	B	40	B

Figure 24. Emission factor of AP42 for natural gas [8]

Lignite Combustion

Table 1.7-1. EMISSION FACTORS FOR SO_x, NO_x, CO, AND CO_2 FROM UNCONTROLLED LIGNITE COMBUSTION[a]

EMISSION FACTOR RATING: C (except as noted)

Firing Configuration	SO_x Emission Factor[b] (lb/ton)	NO_x Emission Factor[c] (lb/ton)	CO Emission Factor[d] (lb/ton)	CO_2 Emission Factor[g] (lb/ton)	TNMOC[j,k] Emission Factor (lb/ton)
Pulverized coal, dry bottom, tangential (SCC 1-01-003-02)	30S	7.1[i]	ND	72.6C	0.04
Pulverized coal, dry bottom, wall fired[e], Pre-NSPS[f] (SCC 1-01-003-01)	30S	13	0.25	72.6C	0.04
Pulverized coal, dry bottom, wall fired[e], NSPS[f] (SCC 1-01-003-01)	30S	6.3	0.25	72.6C	0.04
Cyclone (SCC 1-01-003-03)	30S	15	ND	72.6C	0.07
Spreader stoker (SCC 1-01-003-06)	30S	5.8	ND	72.6C	0.03
Traveling Grate Overfeed stoker (SCC 1-01-003-04)	30S	ND	ND	72.6C	0.03
Atmospheric fluidized bed combustor (SCC 1-01-003-17/18)	10S[l]	3.6	0.15[h]	72.6C	0.03

Figure 25. Emission factors of AP42 for lignite (1) [8]

Table 1.7-5. EMISSION FACTORS FOR FILTERABLE PM EMISSIONS FROM CONTROLLED LIGNITE COMBUSTION[a]

EMISSION FACTOR RATING: C (except as noted)

Firing Configuration	Control Device	Filterable PM Emission Factor (lb/ton)
Subpart D Boilers[b] (SCC 1-01-003-01/-02)	Baghouse Wet scrubber	0.08A 0.05A
Subpart Da Boilers[b] (SCC 1-01-003-01/-02)	Wet scrubber	0.01A
Atmospheric fluidized bed combustor (SCC 1-01-003-17/18)[b,c]	ESP	0.07A

Figure 26. Emission factors of AP42 for lignite (2) [8]

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Table 5 Emission Factors for Black Coal Combustion

Substance	Threshold category	Emission Estimation Technique (a) (number in brackets refers to supporting information in Reference: Pacific Power International 2002) kg/tonne unless otherwise indicated	EFR (b)
Ammonia	1	2.8E-04 **(6.0)**	U
Antimony & compounds	1	0.675 x [(C/A) x PM] $^{0.63}$ kg/PJ **(6.1)** 9E-06 **(I)**	A
Arsenic &compounds	1/2b	2.73 x [(C/A) x PM] $^{0.85}$ kg/PJ **(6.2)** 2.1E-04 **(I)**	A
Benzene	1	3.4 kg/PJ **(6.3)**	U
Beryllium & compounds	1/2b	1.31 x [(C/A) x PM] $^{1.1}$ kg/PJ **(6.4)** 1.1E-05 **(I)**	A
Boron & compounds	1	C x 1E-03 x 0.5 **(c)** **(6.5)**	U
Cadmium & compounds	1/2b	2.17 x [(C/A) x PM] $^{0.5}$ kg/PJ **(6.6)** 2.6E-05 **(I)**	A
Carbon monoxide	1/2a	2.5E-01 **(6.7)**	A
Chromium (III) compounds	1/2b	0.95x2.6x[(C/A)xPM] $^{0.58}$ kg/PJ **(c)** **(6.8)** 1.3E-04	A
Chromium (VI) compounds	1/2b	0.05 x 2.6 x [(C/A) x PM]$^{0.58}$ kg/PJ **(c)(6.8)** 9.0E-05 **(I)**	A
Cobalt & compounds	1	1.31 x [(C/A) x PM] $^{0.69}$ kg/PJ **(6.9)** 5E-05 **(I)**	A
Copper & compounds	1/2b	1.31 x [(C/A) x PM]$^{1.1}$ kg/PJ **(6.10)**	U
Cumene	1	2.7E-06 **(6.11)**	U
Cyanide (inorganic) compounds	1	1.3E-03 **(6.12)**	D
Cyclohexane	1	3.4E-05 **(6.13)**	
Ethylbenzene	1	4.7E-05 **(14)**	U
Fluoride compounds	1/2b	7.5E-02 **(6.15)**	B
n-Hexane	1	3.4E-05 **(6.16)**	U
Hydrochloric acid	1/2a	0.6 **(6.17)**	B
Lead & compounds	1/2b	2.87 x [(C/A) x PM] $^{0.8}$ kg/PJ **(6.18)** 2.1E-04 **(I)**	A
Magnesium oxide fume	1/2b	0 **(6.19)**	U
Manganese & compounds	1	2.71 x [(C/A) x PM] $^{0.6}$ kg/PJ **(6.20)** 2.5E-04 **(I)**	A
Mercury & compounds	1/2b	**C x 8.1 E-04** for fabric filter and Electrostatic Precipitator plant **(I) (6.21)** **3.16 E-05** **For facility specific factors, refer to Table 7**	A
Nickel & compounds	1/2b	2.84 x [(C/A) x PM] $^{0.48}$ kg/PJ **(6.22)** 1.4E-04 **(I)**	A
Nickel carbonyl	1/2b	0 Not emitted during electricity generation by combustion **(e)** **(6.23)**	U
Nickel subsulfide	1/2b	0 Not emitted during electricity generation by combustion **(e)** **(6.23)**	U

Figure 27. Emission factors of NPI for hard coal [11]

Substance	Threshold category	Emission Estimation Technique (a) (number in brackets refers to supporting information in Reference: Pacific Power International 2002) kg/tonne unless otherwise indicated	EFR (b)
Oxides of nitrogen (expressed as nitrogen dioxide, NO_2) **(f)**	1/2a	11.0 Uncontrolled, dry bottom, wall fired, bituminous 5.5 Low NOx burner, dry bottom, wall fired, bituminous 6.0 Uncontrolled, dry bottom, wall fired, sub-bituminous 6.0 Dry bottom, wall fired. Post 1978 **(f)** 3.7 Dry bottom, wall fired, sub-bituminous. Post 1978 **(f)** 7.5 Uncontrolled, dry bottom, tangentially fired, bituminous 4.9 Low NOx burner, dry bottom, tangentially fired, bituminous 4.2 Uncontrolled, dry bottom, wall fired, sub-bituminous 3.6 Dry bottom, wall fired, sub-bituminous. Post 1978 **(f)** 15.5 Uncontrolled, wet bottom, wall fired, bituminous 7.0 Wet bottom, tangentially fired, bituminous. Post 1978 **(f)** 12.0 Wet bottom, wall fired, sub-bituminous 16.5 Cyclone furnace, bituminous 8.5 Cyclone furnace, sub-bituminous 2.5 Fluidised bed, circulating 7.6 Fluidised bed, bubbling **(6.24)** See also Table 6	A A A A A A A A D E E A C D D
PM_{10}	1/2a	A x 1000 x F x (1-ER/100) x FP **(c)** **(6.25)** 0.34 for fabric filter plant 0.96 for ESP plant	A
$PM_{2.5}$	2a	A x 1000 x F x (1-ER/100) x FP **(c&m)** (53%/92%) x 0.34 = 0.20 for fabric filter plant (29%/67%) x 0.96 = 0.42 for ESP plant	A
Polychlorinated dioxin & furans (g) (n)	2b	1E-05 kg/PJ 2.46E-10 kg/tonne for NSW Black Coal 2.34E-10 kg/tonne for Queensland Black Coal 2.04E-10 kg/tonne for WA Black Coal	D
Polycyclic aromatic hydrocarbons **(i)**	2a	1.0E-05 **(6.27)**	B-D
Selenium & compounds	1	6.5E-04 **(6.28)**	A
Sulfur dioxide	1/2a	19 x S for Bituminous coal 17.5 x for S. Sub-Bituminous coal **(6.29)**	A
Sulfuric acid	1	0.2 x S **(j)** **(6.30)**	U
Toluene (methylbenzene)	1	1.2E-04 **(6.31)**	U
TVOCs **(k)**	1a/2a	3E-02 dry bottom boilers, wall and tangentially fired 2E-02 wet bottom boilers 6.0E-01 cyclone furnace **(6.32)**	B
Xylenes	1	1.9E-05 **(6.33)**	U
Zinc and compounds	1	$2.84 \times [(C/A) \times PM]^{0.48}$ kg/PJ **(6.34)**	U

Figure 28. Emission factors of NPI for hard coal (2) [11]

Table 8 Emission Factors for Brown Coal Combustion

Substance	Threshold category	**Emission Estimation Technique** **(number in brackets refers to supporting information in Reference: Pacific Power International 2002)** **kg/tonne unless otherwise indicated**	EFR (a)
Ammonia	1	1.3E-03 **(b)** **(6.37)**	U
Antimony & compounds	1	0.675 x [(C/A) x PM]$^{0.63}$ kg/PJ 1.75 E-06 **(c)** **(e)** **(6.1)**	A A
Arsenic &compounds	1/2b	2.73 x [(C/A) x PM]$^{0.85}$ kg/PJ 3.0E-06 **(c)** **(e)** **(6.2)**	A A
Benzene	1	3.6 E-06	A
Beryllium & compounds	1/2b	1.31 x [(C/A) x PM]$^{1.1}$ kg/PJ 1.7E-06 **(c)** **(e)** **(6.4)**	A A
Boron & compounds	1	C x 1E-03 x 0.5 **(b)** **(6.5)** 6.2E-03	U
Cadmium & compounds	1/2b	2.17 x [(C/A) x PM]$^{0.5}$ kg/PJ 2.5 E-06 **(c)** **(e)** **(6.6)**	A A
Carbon monoxide	1/2a	0.13 wall fired uncontrolled combustion **(d)** 0.24 wall fired, overfire air, Low NOx burners 0.05 tangentially fired, overfire air 0.08 atmospheric fluidised bed See also Table 9 **(6.7)**	C D D
Chromium (III) compounds	1/2b	0.95 x 2.6 x [(C/A) x PM] $^{0.58}$ kg/PJ **(b)** 9.0E-06 **(c)** **(e)** **(6.8)**	A A
Chromium (VI) compounds	1/2b	0.05 x 2.6 x [(C/A) x PM]$^{0.58}$ kg/PJ **(b)** 6.1E-06 **(c)** **(e)** **(6.8)**	A D
Cobalt & compounds	1	1.31 x [(C/A) x PM]$^{0.69}$ kg/PJ 2.7E-06 **(c)** **(e)** **(6.9)**	A A
Copper & compounds	1/2b	1.31 x [(C/A) x PM]$^{1.1}$ kg/PJ **(6.10)** 6.2E-06	U
Cumene	1	5.8E-08 **(6.12 & 6.37)**	U
Cyanide (inorganic) compounds	1	3.6E-06 **(6.37)**	D
Cyclohexane	1	3.6E-06 **(6.13 & 6.37)**	U
Ethylbenzene	1	3.6E-06 **(6.14 & 6.37)**	U
Fluoride compounds (as hydrogen fluoride)	1/2b	3.5E-02 (from a mass balance) **(6.15)**	B
n-Hexane	1	3.6E-06 **(6.16 & 6.37)**	U
Hydrochloric acid	1/2a	4.6E-01 (from a mass balance) **(6.17 & 6.37)**	B
Lead & compounds	1/2b	2.87 x [(C/A) x PM]$^{0.8}$ kg/PJ 8.1E-06 **(6.37)**	A A
Magnesium oxide fume	1/2b	0 **(6.19)**	
Manganese & compounds	1	2.71 x [(C/A) x PM]$^{0.6}$ kg/PJ 2.1E-04 **(6.37)**	A A
Mercury & compounds	1/2b	C x 9.8E-04 2.6E-05 **(6.37)**	A A
Nickel & compounds	1/2b	2.84 x [(C/A) x PM]$^{0.48}$ kg/PJ 3.4E-05 **(6.37)**	A A

Figure 29. Emission factors of NPI for lignite (1) [11]

Substance	Threshold category	Emission Estimation Technique (number in brackets refers to supporting information in Reference: Pacific Power International 2002) kg/tonne unless otherwise indicated	EFR (a)
Nickel carbonyl	1/2b	0 Not emitted during electricity generation by combustion **(g) (6.23)**	U
Nickel subsulfide	1/2b	0 Not emitted during electricity generation by combustion **(g) (6.23)**	U
Oxides of nitrogen (expressed as nitrogen dioxide, NO_2) **(h)**	1/2a	3.5 Dry bottom, tangentially fired 3.4 Tangentially fired, overfire air 6.5 Dry bottom wall fired. Pre 1978 **(i)** 3.2 Dry bottom, wall fired. Post 1978 **(i)** 2.3 Wall fired, overfire air, low NOx burners 7.5 Cyclone furnace 1.8 Atmospheric fluidised bed **(6.24)** Refer also to Table 9.	C C C C C
PM_{10}	1/2a	A x 1000 x F x (1-ER/100) x FP **(b) (6.25)** 1.7 x A for fabric filter 4.8 x A for ESP	A
$PM_{2.5}$	1/2a	A x 1000 x F x (1-ER/100) x FP **(b&o)** (53%/92%) x 1.7 x A = 0.98 x A for fabric filter plant (29%/67%) x 4.8 x A = 2.1x A for ESP plant	A
Polychlorinated dioxin & furans **(j)**	2b	1E-05 kg/PJ **(f) (6.26)** 9.48E-11 kg/tonne for Victorian Brown Coal 1.42E-10 kg/tonne for SA Brown Coal	U D
Polycyclic aromatic hydrocarbons **(l)**	2a	8.0 E-07 **(e) (6.27)**	B-D
Selenium & compounds	1	7.8 E-06 **(c) (e)** 0.7 kg/PJ **(6.28 & 6.37)**	A
Sulfur dioxide	1/2a	15 x S 5 x S (fluidised bed using limestone bed material) **(6.29)**	C C
Sulfuric acid	1	1.6 E-03 **(6.37)** 0.2 x S **(6.30) (m)**	U
Toluene (methylbenzene)	1	3.6 E-06 **(6.31 & 6.37)**	A
TVOCs **(n)**	1a/2a	2 E-02 wall and tangential firing 3.5 E-02 cyclone furnace 1.5 E-02 fluidised bed **(6.32)**	C C C
Xylenes	1	3.6 E-06 **(6.33 & 6.37)**	C
Zinc and compounds	1	7.4 E-05 **(6.37)** 2.84 x $[(C/A) \times PM]^{0.48}$ kg/PJ **(6.34)**	U U

Figure 30. Emission factors of NPI for lignite (2) [11]

Table 11 Emission Factors for Natural Gas Combustion – Steam cycle

Substance	Threshold category	Emission Estimation Technique (number in brackets refers to supporting information in Reference: Pacific Power International 2002) kg/PJ unless otherwise indicated	EFR (a)
Ammonia	1	1.3E+02 **(6.0)**	U
Antimony & compounds	1	No data	
Arsenic &compounds	1/2b	8.5E-02	E
Benzene	1	8.8E-01	B
Beryllium & compounds	1/2b	5.1E-03 **(b)**	E
Boron & compounds	1	No data	
Cadmium & compounds	1/2b	4.6E-01	D
Carbon monoxide	1/2a	3.5E+04 Wall fired 1.0E+04 Tangential firing - uncontrolled 4.1E+04 Tangential – flue gas recirculation See also Table 11	B
Chromium (VI) compounds (c)	1/2b	3.0E-02 **(6.8)**	D
Cobalt & compounds	1	3.5E-02	D
Copper & compounds	1/2b	3.6E-01	D
Cyanide (inorganic) compounds	1	No data	
Formaldehyde	1	3.2 E+01	B
Fluoride compounds	1/2b	No data	
n-Hexane	1	7.6E+02 Note AP-42 (Reference: USEPA 1998a) factor is for hexane not n-Hexane	E
Hydrochloric acid	1/2a	No data	
Lead & compounds	1/2b	2.4E-01	D
Magnesium oxide fume	1/2b	No data **(6.19)**	
Manganese & compounds	1	1.6E-01	D
Mercury & compounds	1/2b	1.1E-01	D
Nickel & compounds	1/2b	8.8E-01	C
Nickel carbonyl	1/2b	0 Not emitted during electricity generation by combustion **(d)(6.23)**	U
Nickel subsulfide	1/2b	0 Not emitted during electricity generation by combustion **(d)** **(6.23)**	U
Oxides of nitrogen (expressed as nitrogen dioxide, NO_2)	1/2a	**Large Wall fired boilers** (>100 GJ/hr heat input) 11.8E+04 Uncontrolled **(e)** 8.0E+04 Uncontrolled **(e)** 5.9E+04 Controlled - Low NOx burners 4.2E+04 Controlled – Flue gas recirculation **Small wall fired** (<100 GJ/hr heat input) 4.2E+04 Uncontrolled 2.1E+04 Controlled – Low NOx burners 1.3E+04 Controlled - Low NOx /flue gas recirc. **Tangential-fired boilers (All sizes)** 7.2E+04 Uncontrolled 3.2E+04 Controlled – Flue gas recirculation See also Table 11 **(6.24)**	 A A A D B D C A D
PM_{10} & $PM_{2.5}$**(f)**	1/2a	3.2E+03 Uncontrolled (AP-42 Reference: USEPA 1998a)	D
Polychlorinated dioxin & furans	2b	5E-07 kg/PJ **(g)** **(6.26)**	U
Polycyclic aromatic hydrocarbons **(b,h)**	2a	2.9E-01 kg/PJ**(6.27)**	E
Selenium & compounds	1	1.0E-02 **(b)**	E

Figure 31. Emission factors of NPI for natural gas [11]

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Table 3-9 Tier 2 emission factors for source category 1.A.1.a, dry bottom boilers using coking coal, steam coal and sub-bituminous coal

Tier 2 emission factors					
	Code	Name			
NFR Source Category	1.A.1.a	Public electricity and heat production			
Fuel	Coking Coal, Steam Coal & Sub-Bituminous Coal				
SNAP (if applicable)	010101 010102	Public power - Combustion plants >= 300 MW (boilers) Public power - Combustion plants >= 50 and < 300 MW (boilers)			
Technologies/Practices	Dry Bottom Boilers				
Region or regional conditions	NA				
Abatement technologies	Abatement assumed except for SO_2 EF				
Not applicable					
Not estimated	NH_3				
Pollutant	**Value**	**Unit**	**95% confidence interval**		**Reference**
			Lower	**Upper**	
NOx	209	g/GJ	200	350	US EPA (1998), chapter 1.1
CO	8.7	g/GJ	6.15	15	US EPA (1998), chapter 1.1
NMVOC	1.0	g/GJ	0.6	2.4	US EPA (1998), chapter 1.1
SOx	820	g/GJ	330	5000	See Note
TSP	11.4	g/GJ	3	300	US EPA (1998), chapter 1.1
PM_{10}	7.7	g/GJ	2	200	US EPA (1998), chapter 1.1
$PM_{2.5}$	3.4	g/GJ	0.9	90	US EPA (1998), chapter 1.1
BC	2.2	% of $PM_{2.5}$	0.27	8.08	See Note
Pb	7.3	mg/GJ	5.16	12	US EPA (1998), chapter 1.1
Cd	0.9	mg/GJ	0.627	1.46	US EPA (1998), chapter 1.1
Hg	1.4	mg/GJ	1.02	2.38	US EPA (1998), chapter 1.1
As	7.1	mg/GJ	5.04	11.8	US EPA (1998), chapter 1.1
Cr	4.5	mg/GJ	3.2	7.46	US EPA (1998), chapter 1.1
Cu	7.8	mg/GJ	0.233	15.5	Expert judgement derived from EMEP/EEA (2006)
Ni	4.9	mg/GJ	3.44	8.03	US EPA (1998), chapter 1.1
Se	23	mg/GJ	16	37.3	US EPA (1998), chapter 1.1
Zn	19	mg/GJ	7.75	155	Expert judgement derived from EMEP/EEA (2006)
PCB	3.3	ng WHO-TEG/GJ	1.1	9.9	Grochowalski & Konieczyński, 2008
PCDD/F	10	ng I-TEQ/GJ	5	15	UNEP (2005); Coal fired power boilers
Benzo(a)pyrene	0.7	µg/GJ	0.245	2.21	US EPA (1998), chapter 1.1
Benzo(b)fluoranthene	37	µg/GJ	3.7	370	Wenborn et al., 1999
Benzo(k)fluoranthene	29	µg/GJ	2.9	290	Wenborn et al., 1999
Indeno(1,2,3-cd)pyrene	1.1	µg/GJ	0.591	2.36	US EPA (1998), chapter 1.1
HCB	6.7	µg/GJ	2.2	20.1	Grochowalski & Konieczyński, 2008

Figure 32. Emission factors of EMEP/EEA for hard coal [10]

Table 3-10 Tier 2 emission factors for source category 1.A.1.a, wet and dry bottom boilers using brown coal/lignite

Tier 2 emission factors					
	Code	Name			
NFR Source Category	1.A.1.a	Public electricity and heat production			
Fuel	Brown Coal/Lignite				
SNAP (if applicable)	010101 010102	Public power - Combustion plants >= 300 MW (boilers) Public power - Combustion plants >= 50 and < 300 MW (boilers)			
Technologies/Practices	Wet and Dry Bottom Boilers				
Region or regional conditions	NA				
Abatement technologies	NA				
Not applicable					
Not estimated	BC, NH_3				
Pollutant	**Value**	**Unit**	**95% confidence interval**		**Reference**
			Lower	**Upper**	
NOx	247	g/GJ	143	571	US EPA (1998), chapter 1.7
CO	8.7	g/GJ	6.72	60.5	US EPA (1998), chapter 1.7
NMVOC	1.4	g/GJ	0.84	3.36	US EPA (1998), chapter 1.7
SOx	1680	g/GJ	330	5000	See Note
TSP	11.7	g/GJ	1.2	117	US EPA (1998), chapter 1.7
PM_{10}	7.9	g/GJ	1	79	US EPA (1998), chapter 1.7
$PM_{2.5}$	3.2	g/GJ	1	32	US EPA (1998), chapter 1.7
Pb	15	mg/GJ	10.6	24.7	US EPA (1998), chapter 1.7
Cd	1.8	mg/GJ	1.29	3	US EPA (1998), chapter 1.7
Hg	2.9	mg/GJ	2.09	4.88	US EPA (1998), chapter 1.7
As	14.3	mg/GJ	10.3	24.1	US EPA (1998), chapter 1.7
Cr	9.1	mg/GJ	6.55	15.3	US EPA (1998), chapter 1.7
Cu	1.0	mg/GJ	0.2	5	EMEP/EEA (2006)
Ni	9.7	mg/GJ	7.06	16.5	US EPA (1998), chapter 1.7
Se	45	mg/GJ	32.8	76.5	US EPA (1998), chapter 1.7
Zn	8.8	mg/GJ	0.504	16.8	EMEP/EEA (2006)
PCBs	3.3	ng WHO-TEG/GJ	1.1	9.9	Grochowalski & Konieczyński, 2008
PCDD/F	10	ng I-TEQ/GJ	5	15	UNEP (2005); Coal fired power boilers
Benzo(a)pyrene	1.3	µg/GJ	0.26	6.5	US EPA (1998), chapter 1.7
Benzo(b)fluoranthene	37	µg/GJ	3.7	370	Wenborn et al., 1999
Benzo(k)fluoranthene	29	µg/GJ	2.9	290	Wenborn et al., 1999
Indeno(1,2,3-cd)pyrene	2.1	µg/GJ	0.42	10.5	US EPA (1998), chapter 1.7
HCB	6.7	µg/GJ	2.2	20.1	Grochowalski & Konieczyński, 2008

Figure 33. Emission factors of EMEP/EEA for lignite [10]

Table 3-12 Tier 2 emission factors for source category 1.A.1.a, dry bottom boilers using natural gas

Tier 2 emission factors					
	Code	Name			
NFR Source Category	1.A.1.a	Public electricity and heat production			
Fuel	Natural Gas				
SNAP (if applicable)	010101 010102	Public power - Combustion plants >= 300 MW (boilers) Public power - Combustion plants >= 50 and < 300 MW (boilers)			
Technologies/Practices	Dry Bottom Boilers				
Region or regional conditions	NA				
Abatement technologies	NA				
Not applicable					
Not estimated	NH_3, PCBs, HCB				
Pollutant	**Value**	**Unit**	**95% confidence interval**		**Reference**
			Lower	**Upper**	
NOx	89	g/GJ	15	185	US EPA (1998), chapter 1.4
CO	39	g/GJ	20	60	US EPA (1998), chapter 1.4
NMVOC	2.6	g/GJ	0.65	10.4	US EPA (1998), chapter 1.4
SOx	0.281	g/GJ	0.169	0.393	US EPA (1998), chapter 1.4
TSP	0.89	g/GJ	0.445	1.34	US EPA (1998), chapter 1.4
PM_{10}	0.89	g/GJ	0.445	1.34	US EPA (1998), chapter 1.4
$PM_{2.5}$	0.89	g/GJ	0.445	1.34	US EPA (1998), chapter 1.4
BC	2.5	% of $PM_{2.5}$	1	6.3	See Note
Pb	0.0015	mg/GJ	0.0005	0.0045	Nielsen et al., 2012
Cd	0.00025	mg/GJ	0.00008	0.00075	Nielsen et al., 2012
Hg	0.1	mg/GJ	0.01	1	Nielsen et al., 2010
As	0.12	mg/GJ	0.04	0.36	Nielsen et al., 2012
Cr	0.00076	mg/GJ	0.00025	0.00228	Nielsen et al., 2012
Cu	0.000076	mg/GJ	0.000025	0.000228	Nielsen et al., 2012
Ni	0.00051	mg/GJ	0.00017	0.00153	Nielsen et al., 2012
Se	0.0112	mg/GJ	0.00375	0.0337	US EPA (1998), chapter 1.4
Zn	0.0015	mg/GJ	0.0005	0.0045	Nielsen et al., 2012
PCDD/F	0.5	ng I-TEQ/GJ	0.25	0.75	UNEP (2005)
Benzo(a)pyrene	0.56	µg/GJ	0.19	0.56	US EPA (1998), chapter 1.4 ("Less than" value based on method detection limits)
Benzo(b)fluoranthene	0.84	µg/GJ	0.28	0.84	US EPA (1998), chapter 1.4 ("Less than" value based on method detection limits)
Benzo(k)fluoranthene	0.84	µg/GJ	0.28	0.84	US EPA (1998), chapter 1.4 ("Less than" value based

Figure 34. Emission factors of EMEP/EEA for natural gas [10]

B. Cement Sector

EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019

Table 3-24 Tier 2 emission factors for source category 1.A.2.f.i, Cement production

Tier 2 emission factors					
	Code	Name			
NFR Source Category	1.A.2.f.i	Stationary combustion in manufacturing industries and construction: Other			
Fuel	Coal/pet. Coke/gas/oil/recovered wastes				
SNAP (if applicable)	030311	Cement			
Technologies/Practices	Cement manufacture				
Region or regional conditions	NA				
Abatement technologies	NA				
Not applicable					
Not estimated	NH3, TSP, PM10, PM2.5, BC				
Pollutant	**Value**	**Unit**	**95% confidence interval**		**Reference**
			Lower	**Upper**	
NOx	1241	g/te clinker	330	4670	European Commission (2010)
CO	1455	g/te clinker	460	4600	European Commission (2010)
NMVOC	18	g/te clinker	2.3	138	European Commission (2010)
SOx	374	g/te clinker	20	11120	European Commission (2010)
Pb	0.098	g/te clinker	0.024	0.4	European Commission (2010)
Cd	0.008	g/te clinker	0.004	0.016	European Commission (2010)
Hg	0.049	g/te clinker	0.01	0.24	European Commission (2010)
As	0.0265	g/te clinker	0.014	0.05	European Commission (2010)
Cr	0.041	g/te clinker	0.028	0.06	European Commission (2010)
Cu	0.0647	g/te clinker	0.022	0.19	European Commission (2010)
Ni	0.049	g/te clinker	0.016	0.15	European Commission (2010)
Se	0.0253	g/te clinker	0.016	0.04	European Commission (2010)
Zn	0.424	g/te clinker	0.2	0.9	European Commission (2010)
PCB	103	μg/te clinker	46	230	VDZ (2011)
PCDD/F	4.1	ng I-TEQ/te clinker	0.0267	627	European Commission (2010)
Benzo(a)pyrene	0.000065	g/te clinker	0.000033	0.000098	US EPA (1995), chapter 11.6
Benzo(b)fluoranthene	0.00028	g/te clinker	0.00014	0.00042	US EPA (1995), chapter 11.6
Benzo(k)fluoranthene	0.000077	g/te clinker	0.000039	0.00012	US EPA (1995), chapter 11.6
Indeno(1,2,3-cd)pyrene	0.000043	g/te clinker	0.000022	0.000065	US EPA (1995), chapter 11.6
HCB	4.6	μg/te clinker	2.3	9.2	SINTEF (2006)

Figure 35. Emission factors of EMEP/EEA for cement [10]

APPENDIX 2 – Controlled and Uncontrolled Emission Factors from Databases

Electricity Sector

Emission factors acquired from selected databases are selected from modules for electricity sector listed as follows:

- AP 42, Fifth Edition, Volume I Chapter 1: External Combustion Sources
  - ✓ 1.1 Bituminous and Subbituminous Coal Combustion
  - ✓ 1.4 Natural Gas Combustion
  - ✓ 1.7 Lignite Combustion
- NPI, Emission Estimation Technique Manual for fossil fuel electric power generation
- EMEP/EEA air pollutant emission inventory guidebook 2019
  - ✓ 1.A.1 Energy industries
  - ✓ 1.A.1.a Public electricity and heat production

5.1.1.1. Controlled Emission Factors

For hard coal, the table displays the emission factors of three databases as follows:

Table 36. Controlled emission factors of AP42 for hard coal [8]

Fuel	**Hard Coal**			
Technology	**AP-42 (kg/ton)**			
	SO_2	NO_x	CO	PM_{10}
Pulverized	5.171	4.740	0.227	0.205
Fluidized Bed (Low Nox)	1.587	2.155	0.816	ND
Fluidized Bed (SCR)	-	1.470	-	-

Table 37. Controlled emission factors of EMEP and NPI for hard coal [10, 11]

Technology	**EMEP/EEA (kg/ton)**			
	SO_2	NO_x	CO	PM_{10}
Pulverized	6.748	5.447	0.227	0.211
Fludized Bed (Low NOx)	2.249	2.150	0.816	0.211
Fludized Bed (SCR)	-	1.472	-	-

Technology	**NPI (kg/ton)**			
	SO_2	NO_x	CO	PM_{10}
Pulverized	5.700	5.500	0.250	0.276
Fluidized Bed (Low Nox)	1.750	2.500	0.815	0.276
Fluidized Bed (SCR)	-	1.625	-	-

For lignite coal, the table displays the emission factors of three databases as follows:

Table 38. Controlled emission factors of AP42, EMEP and NPI for lignite [8,10,11]

Fuel	**Lignite /Brown Coal**			
Technology	**AP-42 (kg/ton)**			
	SO_2	NO_x	CO	PM_{10}
Pulverized	13.608	2.715	0.113	0.278
Fluidized Bed (Low NO_x)	2.228	1.633	0.068	0.278
Fluidized Bed (SCR)	-	-	-	-
Technology	**EMEP/EEA (kg/ton)**			
	SO_2	NO_x	CO	PM_{10}
Pulverized	13.825	2.033	0.227	0.206
Fluidized Bed (Low NO_x)	4.608	1.564	0.339	0.180
Fluidized Bed (SCR)	-	1.471	-	-
Technology	**NPI (kg/ton)**			
	SO_2	NO_x	CO	PM_{10}
Pulverized	15.000	2.300	0.130	0.403
Fluidized Bed (Low NO_x)	5.000	1.800	0.080	0.392
Fluidized Bed (SCR)	-	-	-	-

For natural gas, the table displays the emission factors of three databases as follows:

Table 39. Controlled emission factors of AP42 for natural gas [8]

Technology		AP-42 (g/GJ)		AP-42 (kg/m^3)	
		NO_x	**CO**	**NO_x**	**CO**
Large-Wall fired Boilers	Low NO_x burners	59.119	35.471	2242.589	1345.553
	Flue gas recirculation	42.228	35.471	1601.849	1345.553
Small Boilers	Low NO_x burners	21.114	35.471	800.924	1345.553
	Flue gas recirculation	13.513	35.471	512.592	1345.553
Tangential -Fired Boilers	Flue gas recirculation	32.093	41.383	1217.405	1569.812

Table 40. Controlled emission factors of EMEP/EEA for natural gas [10]

Technology	EMEP/EEA(g/GJ)		EMEP/EEA ((kg/m^3)	
	NO_x	**CO**	**NO_x**	**CO**
Dry -bottom boilers	48.000	39.000	1656.864	1656.864
Gas Turbines	48.000	4.800	1346.202	165.686

Table 41. Controlled emission factors of NPI for natural gas [11]

Technology	NPI(g/GJ)	
	NO_x	CO
Low NO_x burners	59.000	-
Flue gas recirculation	42.000	-
Low NO_x burners	21.000	-
Flue gas recirculation	13.000	-
Flue gas recirculation	32.000	41.000

5.1.1.2. Uncontrolled Emission Factors

For hard coal, the is displayed the emission factors of three databases as follows:

Table 42. Uncontrolled emission factors of AP42, EMEP/EEA and NPI for hard coal [8, 10, 11]

Fuel	**Hard Coal**			
Technology	**AP-42 (kg/ton)**			
	SO_2	NO_x	CO	PM_{10}
Pulverized	17.237	5.897	0.227	8.555
Fluidized Bed (Low NO_x)	4.536	2.268	0.865	ND
Fluidized Bed (SCR)	-	1.966	-	-
Technology	**EMEP/EEA (kg/ton)**			
	SO_2	NO_x	CO	PM_{10}
Pulverized	21.369	6.780	0.227	0.211
Fluidized Bed (Low NO_x)	21.369	2.646	0.857	0.219
Fluidized Bed (SCR)	-	2.371	-	-
Technology	**NPI (kg/ton)**			
	SO_2	NO_x	CO	PM_{10}
Pulverized	26.600	6.000	0.250	11.520
Fluidized Bed (Low NO_x)	14.000	2.500	0.815	11.520
Fluidized Bed (SCR)	-	-	-	-

For lignite coal, the table displays the emission factors of three databases as follows:

Table 43. Uncontrolled emission factors of AP42, EMEP/EEA and NPI for lignite [8,10,11]

Fuel	**Lignite /Brown Coal**			
Technology	**AP-42 (kg/ton)**			
	SO_2	NO_x	CO	PM_{10}
Pulverized	17.237	5.897	0.113	11.567
Fluidized Bed (Low NO_x)	4.536	1.633	0.068	11.567
Fluidized Bed (SCR)	-	-	-	-
Technology	**EMEP/EEA (kg/ton)**			
	SO_2	NO_x	CO	PM_{10}
Pulverized	43.781	6.780	0.227	0.227
Fluidized Bed (Low NO_x)	43.781	1.646	0.089	0.190
Fluidized Bed (SCR)	-	-	-	-
Technology	**NPI (kg/ton)**			
	SO_2	NO_x	CO	PM_{10}
Pulverized	33.000	3.600	0.130	16.800
Fluidized Bed (Low NO_x)	15.000	1.800	0.080	16.320
Fluidized Bed (SCR)	-	-	-	-

For natural gas, the table is displayed the emission factors of three databases as follows:

Table 44. Uncontrolled emission factors of AP42, EMEP/EEA, and NPI for natural gas [8,10,11]

Technology	**AP-42 (g/GJ)**		**AP-42 (kg/m^3)**	
	NO_x	**CO**	**NO_x**	**CO**
Large-Wall fired Boilers	80.232	35.471	3043.513	1345.553
Small Boilers	42.228	35.471	1601.849	1345.553
Tangential -Fired Boilers	71.787	41.383	2723.143	1569.812

Technology	**EMEP/EEA(g/GJ)**		**AP-42 (kg/m^3)**	
	NO_x	**CO**	**NO_x**	**CO**
Dry -bottom boilers	48.000	39.000	1656.864	1656.864
Gas Turbines	48.000	4.800	1346.202	165.686

Technology	**NPI(g/GJ)**	
	NO_x	**CO**
Large-Wall fired Boilers	80.000	-
Small Boilers	72.000	-
Tangential -Fired Boilers	32.000	-

Cement Sector

Emission factors acquired from selected databases are selected from modules for cement sector listed as follows:

- AP 42, Fifth Edition, Volume I Chapter 11: Mineral Products Industry
  - ✓ 11.6 Portland Cement Manufacturing
- NPI, Emission Estimation Technique Manual for Cement manufacturing Version 2.1
- EMEP/EEA air pollutant emission inventory guidebook 2019
  - ✓ 1.A.2 Combustion in manufacturing industries and construction
    - ✓ 2.A Mineral products
      - o 2.A.1 Cement production 2019

Emission factors taken from the EMEP/EEA database were only utilized for the comparison because the total value for pollutants originating from chimneys is given in the CEMS system. The emission factor for total values was also calculated in the EMEP database. However, NPI and AP42 databases calculated emission factors for each process.

EMEP/EEA

Emission factors in the database are presented as follows:

Table 40. Uncontrolled Emission Factors of EMEP/EEA for Cement Sector [17]

Pollutants	**CO**	**NO_x**	**SO_2**	**PM_{10}**	**TOC**
Emission factors	1455 g/ton	1241 g/ton	374 g/ton	234 g/ton	18 g/ton
	Uncontrolled	Uncontrolled	Uncontrolled	Uncontrolled	Uncontrolled

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