Emission Inventory from the Use of Coals and Policy Recommendations for Coal Utilization

by

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MASTER OF SCIENCE IN ENGINEERING

(CHEMICAL)

Department of Chemical Engineering

BANGLADESH UNIVERSITY OF ENGINEERING

AND TECHNOLOGY, DHAKA

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A thesis submitted to the Department of Chemical Engineering for partial fulfilment of the requirements for the degree of

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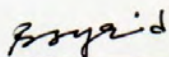(CHEMICAL)

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October, 2018

CERTIFICATION OF THESIS WORK

We, the undersigned, are pleased to certify that **Tanvir Ahmed**, a candidate for the degree of **Master of Science in Engineering (Chemical)** has presented his thesis work on the subject "**Emission Inventory from the Use of Coals and Policy Recommendations for Coal Utilization**". The thesis is acceptable in from and content. The student demonstrated a satisfactory knowledge of the field covered by this thesis in an oral examination held on **October 27, 2018.**
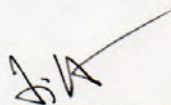

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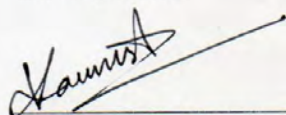
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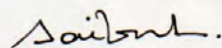Department of Chemical Engineering

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This thesis declares that the thesis is fully my work and has been completed during the course of my degree, and does not breach any ethical rules with regard to conduct of the research work. Moreover, this work is not submitted to any other place for any other degree or diploma.

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ABSTRACT

At present, about 73% of total electricity generation of Bangladesh are done using natural gas fuel. However, as the reserve of natural gas is diminishing day by day at an alarming rate, it has become essential for the country to strive for an alternative fuel source. Coal can be considered as a potential substitute in this scenario which is currently used in power generation, brick production and steel foundries as a secondary alternative in most of the cases. Coal mining has been initiated in 2005 in the Barapukuria coal mine, one of the six bituminous coal mines of Bangladesh. This mine alone cannot cater to the local coal demand. In 2016, 0.51 Mtoe coal was extracted from the mine, while 1.09 Mtoe coal was imported. The demand is expected to go up and to achieve the vision of 2030 Government has considered instigating necessary steps to set up a number of coal-fired power plants across the country. But environmental impact of these proposed coal fired power plants is one of the biggest concerns and most of the coal which will be used in these power plants will be imported coal. So it is essential to analyze these imported coal to predict the extent and exploits of its utilization & pollution factors. Environmentalists and concerned strongly resist coal mining and setting up of coal fired power plants in environment sensitive locations. To overcome these sociopolitical issues Bangladesh Government is trying to form a "Coal Policy" asking for the formation of coal-zone and simultaneously for accelerating subsequent development of coal mines. Several drafts have been prepared, but yet to be formalized. The current draft focuses on the exploration and development of new mines, but lacks specific direction on coal utilization. This research program is mainly experimental based, which determines different proximate, ultimate analysis values of different imported coal sources and also determines several mineral matters and pollution loads from a coal combustion process. The proximate analysis of coal is an assay of the moisture, ash, volatile matter, and fixed carbon as determined by series of prescribed or standard test methods. The ultimate analysis of coal involves determination of the weight percent carbon as well as sulfur, nitrogen, oxygen and chlorine through standard procedures like ASTM methods. Weight percent of constituents like mercury and chlorine were also measured. Thermodynamic simulation was also done to predict the effluent behavior from coal combustion. The objective of the research is to find out the specifics of coal utilization & environmental impact of coal fired power plants to recommend specific policies in order to promote the utilization and import of better quality coals which is a dire need for future energy security of the country. Four coal samples from different sources were analyzed for this study. Ash content varied from 3.37 to 12.31%, where volatile matter and fixed carbon varied from

25.32 to 48.46% and 43.50 to 62.37% respectively (dry basis). Calorific value suggested that, all coal samples would be suitable for power generation as they ranged between 22 to 30 MJ/kg. An overall pollution estimation from power plants and brick kilns by using pollution abatement technologies in these sectors was also shown. This estimation suggested that in 2030, total CO_2 emission from power plants and brick kilns would be 103.6 million tons compared to the current emission of 12 million tons. Whereas, 174 thousand tons of SO_x, 862 thousand tons of NO_x would be emitted in the same year compared to current emission of 103 thousand tons of SO_x and 42 tons of NO_x. Significant increase in ash production (90 thousand tons to 5405 thousand tons in 2030) from power plants in 2030 was seen from the pollution load prediction.

ACKNOWLEDGEMENT

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Chapter 1
INTRODUCTION

1. INTRODUCTION

1.1 Background

Coal is one of the most abundant resource of conventional energy and it forms the backbone of the modern industrial civilization [1]. It contributes 39.3 % in global electricity generation and will continue to play a major role in delivering secure energy in coming decades [2]. As the electrical power generation is the building block of national economy, it is essential to give substantial importance to increasing the electrical power generation for the future energy and economic security of any nation.

Economic development, increasing population and urbanization are the major factors governing the energy demand in Bangladesh. According to *key world energy statistics 2016*, the total primary energy supply has nearly increased from 12.75 Million tonnes of oil equivalent (Mtoe) to 39.55 Mtoe between 1990 and 2016 in Bangladesh [3]. At present the electricity generation is solely dependent on only one fossil fuel, natural gas. As the reserve of natural gas is diminishing, it is required for the nation to look for an alternative fuel source. Bangladesh government has planned to set up several coal fired power plants in the upcoming years to meet its energy requirement. Government has also targeted above 48% of total electricity generation from coal sector (43% from imported coal and 5% from domestic coal) by 2030 [4]. Though, most of the developed countries are moving away from the use of fossils fuels due to its pollution potential, Bangladesh has to consider having a coal based economy, because it is the only realistic alternative. Therefore, it is a major concern to do sincere investigation on the "quality of coal" to identify its potential as both fuel and pollution and understand the environmental impacts and threats on human and animal health associated with coal based power plants through in depth research. The "quality of coal" identifies the properties and characteristics of coal, which influence its behavior and uses. The major properties include moisture content, ash content, volatile matter, fixed carbon, elemental analysis and calorific value [5]. However, proximate and ultimate analyses are usually being followed for coal characterization, absolute identification of trace elements and determination of their characteristics is still a challenge to understand the properties of a certain coal.

1.2 Objectives

The aim of this study was to analyze different characteristics of locally available and imported coals for power generation and identify potential environmental pollution associated with its properties. Moreover, this research can be used to promote coal as an alternative energy source

for Bangladesh, as the study has recommended different policies that can be adopted to lower the pollution load from coal utilization.

Specifically the objectives of this study were:

- Characterization of local and imported coal samples.
- Identify the toxic constituents and their contribution.
- Pollution load calculation from coal combustion.
- Policy recommendation on quality, origin, quantity and usage of coal.
- A guideline for the import and utilization of coal in Bangladesh in near future.

1.3   Methodology

Coals from India, South Africa and Indonesia as well as Barapukuria mine have been analyzed using different ASTM standard methods. The proximate analysis of coal samples was performed using ASTM D 3172. The ultimate analysis of coal involves determination of the weight percent carbon as well as sulfur, nitrogen, and oxygen. ASTM D 3176 was followed for ultimate analysis. Calorific value of coal samples was determined by using bomb calorimeter as per ASTM D 5865. Ash composition of the coal samples was analyzed using XRF as per ASTM D 4326. Mercury and chlorine contents in coal were determined by using ASTM D 6414 and ASTM D 4208, respectively. An emission simulation was done to calculate the concentrations of chemical species from coal combustion using *FactSage Equilib Module*. The simulation data was used to predict the pollution load from the combustion of coal.

1.4   Scope

This research would create a possibility to make coal as an alternative power generation source for Bangladesh and become an essential part of the nation's energy mix. Moreover, scope of this research extends to a certain point which will eventually undermine the myth about the detrimental characteristics of coal based power plants, as a significant number of policies have been recommended in this study, which can be used for the lowering the expected pollution load from power plants and other sectors.

1.5   Thesis Organization

This dissertation is a complete write up of several laboratory experimentations as well as thermodynamic simulation of coal combustion. The investigation comprised of multiple steps: from sample preparation to complete characterization and consisting results and discussions on all aspects.

Chapter 1 of this writing outlines the full thesis in brief. It covers the background, objectives and scopes of the study. Thesis organization is also included in this section.

Chapter 2 provides an overview on coal structure and classification, economic value of coal and coal characterization. Current energy scenario of Bangladesh, use of coal, coal reserves and coal policy of Bangladesh are also discussed in this chapter. Different coal utilization technologies in power plants and brick manufacturing and harmful effects of coal usage are also included.

A detailed materials and methods of both experimental and simulation based works is included in Chapter 3. The standards and relevant equations that were used for calculation are provided in this chapter.

Chapter 4 consists of the results obtained from the experimentations as well as thermodynamic simulation. In depth discussions on the results is also included to give an overview on the investigation outcomes to the reader. Pollution load calculation from several relevant assumptions and obtained data are also included. And finally a series of policies is also recommended that can be used for proper utilization of coal in different sectors.

Chapter 5 is the concluding chapter which is based on the results obtained through investigation and suggests the direction for further research.

Chapter 2
LITERATURE REVIEW

2. LITERATURE REVIEW

2.1 Introduction

Energy is the building block of modern civilization and a prerequisite for sustainable development. The power crisis has become a major constraint to continued economic growth and energy sector of the country is currently facing serious challenge. Due to depleting nature and mono fuel dependent energy policy; finding alternative energy source has become imperative for the country. As the country has a large amount of untapped high quality coal resources, so it can be a great alternative energy source.

"Coal is a rock, a sediment, a conglomerate, a biological fossil, a complex colloidal system, an enigma in solid-state physics and an intriguing object for chemical and physical analyses" – stated by *van Krevelen* [6]. Geologists describe coal as a product of plant remains. Due to the effect of geological conditions, earth's temperature and pressure, the structure of the basic plant molecules brought about changes gradually, by reducing hydrogen and oxygen content of the molecule, and converting to pit, lignite, sub-bituminous coal, bituminous coal, anthracite and ultimately to graphite [7].

In this literature review, a brief discussion on coal, its characteristics and classifications, coal analysis and its social and economic value and utilization technologies of coal will be stated. Current energy scenario of Bangladesh and energy crisis and how coal can be a great alternative for this country will also be discussed. Finally, the effect of coal usage on human health and environment will be addressed.

2.2 Coal Structure and Classification

Until the twentieth century chemists knew very little about the composition and molecular structure of the different kinds of coal, and as late as the 1920s they still believed that coal consisted of carbon mixed with hydrogen-containing impurities. But after enormous amount of research and analysis now we all know that coal is a heterogeneous substance and contains both aromatic and aliphatic structure in different sizes and different kinds along with hetero-atoms like oxygen, nitrogen, sulfur, etc., and thus makes its structure extremely complicated and variable. It is an aggregate of microscopically distinguishable, physically distinctive, and chemically different macerals and minerals [8].

Classification of coal is very important as it gives valuable information to commercial users for power generation or coke manufacturing. It also provides information to researchers for studying the origin of coal. Most classifications are based on the results of chemical analyses

and physical tests, but some are more empirical in nature. The most common classification is based on rank, referring to the degree of coalification that has occurred. The rank of a coal is determined primarily by the depth of burial and temperature to which the coal was subjected over time [9]. Classification of coals based on ASTM standards is stated in Table 2.1.

Table 2.1: Classification of coals by the American Society for Testing and Materials [10]

Class	Group	Fixed Carbon % Dry, mineral free	Volatile Matter % Dry, mineral free	Heating Value MJ/kg Moist, mineral free
Anthracite	Meta Anthracite	>98	<2	
	Anthracite	92-98	2- 8	
	Semi Anthracite	86- 92	8 - 14	
Bituminous	Low Volatile	78-86	14-22	
	Medium Volatile	69-78	22-31	
	High Volatile A	<69	>31	>32.6
	High Volatile B			30.2-32.6
	High Volatile C			26.7-30.2
Subbituminous	Subbituminous A			24.4-26.7
	Subbituminous B			22.1- 24.4
	Subbituminous C			19.3 - 22.1
Lignite	Lignite A			14.7 - 19.3
	Lignite B			<14.7

From the evolutionary pathway of coal, we can see that coal is a colloidal substance at the first formative stage, which is known as lignite. At the intermediate stages, the properties of coal change gradually in such a way that it becomes a crystalloid substance and with passage of more time it almost becomes crystalline substance at the end of the evolutionary series. Thus its hydrophilic nature changes to hydrophobic property at the end of the series. Various forms of coals obtained at these different stages of metamorphic path is classified as follows [7]:

Anthracite coal: These coals are hard in nature, have little porosity and hence low reactivity as well as low volatile matter content. Fixed carbon present in these coals ranges as high as 92–98%.

Semi-bituminous coal: These coals have higher percentage of volatile matter (up to 16%) and fixed carbon in the range 89–91%.

Bituminous coal: It is relatively soft and dark black variety of coal, having volatile matter content 15–20% and fixed carbon around 65–85%. Due to high volatile during burning it gives large flame and is sometimes called long-flame coal also.

Lignite or brown coal: These coals are friable and has a dull black to brown appearance. Their volatile content is about 35–40% and fixed carbon about 47%. Hydrogen content of these coals is high and their reactivity is also higher.

Peat: These are the coals at the lowest rank of the coal series. Their moisture as well as oxygen (30%) and hydrogen content are very high but calorific value and fixed carbon are much lower than bituminous coal.

Till now five major coalfields have been discovered in Bangladesh. In order of discovery year these are Jamalganj (1962), Barapukuria (1985), Khalashpir (1989), Dighipara (1995) and Phulbari (1998). The ranks of coal of these fields are ranged from sub-bituminous to bituminous coal. Some lignite and peat coal are also available. More details about the coalfields and types of coal can be found in Bangladesh are described in Section 2.5.3.

2.3   Economic Value of Coal

As the world's leading source of electric power, coal is the continuing cornerstone of economic development, social progress, and a higher quality of life. Coal was the backbone of the Industrial Revolution in England during the eighteenth century, America's emergence as a major economic power during the late nineteenth and early twentieth centuries, Germany's manufacturing prowess during the early twentieth century; and coal is now powering the twenty-first century economic miracles rapidly unfolding in both China and India. Today, coal supplies a leading 40% of the world's electricity, and coal's availability, affordability, and reliability make it the fuel of choice in the developing world [11].

Coal is an essential resource for tackling the challenges facing the modern world - specifically the rapid increase in energy consumption. It is significantly cheaper and more accessible than other fossil fuels and its reserves are distributed much more equally around the planet. Power

generation is the primary use for coal worldwide. Thermal coal is burnt to create steam that drives turbines and generators for the production of electricity. Coal converted to coke is used to produce around 70% of the world's steel. Coal is also widely used in the production of other metals including aluminium and copper. By-products of coal combustion such as fly ash also play an important role in cement manufacture and the wider construction industry. Coal is liquefied to make synthetic fuels similar to petroleum or diesel. Syngas from gasification can be further processed to produce chemical building blocks such as methanol, ammonia and urea. Other major users of coal include the paper, textile and glass industries. Coal is also used in the manufacture of carbon fibre and specialist ingredients such as silicon metals, which are used to produce ingredients for the household and personal care sectors [12,13].

From Bangladesh point of view economic value of coal is very important as the country's most of the brick production is done by using coal as the fuel. After banning the use firewood in brickfields the demand for coal in brick manufacturing industries increases significantly. Brick kilns burn nearly 6 million tons of coal annually in Bangladesh. Moreover, coal is also used for power generation in this country. Although most of the electricity is generated by using natural gas, but now a day's use of coal for generating power is increasing. Government is also taking necessary steps to introduce coal as a substitute of natural gas for power generation, as the reserve of gas is declining.

2.4 Analysis of Coal

Coal analysis techniques are specific analytical methods designed to measure the particular physical and chemical properties of coals. These methods are used primarily to determine the suitability of coal for coking, power generation or for iron ore smelting in the manufacture of steel. There are two methods to analyze coal which are called proximate analysis and ultimate analysis. The *proximate analysis* determines only the fixed carbon, volatile matter, moisture and ash percentages and it can be determined with a simple apparatus. The *ultimate analysis* determines all coal component elements, solid or gaseous and it needs properly equipped laboratory with skilled chemists. It is useful in determining the quantity of air required for combustion and the volume and composition of the combustion gases. These information are required for the calculation of flame temperature and the flue duct design etc.

Moisture is an important property of coal, as all coals are mined wet. Groundwater and other extraneous moisture is known as adventitious moisture and is readily evaporated. Moisture held within the coal itself is known as inherent moisture and is analyzed quantitatively.

Volatile matter is an index of the gaseous fuels presence. The volatile matters are the methane, hydrocarbons, hydrogen, carbon monoxide and incombustible gases like carbon dioxide and nitrogen found in coal. The typical range of volatile matter is 20 to 35%. It helps in setting the minimum limit on the furnace height and volume and easier ignition of coal.

Ash is an impurity that will not burn. The typical range of ash is 5% to 40%. The Ash Increases handling costs, affects combustion efficiency and boiler efficiency, reduces handling and burning capacity and may causes clinkering and slagging.

The fixed carbon gives a rough estimate of the heating value of coal. Fixed carbon is the solid fuel left in the furnace after volatile matter is distilled off. It consists of maximum carbon but also contains some hydrogen, oxygen, Sulphur and nitrogen not driven off with the gases.

Apart from these there are other physical and mechanical characterization of coal can be done. Relative density depends on the rank of the coal and degree of mineral impurity. Particle Size Distribution, which determines its brittleness, and on the handling, crushing and milling it has undergone. Float sink test will determine the optimum particle size for washing, the density of the wash liquid required to remove the maximum ash value with the minimum work. Abrasion test will describe its propensity and ability to wear away machinery and undergo autonomous grinding. Calorific value of coal measures the specific energy output of a coal during complete combustion. This is required particularly for coals used in steam generation. The behavior of the coal's ash residue at high temperature is a critical factor in selecting coals for steam power generation. Most furnaces are designed to remove ash as a powdery residue and for this reason ash fusion test is required.

2.5   Bangladesh and Coal

2.5.1   Current energy scenario in Bangladesh

Rapid growth of population, urbanization and industrial development sparked energy consumption remarkably in the country. Primary energy consumption was 18.0 Mtoe in 2006 and reached 32.4 Mtoe in 2016, which is almost doubled [14]. There is massive demand for electricity, oil, gas and natural assets in agriculture, industry and service sector as well as daily life of Bangladesh. In this context, the Government is giving top priority to the development of power and energy sector. The total installed electricity generation capacity stood at 15,755 MW of which the highest generation was 9,479 MW in FY2016-17. Besides, net electricity production was 52,193 million kilowatt-hours in FY2015-16 which increased to 57,276 million kilowatt-hours in FY2016-17 [15].

Although primary energy supply has been increased steadily for past 20 years, there is no substantial alternative energy sources have been developed that could provide sustainable solution to bulk energy deficit. Within next few decades, it is expected that Bangladesh will face serious energy crisis. Energy demand is skyrocketing which is currently being supplied by depleting fossil fuel energy sources such as natural gas, coal, oil and petroleum products which is shown in Figure 2-1 [16].
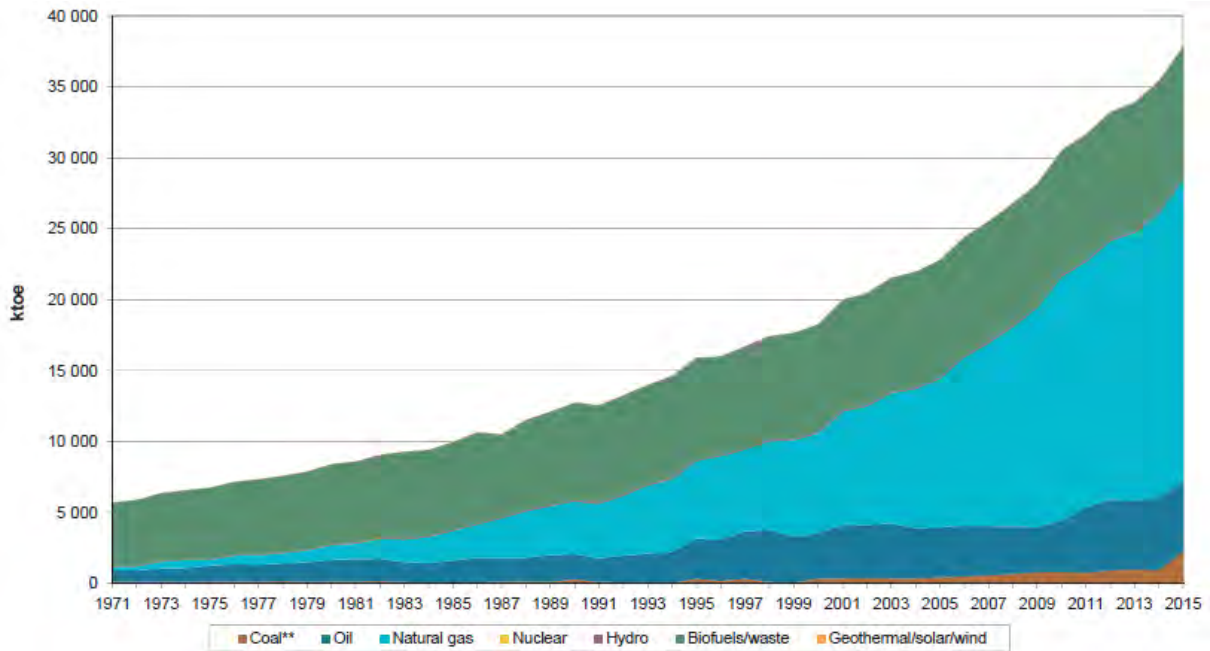
Figure 2-1: Total primary energy supply in Bangladesh [17]

Currently, natural gas accounts for 64.99% of total electricity generation of 13,555 MW. Imported furnace oil, coal, diesel and hydropower also contribute to electricity generation of 2786 MW (20.55%), 249 MW (1.84%), 880 MW (6.49%) and 230 MW (1.70%), respectively as of June 2017 [15]. The contributions of different sources to generate electricity are given in Figure 2-2.

2.5.2 Coal usage pattern

If we want to categorize the usage pattern of coal in Bangladesh, then it can be divided into two groups. One is use of coal in industry (mainly in brick production) and the other one is use for power generation.
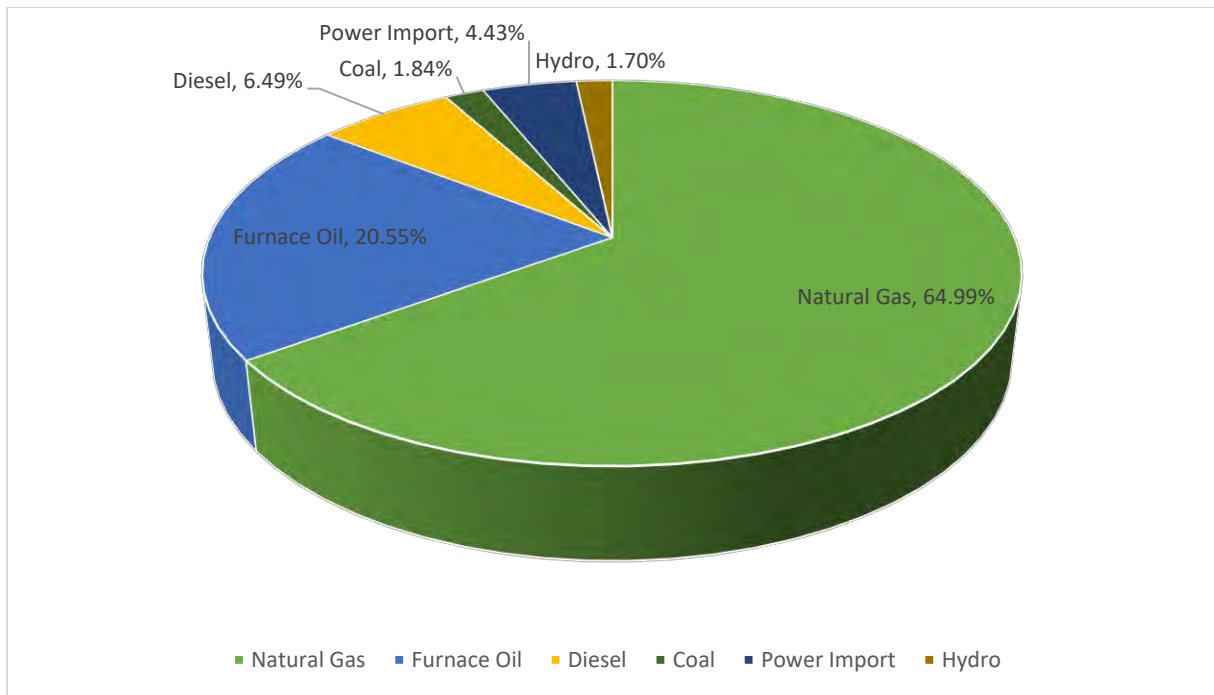
Figure 2-2: Installed capacity as on June 2017 (by fuel type), Source: Bangladesh Power Development Board (BPDB)

Coal is the primary fuel for brick making process in Bangladesh. About 7000 coal fired brick kilns are producing bricks in Bangladesh. Most of these kilns use traditional FCK brick production technology (More details about FCK and other brick production technologies can be found in Section 2.6.1). Coal consumption is higher in FCK technology than other available recent improved technology. As a result, big portion of total coal consumption go under brick production (Figure 2-3).

Although for power generation Bangladesh is mostly dependent on natural gas, power generation from coal is expected to increase significantly in coming years. According to the data from International Energy Agency (IEA), shown in Figure 2-3, coal consumption in 2015 for brick production increased suddenly in a significant manner compared to the previous years. But according to the other sources, for example Energy Information Administration (EIA), this figure varies significantly. According to EIA, total coal consumption in 2015 was 1705 kt, almost half of the amount published by IEA. However, back calculation from the production of bricks and data from the power plant are more consistent with the IEA data and hence used for pollution load calculation.

Among five coalfields, coal is being mined commercially only from the Barapukuria underground coal mine in Dinajpur district at present from year 2005. The produced coal from

this field used mainly in Barapukuria Coal Power Plant, which is a 250 MW coal fired based power plant. Currently the plant has two 125 MW units, but operators are seeking to add an additional 250 MW unit.
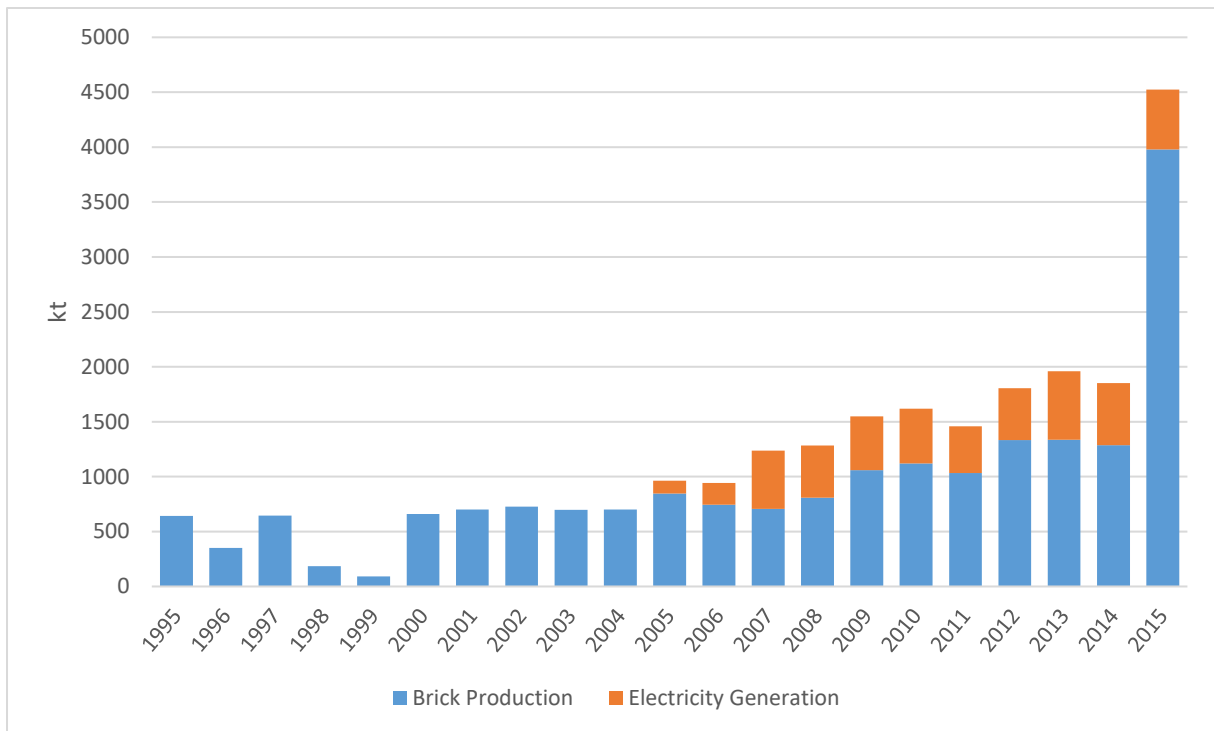
Figure 2-3: Coal consumption data from year 1995 to 2015. Source: International Energy Agency Statistics.

As currently coal is being mined from only one coalfield, so to meet up the increasing demand for coal the nation is highly dependent on imported coal. Moreover, government is planning to establish several coal-fired power plants to reduce the dependency on natural gas for electricity generation. As a result, import of coal will increase more.

Table 2.2 lists the production and import of coal from 1995 to 2015.

2.5.3   Coal reserves in Bangladesh

Right now, natural gas accounts for about three-fourths of the commercial energy used in the country. Too much reliance on natural gas has aided to severe growth in its demand. But reserve of gas is diminishing very fast. Given the insecurity of sustainable supply of natural gas, it is vital to branch out the primary energy sources in the country, and coal can be a major source of primary energy supply in this country in future. Five coal fields have been discovered till now that are shown in Table 2.3.

Table 2.2: Coal domestic production and import data. Source: IEA

Year	Production (*kt*)	Import (*kt*)
1995	0	642
1996	0	352
1997	0	646
1998	0	186
1999	0	92
2000	0	660
2001	0	700
2002	0	727
2003	0	699
2004	0	700
2005	178	700
2006	303	700
2007	388	700
2008	677	700
2009	828	800
2010	705	800
2011	667	924
2012	835	1000
2013	855	1000
2014	947	988
2015	676	3651

Among these five coal fields, Petrobangla has developed the first coal mine of the country at Barapukuria. At present, Barapukuria coal mine is producing approximately 4000-5000 metric tons daily. In the FY2015-16, total 1,021,638 metric tons of coal was produced from this mine [18]. The coal extracted from this mine is mainly used to fuel the only coal fired 250 MW power generation plant in the country located at Barapukuria. The remainder is used in brick fields, boiler industry, steel re-rolling mills, etc. The coalfield has a proved area of about 5.25sq km. It is expected that coal may be found beyond the proven area. This coal is partially bituminous to high volatile bituminous coal.

Table 2.3: Coal fields of Bangladesh [19]

Serial No.	Name of the Coal Field	Reserve in Million MT
1	Barapukuria, Dinajpur	390
2	Khalaspir, Rangpur	685
3	Jamalganj, Joypurhat	5450
4	Phulbari, Dinajpur	572
5	Digipara, Dinajpur	865
	Total =	7962 MMT

Khalashpir coalfield is located in Pirganj Upazila of Rangpur district, about 13 km west of Pirganj town. Khalashpir coalfield was discovered in 1989 by the Geological Survey of Bangladesh. The coalfield was delineated and defined on the basis of the four drill holes done during 1989-90. The coal was encountered at depths ranging from 257 to 482 meter below the surface in a Gondwana basin. Occurrence of coal has been proved in an area of about 2.52 sq km and a further extension of the basin is estimated.

The Jamalganj coalfield is located in Joypurhat district in the vicinity of Jamalganj town and to the west of the north-south broad-gauge railway line. The coalfield was discovered in 1962 by the Geological Survey (of the then Pakistan) under the UN sponsored coal exploration program. Under the program 10 wells were drilled in the Jamaganj-Paharpur area of Joypurhat district. Coal seams were encountered in 9 wells within depth range of 640 to 1158 meter below the surface in Permian Gondwana rocks. The 9 bore holes that penetrated the coal seams are spread over an area having a maximum east-west distance of 12.5 km and a north-south distance of 4.8 km.

The Phulbari coalfield was discovered in 1997 by BHP Minerals. The Phulbari coalfield is located about 10 km south of the Barapukuria coal field and in the vicinity of Phulbari township. The mining area in the Phulbari Basin covers an area of eight kilometers (north-south) by three kilometers (east-west) with coal seam(s) varying between 15-70 meters thick at some 150-270 meters beneath the surface, with average combined thickness of 38 meters. The Phulbari coal is high volatile bituminous coal. It has low ash (average 15%) and low sulfur content (<1%) and therefore suitable for both power generation and for producing semi-soft coking coal.

Dighipara coalfield is located in Dighupara Upazila of Rangpur district, Dighipara coalfield was discovered in 1995 by the Geological Survey of Bangladesh. The coalfield was delineated and defined on the basis of the five drill holes. The coal was encountered at depths is 327meter below the surface.

2.5.4 Coal policy of Bangladesh

From Section 2.5.3 it can be seen that plenty of coal reserves exist in Bangladesh, which are not suitable for extraction through conventional mining and coals never been treated as prime choice of energy sources in Bangladesh because of hazardous & risky extraction procedures as well as environmental pollution. Moreover for many other reasons like to overcome certain political and social pressure, proper extraction method for coal in our country an evident coal policy was mandatory for this country and after several trying Energy and Mineral Resources Division of Bangladesh Government has proposed a draft coal policy named Coal Policy 2010. Salient features of this coal policy are stated below:

- The Coal Policy shall be treated as an integral part of the National Energy Policy.
- Decisions on mining method (either open pit or underground) should be taken carefully. Any environment destructive initiative should not be taken. Consent of independent local committee shall be taken in order for open pit mining.
- The North West part of the country will be announced as the "Coal Region" and all the announced coal region will be developed as electricity produced area.
- Shares of a coal project would have to be offloaded in the local market in phases with 20 percent of the shares reserved for the affected people. The affected would however be allowed to sell their shares only to the government.
- The government will decide the royalty of coal by gazette notification periodically according to advice of the proposed Coal Sector Development Committee.
- In order to maintain long term energy security production of coal should be limited to the annual demand of the country. The coking coal should be transferred to coke and will be used for domestic consumption.
- If there is not enough demand of coal within the country then the surplus coal can be exported.
- The coal mines from which it is not possible to extract coal technically and economically then Underground Coal Gasification method can be introduced there.

This coal policy lacks specific guidelines regarding some issues and some modifications can be introduced to eliminate those lacking. Some recommendations are stated below;

- In proposed coal policy it is admitted that it is important to gain competency in coal resources for domestic uses. But there is no section about how, by which institute, within what time this competency should be gained. Rather it is stated in section 1.2 that for discovering and developing coal mines strategic partner/ joint investor should be appointed.

- In section 21 it is stated that money from Coal Fund can be used for coal exploratory activities, research and study, increase the efficiency of human resources, masterplan in the coal sector. But for best use of coal resources, there should be the establishment of certain institute which will do these types of study stated above, purchase the necessary equipment for the institute, for increasing technical and technological skills establishment of department of mining engineering is also necessary. Coal fund can also be used in these areas, which is not mentioned in proposed coal policy.

- Section 2 and section 4 are contradictory. In section 2 it is stated that leases should extract coal in line with the country's internal demand for coal. But in section 4 it is stated that if there is not enough demand of coal within the country then the surplus coal can be exported. But if coal is extracted by in line with the country's internal demand for coal there should not been any surplus of coal. So this is a huge loop hole for corruption in coal export.

- The draft Coal Policy proposed that the government should fix the royalty rate through gazette notification according to advice of the Coal Sector Development Committee. Absence of lowest ceiling of royalty rate in the coal policy will lead to fix royalty at lower rate that would not be able to preserve country's interest. If the policy makers' intention is to collect corporate tax from the multinational corporations, it should be reminded that these corporations are very expert in creative accounting by increasing expenditure and operating cost in order to show less profit. Thus ultimately they will dodge the Government.

- The draft Coal Policy stated that the decisions on mining method should be taken carefully and opted for a limited open cast mining as a test case at a shallow depth coal field like Barapukuria north field under government supervision in order to assess the environmental, social and geological impact. If the results are satisfactory, this method would be applied to other mines like Phulbari for commercial extraction. However the

coal policy should not dictate the mining method, as the method would vary from mine to mine.

2.5.5 Proposed coal based power plants in Bangladesh

To meet up the government's target to generate around 20,000MW of electricity from coal-fired power projects by 2030 using supercritical and ultra-supercritical technologies, government plans to set up 25 coal-fired power plants by 2022. Of the total, 16 will be built by the public sector and nine by the private sector [20] [21]. In the following Table 2.4 some of the major proposed coal based power plants are listed;

Table 2.4: Major proposed coal based power plants, Source: Global Coal Plant Tracker

Plant	Sponsor	Capacity (MW)	Status
Barapukuria Coal Power Plant (Unit 3)	Bangladesh Power Development Board	275	Construction
Boalkhali power station (Beximco)	Beximco Group, China Resources	660	Announced
Daudkandi power station	ChinaPower, Meghna Group	1320	Announced
Gazaria power station (Orion)	Orion Group, Fujian Zhongde Energy, Firstgen Energy FZE	635	Pre-permit
Maheshkhali power station (BPDB/TNB)	Bangladesh Power Development Board, Tenaga Nasional Berhad	1320	Announced
Maheshkhali power station (PowerChina)	Bangladesh Power Development Board, PowerChina	1320	Announced
Matarbari power station	Sumitomo Corporation	1200	Construction
Mirsarai power station (PowerChina)	Bangladesh Power Development Board, Zhejiang Jindun Holding Group Company	1320	Announced
Patuakhali power station (Ashuganj)	Ashuganj Power Station Company, China Energy Engineering Corporation	1320	Announced
Payra power station	CMC, North-West Power Generation	1320	Construction
Rampal power station	Bangladesh Power Development Board, NTPC	1320	Construction

2.6 Technologies for Coal Utilization

Since coal is a relatively inexpensive energy source, the use of coal for electricity generation is increasing rapidly. However, one critical issue in promoting coal utilization is controlling environmental pollution. As a result, clean coal technologies are required to utilize coal in an

environmentally acceptable way and to improve coal utilization efficiency. Several coal utilization technologies for brick manufacturing and power generation are available now a days. Among some of them are described briefly in this section.

2.6.1 Brick manufacturing

2.6.1.1 *Bull's trench kiln (BTK)*

The Bull's Trench Kiln is essentially an elliptical shaped dug out area in an open field. The kiln is about 250 ft. long and 57 ft. wide and has two 32 ft. high movable chimneys. The green bricks to be fired are set in rows, two to three bricks wide, with holes in between that allow feeding of coal and a sufficient flow of air through the setting (Figure 2-4). A linking layer of bricks is made across the width of the kiln and half way up, to stabilize the setting. On top of the bricks, two layers of bricks, covered with ash or brick dust, seal the setting. A large piece of canvas, paper or metal sheet is placed vertically across the brick setting to block air from entering from the wrong side of the chimneys. The trench contains 200 - 300,000 bricks at a time.
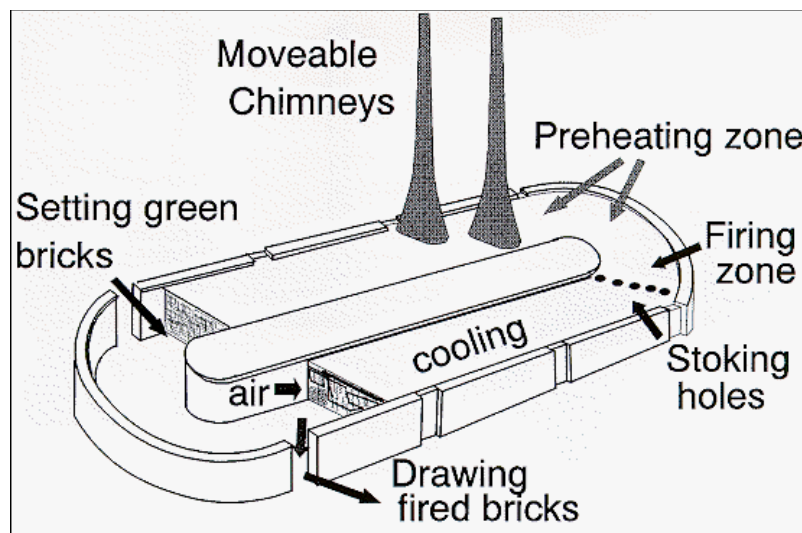
Figure 2-4: Schematic diagram of Bull's Trench Kiln [22]

Chimneys, made of sheet metal, are placed on top of the brick setting. They are moved around as the firing progresses and they have to be light, so that the firing crew can carry them. Wires attached to the top of the steel chimneys support them. The firing in a Bull's trench kiln is continuous, day and night. Green bricks are loaded and finished bricks are drawn all the time. The fuel saving is achieved by reusing part of the energy that is otherwise lost in periodic kilns. The air for combustion is drawn through the already fired but still hot bricks. The cooling bricks transfer their heat to the combustion air, pre-heating it before it enters the firing zone. After

combustion, the hot exhaust gases pass through the yet unfired bricks on their way to the chimneys. This pre-heats the bricks, so less fuel is needed to bring the bricks to the maximum temperature. More fuel efficiency compared to periodic kilns, low initial investment and high capacity are the advantageous features of BTK.

2.6.1.2 Fixed chimney kiln (FCK)

The chimney in the FCK is fixed and approximately 130 ft. high (Figure 2-5). This tall chimney creates a stronger draft thereby improving the combustion process, and releases the flue gas at a height of 130 ft. above the ground thus providing faster and better dispersion. The kiln has underground piping to divert the flue gas from anywhere in the kiln to fixed chimney. The length of the kiln is same as that of the BTK, but its width is greater to accommodate the underground piping. FCK also has better insulation in the sidewalls to reduce heat loss to the surroundings. Construction cost of chimney is almost 50% of the total cost of a FCK.
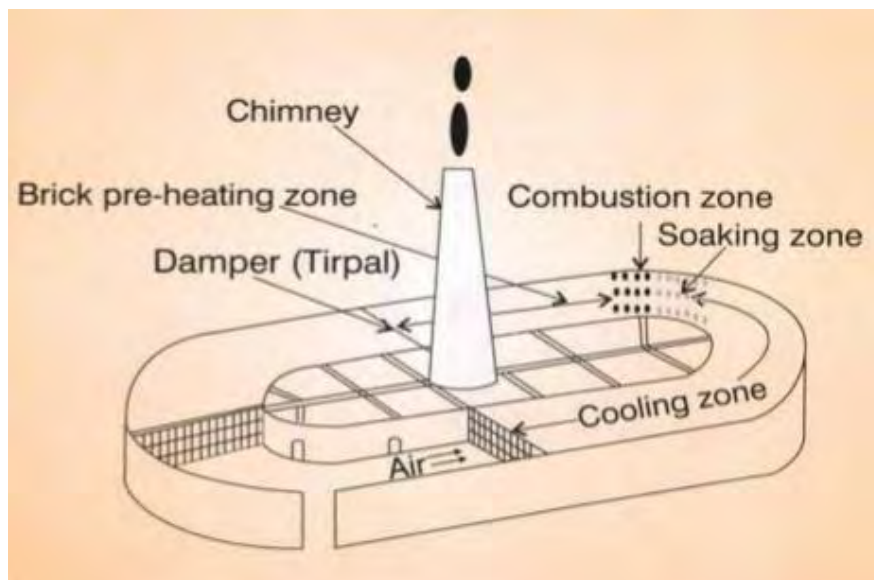
Figure 2-5: Fixed Chimney Kiln [22]

2.6.1.3 Hebla or zigzag kiln

The Hebla or Zigzag kiln is rectangular in shape and measures 250 ft. by 80 ft. It has a 55 ft. high fixed chimney located on one side of the kiln. At the bottom of the chimney there is a blower, which draws the flue gas from the kiln and discharges it to the atmosphere. The kiln is divided into 44 to 52 chambers, which are separated from each other in such a way that the hot gases move in a zigzag path through the kiln. It is 10-15% more efficient than FCK. This kiln is expensive to construct. The construction technology is not easily available.

2.6.1.4 Hoffman kiln

A Hoffman Kiln is rectangular in shape and measures 300-400 ft. by 60 ft. It has a fixed roof, which enables bricks to be fired throughout the year although during the rainy season, which is called off-season. The inside roof of the kiln is arched and has a firebrick lining on the inside surface. The thick walls of the kiln and good insulation minimize heat loss to the surrounding. The chimney is 76 ft high with a blower at the bottom.

Advantages includes; higher efficiency, fuel economy, uniform burning of brick, regulation of heat, preheating of unburnt bricks, higher percentage of good bricks, regularity in shape, no smoke as the combustion of the fuel. High initial construction cost is one of the disadvantages.

Figure 2-6 shows a Hoffman kiln. To adapt this design to using coal instead of natural gas as a fuel, the stoke holes on the roof of the kiln will be used to insert coal fuel into the firing chamber.
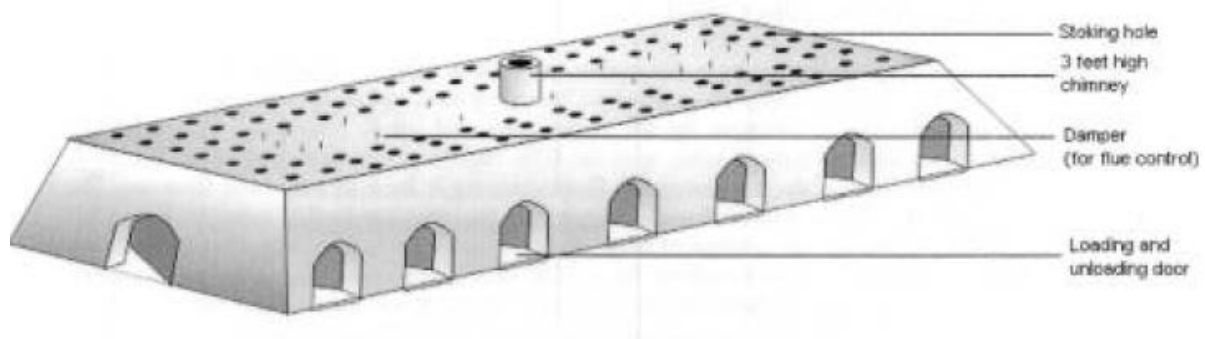
Figure 2-6: Hoffman Kiln [22]

2.6.1.5 Vertical shaft brick kiln (VSBK)

This type of kiln was developed in China in the 1950's with the objective to produce burnt clay bricks of a high standard, with a special view to energy- efficiency and environmental considerations. The VSBK consists of one or more shafts located inside a rectangular brick structure. The shaft is loaded from the top in batches of green bricks. Each batch typically contains four layers of bricks set in a predetermined pattern. For evacuation of exhaust gases, typically, two rectangular chimneys are provided at opposite corners of each shaft. Lids are provided to cover the shaft top, which direct the gases to the chimney through the flue system.

The VSBK technology uses hot exhaust gasses for the gradual preheating of the unfired bricks in a continuous process, thus reducing energy consumption and CO_2 emissions by up to 50% compared to the more commonly used clamp kilns. There is no doubt that the VSBK technology is one of the most energy efficient and cost effective brick firing processes in the

world, with the added benefit of providing a better working environment for staff members. The VSBK makes clay brick an even more sustainable building option by reducing the embodied energy of an average clay brick, at least by half.

2.6.2 Power generation

2.6.2.1 *Pulverized coal combustion technology*

Of the number of coal-fired electricity plants, pulverized coal (PC)-fired power plant is the most used in electricity generation plants around the globe since it has the highest reliability and commercial readiness for high electricity production capacity [23]. This process involves reducing the coal to a powder that is burned in a boiler to generate high-pressure, superheated steam that drives a turbine connected to an electric generator [24].
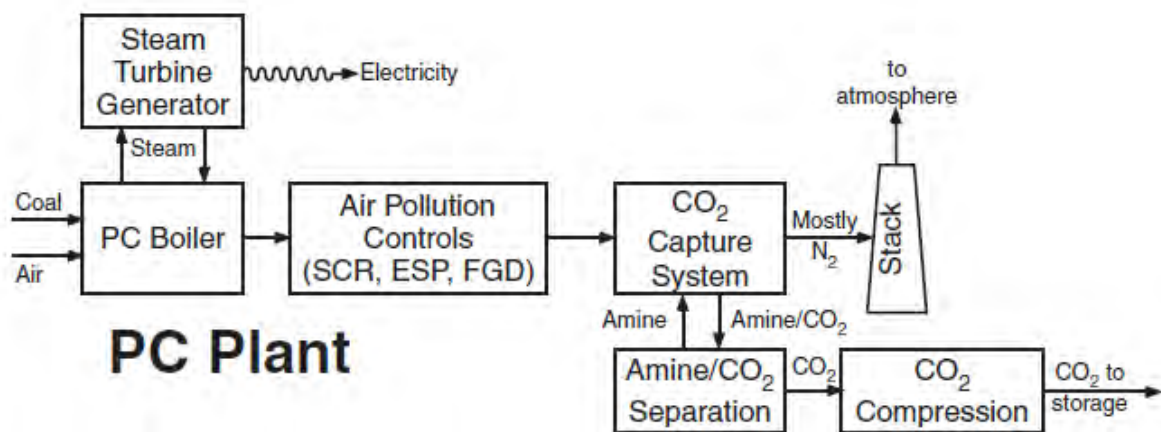
Figure 2-7: A pulverized coal (PC) combustion plant with post-combustion CO_2 capture [25]

The overall efficiency of PC power generation is affected by many factors, including the thermodynamic cycle design, steam temperature and pressure, coal particle size (coal grind), combustion air-to-fuel ratio, fuel mixing, air leakage into the system, cooling (condenser) water temperature, and the "parasitic" energy loads required to power auxiliary equipment such as grinding mills, pumps, fans, and environmental control systems.

2.7 Effect of Coal Usage

Coal has played an important role in the progression of civilization and will continue to be a major fuel source for at least the next quarter century. The value of coal is partially offset by the environmental issues it raises. Some of these environmental issues also have impacts on human health.

2.7.1 Environmental impact

Coal consists of more than 50% by weight and more than 70% by volume of carbonaceous material. After burning or combustion, it can produce carbon di oxide, sulfur dioxide, nitrogen oxides, particulate matter, and heavy metals, leading to smog, acid rain, toxins in the environment. Coal contains many heavy metals. The heavy metal content of coal varies by coal seam and geographic region. Many of the heavy metals released in the mining and burning of coal are environmentally and biologically toxic elements, such as lead, mercury, nickel, tin, cadmium, antimony, and arsenic, as well as radio isotopes of thorium and strontium [26].

Coal mining has a direct impact on the environment. In some surface mines, the generation of acid mine drainage (AMD) is a major problem. AMD is formed by a series of complex geochemical and microbial reactions that occur when water comes in contact with pyrite (iron disulfide minerals) in coal, refuse, or the overburden of a mine operation. The resulting water is usually high in acidity and dissolved metals. The metals stay dissolved in solution until the pH raises to a level where precipitation occurs. Other significant impacts include fugitive dust emissions and disposal of overburden and waste rock.

Environmental impacts result from the transport of coal. Coal transportation is accomplished through rail, truck, water, slurry pipeline, or conveyor; however, most is performed by rail. All forms of coal transportation have certain common environmental impacts, which include use of land, structural damage to facilities such as buildings or highways, air pollution from engines that power the transportation systems [27].

2.7.2 Health impact

There are a number of negative health effects of coal that occur through its mining, preparation, combustion, waste storage, and transport. During coal mining, mine accidents and workers death is a very common issue. Dust issues in mines, particularly underground mines, have had a negative impact on the coal industry. Many miners, particularly underground miners, have contracted respiratory diseases [28].

During coal combustion, emission of both CO_2 and CO gases can cause many health issues directly and indirectly including malaria, cardiovascular diseases and asthma [29]. Coal combustion also releases nitrogen oxides, sulfur dioxide, particulate matter (PM), mercury, and dozens of other substances known to be hazardous to human health. Coal ash, the hazardous waste that remains after coal is burned, can also contain: chromium, which can cause stomach ulcers, anemia, and stomach and lung cancers; selenium, which in excess can cause impaired

vision or paralysis; and boron, which can cause eye, nose, and throat irritation, or in large amounts damage to testes, intestines, liver, kidney, and brain. All effects can eventually lead to death.

2.8   Emission Inventory for Bangladesh

The database of total amount of pollutants discharged into the atmosphere from a specific source is called the emission inventory for that source. It usually contains the total emissions for one or more particular greenhouse gases or air pollutants, devising from that source in a certain geographical area and within a specified time period, usually a specific year. An emission inventory is generally dependent on various factors. The factors include: types of events that causes emissions, chemical and physical characteristics and quantity of pollutants, geographical location, time period over which emissions are estimated and the methods and materials that are used for calculate or predict emission inventory [30].

A series of research works have been done in the aspects of emission inventory from the different sources of Bangladesh [31] [32] [33]. Government of Bangladesh with the help of different global organization has done several projects and activities regarding the pollution emission inventories in Bangladesh. Among them, one of the major works called National Communication have done by the Ministry of Environment and Forest of Government of Bangladesh supported by an international environmental treaty organization United Nations Framework Convention on Climate Change (UNFCCC). Till now UNFCCC has conducted three National Communication in Bangladesh, these are: Initial National Communication (INC), Second National Communication (SNC) and Third National Communication (TNC).

Bangladesh submitted its Initial National Communication report in 2002 and where the focus was given on emission inventory and also on the impact and vulnerability of climate change on different sectors and bio-physical systems [34]. According to the report, CO_2 emission has been the largest due to the energy sector (62.74%), followed by the land use changes and forestry sector (32.26%) and industrial process (5.27%). CH_4 emission from agriculture sector has been contributing about 95% of total methane emission of the country. Due to the application of synthetic fertilizer, agriculture sector emits N_2O also. Insignificant amount of CH_4 and N_2O has emitted from energy sector also. The physical impacts of climate change due to the emission of these pollutants were also stated in the report. The report also included significant amount of mitigation options that can be adopted for climate change.

The Second National Communication (SNC) report was submitted by Government of Bangladesh in 2012, which is an updated status of emission inventory along with the impact, vulnerability, adaptation and mitigation issues are elaborated [35]. Total emission of different greenhouse gases in 2005 and a projection of greenhouse gas emission from different sources from 2006 to 2030 were included in the report. Energy sector and Land-use change and forestry were mainly responsible for the CO_2 emission and agricultural sector was responsible for CH_4 and NOx emission. Different sectors wise impacts of climate changes and the mitigation process of these impacts were also included in the report.

The Third National Communication (TNC) project has started in November 2013 and it is still an active project and the report is yet to be finalized. The main components of the TNC project are: national circumstances, inventories of greenhouse gases for 2006 - 2010, programs containing measures to mitigate GHG emission, studies on vulnerability and impacts and formulate programs containing measures to facilitate adequate adaptation to climate change, programs and plans that are considered relevant towards achieving the objectives of the UNFCCC, and constraints and gaps, and related financial, technical and capacity needs [36].

In conclusion to the discussions of this chapter, it is essential for the nation to do emission inventory from coal utilization in the upcoming years. A significant number of brick kilns are operating throughout the country and the number will increase with time because of the population growth, urbanization and expansion in the real estate business. Moreover, several coal fired power plants have been proposed and will come online in the coming years. As a result, emission from coal utilization will definitely increase in a significant manner in near future. Several coal utilization technologies were discussed in the previous sections. Emission inventory should be done for those available technologies and compare them. Best and most feasible technology should be adopted to lower the emission from coal utilization.

Chapter 3
MATERIALS AND METHODS

3. MATERIALS AND METHODS

This chapter will discuss about the sources of coal samples, preparation of samples, methods used for coal characterization and component analysis methods have been applied for this work.

3.1 Coal Samples

Four different coal samples from four different sources have been used for this work. Barapukuria coal samples were collected from Barapukuria Coal Power Plant, Dinajpur, Bangladesh which originated from Barapukuria Coal Mining Company Limited, Dinajpur, Bangladesh and collected after power generation purpose. Other three coal samples were originated from three different countries; India, Indonesia and South Africa. These were collected from Department of Chemical Engineering, BUET. The department got these types of samples every now and then from various commercial companies for testing purposes. We have collected the samples and made a composite mixture for our study. The coal samples used in this study are mainly bituminous coal.

3.2 Sample Preparation

A standard method for sampling was used to ensure an accurate characterization of the coal from which the samples were taken. Appropriate sampling and sample preparation are essential for precise analysis. Statistically, about 80% of the total variances involved at the different stages of sample collection, preparation and analysis come from errors during its collection [37]. ASTM D 346 [38] method of sampling was followed for collection and preparation for all the coal samples for our study. The samples were crushed, preferably by means of an iron mortar. All types of rubbing actions were avoided, as otherwise the ash yield can be materially increased by the addition of iron from the sampling apparatus. The crushing was done in a place where prevention of loss of samples can be attained and accidental mixture of foreign matters can be avoided. Crushed samples were sieved to particle size 250 μm by passing through No. 60 ASTM sieve. This procedure of crushing, mixing and screening of samples to appropriate size is followed before all experiments and physical and chemical analysis.

3.3 Coal Characterization

To precisely predict the behavior of coal during its conversion processes such as combustion, gasification, or liquefaction, several analytical techniques are needed, which is known as coal characterization [39]. Characterization of coal can be divided into three main categories, proximate analysis, ultimate analysis and miscellaneous analysis [40]. These analysis techniques will be discussed briefly in the later sections.

3.3.1 Proximate analysis

Proximate analysis of coal is required to understand the quality of coal. It is defined by a group of standard test methods and is an assay of moisture, volatile matter, ash content and fixed carbon of a coal sample [41]. By definition, the proximate analysis of coal separates the products into four groups: (1) moisture; (2) volatile matter, consisting of gases and vapors driven off during pyrolysis; (3) fixed carbon, the nonvolatile fraction of coal; and (4) ash, the inorganic residue remaining after combustion [42]. A standard test method ASTM D 3172 [43] was used for proximate analysis of coal, which covers the determination of each of three of the properties and calculation of the fourth (fixed carbon) value. This ASTM test method is a combination of three individual test methods, ASTM D 3173 [44] for moisture, ASTM D 3174 [45] for ash content and ASTM D 3175 [46] for volatile matter. All of these three properties are determined under suitable condition and at prescribed temperatures. These test methods are based on gravimetric analysis techniques.

3.3.1.1 Moisture

Approximately 1 g of coal sample was taken in a crucible and the crucible was placed into a preheated oven. Then the sample was heated for about 1 h through the passes of dry air at 104 to 110°C and then it was cooled to room temperature in a desiccator. Percentage of moisture content of the coal sample was calculated from the following formula;

$$\text{Moisture in analysis sample, } \% = \frac{A\text{-}B}{A} \times 100 \tag{3.1}$$

Where: A = grams of sample used and

B = grams of sample after heating.

3.3.1.2 Ash content

Inorganic residue in coal sample as ash was determined by taking approximately 1 g of thoroughly mixed air dried coal sample to a weighed capsule and placing the capsule containing sample in a muffle furnace and heating the sample to about 750°C for 4 h. Heating was done such a way that in first hour temperature reaches to about 450 to 500°C and in second hour temperature reaches to 700 to 750°C. This final temperature was maintained for additional 2 h. Then the capsule was removed from the furnace and the sample was cooled to room temperature in a desiccator. Ash percent in the analysis sample was calculated as follows;

$$\text{Ash in analysis sample, } \% = \frac{A\text{-}B}{C} \times 100 \tag{3.2}$$

Where: A = weight of capsule, cover, and ash residue;

      B = weight of empty capsule and cover; and

      C = weight of analysis sample used.

3.3.1.3 Volatile matter

The amount of gaseous products, exclusive of moisture vapor, in the analysis sample was determined by taking about 1 g of coal sample into a platinum crucible and heating the sample to about 950°C for 7 minutes in a muffle furnace. Calculation of percent volatile matter was done by following manner;

$$\text{Weight loss, \%} = \frac{A-B}{A} \times 100 \tag{3.3}$$

Where: A = weight of sample used, and

      B = weight of sample after heating.

$$\text{Volatile matter in analysis sample, \%} = C - D \tag{3.4}$$

Where: C = weight loss, %, and

      D = moisture, %.

3.3.1.4 Fixed carbon

Fixed carbon is the material remaining after the determination of moisture, volatile matter, and ash. It is a measure of the solid combustible material that remains after the volatile matter in coal has been removed. The total carbon content in a coal sample is the sum of the carbon present in volatile organic matter and fixed carbon in coal. Therefore, carbon present in volatile matter does not contribute to the amount of fixed carbon.

$$\text{Fixed carbon, \%} = 100\% - (\text{moisture, \%, + ash, \%, + volatile matter, \%.}) \tag{3.5}$$

3.3.2 Ultimate analysis

Ultimate analysis of coal also known as elemental analysis determines various elemental chemical constituents in coal such as carbon, hydrogen, oxygen, sulfur and nitrogen. It is useful in determining the quantity of air required for combustion and volume and composition of combustion gases and for calculation of flame temperature and flue gas duct design. A vario MACRO cube CHNS/O analyzer was used for this study. It is a unique method for combustion gas separation which involves the complete and instantaneous oxidation of the sample by "flash

combustion". The built in chromatographic column converts the compound and elutes it in the form of NO_2, CO_2, SO_2, and H_2O which are then detected with the help of Thermal Conductivity Detector (TCD).

3.3.3 Calorific value

ASTM D 5865 [47] standard test method was used to measure the gross calorific value of the test samples. This value is required to estimate the usefulness of beneficiation processes and to classify coal [42]. An adiabatic bomb calorimeter comprising of a calorimeter vessel, jacket, sample holder, ignition fuse, ignition circuit, water bath, stirrer and thermometer was used for this test method. About 1 g of test coal sample was taken into the sample holder and the fuse wire was attached to the bomb electrodes. The sample holder with the sample was placed into the electrode support of the bomb and the fuse wire was inserted into the sample so that it just touch the surface of the sample. Then the bomb was assembled in the normal manner and was charged with oxygen to a pressure between 20 to 30 atm. The bomb was then placed into the water bath and the sample was ignited by attaching the ignition wires from the firing circuits. Temperature rise in the thermometer due to the combustion at adiabatic condition was noted down and the gross calorific value was calculated from this temperature rise value using empirical formulas.

3.3.4 Ash analysis

Before main ash analysis, first the ash sample was prepared by using a standard test sample method described in section 3.3.1.2. The ash sample was then pelletized into 1 cm diameter tablets by mixing it with appropriate binder using appropriate binder. For ash analysis ASTM D 4326 [48] standard test method was used to determine the metal composition of sample. Shimadzu LAB CENTER sequential X-ray Fluorescence (XRF) Spectrometer – 1800 series was used as analytical device for this test method. A high energy incident X-ray was collided with the atom of sample in a XRF and energy was produced as electron moves between levels and from this, the chemical composition of the samples were analyzed.

3.3.5 Mercury

As the probable emission of mercury that may be found in coal is an environmental concern, it is required to determine the total mercury content in coal. Standard test method of ASTM D 6722 [49] was used to determine the total mercury in the coal sample. The test was involved combusting approximately 1 g of test sample in an oxygen bomb calorimeter with dilute nitric acid to absorb the mercury vapors. Then the bomb was rinsed into reduction vessel with dilute

nitric acid and then the total mercury was determined by using cold vapor atomic absorption technique. For our study Shimadzu AA-6800 series atomic absorption spectrophotometer was used. Precautions was taken during the test so that mercury loss can be avoided.

3.3.6 Chlorine

Total chlorine content of coals may be useful in the evaluation of slagging problems, corrosion in Engineering processes. ASTM D 4208 [50] standard test method was used to determine the total chlorine content of the test sample. The chlorine was quantitatively retained into a solvent by combusting the coal into an adiabatic bomb calorimeter. Approximately 1 g of coal sample was taken into the bomb calorimeter. 5 mL 2% Na_2CO_3 solution was transferred into the bomb and fuse wires were attached to the bomb electrodes. The bomb was charged with oxygen to a pressure between 20 to 30 atm, after assembling the bomb in normal manner. Then it was placed into the cooling water bath. Then the wire was ignited from the firing circuit so that the sample could also be ignited. After cooling the bomb at room temperature, pressure was released uniformly. By rinsing the bomb, electrodes and crucible with distilled water, the volume was kept to about 90 mL. Then Ion Selective Electrode Chromatography method was used to determine the total chlorine content of the coal sample.

3.4 Simulation: Combustion Products Analysis

A simulation software "FactSage" was used to determine the probable phase; gaseous, liquid or solid; of metal oxides after combustion. This simulation software was selected as it can handle solids and it is one of the most established and matured simulating software for thermodynamic equilibrium condition. There are several databases of "FactSage" for various materials. Among them "FactPS" was used for gaseous metal oxides and "FTxid" was used for solid and liquid products. Data obtained from XRF report were used to calculate the weight percentage of metals in coal ash sample. The combustion temperature, pressure and weight percentage of metals present in coal were given as input to the simulating software and output was collected as different metal oxides at different phases. The concentration of metal oxides at different phases varied with the percentage of excess air during combustion.

FactSage is the fusion of two well-known software packages in the field of computational thermochemistry: **FACT-Win** (formerly **F*A*C*T** - *Facility for the Analysis of Chemical Thermodynamics*) and **ChemSage** (formerly **SOLGASMIX**). It is a powerful self-teaching aid. With regular program usage one can rapidly acquire a practical understanding of the principles of thermochemistry especially as these relate to complex phase equilibria. **FactSage** main

menu modules are grouped into four categories: Info, Databases, Calculate and Manipulate. Calculate modules are the central programs of **FactSage**. They permit the calculation of phase diagrams and thermochemical equilibria in various forms with direct access to the databases.

Equilib module of FactSage software was used for this study. **Equilib** module is the Gibbs energy minimization workhorse of **FactSage**. It calculates the concentrations of chemical species when specified elements or compounds react or partially react to reach a state of chemical equilibrium. In most cases the user makes three entries as shown in the **Equilib** *Reactants Window* and *Menu Window*:

> 1st entry: *Define the reactants, then click on 'Next >>'.*
>
> 2nd entry: *Select the possible compound and solution products.*
>
> 3rd entry: *Set the final conditions - T and P, or other constraints, then click on 'Calculate >>'.*

In the *Reactants Window* composition of different species like C, H, N, S, O, Ash Composition data obtained from XRF are defined. In the *Menu Window* the possible products are identified (gas phase, pure solids and liquid phases) together with a range of composition, the temperature and total pressure. One then clicks the "Calculate >>" button and the computation commences. When the calculation is finished one is automatically presented with the Results Window where **Equilib** provides the equilibrium products of the reaction and where the results may be displayed in **F*A*C*T** and **ChemSage** output formats.

This procedure was followed by varying the excess air percentage from 0% to 100% excess air in 5% interval. Both adiabatic and real composition are calculated. These data are then used to predict the emission inventory.

Chapter 4
RESULTS AND DISCUSSIONS

4. RESULTS AND DISCUSSIONS

4.1 Coal Characterization Results

Coal quality is one of the most important factors for its feasibility as raw material for power generation and other applications like brick production. The combustion efficiency and power plant performance is widely dependent on the quality of coal used and large scale power generation from coal in an environmentally sound and economically feasible way is also dependent on the quality of coal [51].

In this section, the experimental results for the characterization of four coal samples have been discussed. The experimental procedures for these analyses are briefly discussed in Chapter 3. The results from proximate analysis, ultimate analysis and mineral matters as well as heating values will be discussed in this section.

4.1.1 Proximate analysis

The proximate analysis of coal is shown below in the Table 4.1. Moisture content and proximate analysis on both dry basis and dry, ash free basis are shown here.

Table 4.1: Proximate analysis of sample coals

Source of Coal Sample	Moisture (wt.%)	Dry Basis			Dry, Ash Free Basis	
		Ash (wt.%)	Volatile Matter (wt.%)	Fixed Carbon (wt.%)	Volatile Matter (wt.%)	Fixed Carbon (wt.%)
Barapukuria	3.61	8.95	35.67	54.77	39.44	60.56
India	6.98	3.37	46.15	43.50	51.48	48.52
Indonesia	10.43	6.40	48.46	45.14	51.78	48.22
South Africa	2.32	12.31	25.32	62.37	28.87	71.13

There are many effects of fuel moisture on unit operation, performance and emissions. Its complexity can be appreciated by following coal through a power plant and analyzing the effect of coal quality on equipment performance and maintenance. As fuel moisture content decreases, its heating value increases and, assuming constant electric power output of a power plant, less coal needs to be fired. This reduces the burden on the coal handling system, conveyers and crushers. Dry coal is also easier to convey and reduces maintenance costs and increases availability of the coal handling system [52]. The moisture content for the four samples ranges from 2.32% to 10.43%. The Indonesian coal sample had the highest moisture content of 10.43%, followed by Indian, Barapukuria and South African coal sample. Moisture

content not only depends on the source of mining and subsequent treatment of coal, but also the rank of it. These moisture content values are between the ranges of bituminous coal (2.2 to 15.9%) [53].

Ash content affects coal and ash handling systems, pulverizers (abrasion), furnace, superheater, reheater, economiser, soot-blowing intervals (slagging and fouling propensity, erosion, and corrosion), pollution control equipment, and unburnt carbon in ash. It is also an obstacle for the economic feasibility of coal based power generation [54]. Indian coal sample with the lowest ash content (3.37%) would cost less in terms of investment in ash handling equipment and pulverizer abrasion followed by Indonesian (6.40%), Barapukuria (8.95%), and South African (12.31%) coal samples.

Volatile matter of coal is an index of the gaseous fraction released during the devolatilization process. Higher volatile content helps in easier ignition of coal. It also affects storage behavior (oxidation, danger of spontaneous combustion, and loss of heating value), pulverizer outlet temperature and required fineness for pulverization, burner settings, furnace, combustion behavior, and efficiency (ignition, flame shape and stability, and burnout and carbon content of fly ash). These gaseous fraction released from the volatile fraction usually contains methane and other hydrocarbons, hydrogen and carbon monoxide; incombustible gases like carbon dioxide and nitrogen are also released. South African coal sample with the lowest volatile matter (25.32%), followed by Barapukuria (35.67%), Indian (46.15%), and Indonesian (48.46%) samples. None of the samples contain volatile matter high enough to cause spontaneous combustion during transport, handling and storage.

Fixed carbon is a measure of the amount of non-volatile carbon remaining in a coal sample. It is a calculated value determined from other parameters measured in a proximate analysis, rather than through direct measurement. Fixed carbon and ash together represents the yield of coke from a particular coal. Therefore, fixed carbon is often used as an indication for the usefulness of a coal for coking process; higher the fixed carbon better is the coal for coke production. Fixed carbon for all four samples were below 69% on dry, mineral-matter free basis. As per the ASTM classification [55] all these samples are high volatile bituminous coals. The coals are therefore not suitable for coking and suitable for steam or power generation and other thermal applications.

The ratio of fixed carbon to volatile matter (fuel ratio) indicates the ease of ignition and burnout, but the heat content of the volatile matter is a more reliable guide to ignition. The

volatile matter content influences NO_x formation. Generally for the same burner and constant nitrogen content, the higher the volatile matter, the lower the NO_x. It can be seen from Figure 4-1 that South African coal sample do possesses the highest fuel ratio.
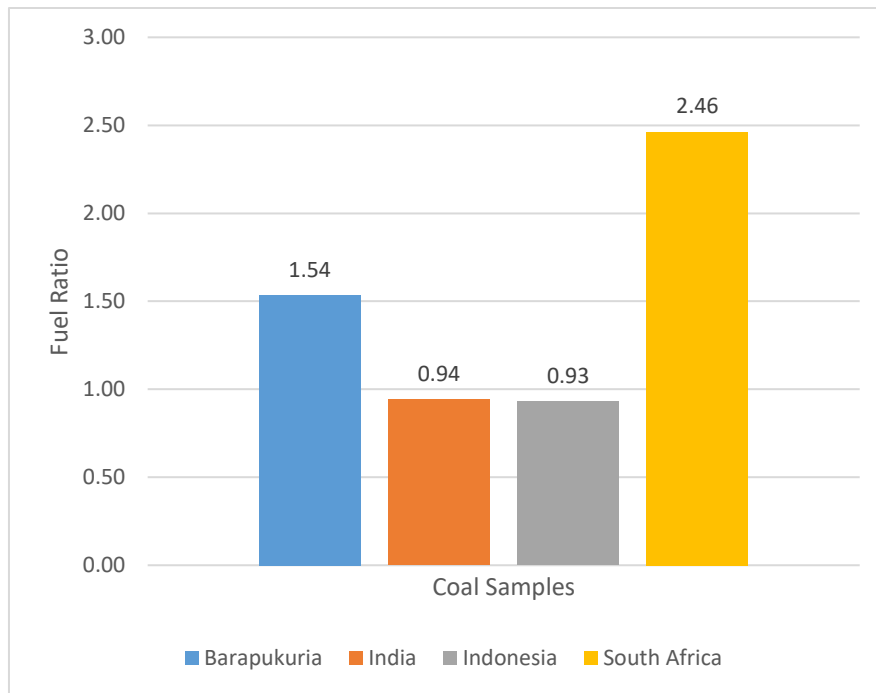
Figure 4-1: Fuel ratio of different coal samples.

According to the results, coal samples from Barapukuria and South Africa can be considered as a good quality coal for combustion than Indian and Indonesian coal, because of having higher percentage of hydrocarbons as fixed carbon and lower percentage of volatile matter and moisture content.

4.1.2 Ultimate analysis

The results obtained from ultimate analysis provide an accurate overview of the main chemical elements present in coal i.e. carbon, hydrogen, nitrogen, sulfur and oxygen. The nitrogen observed is assumed to be present in the coal sample's organic matrix. With regards to the determination of the hydrogen content the hydrogen within the organic minerals of coal as well as the hydrogen associated in the water with coal, is included. Sulfur is present in various forms and the total value of sulfur is used when determining the ultimate analysis. The different forms of sulfur in coal include organic sulfur, inorganic sulfates, and inorganic sulfides in the form of pyrites and marcasite. The oxygen percentage is calculated by difference [42]. The elemental composition of carbon, hydrogen, nitrogen, sulfur, and oxygen in the coal samples is shown in Table 4.2.

Table 4.2: Ultimate analysis data of coal samples

Source of Coal Samples	wt.% of chemical elements (Dry, Ash free basis)				
	Carbon	Hydrogen	Nitrogen	Sulfur	Oxygen
Barapukuria	78.14	6.01	3.03	0.43	12.39
India	75.81	4.64	8.20	1.11	10.24
Indonesia	74.61	5.13	8.72	0.85	10.69
South Africa	77.58	3.85	8.82	0.40	9.35

Carbon and hydrogen are the major combustible constituents of coal, and both of them are high in the coal samples. The higher the carbon content, the higher the calorific value and the better the quality of the coal for power generation. Carbon hydrogen ratio varies from 13 to 20, which is very high value. South African coal has the highest nitrogen content value, followed by Indonesian, Indian and Barapukuria coal samples. The sulfur content is very low in South African and Barapukuria coal, but little bit higher in other two samples. But the range fell into the lower range for bituminous coal (0.7 to 4.0%), which is considered as good quality coal samples, as higher amount of sulfur in coal is responsible for releasing higher amount of SO_x, H_2S and other organic gases which can be a threat to environmental health and also reduces the efficiency of power plant.

4.1.3 Calorific value (dry basis)

Calorific value is the most important parameter that determines the economics of the power plant operation. It indicates the amount of heat that is released when the coal is burned. The Calorific Value varies on the geographical age, formation, ranking and location of the coal mines. The heat of combustion of any organic compound is associated with the bond energies between the atoms forming the chemical structure of the compound and therefore with the character of the bonds. Results obtained from the calorific value determination carried out on the four coal samples are shown in Figure 4-2. The calorific value gives the heating value or the heat of combustion of a substance. It has been suggested that the calorific value of power plant coals is in the range of 9.5 MJ/kg to 27 MJ/kg [56]. Thus, all the coal samples would be suitable for power generation. The Barapukuria coal sample, with the highest heating value of 30.7 MJ/kg (dry basis), would be the best for heating and power generation, followed by South African, Indonesian and Indian coal.
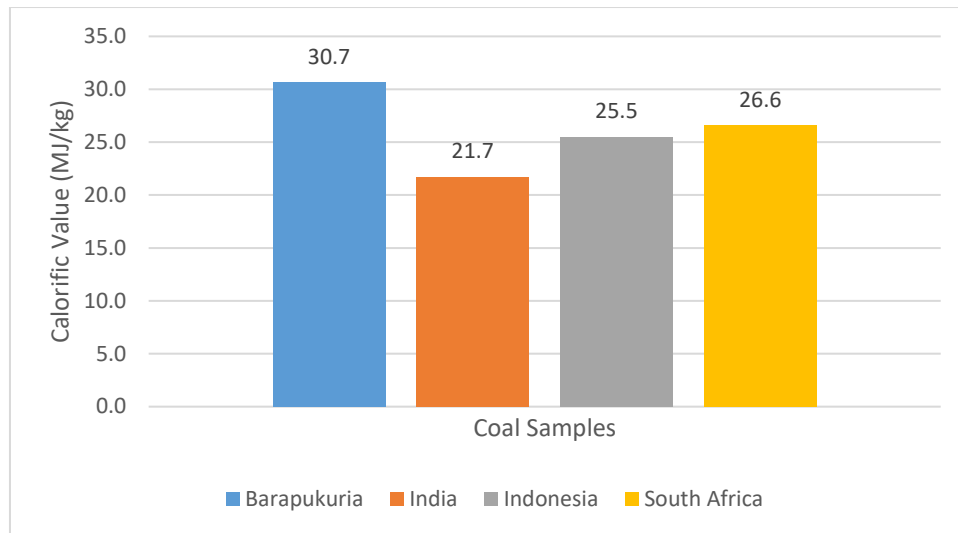
Figure 4-2: Calorific value of different coal samples (dry basis).

4.1.4 Ash analysis

Results obtained from the ash composition test of the four coals samples using the X-ray fluorescence (XRF) are shown in Table 4.3.

Table 4.3: Results of ash composition tests of the coal samples

Component	Coal Sample			
	Barapukuria	**India**	**Indonesia**	**South Africa**
SiO_2 (%)	53.61	15.07	31.69	52.12
Al_2O_3 (%)	24.98	7.22	12.13	25.40
TiO_2 (%)	7.97	0.65	1.03	3.09
Fe_2O_3 (%)	6.45	16.36	9.34	4.18
SO_3 (%)	2.06	31.90	24.54	5.24
CaO (%)	1.75	11.28	11.02	4.93
K_2O (%)	1.42	0.84	1.52	0.98
P_2O_5 (%)	1.06	0.14	0.82	1.77
MgO (%)	0.48	5.82	4.94	0.86
Na_2O (%)	0.22	10.72	2.97	1.43

The increased contents of Si are more characteristic of higher rank coals, while the decreased values of this element are more typical of lignite. The same correlation holds for the aluminum

content in coal. Barapukuria and South African coal has higher Si and Al contents than other two coal samples. The increased contents of Fe are characteristic of lignite and some high-rank coals, while the decreased values of this element are typical of sub-bituminous coals. Highest Fe content is for Indian coal, followed by Indonesian, Barapukuria and South African coal. The increased contents of Ca and Mg are characteristic of lignite, while the decreased values of this element are typical of bituminous coals. Indian and Indonesian coal have higher Ca and Mg content value. The increased contents of K are more characteristic of higher-rank coals, while the decreased values of this element are more typical of lignite. The highest K content is exhibited by Indonesian coal sample. The increased contents of Na are more characteristic of sub-bituminous coals, while the decreased values of this element are more typical of lignite and Indian coal has shown highest Na content. Generally Na and K can be found more in lignite and sub-bituminous coal, because they have higher percentage of volatile matter and as the melting point of Na and K are lower, that is why they are more likely to be found in lignite and sub-bituminous coal. The increased concentrations of SO_3 are characteristic of lignite, while the decreased values of this oxide are typical of bituminous coals. The increased contents of Ti are characteristic of bituminous coals, while the decreased values of this element are typical of lignite and Barapukuria coal has the highest Ti content. It was also noted that the high values of $SiO_2 + Al_2O_3$ and ash contents are normally more characteristic of coals resulting from mountain peat-forming type, while the high concentration of $CaO + MgO + Fe_2O_3$ and low ash yield are more typical of coals resulting from lowland peat-forming type. Barapukuria and South African coal samples fell into mountain peat forming type, while Indian and Indonesian coal samples fell into low-land peat forming type [57].

Some oxide ratios have been used in the literature as geochemical indicators of coal formation. For instance, coals with high SiO_2/Al_2O_3 ratio are presumed to have formed under unstable conditions of deposition, when subsidence in the basin was relatively rapid and irregular, and there was a high degree of tectonic movement [58]. The high values of $CaO + MgO/K_2O + Na_2O$ and CaO/MgO ratios are indicative for coal deposits formed in continental sediments under freshwater conditions [59]. Detrital/authigenic index (DAI) is a parameter to determine the type of coal. The extremely high detrital/authigenic index in some coal samples may indicate their probable allochthonous origin because such seams contain greater detrital mineral matter input than autochthonous coal seams [60].

Coals may indicate their probable allochthonous origin because such seams contain greater detrital mineral matter input than autochthonous coal seams. Respectively, the low values of DAI for other coals indicate that most of these coal seams are probably autochthonous. Barapukuria and South African coal has very high DAI value, whereas Indian and Indonesian coal has lower DAI value.

Table 4.4: Some oxide ratios of the coal samples

Source	SiO_2/Al_2O_3	$CaO+MgO/K_2O+Na_2O$	CaO/MgO	$K_2O//Na_2O$	DAI^a
Barapukuria	2.06	1.36	3.65	6.45	8.31
India	2.09	1.48	1.94	0.08	0.53
Indonesia	2.61	3.55	2.23	0.51	0.99
South Africa	2.05	2.40	5.73	0.69	5.46
Lignites	2.6	8.0	5.3	3.1	2.1
Sub-Bituminous Coal	2.4	3.3	3.3	1.5	5.9
Bituminous Coals and Semi-anthracites	2.4	2.7	3.2	2.1	8.3

$^aDAI= Detrital/authigenic\ index=(SiO_2+Al_2O_3+K_2O+TiO_2+Na_2O)/(Fe_2O_3+CaO+SO_3+MgO)$

The inorganic portion of the coal can yield fly ash, bottom ash and boiler slag during combustion. Bottom ash is the larger particles that accumulate at the bottom of the furnace and fly ash in the fine fraction entrained in the flue gas and captured by the particulate emission control systems. Slag is produced when the combustion temperature is more than the melting temperature of the ash.

It is not possible to predict quantitatively the distribution of inorganic matters between fly and bottom ash from the ash composition. The distribution depends on many factors, some of which are coal dependent while the others are process dependent. However, based on their volatility and portioning in the power plants, inorganic elements have been categorized into three groups [61] [62]. Class I equally distribute between the bottom and fly ash (Al, Si, Fe etc.). Class II (As, Cd, K, Na etc.) elements are enriched in the fly ash and depleted in the bottom ash. Class III elements are not retained by the fly ash. They are volatilized and emitted fully in the vapor phase. Mercury and chlorine are two such elements.

Considering the distribution pattern of the elements and the composition of the ash it can be concluded that combusting Barapukuria and South African coals are likely to produce Class F fly ash while the other two coals are likely to produce Class C fly ash [63]. It must be noted that the class of the fly ash is indicative of their end use.

4.1.5 Chlorine

Chlorine content present in coal sample is responsible for not only fouling problems but also it can cause corrosion problem. It can lead to the formation of hydrogen chloride and can cause corrosion problems in the combustion equipment [64]. Chlorine can cause these types of fouling and corrosion problem if the total weight percent of chlorine in coal is more than 0.3 wt. % [42]. From Table 4.5, it can be said that Barapukuria and South African coal cause high fouling and corrosion problem to the furnace and downstream equipment during the combustion process.

Table 4.5: Concentration of chlorine in coal samples

Coal Samples	Chlorine (wt. %)
Barapukuria	0.35
India	0.16
Indonesia	0.12
South Africa	0.31

4.1.6 Mercury

The presence of mercury in coal is highly toxic to most biological systems at concentration above critical levels. The typical range of mercury in most of the world's coal is 0.02 to 1.0 mg/kg [65]. The obtained result of mercury for our four coal samples are listed in Table 4.6. Concentration of mercury of our coal samples lies between 0.33 to 0.65 mg/kg.

Release of mercury during combustion can occur in three forms: elemental, oxidized, and condensed on ash particles. However, emission in the third form is insignificant compared to the first two [66].

Oxidized mercury (Hg^{2+}), being soluble in aqueous solution, can be removed from the flue gas in the commonly used flue gas treatment systems. On the other hand, the elemental form passes through the pollution abatement system and ends up in the environment. Mercury, released in the environment, goes through a series of chemical reaction and transforms to a highly toxic

form, methylmercury (CH_3Hg). Human, fish-eating mammals and birds are exposed to this toxic chemical as it enters the aquatic food chain: from bacteria to plankton to fish.

Table 4.6: Concentration of mercury in coal samples

Coal Samples	Mercury (mg/kg)
Barapukuria	0.33
India	0.65
Indonesia	0.42
South Africa	0.35

Presence of chloride in coal can be beneficial in terms of mercury emission. In presence of chloride in the coal, the elemental mercury is oxidized to $HgCl_2$. Mercury chloride itself can be removed easily from the flue gas [66].

Barapukuria and South African coals, having lower mercury content and high chloride content are, are likely to have only a small amount of mercury released to the environment as most of the elemental mercury will be converted to oxidized form and effectively removed from the flue gas stream.

4.2   Thermodynamic Simulation of Combustion of Coal Samples

FactSage Equilib module [67] was used for thermodynamic simulation of coal combustion. The ultimate analysis and ash compositions were used to predict the phases and their compositions after combustion by varying the air-fuel ratio. The output data from the module consists of the combustion temperature and composition of three particular product phases: gas, liquid and solid.

The thermodynamic simulation was done in two different conditions, one is adiabatic condition and another one is real condition. In adiabatic condition it was assumed that no heat is transferred in or out of the process. The real condition is where heat can be transferred between process and surroundings. Real temperature was calculated using a value called pyrometric efficiency, which is the ratio of real flame temperature and adiabatic flame temperature [68]. When all of the heat generated by the combustion of a fuel is absorbed by the generated flue gas, then the flue gas reaches its theoretical combustion temperature and this temperature is called adiabatic flame temperature. The pyrometric efficiency, depending on the conditions of combustion, can vary between 0.65 and 0.85 [68]. To carry out the thermodynamic simulation in both condition pyrometric efficiency value was assumed at 0.75.

Data collected from the simulation were used to determine the concentration profiles of the combustion products for different percentages of excess air. These profiles vary depending on the adiabatic or real condition for reaction. The results obtained can help to predict in the yield of three combustion product phases.

4.2.1 Temperature profile

Changes in temperature with change in percentage of excess air were obtained from the simulation result in adiabatic condition for all four coal samples. It is evident from Figure 4-3, for all the coal samples temperature decreases gradually with increase in the percentage of excess air both for adiabatic and real condition and the trend line of decreasing is also more or less same. But temperature profile is highest for South African coal, followed by Barapukuria, Indonesian and Indian coal.
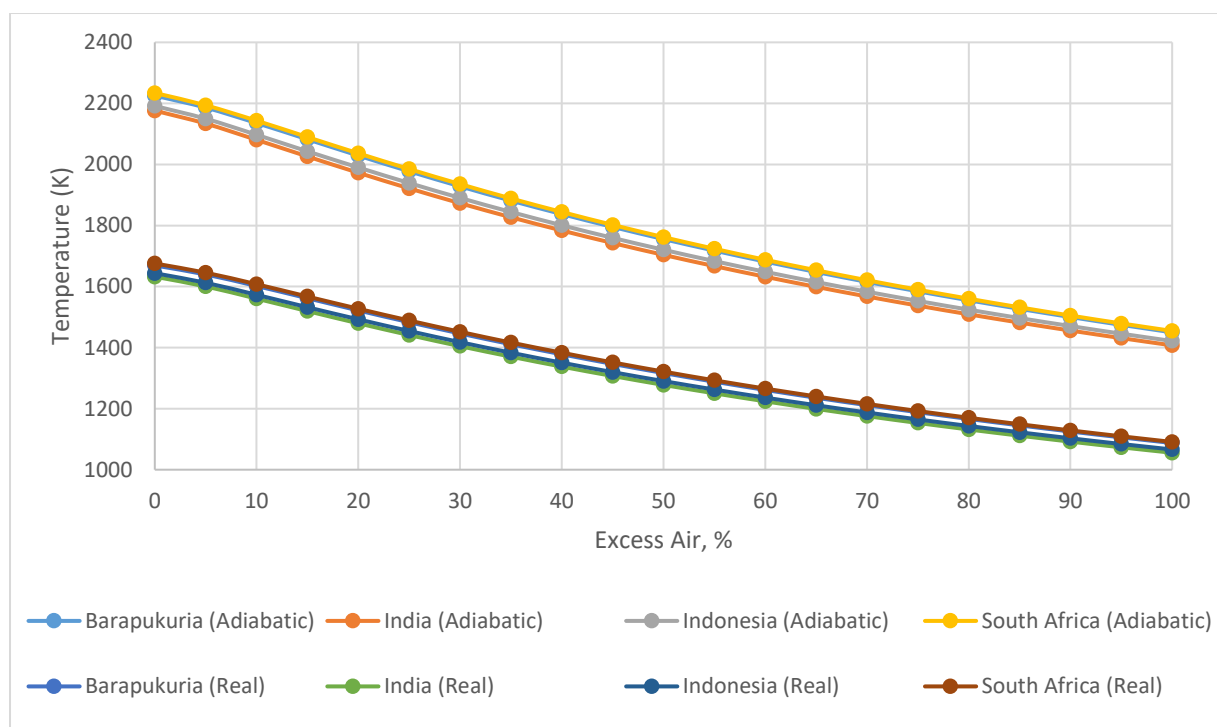
Figure 4-3: Temperature profile for coal samples; both adiabatic and real condition

4.2.2 Gaseous contents

From simulation results obtained, four major gaseous oxides – NO_2, SO_2, CO_2, and SO_3 were plotted against percent excess oxygen at two conditions, adiabatic and real condition. An overall discussion on their profiles can be found by the end of this section.

4.2.2.1 *Barapukuria coal sample*

Carbon Dioxide:

Emission of CO_2 from the combustion of Barapukuria coal sample at different percentage of excess air is shown in Figure 4-4 for both adiabatic and real condition.

Figure 4-4: Relationship between Carbon dioxide emission with percentage of excess air for Barapukuria Coal.

Nitrogen Dioxide:

Emission of NO_2 from the combustion of Barapukuria coal sample at different percentage of excess air is shown in Figure 4-5 for both adiabatic and real condition.

Sulfur Dioxide:

Emission of SO_2 from the combustion of Barapukuria coal sample at different percentage of excess air is shown in Figure 4-6 for both adiabatic and real condition.

Sulfur Trioxide:

Emission of SO_3 from the combustion of Barapukuria coal sample at different percentage of excess air is shown in Figure 4-7 for both adiabatic and real condition.

Figure 4-5: Relationship between Nitrogen dioxide emission with percentage of excess air for Barapukuria Coal.

Figure 4-6: Relationship between Sulfur dioxide emission with percentage of excess air for Barapukuria Coal.

Figure 4-7: Relationship between Sulfur trioxide emission with percentage of excess air for Barapukuria Coal.

Nitric oxide:

Emission of NO from the combustion of Barapukuria coal sample at different percentage of excess air is shown in Figure 4-8 for both adiabatic and real condition.

Figure 4-8: Relationship between Nitric oxide emission with percentage of excess air for Barapukuria Coal.

Nitrous oxide:

Emission of N_2O from the combustion of Barapukuria coal sample at different percentage of excess air is shown in Figure 4-9 for both adiabatic and real condition.

Figure 4-9: Relationship between Nitrous oxide emission with percentage of excess air for Barapukuria Coal.

Thermodynamic conditions during combustion reaction do not affect the concentration profile of CO_2 significantly. Figure 4-4 shows that with the increase in percentage of excess air, amount of CO_2 produced by coal combustion increases gradually for adiabatic condition, but for real condition amount is almost constant throughout the range. After 50% of excess air percentage, amount of CO_2 become almost same for both adiabatic and real condition.

From Figure 4-5, it can be seen that there is no specific trend line for change in amount of NO_2 with increase in percentage of excess air. In both adiabatic and real conditions, the line fluctuates between minimum and maximum value. Although it is sure that in real condition NO_2 emission is lower than in adiabatic condition.

Figure 4-6 shows different trend line for both adiabatic and real conditions for SO_2 emission with increase in the percentage of excess air. In case of real condition SO_2 emission decreases with an increase in percent excess air, but in case of adiabatic condition a slight increase in SO_2 emission till 55% of excess air and after 55% a slight decrease in SO_2 emission. Therefore, the higher the percentage of excess air supplied during combustion reaction, the lower will be SO_2 emission and thus will less contribute to air pollution for real condition. Initially, SO_2 emission is higher in real condition than adiabatic condition, but is lower when percentage of excess air is increased gradually.

Although in case of SO_2, emission of SO_2 reduces in real condition with an increase in percentage of excess air, in case of SO_3, the relation is opposite (Figure 4-7). In real condition, emission is much higher than the emission in adiabatic condition. Emission increases gradually in adiabatic condition with increase in percentage of excess air. For real condition no specific trend line was found. Emission is higher when the percentage of excess air is higher.

From Figure 4-8 and Figure 4-9, it can be seen that for emission of both NO and N_2O, it follows the almost same trend line. In case of real condition no specific trend line is followed by NO and N_2O emission. But in case of adiabatic condition, emission of NO increases till 20% of excess air and then starts to decrease and emission of N_2O increases till 25% of excess air and then decreases.

4.2.2.2 *Indian coal sample*

Carbon Dioxide:

Emission of CO_2 from the combustion of Indian coal sample at different percentage of excess air is shown in Figure 4-10 for both adiabatic and real condition.

Figure 4-10: Relationship between Carbon dioxide emission with percentage of excess air for Indian Coal.

Nitrogen Dioxide:

Emission of NO_2 from the combustion of Indian coal sample at different percentage of excess air is shown in Figure 4-11 for both adiabatic and real condition.
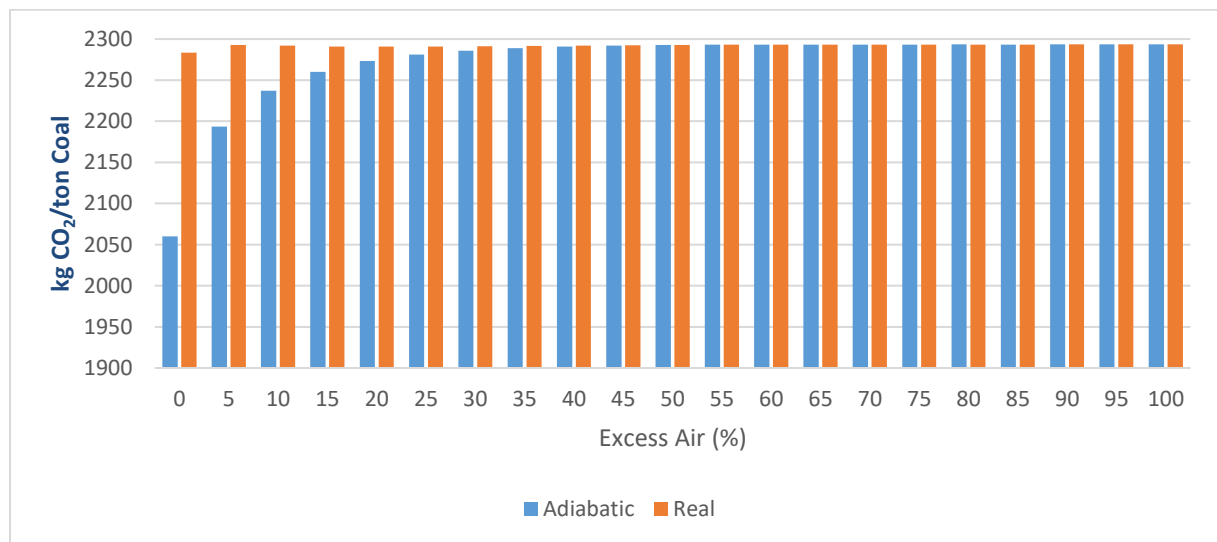
Figure 4-11: Relationship between Nitrogen dioxide emission with percentage of excess air for Indian Coal.

Sulfur Dioxide:

Emission of SO_2 from the combustion of Indian coal sample at different percentage of excess air is shown in Figure 4-12 for both adiabatic and real condition.
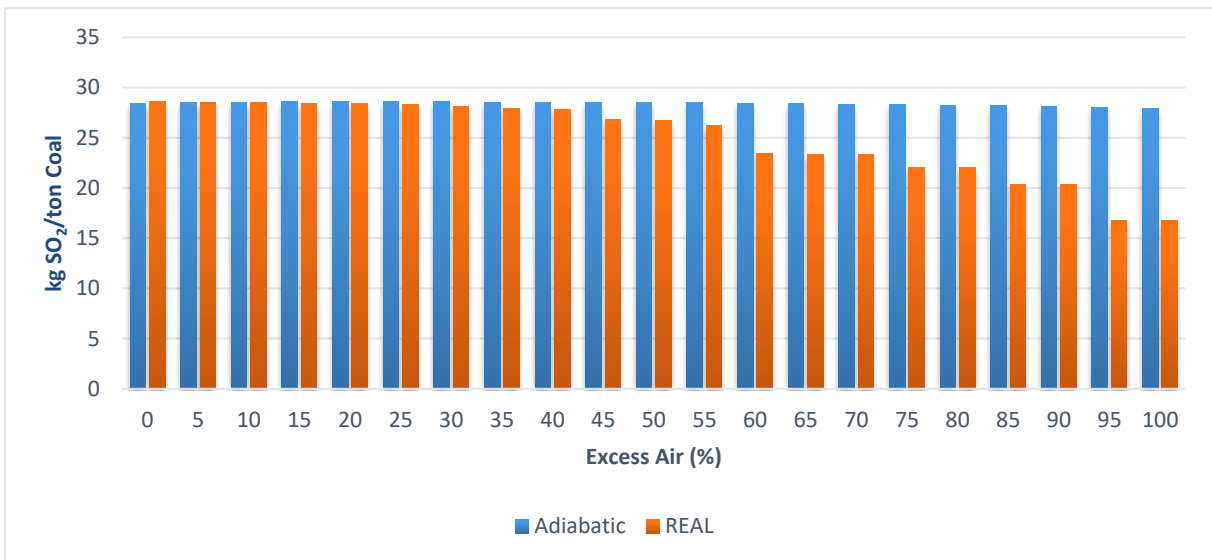
Figure 4-12: Relationship between Sulfur dioxide emission with percentage of excess air for Indian Coal.

Sulfur Trioxide:

Emission of SO_3 from the combustion of Indian coal sample at different percentage of excess air is shown in Figure 4-13 for both adiabatic and real condition.

Figure 4-13: Relationship between Sulfur trioxide emission with percentage of excess air for Indian Coal.

Nitric oxide:

Emission of NO from the combustion of Indian coal sample at different percentage of excess air is shown in Figure 4-14 for both adiabatic and real condition.

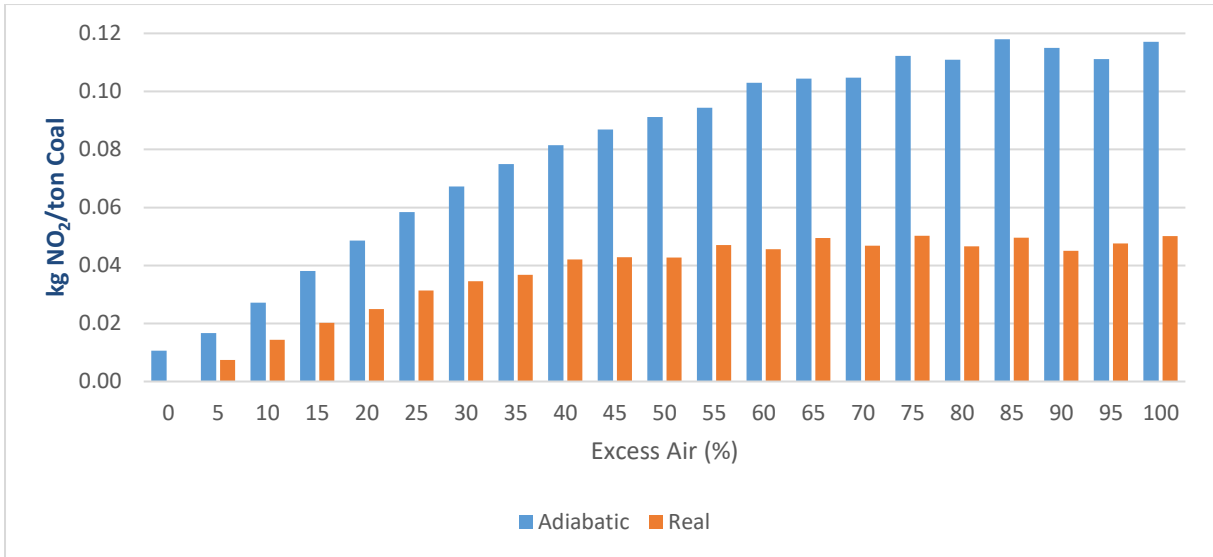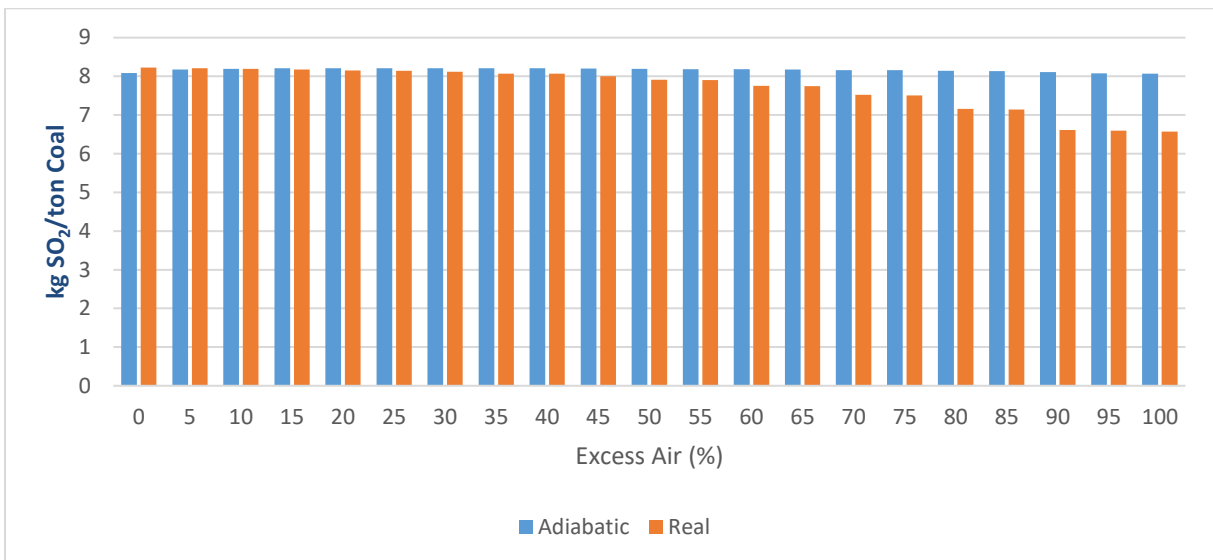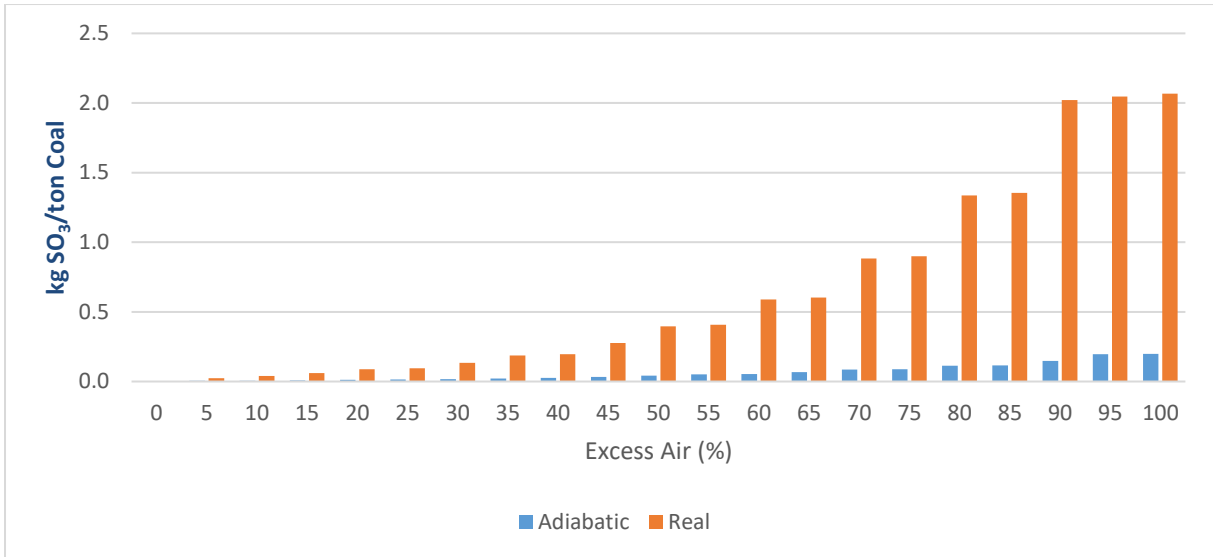Figure 4-14: Relationship between Nitric oxide emission with percentage of excess air for Indian Coal.

Nitrous oxide:

Emission of N_2O from the combustion of Indian coal sample at different percentage of excess air is shown in Figure 4-15 for both adiabatic and real condition.
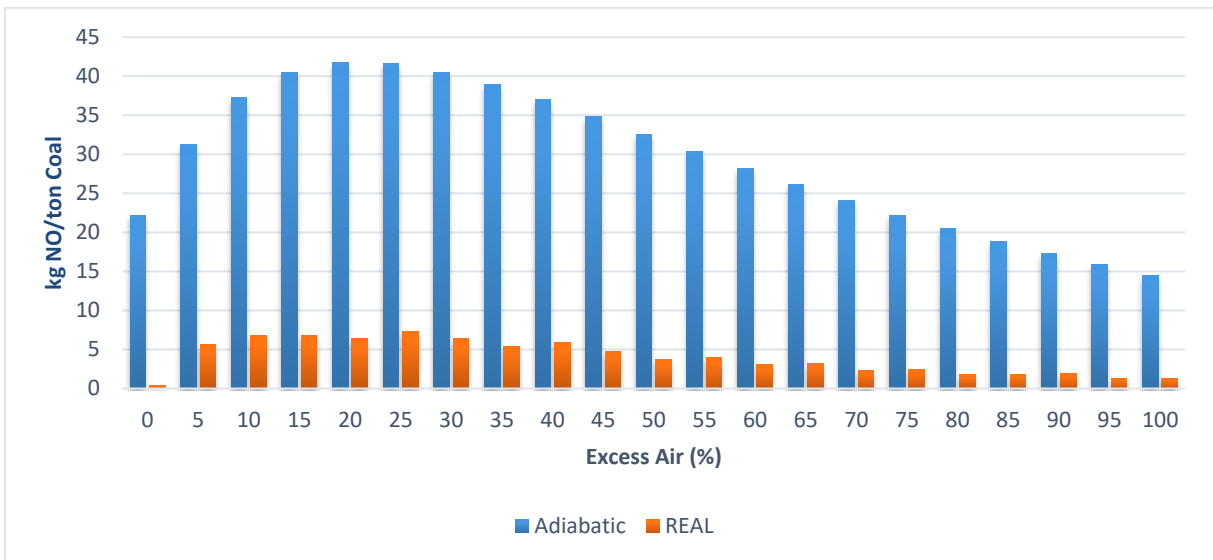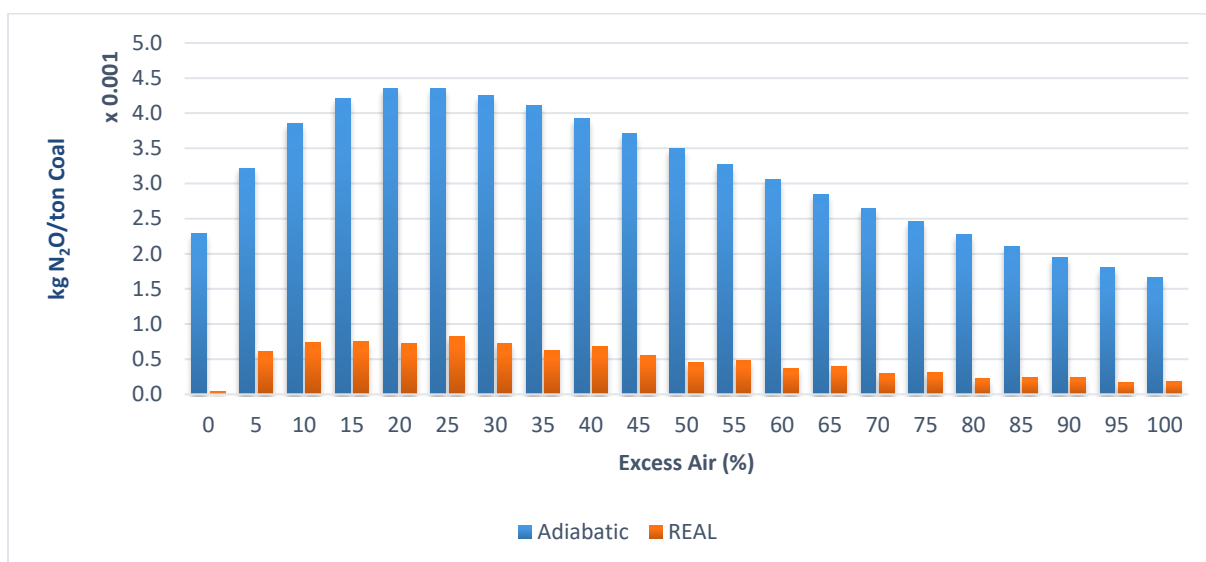
Figure 4-15: Relationship between Nitrous oxide emission with percentage of excess air for Indian Coal.

From Figure 4-10, it is evident that emission of CO_2 increases with increasing percentage of excess air in both adiabatic and real conditions. Rate of increase in emission is much higher in adiabatic condition compared to real condition. Initially emission in real condition is higher than the emission in adiabatic condition. But when the percentage of excess air is increased above 70%, emissions from both real and adiabatic condition become almost equal.

In case of NO_2 emission from Indian coal, it can be seen from Figure 4-11 that, NO_2 emission is always higher in adiabatic condition than in real condition. No specific trend line was followed by Indian coal for NO_2 emission in case of real condition, but in case of adiabatic condition, emission of NO_2 trends to increase with increasing percentage of excess air. In adiabatic condition, emission is highest when the percentage of excess air is highest. In real condition, emission becomes highest when the percentage of excess air is 70%.

Figure 4-12 shows that, emission of SO_2 from the combustion of Indian coal decreases with increasing percentage of excess air in real conditions and in adiabatic condition emission is almost similar throughout the range. For 0-5% of excess air emission from real condition is slightly higher than the emission in adiabatic condition. After 5%, the situation becomes opposite.

It can be seen from Figure 4-13 that, with increasing percentage of excess air emission of SO_3 also increased. Emission is always higher in real condition than in adiabatic condition. In case

of real condition the increasing rate follows a specific trend line, but in case of adiabatic condition no specific trend line was followed.

Figure 4-14 and Figure 4-15 shows that emission of NO and N_2O follows a specific trend line for adiabatic condition, initially increases to a certain percentage of excess air and then starts to decrease after that percentage of excess air. For both NO and N_2O that specific percentage point is 20% for Indian coal. In real condition no specific trend line was followed by both NO and N_2O emission.

4.2.2.3 Indonesian coal sample

Carbon Dioxide:

Emission of CO_2 from the combustion of Indonesian coal sample at different percentage of excess air is shown in Figure 4-16 for both adiabatic and real condition.

Figure 4-16: Relationship between Carbon dioxide emission with percentage of excess air for Indonesian Coal.

Nitrogen Dioxide:

Emission of NO_2 from the combustion of Indonesian coal sample at different percentage of excess air is shown in Figure 4-17 for both adiabatic and real condition.

Sulfur Dioxide:

Emission of SO_2 from the combustion of Indonesian coal sample at different percentage of excess air is shown in Figure 4-18 for both adiabatic and real condition.

Figure 4-17: Relationship between Nitrogen dioxide emission with percentage of excess air for Indonesian Coal.
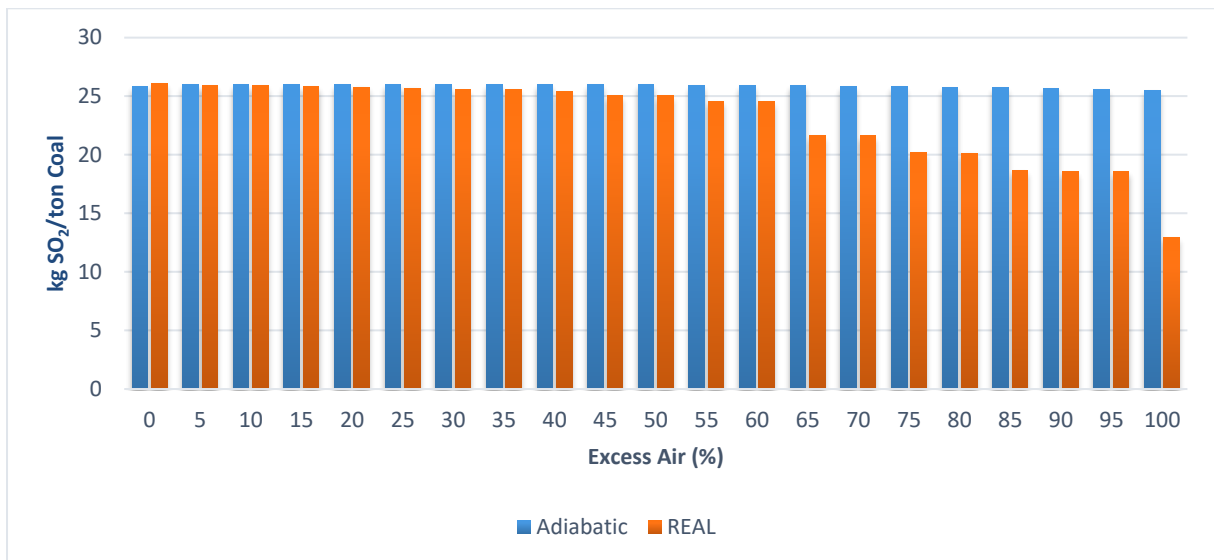
Figure 4-18: Relationship between Sulfur dioxide emission with percentage of excess air for Indonesian Coal.

Sulfur Trioxide:

Emission of SO_3 from the combustion of Indonesian coal sample at different percentage of excess air is shown in Figure 4-19 for both adiabatic and real condition.

Figure 4-19: Relationship between Sulfur trioxide emission with percentage of excess air for Indonesian Coal.

Nitric oxide:

Emission of NO from the combustion of Indonesian coal sample at different percentage of excess air is shown in Figure 4-20 for both adiabatic and real condition.
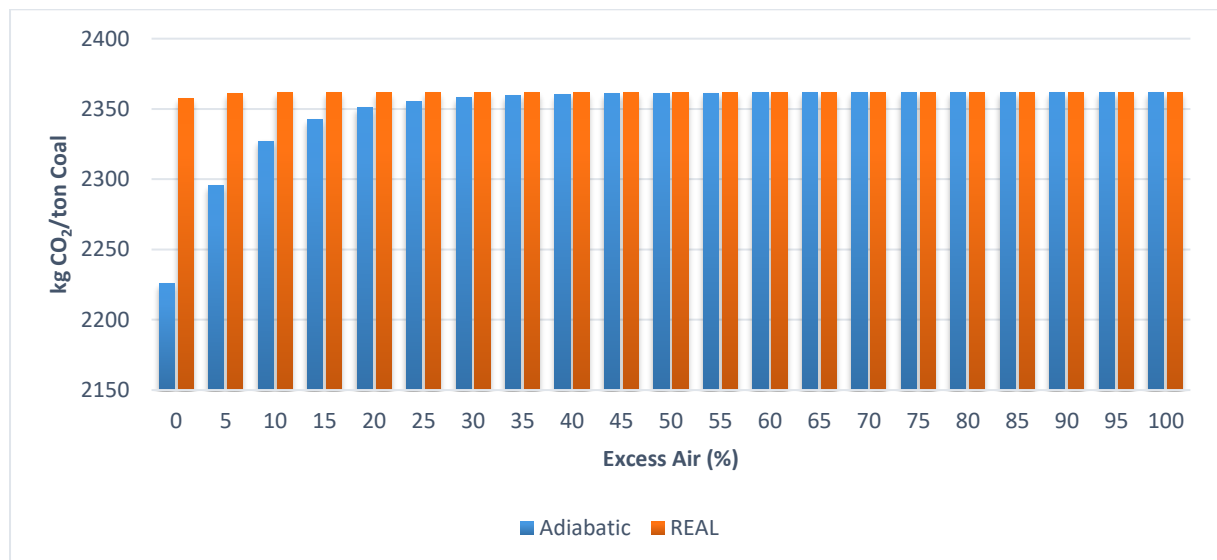

Figure 4-20: Relationship between Nitric oxide emission with percentage of excess air for Indonesian Coal.

Nitrous oxide:

Emission of N_2O from the combustion of Indonesian coal sample at different percentage of excess air is shown in Figure 4-21 for both adiabatic and real condition.
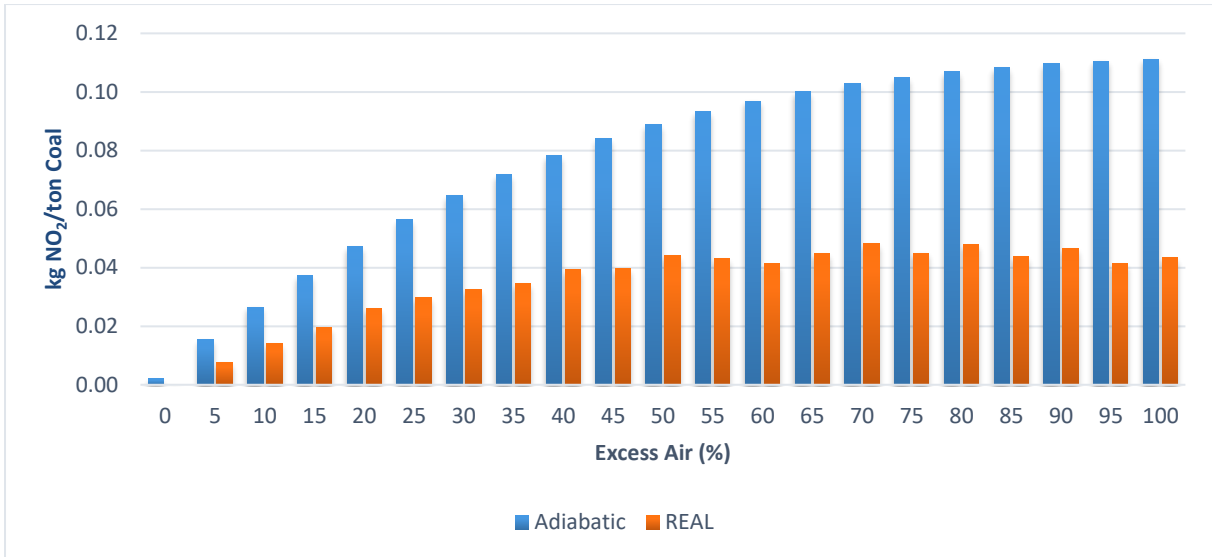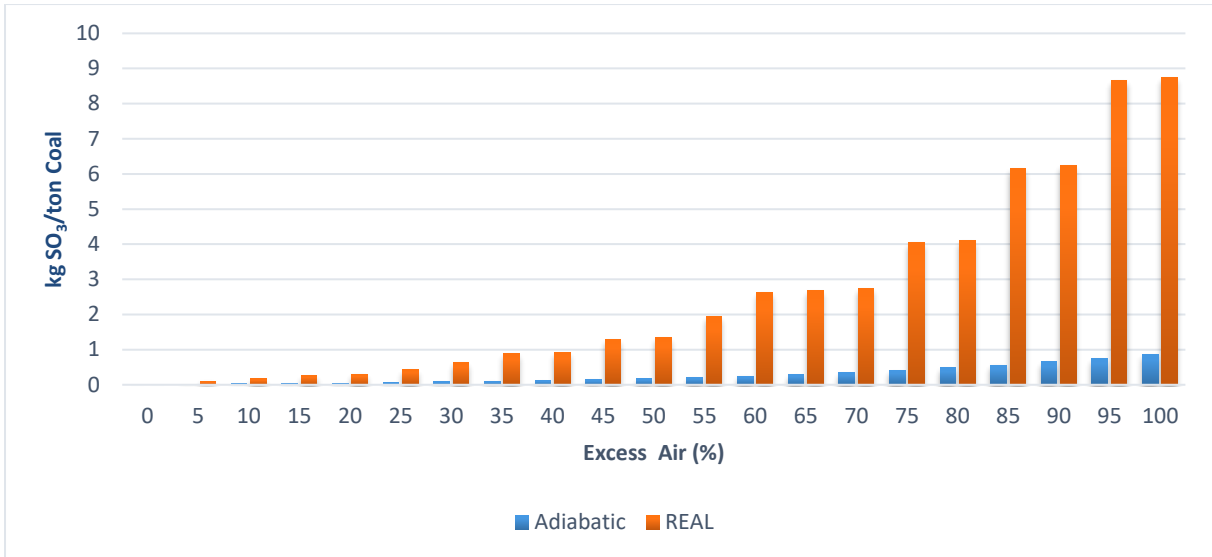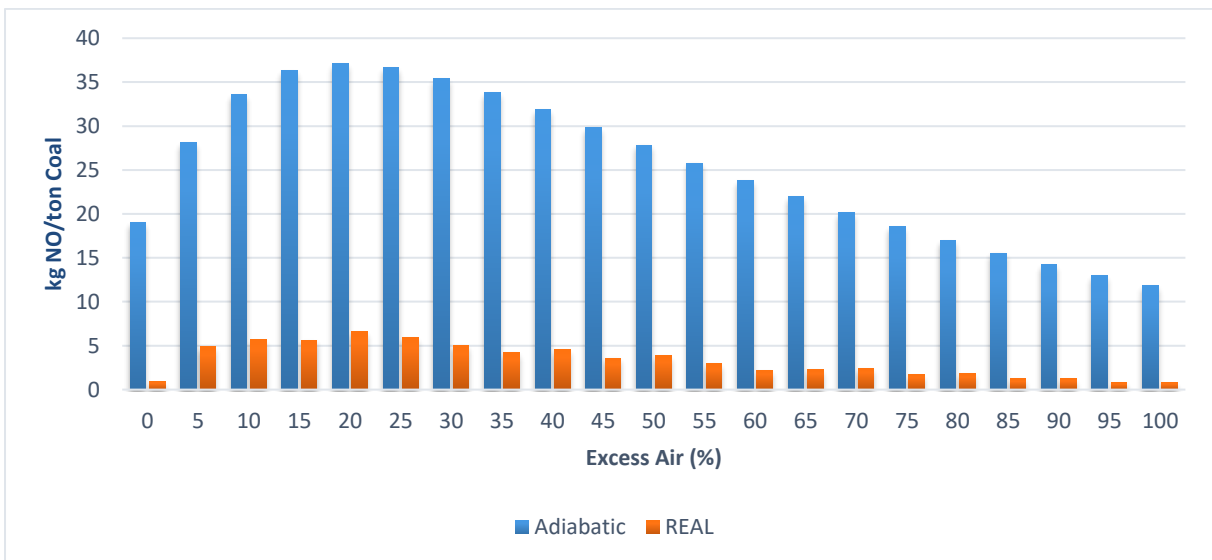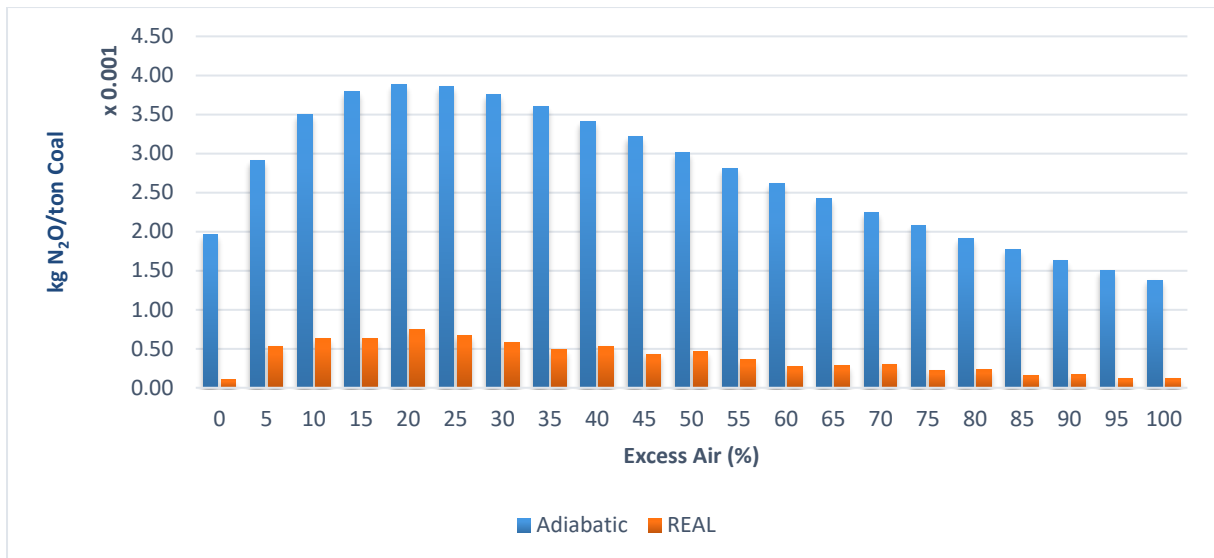
Figure 4-21: Relationship between Nitrous oxide emission with percentage of excess air for Indonesian Coal.

From the simulation data of combustion of Indonesian coal, it is evident that, emission of CO_2 increases with increasing percentage of excess air for adiabatic condition. But for real condition, emission is almost similar, although a slight decrease in emission can be seen till 15% of excess air then became constant. It can be verified from Figure 4-16. So to contribute lower to the air pollution, we must do the combustion reaction at lower percentage of excess air. Initially emission from real condition is higher, but with increasing percentage of excess air, from 30%, the relationship started to become opposite.

No specific trend line for emission of NO_2 from combustion of Indonesian coal was found from Figure 4-17 in real condition, but in case of adiabatic condition emission is gradually increases with increasing percentage of excess air. It can be said that emission in adiabatic condition is always higher than the emission in real condition. In adiabatic condition, maximum concentration of NO_2 is found when the percentage of excess air is increased to 100% range. Concentration of NO_2 in real condition for 0% excess air is almost nil compared to other values.

From Figure 4-18, it is seen that emission of SO_2 decreases gradually for increasing percentage of excess air in case of real condition. But in adiabatic condition emission is almost same for any percentage of excess air amount. For percentage of excess air range 0 to 5%, emission in real condition is higher than the emission in adiabatic condition. But after 5%, the relationship becomes opposite and at 100% of excess air the emission is much higher in adiabatic condition compared to real condition.

In case of emission of SO_3 from the combustion of Indonesian coal, emission is increased with increasing percentage of excess air for both adiabatic and real conditions. This relation can be seen from Figure 4-19. The trend line for adiabatic condition is almost linear with a positive slope. But in case of real condition, no specific trend line was found. Although it is evident from the simulation data that emission at higher percentage of excess air is much higher than the lower percentage of excess air in real condition.

From thermodynamic combustion data of Indonesian coal, it is evident that for NO and N_2O emission follows the almost similar trend line for adiabatic condition, but for real condition no specific trend line is followed (Figure 4-20 and Figure 4-21). Emission of both NO and N_2O increases with increasing percentage of excess air to a certain point, but after that it starts to decrease. For both NO and N_2O that specific percentage of excess air value is 20%.

4.2.2.4 *South African coal sample*
Carbon Dioxide:

Emission of CO_2 from the combustion of South African coal sample at different percentage of excess air is shown in Figure 4-22 for both adiabatic and real condition.
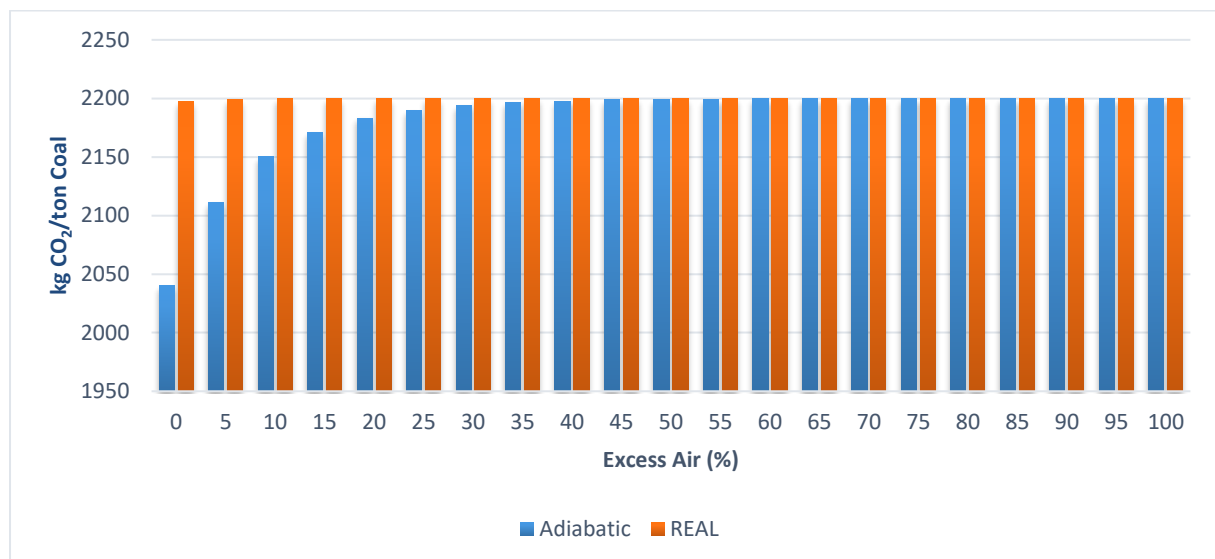
Figure 4-22: Relationship between Carbon dioxide emission with percentage of excess air for South African Coal.

Nitrogen Dioxide:

Emission of NO_2 from the combustion of South African coal sample at different percentage of excess air is shown in Figure 4-23 for both adiabatic and real condition.
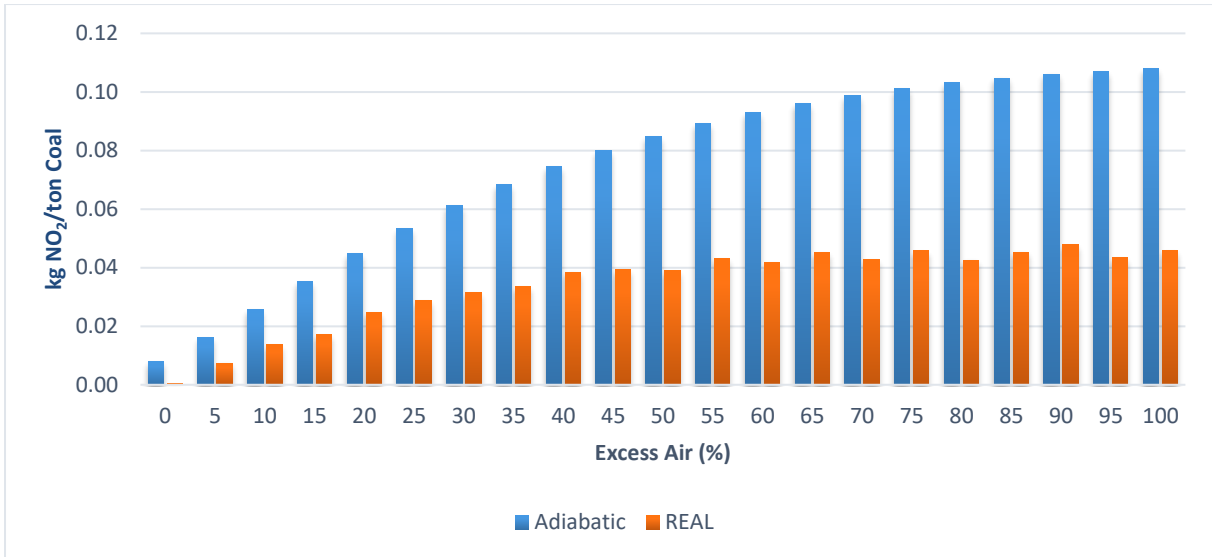
Figure 4-23: Relationship between Nitrogen dioxide emission with percentage of excess air for South African Coal.

Sulfur Dioxide:

Emission of SO_2 from the combustion of South African coal sample at different percentage of excess air is shown in Figure 4-24 for both adiabatic and real condition.
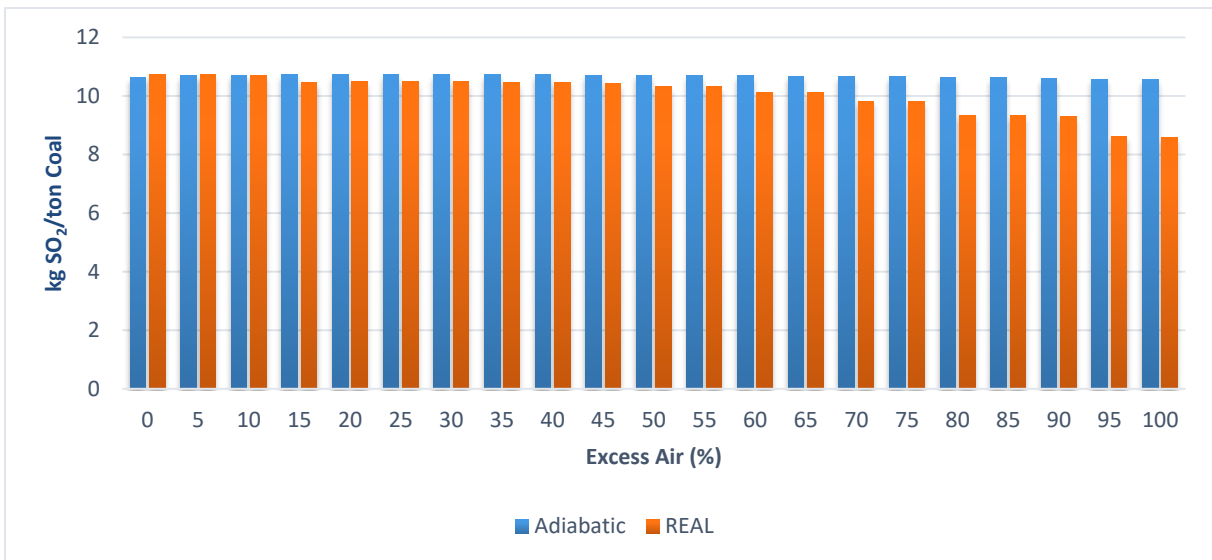
Figure 4-24: Relationship between Sulfur dioxide emission with percentage of excess air for South African Coal.

Sulfur Trioxide:

Emission of SO_3 from the combustion of South African coal sample at different percentage of excess air is shown in Figure 4-25 for both adiabatic and real condition.
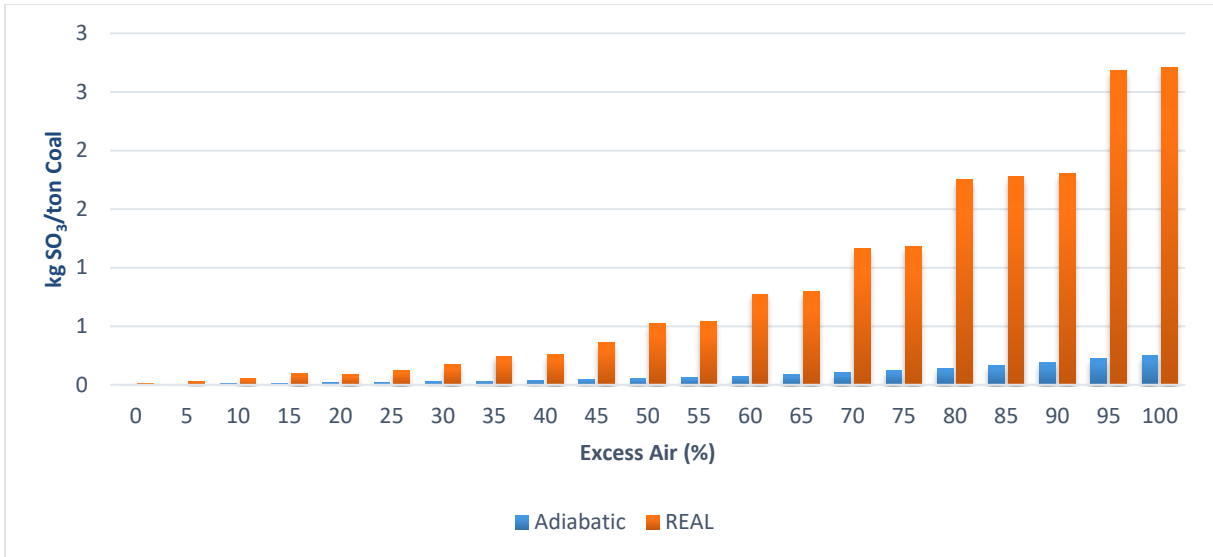
Figure 4-25: Relationship between Sulfur trioxide emission with percentage of excess air for South African Coal.

Nitric oxide:

Emission of NO from the combustion of South African coal sample at different percentage of excess air is shown in Figure 4-26 for both adiabatic and real condition.
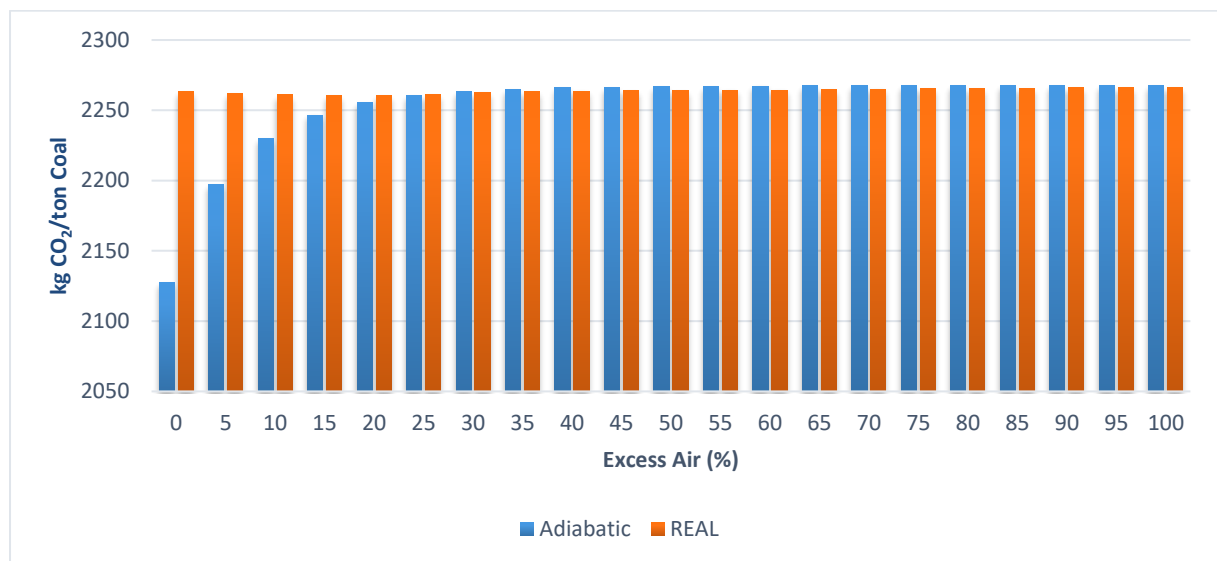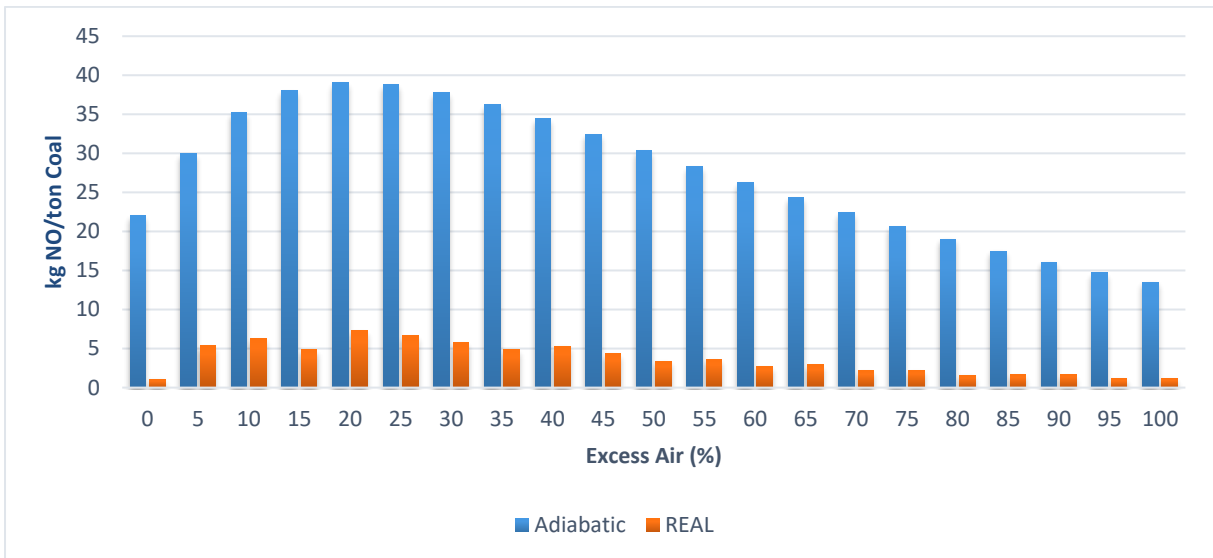

Figure 4-26: Relationship between Nitric oxide emission with percentage of excess air for South African Coal.

Nitrous oxide:

Emission of N_2O from the combustion of South African coal sample at different percentage of excess air is shown in Figure 4-27 for both adiabatic and real condition.
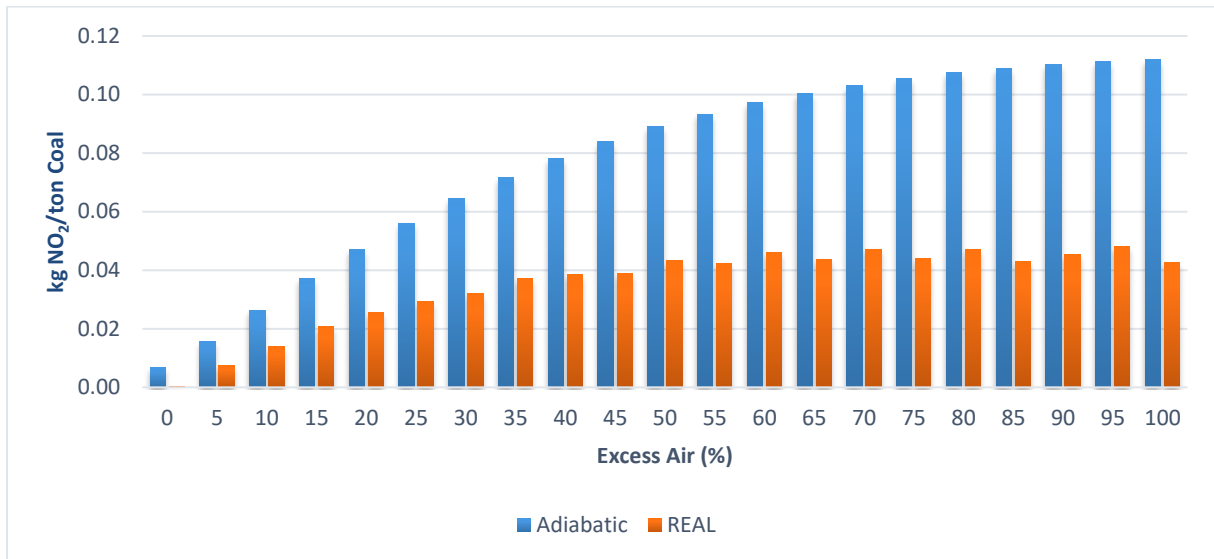
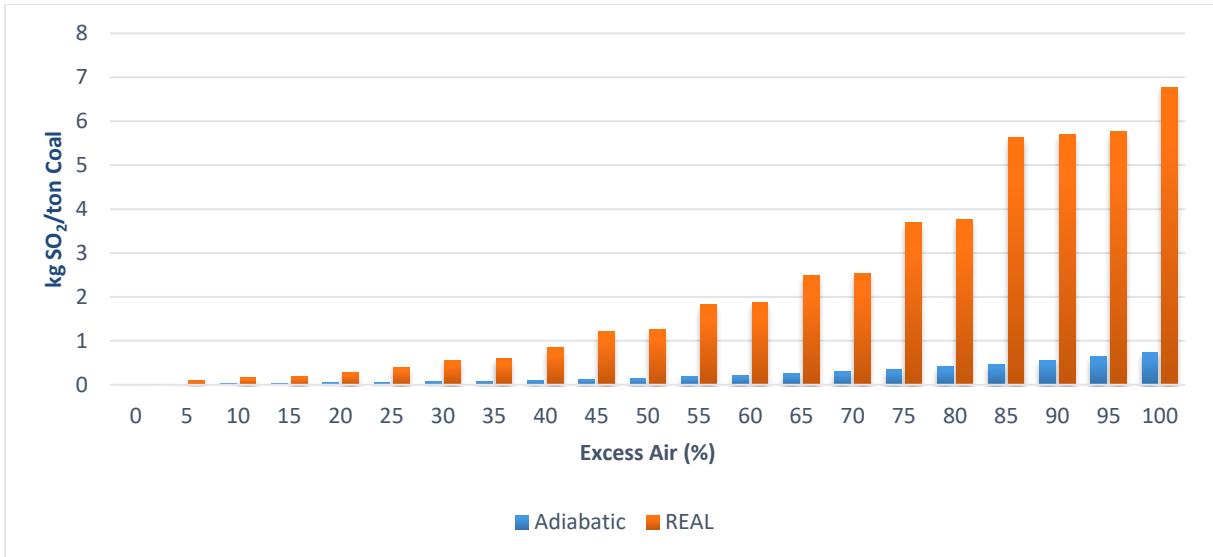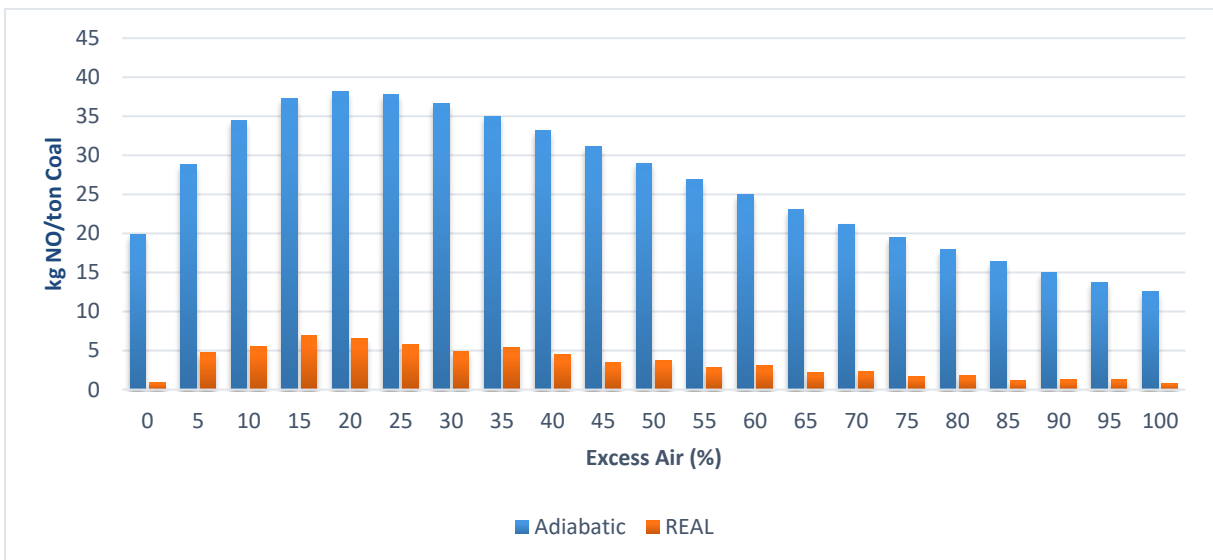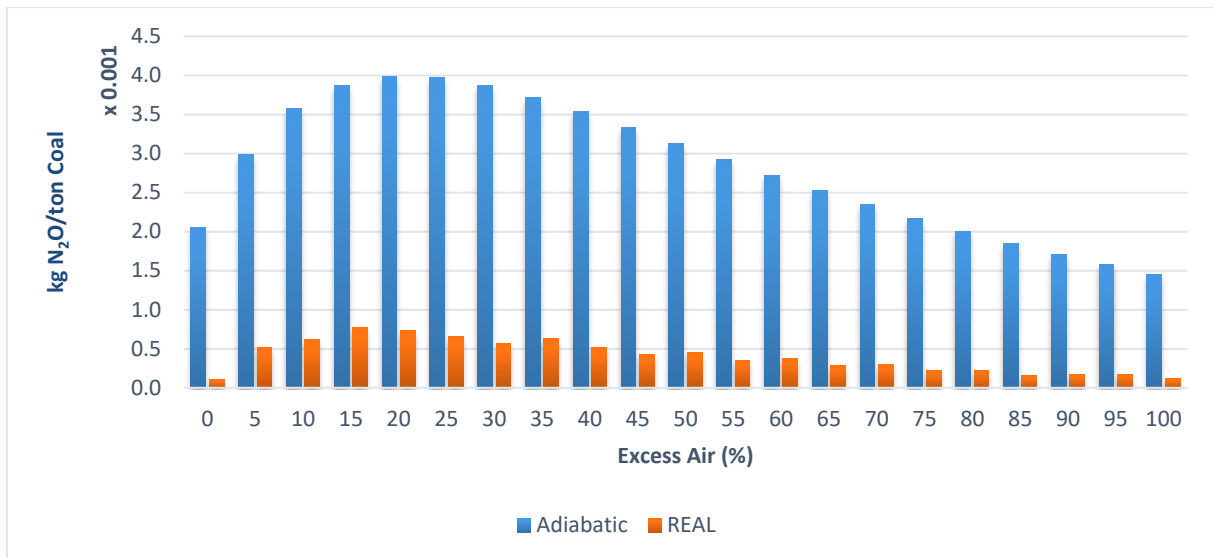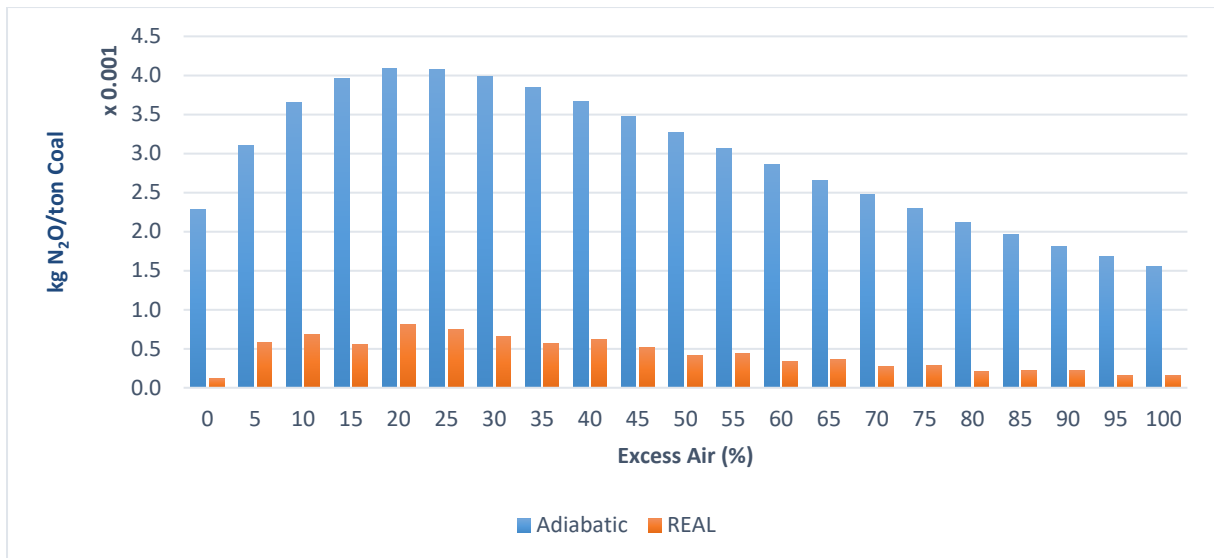Figure 4-27: Relationship between Nitrous oxide emission with percentage of excess air for South African Coal.

It is evident from Figure 4-22 that the emission of CO_2 from the combustion of South African coal increases with increasing percentage of excess air for adiabatic condition. But for real condition no specific trend line is followed till 15% of excess air and in this range emission from real condition is higher than the emission from adiabatic condition. After 15% of excess air in real condition emission starts to increase with increasing percentage of excess air till 70%, then emission became almost constant and in this range emission from both adiabatic and real condition become almost similar.

In case of emission of NO_2, no specific trend line was found for real conditions. In case of adiabatic condition, emission increases with increasing percentage of excess air. No specific trend line is followed for real condition. It can be seen from Figure 4-23 that, emission in adiabatic condition is always higher than the emission in real condition.

From Figure 4-24, almost linear correlation with negative slope between the concentrations of SO_2 with percentage of excess air was found for real condition. In case of adiabatic condition emission is almost similar throughout the range. Emission of SO_2 from the combustion of South African coal decreases with increasing percentage of excess air in real condition. Emission of SO_2 in adiabatic condition is always higher than the emission in real condition, although in the ranges of 0 to 10% of excess air the emission is higher in real condition.

Figure 4-25 shows that, emission of SO_3 increases with the increasing percentage of excess air both for adiabatic and real condition. Emission in adiabatic condition is always lower than the

emission in real condition. In case of adiabatic condition rate of increase in concentration is almost linear. But for real condition no specific trend line was found. Although it is evident from the simulation data that concentration is much higher in higher percentage of excess air in real condition.

No specific trend line is followed by the emission of both NO and N_2O in real condition for South African coal sample and it can be verified from Figure 4-26 and Figure 4-27. In case of adiabatic condition, emission of NO tends to increase till 20% of excess air and then decrease. For N_2O in adiabatic condition emission tends to increase till 25% of excess air and then decrease gradually.

4.2.3 Liquid contents

4.2.3.1 Barapukuria coal sample

The amount of different liquid effluents released at different percentage of excess air after the combustion of Barapukuria coal sample for adiabatic condition are presented in this section.

Table 4.7: Concentration profile of SiO_2 liquid oxides during combustion of 100 gm Barapukuria coal sample in adiabatic condition

Excess Air %	Temperature (K)	SiO₂_liquid
0	2225	3.497
5	2186	3.122
10	2135	2.928
15	2082	2.787
20	2029	2.573
25	1977	2.528

Table 4.8: Concentration profile of Al_2TiO_5 liquid oxides during combustion of 100 gm Barapukuria coal sample in adiabatic condition

Excess Air %	Temperature (K)	Al₂TiO₅_liquid
0	2225	1.426
5	2186	1.436
10	2135	0.888

From simulation output, only two metal oxides were found as liquid state after combustion. Both SiO_2 and Al_2TiO_5 are possibly two major metal oxides that are left as liquid in the coal

residue after coal combustion at adiabatic condition. The amount of SiO_2 gradually decreases with the increase in percentage of excess air. But in case of Al_2TiO_5 the pattern is not well understood. In both cases it was observed that the concentration of both liquid oxides become almost zero after a certain amount of excess air, but they remain present in another form.

4.2.3.2 Indian coal sample

The amount of different liquid effluents released at different percentage of excess air after the combustion of Indian coal sample for adiabatic condition are presented in this section.

Table 4.9: Concentration profile of FeO liquid oxides during combustion of 100 gm Indian coal sample in adiabatic condition

Excess Air %	Temperature (K)	FeO_liquid
0	2176	0.236
5	2133	0.307
10	2080	0.322

Table 4.10: Concentration profile of $CaSiTiO_5$_liquid oxides during combustion of 100 gm Indian coal sample in adiabatic condition

Excess Air %	Temperature (K)	CaSiTiO$_5$_liquid
0	2176	0.0603
5	2133	0.0608
10	2080	0.0613

Table 4.11: Concentration profile of $(FeO)_2(TiO_2)$_liquid oxides during combustion of 100 gm Indian coal sample in adiabatic condition

Excess Air %	Temperature (K)	(FeO)$_2$(TiO$_2$)_liquid
10	2080	0.0696
15	2026	0.0698

From the simulation data of combustion of Indian coal, three types of metal oxides are found in liquid states after combustion reaction. FeO, $CaSiTiO_5$ and $(FeO)_2(TiO_2)$ are three liquid metal oxides that are found in the coal residue after combustion of Indian coal in adiabatic condition. The concentration of all three liquid metal oxides increases with increasing percentage of excess air. $(FeO)_2(TiO_2)$ liquid metal oxide forms after increasing the percentage of excess air to 10%. Concentration of all three metal oxides becomes almost zero after a certain amount of excess air.

4.2.3.3 *Indonesian coal sample*

The amount of different liquid effluents released at different percentage of excess air after the combustion of Indonesian coal sample for adiabatic condition are presented in this section.

Table 4.12: Concentration profile of SiO_2 liquid oxides during combustion of 100 gm Indonesian coal sample in adiabatic condition

Excess Air %	Temperature (K)	SiO_2_liquid
0	2191	0.756
5	2149	0.770
10	2097	0.775
15	2042	0.814

Table 4.13: Concentration profile of $CaSiTiO_5$_liquid oxides during combustion of 100 gm Indonesian coal sample in adiabatic condition

Excess Air %	Temperature (K)	$CaSiTiO_5$_liquid
0	2191	0.153
5	2149	0.154
10	2097	0.154
20	2042	0.155
25	1990	0.155
30	1939	0.155
35	1890	0.155
40	1844	0.155
45	1800	0.155
50	1759	0.155
55	1720	0.155

Table 4.14: Concentration profile of FeO_liquid oxides during combustion of 100 gm Indonesian coal sample in adiabatic condition

Excess Air %	Temperature (K)	FeO_liquid
0	2192	0.143
5	2150	0.223
10	2097	0.291
15	2043	0.228

From the simulation data of combustion of Indonesian coal, three types of metal oxides are found in liquid states after combustion reaction. SiO_2, $CaSiTiO_5$ and FeO are three liquid metal oxides that are found in the coal residue after combustion of Indonesian coal in adiabatic condition. The concentration of SiO_2 and FeO liquid metal oxides increases with increasing percentage of excess air. The concentration of $CaSiTiO_5$ liquid metal oxides increases initially with increasing percentage of excess air from 0 to 20%. After 20%, the concentration does not depend on the percentage of excess air and becomes constant. Concentration of all three metal oxides become nil after a certain amount of excess air.

4.2.3.4 *South African coal sample*

The amount of different liquid effluents released at different percentage of excess air after the combustion of South African coal sample for adiabatic condition are presented in this section.

Table 4.15: Concentration profile of SiO_2 liquid oxides during combustion of 100 gm South African coal sample in adiabatic condition

Excess Air %	Temperature (K)	SiO_2_liquid
0	2234	3.991
5	2194	3.795
10	2143	3.635
15	2090	3.327
20	2036	3.019

Table 4.16: Concentration profile of Al_2TiO_5 liquid oxides during combustion of 100 gm South African coal sample in adiabatic condition

Excess Air %	Temperature (K)	$Al_2TiO_5\_liquid$
0	2234	0.774
5	2194	0.776

From simulation output of South African coal sample, only two metal oxides were found as liquid state after combustion. Both SiO_2 and Al_2TiO_5 are possibly two major metal oxides that are left as liquid in the coal residue after coal combustion at adiabatic condition. The amount of SiO_2 gradually decreases with the increase in percentage of excess air. But in case of Al_2TiO_5 the amount of Al_2TiO_5 increases with increase in percentage of excess air. In both cases it was observed that the concentration of both liquid oxides become zero after a certain amount of excess air, but they remain present in another form.

4.2.4 Solid contents

Some oxides present in both solid and liquid phase after combustion of coal sample. At low percentage of excess air the oxides were found as liquid oxide and at higher percentage of excess air the oxides were found as solid oxide. This liquid to solid phase transition at higher percentage of excess air can be explained by the temperature profile, which was discussed earlier. For all coal samples temperature was higher at low percentage of excess air, therefore, at low percentage of excess air oxides were found as liquid. At higher percentage of excess air, temperature is lower and the oxides turn into solid phase. Mercury concentration was not used in the simulation software to predict emission, because it is difficult to predict the mercury emission by using thermodynamic simulation.

4.2.4.1 *Barapukuria coal sample*

The amount of different solid effluents released at different percentage of excess air after the combustion of Barapukuria coal sample for adiabatic condition are discussed in this section.

From Table 4.17 it is evident that in adiabatic condition, Al_2TiO_5 do not form without the presence of excess air less than 15%. The concentration of Al_2TiO_5 (Tialite) do not vary depending on the change in excess air after 25%. The combustion reaction takes place at stoichiometric ratio and the concentration of Al_2TiO_5 (Tialite) increases about 43% with an increase of 5% excess air.

Table 4.17: Concentration profile of solids during 100 gm coal combustion in adiabatic condition for Barapukuria coal sample

Excess Air %	Temperature (K)	Al_2TiO_5 (Tialite)	Al_2SiO_5 (Sillimanite)	SiO_2 (Cristobalite(h))	SiO_2 (Tridymite(h))	$Fe_2Al_4Si_5O_{18}$ (Ferrocordierite)
0	2226	-	-	-	-	0.751
5	2186	-	-	-	-	1.588
10	2136	-	-	-	-	1.776
15	2082	1.007	-	-	-	1.910
20	2029	1.440	0.312	-	-	2.008
25	1978	1.441	0.264	-	-	2.071
30	1928	1.441	0.233	2.499	-	2.114
35	1882	1.441	0.159	2.497	-	2.147
40	1838	1.441	0.659	3.298	-	-
45	1795	1.441	0.638	3.299	-	-
50	1756	1.441	0.627	3.299	-	-
55	1718	1.441	0.622	-	3.299	-
60	1682	1.441	0.622	-	3.299	-
65	1648	1.441	0.619	-	3.299	-
70	1615	1.441	0.618	-	3.299	-
75	1585	1.441	0.618	-	3.298	-
80	1555	-	1.902	-	2.822	-
85	1527	-	1.902	-	2.822	-
90	1500	-	1.901	-	2.822	-
95	1475	-	1.901	-	2.822	-
100	1450	-	1.901	-	2.822	-

Al_2SiO_5 (Sillimanite) forms after increasing the percentage of excess air to 20%. The concentration of Al_2SiO_5 (Sillimanite) is dependent on percentage of excess air and tends to decrease gradually as the percent excess air increases from 25 to 40%. There is a drastic increase in the concentration of Al_2SiO_5 (Sillimanite) when the percent excess air increases from 40 to 45%. The relationship between concentration and percent excess air for Al_2SiO_5

(Sillimanite) is nonlinear and thus from Table 4.17, it can be concluded that for less amount of solid phase Al_2SiO_5 (Sillimanite) formation, lesser amount of excess air is better.

SiO_2 in Barapukuria coal forms minerals of both phases – solid and liquid. Cristobalite(h) and Tridymite are two forms of solid phase mineral found from simulation data. None of these form without the presence of excess air less than 30%. Although both of these forms of SiO_2 are in solid phase, their behavior varies with the percent of excess air present during combustion. For Cristobalite(h), the lower percentage of excess air present, the higher would be the concentration of this mineral in the solid waste. On the other hand, concentration of Tridymite in coal residue reduces in adiabatic condition with the percent increase in excess air. In both cases, the changes are very small compared to the percentage increase of excess air. Increasing excess air beyond 55%, only Tridymite will be produced.

Barapukuria coal sample is rich in Si and Al in its matrix. Therefore, during combustion with air, these metals are oxidized and complex oxides are formed. $Fe_2Al_4Si_5O_{18}$ (Ferrocordierite) is a solid crystalline mineral that is formed during the combustion reaction of coal. With increase in the percent of excess air, initially, concentration of $Fe_2Al_4Si_5O_{18}$ (Ferrocordierite) increases significantly, the concentration is doubled after an increase of 5% in the excess air. Increasing excess air greater than 40%, production of $Fe_2Al_4Si_5O_{18}$ (Ferrocordierite) can be avoided according to the simulation results.

4.2.4.2 Indian coal sample

The amount of different solid effluents released at different percentage of excess air after the combustion of Indian coal sample for adiabatic condition are discussed in this section.

From Table 4.18 it can be seen that, for adiabatic condition the concentration of $CaAl_2Si_2O_8$ (Anorthite) varies with the change in the percentage of excess air. The concentration of $CaAl_2Si_2O_8$ (Anorthite) remains almost constant as the percentage of excess air increases from 0 to 25%. After 25%, the concentration decreases and remains almost constant from 30 to 65%. After that, the concentration of $CaAl_2Si_2O_8$ (Anorthite) decreases gradually with the percentage increase in excess air.

Concentration of $CaSiO_3$ (Ps-wollastonite) depends on the presence of percentage of excess air in the combustion reaction. The concentration increases gradually with increase of percentage of excess air for 30% excess air. After 30%, the concentration does not vary depending on the change in excess air. Formation of $CaSiO_3$ (Ps-wollastonite) stops after increasing the

percentage of excess air to 75%. So if it is desirable to avoid the formation of of $CaSiO_3$ (Ps-wollastonite) then it is required to use the percentage of excess air amount beyond 75%.

Formation of Ca_2SiO_4 (Alpha) depends on the percentage of excess air amount. Concentration of Ca_2SiO_4 (Alpha) decreases progressively with increasing excess air percentage and from 30% excess air, formation of Ca_2SiO_4 (Alpha) stops.

Table 4.18: Concentration profile of solids during 100 gm coal combustion in adiabatic condition for Indian coal sample

Excess Air %	Temperature (K)	CaAl₂Si₂O₈ (Anorthite)	CaSiO₃ (Ps-wollastonite)	Ca₂SiO₄ (Alpha)	Fe₂O₃ (Hematite)	Ca₃Fe₂Si₃O₁₂ (Andradite(garnet))
0	2176	0.752	0.339	0.149	-	-
5	2134	0.752	0.351	0.141	-	-
10	2081	0.753	0.394	0.131	-	-
15	2026	0.753	0.401	0.115	0.408	-
20	1973	0.753	0.367	0.110	0.533	-
25	1922	0.753	0.440	0.054	0.573	-
30	1873	0.709	0.495	-	0.595	-
35	1827	0.709	0.495	-	0.608	-
40	1784	0.709	0.495	-	0.615	-
45	1743	0.709	0.495	-	0.619	-
50	1704	0.709	0.495	-	0.621	-
55	1667	0.709	0.495	-	0.623	-
60	1632	0.709	0.495	-	0.624	-
65	1599	0.709	0.495	-	0.624	-
70	1568	0.697	0.494	-	0.626	-
75	1538	0.636	0.495	-	0.625	-
80	1509	0.597	-	-	0.399	0.718
85	1482	0.570	-	-	0.400	0.714
90	1456	0.552	-	-	0.401	0.712
95	1431	0.536	-	-	0.399	0.719
100	1407	0.529	-	-	0.399	0.718

Fe_2O_3 (hematite) forms after increasing excess air from 15%. The concentration of Fe_2O_3 (hematite) is dependent on percent of excess air and is gradually increases as the percent excess air increases from 15 to 75%. There is a drastic decrease in the concentration of Fe_2O_3 (hematite) when the percent excess air increases from 75 to 80% and the change is about 36%.

$Ca_3Fe_2Si_3O_{12}$ (Andradite) is a species of the garnet group and is a nesosilicate. It forms during the combustion of Indian coal. $Ca_3Fe_2Si_3O_{12}$ (Andradite) forms after increasing excess air from 80%. The concentration decreases with increasing percentage of excess air from 80 to 90% and the increases.

4.2.4.3 *Indonesian coal sample*

The amount of different solid effluents released at different percentage of excess air after the combustion of Indonesian coal sample for adiabatic condition are discussed in this section.

For Indonesia coal, in adiabatic condition, the concentration of $CaAl_2Si_2O_8$ (Anorthite) depends on the percentage of excess air. Initially, concentration of $CaAl_2Si_2O_8$ (Anorthite) does not vary with increasing percentage of excess air from 0 to 15%. After 15%, the concentration starts to decrease gradually with increasing percentage of excess air. So for low amount of $CaAl_2Si_2O_8$ (Anorthite) it is required to run the combustion reaction in high percentage of excess air.

There is a nonlinear relationship between the concentrations of $CaSiO_3$ (Ps-wollastonite) and percentage of excess air. Initially, the concentration is constant for percentage of excess air for 0 to 10% and then a slight increase in the concentration from 10 to 15% and about 32% decrease in the concentration from 15 to 20% of excess air. After 20%, the concentration starts to increase gradually with increasing percentage of excess air till 75%. The formation of $CaSiO_3$ (Ps-wollastonite) can be avoided by increasing the percentage of excess air to more than 75%.

For Indonesian coal SiO_2 is formed both in solid and liquid states. Cristobalite(h) and Tridymite are two forms of solid phase mineral found from simulation data. Cristobalite(h) starts to from when the percentage of excess air is 20% and Tridymite forms from 50% excess air. Concentration of both Cristobalite(h) and Tridymite decreases with increasing percentage of excess air. Cristobalite(h) formation stops after increasing the percentage of excess air to 50%. So, from the Table 4.19, it can be concluded that at lower percentage of excess air Cristobalite(h) can be found and at higher percentage of excess air Tridymite can be found.

Table 4.19: Concentration profile of solids during 100 gm coal combustion in adiabatic condition for Indonesian coal sample

Excess Air %	Temperature (K)	CaAl₂Si₂O₈ (Anorthite)	CaSiO₃ (Ps-wollastonite)	SiO₂ (Cristobalite(h))	SiO₂ (Tridymite(h))	Fe₂O₃ (Hematite)	KAlSi₃O₈(Sanidine_(feldspar))
0	2192	2.024	0.459	-	-	-	-
5	2150	2.024	0.459	-	-	-	-
10	2097	2.024	0.459	-	-	-	-
15	2043	2.024	0.461	-	-	-	-
20	1990	1.992	0.315	0.808	-	0.455	0.065
25	1939	1.906	0.323	0.727	-	0.505	0.236
30	1890	1.851	0.334	0.672	-	0.533	0.347
35	1844	1.816	0.345	0.636	-	0.549	0.417
40	1801	1.793	0.434	0.591	-	0.558	0.463
45	1760	1.778	0.440	0.575	-	0.563	0.493
50	1720	1.769	0.443	-	0.565	0.566	0.512
55	1683	1.763	0.446	-	0.558	0.568	0.525
60	1648	1.758	0.448	-	0.554	0.569	0.533
65	1615	1.756	0.449	-	0.551	0.570	0.538
70	1583	1.754	0.450	-	0.549	0.570	0.542
75	1553	1.753	0.450	-	0.547	0.571	0.545
80	1524	1.752	-	-	0.546	0.364	0.546
85	1497	1.751	-	-	0.546	0.364	0.547
90	1471	1.751	-	-	0.545	0.364	0.548
95	1446	1.750	-	-	0.545	0.364	0.549
100	1422	1.750	-	-	0.552	0.371	0.549

Fe_2O_3 (hematite) starts to from after increasing the percentage of excess air to 20%. The concentration profile for Fe_2O_3 (hematite) varies differently for different ranges of percentage of excess air. The concentration of Fe_2O_3 (hematite) increases gradually from 20 to 75% of excess air. After 75%, there is a drastic change in the concentration of Fe_2O_3 (hematite) and about 36% decrease in the concentration can be seen from 75 to 80% of excess air. From 80 to

95%, the concentration of Fe_2O_3 (hematite) remains constant and a slight increase in concentration can be seen from 95 to 100% excess air.

Formation of $KAlSi_3O_8$ (Sanidine_feldspar) starts when the percentage of excess air increases to 20%. From 20 to 25%, there is drastic increase in the concentration of $KAlSi_3O_8$ (Sanidine_feldspar), which is about 3.6 times of the previous concentration value. The concentration increases gradually with increasing percentage of excess air. After 70% of excess air the increase in concentration becomes sluggish and not change that much.

4.2.4.4 *South African coal sample*

The amount of different solid effluents released at different percentage of excess air after the combustion of South African coal sample for adiabatic condition are discussed in this section.

From Table 4.20 it is evident that, concentration of $CaAl_2Si_2O_8$ (Anorthite) does not depends on the percentage of excess air. It remains constant for any values of percentage of excess air. So we cannot control the concentration of $CaAl_2Si_2O_8$ (Anorthite) of by varying the percentage of excess air.

Al_2TiO_5 (Tialite) starts to form after increasing the percentage of excess air to 20%. The concentration does not change with increasing percentage of excess air and remains constant from 20 to 75%. Formation of Al_2TiO_5 (Tialite) can be avoided by increasing the percentage of excess air to more than 75%.

Concentration of $Fe_2Al_4Si_5O_{18}$ (Ferrocordierite) increases with increasing percentage of excess air from 0 to 35%. However, rate of increase in concentration is higher initially, and starts to decrease with increasing percentage of excess air. Formation of $Fe_2Al_4Si_5O_{18}$ (Ferrocordierite) stops after increasing the percentage of excess air to 40%.

$KAlSi_3O_8$ (Sanidine_feldspar) formation depends of the percentage of excess air. With increasing the percentage of excess the concentration of $KAlSi_3O_8$ (Sanidine_feldspar) increases gradually. Initially the rate of increase is higher. The concentration at 5% excess air is 8 times higher than the concentration at 0% excess air. After 60% of excess air, the rate of increase in concentration becomes lower and from 80% it becomes almost constant.

Table 4.20: Concentration profile of solids during 100 gm coal combustion in adiabatic condition for South African coal sample

Excess Air %	Temperature (K)	CaAl$_2$Si$_2$O$_8$ (Anorthite)	Al$_2$TiO$_5$ (Tialite)	Fe$_2$Al$_4$Si$_5$O$_{18}$ (Ferrocordierite)	KAlSi$_3$O$_8$ (Sanidine_(feldspar))	Al$_2$SiO$_5$ (Sillimanite)	SiO$_2$ (Cristobalite(h))	SiO$_2$ (Tridymite(h))
0	2234	2.714	-	1.218	0.027	-	-	-
5	2194	2.714	-	1.415	0.221	-	-	-
10	2143	2.714	-	1.565	0.375	-	-	-
15	2090	2.714	-	1.666	0.477	0.534	-	-
20	2036	2.714	0.780	1.730	0.541	1.178	-	-
25	1985	2.714	0.781	1.773	0.579	1.079	3.011	-
30	1936	2.714	0.781	1.801	0.602	0.972	3.023	-
35	1889	2.714	0.781	1.822	0.617	0.919	3.024	-
40	1844	2.714	0.781	-	0.626	1.349	3.703	-
45	1802	2.714	0.781	-	0.632	1.336	3.704	-
50	1762	2.714	0.781	-	0.636	1.328	3.704	-
55	1724	2.714	0.781	-	0.639	1.324	-	3.704
60	1688	2.714	0.781	-	0.641	1.322	-	3.704
65	1653	2.714	0.781	-	0.642	1.320	-	3.704
70	1621	2.714	0.781	-	0.643	1.319	-	3.704
75	1590	2.714	0.781	-	0.643	1.319	-	3.704
80	1560	2.714	-	-	0.644	2.015	-	3.445
85	1532	2.714	-	-	0.644	2.015	-	3.445
90	1505	2.714	-	-	0.644	2.015	-	3.445
95	1479	2.714	-	-	0.644	2.014	-	3.445
100	1455	2.714	-	-	0.644	2.014	-	3.445

Al$_2$SiO$_5$ (sillimanite) starts to form in the combustion reaction when the percentage of excess air is increased to 15%. A very random relationship between the concentrations of Al$_2$SiO$_5$ (sillimanite) and percentage of excess air is found. For certain ranges of percentage of excess

air the concentration decreases, for some ranges it increases and for some ranges it remains constant.

For South African coal SiO_2 is formed both in solid and liquid states. Cristobalite(h) and Tridymite are two forms of solid phase mineral found from simulation. Cristobalite(h) starts to from when the percentage of excess air is 25% and Tridymite forms from 55% excess air. Concentration of Cristobalite(h) increases with increasing percentage of excess air. Concentration of Tridymite remains constant from 55 to 75% of excess air and decreases to about 7% from 75 to 80% excess air. From 80%, it becomes constant again. Cristobalite(h) formation stops after increasing the percentage of excess air to 55%. So, it can be concluded that at lower percentage of excess air Cristobalite(h) can be found and at higher percentage of excess air Tridymite can be found.

4.3   Prediction of Pollution Load

Pollution from the use of coal in the power plants and brick kilns, up to year 2030, has been presented in this section. Thermodynamic calculations performed in the previous section were used as the basis of pollution load calculation.

4.3.1   Pollution from brick kilns

There are three main different technologies being used in brick kilns in Bangladesh. These are Fixed-Chimney Kiln (FCK), Zigzag and Hybrid Hoffman (HHK). The country has more than 7,000 brick kilns, currently producing about 22.8 billion bricks. The industry accounts for approximately 1% of the country's GDP and generating employment for more than a million people. Among these brick kilns, at present about 38% of total bricks are being produced using FCK technology, 56% using Zigzag and 6% using HHK [69].

The structural configuration and method of coal handling in FCK and Zigzag technologies require approximately 500% [70] of excess air during the combustion. To produce 100,000 bricks it requires 22 tons of coal for FCK and 18 tons of coal for Zigzag technology [71]. In this research we have suggested to gradually replace FCK brick kiln with HHK kiln as its construction and operation is very similar to FCK, but it uses 300% of excess air for coal combustion [70]. Moreover, it requires lower amount of coal compared to other brick kiln technologies, 12 ton coal per 100,000 bricks [71]. To estimate the trend of pollution load in upcoming years, a 2.5% annual increment in brick production is assumed. This growth is based on the expansion of market size of real-estate business in Bangladesh [69,72]. The calculations assume that the kilns do not have any of the pre- or post-combustion SO_x or NO_x removal

technologies. It has been assumed that the brick kilns mostly use the coal imported from India. Hence, the composition of Indian coal has been the basis for these calculations.

For the pollution load estimation, three different scenarios have been considered, which are:

Scenario 1: The brick production technologies will remain the same for the upcoming years.

Scenario 2: Existing FCK technology-based kilns will be gradually replaced by HHK.

Scenario 3: Existing FCK and Zigzag technology-based kilns will be gradually replaced by HHK

Table 4.21 shows the percentage breakdown of total brick production for different technologies for the three scenarios. The corresponding coal consumptions are shown in Table 4.22.

Table 4.21: Percentage breakdown of total brick production for three different scenarios

	Scenario 1			Scenario 2			Scenario 3		
	Percentage of total brick production under								
	FCK	Zigzag	HHK	FCK	Zigzag	HHK	FCK	Zigzag	HHK
2018	38	56	6	38	56	6	38	56	6
2019	38	56	6	35	55	10	35	52	13
2020	38	56	6	32	54	14	32	48	20
2021	38	56	6	30	53	17	30	45	25
2022	38	56	6	28	52	20	28	42	30
2023	38	56	6	25	51	24	25	38	37
2024	38	56	6	22	50	28	22	35	43
2025	38	56	6	19	50	31	19	30	51
2026	38	56	6	16	50	34	16	25	59
2027	38	56	6	12	50	38	12	20	68
2028	38	56	6	8	50	42	8	15	77
2029	38	56	6	5	50	45	5	8	87
2030	38	56	6	0	50	50	0	0	100

Table 4.22: Coal requirement for different scenarios

	Total brick production (billion)	Total coal requirement (kilotons)		
		Scenario 1	Scenario 2	Scenario 3
2018	22.8	4154	4154	4154
2019	23.4	4258	4183	4148
2020	24.0	4364	4211	4139
2021	24.6	4474	4260	4162
2022	25.2	4585	4309	4183
2023	25.8	4700	4334	4166
2024	26.4	4818	4357	4159
2025	27.1	4938	4393	4122
2026	27.8	5061	4428	4081
2027	28.5	5188	4436	4009
2028	29.2	5318	4442	3931
2029	29.9	5451	4472	3844
2030	30.7	5587	4446	3680
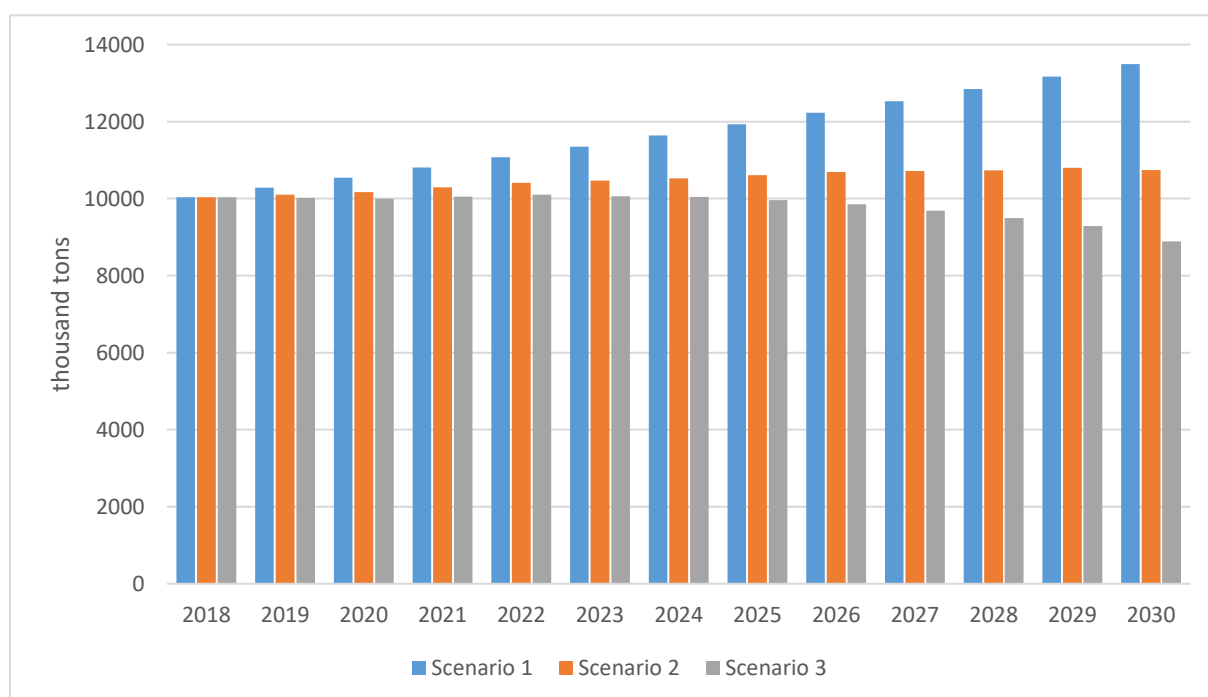
Figure 4-28: Emission trend of CO_2 for different scenarios for brick kilns.
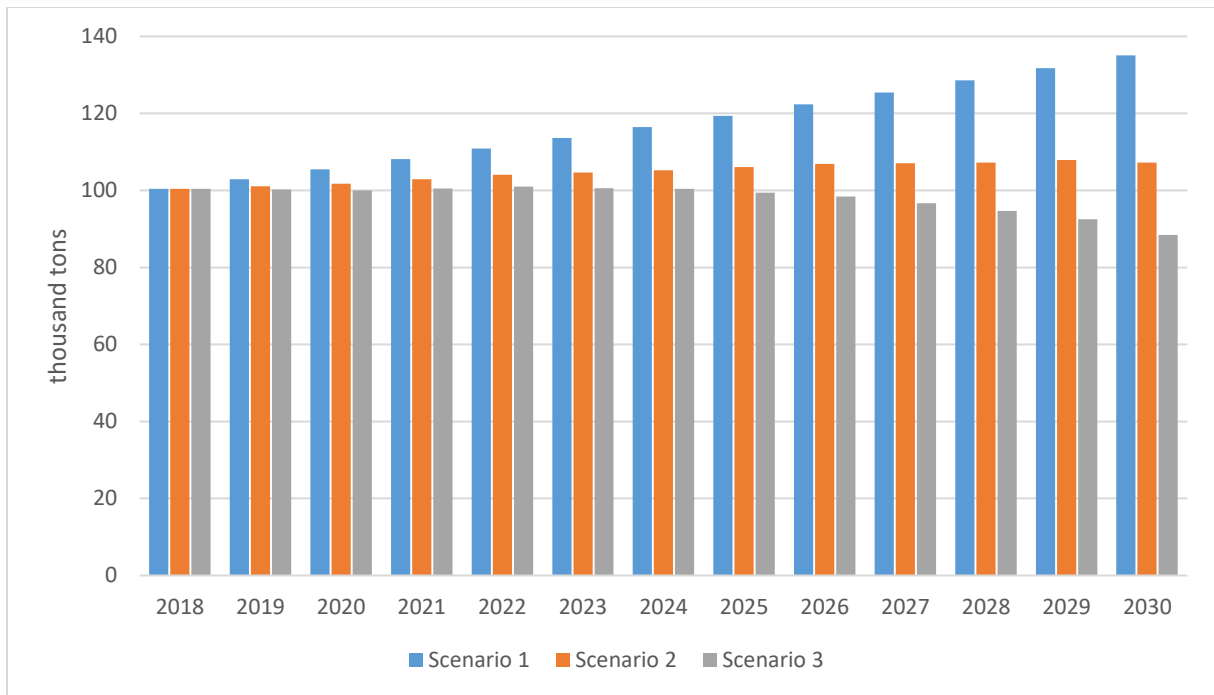
Figure 4-29: Emission trend of SO_x for different scenarios for brick kilns.
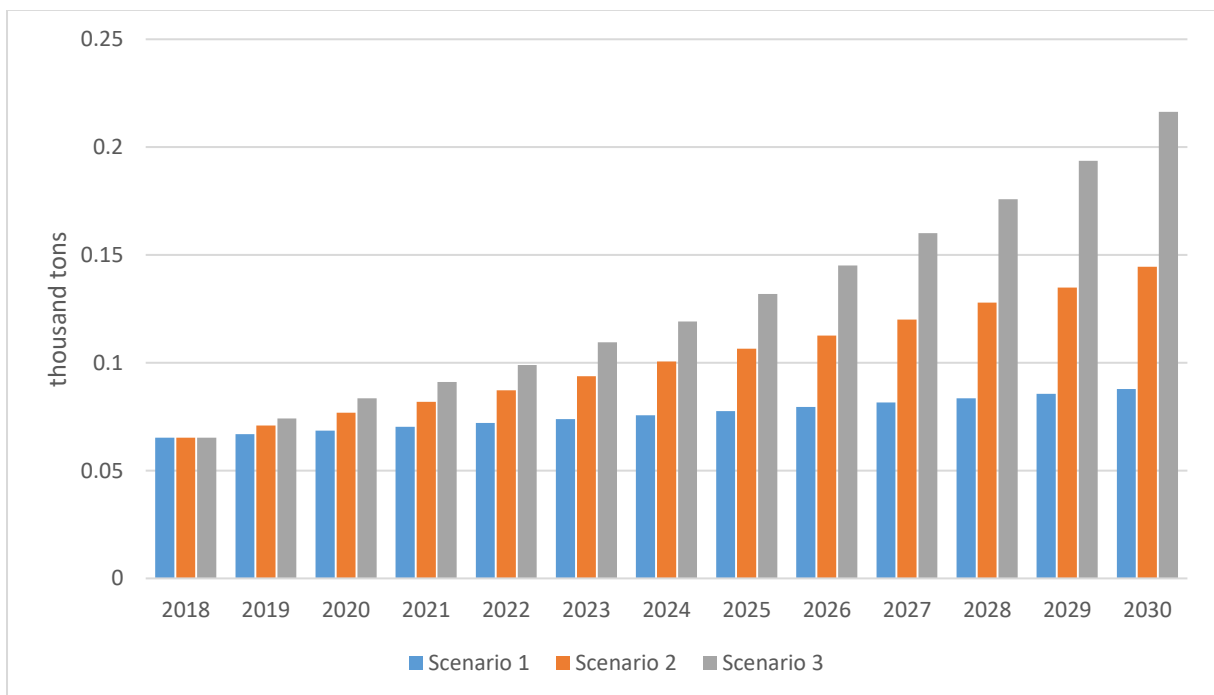
Figure 4-30: Emission trend of NO_x for different scenarios for brick kilns.

It can be seen from Figure 4-28 and Figure 4-29, that the amount of CO_2 and SO_x emission becomes lower due to the implementation of different technology. In case of CO_2, in the year of 2030, emission in scenario 3 is decreased to almost 34% compared to scenario 1 and 17% compared to scenario 2. Similar reduction in SO_x emission was observed. However, NO_x emission become higher for scenario 3 compared to scenario 1 and 2. Being the more energy

efficient technology, HHK uses less air for the combustion of coal and results higher temperature in the kiln. As NO_x formation is favored by increasing temperature, an increase in NO_x formation and emission is expected. The correlation between the temperature and the amount of excess air used has already been discussed in the chapter and shown in Figure 4-3. This is the reason behind higher NO_x emission for scenarios 2 and 3.

4.3.2 Pollution from coal based power plants

As a rule of thumb and taking into account other factors like, calorific value of fuel, coal combustion efficiency, net energy generation etc. we have assumed about 4000 tons per year coal is required to generate 1 MW of electricity for subcritical coal power technology, whereas for supercritical coal power technology about 3600 tons per year coal is required and for ultra-supercritical coal power technology about 2900 tons per year coal is required to generate 1 MW of electricity [73]. Currently only one coal based power plant is running in the country which is Barapukuria Coal Power Plant. It is a 250-megawatt (MW) coal-fired power plant in Dinajpur, Bangladesh. An additional 275 MW was added to the existing capacity in the Year 2018. A list of upcoming coal fired power plants, in both public and private sector, with their capacity and expected commercial operation date (COD) are given in Table 4.23.

Table 4.23: Upcoming Coal Fired Power Plants

Name	Capacity (MW)	Power Plant Type	Expected COD
Barapukuria power station (Unit 3)	275	Sub Critical	June, 2018
Payra, power station (1st Phase)	1320	Ultra-Supercritical	December, 2019
Banshkhali power station (S Alam) Unit 2	612	Ultra-Supercritical	June, 2020
Banshkhali power station (S Alam) Unit 1	612	Ultra-Supercritical	December, 2020
Rampal power station (1st Phase)	1320	Ultra-Supercritical	March, 2021
Patuakhali power station (BCPCL), Unit 1	660	Ultra-Supercritical	June, 2021
Patuakhali power station (Ashuganj), Unit 1	660	Ultra-Supercritical	June, 2021
Barisal power station (ISO Tech)	307	Supercritical	December, 2021
Patuakhali power station (BCPCL), Unit 2	660	Ultra-Supercritical	June, 2022
Gazaria power station (RPCL)	350	Supercritical	June, 2022
Patuakhali power station (RPCL/ NORINCO)	1320	Ultra-Supercritical	December, 2022

Patuakhali power station (Ashuganj), Unit 2	660	Ultra-Supercritical	June, 2023
Matarbari power station, Unit 1	600	Ultra-Supercritical	January, 2024
Matarbari power station, Unit 2	600	Ultra-Supercritical	July, 2024
Bangladesh – Singapore power station (Phase-1)	700	Ultra-Supercritical	June, 2025
CPGCBL-Sumitomo power station	1200	Ultra-Supercritical	June, 2026
Matarbari power station (Phase-2)	1200	Ultra-Supercritical	June, 2028
Bangladesh – Singapore power station (Phase-2)	700	Ultra-Supercritical	June, 2030

For the coal fired power plants, use of 20% excess air in the furnace is a usual practice. Apart from Barapukuria Coal Power Station, all other coal based power plant will utilize Flue-gas desulfurization (FGD) technology for SOx removal and Low NOx Burner (LNB) and other NOx removal technology for NOx removal. About 90% of SOx will be removed by using FGD and 60% of NOx removal will be attained by using LNB. Taking all these assumptions is in action, calculations were done to predict pollution load from power plants.
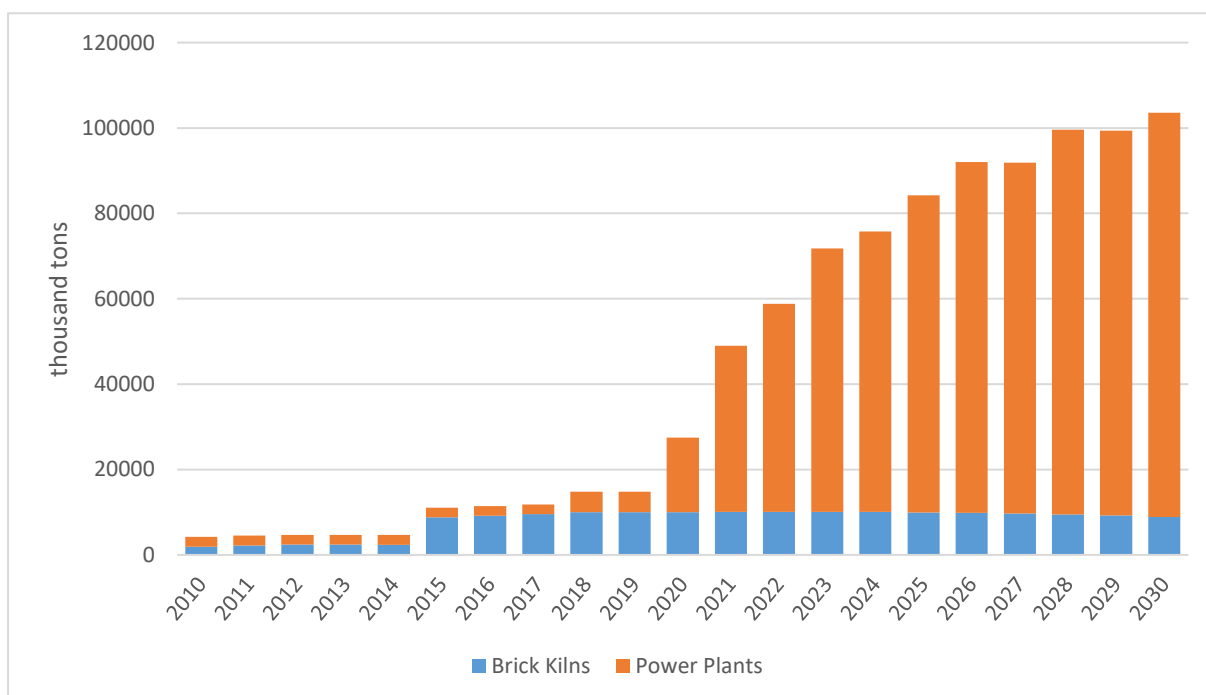
Figure 4-31: Trend in CO_2 emissions from brickfields and power plants.

An overall pollution scenario both from power plants and brick kilns will be discussed in succeeding sections. As it is evident from section 4.3.1, from three scenarios of brick kilns

scenario 3 produces lower pollution content than other two scenarios, so results from scenario 3 is included with power plants result to give an overall pollution scenario. Fly ash and bottom ash emission from power plants also included for further discussion.

It can be seen from Figure 4-31 that the total emission of CO_2 from brick kilns and power plants is increasing gradually. Due to introduction of improved technology in brick kilns, CO_2 emission from brick kilns trends to decrease gradually for brick kilns after year 2018. In case of power plants a significant rise in CO_2 emission after 2019 due to the addition of a numbers coal based power plants. In year 2030, of total 103604 thousand tons of CO_2 emission, 8889 thousand tons come from brick kilns and 94715 thousand tons come from coal fired power plants.
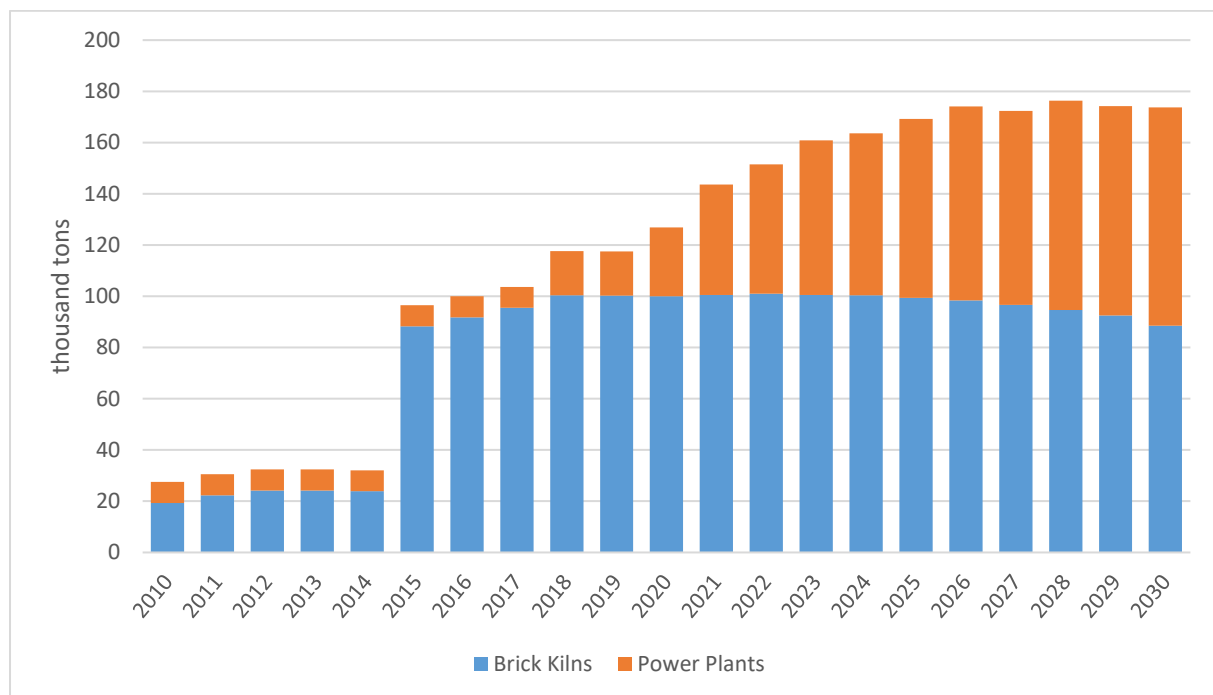
Figure 4-32: Trend in SO_x emissions from brickfields and power plants.

In case of SO_x emission, it can be seen from Figure 4-32 that emission of SO_x increases gradually till year 2019. After 2019, SO_x reduces due to introduction of better technology, but emission increases for a power plants due to establishment of new coal based power plants.. Emission share from power plants increases for newly constructed power plants, but emission decreases in case of brick kilns for replacement of FCK and Zigzag by HHK. In 2030, brick kilns will contribute 88.48 thousand tons of SO_x emission, whereas coal fired power plants will contribute 85.20 thousand tons of SO_x emission.
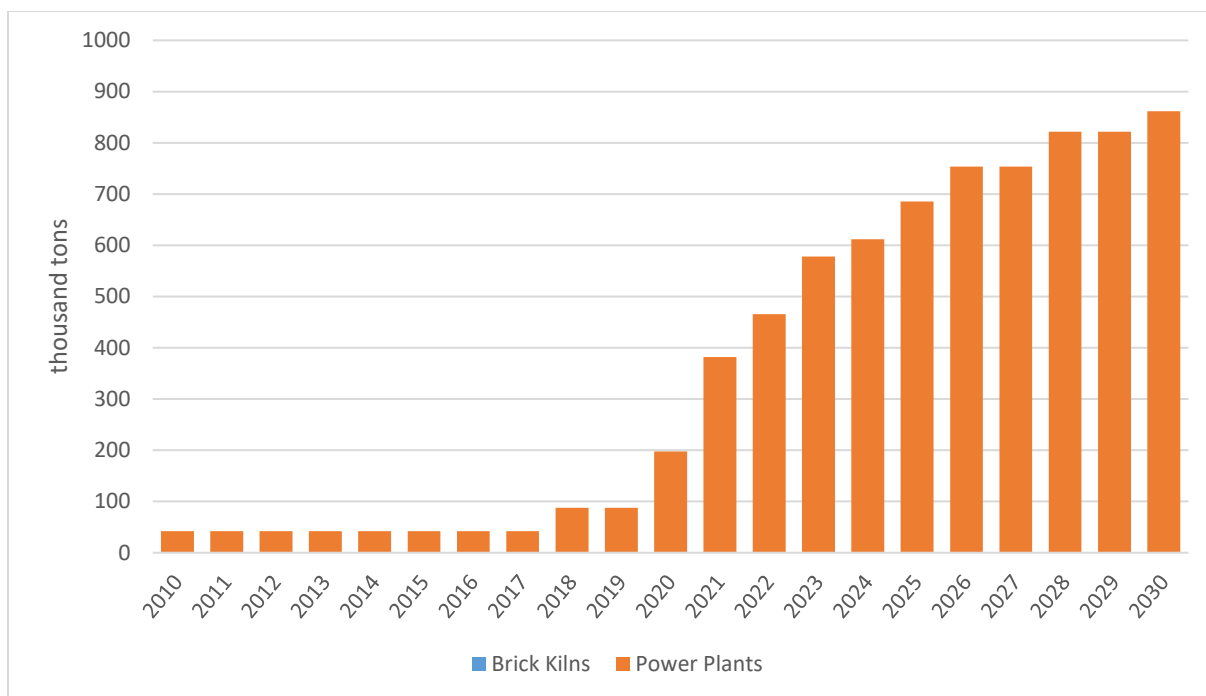
Figure 4-33: Trend in NO$_x$ emissions from brickfields and power plants.

From Figure 4-33, it is evident that almost all of the total NO$_x$ emission comes from power plant and emission of NO$_x$ will be increasing gradually. In year 2030 about 861 thousand tons of NO$_x$ emission from power plants compared to 0.216 thousand tons from brick kilns. Significant change in total NO$_x$ emission after 2019 due to the newly installed coal based power plants. Emission contribution from power plants is higher compared to brick kilns due to lower percentage of excess air used in power plants. Lower percentage of excess air means higher reactor temperature and higher temperature favors NO$_x$ formation.

Production of both the fly ash and bottom ash from power plants remains constant till year 2017. During this period only one coal-based power plant was operational. After 2017 production increases gradually as either new units or new power plants are expected to be added to the existing capacity of coal-fired power plants. The quantities of fly ash and bottom ash expected to be produced in 2030 are 4054 and 1351 thousand tons, respectively. The quantity of ashes being produced is huge and hence proper guidelines for the handling and use of ash products has been formulated well before to ensure environmental issues are properly dealt with. At the same proper use of these by-products can bring additional economic benefits for the power producing companies.
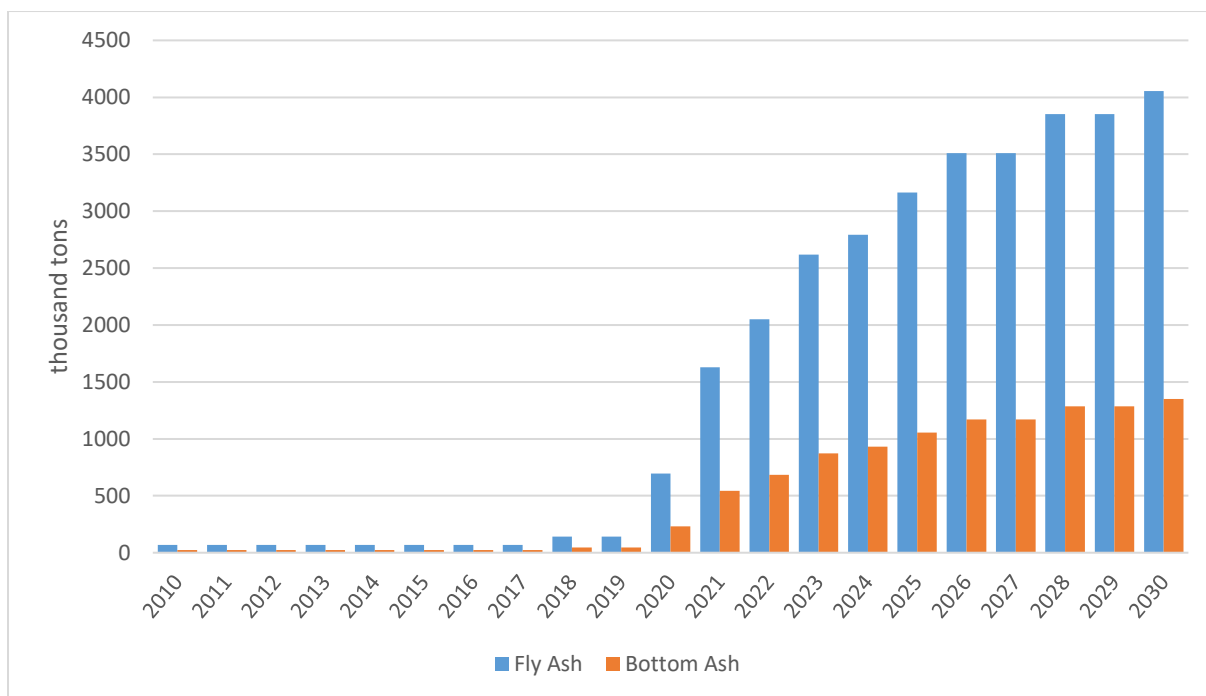
Figure 4-34: Trend in Fly ash and Bottom ash emissions from power plants

4.4 Policy Recommendation for Coal Utilization

Bangladesh has recently experienced robust economic growth by achieving the highest-ever 7.86% GDP growth in the 2017-18 fiscal year, widely surpassing the estimated growth of 7.65% [74]. But chronic power shortages have caused substantial economic losses and limited development opportunities. Bangladesh's power sector is currently dominated by natural gas. However, these local reserves face depletion in the near future. To ensure security of supply the country is diversifying its energy mix, including a long-term power development plan based on coal power plants [75].

To ensure the proper utilization of coal and minimize the pollution from coal it is highly recommended to follow some strict sets of rules provided by the government and energy regulatory divisions. Currently there are some guidelines/regulations regarding the use of coal. These are:

1. Coal Policy, 2010 (Proposed draft), Energy and Mineral Resources Division, Ministry of Power, Energy and Mineral Resources (MPEMR), Government of People's Republic of Bangladesh [76].
2. Environmental Conservation Rules, 1997, Department of Environment, Ministry of Environment and Forest, Government of People's Republic of Bangladesh [77].

3. The Brick Manufacturing and Brick Kilns Establishment (Control) Act, 2013 , Department of Environment, Ministry of Environment and Forest, Government of People's Republic of Bangladesh [78].

However, the regulations or guidelines do not provide substantial guidelines for energy efficient and environment friendly use of coal.

The first draft of the national coal policy was prepared in December 2005. After a series of modifications, the current draft (October 2010) of the policy was made available in public domain through the website of Petrobangla. However, this has not been finalized yet and still holds the draft status.

As stated, the main objective of this coal policy is to ensure the supply of coal along with other fuel sources to meet the demands of commercial fuel needs in long run. In section 3.0, it proposed to declare the North West zone of the country as the center point of commercial fuel and electricity generation as most of the main coal mines are situated in this region. Section 6.0 includes that coal can be exported in case there is a surplus in local coal production after securing the fuel and energy security of the country. The current proposed draft policy also included the environmental aspects of coal usages and mentioned that the licensee must follow the existing environmental acts and rules during coal exploration, mining, storage and usage (Section 7.0). It also proposed waiver of corporate tax for licensees to encourage coal mine exploration, development and marketing, as well as a discount of import duty and tax on the import of machinery for use in coal mining and government will ensure the usage of licensee's produced coal in the coal based power plants in section 15.0. This section also stated that in necessary cases licensees can sell coal to Independent Power Producers' (IPP). Section 15.1 states that commercial industry can build coal based captive power plant for their own use and can also sell their generated electricity to government after meeting their own demand.

Although this proposed draft coal policy has been constructed with great efforts, it has limitation to point out some important features.

- The section 6.0 mentions possibility of exporting coal. However, the current usage of coal and future trends suggests that the extraction of coal from local mines alone would not be sufficient to meet the demand of the power and other sectors. With the current extractable reserve, the coal mines will be able to supply the local needs not more than 40 years, considering only local coals being used in power plants. In addition, current geo-political issues on the ground indicate that efficient mining of coals might not be

possible in a few sites. The method used for extraction (underground) for the Barapukuria mine is highly inefficient and will not be able to extract a significant portion of the available coal. The process being inefficient also has financial drawbacks. The current price of the Barapukuria coal is USD 130 /ton, which is very high compared to the coal price of same quality in the international market. Therefore, it is highly unlikely that our coal will be able to compete with the coal being traded in the international market. Hence, the possibility of exporting coal is almost none. The inclusion of such a clause in the policy is not required and should be omitted.

- Bangladesh has been dependent on imported coal for many years. The future scenario is also similar. The country will need to import coal to meet its future demand in power and other sectors. Therefore, a proper guideline for the import of coal must be included in the coal policy. The guideline must mention the rank of coal, ash content, heating value, moisture and sulfur levels, and must promote import of better quality coals.

- The policy states about captive coal based power plants, but these are very inefficient with very high pollution load per kWh power generation. The policy must not encourage establishment of such power plants. Instead, a guideline regarding the energy efficiency of the boilers and power plants can be included here.

The Environment Conservation Rules (ECR), 1997 provides some guidelines regarding the use of coal. Coal is currently used for producing bricks and power generation. Though, brick kilns are inherently more polluting than the power plants, they are categorized as *Orange-B*, while the power plants are under *Red* category. The process for setting up an *Orange-B* facility is less stringent (requires Initial Environmental Examination (IEE) and Environmental Management Plan (EMP)) than a *Red* category facility (requires IEE, Environmental Impact Assessment (EIA) and EMP). It is highly unlikely that the small brick manufacturing units will be able to provide the cost for a proper EIA. However, the proper evaluation during conducting IEE and EMP must be ensured.

A general guideline is in the ECR for all power plants for particulate matters, chlorine and mercury emission are given in Schedule 11. The same schedule also includes lowest height of stack for coal based power plants based on SOx emission. It also includes some standards for NOx emission gas fuel based power plants, but does not provide any guideline for SOx and NOx emission for brick kilns and coal fired power plants. Although it includes a standard for brick kilns soot, dust and black carbon. In Schedule 12, under sub schedule E, it provides some

general guidelines for soot and particulate matter and NO_x emission for coal, gas and oil fired boilers, but no indication about SO_x and mercury emission.

Department of Environment (DoE), Bangladesh has planned to revise the current ECR and which is under preparation named Environment Conservation Rules (ECR), 2016. This ECR includes a separate guideline of emission of particulate matters, SO_x and NOx for coal fired power plants. But it does not include any standard for chlorine and mercury. The equation and standard for minimum stack height based on SO_x emission is kept same as the previous ECR. Emission standard of soot, dust and black carbon from brick kilns has been lowered in this ECR compared to the previous one. A special guideline for the boilers used in coal fired power plant is also included. ECR 1997 does not include the standard for SO_x and mercury emission for coal fired power plants, but the proposed ECR includes both of these standards.

Use of coal as a source of energy, without proper pollution abatement, can have severe environmental, health and safety damages. Regardless of the conversion process, combustion, gasification or liquefaction, a very large number of pollutants like greenhouse gases (GHG), SO_x, ash, black carbon, particulate matter, toxic hydrocarbons and trace elements can be emitted [79]. GHG gases allow solar energy to reach the earth's surface but delay that energy's escape into space, and thus effectively trapping heat in the lower atmosphere, and as a result global warming can take place [80]. Particulate matters and black carbon are also heat trapping agents and can contribute in climate change. Emission of SOx can cause acid rains. It reacts with airborne substances to form acid which damages forests, crops, soil, lakes, and streams when the acid falls to earth in the form of rain, fog, snow, or dry particles.

4.4.1 Policy recommendations regarding coal quality

Emissions of sulphur and nitrogen oxides are closely related with the composition of the coal. The results of the simulation conducted here showed that the emission of SOx was low for the Barapukuria and South African Coals. Combusting these coals with 20% excess air resulted 8.24 and 10.77 kg SO_x /ton of coal (considering the coal contains 12% moisture; a reasonable equilibrium moisture content). At the same time, Indian and Indonesian coals resulted in approximately 2.5 times SO_x emission compared to the Barapukuria coals. The numbers are clearly indicative of the fact that higher the sulphur content in the parent coal, higher the emission of sulphur oxides. Another index for the SO_x emission can be the kg SO_x per unit thermal energy. The emissions are 0.30, 0.45, 1.48 and 1.14 kg/GJ thermal for the Barapukuria, South African, Indian and Indonesian coals, respectively.

Based on the findings of the simulation, the following recommendations can be made:

- Only the better quality steam coal should be imported whatever might be the source of the coal. There are a few coal blends from Newcastle, Kalimantan or Richards Bay which have sulphur content less than 1% and HHV more than 5000 kcal/kg. Importing coal with lower sulphur content would be beneficial from environmental and operational perspective.

- The ash and moisture content of the coal should also be within a preset range. Lignite coals usually have high moisture and ash. Import of such coals should be discouraged.

4.4.2 Policy Recommendation Regarding Use of Coal in Brick Kilns

Brick Kilns are at present responsible for higher total emissions of CO_2 and SO_x than those of power plants. Brick kilns hardly use any pollution abatement techniques. Therefore, use of coals of better quality in terms of sulphur content is a necessity for brick kilns. At the same time more energy efficient technologies for brick making are environment friendly. Moving to HHK technology approximately 2000 kt of coal can be saved by 2030. This will not only benefit the environment, but also the small business entities involved in the manufacturing of bricks.

Currently, brick kilns are in the Orange category. Therefore, setting up brick kilns does not require a thorough environmental impact assessment (EIA) study; Initial environmental examination (IEE) along with an environmental management plant (EMP) is enough. It is probably unwise to ask small- and medium-scale entrepreneurs to go through EIA for setting up of brick kilns. However, a properly done IEE along with better monitoring will set a pathway for a greener brick-manufacturing sector.

The following recommendations are made for the use of coal in brick kilns:

- The coal quality to be used in brick kilns, especially the maximum sulphur content should be set to limit the emission of sulphur oxides. The calculations for the pollution load assumed use of Indian coal in the brick kilns only. Section 4.4.1 clearly showed that by replacing high-sulphur Indian coal with low-sulphur coal can substantially lower the SO_x emission.

- Current policies, rules and regulations are inadequate for the implementation of pollution abatement in this sector. Improved brick production technology like HHK, VSBK should be introduced to decrease the pollution load.

- Use of non-fired bricks for non-load bearing structures should be encouraged as these kind of bricks are ecofriendly and lower cost. This can further reduce the use of coal in brick making.

4.4.3 Policy Recommendations Regarding the Use of Coal in Power Plants

The projections till 2030, as presented in Section 4.3, clearly indicate that the emissions from power plants are going to significantly higher than that from the brick kilns. The recommendations suggested here are related to the choice of technology in power generation:

- Ultra-super critical power plants are the most efficient option for coal to power generation. Hence, the consumption of coal is less per unit power generation. Therefore, the type of the boilers that will be used in power plants, their operating condition and minimum efficiency should be strictly controlled. High-efficiency, low-emission (HELE) power plants, though require high capital, must be promoted.

- Use of low NOx technologies, such as low-NOx burner (LNB) and selective catalytic reduction (SCR) should be made mandatory. The pollution load calculation considered use of LNB only with 60% removal efficiency. SCR can remove up to 90% NO_x. SCR technology is also capable of oxidizing the elemental mercury to water soluble mercury oxides, and therefore aids in the removal of mercury from the flue gas. Inclusion of this technology can make the process greener.

- To control SO_x emission type of FGD used and their corresponding minimum efficiency should be mentioned. The calculations presented here considered 90% removal of SO_x, which is the typical efficiency of lime- and seawater-based technologies. However, modern lime-based technologies can remove up to 98% SOx from the flue gas.

- Use of seawater for FGD in coastal areas must be made mandatory as seawater-FGD is more environmentally benign, as the products are liquid only. At the same time the operational cost is also lower than the lime-based FGD due to no additional requirement of chemicals.

- The equations provided in the ECR for calculating stack height are not very useful, since they do not consider the current state of the ambient air for stack height calculation. A clear distinction should be made between degraded and non-degraded airsheds. A height of 275 meter stack is also not applicable for cyclone-prone coastal areas of Bangladesh, as the maximum wind gust during category 5 cyclone (such as Sidr) and the soil strength will not permit installation of such an enormous facility in

those areas. Instead of using these equations, stack height should be determined using the guidelines provided by US EPA in 40 CFR Part 51 [81].

- A proper guideline for the handling and use of combustion by-products should be included. Combustion by-products include fly ash, bottom ash, slag, FGD residue like gypsum etc. The policy should promote technologies that would serve as the recipient of these by-products as their raw materials. An industrial ecology has to be developed to ensure a smooth operation and sustainable growth in the utilization of coal. Currently, some of the local cement factories are using imported fly ash from India and China. Use of local fly ash can be promoted by imposing additional tax on fly ash import. The bottom ash and slag materials can be used in brick manufacturing. Special incentive/tax offsets can be provided to the brick manufacturers using combustion by-products from coal-fired power plants.

4.4.4 Policy Recommendations Regarding Emission from Coal-fired Power Plants

Emission standards of several countries/regions for coal-fired power plants and boilers are shown in Table 4.24. It must be mentioned, that ECR 1997 does not have a separate set of emission standards for coal-fired power plants. The numbers presented here are applicable for power plants irrespective of the type of fuel in use. No limits for NOx or SOx are set either. However, there are particulate matter and NOx emission guidelines for coal-fired boilers.

Comparison of the ECR standard with the emission standards of other countries suggests a scope of improvement to improve the environmental performance of the coal-fired power plants (existing and future) of Bangladesh. As coal is going to dominating the energy-mix it is recommended to have a separate set of standards for the coal-fired power plants. The historical changes made in the emission standards of other countries can be studied. By optimizing the trade-off between operational cost and environmental cost, an optimal set of emission standards should be proposed for the benefit to the economy and environment of the country.

Table 4.24: Emission standards for power plants and steam boilers

Parameter	Emission Standards							
	Bangladesh, ECR 1997 [77]	Australia (ACT) [82]	China [83]	EU [84]		India [85]	UN [86]	
				Existing plants	New plants		Existing plants	New plants
Particulate Matter, mg/m^3	150 (>200 MWe) 250 (<200 MWe) 500 (Steam Boilers)	80 (Power Plants) 250 (Steam Boilers)	300	30 (50-100 MWth) 25 (100-300 MWth) 20 (>300 MWth)	20 (50-300 MWth) 10 (>300 MWth)	30		
SO$_X$, mg/m^3	-	200	100 (New) 200 (Existing)	400 (50-100 MWth) 250 (100-300 MWth) 200 (>300 MWth)	400 (50-100 MWth) 200 (100-300 MWth) 150 (>300 MWth)	100	2000 (50-100 MWth) 2000-400 (100-500 MWth) 400 (>500 MWth)	850 (50-100 MWth) 850-200 (100-300 MWth) 200 (>300 MWth)
NO$_X$, mg/m^3	600 (Steam Boilers)	800 (>30 MWe) 500 (<30 MWe) 500 (Steam Boilers)	100	300 (50-100 MWth) 200 (>100 MWth)	300 (50-100 MWth) 200 (100-300 MWth) 150 (>300 MWth)	100		
Level of Desulphurization	-	-	-	92% (50-300 MWth) 96% (>300 MWth)	93% (50-300 MWth) 97% (>300 MWth)		40 (50-100 MWth) 40-90 (100-500 MWth) 90 (>500 MWth)	90 (50-100 MWth) 92 (100-300 MWth) 95 (>300 MWth)
Hg	0.2	-	0.03	-	-	0.03	-	-

Chapter 5
CONCLUSION

5. CONCLUSION

This chapter summarize the findings and discussions of Chapter 4 with concluding remarks. The study performed on four coal samples indicates that Barapukuria and South Africa can be considered as a good quality coal for combustion than Indian and Indonesian coal, because of having higher percentage of hydrocarbons as fixed carbon and lower percentage of volatile matter and moisture content. Higher amount of ash content of Barapukuria and South African coal can favor the formation of slag, fouling, corrosion compared to Indian and Indonesian coal. Chlorine content was found higher than the standard value for Barapukuria and South African coal. Therefore, use of these coal would result higher impact on plant equipment and environment. Although the concentration of mercury was in between the permissible range for all coal samples. However, in bulk condition the amount of mercury release can be alarming, and therefore, mercury emission control must be monitored strictly. Chloro-mercury substances are critical for environment and human health. The interaction between mercury and chlorine during combustion is required to be studied.

Thermodynamic simulation of coal combustion gave an idea about the effluent characteristics of four coal samples with respect to air-fuel ratio. The effluent characteristics were used to predict the pollution load from both power plants and brick kilns. Several technologies for both brick kilns and power plants are considered. Pollution load was calculated for different technologies and a comparative study was performed. Thermodynamic model was used to predict the effluent concentration, although these types of models is not reliable in every case as it consider that equilibrium will be reached after a certain point. In these cases, kinetic model can be used instead of thermodynamic model. Further study can be done in these aspects by considering kinetic model.

A brief discussion on the currently available acts and policies on coal utilization was included. Several guidelines were also suggested which could not be found from existing acts and policies. Major recommended policies include: strict standards regarding the rank and quality of imported coal, establishment of minimum permissible emission of different pollutants from coal fired power plants and brick kilns, introduction of energy efficient brick manufacturing technologies, updating the outdated equations to calculate pollution load, configuration of FGD for SO_x removal, and handling of combustion by-products like fly ash, bottom ash and slags.

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