

**ENERGY AND EXERGY ANALYSES OF
BIOMASS CO-FIRING BASED PULVERIZED
COAL POWER GENERATION**

By

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A Thesis Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Applied Science

in

The Faculty of Engineering and Applied Science

Mechanical Engineering Program

University of Ontario Institute of Technology

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CERTIFICATE OF APPROVAL

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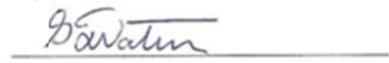
Master of Applied Science in Mechanical Engineering

Date of Defence: April 13, 2011

Thesis title: ENERGY AND EXERGY ANALYSES OF BIOMASS CO-FIRING IN PULVERIZED COAL POWER GENERATION

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ABSTRACT

Biomass co-firing with coal exhibits great potential for large scale utilization of biomass energy in the near future. In the present work, energy and exergy analyses are carried out for a co-firing based power generation system to investigate the impacts of biomass co-firing on system performance and gaseous emissions of CO₂, NO_x, and SO_x. The power generation system considered is a typical pulverized coal-fired steam cycle system, while four biomass fuels (rice husk, pine sawdust, chicken litter, and refuse derived fuel) and two coals (bituminous coal and lignite) are chosen for the analysis. System performance is evaluated in terms of important performance parameters for different combinations of fuel at different co-firing conditions and for the two cases considered. The results indicate that plant energy and exergy efficiencies decrease with increase of biomass proportion in the fuel mixture. The extent of decrease in energy and exergy efficiencies depends on specific properties of the chosen biomass types. The results also show that the increased fraction of biomass significantly reduces the net CO₂ emissions for all types of selected biomass. However, gross CO₂ emissions increase for all blends except bituminous coal/refuse derived fuel blend, lignite/chicken litter blend and lignite/refuse derived fuel blend. The reduction in NO_x emissions depends on the nitrogen content of the biomass fuel. Likewise, the decrease in SO_x emissions depends on the sulphur content of the biomass fuel. The most appropriate biomass in terms of NO_x and SO_x reduction is sawdust because of its negligible nitrogen and sulphur contents.

Keywords: Biomass, Coal, Co-firing, Co-combustion, Emissions, Energy, Exergy, Emissions, CO₂, NO_x, SO_x

ACKNOWLEDGMENTS

First of all, I am very grateful to my supervisors, Dr. Bale V. Reddy and Dr. Marc A. Rosen, for their extraordinary guidance and support throughout the entire process. I would also like to thank Dr. T. Srinivas for his time and valuable suggestions. I would also like to thank the thesis examining committee; Dr. Bale V. Reddy, Dr. Marc A. Rosen, Dr. Hossam A. Gabbar, and Dr. Greg F. Naterer. I would also like to express my great appreciations to the faculty and staff of the Faculty of Engineering and Applied Science at UOIT for their assistance and support. Lastly and the most importantly, I would also like to thank my family for their support, prayers, and encouragement throughout the entire process. I dedicate this thesis to them.

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NOMENCLATURE

Symbols

C_p	Specific heat at constant pressure, kJ/kg.K
\dot{E}	Energy rate, MW
\dot{E}_x	Exergy rate, MW
ex	Specific chemical exergy, kJ/kmol
h	Specific enthalpy, kJ/kg
\bar{h}	Molar specific enthalpy kJ/kmol
h°	Enthalpy of formation, kJ/kmol
HHV	Higher heating value, kJ/kg
LHV	Lower heating value, kJ/kg
\dot{m}	Mass flow rate, kg/s
\dot{n}	Molar flow rate, kmol/s
P	Co-firing ratio
p	Pressure, kPa
\dot{Q}	Heat interaction rate, kW
T	Temperature, K
\dot{W}	Net work produced by system, kW
s	Specific entropy, kJ/kg-K

Greek Letters

Δ	Difference
ψ	Exergy efficiency, %
η	Energy efficiency, %
β	Ratio of chemical exergy to lower heating value

Subscripts

b	Biomass
C	Carbon
c	Coal
H	Hydrogen
<i>i</i>	Identifies the constituent of a mixture
j	Identifies a co-reactant
in	Inlet
N	Nitrogen
O	Oxygen
o	Reference environment state
p	Products
r	Reactants
out	Outlet
S	Sulphur

Superscripts

Ch	Chemical
o	Standard environment state
Ph	Physical

Acronyms

ar	As Received
B	Bituminous coal
BFP	Boiler feed pump
C	Carbon
CL	Chicken litter

CP	Condensate pump
daf	Dry ash free
FWH	Feedwater heater
H	Hydrogen
LPT	Low pressure turbine
HPT	High pressure turbine
M	Moisture
N	Nitrogen
O	Oxygen
RFD	Refuse derived fuel
RH	Rice husk
SD	Sawdust
S	Sulphur
VM	Volatile matter

CHAPTER 1

INTRODUCTION

1.1. Introduction and Motivation

Fossil fuels such as coal, furnace oil, natural gas, gasoline, diesel, and kerosene, despite being non-renewable energy resources and having effects of climate change and global warming, are still the dominant global energy sources. As of 2008, they accounted for 81% of the global total primary energy supply [1]. Due to the large contribution of fossil fuels to world energy mix, it is almost impossible to replace the fossil fuels with other energy resources in the near future. Coal, based on the deposits found to date, is estimated to last for at least 119 years, if consumed and produced at the current rates [2]. In 2006, coal-fired power plants accounted for 41% global electricity production and this trend is expected to continue, with coal based power plants, expected to account for 44% in 2030 [3].

On the other hand, other energy sources like oil and natural gas are depleting with time and the global demand for energy is growing due to the continuous increase in world population. Moreover, emissions of greenhouse gases (CH_4 , CO_2 , etc.) from the combustion of fossil fuels are another major concern. Among these gases, CO_2 is considered the most critical in terms of its contribution to global warming. There was an increase of 1.5% in global CO_2 emissions between 2007 and 2008 [1]. Coal was the major producer of CO_2 emissions and was responsible for 43% of CO_2 emissions from the combustion of fossil fuels. Oil and gas were two other major producers of CO_2 emissions, accounting for 37% and 20% of total CO_2 emissions from fuel combustion respectively, as is illustrated in Figure 1.1. Depletion of fossil fuels and growing greenhouse gases emissions are two major factors that have driven the global interest in the development of sustainable and environmentally friendly energy systems.

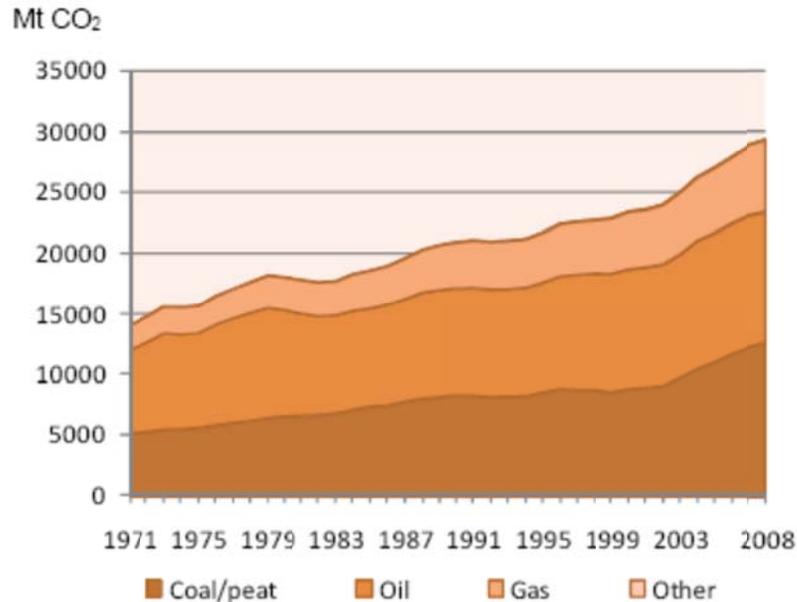


Figure 1.1: Global CO₂ emissions by fuel combustion [1].

Biomass is a renewable energy source, derived from plants and animals. It is one of the oldest energy sources and has been used by mankind for energy purposes since centuries. It is still the major energy source (mainly for cooking and boiling water) in a number of countries and regions (e.g. Bhutan 86%, Nepal 97%, Asia 16%, East Sahelian Africa 81%, and Africa 39%) [4]. Biomass is considered as a CO₂-neutral fuel as it releases no net CO₂ emissions, if carefully managed. The amount of CO₂ released from biomass combustion is absorbed by the plants during photosynthesis. Moreover, biomass fuels have less sulphur and usually have less nitrogen than that of coal. Therefore, biomass fuels have great potential to reduce the greenhouse gases from existing fossil fuel-fired power plants. Due to this reason, the use of biomass as a fuel in the scope of clean environment technologies has gained great interest in recent years.

The world has vast amounts of biomass but most of them are unexploited. The world production of biomass is estimated at 146 billion metric tons a year, mostly as plant growth [5, 6]. Various technologies are available to convert biomass into useful energy through thermochemical and biochemical processes [7-9]. Among these technologies,

biomass co-firing with coal is the most common method and has shown the greatest potential for large scale utilization of biomass energy in the near future [10, 11].

The combustion of biomass alone in the dedicated boilers faces many problems [14]. First of all, the energy content of biomass fuels is much lower than for coals. Due to lower heating values, the efficiency of biomass based power plants is very low. Moreover, the density of biomass fuels is lower and their particle size is higher than that of coal. This means that surplus biomass is required to produce the same amount of heat input produced from the combustion of much lower amount of coal. Cost issues related to dealing with surplus biomass would be another big challenge. Therefore, it is technically and economically more attractive to use biomass as a supplement fuel in existing coal-fired power plants.

Extensive studies [49-71] have been reported on the co-firing of biomass with coal. Experimental studies focus on evaluating the effects of co-firing on a number of factors such as boiler performance, combustion characteristics, gaseous and particulate emissions. Studies related to energy and exergy analyses of such processes are limited. Similarly, there are few modeling studies on biomass co-firing in the literature probably due to the fact that co-firing is a developing technology [67]. Work in all these areas is needed if co-firing technologies for coal and biomass are to develop and become commercial, and the present work aims to address some of these needs. Specifically, the present work presents energy and exergy analyses of a biomass co-firing based conventional pulverized coal power plant.

1.2. Objectives and Approach

Co-firing is a developing technology and currently, there is a great demand for research in this field. There is dearth of studies with regard to energy and exergy analyses of co-firing based power plant reported in the open literature. In particular, there is a severe lack of studies related to exergy analysis. Furthermore, many of the studies conducted are based on experimental results and have not considered exergy analysis.

In this thesis, detailed energy and exergy analyses have been carried out for biomass co-firing based pulverized coal power plants. The main objectives of the present work are to investigate the impacts of co-firing on such parameters as boiler, and plant efficiencies, net work output, furnace gas exit temperature, CO₂, NO_x, and SO_x emissions, energy and exergy losses.

To achieve the objectives, the approach summarized in this paragraph is utilized. A simulation has been performed using Engineering Equation Solver (EES). Four biomass fuels (rice husk, sawdust, chicken litter, and refused derived fuel) and two coals (bituminous coal and lignite) have been considered. Two cases have been considered: fixed fuel input and fixed heat input to the steam cycle. For different combinations of fuels and for each case, the results are compared.

1.3. Thesis Outline

The general outline of the thesis is as follows:

- General background on biomass co-firing with coal (Chapter 2)
- Literature review of relevant studies (Chapter 3)
- Approach and methodology adopted, including assumptions used throughout the study (Chapter 4)
- Description of the power plant and the fuels involved in the analysis (Chapter 5)
- Analysis employed in the investigation with the equations utilized (Chapter 6)
- Results and discussion (Chapter 7)
- General conclusions drawn from the study (Chapter 8)
- Recommendations including how the study results could be used, possible improvements in the present work, and potential areas of future work (Chapter 8)

CHAPTER 2

BACKGROUND

2.1. Co-firing and Its Advantages

Co-firing, also known as co-combustion, is the process of burning two different types of fuels in the same boiler. Although many types of materials can be burned, the term co-firing usually refers to the combustion of solid biomass with coal in coal-fired boilers. Co-firing should not be confused with the combustion of multiple fuels in boilers designed especially for burning of multiple fuels. The basic difference between such a type of combustion and co-firing is that co-firing is achieved in a boiler originally designed to burn only a specific kind of fuel. In simple terms, biomass co-firing can be thought of as the process of partial supplementing of coal with biomass in coal-fired boilers.

Co-firing is a promising technology and it is gaining popularity around the world [7]. It offers many advantages in the energy sector; some of which are discussed here:

- Since, co-firing is carried out in existing coal-fired plants; it can be implemented in a relatively short period of time and with small investment. Therefore, it is a fast way of increasing the use of renewable energy in the energy sector.
- As mentioned earlier, biomass absorbs the same amount of CO₂ as is emitted during its combustion. Therefore, biomass co-firing does not contribute to the greenhouse effect. Hence, biomass co-firing can help reduce overall CO₂ emissions.
- Most biomass fuels have lower sulphur and nitrogen contents than coal; therefore, in many cases, NO_x and SO_x emissions can be decreased by biomass co-firing.

- Disposal of biomass residues is a major source of methane (CH₄) which is considered as 21 times more potent than CO₂ in terms of global warming impact. Co-firing biomass residues brings additional greenhouse gas mitigation by avoiding CH₄ release from the otherwise landfilled biomass [13, 14].
- At present, a number of technologies are available for reducing greenhouse gas emissions. However, co-firing is the least expensive option to mitigate these harmful gases [15].
- Generally, the efficiency of biomass power plants is in the range of 18 to 22% which is much lower than for large coal units [16]. Moreover, biomass co-firing at a 3-5% ratio causes a slight decrease in boiler efficiency (less than 1%) [7]. Thus, co-firing is an efficient way of biomass utilization in power generation.
- Co-firing offers flexibility in terms of fuel use. The plant can still operate at 100% load with coal in case of no biomass supply. This is more feasible in areas where the biomass supply can be seasonal.
- Co-firing can also help companies get credits in countries where government offers incentives for displacing fossil fuels and using renewable energy.
- The local communities who are located in the vicinity of the biomass co-firing plants can benefit economically from the production of biomass fuels.

2.2. Global Status of Co-firing

Biomass co-firing began in the 1980s in Europe and USA and interest in co-firing has grown rapidly in last decade [16]. At present, it is considered as one of the fastest growing renewable technologies. It has become commercial in the USA, Finland, Denmark, Germany, Belgium, The Netherlands, Poland, Austria, Spain, Australia, Japan, Great Britain and a number of other countries [7]. Currently there are over 228 co-firing

installations worldwide [17]. Figure 2.1 illustrates the global distribution of co-firing installations. It can be seen that Continental Europe and USA are currently leaders with more than 100 and 40 plants, respectively. Finland is the leading country with 78 plants, followed by the USA, Germany, UK, Sweden, Denmark, Australia, Canada, Italy, the Netherlands, and Austria. Other countries with co-firing plants include Spain, Belgium, Norway, Indonesia, Taiwan, and Thailand.

Co-firing has been employed using all types of boiler, ranging from 50-700 MWe, although a number of very small plants have also been used [7]. Bubbling and circulating fluidized bed boilers and stoker boilers have been utilized, but most of the boilers involved in the co-firing are pulverized coal boilers, including tangentially-fired, wall-fired, and cyclone units. As of 2004, more than 50% of the boilers utilized in co-firing were of the pulverized fuel type, as illustrated in Figure 2.2.

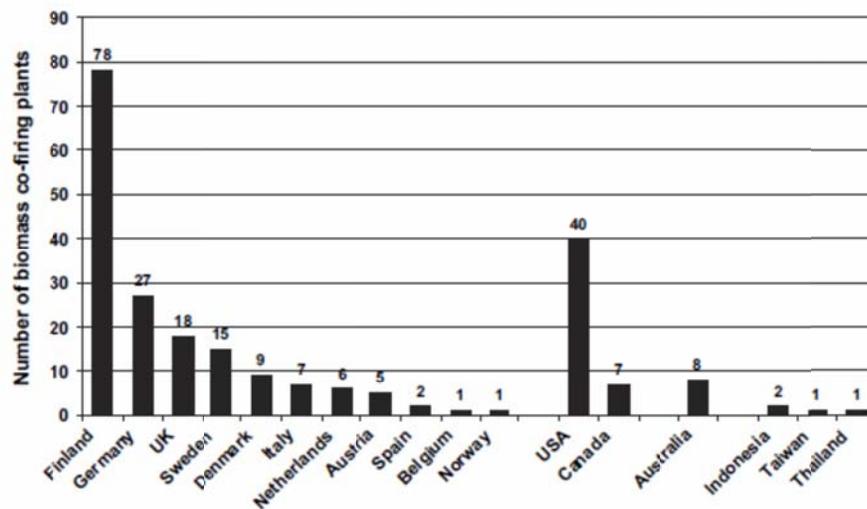


Figure 2.1: Worldwide distribution of biomass co-firing power plants [17].

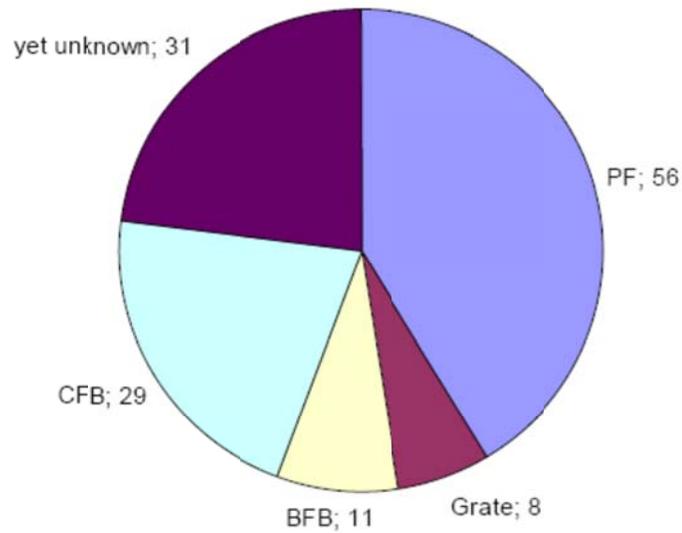


Figure 2.2: Comparison of boiler types utilized in biomass co-firing [7].

2.3. Properties of Biomass and Coal

Biomass and coal are two different fuels and their properties differ significantly. It is important to consider the differences in properties of biomass and coal if biomass co-firing is planned in coal-fired plants. Tables 2.1 and 2.2 compare physical, chemical, and fuel properties of biomass fuels and coal. The tables identify the following differences between biomass fuels and coals:

- In general, biomass is less dense than coal but the particle size of biomass is much higher than that of coal. Due to larger particle size, biomass is much more difficult to reduce to small size.
- Biomass has much less carbon, more oxygen and more moisture than coal. Due to the high moisture and oxygen contents, the heating values of biomass fuels are significantly lower than those of coals [18]. Low heating values and large particle size of biomass fuels cause storage problems.

- The volatile matter of biomass fuels is significantly higher than that of coal and their fixed carbon/volatile ratios are much less than 1.
- Biomass fuels generally have less nitrogen and sulphur contents than coal, which are directly related to NO_x and SO_x emissions.
- Ash and nitrogen contents vary among biomass fuels. In general, woody biomass has less nitrogen and ash compared to agricultural materials. Ash content along with high moisture content in biomass can cause combustion and ignition problems. Moreover, if the melting temperature of the dissolved ash is low, it can also cause slagging and fouling [13].
- Relative to coal, biomass has less aluminum, iron, silica, and titanium, but has more potassium.
- Some biomass types like straw and bark contain relatively large amounts of chlorine. High chlorine and potassium concentrations can cause serious problems, such as slagging, fouling, and corrosion [13]. The major concern is high-temperature corrosion of superheater tubes induced by chlorine on the surface [20, 21].

Table 2.1: Selected properties of biomass fuels and coals [19]

Property	Biomass	Coal
Fuel Density (kg/m ³)	~500	~1300
Particle Size (mm)	~3	~0.1
SiO ₂ Content (wt% of dry ash)	23-49	40-60
K ₂ O Content (wt% of dry ash)	4-48	2-6
Fe ₂ O ₃ Content (wt% of dry ash)	1.5-8.5	8-18
Al ₂ O ₃ Content (wt% of dry ash)	2.4-9.5	15-25
Dry Heating Value (MJ/kg)	14-21	23-28

Table 2.2: Proximate and ultimate analyses (wt %) of biomass fuels and coals [22]

Fuel	Proximate Analysis (ar)*				Ultimate Analysis (daf)**					
	VM	FC	M	A	C	O	H	N	S	Cl
Beech Bark	67.5	17.0	8.4	7.1	51.	41.8	6.0	0.7	0.11	0.11
Oak Wood	73.0	20.0	6.5	0.3	50.	42.9	6.1	0.3	0.10	-
Sawdust	55.1	9.3	34.9	0.7	49.	43.7	6.0	0.5	0.02	0.01
Switch Grass	70.8	12.8	11.9	4.5	49.	43.4	6.1	0.7	0.11	0.08
Straw	64.3	13.8	12.4	9.5	48.	44.5	5.6	1.0	0.13	0.54
Almond Shell	69.5	20.2	7.2	3.1	50.	42.5	6.2	1.0	0.05	0.06
Lignite	32.8	25.7	10.5	31.0	64.	23.7	5.5	1.0	5.8	0.01
Bituminous Coal	33.4	34.1	8.2	24.3	74.	17.7	5.6	1.4	0.9	0.03

*As received basis

**Dry ash free basis

2.4. Technology Options for Co-firing

As mentioned earlier, co-firing has been employed in all kind of boilers used for power generation in coal-fired power plants. According to the current state of the art, there are three basic technology configurations for biomass co-firing in power plants [17]:

- Direct Co-firing
- Parallel Co-firing
- Indirect Co-firing

2.4.1. Direct Co-firing

Direct co-firing involves the burning of biomass and coal in the same furnace. This is the most commonly applied and cheapest co-firing configuration. Depending on the biomass fuel characteristics, the same or separate mills and burners can be used as shown in Figure 2.3. The following four options are available by which direct co-firing can be achieved in pulverized coal boilers [15].

- In the first option, the biomass and coal are blended in the fuel handling systems and then this blend is fed into the furnace. This is the most straightforward and least expensive option; however this option can only be accomplished at low percentages (usually <5%, depending on the pulverizer type) [23], and only in conventional wall or corner-fired boilers [25]. It is also limited to some types of biomass fuels. Olive or palm kernels, cocoa shells and sawdust can be successfully co-fired with coal while herbaceous biomass causes many problems during feeding and sizing [25].
- The second option involves the separate milling of biomass, but the pulverized biomass is injected into the existing pulverized coal pipe work either upstream of the burner or at the burners. This approach involves higher investment but co-firing at elevated ratios can be achieved.
- The third option also involves separate biomass milling, but two separate feeding lines. Coal utilizes the original injection system, whereas biomass is injected into the dedicated burners in the lower furnace. This approach is the most expensive among all direct co-firing options.
- In the final option, biomass is used as a reburn fuel to control the NO_x emissions. Separate milling systems along with separate biomass-fired burners at the exit of the furnace are required in this approach.

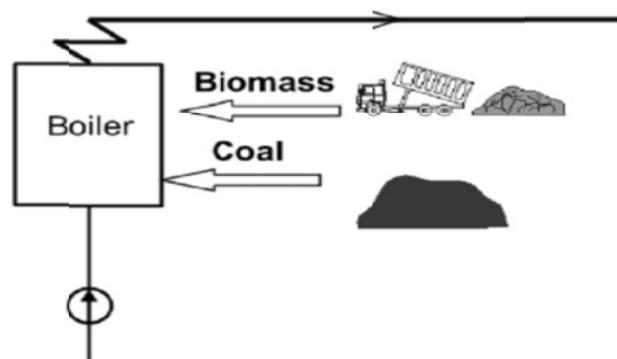


Figure 2.3: Layout of direct co-firing technology [17].

As mentioned earlier, direct co-firing is the most commonly applied approach. There are many plants worldwide which demonstrate this option. An example of such a plant is Gelderland Power Station in the Netherlands [7]. Gelderland Power plant was the first demonstration of direct biomass co-firing in large utility boilers in Europe and commissioned in 1995. Waste wood, having moisture content $< 20\%$, and size $< 1\text{mm}$, is used as a secondary fuel. The total electric output of the plant is 602 MW. 60,000 tonnes of wood is burned per annum, replacing around 45000 tonnes of coal per annum, which is equivalent to 5-8% heat input to the boiler [12]. The handling, metering, and pulverization of wood take place separately, and there are dedicated burners in the lower furnace for the biomass combustion, as is shown in Figure 2.4.

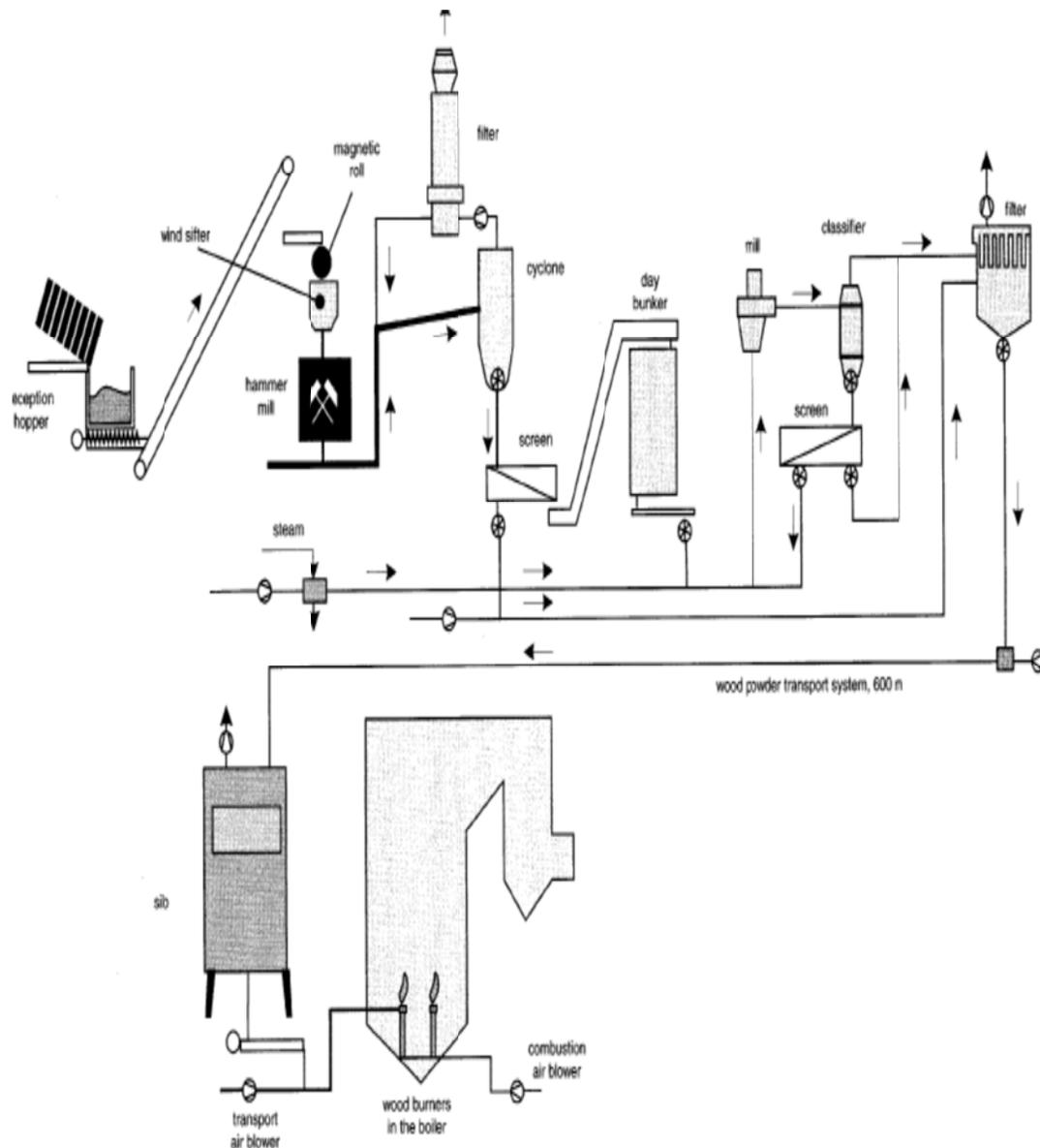


Figure 2.4: Layout of direct co-firing system at Gelderland power station [26].

Another example of direct co-firing is the AES 108 MWe tangentially-fired Greenidge Generation Station in Dresden, New York [12]. The co-firing project was started at Greenidge Generation Station in 1994. At that time, some tests at 5% co-firing ratio were conducted. Based on the test results, the station started co-firing on a sustained basis near the end of 1997. The co-firing system installed at the station has the capability of co-firing wood up to 30% by weight and runs for 16 hours/day. Wood is prepared and introduced into the boiler separately, as illustrated in Figure 2.5.

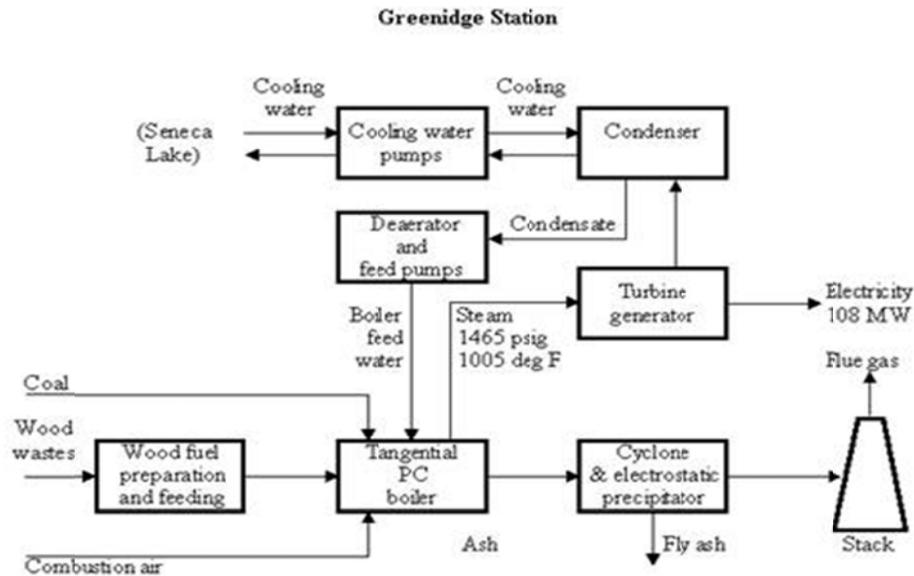


Figure 2.5: Layout of direct co-firing System at Greenidge power station [12].

2.4.2. Parallel Co-firing

In this option, biomass is combusted in a separate boiler to produce low-grade steam for utilization in the coal-fired power plant, as shown in Figure 2.6. The investment in parallel co-firing installations is higher than direct co-firing; however, it has the following advantages:

- The co-firing unit has no effect on the parent unit.
- Relatively difficult fuels with high alkali and chlorine contents can be used.
- This option produces separate streams of biomass and coal ashes.

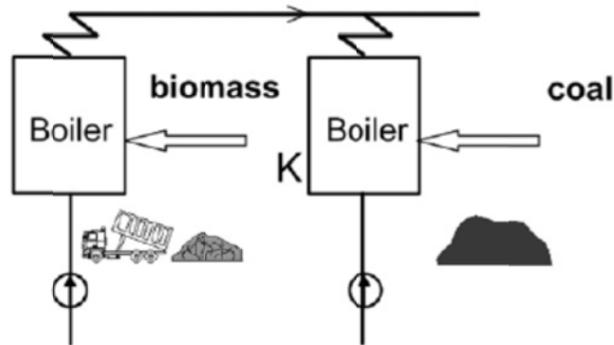


Figure 2.6: Layout of parallel co-firing technology [17]. K represents coal-fired boiler.

The Avedøre Unit 2 project in Copenhagen, Denmark is an example of this option [12]. In this plant, a separate grate-fired boiler is installed to burn straw in parallel to the main boiler, which is an ultra-supercritical boiler and fires natural gas, as illustrated in Figure 2.7. The biomass boiler, rated at $105 \text{ MW}_{\text{th}}$, is the world's largest straw-fired boiler and has the capability to burn 15,000 tonnes of straw per year. It can generate up to 40 kg/s of steam at a temperature 583°C and at pressures up to 310 bars.

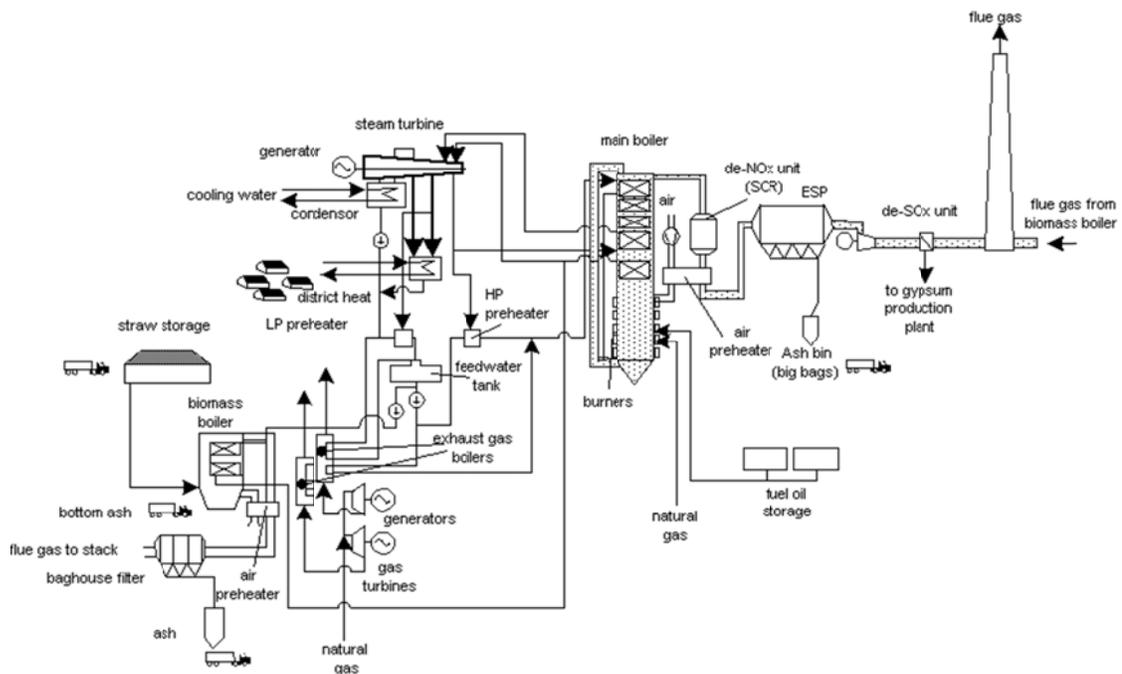


Figure 2.7: Layout of parallel co-firing system at Avedøre power plant [12].

2.4.3. Indirect Co-firing

In this type of co-firing, the solid biomass is gasified separately and the produced gas is combusted in the furnace of existing coal-fired boiler, as shown in Figure 2.8. Although this option has significantly high investment costs, it offers the following advantages:

- Since this type of co-firing requires no blending or mixing, a wide range of biomass fuels can be used. Moreover, biomass ashes are kept separated from coal ashes.
- If the product gas contains impurities, like alkali, chlorine etc., it can be cleaned before its combustion in the furnace. So, the risks of corrosion and fouling are low in this approach.
- The syngas is burnt above the burner, allowing for a reduction of NO_x emissions.

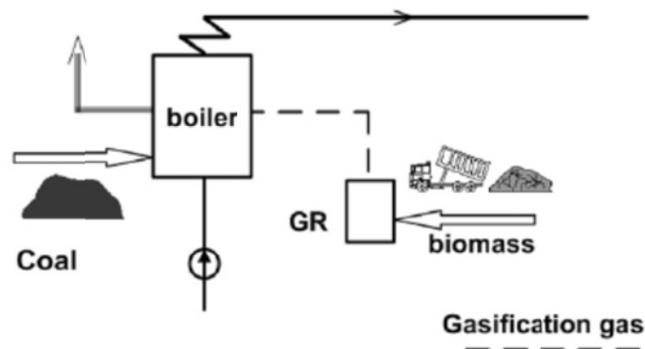


Figure 2.8: Layout of indirect co-firing technology [17]. GR represents biomass gasifier.

The Unit 9 Amer power plant in the Netherlands is an example of indirect co-firing [12]. This project was initiated in 1998 and completed in 2000. About 150 kton/year demolition wood is gasified by the circulating fluidized bed system. The wood is pretreated to have size of 50 mm and moisture content less than 20%. The gasifier

operates at atmospheric pressure and at a temperature between 850°C and 950°C . The system has a capacity of $83 \text{ MW}_{\text{th}}$. Total heat input from the gasification system, i.e. both fuel gas and steam from the fuel gas cooler, is equivalent to 5% of total heat input to the boiler. Biogas is cooled to 500°C and particulate collection is carried out in a hot cyclone, as illustrated in Figure 2.9.

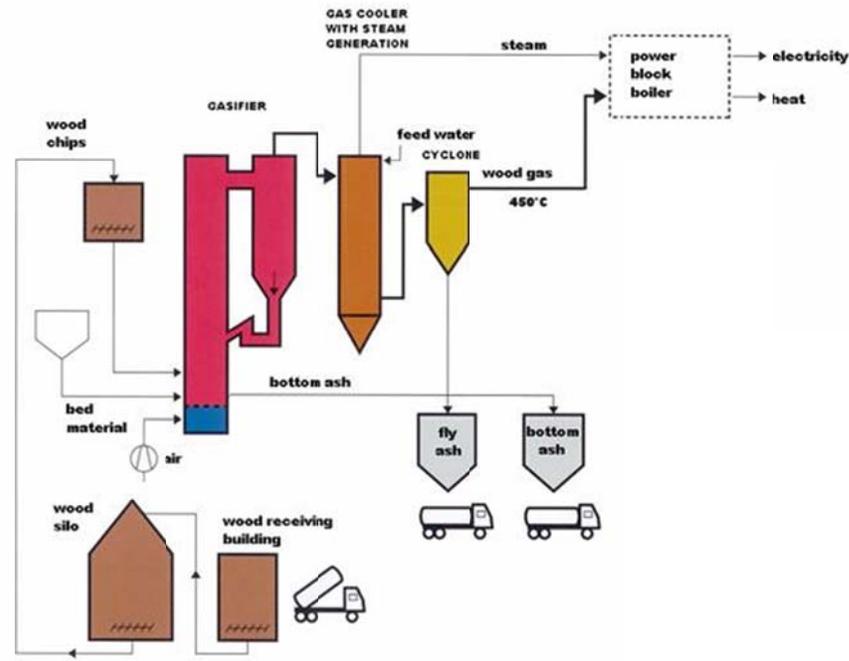


Figure 2.9: Indirect co-firing system at Amer power station [12].

2.5. Aspects of Exergy Analysis

In the present work, energy and exergy analyses of a co-firing based steam power plant are carried. This section deals with general aspects of exergy analysis.

Energy and exergy analyses are of scientific interest to evaluate and optimize the performance of energy-related systems or processes. Energy analysis, which is based on first law of thermodynamics, is the most commonly employed method for the analysis of the energy conversion processes. However, energy analysis does not account for the

internal losses in the process. In contrast, exergy analysis is based on the second law of thermodynamics and helps to identify the magnitude and locations of the imperfections in order to improve the performance of the system or process. Exergy is the useful work potential of a system or stream as it proceeds to an equilibrium state with respect to a reference environment. It is generally not conserved and can be viewed as the quality of the energy [27].

Exergy analysis has been developed over several decades and has been used since 1960 [28, 29]. Many researchers [30-36] have dedicated their studies to the principles and practice of exergy analysis. In recent years, numerous studies [37-48] have been reported by many all over the world in various system applications. However, there are few studies related to energy and exergy of biomass co-firing with coal in open literature. In the present work, energy and exergy analyses are carried out for a biomass co-firing based conventional pulverized coal power plant to investigate the impacts of co-firing on system performance and gaseous emissions of CO_2 , NO_x , and SO_x .

CHAPTER 3

REVIEW OF RELEVANT STUDIES

3.1. General Studies

In this section, general studies related to biomass co-firing in which researchers have summarized their experiences and reviewed the literature on co-firing, are summarized here:

- Demirbas et al. [49] undertook a comprehensive study on the co-firing of biomass with coal. He compared the physical, chemical, combustion, and ash properties of various biomass fuels with those of coal. Fundamental differences in coal and biomass combustion, biomass combustion technologies, technology options for co-firing, and definitions related to co-firing were also listed. Also, mechanisms of co-firing, gasification, and pyrolysis were discussed in detail.
- D. A. Tillman [23] presented a review study on co-firing of biomass and coal. After a brief description of technology options for co-firing, he summarized his experiences at various co-firing based power plants in USA. The influence of co-firing on combustion process, gaseous emissions, and boiler efficiency were documented for each power plant in this study.
- Sami et al. [13] reviewed the literature on co-firing of coal with biomass. In the first part of the review, the basic concepts related to coal and biomass combustion were summarized. Then, the technologies options for the co-firing were discussed. After, the results from various experimental and numerical studies carried out on co-firing were presented. The issues related to co-firing of coal with biomass were also identified.

- Savolainen et al. [50] described his experiences at Naantali Power Plant where co-firing tests of coal with sawdust were performed to investigate the impact of co-firing on boiler performance, flame stability, and emissions. From the results, it was observed that performance of boiler, electrostatic precipitator (ESP), and flu-gas desulfuration (FGD) remained unaffected during co-firing, even with large proportions of sawdust. Flame stability was also found to be normal in all cases. Meanwhile, co-firing led to decrease in CO₂ and SO₂, and NO_x emissions.
- A comprehensive study on technical boiler issues associated with co-firing was provided by Baxter et al. [22]. The major issues on boiler operation during co-firing identified include fuel supply, handling, and storage challenges, ash deposition, fuel conversion, pollutant formation, corrosion, fly ash utilization, impacts on selective catalytic reduction (SCR) systems, and formation of strained flows. Possible measures for managing issues of corrosion, fly ash utilization, formation of strained flows, and impacts on SCR systems are also discussed in this study.
- Pronobis et al. [51] presented a general study to assess the impacts of biomass co-combustion on boiler fouling and thermal efficiency. The calculations were performed for a pulverized fuel fired Polish steam generator by choosing Silesian coal as a base fuel and three types of biomass (straw, wood, and dried sewage sludge). The study indicated that biomass addition results in a deterioration of boiler efficiency and a change in operational parameters. The trends of boiler efficiency found in this study provide a data source for validation in the current thesis.
- A very recent literature review on the biomass co-firing experiences worldwide was reported by Zuwala et al. [17]. Starting with describing the current status of co-firing power plants and current/available co-firing technologies worldwide, key parameters to evaluate the biomass co-firing technologies has been presented. An assessment of implemented co-firing technologies in Europe was carried out and showed that indirect co-firing is the best technology followed by direct co-firing in pulverized fuel, bubbling fluidized boiler, and circulating fluidized bed boilers.

3.2. Experimental Studies

The majority of the experimental studies related to co-firing are limited to studying its impact on gaseous emissions and boiler operation. Some of them investigate flame stability, particulate matter emissions, and combustion characteristics. Experimental studies that are relevant to the present work are summarized here:

- Spliethoff and Hein [52] presented an experimental study to determine the effects of coal co-combustion with straw, miscanthus, wood and municipal sewage sludge on SO_x and NO_x emissions. The experiments were performed on a 0.5 MW semi-industrial pulverized fuel test rig at University of Stuttgart, Germany. The results obtained showed that SO_x emissions decreased for straw, miscanthus, and wood as these fuels have less sulphur content than coal. But, municipal sewage sludge co-firing led to increased SO_x emissions due to its higher sulphur content than coal. For NO_x emissions, they concluded that these emissions depend on the raw fuel content and can be reduced by air staging and reburning the fuel. Thus, the results of Spliethoff and Hein [52] are applicable to the present work for validation.
- Skodras et al. [53] evaluated the effects of biomass co-firing with coal on the boiler performance along with emissions of CO, SO_2 , NO, and polychlorinated dibenzo-p-dioxins (PCCD)/dibenzo-furans (PCDF). The fuels used in this study were lignite, natural wood, medium density fibre (MDF), and wood poles, while co-combustion tests were carried out on a 13.8 MW_{th} industrial steam boiler, by keeping the operating conditions constant for all the experiments. In all cases, co-combustion of lignite with wood and wood residues improved the combustion efficiency and all types of emissions were also found to be lower than combustion of lignite alone.
- Azevedo et al. [54] investigated the effects of pulverized coal co-combustion with pine shells, and textile wastes on particle burnout fraction, unburned hydrocarbons (UHCs), and CO emissions. This study revealed that propane/pine shells flame exhibited the largest UHC and CO emissions in the near burner region, followed by

the propane/textile wastes flame, while for pure propane and propane/coal flames these emissions were observed to be zero. The authors claimed that this was because of relatively large sizes of solid particles of textile wastes and pine shells which resulted insufficient residence time of combustible gases in the near-burner region. Due to the higher volatile matter content of pine shells and textile wastes, the particle burnout fractions from the co-firing of these two fuels wastes were also found to be much higher than that of coal co-firing with propane. As far as NO_x emissions are concerned, they concluded that these emissions depend on the nitrogen content of the fuel and hence were observed to be highest in case of coal, followed by pine shells and textiles wastes, respectively.

- Gani et al. [55] performed experiments on an electrically heated tube furnace to investigate the effects of co-combustion coal/coal mixtures with biomass on ignition behavior, combustion efficiency, NO_x emissions, and size of ash particles. The results showed that biomass enhanced the ignition behavior of low rank coal during co-firing. They claimed that this was because of the high volatile matter content of biomass. The concentrations of NO and N_2O during co-combustion remained the same as were during coal combustion alone. However, co-combustion shifted particle size distributions from fine to coarse particles.
- Kruczek et al. [56] conducted a series of experiments on a laboratory scale isothermal flow reactor by varying fuel type, particle size, combustion temperature, and excess air ratio. Results from this study showed that biomass addition enhanced the combustion process. An increase in biomass proportion in the mixture also resulted in a reduction of NO_x and SO_x emissions. The trends found for NO_x and SO_x emissions also provide a data source for validation in the present thesis.
- Chao et al. [57] evaluated the effects of coal co-firing with rice husk and bamboo on particulate matters and associated polycyclic aromatic hydrocarbon (PAH) emissions. The results showed that the combustion performance of the system was improved during the co-firing. They claimed that this was due to the higher volatile matter

content of biomass which shortened the combustion time scale. As a result of shortened combustion time, the particulate matters and PAH emissions reduced during the co-firing. It was also observed that enlarged grinding size of biomass had no significant effect on the combustion performance.

- Chao et al. [58] continued the previous work and this time the target was to investigate the effects of co-combustion on combustion temperature and gaseous emissions of CO₂, CO, NO_x, and SO_x. It was observed that combustion temperature and all gaseous emissions decreased with increased biomass blending ratio in the mixture. An important result that was found from this experimental study was that biomass grinding size has no obvious effect on combustion temperature and gaseous emissions. However, relative moisture content seemed to have effect on these parameters. Higher moisture content in the mixture caused a further reduction in the combustion temperature which resulted in a higher unburned fraction. The higher unburned fraction led to a decrease in CO₂ and NO_x emissions and an increase in SO_x and CO emissions. The results of Chao et al. [58] are also a means of validation in the present work.
- The effect of co-combustion of pulverized biomass with natural gas on pollutant emissions and particle burnout during was investigated by Casaca et al. [59]. From the results, it was observed that co-combustion of biomass with natural gas had no significant effect on NO_x emissions unless the fuel-bound nitrogen content of the biomass was low. However, CO and hydrocarbon emissions seemed to be dependent on the particle size of the biomass and these emissions were low for large particles. Moreover, it was also seen that large particle sizes of biomass fuels had no deleterious impact on the particle burnout performance.
- Lawrence et al. [60] presented an experimental study on coal co-firing with dairy biomass in a small-scale 29 kW_t furnace. The effect of co-firing on combustion and NO_x emissions were evaluated. This study showed that a blend of dairy biomass and coal burned more completely than coal alone due to the earlier release of biomass

volatiles than those of coal. Further, NO_x emissions were found to be increased in lean mixtures but a very low reduction was observed in rich mixtures due to a lower fraction of fuel bound nitrogen to convert to NO_x .

- Patumaswad et al. [61] reported an experimental study on the co-combustion of high moisture municipal solid waste with coal, using a laboratory scale fluidized bed combustor. This study revealed that municipal solid having moisture waste up to 20% could be burned successfully. The combine impact of moisture and ash content on combustion efficiency was also investigated and it was observed that the effect of ash content was more pronounced than that of moisture content.
- Another study on the co-firing of municipal solid waste (MSW) and coal in a bench-scale bubbling fluidized bed combustor was performed by Demirbas et al. [62]. After discussing the differences in fundamental properties and ash properties of coal and MSW, he investigated the effects of co-firing MSW with coal on gaseous emissions.

3.3. Modeling Studies

Some modeling and simulation studies related to biomass co-firing with coal are presented in this section:

- Abbas et al. [63] developed a numerical model for sawdust co-firing with coal in a 0.5 MW pulverized coal boiler. Turbulence decay model for volatile combustion, diffusive radiation model, and $k-\varepsilon$ model were utilized to develop the code. The influence of burned injection mode on burnout and NO emissions was investigated with the help of this model. From the results, the authors predicted early devolatilization of coal particles. They claimed that this was due to early ignition of biomass volatiles in the near burner region. The increased devolatilization rate of coal particles led to a decrease in NO emissions.

- Backreedy et al. [64] modeled the co-firing of pulverized coal and pinewood in a 1 MW combustor. A commercially available computational fluid dynamics (CFD) code (Fluent version 6) was used for this study. The model investigated the impact of biomass particle size and shape on the burnout of blended char. The modeling results showed that a small wood particle of size 200 μm burned rapidly compared to coal particles of the same size.
- Huang et al. [65] conducted a study using the ECLIPSE process simulator on a pressurized fluidized bed combustion (PFBC) combined cycle power plant to examine the impacts of coal co-firing ratio of biomass on energy efficiency, plant equipment, and gaseous emissions. They selected an American Federal coal of medium calorific value, and five types of biomass fuels (willow chips, straw, switch grass, miscanthus, and olive pits). They observed that the gas turbine output increased while that of steam turbine decreased with an increase in co-firing ratio. For all types of biomass, net CO_2 and SO_x emissions were found to decline as the amount of biomass in the blend increased. On the contrary, NO_x increased, except for willow chips because of its lowest nitrogen content than coal and the other biomass fuels which have higher nitrogen contents than that of coal. As expected, with an increase of co-firing ratio, the overall plant efficiency decreased and the lowest value was found for willow chips due to its highest moisture content among the selected biomass fuels. The results found in this study also provide a data source for validation in the current thesis.
- Doshi et al. [66] presented a mathematical model to determine the ash formation behavior during co-firing. The method developed in this model can be used to predict the ash transformation and formation behavior during co-firing of biomass and coal.
- Ghenai and Janajreh [67] carried out a computational fluid dynamics (CFD) analysis of a co-pulverized coal/wheat straw furnace. They investigated the effects of co-firing on flow field, gas and particle temperature distributions, particle trajectories, and gas emissions. They predicted the velocity vectors to present the flow field of coal

combustion and found similar vectors for co-firing coal with wheat straw. But the furnace gas exit temperature was observed to decrease as the proportion of wheat straw proportion blended with coal increased. Also, this study showed that co-combustion of coal with biomass reduced CO₂ and NO_x emissions.

- Gasification based biomass co-firing was modeled by Dong et al. [68]. The authors carried out a computational fluid dynamics (CFD) analysis for a 600 MW tangential pulverized coal boiler. From the simulation results, it was observed that about a 50-70% reduction in NO_x emissions occurred when the product gas was injected through the lowest layer burner. Moreover, the fouling problem could be reduced by decreasing furnace temperature.

3.4. Energy and Exergy Analyses

There is a lack of studies on energy and exergy analyses of coal co-firing with biomass in the open literature. Some of those reported follow:

- Zuwala et al. [69] performed an energy analysis of a tangentially-fired co-pulverized boiler. The experimental results showed that co-firing of coal and bio-waste consisting of biomass in the mass share of 6.6% or sawdust in the mass share of 9.5% had no adverse effect on boiler efficiency. However, slagging and fouling conditions became worse as a result of co-firing than using coal alone. Moreover, calculated emission indices showed that biomass co-firing reduces CO₂ and SO₂ emissions. The results of this study are also applicable for validation in the current thesis.
- Martín et al. [70] performed an exergy analysis of atmospheric bubbling fluidized bed co-combustion of low grade coal mixtures with pine chips. Exegetic efficiencies and irreversibility were calculated for nine experiments in order to identify the sources of exergy destruction. The exergy efficiency ranged from 31% to 35% and it was found that the performance of the plant can be improved by decreasing the exit temperature

of the exhaust gas. It was also deduced that fluidization velocity has no effect on the exergy efficiency, whereas it is directly proportional to the bed temperature.

3.5. Economic Analysis

Like energy and exergy analyses, studies on the economic analyses of co-firing plant are also limited. Some examples follow:

- De and Assadi [71] developed a tech-economic model to investigate the economics of biomass co-firing. The model is based on the pilot plant test results for co-firing and heat and mass balances. Total additional cost as well as additional specific costs can be estimated with the help of this model. The model can also be applied to assess the economic feasibility of retrofitting for biomass co-firing as well to estimate the required incentives for this purpose.
- Basu et al. [15] carried out an economic analysis of an existing 150 MW pulverized coal fired power plant in Eastern Canada by considering all three co-firing options (direct, indirect, gasification based). Capital and operating costs were calculated to determine the internal rate of return (IRR). CO₂ reduction cost was also computed for these three options and this cost was also compared with CO₂ sequestration cost. The cost of CO₂ sequestration was higher than that of all three technologies. IRR of direct co-firing observed to be more than twice than that of indirect co-firing. But large uncertainties of fouling and corrosion of superheaters in case of direct co-firing make this option less feasible. Although the capital investment required for the implementation of indirect co-firing is the highest, the risk of uncertainties is the least minimum.

CHAPTER 4

APPROACH/METHODOLOGY AND ASSUMPTIONS

4.1. Approach and Methodology

Evaluation of a thermodynamic system is a complex process and involves consideration of its components and their characteristics, chemical reactions and thermodynamic losses. At present, there is growing interest on co-firing of coal and biomass to reduce CO₂ emissions responsible for global warming. In the thesis, energy and exergy analyses have been carried out for a co-firing based power generation system. The power generation system considered is a typical pulverized coal-fired steam cycle system.

The main focus of the present study is to analyze the impacts of co-firing on the performance of system and the gaseous emissions. To achieve this goal, a series of balance equation based on the energy and exergy analyses are developed for each component of the system and the whole system as well. The balanced equations are presented in Chapter 6. Some specific assumptions are made to derive these balance equations, which are described in section 4.2. Using the derived equations, a model is generated using Engineering Equation Solver (EES). With the help of this model, the system performance and emissions are investigated by varying a series of input conditions.

The system is analyzed based on the assumption that the operating temperature and pressure of the components of the steam cycle are not changing while the feeding rate to the boiler is changed by varying fuel type and co-firing ratio. In order to investigate the effect of biomass addition in the blend, the boiler is first fed with coal alone and the system performance and emissions are analyzed. Then, the boiler is fed with biomass and coal in a co-firing mode and system performance and emissions are compared with that of coal firing alone for different co-firing conditions and different fuel types.

Two cases have been considered with respect to boiler feeding conditions. In both cases, mass flow rate of coal at one particular co-firing condition for all the combinations of fuels remains constant. In the first case, the fuel flow rate fed into the boiler is kept fixed and the calculations are done on the basis of unit fuel flow rate. The mass flow rate of coal is decreased from 1 kg/s to 0.75 kg/s in the interval of 0.05 kg/s, while that of biomass is increased from 0 kg/s to 0.30 kg/s. Second case involves keeping the same heat input to the steam cycle as is produced by the burning 1 kg/s of coal alone in the boiler. For this purpose, the mass flow rate of coal is decreased from 1 kg/s to 0.75 kg/s in the interval of 0.05 kg/s while the additional amount of biomass fuel required to produce so much heat in the boiler is found with respect to each case.

The system performance has been evaluated in terms of key parameters. Furnace gas exit temperatures, boiler, and plant efficiencies, net work output, irreversibilities, and major losses are calculated for different combinations of fuels and co-firing conditions. Trends are identified and described in order to investigate the impacts of co-firing on these parameters in detail. These trends are presented in Chapter 7.

The effect of biomass co-firing with coal on gaseous emissions of CO_2 , NO_x , and SO_x are also investigated. In the present study, an attempt has been made to match the NO_x emissions formation with its real formation in the pulverized coal boilers with the assumptions and observations described in the literature. NO_x emitted from the combustion process are in the form of nitric oxide (NO) and nitrogen dioxide emissions (NO_2). These oxides are predominantly NO with a small fraction of NO_2 , usually less than 5% [72-76]. The formation of NO takes place through three paths: fuel bound nitrogen conversion, thermal fixation of atmospheric nitrogen at elevated temperatures (typically greater than 1500°C), and due to prompt formation resulting from the fast reactions within the flame zone involving nitrogen and fuel bound hydrocarbon radicals. About 80% of NO emissions are due to fuel bound nitrogen [73] and 10-50% of the fuel nitrogen is normally converted to NO [72, 74]. Moreover, NO emission through prompt mechanism is less than 5% [74]. All these considerations have been taken into account to match the simulated results with the real results.

4.2. Assumptions

The following simplified assumptions are made in the present work:

- All the components operate at steady state conditions.
- All the gases are ideal gases.
- Ambient air is considered as 79% nitrogen and 21% oxygen on the volume basis.
- The excess air is 20% as is recommended excess air for the pulverized boilers [77, 79].
- Ambient temperature and pressure of the reference environment are 8°C and pressure 1.013 bar respectively.
- Typical fly ash and bottom ash ranges in the pulverized boilers are 70-90% and 10-30% respectively [80]. 80% of the ash in coal being fired is assumed to carry as fly ash. The other about 20% gets collected as bottom ash. Moreover, the ash is inert.
- For pulverized boilers with dry bottom, the bottom ash temperature is 600°C [77]. The same value is used in the analysis.
- All the carbon in the fuel is converted to CO₂. For pulverized coal boilers, the incomplete combustion loss is zero [73, 77]. Moreover, the addition of biomass in the blend enhances the combustion characteristics because of its high volatile content. Therefore, in the view of above facts, this assumption is reasonably valid.
- All the sulphur in the fuel is oxidized to SO₂. This is the only source of SO_x emissions. SO_x emissions are due to formation of SO₂ and SO₃. However, sulphur trioxide (SO₃) only constitutes 10% of SO_x emissions [73]. Both biomass and coal

contain negligible amount of sulphur. So, if any traces of SO_3 are produced, they would be so small that they can be neglected. Therefore, the assumption of complete oxidization of fuel sulphur to SO_2 is also valid.

- NO_x emissions emitted from the combustion process are predominantly NO with a small fraction of NO_2 , usually less than 5% [72-76]. In this analysis, it is assumed that 96% of NO_x emissions are through the formation of NO and 4% are through NO_2 formation.
- As, 10-50% of the fuel nitrogen is normally converted to NO [72, 74]. It is assumed that 30% of the fuel nitrogen is converted to NO.
- For a typical pulverized coal system, approximately, 80% of NO emissions are due to fuel bound nitrogen [73] and NO emission through prompt mechanism is less than 5% [74]. In the present work, it is assumed that the formation of NO emissions through fuel bound, prompt and thermal paths are 80%, 4% and 16% of the total NO emissions formed respectively.
- Radiation and convective heat losses through large boilers are 1-2% of fuel energy input [77, 78]. A mean value, 1.5% is chosen for this work.
- Unburned losses due to combustibles in the ash are equal or less than 2% of fuel energy input [77]. A mean value of 1.5% is chosen to account these losses.
- For large boilers, the stack gas temperature is in the range of 120-180°C [77]. A mean value, 150°C is chosen as the stack gas temperature.
- All the components of the steam cycle have adiabatic boundaries.
- Real steam turbines have isentropic efficiencies in the range of 60-90%, while pumps have isentropic efficiencies in the range of 75-100% [80]. It is assumed that isentropic

efficiency of each turbine is 85%, while each pump has an isentropic efficiency of 88%.

- Mechanical efficiency of turbine found in literature [81-83] is in the range of 95-99%. Mechanical efficiency of each steam turbine is assumed to be 99% in the present analysis.
- Generator efficiency found in the literature [81-83] is in the range of 98-99%. In the present work, the generator is assumed to be 98% efficient.
- Kinetic and potential energy effects are neglected.

CHAPTER 5

SYSTEM CONFIGURATIONS AND CHARACTERISTICS OF FUELS

This chapter deals with the description of the system modeled for this study. The properties of the fuels considered for the analysis are also listed.

5.1. System Description

Figure 5.1 presents a schematic of the co-firing based power plant, modeled for the analysis.

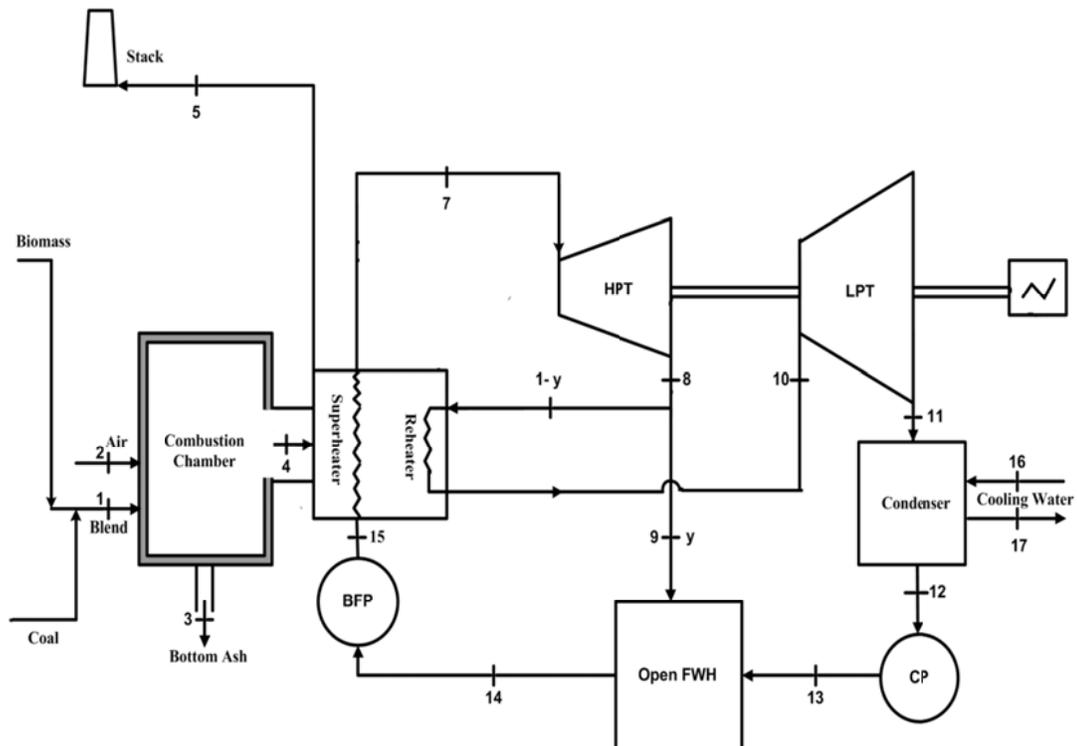


Figure 5.1: Schematic diagram of simulated co-firing power plant. Devices are identified as HPT: high pressure turbine, LPT: low pressure turbine, CP: condensate pump, FWH: feedwater heater, BFP: boiler feed pump.

The co-firing configuration employed is of direct co-firing type because this is the most commonly applied co-firing configuration [7]. Moreover, recall from chapter 2 that if the biomass is injected into the existing pulverized coal pipe work either upstream of the burner or at the burners, co-firing at elevated ratios can be achieved. Therefore, it is assumed that pulverized biomass mixes with pulverized coal in the fuel transport lines just before the burners.

Both air and the fuels enter the boiler at the environment temperature and pressure. Combustion takes place in the combustion chamber and the flue gases after exchanging the heat with the feedwater exit through the stack at 150°C. The majority of the ash (80% is assumed as fly ash) leaves the boiler with the flue gases through the stack while the remaining ash exits at the bottom at 600°C.

Steam which is generated and superheated in the superheater enters the high pressure turbine at 12 MPa and 600°C. After expansion through the first turbine, some of the steam is extracted from the turbine and routed to the open feedwater heater while the remaining is reheated to 600°C and expands through the low pressure turbine to the condenser pressure of 6 kPa. The reheat pressure is $\frac{1}{4}$ of the original pressure. Steam and condensate leaves the feedwater heater as a saturated liquid at the extraction pressure. The condensate leaving the condenser mixes with the feedwater leaving the feedwater heater and mixer is then pumped back to the boiler pressure.

With respect to boiler feeding conditions, two cases are considered. First case involves the same fuel flow rate, while heat input to the steam cycle is kept constant in the second case. Operating temperature and pressure of all the steam cycle components remain the same at all co-firing conditions and for both the cases considered. In the second case, the steam flow rate to cycle also remains constant. However, in the first case, due to changing feeding rate to the boiler, mass flow rate of the steam produced varies at different co-firing conditions which consequently changes the energy and exergy flows at the inlet and outlet of the all components. As a result, net work output of the plant also

changes at different co-firing ratios. The stream data for all the components for both base coals (100% coal) is described in Tables 5.1 and 5.2.

Table 5.1: Stream data for 100% bituminous coal-fired power plant

Stream	Mass Flow Rate (kg/s)	Temperature (°C)	Pressure (bar)	Energy Rate (MW)	Exergy Rate (MW)
1	1	8	1.013	28.33	29.27
2	2.31	8	1.013	0.00	0.046
3	0.002	600	1.013	0.01	0.001
4	11.87	1886	1.013	26.22	20.96
5	11.87	150	1.013	2.867	2.47
6*	0.08	150	1.013	0.009	0.01
7	8.44	600	120	30.46	29.33
8	8.44	395.9	30	27.20	26.07
9	2.35	395.9	30	7.57	7.22
10	6.09	600	30	22.44	21.60
11	6.09	36.17	0.06	15.35	14.50
12	6.09	36.17	0.06	0.92	0.14
13	6.09	36.35	3	0.94	0.16
14	8.44	233.9	3	8.51	7.41
15	8.44	236.2	120	8.62	7.52
16	596.4	8	1.013	20.10	0.00
17	596.4	16	1.013	40.07	19.52

*6 (not shown in figure 5.1) represents fly ash carried with flue gases through stack

Table 5.2: Stream data for 100% lignite-fired power plant

Stream	Mass Flow Rate (kg/s)	Temperature (°C)	Pressure (bar)	Energy Rate (MW)	Exergy Rate (MW)
1	1	8	1.013	20.07	21.19
2	2.31	8	1.013	0.00	0.031
3	0.001	600	1.013	0.009	0.001
4	8.40	1734	1.013	18.12	14.59
5	8.40	150	1.013	3.086	2.24
6	0.06	150	1.013	0.007	0.014
7	5.82	600	120	21.00	20.21
8	5.82	395.9	30	18.75	17.96
9	1.62	395.9	30	5.22	4.96
10	4.24	600	30	15.47	14.88
11	4.24	36.17	0.06	10.58	9.80
12	4.24	36.17	0.06	0.64	0.10
13	4.24	36.35	3	0.65	0.11
14	5.82	233.9	3	5.87	5.11
15	5.82	236.2	120	5.94	5.18
16	411.3	8	1.013	13.86	0.00
17	411.3	16	1.013	27.63	13.46

5.2. Fuel Characteristics

Four biomass fuels and two coals have been chosen for the analysis. Each biomass is selected from a different biomass classification. Pine sawdust, rice husk, chicken litter, and refuse derived fuel (RFD) are the biomass fuels considered in the analysis. Similarly, the coals utilized in the study are from two different classes. One is bituminous coal and the other is lignite. Tables 5.3, 5.4, 5.5, and 5.6 contain the basic information about the feedstocks utilized in the simulations.

The higher heating value (HHV) of the biomass is calculated from the following formula [7]:

$$\begin{aligned}
 HHV_b = & 0.3491C_b + 1.1783H_b + 1.005S_b + 0.0151N_b - 0.1034O_b \\
 & - 0.0211A_b
 \end{aligned} \tag{5.1}$$

where, subscript b represents biomass, while C, H, S, N, O, and A are the carbon, hydrogen, sulphur, nitrogen, oxygen, and ash contents of biomass in weight%.

The lower heating value (LHV) of coal is calculated from the following formula proposed by Ghamarian et al. [84]:

$$LHV_c = 427.0382n_c + 90.88110n_H - 207.46424n_O + 297.0116n_S \quad (5.2)$$

Here, C, H, S, and O are already defined above. Subscript c stands for coal, while n is the number of moles of respective constituent.

For a given substance, the higher and lower heating values are related as:

$$HHV = LHV + 21.978n_H \quad (5.3)$$

Table 5.3: Proximate analysis (wt % of fuels utilized in the analysis)

Fuel	Proximate Analysis (ar)*				Ref*
	Ash	FC*	VM*	Moisture	
Chicken litter	34.3	13.1	43.	9.3	[22]
Pine sawdust	0.1	14.2	70.4	15.3	[22]
Refuse derived fuel	25.0	0.5	70.3	4.2	[22]
Rice husk	14	20.1	55.6	10.3	[85]
Bituminous coal	10.1	53.9	28.2	7.8	[86]
Lignite	8.1	35.0	44.5	12.4	[86]

*ar, FC, VM, and Ref stand for as received basis, fixed carbon, volatile matter, and reference.

Table 5.4: Ultimate analysis (wt %) of fuels utilized in the analysis

Fuel	Ultimate Analysis (ar)					Ultimate Analysis (daf)*					Ref
	C	O	H	N	S	C	O	H	N	S	
Chicken litter	34.1	14.4	3.8	3.50	0.67	60.1	25.3	6.8	6.2	1.20	[22]
Pine sawdust	43.2	36.3	5.0	0.08	-	51.0	42.9	6.0	0.1	-	[22]
RDF	38.1	26.1	5.5	0.78	0.33	53.8	38.8	7.8	1.1	0.47	[22]
Rice husk	38.0	32.4	4.5	0.69	0.06	50.2	6.01	42.8	0.9	0.08	[85]
Bituminous coal	70.3	6.4	3.9	1.07	0.41	85.6	7.8	4.8	1.3	0.5	[86]
Lignite	51.0	23.8	4.1	0.4	0.16	64.2	29.9	5.2	0.5	0.2	[86]

*dry ash free basis

Table 5.5: Ash analysis of fuels utilized in the analysis [22, 85]

Fuel	Constituent										Ref
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	SO ₃	MgO	K ₂ O	TiO ₂	Na ₂ O	P ₂ O ₅	
Chicken Litter	5.77	1.01	0.45	56.85	3.59	4.11	12.19	0.03	0.60	15.40	[22]
Pine sawdust	9.71	2.34	0.10	48.88	2.22	13.80	14.38	0.14	0.35	6.08	[22]
RDF	38.67	14.54	6.26	26.81	3.01	6.45	0.23	1.90	1.36	0.77	[22]
Rice Husk	94.48	0.21	0.22	0.97	0.92	0.19	2.29	0.02	0.16	0.54	[85]
Bituminous Coal	51.67	14.54	10.73	3.72	1.47	1.41	0.29	1.36	0.31	-	[86]
Lignite	46.15	20.91	6.77	12.54	8.00	2.35	1.49	0.77	0.73	0.54	[86]

Table 5.6: Heating values of fuels utilized in the analysis

Fuel	Heating Value (kJ/kg)*	
	Lower Heating Value	Higher Heating Value
Chicken Litter	13,410	14240
Pine Sawdust	16,180	17.28
RDF	15,410	16620
Rice Husk	13,990	14980
Bituminous Coal	27,340	28330
Lignite	19,070	20070

*Calculated from equations 5.1-5.3

CHAPTER 6

ANALYSIS

This chapter deals with energy and exergy analyses performed on the co-firing based steam power plant. Included are the basic equations involved in analysis. We start with analyzing each component of the plant in order to find energy and exergy flows, and irreversibility in each component. Then the overall energy and exergy efficiencies and exergy destructions are found for the whole plant.

6.1. General Balance Equations

The basic equations involved in any thermodynamics analysis are mass, energy and exergy balances, and efficiency equations. With the help of these balances, the net input and output are found. From these, the energy and exergy efficiencies, and irreversibilities can be calculated. The presentations by Rosen et al. [87] and Moran et al. [88] are utilized to write the respective balances and find the appropriate efficiencies here.

For a steady state process, the general balance equations for mass, energy, and exergy can be written as:

Mass Balance:

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e \quad (6.1)$$

Energy Balance:

$$\sum_i \dot{E}_i + \dot{Q}_i = \sum_e \dot{E}_e + \dot{W} \quad (6.2)$$

Neglecting potential and kinetic energy, the above equation can be written as:

$$\sum_i \dot{m}_i h_i + \dot{Q} = \sum_e \dot{m}_e h_e + \dot{W} \quad (6.3)$$

Exergy Balance:

$$\sum_i \dot{E}x_i + \sum_j \left[1 - \frac{T_o}{T_j} \right] \dot{Q}_j = \sum_e \dot{E}x_e + \dot{W} + \dot{I} \quad (6.4)$$

The exergy associated with a flowing matter is the sum of the physical and chemical exergy. In the boiler, both physical and chemical exergy terms will be involved because chemical reaction takes place in the combustion chamber while only physical exergy is associated with the steam cycle components. The specific flow exergy associated with a specified state can be written as:

$$ex = ex^{ph} + ex^{ch} \quad (6.5)$$

The specific physical exergy is defined as:

$$ex^{ph} = (h - h_o) - T_o(s - s_o) \quad (6.6)$$

Similarly, the specific chemical exergy for an ideal gas mixture can be written as

$$ex^{ch} = ex_o^{ch} + R_u T_o \ln x_i \quad (6.7)$$

Here, x_i is the mole fraction of species i and ex_o^{ch} is the molar exergy at the reference temperature. Many researchers [89-93] have proposed methods to calculate the chemical exergy of elements, organic, and inorganic substances. However, the chemical values used in the thesis have been taken from Szargut and Morris [94]. The values given in this

model are based on standard temperature (25°C). These values were corrected for the reference temperature by the following equation [95]:

$$ex_o^{ch} = \frac{T_o}{T^o} ex_{ch}^o - \bar{h}_f^o \frac{T^o - T_o}{T_o} \quad (6.8)$$

where ex_{ch}^o , \bar{h}_f^o , T^o , and T_o are standard molar chemical exergy, enthalpy of formation of formation, standard temperature, and reference temperature, respectively. The values for standard molar exergy for the substances used in the analysis are listed in the Table 6.1.

Table 6.1: Standard enthalpy and exergy of various substances used in analysis [88]

Substance	Standard Enthalpy (MJ/mol)	Standard Exergy (MJ/mol)
O _{2(g)}	0	3.97
N _{2(g)}	0	0.72
CO _{2(g)}	-393.52	19.87
H ₂ O _(g)	-241.82	9.5
H ₂ O _(l)	-285.83	0.9
SO _{2(g)}	-297.10*	313.40
NO _(g)	90.59*	88.90
NO _{2(g)}	33.72*	55.60

* Values for these constituents are not given in [88] and have been taken from EES.

6.2. General Efficiency Equations

The overall energy efficiency, also known as thermal efficiency, can be expressed as:

$$\eta = \frac{\text{Net Energy Output}}{\text{Energy Input}} \quad (6.9)$$

Similarly, the exergy efficiency of the power producing plant is calculated as follows:

$$\psi = \frac{\text{Net Work Output}}{\text{Exergy input}} \quad (6.10)$$

For evaluating the performance of an individual component, a term called exergy destruction ratio is used, which is defined as:

$$Y_d = 1 - \frac{\dot{I}_x}{\sum \dot{I}_x} \quad (6.11)$$

Where, \dot{I}_x represents the irreversibility of component x and $\sum \dot{I}_x$ is the sum of irreversibilities of all the components.

6.3. Energy Analysis

The basic equations employed in the energy analysis performed on the selected co-firing based steam power plant are presented in this section.

6.3.1. Energy Analysis of Boiler

The boiler is divided into two subsystems: combustor and heat exchangers (superheaters and reheater). Mass and energy balances are written for each of these subsystems. Then, overall balances and energy efficiency are found for the boiler.

6.3.1.1. Energy Analysis of Combustor

Both fuel and air enter the combustion chamber at ambient conditions and produce the combustion products at T_p . For a steady state reacting process involving no work, the energy and exergy balances reduce to

$$\sum_i \dot{n}_R \bar{h}_R + \dot{Q} = \sum_i \dot{n}_P \bar{h}_P \quad (6.12)$$

Here, \dot{n}_R , \dot{n}_P , \bar{h}_R , \bar{h}_P , \dot{Q} , are the molar flow rate of reactants, molar flow rate of products, molar specific enthalpy of reactants, molar specific enthalpy of the products, and heat loss from the combustor or boiler respectively.

The molar flow rate of the reactants is the sum of molar flow rate of carbon, hydrogen, oxygen, sulphur, ash, moisture, and air. The molar flow rate of all the reactants, excluding air can be found from the ultimate analysis of the fuels.

$$a_1 = \frac{(P_c C_c + P_b C_b)}{M_C} \quad (6.13)$$

$$a_2 = \frac{(P_c H_c + P_b H_b)}{M_H} \quad (6.14)$$

$$a_3 = \frac{(P_c O_c + P_b O_b)}{M_O} \quad (6.15)$$

$$a_4 = \frac{(P_c N_c + P_b N_b)}{M_N} \quad (6.16)$$

$$a_5 = \frac{(P_c S_c + P_b S_b)}{M_S} \quad (6.17)$$

$$a_6 = \frac{(P_c w_c + P_b w_b)}{M_{H_2O}} \quad (6.18)$$

For convenience, the calculations for the ash are done on a mass basis. The mass flow rate of ash is found as:

$$\dot{m}_{ash} = P_c \dot{m}_{ash,c} + P_b \dot{m}_{ash,b} \quad (6.19)$$

The mass flow rate of the fuel is determined in a similar way:

$$\dot{m}_{fuel} = P_c \dot{m}_c + P_b \dot{m}_b \quad (6.20)$$

In equations 6.13 - 6.20, a_1 to a_6 are the molar flow rates of carbon, hydrogen, oxygen, nitrogen, sulphur, and moisture, respectively. The subscripts c and b denote coal and biomass, while the letters P, M, and m represent the percent share of co-firing, molecular weight, and mass respectively.

The molar specific enthalpy of a compound at a state other than the standard state is sum of the enthalpy of formation of the compound and the specific enthalpy change between the standard state and the state of interest. That is,

$$\bar{h}(T, p) = \bar{h}_f^\circ + \bar{h}(T, p) - \bar{h}_o \quad (6.21)$$

The enthalpy flow of reactants to the control volume contains contributions of the fuels and the air. The enthalpies of formation for several compounds used in the analysis are included in the EES database. However, the enthalpy of formation of both coal and biomass are found from the following formula [96]:

$$\bar{h}_{fuel}^\circ = \overline{HHV}_{fuel} + a_1 \bar{h}_{CO_2}^\circ + \frac{a_2}{2} \bar{h}_{H_2O}^\circ + a_5 \bar{h}_{SO_2}^\circ \quad (6.22)$$

where a_1 , a_2 , and a_5 have already defined by equations 6.13, 6.14, and 6.17. Also, \overline{HHV}_{fuel} is found as:

$$\overline{HHV}_{fuel} = P_c \overline{HHV}_c + P_b \overline{HHV}_b \quad (6.23)$$

The value for standard enthalpy of formation for ash is given in [96]. However, that value of standard enthalpy is for coal ash. The compositions of biomass and ashes are different. So, the standard enthalpy of formation for these two ashes would be different. In the present work, the standard enthalpy of both biomass and coal ashes are calculated from their real composition, given in chapter 5, in order to maintain more accurate results. The standard enthalpy of ash is computed by summing the products of the weight percent and enthalpy for each of the individual ash constituents. The corresponding molecular weight and standard enthalpies of constituents of ash are given in Table 6.2.

Table 6.2: Molecular weight and standard enthalpies of ash constituents [96]

Constituent	Molecular Weight (kg/kmol)	Standard Enthalpy (MJ/kmol)
Silica (SiO ₂)	60	-911.3
Aluminum Oxide (Al ₂ O ₃)	102	-1674.4
Ferric Oxide (Fe ₂ O ₃)	160	-825.9
Calcium Oxide (CaO)	56	-634.6
Magnesium Oxide (MgO)	40	-601.5
Titanium Oxide (TiO ₂)	80	-945.2
Alkalies (Na ₂ O + K ₂ O)	62	-418.2
Sulphur Trioxide (SO ₃)	80	-437.9
Phosphorus Pentaoxide (P ₂ O ₅)*	142	-1505.99

*Reference: [97]

In order to calculate the change in enthalpy ($\Delta\bar{h}$), the values for the enthalpies at different temperatures are required. In EES, the values for different compounds used in the analysis at various temperatures are included in the program database. However, the change in enthalpies of the fuel and ash are calculated as:

$$\Delta h_{fuel} = C_{p,fuel}(T - T^o) \quad (6.24)$$

$$\Delta h_{ash} = C_{p,ash}(T - T^o) \quad (6.25)$$

For the calculation of $\Delta \bar{h}$ of fuel and ash from equations 6.24 and 6.25, specific heats of the fuels are needed. They are calculated by the correlation given in [96]:

$$C_{p,fuel} = FC_F + V_1C_{V_1} + V_2C_{V_2} \quad (6.26)$$

where the subscripts $C_{p,fuel}$, denotes specific heat of fuel (kJ/kg), while F , V_1 , and V_2 are mass fractions of fixed carbon, primary volatile matter, and secondary volatile matter on dry ash free basis, respectively. Fixed carbon is taken from proximate analysis of the fuel. Primary volatile matter is taken to be the amount in excess of 10% on a dry, ash-free basis. The secondary volatile matter is taken to be 10% if the total volatile matter content is greater than 10%. The relationships for the specific heats of fixed carbon, primary volatile matter, and secondary volatile matter are given below:

$$C_F = -0.218 + 3.807 \times 10^{-3}T - 1.7558 \times 10^{-3}T^2 \quad (6.27)$$

$$C_{V_1} = 0.728 + 3.391 \times 10^{-3}T \quad (6.28)$$

$$C_{V_2} = 2.273 + 2.554 \times 10^{-3}T \quad (6.29)$$

The specific heat capacity of fuel calculated from the Equation 6.26 is based on the dry, ash-free basis. In order to determine the specific heat on an as-received basis, the specific heats of ash and moisture are added up in the Equation 6.26.

The specific heat of ash is computed by summing the products of the weight percent and specific heat for each of the individual components. The relationship for calculating the specific heat for the constituents of the ash is provided by Berman et al. [98]:

$$C_{pac} = K_0 + K_1 T^{-0.5} + K_2 T^{-2} + K_3 T^{-3} \quad (6.30)$$

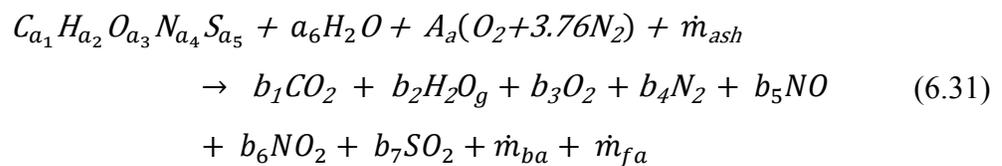
The values for the coefficients k_0 , k_1 , k_2 , and k_3 for the constituents of the ash are given in Table 6.3.

Table 6.3: Coefficients for correlation for specific heat capacity of ash (kJ/kmol) [98]

Constituent	K_0	$K_1 \times 10^{-2}$	$K_2 \times 10^{-5}$	$K_3 \times 10^{-7}$
SiO ₂	80.01	-2.403	-35.47	49.16
Al ₂ O ₃	155.02	-8.28	-38.61	40.91
Fe ₂ O ₃	146.86	0	-55.77	52.56
CaO	58.79	-1.34	-11.47	10.30
MgO	58.179	-1.61	-14.05	11.27
TiO ₂	77.84	0	-33.68	40.29
Na ₂ O	95.148	0	-51.04	83.36
K ₂ O	105.40	-5.77	0	0

The specific heats of SO₃ and P₂O₅ are given in [98]. These values are taken from [99].

The contributions of the combustion products leaving the furnace are the flue gases, ash, heat loss due to radiation and convection from the exterior surface of the boiler, and unburned losses due to combustibles in ash. A value of 1.5% has been chosen to account for each unburned losses due to combustibles in ash and radiation and convective heat losses. The molar flow rate of the products and the excess air are found from the combustion equation. The following general chemical reaction equation for reactants and products entering and leaving the chamber can be written:



Balancing each element in the reactants and products, the following relations are found.

C-Balance:

$$b_1 = a_1 \quad (6.32)$$

H-Balance:

$$b_2 + a_6 = 2b_2 \quad (6.33)$$

O-Balance:

$$a_3 + a_6 + 2A_a = 2b_1 + b_2 + 2b_3 + b_5 + 2b_6 + 2b_7 \quad (6.34)$$

N-Balance:

$$a_5 + 7.52A_a = 2b_4 + b_5 + b_6 \quad (6.35)$$

Here, the second term on the right hand side (b_5) is the molar flow rate of nitrogen oxide (NO). With assumptions, described in Chapter 4, its balance can be written as:

$$b_5 = 0.3a_4 + 3.76\alpha A_a + \beta \quad (6.36)$$

where the first term (β), the second term, and third term on the right hand side represent the formation of nitrogen oxide through prompt, thermal, and fuel-bound nitrogen paths, respectively. Since, 30% (or 0.30) of fuel nitrogen is assumed to be converted to nitrogen oxide, 0.3 is multiplied by a_4 . As, thermal NO is assumed to be 16% of the total NO, we can write:

$$3.76\alpha A_a = 0.16b_5 \quad (6.37)$$

Recall that prompt NO is less than 5% of total NO formation. A value of 4% has been assumed. Thus, the balancing equation for β is:

$$\beta = 0.04b_5 \quad (6.38)$$

In equation 6.36, b_5 is the molar rate of NO_2 . It is assumed to be 4% of the total NO_x emissions. So, its balance equation becomes:

$$b_6 = 0.04(b_5 + b_6) \quad (6.39)$$

S-Balance:

$$a_5 = b_7 \quad (6.40)$$

Ash Balance:

About 80% of the ash in coal being fired is assumed to carry as fly ash. The other 20% gets collected as bottom ash. So, the ash balance can be written as:

$$\dot{m}_{ash} = 0.2\dot{m}_{ba} + 0.8\dot{m}_{fa} \quad (6.41)$$

6.3.1.2. Energy Analysis of Heat Exchangers (Superheater and Reheater)

As seen in the Figure 5.1, water enters the superheater at state 15 and is heated to the temperature of state 7. Similarly, steam enters the reheater at state 8 and exits at state 10. The flue gases after exchanging heat with water exit through the stack to the environment.

The energy balance equation for heat exchangers is:

$$\begin{aligned} \sum_i \dot{n}_{fg} \bar{h}_{fg} + \dot{m}_{fa} \Delta h_{fa} + \dot{Q}_{ub} \\ = \sum_i \dot{n}_{st} \bar{h}_{st} + \dot{m}_s [(h_7 - h_{15}) + (1 - y)(h_{10} - h_8)] \end{aligned} \quad (6.42)$$

In the above equation, \dot{n}_{fg} , \bar{h}_{fg} , \dot{m}_{fa} , Δh_{fa} , \dot{Q}_{ub} , \dot{n}_{st} , \bar{h}_{st} , \dot{m}_s , h_7 , h_{15} , h_{10} , h_8 , and y are molar flow rate of flue gases leaving the furnace, molar specific enthalpy of flue gases leaving the furnace, mass flow rate of fly ash, enthalpy change of fly ash, the heat loss carried by the incombustibles with the fly ash through stack, molar flow rate of flue gases leaving through stack, enthalpy of flue gases leaving through stack, mass flow rate of steam produced, specific enthalpy of feedwater entering superheater, specific enthalpy of steam leaving superheater, specific enthalpy of steam entering reheater, specific enthalpy of steam leaving reheater, and fraction of steam diverted towards open feedwater heater respectively.

The enthalpies values for several compounds used in the analysis are included in the EES database. Heat loss due to incombustibles in ash is assumed to be 1.5% of fuel energy input. The method for calculating Δh of ash is as described above. Moreover, as the composition of the flue gases flowing through the stack is same as of the flue gases leaving the combustor, the mass balance equation for the flue gases through the stack is:

$$\sum_i \dot{n}_{st} = \sum_i \dot{n}_{fg} \quad (6.43)$$

6.3.2. Energy Analysis of High Pressure Turbine

All the steam generated in the boiler expands through high pressure turbine from state 7 to state 8. The mass and energy balances, respectively, are:

$$\dot{m}_7 = \dot{m}_8 = \dot{m}_s \quad (6.44)$$

$$\dot{W}_{HPT} = \dot{m}_s(h_7 - h_8) \quad (6.45)$$

6.3.3. Energy Analysis of Low Pressure Turbine

After expansion through the high pressure turbine, a fraction (y) of steam is diverted at state 8 towards the open feedwater heater. The remaining steam after reheating expands through the low pressure turbine. So, the mass and energy balances, respectively, for low pressure turbine are:

$$\dot{m}_{10} = \dot{m}_{11} = (1 - y)\dot{m}_s \quad (6.46)$$

$$\dot{W}_{LPT} = (1 - y)\dot{m}_s(h_{10} - h_{11}) \quad (6.47)$$

6.3.4. Energy Analysis of Condenser

The exhaust steam from the low pressure turbine enters the condenser at state 11 and leaves at state 12. The cooling water stream enters at 8°C and exits at 16°C. The heat released by the steam flow is equal to the heat absorbed by the cooling water stream. Thus mass and energy balance equations, respectively, are:

$$\dot{m}_{11} = \dot{m}_{12} = (1 - y)\dot{m}_s \quad (6.48)$$

$$\dot{Q}_{condenser} = \dot{m}_4(h_{11} - h_{12}) = \dot{m}_{cw}(h_{17} - h_{16}) \quad (6.49)$$

The mass flow rate of the cooling water is found as

$$\dot{m}_{cw} = \frac{\dot{m}_4(h_4 - h_5)}{\dot{m}_{cw}(h_{17} - h_{16})} \quad (6.50)$$

6.3.5. Energy Analysis of Condensate Pump

Water as a saturated liquid enters condensate pump where its pressure is raised to the open feedwater heater pressure. The respective mass and energy balances are:

$$\dot{m}_{12} = \dot{m}_{13} = (1 - y)\dot{m}_s \quad (6.51)$$

$$\dot{W}_{pump,1} = (1 - y)\dot{m}_s(h_{13} - h_{12}) \quad (6.52)$$

6.3.6. Energy Analysis of Boiler Feed Pump

The mass balance and pump power input for boiler feed pump, respectively, can be expressed as:

$$\dot{m}_{14} = \dot{m}_{15} = \dot{m}_s \quad (6.53)$$

$$\dot{W}_{pump,2} = \dot{m}_s(h_{15} - h_{14}) \quad (6.54)$$

6.3.7. Energy Analysis of Open Feedwater Heater

Mass and energy balances are employed to find the fraction of the steam extracted for this heater. The extracted fraction is found as

$$y = \frac{h_{14} - h_{13}}{h_9 - h_{13}} \quad (6.55)$$

6.3.8. Overall Energy Efficiencies:

Overall boiler, cycle, and plant energy efficiencies can be written as:

$$\eta_{boiler} = \frac{\dot{m}_s[(h_7 - h_{15}) + (1 - y)(h_8 - h_{10})]}{\dot{m}_c LHV_c + \dot{m}_b LHV_b} \quad (6.56)$$

$$\eta_{cycle} = \frac{\dot{W}_{HPT} + \dot{W}_{LPT} - \dot{W}_{pump,1} - \dot{W}_{pump,2}}{\dot{m}_s[(h_7 - h_{15}) + (1 - y)(h_8 - h_{10})]} \quad (6.57)$$

$$\eta_{plant} = \frac{\dot{W}_{HPT} + \dot{W}_{LPT} - \dot{W}_{pump,1} - \dot{W}_{pump,2}}{\dot{m}_c LHV_c + \dot{m}_b LHV_b} \quad (6.58)$$

6.4. Exergy Analysis

The basic equations employed in the exergy analysis performed on the selected co-firing based steam power plant are presented in this section. In a similar way as for the energy analysis, exergy balances for individual components are written, and exergy flows and irreversibilities for each component are found. Then overall exergy efficiency and exergy destruction are found for the whole system.

6.4.1. Exergy Analysis of Boiler

Exergy balances are obtained for the combustion chamber and heat exchangers, and exergy flows and irreversibilities for these components are next found. Then, the exergy efficiency and exergy losses of the boiler are determined.

6.4.1.1. Exergy Analysis of Combustion Chamber

The exergy balance for combustion chamber can be written as:

$$\dot{E}x_f + \dot{E}x_a + \dot{E}x_{Heat} = \sum_e \dot{E}x_{fg} + \dot{I}_{cc} \quad (6.59)$$

Here, $\dot{E}x_1$, $\dot{E}x_2$, $\dot{E}x_{fg}$, \dot{I}_{cc} , and $\dot{E}x_{Heat}$ are exergy flow rate of fuel, exergy flow of air, exergy flow rate of hot products, irreversibility rate of combustion chamber, and the exergy loss rate due to the radiation and convective from the exterior surface of the furnace.

The physical exergy of biomass, coal, and air is zero because they are entering at T_o and P_o . For finding the specific chemical exergy of coal and biomass, the method proposed by Szargut et al. [35] is used. According to that method, the specific chemical exergy of a solid fuel can be expressed as:

$$ex_f^{ch} = \beta_f (LHV_f + wh_{fg}) + w ex_{ch,water}^o \quad (6.60)$$

where w is weight percent of moisture in fuel and $ex_{ch,water}^o$ is the specific chemical exergy of water liquid at the reference conditions. The coefficient β_f is developed from statistical correlations and the relations for coal and biomass are:

$$\beta_b = \frac{1.044 + 0.0160[H/C] - 0.3493[O/C]\{1 + 0.0531[H/C]\}}{1 - 0.4124[O/C]} \quad (6.61)$$

$$\beta_c = 1.0437 + 0.1869[H/C] + 0.0617[O/C] + 0.0428[N/C] \quad (6.62)$$

C, H, O, and N are weight percent of the carbon, hydrogen, oxygen, and nitrogen respectively in the fuel, and are found from ultimate analysis.

The chemical exergy of the air can be calculated with equation 6.7 as:

$$\dot{E}x_{air}^{ch} = A_a [\epsilon_{O_2}^o + 3.76 \epsilon_{N_2}^o + R_u T_o \{\ln(0.21) + \ln(0.79)\}] \quad (6.63)$$

In the above equation, $\dot{E}x_{air}^{ch}$, $\epsilon_{O_2}^o$, $\epsilon_{N_2}^o$, and A_a are chemical exergy flow rate of air, specific chemical exergy of oxygen at reference temperature, specific chemical exergy of nitrogen at reference temperature, and molar flow rate of air.

Similarly, the chemical exergy and physical exergy for the flue gases can be written with equations 6.6 and 6.7. For example, the physical and chemical exergies for carbon dioxide gas can be expressed, respectively, as:

$$Ex_{CO_2}^{ch} = b_1 \left[\epsilon_{CO_2}^o + R_u T_o \left\{ \ln \left(\frac{b_1}{\sum_i b_i} \right) \right\} \right] \quad (6.64)$$

$$Ex_{CO_2}^{ph} = b_1 [(\bar{h}_P - \bar{h}_o) - T_o(\bar{s}_P - \bar{s}_o)] \quad (6.65)$$

For finding the exergy flow rate with ash, changes in enthalpy and entropy are required. The method for finding the change in enthalpy has already been described above. The change in entropy is found as:

$$\Delta s = c_p \ln \frac{T}{T_o} \quad (6.66)$$

Moreover, standard entropy of the ash is found in a similar way as the standard enthalpy of the ash is found. The standard entropies of ash constituents are listed in the Table 6.4.

Table 6.4: Standard entropies of ash constituents [96]

Constituent	Standard Entropy (MJ/kmol)
Silica (SiO ₂)	41.9
Aluminum Oxide (Al ₂ O ₃)	51.1
Ferric Oxide (Fe ₂ O ₃)	90.0
Calcium Oxide (CaO)	39.8
Magnesium Oxide (MgO)	26.8
Titanium Oxide (TiO ₂)	50.2
Alkalies (Na ₂ O + K ₂ O)	72.9
Sulphur Trioxide (SO ₃)	132.7
Phosphorus Pentaoxide (P ₂ O ₅)*	114.19

*Reference: [97]

In order to find the exergy transfer loss rate from the exterior surface of boiler, the boundary or wall temperature of the furnace is required. A relationship given in [78] is used to find the furnace external wall temperature. This method assumes insulation on the entire outer surface of the furnace which represents the main resistance for the heat transfer to the ambient surroundings. The wall temperature is calculated as:

$$U [T_{ow} - T_o] = \frac{k_{ins}}{X_{ins}} [T_f - T_w] \quad (6.67)$$

where U , k_{ins} , X_{ins} , and T_f are overall heat transfer coefficient, thermal conductivity of the wall insulation material, the insulation thickness, and the furnace temperature. The thermal conductivity and insulation thickness are assumed to be 0.06 W/m K and 5 mm respectively.

The overall heat transfer coefficient can be written as:

$$U = 1.9468[T_{ow} - T_o]^{1/4}(2.68633V + 1)^{1/2} + 5.75 \\ \times 10^{-8} \epsilon_{ins} \frac{T_{ow}^4 - T_o^4}{T_{ow} - T_o} \quad (6.68)$$

V and ϵ_{ins} are the wind velocity and insulation emissivity. The average wind velocity for Toronto is 9 mph. A value of 0.01 is assumed for the insulation.

The furnace temperature is estimated by the empirical formula given in [77]:

$$T_f = 0.925 \sqrt{T_{ad} \times T_p} \quad (6.69)$$

Here, T_{ad} and T_p are the adiabatic flame temperature and furnace gas exit temperature, respectively.

6.4.1.2. Exergy Analysis of Heat Exchangers

The exergy analysis for this component takes the following form:

$$\sum_i \dot{E}x_{fg} + \dot{E}x_{fa} + \dot{E}x_{15} + \dot{E}x_8 = \sum_e \dot{E}x_{st} + \dot{E}x_{10} + \dot{E}x_7 + \dot{I}_{rs} \quad (6.70)$$

The procedure for finding the exergy of the flue gases and fly ash has already been described above. The chemical exergy of the flue gases leaving the stack would be the same as of the gases leaving the furnace. The physical exergy would be different and can be calculated with equation 6.6 with respect to the stack temperature, which is assumed to be 150°C. Moreover, only physical exergy would be associated at state 7 to 15 and the exergy at all these states are found from equation 6.6.

6.4.2. Exergy Analysis of High Pressure Turbine

For high pressure turbine, the exergy rate balance and irreversibility rate, respectively, are:

$$\dot{E}x_7 = \dot{E}x_8 + \dot{W}_{HPT} + \dot{I}_{HPT} \quad (6.71)$$

$$\dot{I}_{HPT} = \dot{m}_s T_o (s_8 - s_7) \quad (6.72)$$

6.4.3. Exergy Analysis of Low Pressure Turbine

The exergy balance and irreversibility rate for low pressure turbine are as follows:

$$\dot{E}x_{10} = \dot{E}x_{11} + \dot{W}_{LPT} + \dot{I}_{LPT} \quad (6.73)$$

$$\dot{I}_{LPT} = (1 - y) \dot{m}_s T_o (s_{11} - s_{10}) \quad (6.74)$$

6.4.4. Exergy Analysis of Condenser

The following exergy rate balance and irreversibility rate equations can be written for the condenser:

$$\dot{E}x_{11} + \dot{E}x_{cw,in} = \dot{E}x_{12} + \dot{E}x_{cw,out} + \dot{I}_{condenser} \quad (6.75)$$

$$\dot{I}_{condenser} = T_o[(1 - y)\dot{m}_s(s_{12} - s_{11}) + \dot{m}_{cw}(s_{cw,out} - s_{cw,in})] \quad (6.76)$$

6.4.5. Exergy Analysis of Condensate Pump

The exergy rate balance and irreversibility rate of condensate pump can be written as:

$$\dot{E}x_{12} = \dot{E}x_{13} + \dot{W}_{pump,1} + \dot{I}_{pump,1} \quad (6.77)$$

$$\dot{I}_{pump,1} = (1 - y)\dot{m}_s T_o(s_{13} - s_{12}) \quad (6.78)$$

6.4.6. Exergy Analysis of Boiler Feed Pump

For boiler feed pump, exergy rate balance and irreversibility rate equations are

$$\dot{E}x_{14} = \dot{E}x_{15} + \dot{W}_{pump,2} + \dot{I}_{pump,2} \quad (6.79)$$

$$\dot{I}_{pump,2} = \dot{m}_{steam} T_o(s_{15} - s_{14}) \quad (6.80)$$

6.4.7. Exergy Analysis of Open Feedwater Heater

There are two inputs at points 9 and 13, and one output at point 14 to the open feedwater heater. The equations of exergy balance and irreversibility rate of feedwater can be written as follows:

$$\dot{E}x_9 + \dot{E}x_{13} = \dot{E}x_{14} + \dot{I}_{FWH} \quad (6.81)$$

$$\dot{I}_{FWH} = \dot{m}_{steam} T_o [s_{14} - (1 - y)s_{13} - ys_9] \quad (6.82)$$

6.4.8. Overall Exergy Efficiencies:

The exergy efficiencies for the boiler, the steam cycle and the plant can be written as:

$$\Psi_{boiler} = \frac{\dot{E}x_7 + \dot{E}x_{10} - \dot{E}x_{15} - \dot{E}x_8}{\dot{m}_c ex_c^{ch} + \dot{m}_b ex_b^{ch}} \quad (6.83)$$

$$\Psi_{cycle} = \frac{\dot{W}_{HPT} + \dot{W}_{LPT} - \dot{W}_{pump,1} - \dot{W}_{pump,2}}{\dot{E}x_1 + \dot{E}x_3 - \dot{E}x_8 - \dot{E}x_2} \quad (6.84)$$

$$\Psi_{plant} = \frac{\dot{W}_{HPT} + \dot{W}_{LPT} - \dot{W}_{pump,1} - \dot{W}_{pump,2}}{\dot{m}_c ex_c^{ch} + \dot{m}_b ex_b^{ch}} \quad (6.85)$$

CHAPTER 7

RESULTS AND DISCUSSION

The trends and main findings of the simulated results are presented in this chapter. A series of investigations has been performed for different combinations of fuels and two cases considered. First of all, overall system performance is investigated in terms of inlet energy and exergy flows, and the useful plant outputs. Then, the performance of individual components is explored in terms of energy and exergy losses. The effect of co-firing on energy and exergy efficiencies of boiler and plant is also explored. In the end, the impacts of biomass co-firing on efficiencies and gaseous emissions of CO₂, NO_x, and SO_x are also investigated.

Engineering Equation Solver (EES) is used to generate the simulated model based on the assumptions and equations presented in Chapters 4 and 6. EES includes built in libraries of thermodynamic data for many common substances. To confirm that the simulation program runs accurately, simulated results are compared with hand calculations. The thermodynamic data for hand calculations were taken from Moran et al. [88]. The values obtained from simulated results coincide with those found by hand calculations.

Since, the analysis involves different combinations of fuels; some acronyms are used in order to compare the results with each other. The name of fuels mixture blend is based on the first letter of the coal and first and last letters of the biomass. For example, the name of the bituminous and rice husk blend would be B/RH. Some definitions related to flow rate are also used. Co-firing share of coal (P_c) is defined as the ratio of the mass of coal to the total mass of coal and biomass mixture and can be written as:

$$P_c = \frac{\text{Mass of Coal}}{(\text{Mass of Coal}) + (\text{Mass of Biomass})} \times 100 \quad (7.1)$$

Similarly, co-firing share of biomass, also named as co-firing ratio (P_b) is the ratio of the mass of biomass to the total mass of coal and biomass mixture and can be written as:

$$P_b = \frac{\text{Mass of Biomass}}{(\text{Mass of Coal}) + (\text{Mass of Biomass})} \times 100 \quad (7.2)$$

Moreover, all the graphs for case 1 (fixed fuel flow analysis) are drawn against co-firing ratio. Since, the second case (fixed heat input to steam cycle analysis) involves different co-firing ratios due to varying fuel mass flow rate, the graph in this case are drawn against coal flow rate because coal flow is rate same at one particular co-firing condition for all blends and two cases considered.

7.1. Overall System Performance

The comparison of mass, energy and exergy flows at inlet and the plant useful outputs for different blends and two cases considered is explored in this section. The input to the plant are fuel energy input and exergy input, air energy input and exergy input, and the useful outputs of the plant are the heat and exergy inputs to the steam cycle, and the net power output.

Table 7.1 illustrates the overall inlet flows and plant outputs for the bituminous coal/biomass blends based on a fixed overall fuel flow. The results from the Table 7.1 show that the energy input, exergy input, and air flow rate to the plant decrease with the addition of biomass. The corresponding heat produced in the boiler, useful exergy, and net work outputs also decrease due to the lower input to the system. For every blend, a decrease of more than 2% is observed in these parameters for every 5% biomass addition with respect to the base coal.

Table 7.1: Overall system performance parameters for bituminous coal/biomass blends based on a fixed fuel flow*

Blend	Fuel Flow Rate		Co-firing Share		Input			Output		
	\dot{m}_c (kg/s)	\dot{m}_b (kg/s)	P_c (%)	P_b (%)	Air (mol/s)	\dot{E} (MW)	\dot{E}_x (MW)	\dot{Q} (MW)	\dot{W}_{net} (MW)	\dot{E}_{x_u} (MW)
Base**	1	0	100	0	79.86	28.33	29.30	24.65	9.92	13.74
B/RH	0.95	0.05	95	5	77.85	27.66	28.66	24.04	9.67	13.43
	0.90	0.10	90	10	75.83	27.00	28.02	23.42	9.43	13.09
	0.85	0.15	85	15	73.81	26.33	27.38	22.80	9.18	12.74
	0.80	0.20	80	20	71.79	25.66	26.74	22.18	8.93	12.4
	0.75	0.25	75	25	69.77	24.99	26.10	21.56	8.68	12.06
	0.70	0.30	70	30	67.76	24.33	25.46	20.95	8.43	11.70
B/SD	0.95	0.05	95	5	78.10	27.78	28.79	24.14	9.71	13.49
	0.90	0.10	90	10	76.34	27.23	28.29	23.62	9.51	13.20
	0.85	0.15	85	15	74.58	26.67	27.78	23.10	9.30	12.91
	0.80	0.20	80	20	72.81	26.12	27.27	22.58	9.09	12.61
	0.75	0.25	75	25	71.05	25.57	26.77	22.06	8.88	12.32
	0.70	0.30	70	30	69.29	25.02	26.26	21.54	8.67	12.03
B/CL	0.95	0.05	95	5	77.91	27.63	28.58	24.00	9.66	13.41
	0.90	0.10	90	10	75.99	26.92	27.86	23.35	9.40	13.05
	0.85	0.15	85	15	74.03	26.22	27.14	22.69	9.14	12.69
	0.80	0.20	80	20	72.10	25.51	26.42	22.04	8.87	12.32
	0.75	0.25	75	25	70.13	24.81	25.70	21.39	8.61	11.96
	0.70	0.30	70	30	68.19	24.10	24.98	20.74	8.34	11.46
B/RFD	0.95	0.05	95	5	77.92	27.75	28.74	24.11	9.70	13.48
	0.90	0.10	90	10	75.98	27.16	28.19	23.56	9.49	13.17
	0.85	0.15	85	15	74.02	26.57	27.64	23.02	9.27	12.87
	0.80	0.20	80	20	72.09	25.99	27.08	22.48	9.05	12.56
	0.75	0.25	75	25	70.14	25.40	26.53	21.93	8.83	12.25
	0.70	0.30	70	30	68.20	24.82	25.98	21.39	8.61	11.87

* \dot{m}_c , \dot{m}_b , P_c , P_b , \dot{E} , \dot{E}_x , \dot{Q} , \dot{W}_{net} , and \dot{E}_{x_u} are mass flow rate of coal, mass flow rate of biomass, percent co-firing share of coal, percent co-firing share of biomass or co-firing ratio, energy input rate, exergy input rate, useful heat inputs to steam cycle, useful exergy input to the steam cycle, and net power output of the plant.

**B/RH, B/SD, B/CL, and B/RFD denote bituminous coal/rice husk blend, bituminous coal/sawdust blend, bituminous coal/chicken litter blend, and bituminous coal/refuse derived fuel blend respectively.

The decrease in these parameters mainly depends on the energy density or heating value of the biomass. Chicken litter has the lowest heating value among the selected biomass fuels, so the largest decrease is observed for bituminous coal/chicken litter blend. In contrast, sawdust has the highest heating value among all chosen biomass fuels; hence,

the decreases in these parameters are the smallest for bituminous coal/sawdust blend. In comparison with baseline (100% coal firing), energy input is decreased by 15.29% for bituminous coal/chicken litter blend when co-firing share of chicken litter (co-firing ratio) increases from 0% to 30%. Energy input reduces to 14.67%, 12.25%, and 13.10% for bituminous coal/rice husk blend, bituminous coal/sawdust blend, and bituminous coal/refuse derived fuel blend respectively when co-firing ratio is 30%.

From Table 7.1, we also see that the exergy values are greater than energy values. Energy is a measure of quantity, while exergy is a measure of both energy quantity and quality. Exergy is greater than energy by exergy factor (β). The exergy factors of all biomass fuels are larger than that of bituminous coal. Therefore, the addition of biomass in the blend does not decrease exergy input as much as energy input. The exergy input declines by 14.53% for bituminous coal/chicken litter blend at 30% co-firing ratio.

With less energy input, less air is needed. With respect to baseline, the air flow decreases by 15.15%, 13.23%, 14.61%, and 14.60% for bituminous coal/rice husk blend, bituminous coal/sawdust blend, bituminous coal/chicken litter blend, and bituminous coal/refuse derived fuel blend respectively at 30% co-firing ratio.

From Table 7.1, it is also observed that about 90% of total energy supplied to the boiler is transferred to the steam cycle as useful heat, while around 41% of this useful heat is converted to power. In contrast, 47% of the total exergy supplied to the boiler is carried by water. With decrease in input parameters, output parameters decrease. For each output parameter, reduction of 15.73% is seen for bituminous coal/chicken litter blend at 30% co-firing ratio. But, the output parameters decrease by 15.03%, 12.66%, and 13.14% for bituminous coal/rice husk blend, bituminous coal/sawdust blend, and bituminous coal/refuse derived fuel blend respectively when co-firing ratio increases to 30%.

In case 2, the heat input to the steam cycle is kept constant. Furthermore, the steam cycle conditions are also fixed. Therefore, output parameters are same for all biomass fuels and at all co-firing ratios, as can be seen from the Table 7.2.

Table 7.2: Overall system performance parameters for bituminous coal/biomass blends based on fixed heat input to steam cycle

Blend	Fuel Flow Rate		Co-firing Share		Input			Output		
	\dot{m}_c (kg/s)	\dot{m}_b (kg/s)	P_c (%)	P_b (%)	Air (mol/s)	\dot{E} (MW)	\dot{E}_x (MW)	\dot{Q} (MW)	\dot{W}_{net} (MW)	\dot{E}_{x_u} (MW)
Base	1	0	100	0	79.86	28.30	29.30	24.65	9.92	13.74
B/RH	0.95	0.10	90.45	9.55	79.80	28.40	29.47	24.65	9.92	13.74
	0.90	0.20	81.77	18.23	79.80	28.49	29.66	24.65	9.92	13.74
	0.85	0.30	73.85	26.15	79.70	28.58	29.85	24.65	9.92	13.74
	0.80	0.40	66.59	33.41	79.70	28.66	30.04	24.65	9.92	13.74
	0.75	0.50	59.91	40.09	79.70	28.75	30.23	24.65	9.92	13.74
	0.70	0.60	53.76	46.24	79.70	28.84	30.41	24.65	9.92	13.74
B/SD	0.95	0.09	91.63	8.37	79.70	28.40	29.48	24.65	9.92	13.74
	0.90	0.17	83.84	16.16	79.60	28.48	29.68	24.65	9.92	13.74
	0.85	0.26	76.56	23.44	79.50	28.57	29.88	24.65	9.92	13.74
	0.80	0.35	69.74	30.26	79.30	28.65	30.08	24.65	9.92	13.74
	0.75	0.43	63.36	36.64	79.20	28.73	30.28	24.65	9.92	13.74
	0.70	0.52	57.35	42.65	79.10	28.81	30.48	24.65	9.92	13.74
B/CL	0.95	0.11	89.97	10.03	80.20	28.41	29.40	24.65	9.92	13.74
	0.90	0.21	80.95	19.05	80.50	28.50	29.51	24.65	9.92	13.74
	0.85	0.32	72.79	27.21	80.90	28.59	29.63	24.65	9.92	13.74
	0.80	0.42	65.37	34.63	81.20	28.68	29.74	24.65	9.92	13.74
	0.75	0.53	58.60	41.40	81.60	28.78	29.85	24.65	9.92	13.74
	0.70	0.64	52.40	47.60	82.00	28.87	29.97	24.65	9.92	13.74
B/RFD	0.95	0.09	91.38	8.62	79.50	28.39	29.45	24.65	9.92	13.74
	0.90	0.18	83.40	16.60	79.20	28.46	29.62	24.65	9.92	13.74
	0.85	0.27	75.97	24.03	78.90	28.54	29.79	24.65	9.92	13.74
	0.80	0.36	69.05	30.95	78.60	28.61	29.96	24.65	9.92	13.74
	0.75	0.45	62.59	37.41	78.20	28.68	30.12	24.65	9.92	13.74
	0.70	0.54	56.55	43.45	77.90	28.76	30.29	24.65	9.92	13.74

Table 7.2 shows that the amount of additional biomass required to produce the same heat as can be produced by burning 1 kg/s of bituminous coal also depends on the energy content of biomass. It can be seen from Table 7.2 that when the coal flow rate decreases to 0.70 kg/s, mass flow rate of chicken litter is 0.64 kg/s for bituminous coal/chicken litter blend that is about 113% more as compared to case 1 (fixed fuel flow analysis).

It should be noted that input parameters are not same as are output parameters. All selected biomass, except refuse derived fuel contain more moisture than bituminous coal.

Moreover, all chosen biomass types, except sawdust, have more ash content than bituminous coal. Therefore, in order to cope with the increase in losses caused by biomass moisture and ash, more biomass than coal is needed in order to have same heat rate in the boiler. As a result, energy input and exergy input increase with increasing biomass fraction in the blend. With respect to baseline, increases of 1.91%, 1.80%, 2.01%, and 1.63% in energy input are found for bituminous coal/rice husk blend, bituminous coal/sawdust blend, bituminous coal/chicken litter blend, and bituminous coal/refuse derived fuel blend respectively when coal flow rate decreases from 1 kg/s to 0.70 kg/s. Similarly, the exergy input increases by 3.78% for bituminous coal/rice husk blend, 4.03% for bituminous coal/sawdust blend, 2.28% for bituminous coal/chicken litter blend, and 3.38% for bituminous coal/refuse derived fuel blend when coal flow rate is 0.70 kg/s.

For air flow rate, a slight decrease with respect to base coal is observed with the addition of biomass to the mixture for all blends, except for bituminous coal/chicken litter blend. This is due to fact that all chosen biomass fuels have more oxygen content than that of bituminous coal. This means that amount of oxygen required for combustion is decreased with the addition of biomass to the blend. Moreover, all selected biomass types, except chicken litter contain less nitrogen than bituminous coal. Therefore, addition of all selected biomass fuels except chicken litter to blend further decreases the oxygen required for oxidation of fuel nitrogen to nitric oxide and nitrogen dioxide. The oxygen content of chicken litter is 1.45 times more than that of bituminous coal, while it contains 3.27 times more nitrogen than bituminous coal. As a result, more oxygen is needed for oxidation of its nitrogen. Due to this reason, air flow increases with increase of chicken litter fraction in mixture.

Lignite is the lowest grade of coal and the higher heating value of the selected lignite is 20.07kJ/kg. This means that less energy and exergy are available than that of bituminous coal. Consequently, less heat is produced by its combustion and less air is required for its combustion compared to bituminous coal. Moreover, the differences in composition contents and heating values between lignite and the selected biomass fuels are smaller

than that of bituminous coal and biomass fuels. Hence, relatively smaller reductions percentages are observed for lignite/biomass blends than bituminous coal/biomass blends.

Table 7.3: Overall system performance parameters for lignite/biomass blends based on a fixed fuel flow

Blend	Fuel Flow Rate		Co-firing Share		Input			Output		
	\dot{m}_c (kg/s)	\dot{m}_b (kg/s)	P_c (%)	P_b (%)	Air (mol/s)	\dot{E} (MW)	\dot{E}_x (MW)	\dot{Q} (MW)	\dot{W}_{net} (MW)	\dot{E}_{x_u} (MW)
Base*	1	0	100	0	54.53	20.07	21.22	17.00	6.84	9.49
L/RH	0.95	0.05	95	5	53.75	19.82	20.99	16.76	6.75	9.36
	0.90	0.10	90	10	53.00	19.56	20.75	16.53	6.65	9.23
	0.85	0.15	85	15	52.25	19.31	20.52	16.29	6.56	9.09
	0.80	0.20	80	20	51.50	19.05	20.28	16.06	6.46	8.96
	0.75	0.25	75	25	50.75	18.80	20.05	15.82	6.37	8.83
	0.70	0.30	70	30	50.00	18.54	19.81	15.59	6.27	8.70
L/SD	0.95	0.05	95	5	54.01	19.93	21.12	16.85	6.79	9.41
	0.90	0.10	90	10	53.51	19.79	21.02	16.73	6.73	9.33
	0.85	0.15	85	15	53.02	19.65	20.92	16.58	6.67	9.25
	0.80	0.20	80	20	52.52	19.51	20.81	16.44	6.62	9.18
	0.75	0.25	75	25	52.03	19.37	20.71	16.29	6.56	9.10
	0.70	0.30	70	30	51.53	19.23	20.61	16.18	6.51	9.02
L/CL	0.95	0.05	95	5	53.82	19.78	20.91	16.73	6.73	9.34
	0.90	0.10	90	10	53.14	19.49	20.60	16.47	6.63	9.19
	0.85	0.15	85	15	52.47	19.20	20.29	16.20	6.52	9.04
	0.80	0.20	80	20	51.79	18.90	19.98	15.94	6.41	8.89
	0.75	0.25	75	25	51.12	18.61	19.67	15.65	6.31	8.74
	0.70	0.30	70	30	50.44	18.32	19.35	15.39	6.19	8.59
L/RFD	0.95	0.05	95	5	53.83	19.90	21.08	16.85	6.78	9.40
	0.90	0.10	90	10	53.15	19.73	20.93	16.67	6.71	9.31
	0.85	0.15	85	15	52.48	19.55	20.78	16.53	6.65	9.22
	0.80	0.20	80	20	51.80	19.38	20.63	16.35	6.58	9.13
	0.75	0.25	75	25	51.13	19.21	20.49	16.20	6.52	9.04
	0.70	0.30	70	30	50.45	19.04	20.34	16.03	6.45	8.95

*Acronyms are identified as L/RH: lignite/rice husk blend, L/SD: lignite/sawdust blend, L/CL: lignite/chicken litter blend, L/RFD: lignite/refuse derived fuel blend.

Table 7.3 illustrates that the maximum reductions in energy and exergy inputs are found to be 8.91% and 8.80% respectively for lignite/chicken litter blend when co-firing ratio increases from 0% to 30%. Also, decreases of 7.97%, 4.56%, and 5.77% are found for lignite/rice husk blend, lignite/sawdust blend, and lignite/refuse derived fuel blend,

respectively at 30% co-firing ratio. Like bituminous coal/rice husk blend, the maximum decrease in air flow rate is found for lignite/rice husk blend. Air flow rate is reduced by 8.26% for this blend at 30% co-firing ratio.

From Table 7.3, it is found that about 89% of total energy supplied by lignite to the boiler is transferred to steam cycle as useful heat, while around 41% of this useful heat is converted to power. In contrast, 44% of the total exergy supplied to the boiler is carried by water. With respect to base coal, maximum reductions found in output parameters are for lignite/chicken litter blend. For each output parameter a decrease of 9.45% is observed for lignite coal/chicken litter blend at 30% co-firing ratio.

Table 7.4 shows the overall system performance parameters for lignite/biomass blends for case 2.

From Table 7.4, it is evident that the amounts of additional biomass required to produce same heat as can be produced by burning 1 kg/s of lignite are also smaller for lignite and biomass co-firing than that of bituminous coal and biomass co-firing. When the coal flow rate decreases to 0.70 kg/s, mass flow rate of chicken litter is 0.44kg/s while that of rice husk, sawdust, and refuse derived fuel is 0.41 kg/s, 0.36 kg/s and 0.37 kg/s respectively. The comparison of coal and biomass flow rate for all blends based on fixed for case 2 is shown in Figure 7.1.

Table 7.4: Overall system performance parameters for lignite/biomass blends based on fixed heat input to steam cycle

Blend	Fuel Flow Rate		Co-firing Share		Input			Output		
	\dot{m}_c (kg/s)	\dot{m}_b (kg/s)	P_c (%)	P_b (%)	Air (mol/s)	\dot{E} (MW)	\dot{E}_x (MW)	\dot{Q} (MW)	\dot{W}_{net} (MW)	\dot{E}_{x_u} (MW)
Base	1	0	100	0	54.53	20.07	21.22	17.00	6.84	9.49
L/RH	0.95	0.07	93.27	6.73	54.51	20.10	21.30	17.00	6.84	9.49
	0.90	0.14	86.74	13.26	54.49	20.13	21.38	17.00	6.84	9.49
	0.85	0.21	80.44	19.56	54.48	20.16	21.46	17.00	6.84	9.49
	0.80	0.28	74.36	25.64	54.47	20.19	21.54	17.00	6.84	9.49
	0.75	0.34	68.50	31.50	54.46	20.22	21.63	17.00	6.84	9.49
	0.70	0.41	62.84	37.16	54.45	20.26	21.71	17.00	6.84	9.49
L/SD	0.95	0.06	94.12	5.88	54.42	20.09	21.31	17.00	6.84	9.49
	0.90	0.12	88.31	11.69	54.36	20.12	21.39	17.00	6.84	9.49
	0.85	0.18	82.62	17.38	54.30	20.15	21.48	17.00	6.84	9.49
	0.80	0.24	77.03	22.97	54.25	20.18	21.57	17.00	6.84	9.49
	0.75	0.30	71.54	28.46	54.19	20.21	21.65	17.00	6.84	9.49
	0.70	0.36	66.16	33.84	54.13	20.24	21.74	17.00	6.84	9.49
L/CL	0.95	0.07	92.92	7.08	54.74	20.10	21.26	17.00	6.84	9.49
	0.90	0.15	86.10	13.90	55.01	20.13	21.29	17.00	6.84	9.49
	0.85	0.22	79.57	20.43	55.28	20.17	21.32	17.00	6.84	9.49
	0.80	0.29	73.31	26.69	55.54	20.21	21.36	17.00	6.84	9.49
	0.75	0.36	67.32	32.68	55.81	20.24	21.39	17.00	6.84	9.49
	0.70	0.44	61.56	38.44	56.08	20.28	21.42	17.00	6.84	9.49
L/RFD	0.95	0.06	93.95	6.05	54.29	20.09	21.29	17.00	6.84	9.49
	0.90	0.12	87.99	12.01	54.09	20.11	21.36	17.00	6.84	9.49
	0.85	0.18	82.16	17.84	53.89	20.13	21.42	17.00	6.84	9.49
	0.80	0.25	76.46	23.54	53.70	20.15	21.49	17.00	6.84	9.49
	0.75	0.31	70.89	29.11	53.50	20.18	21.56	17.00	6.84	9.49
	0.70	0.37	65.44	34.56	53.30	20.20	21.63	17.00	6.84	9.49

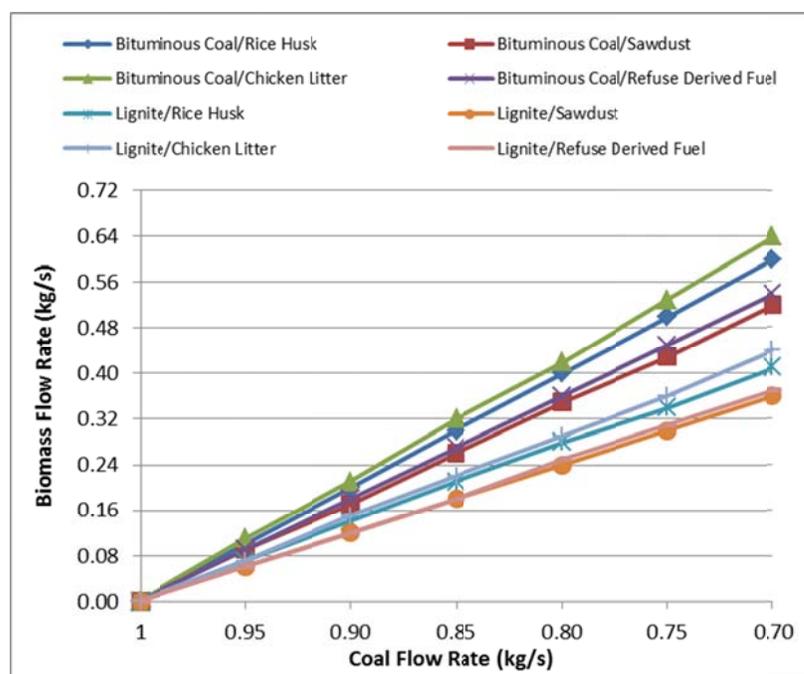


Figure 7.1: Comparison of coal and biomass flow rates based on fixed heat input to steam cycle.

It can be seen from Table 7.4 that there is an increase in energy input and exergy input with increase of biomass in mixture. In comparison with baseline, increases of 1%, 0.90%, 1.10%, and 0.70% are found in energy input for lignite/rice husk blend, lignite/sawdust blend, lignite/chicken litter blend, and lignite/refuse derived fuel blend respectively when coal flow rate decrease to 0.70 kg/s. Similarly, exergy input is increased by 2.17%, 2.40%, 0.75%, and 1.79% for lignite/rice husk blend, lignite/sawdust blend, lignite/chicken litter blend, and lignite/refuse derived fuel blend respectively with 0.70 kg/s coal flow rate.

For air flow rate, trends for lignite and biomass co-firing are also same as were for bituminous coal and biomass co-firing. Air flow decreases with an increase of biomass for lignite/rice husk blend, lignite/sawdust blend, and lignite/refuse derived fuel blend, while air flow rate increases for lignite/chicken litter blend, due to much higher nitrogen content of chicken litter than that of lignite. When coal flow rate decreases to 0.70 kg/s, the reductions of 0.15%, 0.73%, and 2.25% are found in air flow rate for lignite/rice husk

blend, lignite/sawdust blend, and lignite/refuse derived fuel blend respectively. In contrast, air flow is increased by 2.82% for lignite/chicken litter blend with 0.70 kg/s of coal.

7.2. Effect of Co-firing on Energy and Exergy losses

In section 7.1, system performance was investigated with input and output parameters. In this section, the system is evaluated based on energy and exergy losses of its components. It is important to note that exergy loss is made up of waste exergy emissions to environment (or external exergy losses) and internal exergy destructions (or internal exergy losses) caused by irreversibilities. On the other hand, energy loss is simply waste energy emissions to environment. Energy losses and external exergy losses associated with the boiler are due to moisture in fuel, exit flue gases, ash, unburned combustibles, and radiation and convection from the furnace exterior. Energy losses and exergy losses associated with steam cycle components are due to heat rejection from condenser and irreversibilities. In this section, energy losses and external exergy losses are discussed together. The effect of co-firing on irreversibilities is investigated separately. Moreover, furnace exit gas temperature is an important parameter for investigating performance of boiler, so the impact of co-firing on furnace exit gas temperature is also explored in this section.

7.2.1. Effect of Co-firing on Furnace Exit Gas Temperature

One of the most important performance measures for boiler is furnace exit gas temperature. Heat transfer between furnace exit gas and feed water depends upon furnace exit gas temperature.

Figures 7.2 and 7.3 show the effect of co-firing on furnace exit gas temperature. It is evident that furnace exit gas temperature decreases with increase of biomass for all blends. The extent of decrease in furnace exit gas temperature depends upon heating value, moisture content, and ash content of biomass fuels. If the heating value of biomass

is too low, energy input would also be low. Similarly high moisture content of biomass implies that part of heat supplied would be wasted to vaporize the moisture. Likewise, higher ash content results in more sensible heat leaving the combustion chamber. Consequently, furnace exit gas temperature would be low. Among all chosen biomass, chicken litter has the lowest calorific value and the highest ash content. It also contains more moisture than bituminous coal. Therefore, the largest reductions in furnace exit gas temperature are found for bituminous coal/chicken litter blend and lignite/chicken litter blend. With respect to base coal, furnace exit gas temperature decreases from 2079 K to 2031 K and from 2007 K to 1962 K for bituminous coal/chicken litter blend and lignite/chicken litter blend respectively when co-firing ratio increases from 0% to 30%.

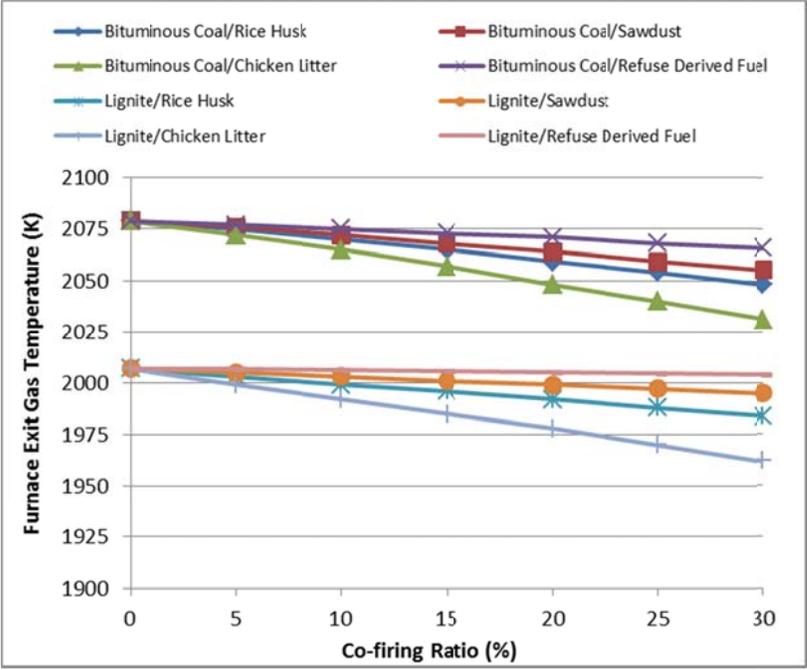


Figure 7.2: Effect of co-firing on furnace exit gas temperature based on a fixed fuel flow.

It is also found that moisture content of biomass has a much more significant effect than ash content on the reduction of furnace exit gas temperature. Refuse derived fuel has much higher ash content than that of sawdust. However, sawdust has much higher moisture content than that of refuse derived fuel. Higher moisture content of sawdust

implies that more heat is transferred to the latent heat of vaporization during its combustion compared to refuse derived fuel combustion. Hence, decrease in furnace exit gas temperature is observed more for bituminous coal/sawdust blend than bituminous coal/refuse derived fuel blend. Similarly, lignite has higher calorific value and lower ash content than that of refuse derived fuel, but contains about 8% more moisture than refuse derived fuel. Much more heat needed to vaporize moisture of lignite than that of refuse derived fuel diminishes the gap between heating values of these two fuels. Due to this reason, furnace exit gas temperature is observed to be decreased the least for lignite/refuse derived fuel blend compared to all other blends.

In case 2 (fixed heat rate to steam cycle analysis), a larger amount of biomass is fed to the boiler than for case 1 (fixed fuel flow rate analysis) in order to have same heat rate. Therefore, the decrease in furnace exit gas temperature is observed to be more pronounced in case 2 than in case 1. The trends are same as for case 1. Maximum decreases in furnace exit gas temperature are found for chicken litter blends. Temperature is reduced from 2079 K to 2065 K and 2007 K to 1994 K for bituminous coal/chicken litter blend and lignite/chicken litter blend respectively when coal flow rate decreases from 1 kg/s to 0.7 kg/s. Similar to case 1, furnace exit gas temperature is observed to decrease the least for lignite/refuse derived fuel blend compared to all other blends.

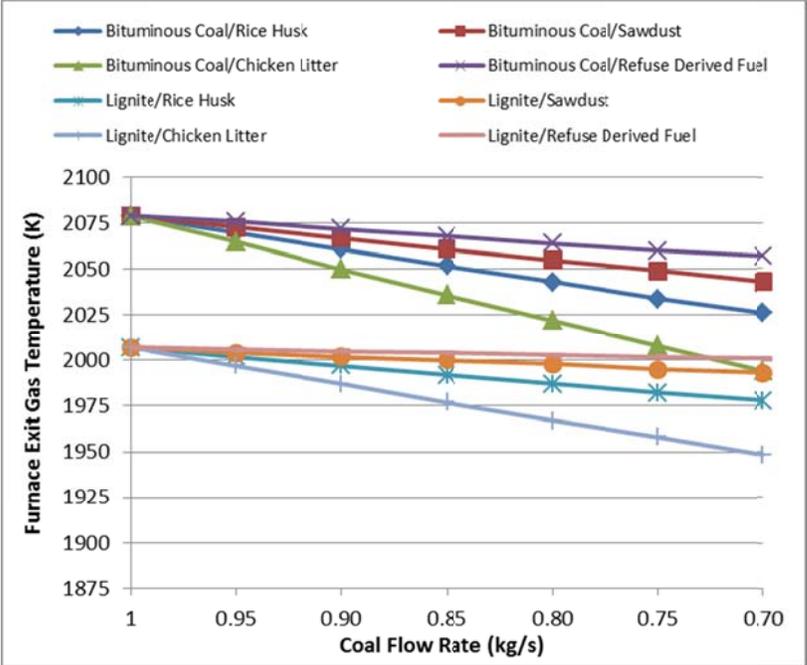


Figure 7.3: Effect of co-firing on furnace exit gas temperature based on fixed heat input to steam cycle.

7.2.2. Effect of Co-firing on Energy Losses and External Exergy Losses

Table 7.5 illustrates energy losses and external exergy losses of the system for bituminous coal/biomass blends for case 1.

For 100% coal, it is noted that the overall plant energy losses and external exergy losses are about 65% and 10% respectively. It is also observed that around 53% energy losses are occurred in the condenser. Moreover, energy losses and external exergy losses occurred through boiler are about 13% and 14% respectively. From Table 7.5, it is also evident that energy and exergy losses due to ash and radiation and convection from the furnace exterior surface are negligible. Energy and exergy losses through flue gas are found to be around 6% and 10% respectively, whereas, energy and exergy losses due to moisture are about 4% and 4.50% respectively. Heat losses due to unburned combustibles and radiation and convection are 3% of energy input, as assumed.

Table 7.5: Energy losses and external exergy losses for bituminous coal/biomass blends based on a fixed fuel flow*

Blend	Co-firing Share (%)		Energy Loss Rate (MW)					Exergy Loss Rate (MW)			
	P _c	P _b	M	FG	Ash	Q̇	Q̇ _{cond}	M	FG	Ash	Ẓ _h
Base	100	0	1.237	1.630	0.021	0.850	14.52	1.39	2.469	0.013	0.070
B/RH	95	5	1.257	1.590	0.022	0.830	14.16	1.341	2.409	0.013	0.068
	90	10	1.277	1.549	0.022	0.810	13.80	1.362	2.349	0.013	0.066
	85	15	1.297	1.509	0.023	0.790	13.44	1.383	2.290	0.014	0.065
	80	20	1.316	1.468	0.023	0.770	13.08	1.404	2.230	0.014	0.063
	75	25	1.336	1.428	0.024	0.750	12.71	1.425	2.171	0.014	0.061
	70	30	1.356	1.388	0.024	0.730	12.34	1.446	2.111	0.014	0.059
B/SD	95	5	1.297	1.595	0.020	0.833	14.23	1.383	2.417	0.012	0.069
	90	10	1.356	1.560	0.019	0.817	13.92	1.446	2.365	0.012	0.067
	85	15	1.416	1.525	0.018	0.800	13.61	1.510	2.312	0.011	0.066
	80	20	1.475	1.490	0.017	0.784	13.30	1.573	2.260	0.011	0.064
	75	25	1.534	1.454	0.016	0.767	12.99	1.637	2.208	0.010	0.063
	70	30	1.594	1.419	0.015	0.750	12.68	1.700	2.156	0.010	0.061
B/CL	95	5	1.249	1.590	0.024	0.829	14.14	1.332	2.409	0.015	0.068
	90	10	1.261	1.551	0.026	0.808	13.76	1.345	2.349	0.017	0.066
	85	15	1.273	1.511	0.028	0.787	13.39	1.358	2.289	0.019	0.064
	80	20	1.285	1.471	0.030	0.765	12.99	1.370	2.230	0.021	0.062
	75	25	1.297	1.431	0.033	0.744	12.61	1.383	2.170	0.023	0.060
	70	30	1.308	1.392	0.035	0.723	12.23	1.396	2.110	0.025	0.058
B/RDF	95	5	1.209	1.591	0.023	0.832	14.21	1.289	2.411	0.014	0.068
	90	10	1.180	1.552	0.024	0.815	13.88	1.259	2.353	0.015	0.067
	85	15	1.151	1.513	0.026	0.797	13.56	1.228	2.295	0.016	0.066
	80	20	1.123	1.473	0.028	0.780	13.25	1.198	2.237	0.017	0.064
	75	25	1.094	1.434	0.029	0.762	12.92	1.167	2.178	0.017	0.063
	70	30	1.066	1.395	0.031	0.745	12.61	1.137	2.120	0.018	0.061

*M, FG, Q̇, Q̇_{cond}, and Ẓ_h denote moisture, flue gases, heat loss due to unburned combustibles and radiation and convection from the exterior surface of boiler, energy loss in condenser, and exergy loss due to radiation and convection heat transfer from the exterior surface of boiler respectively.

From Table 7.5, it can be seen that energy and exergy losses due to fuel moisture increase with increase of biomass in blend for all blends except bituminous coal/refuse derived fuel blend. As mentioned earlier, all chosen biomass, except refuse derived fuel contain more moisture than bituminous coal. For this reason, energy and exergy losses due to moisture are increased for bituminous coal/rice husk blend, bituminous coal/sawdust

blend, and bituminous coal/chicken litter blend, and that of bituminous coal/refuse derive fuel blend is decreased with increase of biomass.

Energy and exergy losses through ash are also observed to increase with an increase of biomass for bituminous coal/rice husk blend, bituminous coal/chicken litter blend, and bituminous coal/refuse derived fuel blend. However, energy and exergy losses through sensible heat of ash are decreased for bituminous coal/sawdust blend due to the lower ash content of sawdust than that of bituminous coal.

It is also observed that energy and exergy losses due to stack gas decrease with increase of biomass in blend. This is due to decrease in both furnace exit gas temperature and mass flow rate of flue gases. Due to the low temperature of product gas, less heat is transferred to the environment. From the composition of flue gases (attached in the appendix), it is noted that increasing biomass fraction in blend decreases overall flue gas mass flow rate which results in a further decrease in heat flow to the environment. With respect to base coal, energy loss through stack gas decreases by 14.85%, 12.94%, 14.60%, and 14.42% for bituminous coal/rice husk blend, bituminous coal/sawdust blend, bituminous coal/chicken litter blend, and bituminous coal/refuse derived fuel blend respectively at 30% co-firing ratio. Likewise, the exergy loss due to exhaust gas increases by 14.50%, 12.68%, 14.54%, and 14.14% for bituminous coal/rice husk blend, bituminous coal/sawdust blend, bituminous coal/chicken litter blend, and bituminous coal/refuse derived fuel blend respectively at 30% co-firing ratio.

Furthermore, due to a decrease in the energy input with an increase of biomass, energy losses due to unburned combustibles, and radiation and convection also decrease. With less energy input, less steam is produced. Hence, heat loss from the condenser decreases with an increase of biomass in the blend. In the same way, exergy loss due to radiation and convection from boiler exterior surface decreases due to a decrease in exergy input.

It is observed that when the system operates with fixed heat rate to steam cycle, energy and exergy losses due to flue gases increase for bituminous coal /rice husk blend and

bituminous coal/chicken litter blend and decrease for bituminous coal /sawdust blend and bituminous coal/refuse derived fuel blend, as illustrated in Table 7.6. This trend is again dependent on both exit flue gas composition and furnace exit gas temperature. From composition of flue gases (attached in appendix), it is found that the net flue gas mass flow rate increases for bituminous coal /rice husk blend and bituminous coal/chicken litter blend, while that of bituminous coal /sawdust blend and bituminous coal/refuse derived fuel blend decreases with an increase of biomass in the blend. Among the selected biomass fuels, sawdust has the least nitrogen. Therefore, the amount of inert nitrogen in the products is also smallest for bituminous coal/sawdust blend compared to other blends. The amounts of nitric oxide, nitrogen dioxide, and sulphur dioxide are also smallest for bituminous coal/sawdust blend than for other blends. However, compared to other flue gases, these oxides are negligible. Therefore, the effect of mass flow rate of these oxides on the overall composition of flue gases is also negligible. For bituminous coal/sawdust blend, it is observed that a decrease in the mass flow rate of nitrogen is slightly greater than the increase in mass flow rate of other flue gases at all co-firing ratios. Since the temperature of flue gases leaving the combustor also decreases as the amount of sawdust increases in the blend, energy and exergy losses through the stack gas decrease slightly for bituminous coal/sawdust blend with an increase of sawdust in the blend. In a similar way, nitrogen produced for bituminous coal/refuse derived fuel blend is smaller compared to that of bituminous coal/rice husk blend and bituminous coal/chicken litter blend at all co-firing ratios. Moreover, the amount of carbon dioxide gas produced is also smaller for bituminous coal/refuse derived fuel blend at all co-firing ratios with respect to base coal. Because of a lower overall mass flow rate of flue gases and low furnace exit gas temperature, energy and exergy losses also decrease for the bituminous coal/refuse derived fuel blend with an increase of refused derived fuel in the blend. For bituminous coal/rice husk blend and bituminous coal/ chicken litter blend, the increased mass flow rate of flue gases results in increase in energy and exergy losses through the stack.

Table 7.6: Energy losses and external exergy losses for bituminous coal/biomass blends based on fixed heat input to steam cycle

Blend	Co-firing Share (%)		Energy Loss Rate (MW)					Exergy Loss Rate (MW)			
	P _c	P _b	M	FG	Ash	Q̇	Q̇ _{cond}	M	FG	Ash	Ẃ _h
Base	100	0	1.237	1.630	0.021	0.850	14.52	1.319	2.469	0.013	0.070
B/RH	90.45	9.55	1.338	1.631	0.024	0.852	14.52	1.427	2.472	0.015	0.070
	81.77	18.23	1.44	1.632	0.028	0.855	14.52	1.536	2.477	0.017	0.070
	73.85	26.15	1.542	1.633	0.032	0.857	14.52	1.644	2.482	0.019	0.070
	66.59	33.41	1.644	1.634	0.035	0.860	14.52	1.753	2.487	0.021	0.070
	59.91	40.09	1.746	1.635	0.039	0.863	14.52	1.862	2.491	0.023	0.070
	53.76	46.24	1.848	1.636	0.044	0.865	14.52	1.971	2.496	0.026	0.070
B/SD	91.63	8.37	1.384	1.628	0.021	0.852	14.52	1.476	2.468	0.013	0.070
	83.84	16.16	1.533	1.627	0.020	0.855	14.52	1.635	2.469	0.013	0.070
	76.56	23.44	1.681	1.626	0.020	0.857	14.52	1.793	2.469	0.013	0.070
	69.74	30.26	1.83	1.625	0.019	0.859	14.52	1.952	2.469	0.013	0.070
	63.36	36.64	1.979	1.624	0.019	0.862	14.52	2.110	2.470	0.013	0.070
	57.35	42.65	2.127	1.623	0.018	0.864	14.52	2.269	2.470	0.012	0.070
B/CL	89.97	10.03	1.330	1.636	0.029	0.852	14.52	1.419	2.479	0.018	0.070
	80.95	19.05	1.424	1.643	0.037	0.855	14.52	1.519	2.490	0.025	0.070
	72.79	27.21	1.519	1.650	0.046	0.858	14.52	1.620	2.502	0.032	0.070
	65.37	34.63	1.613	1.657	0.055	0.861	14.52	1.721	2.514	0.040	0.070
	58.60	41.40	1.708	1.664	0.065	0.863	14.52	1.822	2.526	0.048	0.070
	52.40	47.60	1.803	1.671	0.075	0.866	14.52	1.922	2.538	0.058	0.070
B/RDF	91.38	8.62	1.234	1.624	0.026	0.852	14.52	1.317	2.461	0.016	0.070
	83.40	16.60	1.232	1.618	0.031	0.854	14.52	1.314	2.455	0.019	0.070
	75.97	24.03	1.23	1.613	0.036	0.856	14.52	1.312	2.449	0.022	0.070
	69.05	30.95	1.228	1.607	0.041	0.858	14.52	1.310	2.443	0.025	0.070
	62.59	37.41	1.226	1.601	0.047	0.861	14.52	1.307	2.437	0.028	0.070
	56.55	43.45	1.224	1.596	0.053	0.863	14.52	1.305	2.431	0.032	0.070

The trends for energy and exergy losses due to ash and moisture are the same as for case 1. However, the increase or decrease in these losses is found to be larger than for case 2 due to the larger amount of biomass feeding to the boiler compared to case 1. For example, the exergy loss due to moisture increases by 49.43% for bituminous coal/rice husk blend, with respect to base coal when coal flow rate decrease to 0.70 kg/s (at 46.24% co-firing ratio).

Energy losses due to unburned carbon and radiation convection increase due to an increase in energy input. However, exergy loss due to convection and radiation from boiler exterior surface remains same at all co-firing ratios for all blends due to the fact that increase in heat loss through radiation and convection is diminished by decrease in furnace exterior wall temperature that decreases with a decrease in furnace temperature.

Table 7.7 illustrates energy losses and exergy waste emissions of the system when fuels burned in boiler are lignite/biomass blends. It is noted that overall plant energy losses and external exergy losses are about 68% and 18% respectively when 100% lignite is used. It is also observed that around 50% energy losses are occurred in the condenser. Moreover, energy losses and external exergy losses occur through boiler are about 18% each. Since, lignite contains more moisture than bituminous, it can also be observed from Table 7.7 that energy and exergy losses due to moisture for lignite are greater than that of bituminous. It is also found that losses due to flue gases and ash are smaller for lignite than that of bituminous. Energy and exergy losses through flue gas are found to be around 5.5% and 8% respectively, whereas, energy and exergy losses due to moisture are about 10% and 8% respectively. Heat losses due to unburned combustibles and radiation and convection are 3% of energy input, as assumed.

It is evident from Table 7.7 that energy and exergy losses due to moisture decrease with increase of biomass for all blends except lignite/sawdust blend. Since the selected lignite has more moisture than all chosen biomass types except sawdust; moisture loss is seen to decrease with increase of biomass for lignite/rice husk blend, lignite/refuse derived fuel blend, and lignite/chicken litter blend. Largest decreases are found for lignite/refuse derived fuel blend due to the fact that refuse derived fuel has the least moisture content than that of all selected biomass fuels. At 30% co-firing ratio, both energy and exergy losses decrease by 19.82% with respect to base coal for lignite/refuse derived fuel blend.

Similar to bituminous coal/biomass blends, energy and exergy losses through ash also increase with an increase of biomass for all lignite/biomass blends except lignite/sawdust

blend. For lignite/chicken litter blend, energy and exergy losses through ash increase by 64% and 70% when co-firing ratio increase from 0% to 30%.

Table 7.7: Energy losses and external exergy losses for lignite/biomass blends based on a fixed fuel flow

Blend	Co-firing Share (%)		Energy Loss Rate (MW)					Exergy Loss Rate (MW)			
	P _c	P _b	M	FG	Ash	Q̇	Q̇ _{cond}	M	FG	Ash	Ẓ _h
Base	100	0	1.967	1.126	0.017	0.602	10.01	2.098	1.742	0.010	0.048
L/RH	95	5	1.950	1.111	0.018	0.595	9.88	2.080	1.719	0.011	0.047
	90	10	1.933	1.095	0.018	0.587	9.74	2.062	1.695	0.011	0.046
	85	15	1.917	1.080	0.019	0.579	9.60	2.044	1.672	0.012	0.046
	80	20	1.900	1.065	0.020	0.572	9.46	2.027	1.649	0.012	0.045
	75	25	1.883	1.050	0.021	0.564	9.33	2.009	1.625	0.012	0.044
	70	30	1.867	1.035	0.021	0.556	9.19	1.991	1.602	0.013	0.043
L/SD	95	5	1.990	1.116	0.016	0.598	9.93	2.122	1.726	0.010	0.047
	90	10	2.013	1.106	0.015	0.594	9.86	2.147	1.710	0.010	0.047
	85	15	2.036	1.096	0.014	0.590	9.77	2.171	1.695	0.009	0.047
	80	20	2.059	1.086	0.014	0.585	9.69	2.196	1.679	0.009	0.046
	75	25	2.082	1.076	0.013	0.581	9.60	2.220	1.664	0.008	0.046
	70	30	2.105	1.066	0.012	0.577	9.53	2.245	1.648	0.008	0.046
L/CL	95	5	1.942	1.111	0.020	0.593	9.86	2.071	1.718	0.012	0.047
	90	10	1.918	1.097	0.022	0.585	9.70	2.045	1.695	0.014	0.046
	85	15	1.893	1.082	0.025	0.576	9.55	2.019	1.671	0.016	0.045
	80	20	1.868	1.068	0.027	0.567	9.39	1.993	1.648	0.018	0.044
	75	25	1.844	1.053	0.030	0.558	9.22	1.967	1.625	0.020	0.044
	70	30	1.819	1.039	0.032	0.550	9.07	1.940	1.601	0.023	0.043
L/RDF	95	5	1.902	1.112	0.019	0.597	9.93	2.028	1.720	0.011	0.047
	90	10	1.837	1.098	0.021	0.592	9.82	1.959	1.698	0.012	0.047
	85	15	1.772	1.084	0.022	0.587	9.74	1.890	1.677	0.014	0.047
	80	20	1.707	1.070	0.024	0.581	9.64	1.820	1.655	0.015	0.046
	75	25	1.642	1.056	0.026	0.576	9.55	1.751	1.633	0.016	0.046
	70	30	1.577	1.042	0.028	0.571	9.45	1.682	1.612	0.017	0.045

Moreover, energy and exergy losses through flue gases decrease with increase of biomass for all lignite/biomass blends. With respect to base coal, energy loss due to exhaust gas decreases by 8.09%, 5.33%, 7.73%, and 7.46% for lignite/rice husk blend, lignite/sawdust blend, lignite/chicken litter blend, and lignite/refuse derived fuel blend at 30% co-firing ratio. Likewise, exergy loss through flue gases increases by 8.04%, 5.39%,

8.09%, and 7.46% for lignite/rice husk blend, lignite/sawdust blend, lignite/chicken litter blend, and lignite/refuse derived fuel blend when co-firing ratio increase to 30%.

When, the system operates with same heat input to steam cycle, net flue gas mass flow rate increases for lignite/rice husk blend and lignite/chicken litter blend and decrease for lignite/sawdust blend and lignite/refuse derived fuel blend with increase of biomass. Hence, energy and exergy losses through flue gases increase for lignite/rice husk blend and lignite/chicken litter blend. In contrast, these losses decrease for lignite/sawdust blend and lignite/refuse derived fuel blend due to decrease in product gas temperature and net mass flow rate of flue gases, as illustrated in Table 7.8.

Since a larger amount of biomass compared to case 1 is fed to boiler, the decrease or increase in other losses is found larger than case 1. For example, for lignite/rice husk blend, energy loss due to moisture increases by 4.42% when coal flow rate decrease to 0.70 kg/s (at 37.16% co-firing ratio). Moreover, due to increase in energy input, energy losses due to unburned combustibles and radiation and convection increase with increase of biomass in blend. Similar to bituminous/biomass blends, exergy loss due to radiation and convection from the exterior surface of the boiler is same at all co-firing ratios for all blends.

Table 7.8: Energy losses and external exergy losses for lignite/biomass blends based on fixed heat input to steam cycle

Blend	Co-firing Share (%)		Energy Loss Rate (MW)					Exergy Loss Rate (MW)			
	P_c	P_b	M	FG	Ash	\dot{Q}	\dot{Q}_{cond}	M	FG	Ash	$\dot{E}x_h$
Base	100	0	1.967	1.126	0.017	0.602	10.01	2.098	1.742	0.010	0.048
L/RH	93.27	6.73	1.980	1.127	0.019	0.603	10.01	2.112	1.719	0.011	0.048
	86.74	13.26	1.995	1.128	0.020	0.604	10.01	2.128	1.695	0.012	0.048
	80.44	19.56	2.010	1.129	0.022	0.605	10.01	2.144	1.672	0.013	0.048
	74.36	25.64	2.024	1.130	0.024	0.606	10.01	2.159	1.649	0.014	0.048
	68.50	31.50	2.039	1.131	0.026	0.607	10.01	2.175	1.625	0.015	0.048
	62.84	37.16	2.054	1.132	0.028	0.608	10.01	2.190	1.602	0.016	0.048
L/SD	94.12	5.88	2.012	1.125	0.016	0.603	10.01	2.146	1.726	0.010	0.048
	88.31	11.69	2.059	1.124	0.016	0.604	10.01	2.196	1.710	0.010	0.048
	82.62	17.38	2.106	1.123	0.015	0.605	10.01	2.246	1.695	0.009	0.048
	77.03	22.97	2.153	1.122	0.014	0.606	10.01	2.296	1.679	0.009	0.048
	71.54	28.46	2.200	1.121	0.013	0.606	10.01	2.346	1.664	0.009	0.048
	66.16	33.84	2.246	1.120	0.013	0.607	10.01	2.396	1.648	0.008	0.048
L/CL	92.92	7.08	1.975	1.130	0.022	0.603	10.01	2.107	1.718	0.014	0.048
	86.10	13.90	1.984	1.135	0.026	0.604	10.01	2.117	1.695	0.017	0.048
	79.57	20.43	1.994	1.139	0.031	0.605	10.01	2.127	1.671	0.021	0.048
	73.31	26.69	2.003	1.144	0.036	0.606	10.01	2.137	1.648	0.025	0.048
	67.32	32.68	2.012	1.149	0.041	0.607	10.01	2.147	1.625	0.030	0.048
	61.56	38.44	2.022	1.153	0.047	0.608	10.01	2.156	1.601	0.034	0.048
L/RDF	93.95	6.05	1.909	1.121	0.020	0.603	10.01	2.036	1.720	0.012	0.048
	87.99	12.01	1.852	1.117	0.022	0.603	10.01	1.975	1.698	0.014	0.048
	82.16	17.84	1.795	1.113	0.025	0.604	10.01	1.914	1.677	0.015	0.048
	76.46	23.54	1.738	1.109	0.028	0.605	10.01	1.853	1.655	0.017	0.048
	70.89	29.11	1.680	1.105	0.031	0.605	10.01	1.792	1.633	0.018	0.048
	65.44	34.56	1.623	1.101	0.034	0.606	10.01	1.731	1.612	0.020	0.048

7.2.3. Effect of Co-firing on Irreversibilities

In this section, impacts of co-firing on components irreversibilities are explored. Trends are identified and described for different combinations of fuels used and for two cases considered.

The comparison of irreversibilities between system components for bituminous/biomass blends at different co-firing ratios and fixed fuel input to boiler is shown in Table 7.9.

Table 7.9: Effect of co-firing on irreversibilities in components for bituminous coal/biomass blends based on a fixed fuel flow

Blend	Co-firing Share (%)		Irreversibility Rate (MW)							
	P _c	P _b	I _c *	I _{rs} *	I _b *	I _{cond} *	I _{HPT} *	I _{LPT} *	I _{FWH} *	I _t *
Base	100	0	8.20	4.52	12.72	6.58	0.25	1.14	0.821	21.51
B/RH	95	5	8.09	4.39	12.48	6.42	0.24	1.11	0.801	21.06
	90	10	7.97	4.27	12.24	6.25	0.23	1.08	0.780	20.59
	85	15	7.84	4.15	11.99	6.09	0.23	1.05	0.760	20.14
	80	20	7.73	4.02	11.75	5.92	0.22	1.03	0.739	19.67
	75	25	7.60	3.91	11.51	5.76	0.22	1.00	0.719	19.22
	70	30	7.48	3.79	11.27	5.59	0.21	0.97	0.697	18.73
B/SD	95	5	8.13	4.41	12.55	6.43	0.24	1.12	0.804	21.15
	90	10	8.06	4.30	12.37	6.31	0.24	1.09	0.787	20.81
	85	15	7.99	4.20	12.20	6.17	0.23	1.07	0.769	20.45
	80	20	7.91	4.10	12.02	6.03	0.23	1.04	0.752	20.08
	75	25	7.85	3.99	11.85	5.89	0.22	1.02	0.734	19.72
	70	30	7.77	3.89	11.67	5.75	0.22	0.99	0.717	19.35
B/CL	95	5	8.05	4.38	12.43	6.41	0.24	1.11	0.800	20.99
	90	10	7.87	4.26	12.13	6.24	0.23	1.08	0.778	20.47
	85	15	7.71	4.12	11.83	6.07	0.23	1.05	0.757	19.95
	80	20	7.56	3.98	11.53	5.89	0.22	1.02	0.734	19.40
	75	25	7.39	3.85	11.24	5.72	0.21	0.99	0.713	18.88
	70	30	7.22	3.72	10.94	5.54	0.21	0.96	0.692	18.35
B/RDF	95	5	8.10	4.42	12.52	6.44	0.24	1.11	0.803	21.14
	90	10	8.02	4.31	12.33	6.29	0.24	1.09	0.785	20.74
	85	15	7.92	4.21	12.13	6.14	0.23	1.06	0.767	20.33
	80	20	7.82	4.11	11.93	6.00	0.23	1.04	0.749	19.95
	75	25	7.73	4.00	11.73	5.86	0.22	1.01	0.731	19.55
	70	30	7.63	3.90	11.53	5.69	0.21	0.99	0.713	19.15

*I_c, I_{rs}, I_{cond}, I_{HPT}, I_{LPT}, I_{cond}, I_{FWH}, and I_t are irreversibility rates of combustion chamber, heat exchanger (reheater and superheater), boiler, high pressure turbine, low pressure turbine, condenser, feedwater heater, and total plant respectively.

It can be noted that maximum exergy destruction occurs in boiler because of chemical reaction and large temperature difference between product gas and feedwater. It is found that 38.70% of exergy supplied is destroyed due to irreversibilities in boiler. Also, out this, 23.31% is destroyed in combustor only. It is also observed that maximum exergy destruction in steam cycle takes place in condenser. In fact, irreversibility rate of condenser is greater than that of heat exchanger and accounts for 32.64% of total plant

exergy destruction. Total plant exergy destruction is calculated as 68.80% of exergy input.

It can be seen from Table 7.9 that as amount of biomass increases, total irreversibility rate of plant decreases. This is due to the fact that irreversibility rate of all components decreases with increase in biomass amount in blend. As percent share of biomass co-firing increases, exergy input to plant decreases; hence less amount of exergy is destroyed in combustor. Moreover, exergy of the product gas decreases because furnace exit gas temperature decreases. Irreversibility rate of heat exchanger decreases because a lower temperature product gas decreases the temperature difference between feedwater and product gas. As a result, irreversibility rate of boiler decreases. Since, steam cycle conditions are fixed, irreversibility rate of all other components decreases because of less exergy input to cycle. With respect to base coal, total irreversibility rate of plant decreases from 21.51 MW to 19.35 MW, 17.43, 18.35 MW, and 19.15 MW for bituminous coal/rice husk blend, bituminous coal/sawdust blend, bituminous coal/chicken litter blend, and bituminous coal/refuse derived fuel blend respectively at 30% co-firing ratio.

Among all bituminous/biomass blends, the largest decrease in irreversibility rate occurs for bituminous coal/chicken litter blend because of the fact that decrease in furnace exit gas temperature with increase of chicken litter is the largest for this blend due to which decrease in the irreversibility of heat exchanger is the highest at all co-firing ratios for this blend. Moreover, the exergy carried by this blend at all co-firing ratios is the smallest compared to other blends. So, less exergy is destroyed in combustion chamber. For this blend, every 5% addition of chicken litter decreases boiler and hence plant irreversibility rate by roughly 3%. In contrast, the lowest decrease in irreversibility occurs for bituminous coal/sawdust blend because of the largest amount of exergy destroyed in the chamber. Although, at all co-firing ratios, irreversibility rate of heat exchanger decreases more for bituminous coal/sawdust blend than does for bituminous coal/refuse derived fuel blend because product gas temperature decreases more for bituminous coal/sawdust blend than bituminous coal/refuse derived fuel blend, however, due to relatively larger

amount of exergy destruction occurring in combustor for bituminous coal/sawdust blend than bituminous coal/refuse derived fuel blend, the irreversibility rate of bituminous coal/sawdust blend is larger than bituminous coal/refuse derived fuel blend, and hence, is the largest among all blends. For this blend, every 5% addition of sawdust, boiler and hence plant irreversibility rate decreases by about 1.60%. Similarly, decrease in irreversibility rate for bituminous coal/rice husk blend is greater than for bituminous coal/sawdust blend because furnace exit gas temperature decreases more for bituminous coal/rice husk blend than bituminous coal/sawdust blend with increase in biomass amount in the blend.

Table 7.10 shows the effect of co-firing on components irreversibilities for bituminous coal/biomass blends when the system operates with fixed heat input to steam cycle.

Since, temperature and pressure of steam cycle components are fixed; useful exergy transferred to cycle is same for all blends and at all co-firing ratios. Therefore, irreversibility rate of turbines, pumps, feedwater heater, and condenser are not changing. However, irreversibility rate of boiler subsystem is changing due to temperature changes and varying fuel consumption.

It is observed that irreversibility rate of combustor increases and that of heat exchanger decreases with increase of biomass for all blends. Due to larger fuel consumption compared to case 1, exergy input to combustor increases. As the exergy input to steam cycle is fixed, so only fixed amount of exergy is transferred between feedwater and product gas and rest is destroyed in chamber. Irreversibility rate of combustor increases due to decrease in product gas temperature, so that exergy of the product gas decreases. Irreversibility rate of heat exchanger decreases because lower furnace exit gas temperature decreases temperature difference between product gas and feedwater heater.

From Table 7.10, it can be observed that irreversibility rate of boiler increases with increase of biomass for all blends. This is due to the fact that decrease in irreversibility rate of heat exchanger is smaller than increase in irreversibility rate of combustor which

results in increase in overall irreversibility rate of boiler, so as of plant. Like case 1, irreversibility rate of boiler and hence plant is the largest for bituminous coal/sawdust blend and the smallest for bituminous coal/chicken litter blend at all co-firing ratios compared to other blends. With respect to base coal, plant irreversibility rate increases from 21.52 MW to 22.44 MW for bituminous coal/rice husk blend at 46.24 co-firing ratio, 22.50 MW for bituminous coal/sawdust blend at 42.65 co-firing ratio, 22.01 MW for bituminous coal/chicken litter blend at 47.60% co-firing ratio, and 22.40 MW for bituminous coal/refuse derived fuel at 43.45% co-firing ratio.

Table 7.10: Effect of co-firing on irreversibilities in components for bituminous coal/ biomass blends based on fixed heat input to steam cycle

Blend	Co-firing Share (%)		Irreversibility Rate (MW)							
	P_c	P_b	\dot{I}_c	\dot{I}_{rs}	\dot{I}_b	\dot{I}_{cond}	\dot{I}_{HPT}	\dot{I}_{LPT}	\dot{I}_{FWH}	\dot{I}_t
Base	100	0	8.20	4.51	12.72	6.58	0.25	1.14	0.82	21.52
B/RH	90.45	9.55	8.38	4.49	12.88	6.58	0.25	1.14	0.82	21.67
	81.77	18.23	8.55	4.48	13.03	6.58	0.25	1.14	0.82	21.82
	73.85	26.15	8.72	4.46	13.18	6.58	0.25	1.14	0.82	21.98
	66.59	33.41	8.98	4.43	13.34	6.58	0.25	1.14	0.82	22.13
	59.91	40.09	9.07	4.41	13.49	6.58	0.25	1.14	0.82	22.28
	53.76	46.24	9.25	4.40	13.65	6.58	0.25	1.14	0.82	22.44
B/SD	91.63	8.37	8.40	4.49	12.89	6.58	0.25	1.14	0.82	21.68
	83.84	16.16	8.56	4.49	13.05	6.58	0.25	1.14	0.82	21.84
	76.56	23.44	8.75	4.47	13.22	6.58	0.25	1.14	0.82	22.01
	69.74	30.26	8.92	4.46	13.38	6.58	0.25	1.14	0.82	22.17
	63.36	36.64	9.09	4.45	13.54	6.58	0.25	1.14	0.82	22.34
	57.35	42.65	9.26	4.44	13.71	6.58	0.25	1.14	0.82	22.50
B/CL	89.97	10.03	8.33	4.47	12.81	6.58	0.25	1.14	0.82	21.60
	80.95	19.05	8.45	4.44	12.89	6.58	0.25	1.14	0.82	21.68
	72.79	27.21	8.54	4.42	12.97	6.58	0.25	1.14	0.82	21.76
	65.37	34.63	8.66	4.39	13.05	6.58	0.25	1.14	0.82	21.85
	58.60	41.40	8.78	4.35	13.14	6.58	0.25	1.14	0.82	21.93
	52.40	47.60	8.89	4.32	13.22	6.58	0.25	1.14	0.82	22.01
B/RDF	91.38	8.62	8.37	4.50	12.87	6.58	0.25	1.14	0.82	21.66
	83.40	16.60	8.52	4.50	13.02	6.58	0.25	1.14	0.82	21.81
	75.97	24.03	8.68	4.49	13.17	6.58	0.25	1.14	0.82	21.96
	69.05	30.95	8.83	4.48	13.32	6.58	0.25	1.14	0.82	22.11
	62.59	37.41	8.99	4.47	13.46	6.58	0.25	1.14	0.82	22.26
	56.55	43.45	9.14	4.47	13.61	6.58	0.25	1.14	0.82	22.40

Table 7.11 illustrates the effect of co-firing on components irreversibility based on a fixed fuel flow analysis when lignite is used as base coal rather than bituminous coal. It is evident from that boiler is the major source of destruction. It can also be noted that condenser irreversibility rate is greater than that of combustor and heat exchanger. Total exergy destruction rate occurring in boiler is 34.89% of exergy input; out of which 20.65% occurs in combustor, while 14.24% exergy is destroyed in heat exchanger. Total irreversibility rate of plant is found as 63.47% of exergy input.

Table 7.11: Effect of co-firing on Irreversibilities in components for lignite/biomass blends based on a fixed fuel flow

Blend	Co-firing Share (%)		Irreversibility Rate (MW)							
	P_c	P_b	\dot{I}_c	\dot{I}_{rs}	\dot{I}_b	\dot{I}_{cond}	\dot{I}_{HPT}	\dot{I}_{LPT}	\dot{I}_{FWH}	\dot{I}_t
Base	100	0	6.51	3.01	9.52	4.54	0.17	0.79	0.57	15.59
L/RH	95	5	6.48	2.96	9.44	4.48	0.17	0.77	0.56	15.42
	90	10	6.43	2.92	9.35	4.41	0.17	0.76	0.55	15.25
	85	15	6.40	2.87	9.27	4.35	0.16	0.75	0.54	15.09
	80	20	6.37	2.82	9.19	4.29	0.16	0.74	0.54	14.92
	75	25	6.33	2.77	9.11	4.23	0.16	0.73	0.53	14.75
	70	30	6.29	2.74	9.02	4.16	0.16	0.72	0.52	14.59
L/SD	95	5	6.50	2.99	9.49	4.50	0.17	0.78	0.56	15.51
	90	10	6.47	2.96	9.43	4.47	0.17	0.77	0.56	15.47
	85	15	6.42	2.93	9.35	4.43	0.17	0.77	0.55	15.40
	80	20	6.39	2.90	9.27	4.39	0.16	0.76	0.55	15.32
	75	25	6.36	2.88	9.24	4.35	0.16	0.75	0.54	15.25
	70	30	6.28	2.85	9.13	4.32	0.16	0.75	0.54	15.21
L/CL	95	5	6.43	2.95	9.38	4.47	0.17	0.77	0.56	15.36
	90	10	6.35	2.90	9.25	4.40	0.16	0.76	0.55	15.12
	85	15	6.28	2.83	9.11	4.33	0.16	0.75	0.54	14.90
	80	20	6.19	2.78	8.97	4.26	0.16	0.74	0.53	14.67
	75	25	6.12	2.72	8.83	4.18	0.16	0.72	0.52	14.42
	70	30	6.03	2.67	8.70	4.11	0.15	0.71	0.51	14.19
L/RDF	95	5	6.50	2.98	9.48	4.50	0.17	0.78	0.56	15.50
	90	10	6.49	2.95	9.44	4.45	0.17	0.77	0.56	15.39
	85	15	6.47	2.93	9.40	4.41	0.17	0.76	0.55	15.31
	80	20	6.46	2.90	9.36	4.37	0.16	0.76	0.54	15.20
	75	25	6.45	2.87	9.32	4.30	0.16	0.75	0.54	15.09
	70	30	6.44	2.84	9.28	4.28	0.16	0.74	0.53	15.00

Similar trends for irreversibility rate are observed as were found for bituminous coal when lignite is used. That is irreversibility rate of all components decreases as co-firing share of increases. With increase of biomass, the largest decrease in irreversibility rate occurs for lignite/chicken litter blend due to the largest decrease in furnace exit gas temperature takes place for this blend. Also, the exergy carried by this blend at all co-firing ratios is the smallest compared to other blends. Every 5% addition of chicken litter decreases system irreversibility rate by about 1.6%. In contrast, the lowest decrease in irreversibility rate with addition of biomass occurs for lignite/sawdust blend. Similarly, irreversibility rate for lignite/rice husk blend decreases more than does for lignite/refuse derived fuel blend. With respect base coal, plant irreversibility rate decreases from 15.59 MW to 14.59 MW, 15.06 MW, 14.19 MW, and 15.00 MW for lignite/rice husk blend, lignite/sawdust blend, lignite/chicken litter blend, and lignite/refuse derived fuel blend respectively when co-firing ratio increases to 30%.

Table 7.12 shows the effect of co-firing on irreversibilities when the system operates with fixed heat input to cycle and lignite is used as base fuel. As can be seen that irreversibility rate of combustor increases and that of heat exchanger decreases with increase of biomass for all blends. Irreversibility rate of combustor increases due to decrease in furnace exit gas temperature which decreases the exergy of product gas. As a result, exergy destruction rate of heat exchanger decreases because low product gas temperature decreases the temperature difference between product gas and feedwater heater.

It is found that irreversibility rate of boiler increases with increase of biomass for all blends. This is due to the fact that decrease in irreversibility rate of heat exchanger is smaller than increase in irreversibility rate of combustor which results in increase in overall irreversibility rate of boiler, so as of plant. With respect to base coal, total plant irreversibility rate increases from 15.59 to 15.99 MW, 16.03 MW, 15.70 MW, and 15.97 MW for lignite/rice husk blend, lignite/sawdust blend, lignite/chicken litter blend, and lignite/refuse derived fuel blend respectively when coal flow rate decreases to 0.70 kg/s.

Table 7.12: Effect of co-firing on Irreversibilities in components for lignite/biomass blends based on fixed heat input to steam cycle

Blend	Co-firing Share (%)		Irreversibility Rate (MW)							
	P_c	P_b	\dot{I}_c	\dot{I}_{rs}	\dot{I}_b	\dot{I}_{cond}	\dot{I}_{HPT}	\dot{I}_{LPT}	\dot{I}_{FWH}	\dot{I}_t
Base	100	0	6.51	3.01	9.52	4.54	0.17	0.79	0.57	15.59
L/RH	93.27	6.73	6.59	3.00	9.59	4.54	0.17	0.79	0.57	15.65
	86.74	13.26	6.67	2.99	9.66	4.54	0.17	0.79	0.57	15.72
	80.44	19.56	6.74	2.98	9.72	4.54	0.17	0.79	0.57	15.79
	74.36	25.64	6.80	2.99	9.79	4.54	0.17	0.79	0.57	15.85
	68.50	31.50	6.88	2.98	9.86	4.54	0.17	0.79	0.57	15.92
	62.84	37.16	6.96	2.97	9.92	4.54	0.17	0.79	0.57	15.99
L/SD	94.12	5.88	6.59	3.01	9.60	4.54	0.17	0.79	0.57	15.66
	88.31	11.69	6.67	3.00	9.67	4.54	0.17	0.79	0.57	15.74
	82.62	17.38	6.75	3.00	9.75	4.54	0.17	0.79	0.57	15.81
	77.03	22.97	6.82	3.00	9.82	4.54	0.17	0.79	0.57	15.89
	71.54	28.46	6.90	3.00	9.90	4.54	0.17	0.79	0.57	15.96
	66.16	33.84	6.98	2.99	9.97	4.54	0.17	0.79	0.57	16.03
L/CL	92.92	7.08	6.55	2.99	9.54	4.54	0.17	0.79	0.57	15.60
	86.10	13.90	6.58	2.98	9.56	4.54	0.17	0.79	0.57	15.62
	79.57	20.43	6.61	2.96	9.58	4.54	0.17	0.79	0.57	15.64
	73.31	26.69	6.65	2.95	9.60	4.54	0.17	0.79	0.57	15.66
	67.32	32.68	6.68	2.93	9.61	4.54	0.17	0.79	0.57	15.68
	61.56	38.44	6.71	2.92	9.63	4.54	0.17	0.79	0.57	15.70
L/RDF	93.95	6.05	6.58	3.01	9.59	4.54	0.17	0.79	0.57	15.65
	87.99	12.01	6.64	3.01	9.65	4.54	0.17	0.79	0.57	15.71
	82.16	17.84	6.70	3.01	9.71	4.54	0.17	0.79	0.57	15.78
	76.46	23.54	6.77	3.01	9.77	4.54	0.17	0.79	0.57	15.84
	70.89	29.11	6.82	3.02	9.84	4.54	0.17	0.79	0.57	15.90
	65.44	34.56	6.89	3.01	9.90	4.54	0.17	0.79	0.57	15.97

7.3. Effect of Co-firing on Efficiencies

The effect of biomass co-firing on boiler and plant efficiencies is explored in this section. Both energy and exergy efficiencies are calculated for all blends and both cases considered.

7.3.1. Boiler Energy Efficiency

The effect of co-firing on boiler energy efficiency based on a fixed fuel flow (case 1) is shown in Figure 7.4. It can be seen that boiler efficiency decreases as biomass proportion increases. For all blends, efficiency has decreased less than 1% at 30 % co-firing ratio with respect to base coal. Reduction in efficiency is the relative effect of low heating value, moisture content, and ash content of biomass.

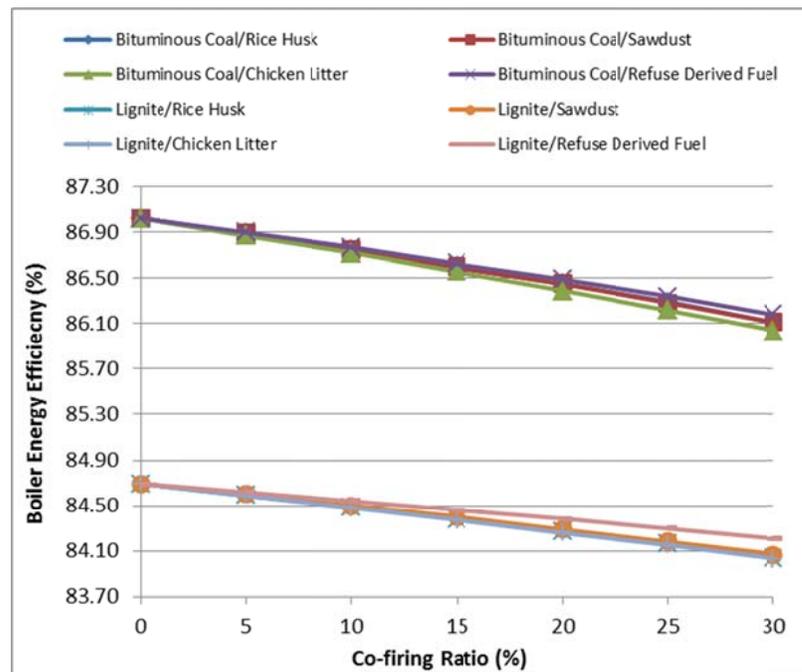


Figure 7.4: Effect of co-firing on boiler energy efficiency based on a fixed fuel flow.

It is observed that the highest efficiency drops occur for chicken litter blends. In section 7.2.1, we observed that maximum reductions in furnace exit gas temperature occurs for chicken litter blends which results the lowest heat transfer between product gas and feedwater compared to other blends. Due to this reason, drops in boiler energy efficiency are the highest for bituminous coal/chicken litter blend and lignite/chicken litter blend. When co-firing ratio increases from 0% to 30%, boiler energy efficiency decreases from 87.02% to 86.04% for bituminous coal/chicken litter blend and from 84.69% to 84.03% for lignite/chicken litter blend. In contrast, boiler energy efficiency is observed to be the

least decreased for refuse derived fuel blends because furnace exit gas temperature decreases the least for its blends. In comparison with 100% coal, efficiency decreases from 87.02% to 86.18% for bituminous coal/refuse derived fuel blend and from 84.69% to 84.21% for lignite/refuse derived fuel blend at 30% co-firing ratio.

Figure 7.5 shows the effect of co-firing on boiler energy efficiency based on fixed steam input to steam cycle (case 2). The trends are same as were for case 1. However efficiency decreases more than case 1 because of increased fuel input to boiler with increase of biomass.

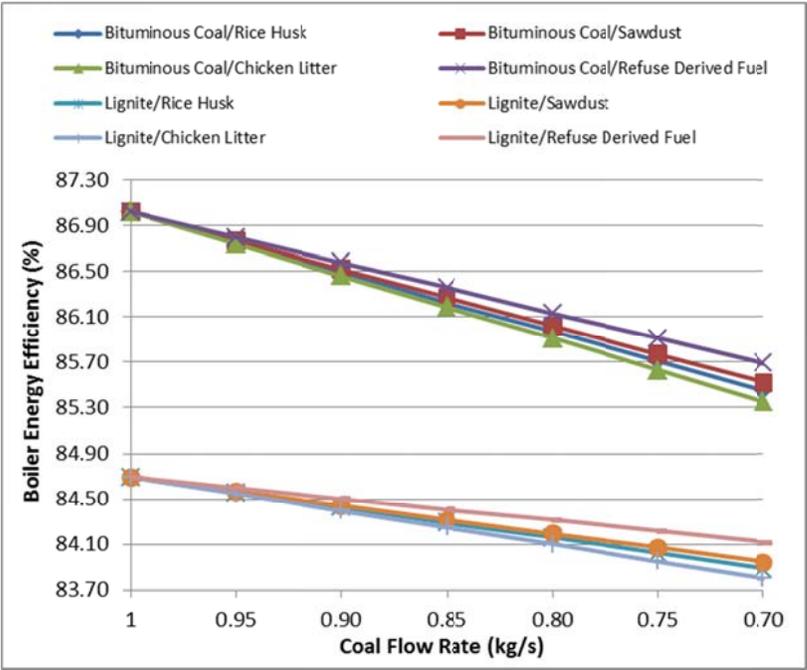


Figure 7.5: Effect of co-firing on boiler energy efficiency based on fixed heat input to steam cycle.

It is seen from Figure 7.5 that drops in boiler energy efficiency are the highest for chicken litter blends. This is due to the fact that chicken litter has the lowest heating value. Therefore, compared to other biomass, the highest amount of chicken litter is needed to produce equivalent heat as can be produced from the combustion of 1 kg/s of coal, as was shown in section 7.1. In comparison with base coal, boiler energy efficiency

drops to 85.35% for bituminous coal/chicken litter blend and 83.80% for lignite/chicken litter blend when coal mass flow rate decreases to 0.70 kg/s. In comparison, boiler energy efficiency drops to 85.69% for bituminous coal/refuse derived fuel blend and 84.12% for lignite/refuse derived fuel blend with 0.70 kg/s of coal.

7.3.2. Plant Energy Efficiency

Figures 7.6 illustrates that overall plant energy efficiency also decreases as the biomass proportion increases. The trends are the same as were for boiler energy efficiency. Plant energy efficiency decreases from 35.01% to 34.64%, 34.66%, 34.62%, and 34.71% for bituminous coal/rice husk blend, bituminous coal/sawdust blend, bituminous coal/chicken litter blend, and bituminous coal/refuse derived fuel blend respectively when co-firing ratio increase to 30%. Similarly, with respect to base coal, plant energy efficiency reduces from 34.07 to 33.80%, 33.84%, 33.79%, and 33.90% lignite/rice husk blend, lignite/sawdust blend, lignite/chicken litter blend, and lignite/refuse derived fuel blend respectively at 30% co-firing ratio.

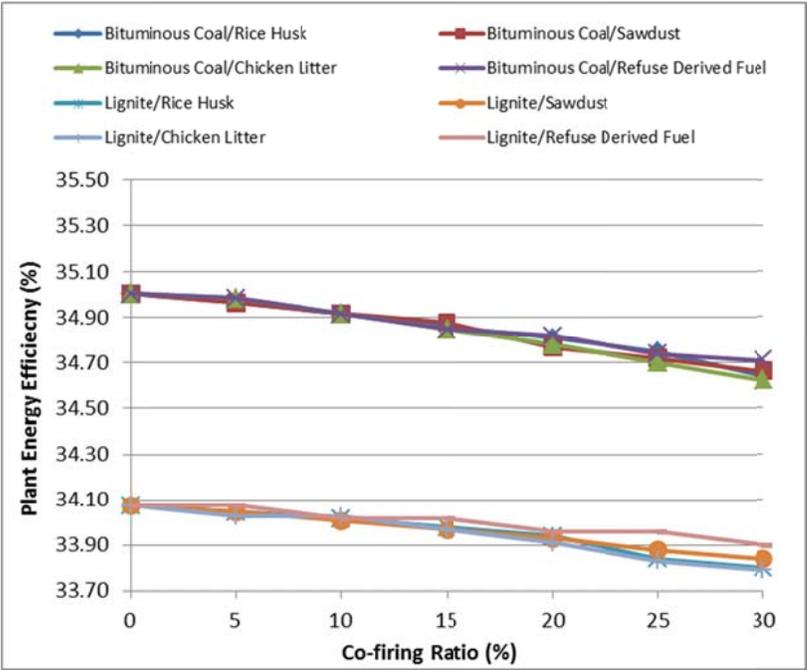


Figure 7.6: Effect of co-firing on plant energy efficiency based on a fixed fuel flow.

The comparison of plant efficiency for different blends used in analysis for case 2 is given in Figure 7.7. It can be seen that efficiency drops are greater in this case than for case 1. With 0.70 kg/s of coal, plant energy efficiency drops to 34.40%, 34.43%, 34.35%, and 34.49% for bituminous coal/rice husk blend, bituminous coal/sawdust blend, bituminous coal/chicken litter blend, and bituminous coal/refuse derived fuel blend respectively. Similarly, plant energy efficiency decreases to 33.76%, 33.79%, 33.73%, and 33.86% for lignite/rice husk blend, lignite/sawdust blend, lignite/chicken litter blend, and lignite/refuse derived fuel blend respectively when coal flow rate decreases to 0.70 kg/s.

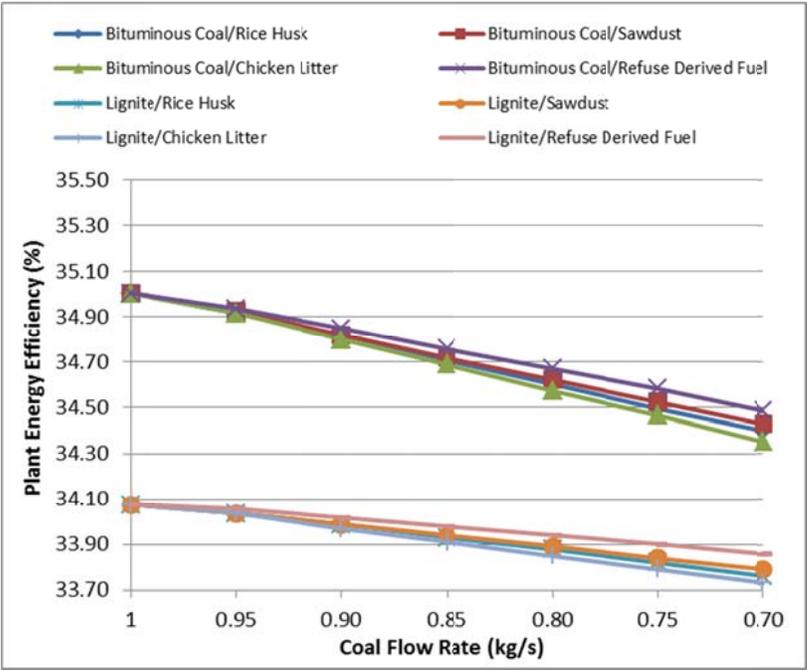


Figure 7.7: Effect of co-firing on plant energy efficiency based on fixed heat input to steam cycle.

7.3.3. Boiler Exergy Efficiency

For case 1, the effect of co-firing on boiler exergy efficiency for all the blends is shown in Figure 7.8. It can be seen that boiler exergy efficiency is about 38% less than boiler

energy efficiency that is actually the amount of exergy destroyed in boiler due to irreversibilities.

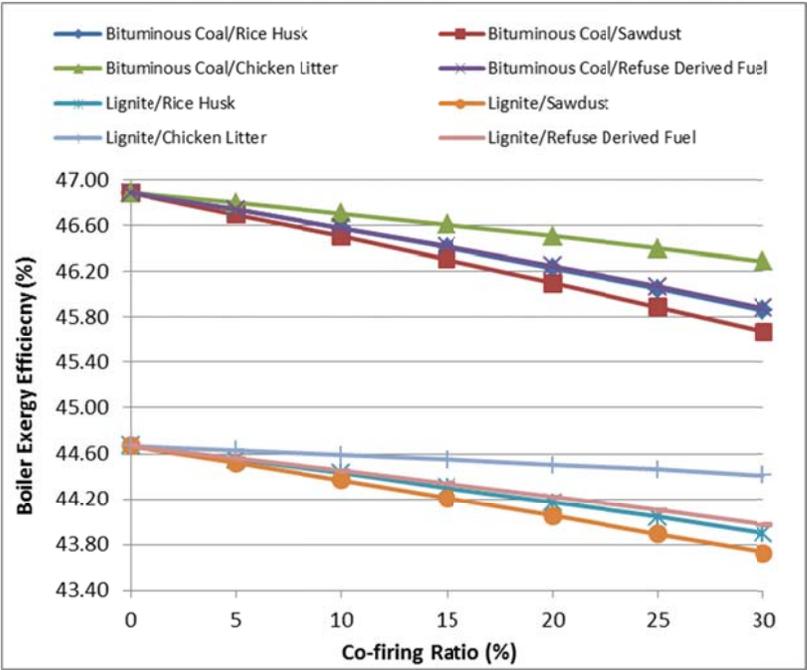


Figure 7.8: Effect of co-firing on boiler exergy efficiency based on a fixed fuel flow.

As is shown from Figure 7.8 that the highest efficiency drops occurs for sawdust blends, while boiler exergy efficiency decreases the least for chicken litter blends at all co-firing ratios. This is due to the fact that sawdust blends exhibit the largest exergy losses at all co-firing ratios compared to other blends. Therefore, drops in boiler exergy efficiency are the largest for sawdust blends. In contrast, chicken litter blends exhibit the smallest exergy losses at co-firing ratios compared to other blends, therefore, drops in boiler exergy efficiency are the smallest for its blends. In similar way, efficiency drops more for rice husk blends than refuse deived fuel blends. In comparison with 100% coal, boiler exergy efficiency decreases from 46.89% to 45.88% for bituminous coal/chicken litter blend and from 44.67% to 44.41 for lignite/chicken litter blend at 30% co-firing ratio. On the other hand, boiler exergy efficiency drops to 45.67% and 43.73% for bituminous coal/sawdust blend and lignite/sawdust blend respectively when co-firing ratio increases to 30%.

Figure 7.9 compares the boiler exergy efficiency for all blends for case 2. Similar to case 1, the highest drops in boiler exergy efficiency occurs for sawdust blends, while boiler exergy efficiency decreases the least for chicken litter blends. Moreover, boiler exergy efficiency drops more for rice husk blends than does for refuse derived fuel blends. Boiler exergy efficiency decreases to 45.15%, 45.06%, 45.83%, and 45.34% for bituminous coal/rice husk blend, bituminous coal/sawdust blend, bituminous coal/chicken litter blend, and bituminous coal/refuse derived fuel blend respectively when coal flow rate decreases to 0.70 kg/s. Similarly, boiler exergy efficiency decreases from 44.67% to 43.70%, 43.61%, 44.32, and 43.87% for lignite/rice husk blend, lignite/sawdust blend, lignite/chicken litter blend, and lignite/refuse derived fuel blend respectively with 0.70 kg/s of coal.

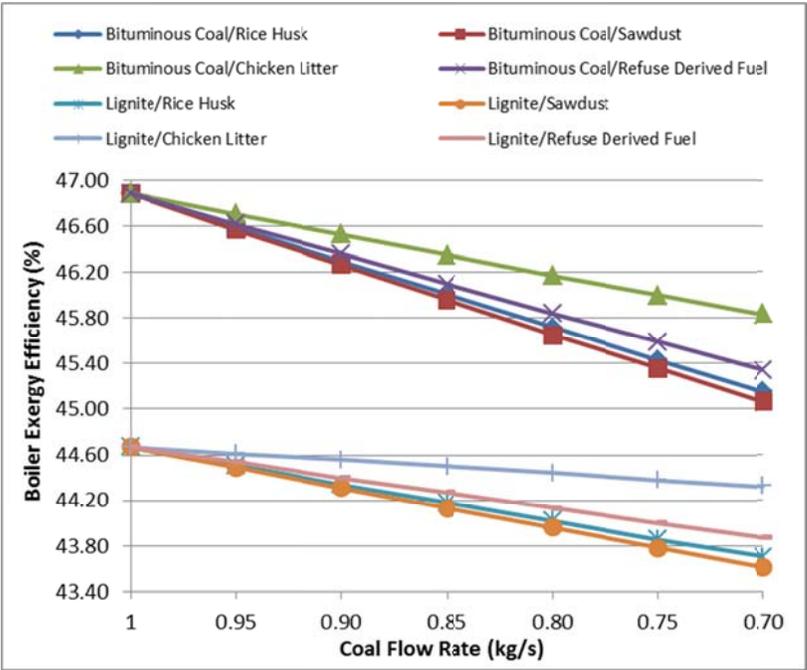


Figure 7.9: Effect of co-firing on boiler exergy efficiency based on fixed heat input to steam cycle.

7.3.4. Plant Exergy Efficiency

The comparison of plant exergy efficiency for all blends for case 1 is illustrated in Figure 7.10. The trends are the same as are for boiler exergy efficiency. Plant exergy efficiency decreases the least for chicken litter blends and the highest for sawdust dust blends. With respect to base coal, plant exergy efficiency drops from 33.82% to 33.07%, 32.94%, 33.39%, and 33.09% for bituminous coal/rice husk blend, bituminous coal/sawdust blend, bituminous coal/chicken litter blend, and bituminous coal/refuse derived fuel blend respectively when co-firing ratio increases from 0% to 30%. Similarly, in comparison with 100% coal firing, plant exergy efficiency reduces to 31.66%, 31.54%, 32.03%, and 31.72% for lignite/rice husk blend, lignite/sawdust blend, lignite/chicken litter blend, and lignite/refuse derived fuel blend respectively at 30% co-firing ratio.

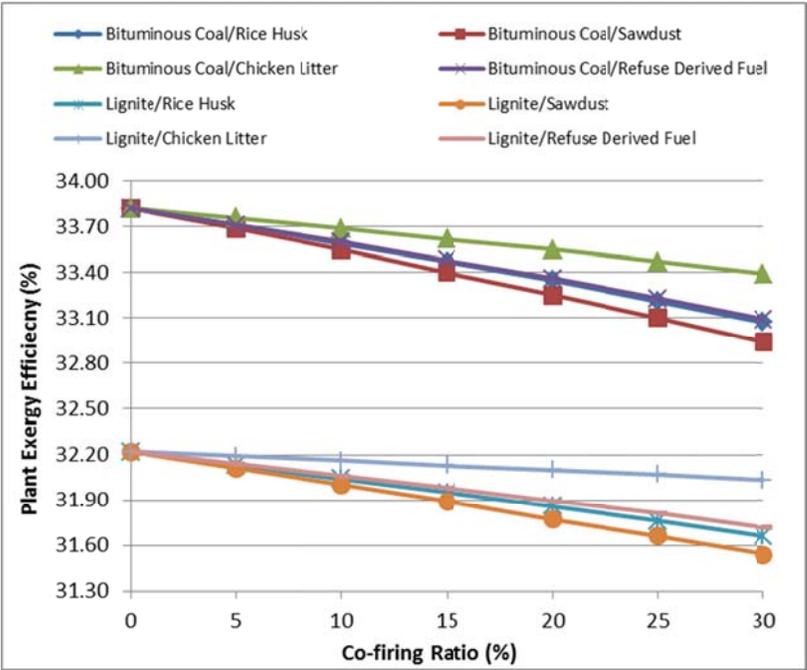


Figure 7.10: Effect of co-firing on plant exergy efficiency based on a fixed fuel flow.

Figure 7.11 compares the plant exergy efficiency for all blends for case 2. When coal flow rate decreases to 0.70 kg/s, plant exergy efficiency drops to 32.57%, 32.50%, 33.05%, and 33.05% for bituminous coal/rice husk blend, bituminous coal/sawdust blend, bituminous coal/chicken litter blend, and bituminous coal/refuse derived fuel blend respectively at 30% co-firing ratio.

bituminous coal/chicken litter blend, and bituminous coal/refuse derived fuel blend respectively. Whereas, plant exergy efficiency reduces from 32.22% to 31.52%, 31.45%, 31.97%, and 31.64% for lignite/rice husk blend, lignite/sawdust blend, lignite/chicken litter blend, and lignite/refuse derived fuel blend respectively with 0.70 kg/s of coal.

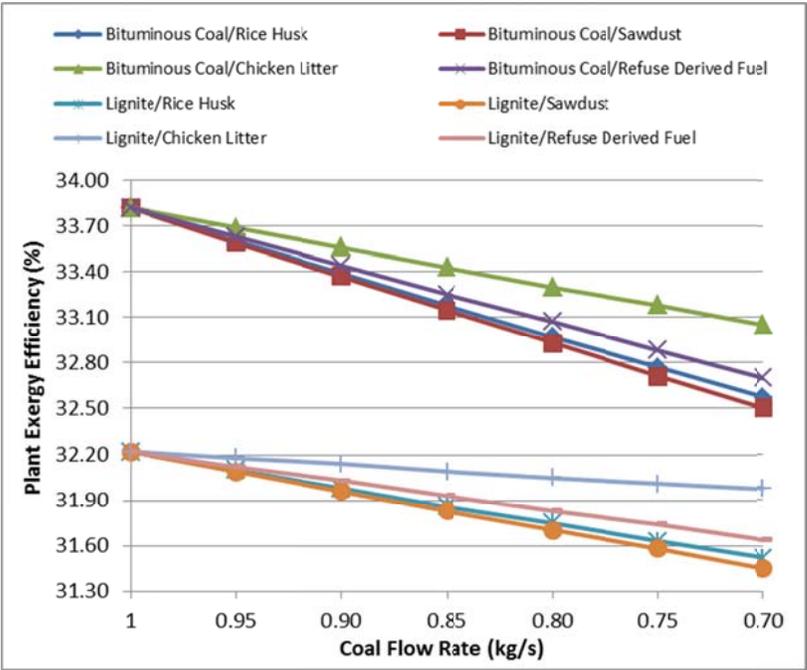


Figure 7.11: Effect of co-firing on plant exergy efficiency based on fixed heat input to steam cycle.

7.4. Effect of Co-firing on Emissions

The trends and main findings of the simulated results to evaluate the impacts of co-firing on CO₂, NO_x, and SO_x emissions are presented in this section. Emission factors presented in the following sections are in energy-based (g/kWh) and weight-based (kg/Mg) units.

The weight-based emission factors for all the blends and two cases considered are shown in Tables 7.13 and 7.14. Since biomass fuels have less carbon content than coals, therefore, weight-based CO₂ emission factors decrease for all blends. The most

appropriate biomass in terms of CO₂ emissions reduction is chicken litter because of its lowest carbon content among all selected biomass fuels. Based on a fixed fuel flow (case 1), weight-based CO₂ emission factor has decreased by 15.43% and 9.94% for bituminous coal/chicken litter blend and lignite/chicken litter blend respectively at 30% co-firing ratio. Similarly, based on fixed heat input to steam cycle (case 2), the reductions of 24.52% and 12.75% are observed in weight-based CO₂ emission factor for bituminous coal/chicken litter blend and lignite/chicken litter blend respectively when coal flow rate decreases to 0.70kg/s.

Table 7.13: Weight-based emission factors for bituminous coal/biomass blends

Blend	Based on a Fixed Fuel Flow					Based on Fixed Heat Input to Steam Cycle				
	Co-firing Share (%)		Emission Factor (kg/Mg)			Co-firing Share (%)		Emission Factor (kg/Mg)		
	P _c	P _b	CO ₂	NO _x	SO _x	P _c	P _b	CO ₂	NO _x	SO _x
Base	100	0	2839	10.08	9.03	100	0	2839	10.08	9.03
B/RH	95	5	2773	9.90	8.64	90.45	9.55	2715	9.74	8.30
	90	10	2708	9.72	8.26	81.77	18.23	2600	9.43	7.62
	85	15	2643	9.54	7.87	73.85	26.15	2498	9.14	7.01
	80	20	2578	9.36	7.49	66.59	33.41	2404	8.89	6.46
	75	25	2513	9.18	7.10	59.91	40.09	2316	8.64	5.94
	70	30	2447	9.00	6.72	53.76	46.24	2236	8.43	5.47
B/SD	95	5	2784	9.61	8.58	91.63	8.37	2747	9.30	8.27
	90	10	2729	9.15	8.13	83.84	16.16	2661	8.57	7.57
	85	15	2675	8.68	7.68	76.56	23.44	2583	7.90	6.92
	80	20	2620	8.22	7.22	69.74	30.26	2507	7.26	6.30
	75	25	2565	7.75	6.77	63.36	36.64	2437	6.66	5.72
	70	30	2510	7.28	6.32	57.35	42.65	2371	6.10	5.18
B/CL	95	5	2766	11.23	9.31	89.97	10.03	2692	12.38	9.60
	90	10	2693	12.37	9.60	80.95	19.05	2560	14.44	10.12
	85	15	2620	13.52	9.89	72.79	27.21	2441	16.31	10.59
	80	20	2547	14.66	10.18	65.37	34.63	2333	18.01	11.01
	75	25	2474	15.80	10.46	58.60	41.40	2234	19.55	11.40
	70	30	2401	16.95	10.75	52.40	47.60	2143	20.98	11.76
B/RDF	95	5	2774	9.94	8.94	91.38	8.62	2726	9.84	8.87
	90	10	2709	9.81	8.86	83.40	16.60	2623	9.63	8.74
	85	15	2644	9.67	8.76	75.97	24.03	2526	9.42	8.61
	80	20	2579	9.53	8.68	69.05	30.95	2436	9.23	8.48
	75	25	2514	9.40	8.59	62.59	37.41	2353	9.06	8.37
	70	30	2449	9.26	8.50	56.55	43.45	2274	8.89	8.27

Table 7.14: Weight-based emission factors for lignite/biomass blends

Blend	Based on a Fixed Fuel Flow					Based on Fixed Heat Input to Steam Cycle				
	Co-firing Share (%)		Emission Factor (kg/Mg)			Co-firing Share (%)		Emission Factor (kg/Mg)		
	P _c	P _b	CO ₂	NO _x	SO _x	P _c	P _b	CO ₂	NO _x	SO _x
Base	100	0	2062	3.77	3.52	100	0	2062	3.77	3.52
L/RH	95	5	2036	3.91	3.41	93.27	6.73	2026	3.95	3.38
	90	10	2009	4.04	3.30	86.74	13.26	1992	4.13	3.23
	85	15	1983	4.18	3.19	80.44	19.56	1959	4.30	3.09
	80	20	1957	4.31	3.08	74.36	25.64	1926	4.47	2.96
	75	25	1930	4.45	2.97	68.50	31.50	1895	4.63	2.83
	70	30	1904	4.59	2.86	62.84	37.16	1865	4.78	2.70
L/SD	95	5	2046	3.62	3.35	94.12	5.88	2042	3.59	3.31
	90	10	2030	3.47	3.17	88.31	11.69	2024	3.41	3.11
	85	15	2014	3.32	3.00	82.62	17.38	2007	3.24	2.91
	80	20	1998	3.17	2.82	77.03	22.97	1989	3.08	2.71
	75	25	1982	3.01	2.64	71.54	28.46	1971	2.91	2.52
	70	30	1966	2.86	2.47	66.16	33.84	1953	2.75	2.33
L/CL	95	5	2027	5.23	4.09	92.92	7.08	2013	5.85	4.32
	90	10	1993	6.69	4.65	86.10	13.90	1966	7.84	5.09
	85	15	1959	8.15	5.21	79.57	20.43	1921	9.75	5.82
	80	20	1925	9.61	5.77	73.31	26.69	1879	11.58	6.53
	75	25	1891	11.07	6.33	67.32	32.68	1838	13.32	7.20
	70	30	1857	12.53	6.89	61.56	38.44	1799	15.01	7.84
L/RDF	95	5	2036	3.95	3.71	93.95	6.05	2029	3.98	3.75
	90	10	2009	4.13	3.90	87.99	12.01	2000	4.20	3.98
	85	15	1983	4.31	4.09	82.16	17.84	1969	4.41	4.19
	80	20	1957	4.48	4.27	76.46	23.54	1938	4.61	4.41
	75	25	1931	4.66	4.46	70.89	29.11	1909	4.81	4.61
	70	30	1905	4.84	4.65	65.44	34.56	1882	5.01	4.82

It is evident from Tables 7.13 that weight-based NO_x emission factor decreases for all blends except for bituminous coal/chicken litter blend due to that fact that all selected biomass fuels except chicken litter have less nitrogen than bituminous coal. Since, all chosen biomass fuels except sawdust contain more nitrogen than lignite, therefore, in case of lignite/biomass blends, NO_x emission factor increases for all blends except lignite/sawdust blend as is shown from Table 7.14. Sawdust is the most suitable biomass for reduction of NO_x emission because of its negligible nitrogen content. At 30% co-firing ratio, weight-based NO_x emission factor reduces by 27.78% and 24.14% for

bituminous coal/sawdust blend and lignite/sawdust blend respectively in case 1. Similarly, for case 2, the decreases of 39.48 % and 27.05% are found for bituminous coal/sawdust blend and lignite/sawdust blend respectively when coal flow rate reduces to 0.70kg/s.

As far as weight-based SO_x emission factor is concerned, in case of bituminous coal and biomass co-firing, this factor decreases for all blends except bituminous coal/chicken litter blend because all selected biomass fuels except chicken litter have less sulphur content than that of bituminous coal. However, in case of lignite and biomass co-firing, weight-based SO_x emission factor decreases for lignite/rice husk blend and lignite/sawdust blend, while this factor increases for lignite/chicken litter blend and lignite/refuse derived fuel blend. Sawdust is the most suitable biomass in terms of SO_x reduction. For case 1, weight-based SO_x emission factor decreases by 30.01% and 29.83% for bituminous coal/sawdust blend and lignite/sawdust blend respectively at 30% co-firing ratio. Similarly, for case 2, the reductions of 42.62% and 33.81% are observed in weight-based SO_x emission factor for bituminous coal/sawdust blend and lignite/sawdust blend respectively when coal flow rate decreases to 0.70kg/s.

7.4.1. CO₂ Emissions

As far as total (gross) CO₂ energy-based emission factor from the stack is concerned, in case of bituminous coal/biomass blends, this factor decreases for all blends except bituminous coal/refuse derived fuel blend, in case of lignite/biomass blends, gross CO₂ energy-based emission factor decreases for lignite/chicken litter blend and lignite/refuse derived fuel blend, while gross CO₂ emission factor increases for lignite/rice husk blend and lignite/sawdust blend as is illustrated in Figure 7.12.

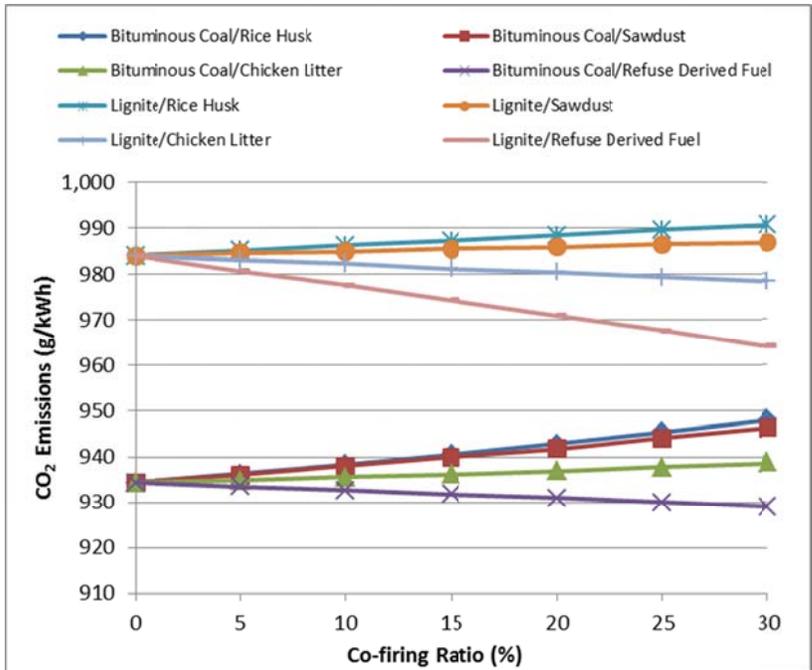


Figure 7.12: Effect of co-firing on gross CO₂ emissions based on a fixed fuel flow.

The increase in gross CO₂ emissions is due to decrease in net work output with increase of co-firing ratio which generally gives higher emissions compared with 100% coal. The decrease in CO₂ emissions for bituminous coal/refuse derived fuel blend, lignite/refuse derived fuel blend and lignite/chicken litter blend is due to relatively low carbon content of refuse derived fuel and chicken litter which diminishes the effect of work output reduction. CO₂ emissions are 948.1 g/kWh, 946.3 g/kWh, 936.6 g/kWh, and 929 g/kWh for bituminous coal/rice husk blend, bituminous coal/sawdust blend, bituminous coal/chicken litter blend, and bituminous coal/refuse derived fuel blend respectively at 30% co-firing ratio. Similarly, CO₂ emissions factors are 990.8 g/kWh, 986.9 g/kWh, 978.5 g/kWh, and 964.2 g/kWh for lignite/rice husk blend, lignite/sawdust blend, lignite/chicken litter blend, and lignite/refuse derived fuel blend respectively when co-firing ratio is 30%.

Figure 7.13 shows the effect of co-firing on gross CO₂ emissions for case 2. Trends are same as were for case 1. Gross CO₂ emissions decrease only for bituminous coal/refuse derived fuel blend, lignite/refuse derived fuel blend, and lignite/chicken litter blend,

while these emissions increase for all other blends. However, it should be noted that increase in gross CO₂ emissions is due to increase in mass flow of CO₂ in flue gases because of more biomass consumption than case 1. With respect to base coal gross CO₂ emissions decrease to 927.5 g/kWh, 977.9 g/kWh, 961.9 g/kWh for bituminous coal/refuse derived fuel blend, lignite/chicken litter blend, and lignite/refuse derived fuel blend respectively when coal flow rate decrease to 0.70kg/s.

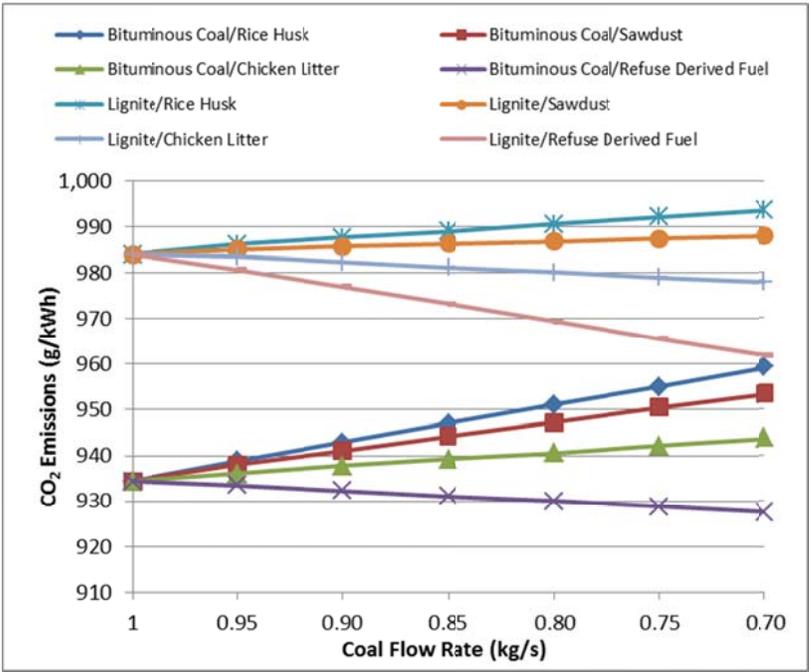


Figure 7.13: Effect of co-firing on gross CO₂ emissions based on fixed heat input to steam cycle.

If the net CO₂ emissions to the environment are calculated, i.e. taking the fact that the biomass is considered to be CO₂ neutral, subsequently the co-firing process, demonstrates a much lower level of CO₂ emissions, as is shown in Figure 7.14. With reference to base coal, net CO₂ emissions decrease from 934.3 g/kWh to 769.8 g/kWh, 749.2 g/kWh, 776.9 g/kWh, and 753.9 g/kWh for bituminous coal/rice husk blend, bituminous coal/sawdust blend, bituminous coal/chicken litter blend, and bituminous coal/refuse derived fuel blend respectively at 30% co-firing ratio. Similarly, at 30% co-firing ratio, net CO₂ emissions lignite/rice husk blend, lignite/sawdust blend, lignite/chicken litter blend, and

lignite/refuse derived fuel blend are 751.2 g/kWh, 724.5 g/kWh, 760.5 g/kWh, and 730.5 g/kWh respectively. It is evident that the most suitable biomass in terms of CO₂ reduction is sawdust due to its highest carbon content among the selected biomass fuels.

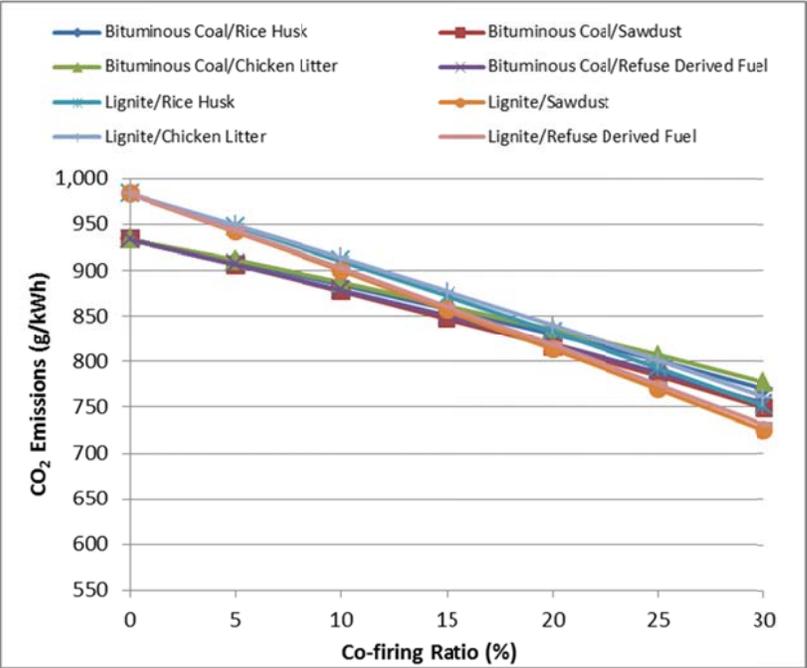


Figure 7.14: Effect of co-firing on net CO₂ emissions based on a fixed fuel flow.

Since, work output of plant is constant in case 2; net CO₂ emission factors are same for all biomass blends with respect to base coal, as is shown in Figure 7.15. For example, when coal flow rate is 0.70 kg/s, net CO₂ emissions for bituminous coal/biomass blends and lignite/biomass blends are 654 g/kWh and 688.9 g/kWh respectively.

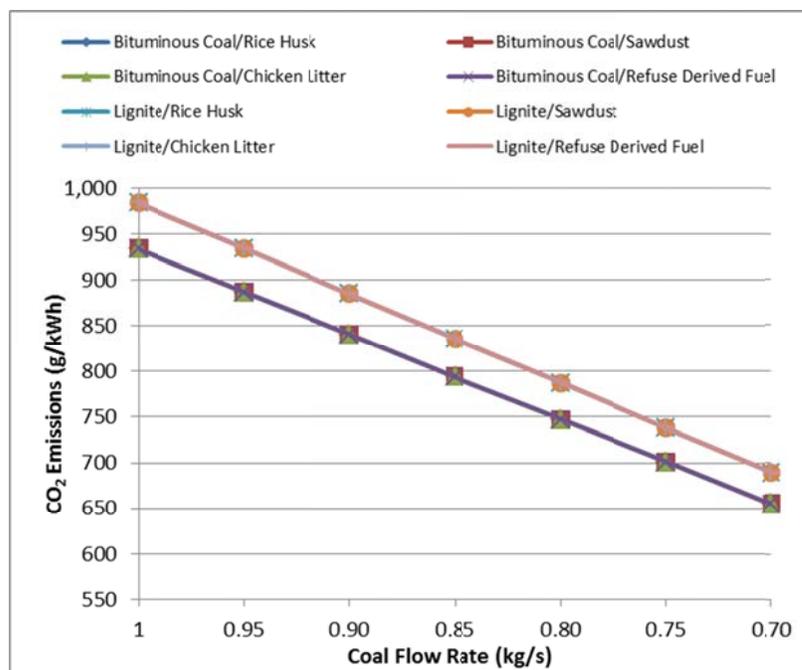


Figure 7.15: Effect of co-firing on net CO₂ emissions based on fixed heat input to steam cycle. The upper and bottom lines denote emission factors for lignite/biomass blends and bituminous coal/biomass blends respectively.

7.4.2. NO_x Emissions

The effect of co-firing on NO_x emissions for both cases is shown in Figures 7.16 and 7.17. Since, all biomass fuels contain more nitrogen than lignite, therefore, NO_x emissions increase for all blends except lignite/sawdust blend in case of lignite. However, in case of bituminous coal, regardless of less nitrogen content of both rice husk and refuse derived fuel than that of bituminous coal, NO_x emissions increase slight for bituminous coal/rice husk blend and bituminous coal/refuse derived fuel blend due to decrease in work output. It is also evident that the most appropriate biomass in terms of NO_x reduction is sawdust because of its very low nitrogen content. For case 1, NO_x emissions decrease from 3.32 g/kWh to 2.75 g/kWh for bituminous coal/sawdust blend and from 1.80 g/kWh to 1.44 for lignite/sawdust blend at 30% co-firing ratio. Similarly, for case 2, with 0.70 kg/s of coal, NO_x emissions reduce to 2.45 g/kWh and 1.44 g/kWh for bituminous coal/sawdust blend and lignite/sawdust blend respectively.

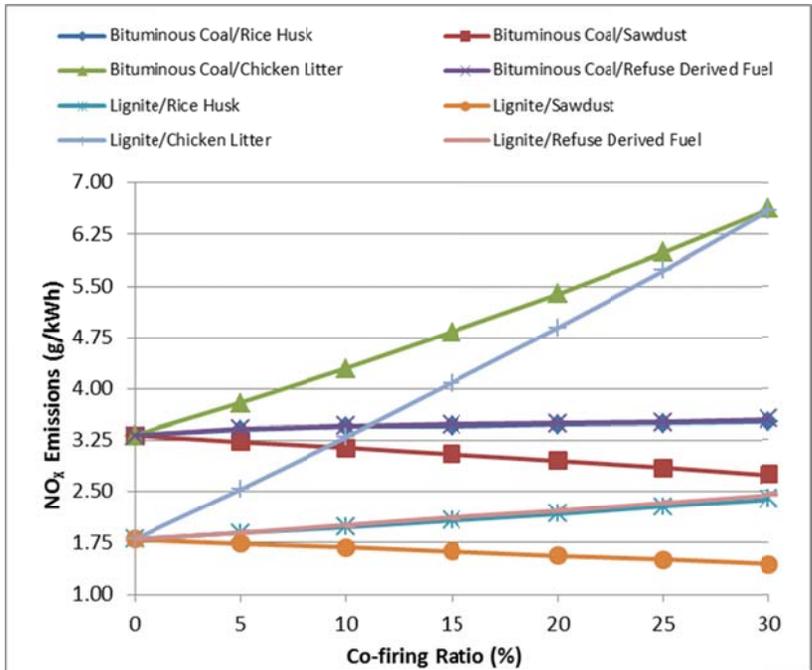


Figure 7.16: Effect of co-firing on NO_x emissions based on a fixed fuel flow.

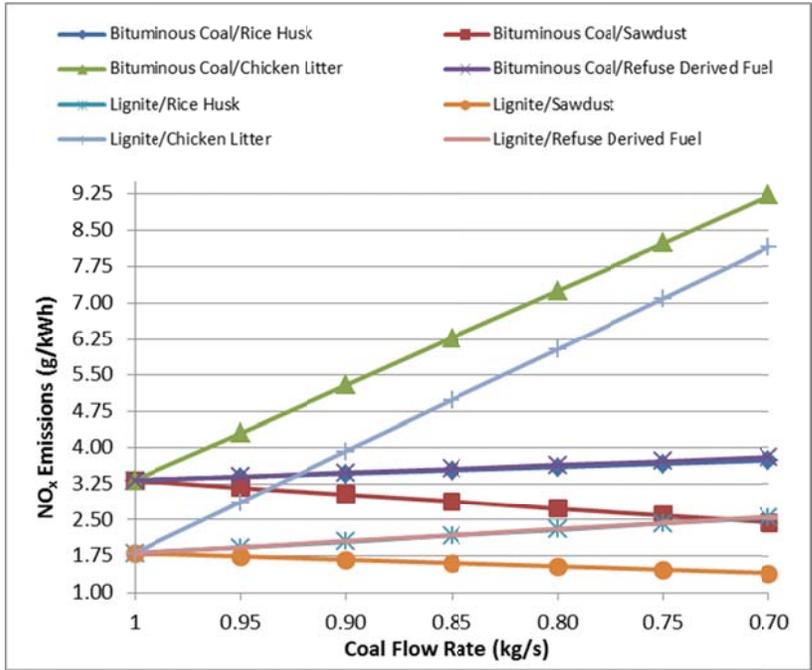


Figure 7.17: Effect of co-firing on NO_x emissions based on fixed heat input to steam cycle.

7.4.3. SO_x Emissions

The sulphur content in fuel has a direct effect on the generation of sulphur dioxide during combustion. Among the chosen biomass, rice husk and sawdust have negligible sulphur content. So, their addition in mixture results in overall reduction in SO_x emissions, as is illustrated in Figure 7.18.

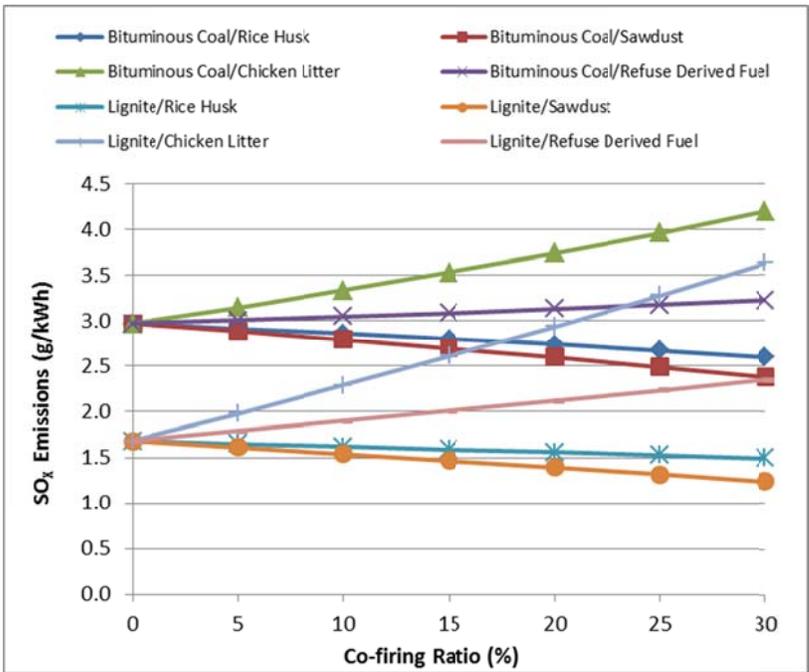


Figure 7.18: Effect of co-firing on SO_x emissions based on a fixed fuel flow.

Since chicken litter has much higher sulphur content than that of bituminous coal and lignite; SO_x emission factor increases for bituminous coal/chicken litter blend and lignite/chicken litter blend. In comparison with 100% coal, SO_x emission factor increases from 2.97 g/kWh to 4.20 g/kWh for bituminous coal/chicken litter blend and from 1.39 g/kWh to 3.63 g/kWh for lignite/chicken litter blend when the co-firing ratio is 30%. Moreover, sulphur content of refuse derived fuel is slightly smaller than that of bituminous coal. Due to decrease in work output, SO_x emission factor increases for bituminous coal/refuse derived fuel blend.

The effect of co-firing on SO_x emissions for case 2 is shown in Figure 7.19. Like case 1, SO_x emissions increase for chicken litter and refuse derived fuel blends and decrease for rice husk and sawdust blends.

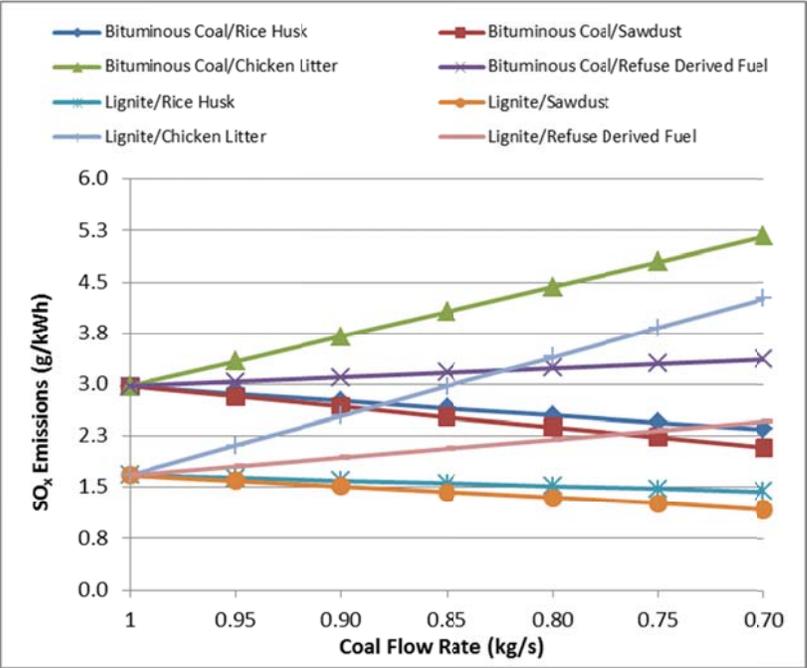


Figure 7.19: Effect of co-firing on SO_x emissions based on fixed heat input to steam cycle.

7.5. Validation of Results

In the present study, efforts were made to establish realistic operating conditions for the system components based on the data ranges given in the literature. The trends found from the simulation results follow the same trends as those presented in the past studies. The trends for plant energy efficiency are matching with those of Huang et al. [65]. From the results presented in [65], it is observed that biomass co-firing (till 20% mass) results in less than 1% reduction in boiler energy efficiency, which is compliant with the results of the present study.

The weight-based CO₂ emission factors (kg/Mg) found in all cases are less than CO₂ emission factors (3125 kg/Mg for bituminous coal and 2300 kg/Mg for lignite), suggested by the US Environmental Protection Agency. Moreover, the trends found for energy-based emission factors are also compliant with those of Chao et al. [58] and Huang et al. [65]. The results of the study conducted by Huang et al. [65] revealed that total (gross) CO₂ emission factor generally increases due to reduction in work output. However, gross CO₂ emission factor may decrease if the carbon content of the selected biomass is too low and diminishes the effect of work output reduction. The present study showed the similar results.

In all cases, except for chicken litter blends at high co-firing ratios (<20%), weight-based NO_x emission factor is also less than NO_x emission factors (15.5 kg/Mg for bituminous coal and 7.5 kg/Mg for lignite), proposed by the US Environmental Protection Agency. The findings and observations regarding NO_x emissions found in this study are compliant with those of Spliethoff and Hein [52], Kruczek et al. [56], Chao et al. [58], and Huang et al. [65].

As far SO_x emissions are concerned, in case of bituminous coal/biomass blends weight-based SO_x emission factor found in this study at all co-firing ratios is less than weight-based SO_x emission factor (around 13 kg/Mg for bituminous coal), suggested by the US Environmental Protection Agency. However, in case of lignite/biomass blends weight-based SO_x emission factor is less than proposed emissions factor (around 5 kg/Mg for lignite) by the US Environmental Protection Agency for rice husk and sawdust only.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

In this chapter, summary of principal findings, main conclusions drawn from the analysis and recommendations are presented.

8.1. Summary of Principal Findings

- Investigation of system performance in terms of key parameters indicates that addition of biomass in the blend decreases the energy input, exergy input, and air flow rate to the plant when the fuel flow rate is constant. Because of low input to the plant, output parameters (heat produced in the boiler, useful exergy, and net power outputs) also decrease. The extent of decrease in these parameters mainly depends on heating value of the biomass. Moreover, the amount of additional biomass required to produce the same heat as can be produced by burning 1 kg/s of coal also depends on the energy content of the biomass. Among the selected biomass fuels used in analysis, chicken litter has the lowest heating value; therefore, the largest decrease in key parameters and the largest amount of additional biomass required are found for its blends. On the contrary, the smallest reduction in key parameters and the smallest amounts of additional biomass required are found for sawdust blends due to its highest heating value among the chosen biomass.
- In both cases, energy and exergy losses due to moisture increase the highest for sawdust blends because the moisture content of sawdust is the highest of the chosen biomass fuels and is greater than that of bituminous coal and lignite. Similarly, energy and exergy losses due to ash increase with co-firing of all chosen biomass except sawdust. Co-firing of chicken litter results in the highest energy and exergy losses through ash due to the fact that the ash content of chicken is the highest of the selected biomass fuels. As far as energy and exergy losses through stack gas are concerned, these losses decrease for all biomass blends in case 1 due to decrease in

both furnace exit gas temperature and net mass flow rate of flue gases. However, in case 2, energy and exergy losses through stack increase for rice husk and chicken litter blends and decrease for refuse derived fuel and sawdust blends. Moreover, it is also found that irreversibility rate of both boiler and plant decreases with increase of co-firing ratio when the fuel flow rate is fixed. However, irreversibility rate of boiler, and subsequently plant increases when the heat rate produced in boiler is fixed. Among selected biomass fuels, blends of sawdust exhibit the largest irreversibility rate at all co-firing ratios, while blends of chicken litter exhibit the smallest irreversibility rate at all co-firing ratios compared to other blends.

- Co-firing of biomass decreases the energy and exergy efficiencies of both boiler and plant. The decrease in energy and exergy efficiencies caused by biomass fuels depends on their heating value, moisture content, and ash content. Energy efficiency seems to decrease the least for the biomass which has relatively high calorific value, while exergy efficiency seems to decrease the least for biomass which has relatively low calorific value. Moreover, it is found that moisture content has much more significant effect on efficiency reduction than ash content. Among the selected biomass fuels used in the present analysis, energy efficiency drops the least for refuse fuel blends, while the highest drop in energy efficiency occurs for chicken litter blends at all co-firing ratios and in both cases considered. On the other hand, the highest drop in exergy efficiency of plant and boiler occurs for sawdust blends, while exergy efficiency decreases the least for chicken litter blends at all co-firing ratios and in both cases considered.
- Since, biomass co-firing also causes reduction in work output; gross (total) CO₂ emissions through stack may decrease or increase depending on the carbon content of the selected biomass. In the present analysis, total (gross) CO₂ emissions from the stack are observed to increase for all blends except bituminous coal/refuse derived fuel blend, lignite/refuse derived fuel blend and lignite/chicken litter blend with an increase in biomass fraction in the blend, while total CO₂ emissions are found to be decreased for refuse derived fuel and chicken litter blends. On the other hand, net

CO₂ emissions decrease for all selected biomass fuels. The most suitable biomass in terms of CO₂ reduction is chicken litter due to its lowest carbon content among selected biomass fuels.

- Reduction in NO_x emissions also depends on the nitrogen content of biomass. Among the selected biomass fuels, sawdust has lower nitrogen content than that of bituminous coal and lignite. Therefore, NO_x emissions are observed to decrease for sawdust blends at all co-firing conditions. On the other hand, the nitrogen content of chicken is much greater than that of bituminous coal and lignite. As a result, NO_x emissions are found to decrease for sawdust blends at all co-firing conditions.
- Like CO₂ and NO_x emissions, reduction in SO_x emission with biomass co-firing also depends on the sulphur content of biomass fuels. Since, rice husk and sawdust have negligible sulphur content compared with that of bituminous coal and lignite; so, their addition in mixture results in overall reduction in SO_x emissions at all co-firing ratios. In contrast, addition of chicken litter in the blend increases the overall SO_x emissions because of its higher sulphur content than that of bituminous coal and lignite.

8.2. Conclusions

In this thesis, energy and exergy analyses are carried out for a co-firing based power generation system to evaluate the impacts of biomass co-firing with coal on system performance and gaseous emissions of CO₂, NO_x, and SO_x. The main conclusions drawn from the present study follow:

- Energy and exergy efficiencies of both boiler and plant decrease due to biomass co-firing. For all biomass fuels, the reduction in energy and exergy efficiencies is relatively small at low co-firing ratios (5-10% on mass basis).

- If biomass is considered to be CO₂ neutral, the co-firing process demonstrates a much lower level of CO₂ emissions. Gross (total) CO₂ emissions through stack may also decrease if the carbon content of the selected biomass is relatively low and it diminishes the effect of work output reduction caused by biomass addition in the blend.
- If the selected biomass has lower nitrogen content than that of coal, then the reduction in NO_x emissions is also possible by biomass co-firing with coal.
- SO_x can also decrease by biomass co-firing if the selected biomass has lower sulphur content than that of coal.
- Therefore, from thermodynamic perspective, co-firing of biomass is not worthwhile because it does result in drop in energy and exergy efficiencies of boiler and plant. However, proper choices of biomass can lead to have substantial benefits in terms of CO₂, NO_x, and SO_x emissions reduction and so as the reduction in efficiency is also compensated by the reduction in these harmful emissions. Hence, co-firing of biomass with coal has potential to decrease harmful emissions and is an acceptable means of promoting the use of renewable energy.

8.3. Recommendations

The results and findings of the present study illustrate the impacts of biomass co-firing on the system performance and gaseous emissions of CO₂, NO_x, and SO_x for a co-firing based power generation system. Recommendations how and where this study can be used follow:

- As mentioned earlier, there is a lack of studies on energy and exergy analyses of biomass co-firing with coal in open literature. So, the present results and findings will enhance the available information on energy and exergy analyses of biomass co-firing

with coal. Therefore, it is recommended that the present work be used as a guide for future studies on such processes.

- The results and findings of the present study will assist the plant owners to have insight into how a co-firing based system will perform at different co-firing conditions and for different combinations of fuels if they are considering retrofitting of their existing coal-based plants for biomass co-firing.
- The present study will also help the plant owners to decide which type of biomass is the most suitable option in terms of environmental perspective if they are planning to switch over to biomass co-firing.

Although the objectives of the present work have been satisfied, recommendations to improve the study exist and are as follow:

- In the present study, operating temperature and pressure of the steam cycle components are kept constant. Parametric analysis should be done to study the impact of co-firing at varying conditions of steam cycle components.
- Biomass and coal ashes are different in compositions. Biomass ash can have relatively high alkaline metal contents, particularly sodium and potassium. Sodium and potassium lower the melting point of the ash and, hence, can increase ash deposition and fouling of boiler tubes [13]. A study conducted by Pronobis et al. [51] revealed that 20% (by mass) co-firing of the sewage sludge that had 50% ash content, caused severe deterioration of the boiler. The present study has not studied the impact of biomass ash on slagging and fouling of boiler convection surfaces. In the literature, information is available to estimate the fouling and slagging of boiler convection surfaces. Therefore, it is recommended that the impact of biomass co-firing on the boiler fouling and slagging should be included to enhance the present results.

While completing the present work, the following opportunities for further work in the area of biomass co-firing have been identified.

- In the present study, the analysis is carried out for direct co-firing configuration which is the most common among all co-firing configurations. However, indirect co-firing and parallel co-firing are also very attractive co-firing options and have been demonstrated around the world. Therefore, it is recommended that impacts of biomass for these two options should also be investigated.
- The present study has investigated the effect of co-firing for a pulverized coal boiler because of the fact that majority of the power plants in which biomass co-firing has been applied employ pulverized coal boiler. Co-firing has also been applied in fluidized bed boilers. Therefore, investigating the impacts of biomass co-firing for a fluidized bed boiler should also be considered for future work.
- Some experimental studies are also carried out on biomass co-firing with natural gas. Therefore, it is recommended that co-firing of biomass and natural gas should also be considered for future work.

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APPENDIX: COMPOSITION OF FLUE GASES LEAVING THROUGH STACK

Table A1: Flue gas composition leaving through stack for bituminous coal/biomass blends based on a fixed fuel flow

Blend	Co-firing Ratio (%)	Flue Gas Flow Rate (kmol/s)						
		CO ₂	H ₂ O	O ₂	N ₂	NO×10 ⁻²	NO ₂ ×10 ⁻³	SO ₂ × 10 ⁻²
Base	0	0.0585	0.0239	0.0133	0.3005	0.02865	0.0119	0.0128
B/RH	5	0.0572	0.0241	0.0130	0.2929	0.02814	0.0117	0.0122
	10	0.0558	0.0243	0.0126	0.2853	0.02763	0.0115	0.0117
	15	0.0545	0.0245	0.0123	0.2777	0.02712	0.0113	0.0112
	20	0.0531	0.0248	0.0120	0.2702	0.02661	0.0111	0.0106
	25	0.0518	0.0250	0.0116	0.2626	0.02610	0.0109	0.0101
	30	0.0504	0.0252	0.0113	0.2550	0.02559	0.0107	0.0095
B/SD	5	0.0574	0.0244	0.0130	0.2939	0.02732	0.0114	0.0122
	10	0.0562	0.0249	0.0127	0.2872	0.02600	0.0108	0.0115
	15	0.0551	0.0253	0.0124	0.2806	0.02467	0.0103	0.0109
	20	0.0540	0.0258	0.0121	0.2740	0.02335	0.0097	0.0102
	25	0.0529	0.0263	0.0118	0.2673	0.02202	0.0092	0.0096
	30	0.0517	0.0268	0.0116	0.2607	0.02070	0.0086	0.0090
B/CL	5	0.0570	0.0239	0.0130	0.2932	0.03190	0.0133	0.0132
	10	0.0555	0.0239	0.0127	0.2860	0.03515	0.0147	0.0136
	15	0.0540	0.0239	0.0123	0.2787	0.03841	0.0160	0.0140
	20	0.0525	0.0239	0.0120	0.2714	0.04166	0.0174	0.0144
	25	0.0510	0.0239	0.0117	0.2641	0.04491	0.0187	0.0148
	30	0.0495	0.0240	0.0114	0.2569	0.04816	0.0201	0.0152
B/RFD	5	0.0572	0.0242	0.0130	0.2932	0.02826	0.0118	0.0127
	10	0.0558	0.0245	0.0127	0.2859	0.02787	0.0116	0.0125
	15	0.0545	0.0248	0.0123	0.2786	0.02748	0.0115	0.0124
	20	0.0531	0.0251	0.0120	0.2713	0.02709	0.0113	0.0123
	25	0.0518	0.0253	0.0117	0.2640	0.02671	0.0111	0.0122
	30	0.0505	0.0256	0.0114	0.2566	0.02632	0.0110	0.0120

Table A2: Flue gas composition leaving through stack for bituminous coal/biomass blends based on fixed heat input to cycle

Blend	Co-firing Ratio (%)	Flue Gas Flow Rate (kmol/s)						
		CO ₂	H ₂ O	O ₂	N ₂	NO×10 ⁻²	NO ₂ ×10 ⁻³	SO ₂ ×10 ⁻²
Base	0	0.0585	0.0239	0.0133	0.3004	0.0286	0.0119	0.0128
B/RH	9.55	0.0587	0.0255	0.0133	0.3003	0.0291	0.0121	0.0123
	18.23	0.0590	0.0271	0.0133	0.3002	0.0295	0.0123	0.0119
	26.15	0.0592	0.0288	0.0133	0.3001	0.0299	0.0125	0.0114
	33.41	0.0595	0.0304	0.0133	0.3000	0.0303	0.0126	0.0110
	40.09	0.0597	0.0321	0.0133	0.2999	0.0307	0.0128	0.0105
	46.24	0.0600	0.0337	0.0133	0.2998	0.0312	0.0130	0.0101
B/SD	8.37	0.0587	0.0256	0.0133	0.2999	0.0274	0.0114	0.0122
	16.16	0.0589	0.0273	0.0133	0.2995	0.0262	0.0109	0.0115
	23.44	0.0591	0.0290	0.0132	0.2990	0.0249	0.0104	0.0109
	30.26	0.0593	0.0308	0.0132	0.2985	0.0237	0.0099	0.0102
	36.64	0.0595	0.0325	0.0132	0.2980	0.0224	0.0093	0.0096
	42.65	0.0596	0.0342	0.0132	0.2976	0.0212	0.0088	0.0090
B/CL	10.03	0.0586	0.0252	0.0134	0.3018	0.0371	0.0154	0.0143
	19.05	0.0587	0.0266	0.0134	0.3032	0.0456	0.0190	0.0159
	27.21	0.0588	0.0280	0.0135	0.3046	0.0541	0.0225	0.0175
	34.63	0.0588	0.0293	0.0135	0.3060	0.0626	0.0261	0.0191
	41.40	0.0589	0.0307	0.0136	0.3074	0.0711	0.0296	0.0207
	47.60	0.0590	0.0321	0.0137	0.3088	0.0796	0.0332	0.0222
B/RFD	8.62	0.0584	0.0253	0.0133	0.2992	0.0291	0.0121	0.0131
	16.60	0.0583	0.0268	0.0132	0.2980	0.0295	0.0123	0.0134
	24.03	0.0583	0.0283	0.0132	0.2968	0.0300	0.0125	0.0136
	30.95	0.0582	0.0298	0.0131	0.2956	0.0304	0.0127	0.0139
	37.41	0.0581	0.0312	0.0130	0.2944	0.0308	0.0129	0.0142
	43.45	0.0580	0.0327	0.0130	0.2933	0.0313	0.0130	0.0145

Table A3: Flue gas composition leaving through stack for lignite/biomass blends based on a fixed fuel flow

Blend	Co-firing Ratio (%)	Flue Gas Flow Rate (kmol/s)						
		CO ₂	H ₂ O	O ₂	N ₂	NO×10 ⁻²	NO ₂ ×10 ⁻³	SO ₂ ×10 ⁻²
Base	0	0.0425	0.0274	0.0091	0.2050	0.0107	0.0045	0.0050
L/RH	5	0.0420	0.0274	0.0090	0.2022	0.0111	0.0046	0.0048
	10	0.0414	0.0275	0.0088	0.1994	0.0115	0.0048	0.0047
	15	0.0409	0.0275	0.0087	0.1966	0.0119	0.0049	0.0045
	20	0.0403	0.0276	0.0086	0.1937	0.0123	0.0051	0.0044
	25	0.0398	0.0276	0.0085	0.1909	0.0127	0.0053	0.0042
	30	0.0392	0.0276	0.0083	0.1881	0.0130	0.0054	0.0041
L/SD	5	0.0422	0.0277	0.0090	0.2032	0.0103	0.0043	0.0047
	10	0.0418	0.0280	0.0089	0.2013	0.0099	0.0041	0.0045
	15	0.0415	0.0283	0.0088	0.1994	0.0094	0.0039	0.0042
	20	0.0412	0.0286	0.0088	0.1976	0.0090	0.0037	0.0040
	25	0.0409	0.0289	0.0087	0.1957	0.0086	0.0036	0.0037
	30	0.0405	0.0293	0.0086	0.1938	0.0081	0.0034	0.0035
L/CL	5	0.0418	0.0272	0.0090	0.2025	0.0149	0.0062	0.0058
	10	0.0411	0.0271	0.0089	0.2000	0.0190	0.0079	0.0066
	15	0.0404	0.0269	0.0087	0.1975	0.0232	0.0096	0.0074
	20	0.0397	0.0267	0.0086	0.1950	0.0273	0.0114	0.0082
	25	0.0390	0.0266	0.0085	0.1925	0.0315	0.0131	0.0090
	30	0.0383	0.0264	0.0084	0.1900	0.0356	0.0148	0.0098
L/RFD	5	0.0420	0.0275	0.0090	0.2025	0.0112	0.0047	0.0053
	10	0.0414	0.0276	0.0089	0.1999	0.0117	0.0049	0.0055
	15	0.0409	0.0277	0.0087	0.1974	0.0122	0.0051	0.0058
	20	0.0403	0.0279	0.0086	0.1949	0.0127	0.0053	0.0061
	25	0.0398	0.0280	0.0085	0.1923	0.0133	0.0055	0.0063
	30	0.0393	0.0281	0.0084	0.1898	0.0138	0.0057	0.0066

Table A4: Flue gas composition leaving through stack for lignite/biomass blends based on fixed heat input to steam cycle

Blend	Co-firing Ratio (%)	Flue Gas Flow Rate (kmol/s)						
		CO ₂	H ₂ O	O ₂	N ₂	NO×10 ⁻²	NO ₂ ×10 ⁻³	SO ₂ ×10 ⁻²
Base	0	0.0425	0.0274	0.0091	0.2050	0.0107	0.0045	0.0050
L/RH	6.73	0.0426	0.0279	0.0091	0.2050	0.0114	0.0048	0.0049
	13.26	0.0426	0.0285	0.0091	0.2050	0.0122	0.0051	0.0047
	19.56	0.0427	0.0291	0.0091	0.2050	0.0129	0.0054	0.0046
	25.64	0.0427	0.0297	0.0091	0.2051	0.0137	0.0057	0.0045
	31.50	0.0428	0.0303	0.0091	0.2051	0.0144	0.0060	0.0044
	37.16	0.0429	0.0309	0.0091	0.2051	0.0152	0.0063	0.0043
L/SD	5.88	0.0425	0.0280	0.0091	0.2047	0.0103	0.0043	0.0047
	11.69	0.0425	0.0286	0.0091	0.2045	0.0099	0.0041	0.0045
	17.38	0.0426	0.0293	0.0091	0.2043	0.0095	0.0040	0.0042
	22.97	0.0426	0.0299	0.0090	0.2041	0.0091	0.0038	0.0040
	28.46	0.0426	0.0306	0.0090	0.2039	0.0087	0.0036	0.0037
	33.84	0.0426	0.0312	0.0090	0.2036	0.0083	0.0034	0.0035
L/CL	7.08	0.0424	0.0278	0.0091	0.2060	0.0170	0.0071	0.0063
	13.90	0.0424	0.0282	0.0092	0.2071	0.0233	0.0097	0.0075
	20.43	0.0423	0.0285	0.0092	0.2081	0.0296	0.0123	0.0088
	26.69	0.0423	0.0289	0.0093	0.2092	0.0359	0.0150	0.0101
	32.68	0.0422	0.0293	0.0093	0.2103	0.0422	0.0176	0.0114
	38.44	0.0422	0.0297	0.0094	0.2113	0.0485	0.0202	0.0126
L/RFD	6.05	0.0423	0.0278	0.0090	0.2042	0.0115	0.0048	0.0054
	12.01	0.0422	0.0283	0.0090	0.2035	0.0122	0.0051	0.0058
	17.84	0.0420	0.0288	0.0090	0.2028	0.0130	0.0054	0.0061
	23.54	0.0418	0.0292	0.0090	0.2021	0.0137	0.0057	0.0065
	29.11	0.0417	0.0297	0.0089	0.2014	0.0145	0.0060	0.0069
	34.56	0.0415	0.0302	0.0089	0.2006	0.0152	0.0063	0.0073