Department of Chemical and Petroleum Engineering

Development of Modelling Tool to Predict Carbon Credits for Biomass Co-fired Boilers

Harshani Manjula Karunarathna

This thesis is presented for the
Master of Philosophy (Chemical Engineering)
of
Curtin University

June 2016

Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature:

Date: 24/06/16

Abstract

Coal power generation is accompanied with numerous pollutant gases which inflict a direct impact on global warming. Technological advancements of boilers, quality improvements of coal types and blending of coal with various kinds of alternative fuels etc., are some of the positive approaches being implemented as proactive solutions for the alarming problem of gaseous emissions.

Co-firing is well known to provide a near-term solution for mitigating Greenhouse Gas (GHG) emissions from conventional coal power plants. Quantitative analysis of emission reductions provides liable information to the power utilities, to move towards the sustainable energy generation with less environmental impacts. Since biomass burning is carbon neutral, it can be introduced as a successful alternative, to blend with coal (5-20 w/w %), resulting in an effective reduction of emissions from utilization of coal alone. This reduction can be estimated by means of equivalent carbon credits (1 tonne of CO_2e is equivalent to 1 carbon credit). The areas of technical effectiveness and financial feasibility of co-firing has been investigated intensively; however, a comprehensive predictive tool of carbon credits is non-existent in the literature.

In the present work, an attempt has been made to develop a predictive tool to estimate carbon credits relevant to co-firing systems. Additionally, an eligibility analysis has been carried out to determine the perfect blends, optimum blend ratios against seven coals of varying ranks blended with fifteen types of biomass types at known boiler efficiency of 85%. The model equations have been developed under two main categories of biomass (woody and non-woody) and each coal type has its own two model equations against the biomass types which will immediately provide the amount of carbon credits generated per unit of energy released for a given ratio of biomass-coal blends. Model results indicated that lignite is the most appropriate coal type for blending with biomass since it gives the highest emission reduction (or the most carbon credits) of 0.31 tCO_2/MWh with woody and 0.28 tCO_2/MWh with non-woody at the blend ratio of 80:20 (coal/biomass). As a percentagewise, it is more than 20% of carbon credits with less than 1% and 3% of energy loss with woody and non-woody biomass types respectively. Overall our model approach indicates that conventional boilers utilising low rank coals (Lignite and Sub bituminous) are best suited for co-firing with biomass to mitigate GHG emissions.

Acknowledgements

I would like to express my deepest appreciation to all those who provided me the possibility to complete this project. A special gratitude I give to my supervisor, Associate Professor Hari Vuthaluru and co-supervisor; Dr. Chi Phan, whose contribution in stimulating suggestions and encouragement, helped me to coordinate my research. I am very grateful to them for their enormous time and effort spent guiding and assisting me throughout my dissertation period.

I express my sincere gratitude to the Chairperson of Thesis Committee Professor Ming Ang and Head of the Department Professor Hongwei Wu for their constant support and advise. Furthermore I would also like to acknowledge with much appreciation the crucial role of the staff of the administrations at Chemical Engineering Department, as well as library staff who gave the permission to use all required sources during the completion of the project.

Foremost I would like to thank my beloved husband, Damitha Silva, for his outstanding assistant in proof reading of my thesis and all his encouragements throughout my study period.

Finally, all the credentials of this degree go to my beloved parents. This journey would not have been possible without their love and support. I am deeply indebted to my parents, and my family, who have been with me at every step before and during this project completion. Furthermore, I would like to thank every hand that helped me directly or indirectly in completion of this project work.

Brief Biography of Author

Author of this thesis Mrs Harshani Manjula Karunarathna has completed her bachelor in Chemical & Process Engineering from University of Moratuwa, Sri Lanka with second class. In July 2013, she has joined Curtin University of Technology, WA, to conduct a Master of Philosophy (Chemical Engineering) by research.

She has written a review paper on:

1) **"Adverse effects of anthropogenic greenhouse gases & potential mitigation strategies through international emission trading"**

And a paper in support of thesis:

2) **"Blending biomass and coal for targeting carbon credits in co-fired power plants"**

These papers are submitted to the following journals for publication.

- Energy Policy (Paper 1)
- Biomass and Bioenergy (Paper 2)

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Nomenclature

Symbol	**Definition**
O_{2st}	Stoichiometric Oxygen (kgmol)
O_{2req}	Require Oxygen (kgmol)
O_{2ent}	Entering Oxygen (kgmol)
A_{ex}	Excess air (%)
$\Delta H°_f$	Heat of formation (kJ/kgmol)
$\Delta H°_c$	Heat of combustion (kJ/kgmol)
$\Delta\widehat{H_s}$	Sensible heat (kJ/kgmol)
L	Latent heat (kJ/kgmol)
$\Delta H_{st_{in}}$	Stream sensible heat input (kJ/h)
$\Delta H_{st_{out}}$	Stream sensible heat output (kJ/h)
ΔH	Enthalpy difference (kJ/h)
ΔPE	Potential energy difference (kJ/h)
ΔKE	Kinetic energy difference (kJ/h)
CE	Chemical Elements
Q_{in}	Rate of boiler heat in (kJ/h)
Q_o	Rate of boiler heat out (kJ/h)
η	Boiler efficiency
n	No of moles (kgmol)
$\dot{n}$	Mole flow rate (kgmol/h)
$\acute{c}$	Coal
$\acute{b}$	Biomass
f	Fuel
a, b, c, d, e	Known constants
T	Temperature (°C)

Chapter 1: Introduction

1.1. Background

1.1.1. Correlation between energy generation and GHG emissions

In the current competitive world, GHG (Greenhouse Gas) emission reduction in the energy sector is a highly regarded matter in terms of global pollution. The CO_2 (carbon dioxide) contribution exclusively from energy production has been projected as 69% ("*The latest GHG evaluation carried out by the IEA (International Energy Agency) in 2014*") (IEA 2014). Among those, although coal denoted 29% of the world TPES ("Total Primary Energy Supply") in 2012, it is responsible for 44% of the total world CO_2 discharge due to its substantial carbon content per unit of energy output. In addition, according to the (IEA 2014), CO_2 emissions from combustion of coal is estimated as 13.9GtCO_2 in 2012 and this figure shows 1.3% increment from the previous report values.

Instead of CO_2, there are huge amount of other gaseous emissions such as SO_2 (Sulphur Dioxide gas), NO_x (Nitrogen Oxides' Gases) and particulate matter released to the atmosphere by coal burning which will directly contribute to the global air pollution. In addition, the trace elements contain in coal such as mercury has been further concerned in releasing mercury emissions from coal-fired power plants. However, the growing energy demand due to rapid development of energy intensive industries in developing countries such as China and India is still filled by coal since this is the largely be existent energy reserve among the other energy sources (Miller 2011).

1.1.2. Towards renewable energy

It is predicted that the fossil fuel resources will be ended in next few decades (Shafiee and Topal 2009) Furthermore, environmental consequences associated with combustion emissions of fossil fuels such as global warming and climate change (Hughes 2000), (Baker, Glynn et al. 2008) has made a global requirement for reliable and realistic energy alternatives. Despite the fact that there is no evidence of any distinctive technology has been established so far for the complete replacement of fossil fuel energy. Commonly available energy sources such as wind and solar are yet to be considered as luxurious energy sources. In addition, there are some other technical barriers associated with these two energy sources such as intermittency and high cost of storage during the large scale generation.

Nuclear energy has the safety issues due to risk of explosions, and long-standing storage considerations, capital cost and availability of technology as well. Hydroelectricity is uncommon everywhere, time consuming and expensive construction process, involves widespread transmission, and has undesirable environmental consequences. Furthermore, biomass is comprised with lower energy density and some adverse environmental effects if it is not sourced from renewable resources (ex: Re-planting facilities with remaining canopy cover). The most common concern with many of these energy sources is the unavailability of constant supply to meet the growing energy demand (Felder, Andrews et al. 2011). Thus, it is high time to investigate a renewable alternative fuel which is not to switch the fossil fuel but to match and syndicate with in terms of generating a combined energy. In this case, coal will get the priority hence it is the primary energy source of electric power generation amongst the all kinds of fossil fuels (Miller 2011). Therefore, it is noted that the renewable combination has to be chosen accompanied with coal power production.

1.1.3. Co-firing biomass with coal

> *"Biomass is the world's third largest primary energy resource after coal and oil and further it is the only source which use the same technology of "combustion" to generate energy as coal" (Zulfiqar, Moghtaderi et al. 2006).*

Then, unarguably co-firing of biomass with coal would be the most sustainable future energy source and thus, more research and development on advancement of the blend energy technology of biomass and coal is essential. Technological advancements of boilers, quality improvements of coal types and blending of coal with various kinds of alternative fuels etc., are some of the positive approaches being implemented as proactive solutions for the alarming problem of gaseous emissions. Since the net emission of biomass burning is proven to be zero, it has been identified as one of the successful alternatives, to blend with coal during the process of co-firing (with shares of typically 5-20%), that will result in an effective reduction of emissions arising from coal utilization.

The biomass co-firing technologies used in power sector are mainly classified under three types: "*direct co-firing, indirect co-firing, and gasification based co-firing*". (Description of the technologies are given in Chapter 2 – Literature review) Among three options, the direct co-firing has the relatively low investment cost of turning an existing coal power plant to co-firing plant and hence this is the most popular option at present (Basu, Butler et al. 2011).

With the elevated atmospheric temperature due to global warming, GHG emission reduction is the commonly debated topic in the coal power industry. Some viable alternatives such as CO_2 sequestration, oxy-firing and carbon loop combustion are being discussed as long-term GHG reduction technologies, but all of them are in the primary to mid-stages of progress. Under these circumstances, co-firing offers the ideal solution with a well-proven technology amongst the rest even though it will not eliminate GHG emissions entirely.

(Basu, Butler et al. 2011) has emphasized in their paper,

> *"An incremental gain in GHG reduction can be achieved by immediate implementation of biomass co-firing in nearly all coal-fired power plants with minimum modifications and moderate investment, making co-firing a perfect solution for the greenhouse gas emission problem. If a majority of coal-fired boilers operating around the world adopt co-firing systems, the total reduction in GHG emissions would be substantial."*

The renewable energy options and low-carbon technologies like biomass co-firing is being considered over energy safekeeping and climate change, but stagnant or slow moving forward. The common argument for the sluggish development of new technologies is the cost levied on the economy due to deserve for the huge capital investments. Nevertheless, the market for carbon credits (1 tCO_{2e} equivalents to 1

Carbon credit) is absolutely developing promptly and is serving at present to diverge from fossil fuel energy sources in the direction of diverse renewable energy alternatives and a “*low carbon economy*” (Mathews 2008). However, lack of information on benefits of carbon credits, is creating a barrier between the project developers and the low carbon schemes (Clean Development Mechanisms, Joint Implementation etc.), making an unfavorable circumstances for them entering into novel renewable energy technologies.

1.1.4. Background of the current study

In this work, an attempt has been made to bridge the information gap between project developers and low carbon schemes up to certain extent, by developing a model which would be an accurate method to predict the carbon credits generation from the process of biomass co-firing with pulverized coal. Basically, ten different wood types in three categories (hard wood, soft wood and energy crops), five different non woody biomass species (especially agricultural wastes) have been analysed as a blend with seven different coal ranks. The main objective of this study is to develop a model predicting potential carbon credits generation per unit of energy out of each blend. Meanwhile, the results will further be used to study and compare the pros and cons of Coal-Biomass blends in order to assess their excess air requirement for complete combustion, percentage O_2 in flue gas, amount of CO_2 and SO_2 reductions, amount of energy loss when co-firing as well as to conclude the better blends in terms of all the above parameters.

Furthermore, this study is an effort to link the long existing gap between carbon trading and energy industries and to motivate fuel practitioners as well as other stakeholders in power sector for the prediction of environmental and financial feasibility of co-firing proposals.

1.2. Objectives

Mitigation of GHG emissions in coal power plants by making a better blend of biomass-coal would be one of the most sustainable options in power generation. The key intention of the study is to analyze the privileges for power plants to enter the carbon trading scheme by co-firing of biomass with pulverized coal. Specific objectives of the research program include;

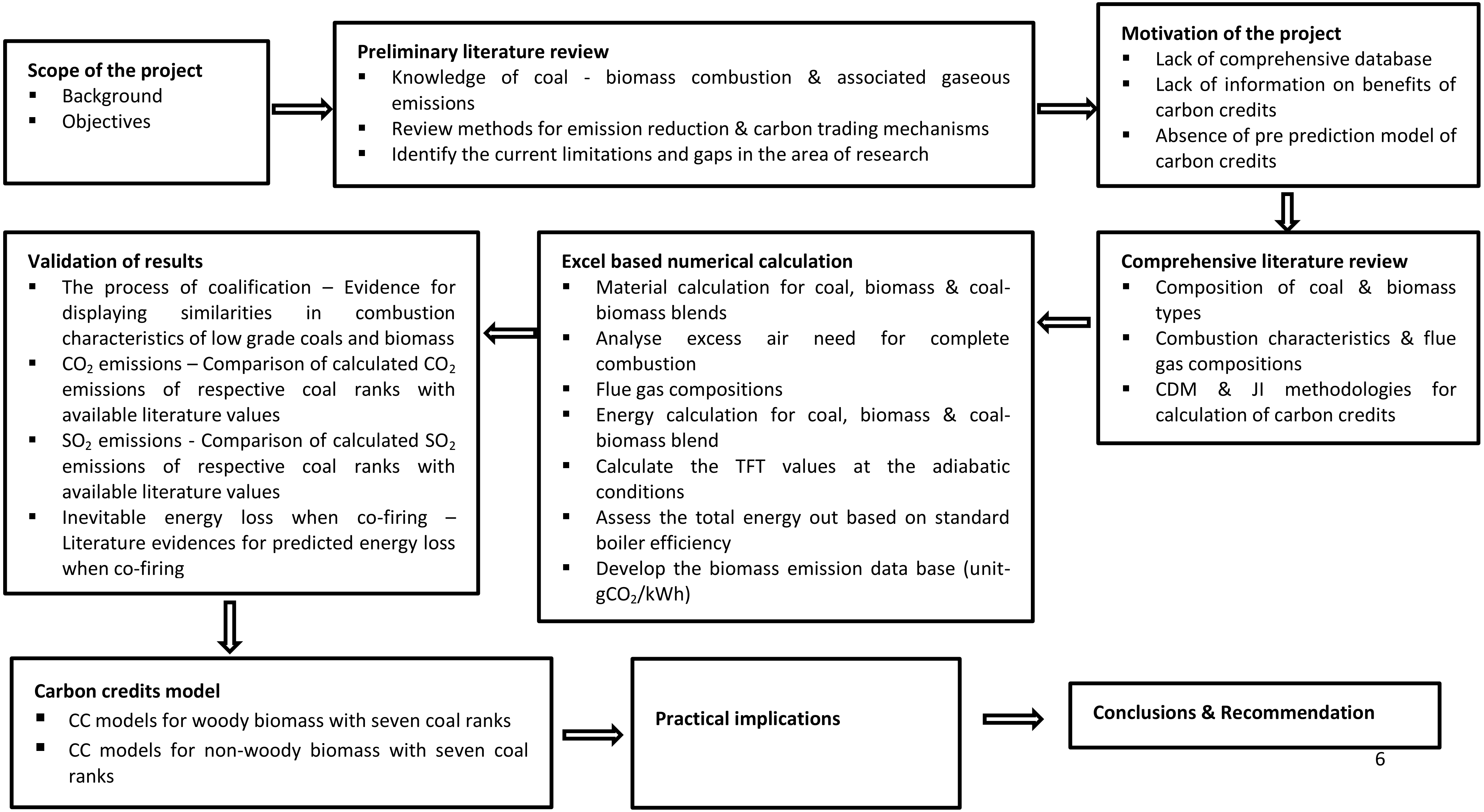
1) Analyze the eligibility of power plants for carbon trading
2) Identify feasible pathways for industries to deviate from non-renewable to renewable
3) Identify prolonged technologies and optimal blends in reducing pollutant levels to generate more carbon credits

Simultaneously, efforts will be directed towards linking them with an internationally accepted emission trading mechanisms while encouraging the industries towards clean technologies by developing prediction tools for carbon credit estimation for boilers.

The goals of this work can be further summarized in the following sequence:

- Develop excel based calculations for material and energy balances for individual coal ranks, biomass types and coal-biomass blends
- Calculate the particular gaseous emission reductions of the blends per unit of energy production
- Develop an individual data bases of emission reduction factors for ten different woody biomass types and five of the non-woody biomass species with 7 coal ranks separately
- Develop the model equations for woody biomass and non-woody biomass with seven coal ranks respectively for the prediction of specific carbon credits
- Identify the optimal coal and biomass blends

1.3. Thesis Outline



Scope of the project
- Background
- Objectives

Preliminary literature review
- Knowledge of coal - biomass combustion & associated gaseous emissions
- Review methods for emission reduction & carbon trading mechanisms
- Identify the current limitations and gaps in the area of research

Motivation of the project
- Lack of comprehensive database
- Lack of information on benefits of carbon credits
- Absence of pre prediction model of carbon credits

Comprehensive literature review
- Composition of coal & biomass types
- Combustion characteristics & flue gas compositions
- CDM & JI methodologies for calculation of carbon credits

Excel based numerical calculation
- Material calculation for coal, biomass & coal-biomass blends
- Analyse excess air need for complete combustion
- Flue gas compositions
- Energy calculation for coal, biomass & coal-biomass blend
- Calculate the TFT values at the adiabatic conditions
- Assess the total energy out based on standard boiler efficiency
- Develop the biomass emission data base (unit-gCO_2/kWh)

Validation of results
- The process of coalification – Evidence for displaying similarities in combustion characteristics of low grade coals and biomass
- CO_2 emissions – Comparison of calculated CO_2 emissions of respective coal ranks with available literature values
- SO_2 emissions - Comparison of calculated SO_2 emissions of respective coal ranks with available literature values
- Inevitable energy loss when co-firing – Literature evidences for predicted energy loss when co-firing

Carbon credits model
- CC models for woody biomass with seven coal ranks
- CC models for non-woody biomass with seven coal ranks

Practical implications

Conclusions & Recommendation

Chapter 2: Literature Review

2.1. Coal and coal combustion

Coal is a solid fuel which is scattered all over the world. However, Coal mining industries have been developed nearly among 70 nations. Coal is recognized as the primary energy source in the power sector, and due to the rapid development of industries specially in the developing countries, higher rate of consumption of fossil fuel can be expected in next few decades (Miller 2011). The industrial revolution was the key turning point for increasing the coal utilisation, however it has slightly declined with the introduction of oil resources, hence oil acquired privilege to lead the domestic heating and transportation sectors. At present, a negligible amount of coal is being utilised for domestic purposes and process steam generation in industries. In consequence, coal has become the leader in the entire power sector by generating coal fired electricity in utility boilers. For an instance, the latest Chinese study reveals;

"Coal holds dominant position in China's primary energy mix, and roughly 45% of China's coal consumption is used for power generation"(Yuan, Na et al.)

2.1.1. The chemistry of coal combustion

The coal combustion occurs in several steps since the coal consists of various constituents which are released during different stages of the combustion process. Some constituents such as water particles will be driven-off during the initial heating process (Drying process). Following the moisture release, "*de-volatilization*" will occur. Consequently, two parallel reactions will be initiated with the release of organic matter during the de-volatilization. They are "homogenous combustion of organic matter in the gas phase" and the "heterogeneous burning of char particles". The surface reaction of the char burning has the longest reaction time and this regulates the reaction time of overall combustion process.

The size of the coal particles and the combustion techniques are the two main criteria which will distinguish the three methods of coal burning.

- Large pieces in a fixed bed or on a grate
- As smaller or crushed pieces in a fluidized bed
- As very fine particles in suspension

The above three methods are specified at the practical scenarios according to the size of the coal particles due to some engineering limitations; nevertheless, in theory, the particle size is independent of the combustion method. Furthermore, it is noted that the particle dimension is one of the key parameter which will directly influence the thermal behavior and the reaction characteristics (i.e., rate of heating) of the combustion process. The yield and the composition of the volatiles will be regulated by the heating rate of the particles and thus particle size would get more attention. The key features of the three techniques are detailed below in Table 2.1 (Miller 2011).

Table 2.1 : Comparison of characteristics of combustion methods (Miller 2011)

Variables	Combustion Method		
	Fixed Bed (Stoker)	Fluidized Bed	Suspension
Particle size			
Approximate top size	<2 inches	<0.2 inches	180 µm
Average size	0.25 inches	0.04 inches	45 µm
System/bed temperature	<1500°F	1500-1800°F	>2200°F
Particle heating rate	≈ 1°/s	10^3-10^4 °/s	10^3-10^6 °/s
Reaction time			
Volatiles	≈ 100 seconds	10-50 seconds	<0.1 seconds
Char	≈ 1000 seconds	100-500 seconds	<1 second
Reactive element description	Diffusion-controlled combustion	Diffusion-controlled combustion	Chemically controlled combustion

2.1.2. Formation of coals

Coals included for the current study and their classifications are given in Table 2.2 (Speight 2011).

Table 2.2 : Coal ranks (Speight 2011)

Coal Rank	Other names	Standings	Utilization
Lignite	Brown coal	Lowest rank	Entirely as fuel for steam-electric power generation
Sub-bituminous (C/B)		Range from lignite to bituminous	Primarily as fuel for steam-electric power generation
Bituminous (High volatile, Medium & Low volatile)	A dense coal (usually black, sometimes dark brown)	Often with well-defined bands of bright and dull material	Primarily as fuel in steam-electric power generation Substantial quantities used for heat/power applications in manufacturing and to make coke
Anthracite	A hard, glossy, black coal	Highest rank	Primarily for residential and commercial space heating

During the process of coalification, the lignin structure of the plants starts to transform into lower grade coals and further chemical formation and destruction reactions would be occurred in order to transform lower grade coals into higher grades. There are three main physical parameters which can be observed with the increase of the coal ranks.

- Increase in heating value
- Increase in overall density
- Decrease in moisture content

In addition, the chemical composition of the coal will be improved and the original plant structure will be disappeared with the progression of coal.

- Increase in C content due to the increment in aromatic cluster size (especially in Bituminous coal and Anthracite)
- Decrease in O moles (the maturation of oxygen groups during the de-hydroxylation reaction)

Nitrogen content in coal is below 2% in most coals and it behaves independently with the coal rank (O'Keefe, Bechtel et al. 2013). Hydrogen content of about 5.0%

persists through ranks including medium volatile bituminous and decrease in sub bituminous coal and lignite (Vaysman and Lu 2012).

2.1.3. Coal specifications

Proximate and ultimate analysis of different coal types which are used specially in steam electric power generation is given in Table 2.3 and Table 2.4 accordingly (Vaysman and Lu 2012). As detailed in following tables, the amount of carbon present in coals will determine the rank and therefore, the rank will be ascending accordingly from lower grades to higher grades. Furthermore, the lower grade coals consist of high oxygen and moisture compared to higher grade coals.

Table 2.3: Proximate analysis (Vaysman and Lu 2012)

Coal rank	Coal name	Abbreviation (in calculation)	Fixed carbon %	Volatile matter%	Moisture %	Ash %
Lignite A	High sodium lignite	LIG	27.54	26.52	36.08	9.86
Sub-bituminous	PRB	SUB B - B	35.70	30.34	25.77	8.19
Sub-bituminous C	PRB	SUB B - C	36.43	31.65	27.42	4.50
Bituminous-High volatile A (2)	Illinois no 6	HVB - B	44.19	34.99	11.12	9.70
Bituminous-High volatile A (1)	Pittsburgh no 8	HVB - A	52.38	35.82	2.63	9.17
Bituminous-Medium volatile	N/A	MVB	56.41	29.43	1.13	13.03
Bituminous-Low volatile	N/A	LVB	75.47	19.14	0.65	4.74

Table 2.4 : Ultimate analysis (Vaysman and Lu 2012)

Coal type	C%	H%	O%	N%	S%	Cl%	Moisture%	Ash %
LIG	39.55	2.74	10.51	0.63	0.63	0.00	36.08	9.86
SUB B - B	50.07	3.38	11.14	0.71	0.73	0.01	25.77	8.19
SUB B - C	50.23	3.41	13.55	0.65	0.22	0.02	27.42	4.50
HVB - B	63.75	4.50	6.88	1.25	2.51	0.29	11.12	9.70
HVB - A	73.15	4.97	6.22	1.46	2.36	0.04	2.63	9.17
MVB	73.39	4.03	4.80	1.33	2.29	0.00	1.13	13.03
LVB	86.15	4.20	2.15	1.26	0.66	0.19	0.65	4.74

2.1.4. Emissions

As a hydrocarbon, coal basically releases carbon dioxide (CO_2) as the major gaseous emission during its combustion process. Additionally it produces three major emissions which adversely affect the environment such as sulfur dioxide (SO_2), nitrogen oxides (NO_x) and particulate matter (PM). Latest research on the health effects of mercury have alarmed about mercury emissions from coal-fired power plants. (Hu and Cheng 2016) have also provided some evidences for the mercury emissions associated with coal burning;

> *"Coal burning in power plants and industrial boilers is the largest combustion source of mercury emissions in China. Together, power plants and industrial boilers emit around 250 tonnes of mercury each year, or around half of atmospheric mercury emissions from anthropogenic sources in the country."*

In addition, some trace elemental emissions such as carbon monoxide (CO), lead, ozone, and some organic emissions are commonly observed as by-products of coal burning (Miller 2011).

The IEA report on GHG emissions published in 2014 has estimated the total CO_2 emissions only from the power sector as 69% and out of which 44% is from coal combustion. Even though, coal represent 29% of world TPES in 2012, it is obvious to give higher CO_2 emissions due to its heavy carbon content per unit energy release Figure 2.1 (IEA 2014).

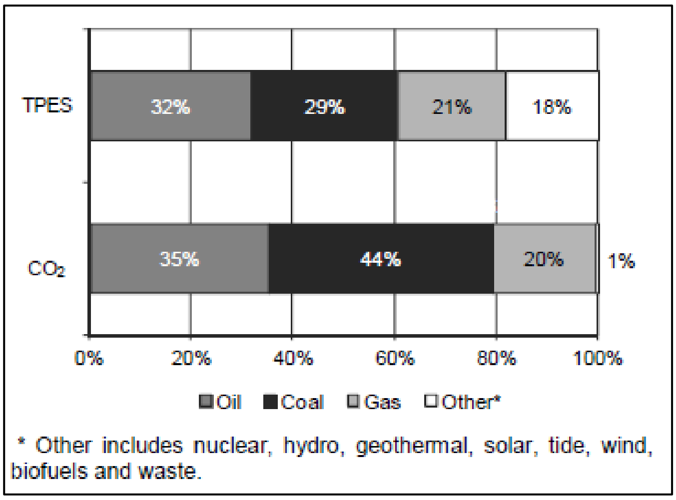


Figure 2.1 :World primary energy supply and CO_2 emissions shares by fuel in 2012 (IEA 2014).

2.1.5. Health and environmental issues due to coal and other petroleum emissions

Combustion is a thermo chemical process which has inherent characteristics that leads to releasing of both gaseous and particulate pollutants to the environment. Consequently, these pollutants have primary and secondary impacts on air quality, human health, climate etc.

CO_2 gas and H_2O vapour are the most prominent pollutants of global warming which are the foremost by-products of the combustion process.(Gaffney and Marley 2009) has also emphasized in his paper that

> *"Coal has the highest carbon content of all fossil fuels and therefore has the highest yield rate of CO_2 per kilowatt hour (kW h) generating 2.1 lbs CO_2 per kw h resulting in the release of 1.8 x 10^9 metric tons of CO_2 in 1998. Along with the CO_2 emissions, coal-fired power plants are also key sources of CH_4 and nitrous oxide (N_2O), also greenhouse gasses".*

As mentioned earlier, the other key air pollutants of SO_2 and NO_x emissions are produced during the combustion of coal through the oxidization of S and N present in coal. In addition, NO_x emission can further be produced due to the thermal oxidation of atomic nitrogen in air. Still, fuel NO_x is the major contributor of 80% of the total NO_x emissions from coal burning (Gaffney and Marley 2009). Furthermore, coal has comparatively higher nitrogen content than other fuel sources such as oil and natural gas and hence coal-fired utility boilers produce more NO_x emissions (Zhao, Shen et al. 2017).

There are a number of huge environmental problems which have been identified so far due to coal emissions. As mentioned above CO_2, CH_4 and NO_2 are accelerating the global warming and climate change. In the meantime one of the other noticeable effects of sulphur dioxide was the degradation of materials. Gaseous SO_2 will be transformed into sulphuric acid (acid rains) due to moisture and other atmospheric conditions will deposit on sandstone monuments and ornaments on historical buildings expected most consideration. Also the role of nitrogen oxides and photochemical oxidants is not fully discovered (Fenger 2009).

Primary fly ash particulate matter is another air pollutant from coal burning. The fly ash released into the flue gas will depend on the boiler or the furnace type (dry-bottom boilers, wet-bottom boilers, and cyclone furnaces) and the form of the coal use (ex: pulverized form). It is noted that the wet-bottom furnace has the minimum release of fly ash about 50% of the total ash formed. However, both dry-bottom boiler and cyclone furnace would produce around 80% of fly ash with pulverized coal. Novel technological separation methods such as electrostatic precipitators are used for particulate control in order to remove the fly ash from the flue gasses with the efficiency of 99.9%. However, extensive volumes of fly ash are still discharged to the atmosphere since the massive amounts of coal utilise for electric power generation (Gaffney and Marley 2009).

(Gaffney and Marley 2009) has further stated that

> *"A 1000 MW power station with a normal consumption of 12,000 tons per day (t d^{-1}) of sub-bituminous coal, has a mean combustion fly ash production of about 2,400 (t d^{-1}). Even with a particulate removal efficiency of 99.9%, almost 900 tons per year (t yr^{-1}) are emitted to the atmosphere as primary PM."*

In addition to primary fly ash PM, gas to particle conversion gives rise to significant amounts of acidic secondary PM during the reaction of atmospheric moisture with SO_2 and NO_2 emissions. According to the recently conducted epidemiological studies has evaluated that the particles with a size below 2.5 µm have a substantial influence on people suffering from respiratory and cardio-pulmonary diseases and on the everyday mortality (Fenger 2009).

2.1.6. Global requirements for emission reduction and energy alternatives

Industrialization or the "*industrial revolution*" was the turning point which interrupted to the natural process of the atmosphere and imbalance the atmosphere by increasing the concentration of GHGs. As discussed above carbon dioxide leads to the team of GHGs and, it is estimated the percentage increment of atmospheric CO_2 of 31% since 1750.

According to the recently reported study (Houghton, Ding et al. IPCC 2001), burning of fossil fuels has been nominated as the major CO_2 contributor amounting to ¾ of total discharges during last two decades. Energy is a crucial requirement in the current world and fossil fuels have been the basic energy source thus far and its demand has continually been increased. This can be expressed in million tons of oil equivalents (Mtoe); it expanded 2.4 fold from 5000 Mtoe in 1971 to 11,700 Mtoe in 2010 (Matsuo, Yanagisawa et al. 2013).

Thus, due to all these facts it is obvious that the unavoidable conflict between the demand and supply of energy will be inevitable if the energy supply will only be limited to fossil fuels. In the meantime, the environmental consequences (Hughes 2000); (Baker, Glynn et al. 2008) have also created a huge pressure on inventing novel energy alternatives which are reliable, realistic and renewable.

Due to all of the pros and cons of readily available alternative energy sources (Solar, wind, hydro, nuclear, biomass etc.) which were earlier stated in the introduction section, are not scalable to meet substantial global energy needs as an individual source. Thus, a combination of existing and new technologies as well as energy sources is needed. In order to identify the optimal mix, further research and developments are vital.

2.2. Combination of fossil fuel with renewable energy

The combustion is the basic technology of energy generation from fossil fuels. Hence, it is obvious that the combined power production has to be chosen from a fuel which can follow similar technology as fossil fuel in order to get the optimum benefit out of it with less capital and maintenance expenses.

Among all of the renewable sources (wind, solar, hydro, nuclear, biomass etc.,) biomass is the world’s third biggest major energy resource next to coal and oil (Zulfiqar, Moghtaderi et al. 2006). Furthermore it is the only source which uses the same technology of combustion to generate energy as coal. Therefore, biomass has obtained more attraction and attention as a combined energy source in the recent years and co-firing technology has constantly been improving over the last few decades. More research and developments, education programs on co-firing technology have been facilitated among the power producers across the world including Australia, Europe and United States (Zulfiqar, Moghtaderi et al. 2006). There are more evidences been provided by (Liu, Johnson et al. 2016) in their paper that

> *“Co-firing biomass for electricity is one that is potentially feasible in many states and regions of the USA”*
>
> *“While biomass residues can replace more than 50% of coal in coal-fired plants with large capital investments and up to 20% biomass can be co-fired with coal without significant modification to current equipment”*

2.3. Biomass

Biomass is only an organic petroleum substitute that is renewable. The definition of biomass as per (Roberts, Cassula et al. 2015) is "*Biomass comprises all biological material derived from living, or recently living organisms*"

The wide range of plant, vegetable and animal derived materials classified under biomass are listed below (Roberts, Cassula et al. 2015).

- Virgin wood derived from forestry
- Arboricultural activities or from wood processing
- Agricultural residues from agriculture harvesting or processing
- Industrial waste and co-products from manufacturing and industrial processes
- Food waste from food and drink manufacture, preparation and processing and post-consumer waste
- Domestic and municipal waste
- Animal manure

2.3.1. Biomass as a fuel

Biomass as fuels possibly include wood wastes, short rotation woody crops, agricultural wastes, short rotation herbaceous crops, animal wastes and a host of other materials. The examples for each category are presented in Table 2.5. Among the biomass materials, the woody biomass materials tend to be low in nitrogen and ash content, while agricultural materials can have high nitrogen and ash contents (Demirbaş 2003).

Table 2.5 : Biomass types used as fuel (Demirbaş 2003)

Biomass type	Examples
Wood wastes	Sawdust, planer shavings, chips, bark, firewood plantations, forestry residues, urban wood wastes
Short rotation woody crops	Hybrid poplar
Agricultural wastes	Rice hulls, straws, orchard and vineyard prunings, corn stover, out-of-date corn seed
Short rotation herbaceous crops	Switch grass
Animal wastes	Cow dung, chicken manure

2.3.2. The chemistry of biomass combustion

The biomass fuel is chemically composed mainly of cellulose, hemicelluloses and lignin polymers (hydrocarbons). Other components include minerals, water, salts, and organics such as proteins, starches, nucleic acids, oils, and resins. In majority of fuels, cellulose is the key component (Table 2.6) (Sullivan and Ball 2012).

Table 2.6 : Analysis of some biomass types and species found in literature (Sullivan and Ball 2012)

Type or species	Cellulose (%)	Hemi-cellulose (%)	Lignin (%)	Other [a]
Soft wood	41	24	28	7
Hard wood	39	35	20	7
Wheat straw	40	28	17	15
Rice straw	30	25	12	33
Bagasse	38	38	20	3
Eucalyptus saligna	45	15	25	15
Eucalyptus gummifera	38	16	37	9
Sweet sorghum	36	18	16	30
Sugar cane bagasse	36	17	17	30
Populus deltoides	39	21	26	14

[a] Other includes organic compounds such as starch and inorganic material such as salt, mineral and water.

The overall oxidative conversion of unburnt solid fuel to gases, ash and residue is described as combustion. Often this is represented as a single process.

$$(CH_2O)_{n(s)} + n\ O_{2(g)} \rightarrow n\ CO_{2(g)} + n\ H_2O_{(g)}$$

However, as coal combustion occurred in several steps, biomass also has three sequential combustion stages during its combustion process, linked by nonlinear chemical and thermal reactions (Sullivan and Ball 2012).

1) Pre-ignition: Solid fuels are heated, dried and partially volatilised
2) Flaming: Combustion of the vapour-phase volatiles and CO
3) Glowing (or smouldering):Combustion of some of the char residue

2.3.3. World's biomass demand and availability

The world's primary energy demand will almost be doubled in 2050 compared to the demand in 2008 of 500 EJ/year. It is projected to be ranging between 600 and 1000 EJ/year (Roberts, Cassula et al. 2015). In recent studies published by World Energy Council (WEC 2013), shows that the worldwide technically available biomass potential may reach 1500 EJ/year in 2050. However, sustainable point of view, the renewable potential would be between 200 and 500 EJ/year (Figure 2.2). As seen in the (Figure 2.2) expecting a bioenergy demand of 250 EJ/year in 2050 can sustainably supply between one quarter and one third of the estimated primary energy demand for 2050. (WEC 2013).

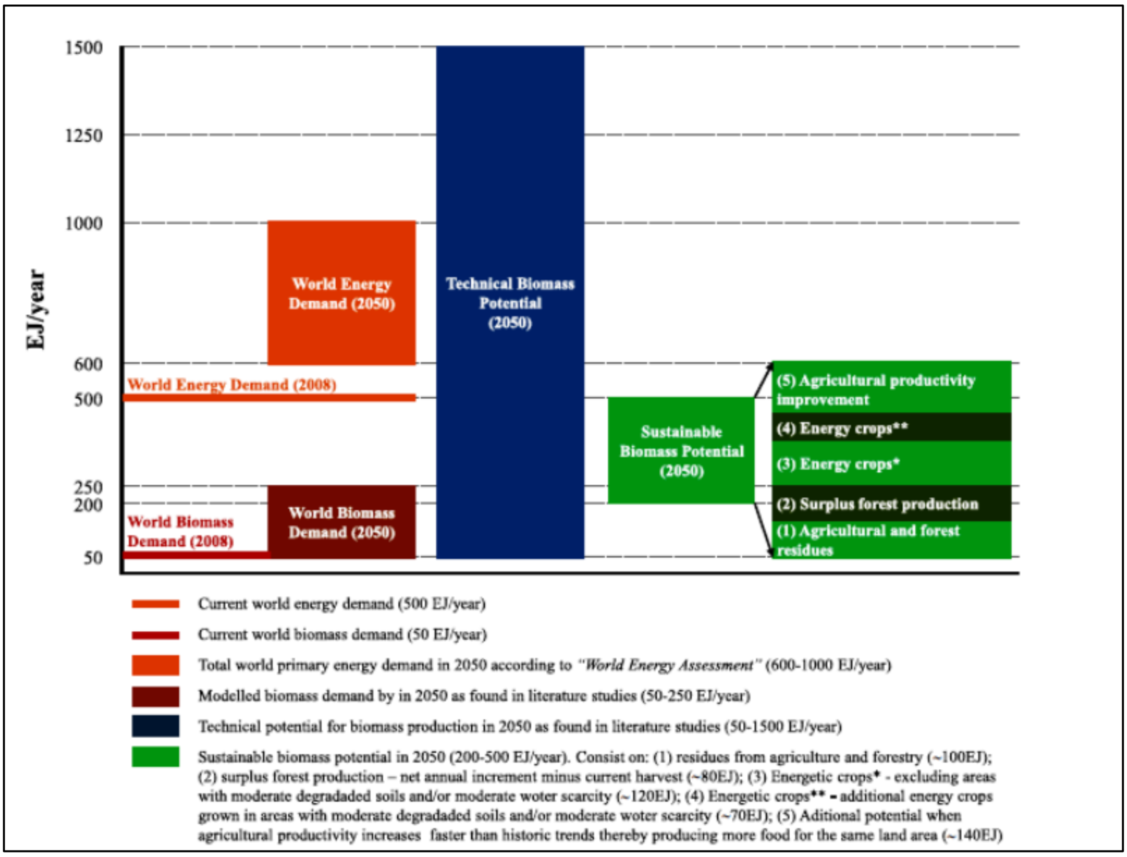


Figure 2.2 : Technical and sustainable biomass supply potentials and expected demand (Roberts, Cassula et al. 2015); (WEC 2013).

2.3.4. Biomass specifications

In the current study, fifteen different biomass species have been selected as the fuels to be blend with coals chosen from seven ranks. The proximate and ultimate analysis of each biomass types is given in Table 2.7 and Table 2.8 respectively. As detailed in the tables, the carbon content of woody biomass is slightly higher than the non-woody types; however there are some exemptions such as sugar cane bagasse and corn stover which contains the carbon content in similar range to that of woody biomass. Hydrogen content in biomass is independent of the type. Furthermore, the percentage nitrogen in biomass is well below 1% except rice straw which contented the highest recorded amount among the selected biomass types in the current study.

Table 2.7 : Proximate analysis (Phyllis2 2012)

Biomass species	Biomass name	ECN Phyllis classification	Fixed carbon %	Volatile matter %	Moisture %	Ash %
Hard wood	Eucalyptus	#699	11.66	78.52	9.34	0.48
	Ailanthus	#986	-	-	8.50	0.46
	Oak wood	#2074	-	-	8.50	0.17
	Black Locust	#1225	16.71	74.06	8.50	0.73
Soft wood	Spruce	#2079	-	-	9.00	0.02
	Douglas fir	#2842	16.39	73.91	9.00	0.70
	Monterey Pine	#126	12.66	77.13	10.00	0.21
Energy crops	Willow wood	#851	12.09	73.38	13.58	0.95
	Switch grass	#701	14.89	72.73	8.16	4.22
	Hybrid poplar	#806	11.63	78.97	6.89	2.51
Non woody	Barley straw	#2909	4.84	78.48	6.90	9.78
	Rice straw	#702	12.56	57.92	11.73	17.73
	Wheat straw	#459	14.98	62.32	15.10	7.60
	Sugar cane bagasse	#894	10.71	76.72	10.39	2.19
	Corn stover	#704	13.23	75.96	6.06	4.75

Table 2.8 : Ultimate analysis (Phyllis2 2012)

Biomass type	C%	H%	O%	N%	S%	Moisture%	Ash %
Eucalyptus	44.89	5.21	39.87	0.13	0.03	9.34	0.48
Ailanthus	45.28	5.67	37.52	0.27	0.01	8.50	0.46
Oak wood	45.87	5.47	40.96	0.07	0.03	8.50	0.17
Black Locust	46.42	5.22	38.37	0.52	0.01	8.50	0.73
Spruce	44.51	5.46	40.63	0.11	0.01	9.00	0.02
Douglas fir	45.41	5.73	38.9	0.17	0.01	9.00	0.7
Monterey Pine	46.42	5.20	38.09	0.05	0.01	10.00	0.21
Willow wood	41.43	5.05	38.39	0.54	0.05	13.58	0.95
Switch grass	43.04	5.37	38.12	0.53	0.10	8.16	4.22
Hybrid poplar	46.72	5.64	37.64	0.56	0.02	6.89	2.51
Barley straw	34.50	5.17	43.13	0.52	0.01	6.90	9.78
Rice straw	34.64	4.39	29.69	1.12	0.09	11.73	17.73
Wheat straw	37.29	4.69	34.29	0.62	0.19	15.10	7.60
Sugar cane bagasse	43.59	5.26	38.37	0.14	0.04	10.39	2.19
Corn stover	43.98	5.39	38.85	0.62	0.10	6.06	4.75

2.3.5. Biomass availability in Australia

The research carried out by (Rodriguez, May et al. 2011) on “*the potential biomass resources available for energy generation from forestry and agriculture in the Green Triangle, one of the most promising Australian Regions for biomass production*” would provide evidences on the availability of biomass species for power generation and the available infrastructure facilities for transportation and post processing techniques in Australia in some extent.

> *“The Green Triangle region covers an area of about 6 million ha in south eastern South Australia and Western Victoria and included three separate statistical divisions (SD): South East, Wimmera and Western District. This region was selected because it already has a large, well developed forest industry in the south based on softwood and hardwood plantations, and a major grain growing industry in the north. .”(Figure 2.3) (Rodriguez, May et al. 2011)*

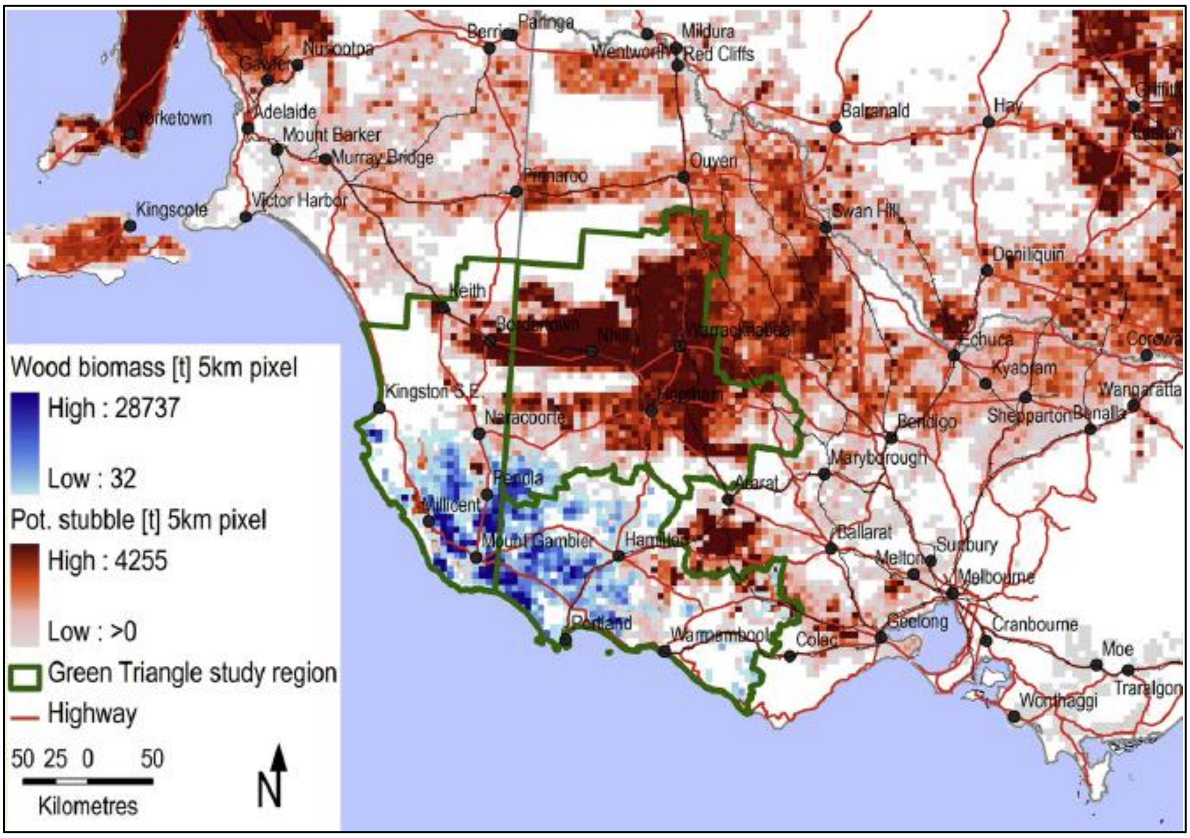


Figure 2.3 : Biomass feedstock sources in the Green Triangle (Rodriguez, May et al. 2011)

“The climate is mostly temperate, with average annual rainfall varying from below 400 mm in the north (Warracknabeal) to over 800 mm in the southeast (Portland), while mean maximum temperatures range from 14 to 22 °C in the south to14 to31°C in the north. The region is well connected by roads and rail and the port of Portland is an important export terminal. The total population is 210,000 with Mount Gambier in South Australia and Warrnambool in Victoria the largest towns each with populations in excess of 20,000 Forestry industries include saw milling, wood panels, pulp and paper manufacture, and wood chip export while agricultural industries include beef, dairy, wheat, canola, viticulture, and horticulture.” (Rodriguez, May et al. 2011).

2.4. Co-firing technology - Coal and Biomass

2.4.1. Biomass co-firing techniques

The most commonly categorized co-firing techniques of biomass in the power sector are detailed below:

- Direct co-firing,
- Indirect co-firing
- Gasification based co-firing

In direct co-firing system, the biomass powder will be produced by pulverizing solid biomass in the mill system, and then introduced into boiler either separately or blend with coal. Indirect co-firing will be carried out in a totally separated boiler system which is dedicated to the biomass burning alone. These boilers are mainly used in producing low-grade steam in the coal fired power plant before being upgraded. A fuel gas with great fuel flexibility will be formed during the process of gasification of dense biomass in the coal fired furnaces (Basu, Butler et al. 2011).

In addition, the combustion technologies applicable to individual coal and biomass burning are easily used for co-firing the fuel blend. Amongst cyclone boilers, wall-fired and tangentially fired pulverised coal boilers, fluidised bed boilers, as well as stoker fired boilers are well known. Furthermore, the plant capacity has ranged between 50-600MW in tests and commercial uses (Zulfiqar, Moghtaderi et al. 2006).

2.4.2. Greenhouse gas emission reduction via co-firing

The CO_2 emission due to biomass burning has a closed loop cycle compared to other fuels (Figure 2.4). An equal amount of CO_2 emissions discharged during the combustion will be absorbed during the life time of the biomass growth in order to make the biomass renewable. Hence, this recycle process prevents the biomass contribution to greenhouse effect due to its CO_2 emissions. In addition, when biomass replaces some portion of coal during the process of co-firing which leads to a reduction of fossil based emissions instead of neutralisation (Demirbaş 2003).

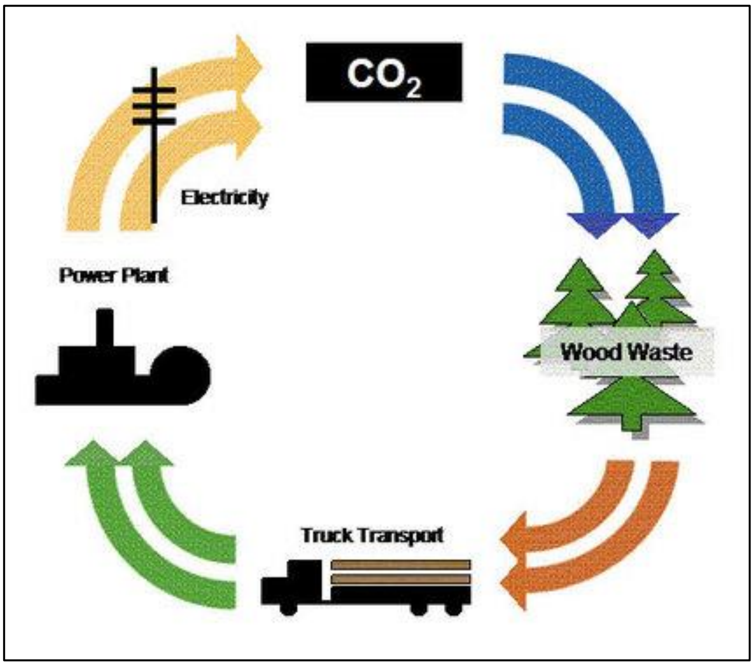


Figure 2.4 - Renewable biomass (https//bodeenergychallenge.wikispaces.com/Biomass)

The most important fact involved in biomass co-firing is the substantial achievement in GHG reduction by instantaneous operation of biomass co-firing in virtually all coal-fired power plants with least variations and reasonable investment, making co-firing a most appropriate answer for the GHG problem (Basu, Butler et al. 2011).

Nevertheless, due to irregular availability of the resources and comparatively high maintenance cost have made some barriers to convince project developers switching from their conventional power generation systems to co-firing (Baños, Manzano-Agugliaro et al. 2011); (Felder, Andrews et al. 2011). Consequently, the concept of “carbon trading” was globally introduced in 1997 with acceptance of the Kyoto Protocol in order to overcome such barriers associated with renewable power generation (Austin 2007).

2.5. Carbon trading mechanism

Carbon trading mechanism is a well-established financial supportive scheme for GHG reduction projects such as renewable power generation. The low-carbon technologies like biomass co-firing is a most concern renewable energy technique at present over energy security and climate change. The common argument against renewable energy technologies is the substantial upfront cost to be bared and other maintenance expenses (Mathews 2008).

Nevertheless, the market for carbon credits is absolutely developing and is serving to project developers to move in the direction of renewable technologies with the help of low carbon benefits. Due to lack of understanding of the role of carbon credits in their projects, the methodologies and path ways of entering into the system and unavailability of tools for upfront prediction of carbon credits generated by their projects, a huge gap still remains between project developers and low carbon schemes.

2.5.1. Carbon Trading – International Emission Trading

"*Carbon Trading*", which denotes to the trading of emission reductions of six main greenhouse gases (Perdan and Azapagic 2011);

1) Carbon dioxide (CO_2),
2) Methane (CH_4)
3) Nitrous oxide (N_2O)
4) Hydro fluorocarbons (HFCs)
5) Per fluorocarbons (PFCs)
6) Sulphur hexafluoride (SF_6)

(Perdan and Azapagic 2011) has further described the carbon trading,

> *"This is a market-based mechanism aimed at mitigating climate change. Currently there are several emissions trading schemes (ETSs) operating across the world. They differ in size, scopes and designs. Some of the schemes are linked with the Kyoto commitments (UNFCC, 1998), while others are operating*

> *in countries which have not ratified the Kyoto Protocol (e.g. the USA). Some schemes are voluntary, others are mandatory. The schemes vary in sectoral and temporal coverage having different emission targets."*

The UNFCCC definition on international emission trading is the "*trading of rights to emit greenhouse gases between capped countries*". In order to the "*project-based mechanisms*", GHG reductions from particular schemes or projects can be traded. The emission reductions have been quantified in weight basis and the tradable unit would be "*tonne of CO_2 equivalent*" (REFOCUS 2002).

2.5.2. GHG reduction targets and Kyoto Protocol

"*The Kyoto Protocol*" was signed among the countries which are accountable for high emissions during that period including largely industrialized and economically developed countries ("*including Central and Eastern Europe*") (Annex I countries). It obligates industrialised countries to decrease their gaseous discharges by an average of 5.2% lower than 1990 levels by 2008 to 2012. However, the Kyoto Protocol has designed to provide more flexibility for countries in achieving their reduction targets through any of the lowest possible ways (REFOCUS 2002).

The international target of emission reductions has been divided and clearly specified in country or regional wise and each country has encountered for its own emission reduction targets, as detailed in Table 2.9. The USA was also responsible for a reduction target under the protocol principles however; they were withdrawn from the Kyoto Protocol and developed their own reduction targets under voluntary mechanisms.

Table 2.9 : International GHG reduction targets by country and region (REFOCUS 2002)

Industrialized country	Agreed GHG cap(% on 1990 level emissions)
Australia	-8
Bulgaria	-8
Canada	-6
Croatia	-5
Czech Republic	-8
Estonia	-8
European Community	-8
Hungary	-6
Iceland	+10
Japan	-6
Latvia	-8
Lithuania	-8
Monaco	-8
New Zealand	0
Norway	+1
Poland	-6
Romania	-8
Russian Federation	0
Slovakia	-8
Slovenia	-8
Switzerland	-8
Ukraine	0
United States of America	-7
Notes: “The EU targets of -8% on 1990 emissions of GHG has been disaggregated into country targets. The US has withdrawn from the Kyoto Protocol. The table shows the US’s reduction targets because the possibility exists that the US may re-join the agreement in the future. Meanwhile, the US has committed itself to following an internal GHG reduction strategy.”	

2.5.3. GHG accounting programs

The GHG reduction programs or GHG accounting programs categorized under Kyoto Protocol such as CDM and JI are the compliance regimes which have their own GHG standards as mentioned earlier, and performance of declaration is only conducted by attributed bodies (like DOEs, AIEs). In addition to these compliance regimes there are several voluntary programs have been created and the variation between these two kinds of regimes depend on “level of compliance” (Compliance regulatory/Voluntary), “assurance engagement” and “spatial scope” (Uddin and Holtedahl 2013). The currently available programs for GHG accounting are detailed in Table 2.10.

Table 2.10 : Programs for greenhouse gas accounting (Uddin and Holtedahl 2013)

Program	Compliance regulatory/Voluntary	Assurance engagement	Spatial scope
Clean Development Mechanism (CDM)	Compliance	Designated Operational Entity(DOE)accredited under CDM EB	Non-Annex I[a]
Joint Implementation (JI)(Track II)	Compliance	Accredited Entity(AE) under Join Implementation Supervisory Committee(JISC)	Annex I
Joint Implementation (JI)(Track I)	Compliance	DOEs, AEs, Organization Accredited under ISO 14064-3and ISO 14065as per Annex I party requirement	Annex I
Regional Greenhouse gas Initiative (RGGI)	Compliance	Accredited independent verifiers under RGGI	North-East USA
Climate Action Reserve (CAR)	Voluntary	Accredited organization under CAR	Mostly USA
Verified Carbon Standards(VCS)	Voluntary	Accredited organization under VCS, DOEs and AEs	International
Gold Standards	Voluntary	DOEs, AEs	International
American Carbon Registry(ACR)	Voluntary	ACR accredited validation and verification body	Mostly USA
Alberta Offset System	Voluntary	ISO 14065 accredited organizations	Alberta, Canada
Pacific Carbon Trust	Compliance	Third party independent organization	British Columbia, Canada
VER + (Verified Emission Reduction)	Voluntary	TUV-SUD as DOE	International

[a] As per Kyoto protocol, Non-Annex I parties do not require to reduce emission of GHG as required by Annex I

2.5.4. Approved methodologies available for carbon credits prediction under CDM and JI mechanisms

Approved consolidated baseline and monitoring methodology ACM0020 - “Co-firing of biomass residues for heat generation and/or electricity generation in grid connected power plants” is the most applicable methodology to estimate the GHG emission of biomass co-fired boilers under CDM and JI mechanisms. Applicable guidelines in this methodology have been referred when developing the model to predict carbon credits and hence the model results could be used for any of the co-firing projects which are eligible under CDM /JI programs, during the pre-feasibility analysis stage of the project in order to assess the project viability with and without carbon credits benefits without further hesitation.

(http://cdm.unfccc.int/methodologies)

Chapter 3: Numerical Calculations

3.1. Introduction

In this study, the numerical evaluations are based on basic chemical engineering principles and calculations. The Material and Energy balances have been applied for the combustion systems at the furnace boundary. The main objective of the calculation is assessing the unknown parameters in input and output flows to and from the combustor. The combustion is assumed to be taken place in a steady state and open system. All the assumptions made will be given in bellow sections.

The assessment has mainly been conducted under three cases. Case study one is for the coal combustion systems and then calculations are extended to biomass combustion systems, case study two, and further to case study three which is coal-biomass co-firing systems. It is important to mention that all three case studies have the generic calculation method and extensions are available with the hierarchy (Table 3.1).

Table 3.1 : Case studies

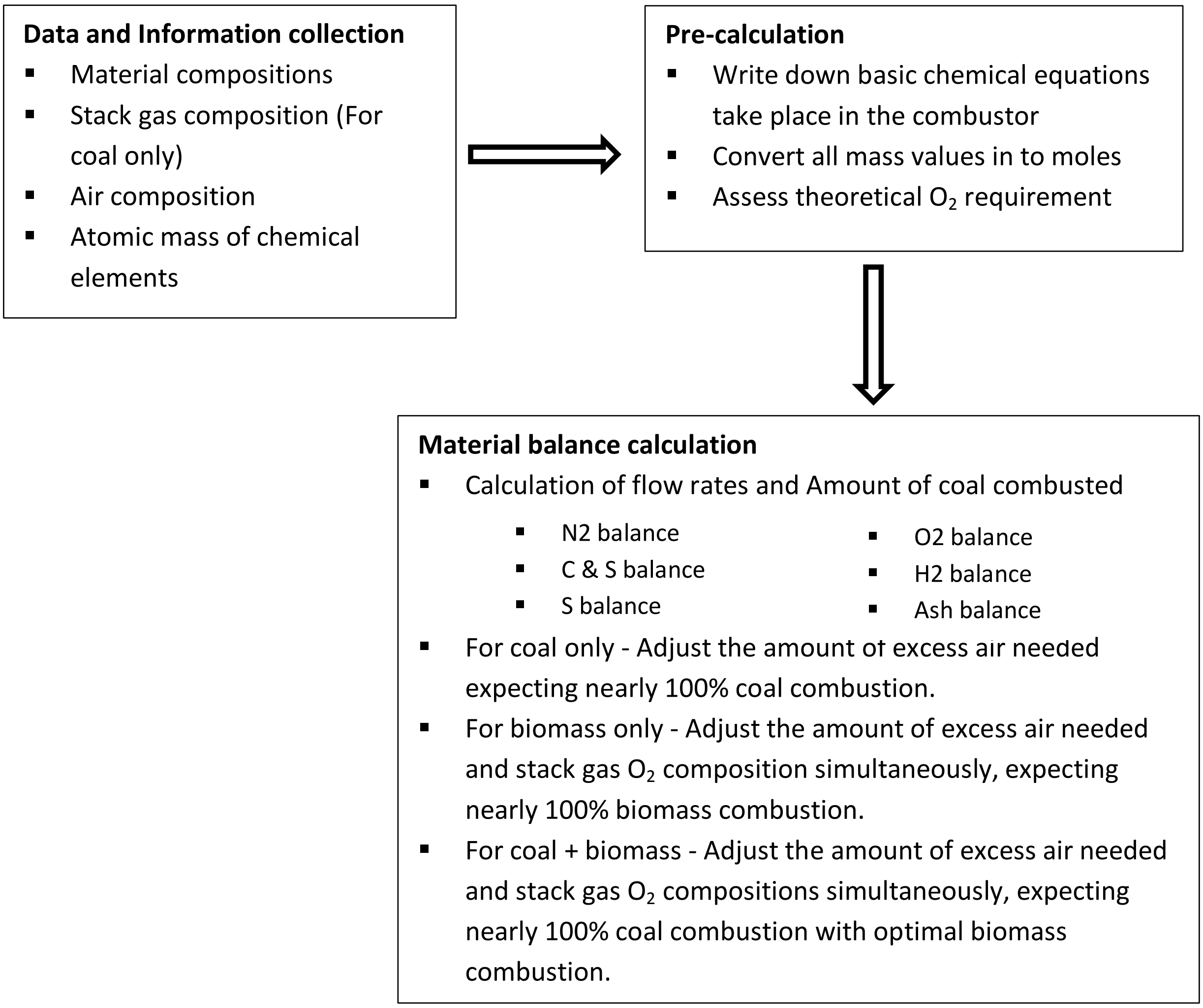
	Coal	**Biomass**	**Biomass blend**
Case 1	100%	-	-
Case 2	-	100%	-
Case 3	-	-	1-20%

In this chapter, the complete combustion calculation will be explained with the equations for a standard combustion system and all three case studies will be given in Appendix A for further clarification. The steps of the calculations have been outlined in the next section providing a foundation to get a basic understanding of the assessment.

3.2. Calculation outline - Material

The material balance calculation has been conducted under three stages. It is obvious that the first step would be the collection of data and information required such as composition of chemical elements, atomic numbers etc. As a pre-start of the calculation, the general chemical conversion equations which have taken place in the combustor would be written down and then the mass numbers of elements would be converted into moles (the main unit used for the basic calculations except ash balance). As the last step of the pre-calculation stage, the theoretical oxygen demand could be assessed. Pre calculated values and other raw data obtained from the literature have been linked together at the last step of the calculation to finalize the material balance.

Given below is the flow chart, detailing the material balance calculations performed on coal, biomass and blends.



Data and Information collection

- Material compositions
- Stack gas composition (For coal only)
- Air composition
- Atomic mass of chemical elements

Pre-calculation

- Write down basic chemical equations take place in the combustor
- Convert all mass values in to moles
- Assess theoretical O_2 requirement

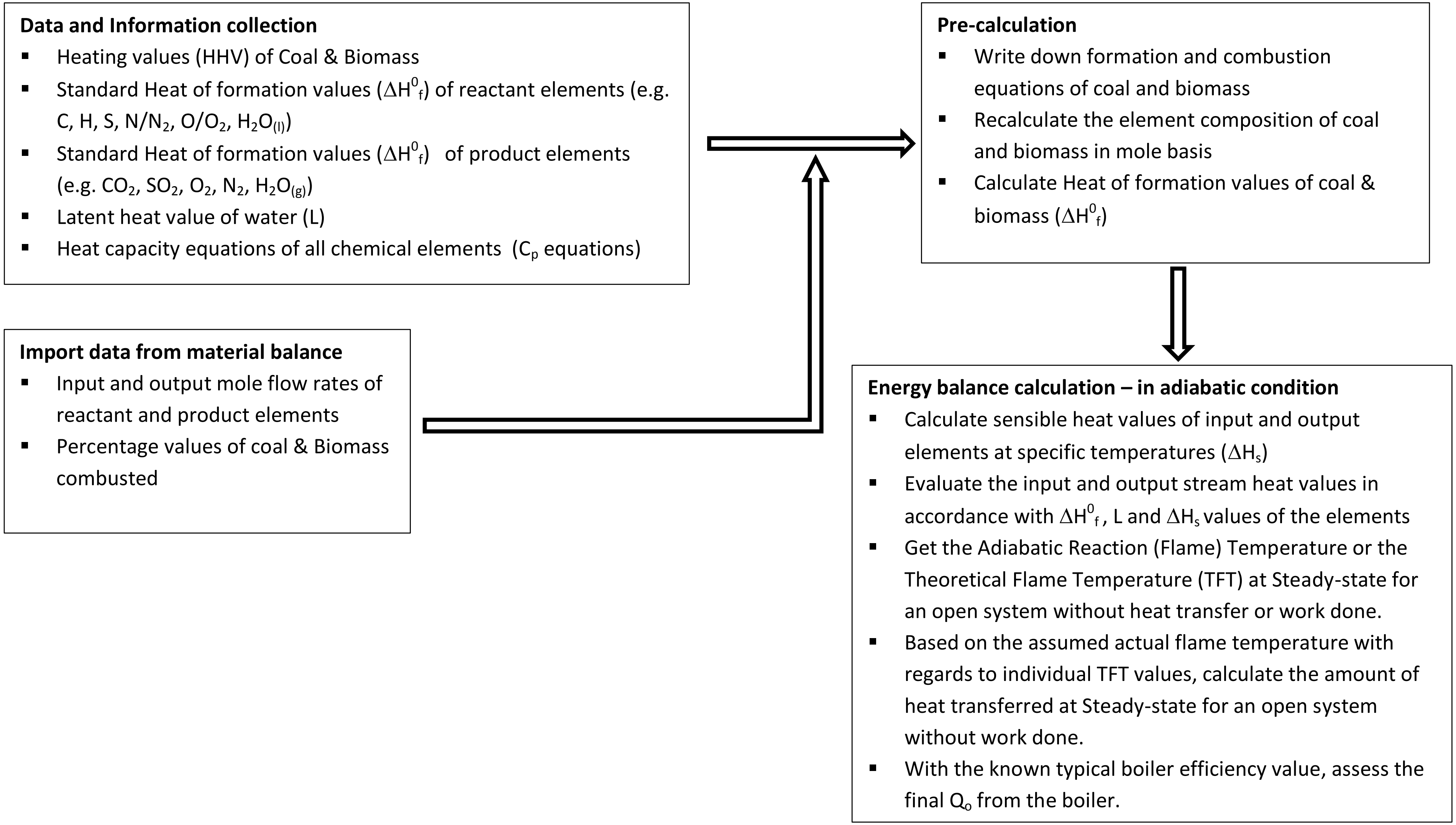
Material balance calculation

- Calculation of flow rates and Amount of coal combusted
    - N2 balance
    - C & S balance
    - S balance
    - O2 balance
    - H2 balance
    - Ash balance
- For coal only - Adjust the amount of excess air needed expecting nearly 100% coal combustion.
- For biomass only - Adjust the amount of excess air needed and stack gas O_2 composition simultaneously, expecting nearly 100% biomass combustion.
- For coal + biomass - Adjust the amount of excess air needed and stack gas O_2 compositions simultaneously, expecting nearly 100% coal combustion with optimal biomass combustion.

3.3. Calculation outline – Energy

Heating values of coal and biomass, heat of formation values of elementary chemicals such as C, H, S etc. heat capacity equations of all the chemicals etc. were gained from the sources available at the beginning and few preliminary calculations have been conducted in advance to find out the heat of formation values of compounds such as coal and biomass (not available in the literature) at the pre-calculation stage. In order to achieve the final result of the energy calculation which is evaluating the rate of heat out from the combustor at Steady-state conditions, the theoretical flame temperature (TFT) could be obtained under adiabatic conditions. Consequently, the actual flame temperature used for the final calculation has been worked out in accordance with the TFT of each fuel type.

Given below in page 35 is the flow chart, detailing the energy balance calculations performed on coal, biomass and blends.



Data and Information collection

- Heating values (HHV) of Coal & Biomass
- Standard Heat of formation values (ΔH^0_f) of reactant elements (e.g. C, H, S, N/N_2, O/O_2, $H_2O_{(l)}$)
- Standard Heat of formation values (ΔH^0_f) of product elements (e.g. CO_2, SO_2, O_2, N_2, $H_2O_{(g)}$)
- Latent heat value of water (L)
- Heat capacity equations of all chemical elements (C_p equations)

Import data from material balance

- Input and output mole flow rates of reactant and product elements
- Percentage values of coal & Biomass combusted

Pre-calculation

- Write down formation and combustion equations of coal and biomass
- Recalculate the element composition of coal and biomass in mole basis
- Calculate Heat of formation values of coal & biomass (ΔH^0_f)

Energy balance calculation – in adiabatic condition

- Calculate sensible heat values of input and output elements at specific temperatures (ΔH_s)
- Evaluate the input and output stream heat values in accordance with ΔH^0_f, L and ΔH_s values of the elements
- Get the Adiabatic Reaction (Flame) Temperature or the Theoretical Flame Temperature (TFT) at Steady-state for an open system without heat transfer or work done.
- Based on the assumed actual flame temperature with regards to individual TFT values, calculate the amount of heat transferred at Steady-state for an open system without work done.
- With the known typical boiler efficiency value, assess the final Q_o from the boiler.

3.4. Assumptions, Limitations and Validation

3.4.1. Assumptions used in material balance calculation

Given below are the assumptions used in material balance calculation.

1) A complete combustion will take place in the furnace and therefore; flue gas consists only CO_2, SO_2, H_2O, excess O_2 and N_2.
2) CO and NO_2 are assumed to be zero.
3) N in fuel will be reduced to N_2 only. It is assumed that injection of NH_3 at later stages of burning to reduce NOx to N_2 (thermal DeNOx process) (Sami, Annamalai et al. 2001).
4) Low pressure conditions will be assumed and therefore; no any phase changes occurred except for water.
5) Feeding method: Common feed lines and a common burner with premixed coal biomass blends (Sami, Annamalai et al. 2001).

3.4.2. Assumptions used in energy balance calculation

Given below are the assumptions used in energy balance calculation.

1) Material inlet temperature assumed to be 100°C (373 K).
2) Flue gas temperature will be 180°C (453K).
3) ΔPE and ΔKE values were assumed negligible compared to ΔH.
4) With regards to the TFT values of each fuel type, actual flame temperature assumed to be 400°C (673K) less than the TFT respectively.
5) Typical boiler efficiency of 85% assumed in general

3.4.3. Limitations

The basic material calculation and energy calculation have been conducted referring the Example 5.14 Combustion of coal (Himmelblau and Riggs 2011) The energy calculation is accordance with few examples in chapter 10 - (Himmelblau and Riggs 2011).

- Example 10.4 – Calculation of the Heat of reaction in a process in which the reactants enter and the products leave at different temperatures
- Example10.5 – Redone with the Heats of formation merged with the sensible heats in the calculation
- Example 10.7 – Calculation of an Adiabatic Reaction (Flame) Temperature (TFT)

The limitations with reference to the example calculations will be further applicable to this calculation. They are;

1) The flue gas composition of coal is limited to five components (CO_2, SO_2, CO, O_2 and N_2)
2) The heat capacity equations are given at low pressure condition and with narrow temperature ranges of 0-1500°C.

The composition of flue gas oxygen (4.0-5.0%) has been considered as the validating parameter in material balance calculation. The reason being the exit flue gas contains typically oxygen concentration of 4-5% in power generation units.

3.5. Description of the Calculation

As outlined in sections 1.3, fundamental calculations have been conducted under two main categories such as material balances and energy balances. The data and information obtained from literature and pre-calculated values have been used in the main calculations. The calculation boundary is the boiler furnace (Combustor) and all the assessments are made in steady state condition. The mass flow rates and compositions of inputs and outputs have been achieved by material balance calculations and will be further consumed in the energy balances subsequently. The calculation methods and equations were originally sourced from the book "Basic Principles and Calculations in Chemical Engineering-Eighth edition, (Himmelblau and Riggs 2011)" and modified accordingly. Consequently, the combination of results achieved from material and energy balances has been used to develop the carbon credits model which will be described in Chapter 6. Furthermore, calculation boundary is presented in Figure 3.1.

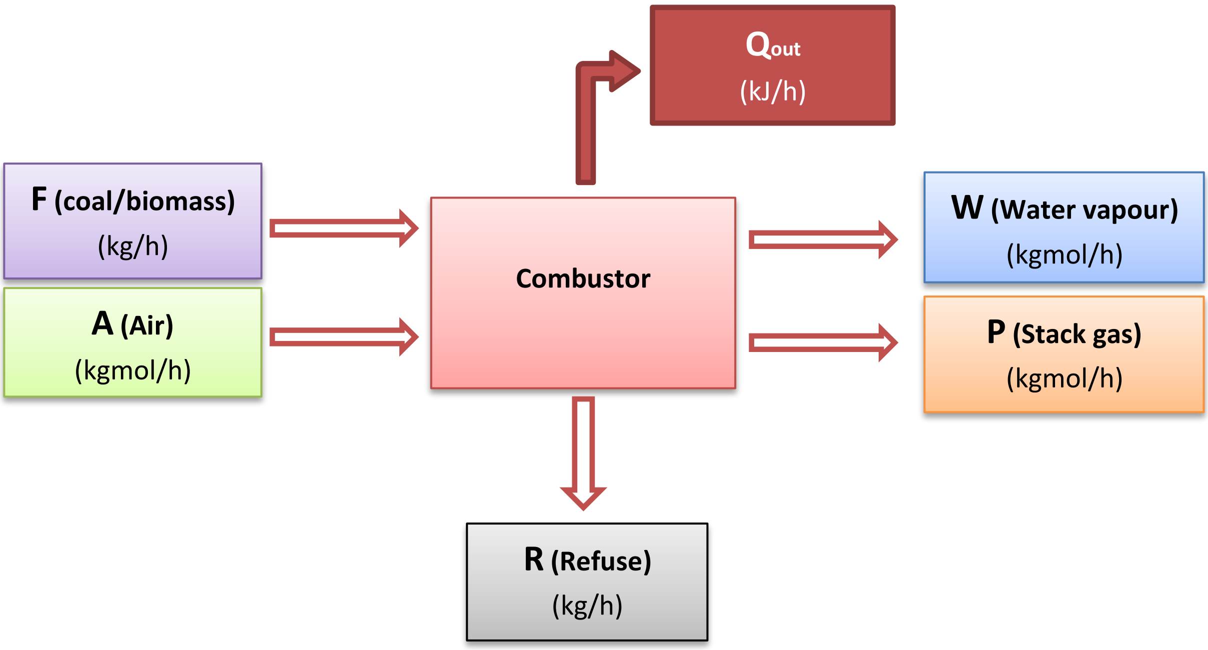


Figure 3.1 : Calculation boundary – Material & Energy Flows (Himmelblau and Riggs 2011)

3.5.1. Material balance calculation

Combustion reactions of coal, biomass and coal-biomass blends are considered in this assessment. The combustion characteristics of coal and biomass are detailed in Chapter 3. Similar type of combustion behaviours would be expected for each fuel type and blends since both coal and biomass fuels are represented as composition of C, H, O, N, S, Ash and H_2O in different combinations. Majority of the mass balance calculations are reported in kgmol basis except the ash balances which are in kg basis (ash is collected as the waste product during the combustion process which helps eliminating the complexity of the calculation). Several reactions and associated input parameters necessary for material balances are detailed in the following section.

Combustion reaction

Chemical elements in coal and biomass would react with the Oxygen in air during the combustion and combination of gaseous products would be discharged to the atmosphere.

$$C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)} \qquad (1)$$

$$S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)} \qquad (2)$$

$$2H_{(s)} + {}^{1}/_{2}\, O_{2(g)} \rightarrow H_2O_{(g)} \qquad (3)$$

$$2N_{(s)} \rightarrow N_{2(g)} \qquad (4)$$

$$2O_{(s)} \rightarrow O_{2(g)} \qquad (5)$$

$$NO_{2(g)} \rightarrow O_{2(g)} \qquad (6)$$

Stoichiometric and theoretical oxygen requirements for complete combustion of coal/biomass

The amount of Oxygen required (in kgmols) for each reaction could be calculated based on the combustion reactions (Equations 1-6) taken place in the combustor. This will enable to determine the net stoichiometric Oxygen requirement for the total combustion of coal, biomass or coal-biomass blends.

Stoichiometric oxygen requirement

$$O_{2st} = \sum_{i=1}^{n} n(o_2)_{(CE)i}$$

The amount of oxygen present in the fuel needs to be deducted when calculating the theoretical oxygen requirement for the complete combustion.

Theoretical oxygen requirement:

$$O_{2req} = O_{2st-} O_{2f}$$

Amount of excess air needed for the complete combustion of coal/biomass

A certain percentage of excess air required to be introduced into the combustor in order to achieve the complete combustion under the practical circumstances. (Himmelblau and Riggs 2011) (Vuthaluru and Vuthaluru 2006)

$$A_{ex} = \frac{O_{2ent-} O_{2req}}{O_{2req}}$$

The excess air requirement in this particular assessment would be considered as an independent variable while the amount of fuel combusted being the dependant variable for the individual combustion reactions of Coal and Biomass. During the combustion of blends, another independent variable would be added which is the stack gas oxygen composition of biomass to arrive at practicably feasible results.

Elementary mass balance calculations

The elementary mass balance calculation has been conducted to evaluate the interactions between input and output material flows while assessing the flow rates of F, A, W, P, R and the composition of individual elements. The various relations linking these elements are detailed below.

C balance:

kgmol of C combusted = kgmol of C in P

$$c_1 . P = n(C)_f \, . FX$$

S balance:

kgmol of S combusted = kgmol of S in P

$$s_1.P = n(S)_f\ .FX$$

N balance:

kgmol of N in combusted F + kgmol of N in A = kgmol of N in P

$$n_1.P = n(N_2)_f\ .FX + n(N_2)_a$$

H balance:

kgmol of H combusted +kgmol of H as moisture in fuel = kgmol of H in W

$$W = n(H_2)_f\ .FX + n(H_2O)_f.F$$

O balance**:**

kgmol of O in F + kgmol of O in A = kgmol of O required + kgmol of O in P

$$n(O_2).P = n(O_2)_f\ .F + n(O_2)_a - nO_{2req}$$

Ash balance:

kg of ash in coal = kg of ash in R

$$YR = m(AS)_f\ .F$$

$$(1-X)F = (1-Y)R$$

3.5.2. Energy balance calculation

Energy balance calculations have been conducted for a steady state system, primarily under the adiabatic conditions for calculating Adiabatic Flame Temperature (TFT) and then calculation would be extended to an open system with heat transfer to get the final rate of heat out from the boiler furnace with known boiler efficiency. Mass flow rate values would be imported from the material balance calculations combined with pre calculated parameters such as heat of formation values of fuels which are not readily available in literature.

Heat of formation of coal and Biomass

Heating values of coal (Vaysman and Lu 2012) and biomass (http://www.nrel.gov/biomass/) are available in the literature. As a rule of thumb, the heat of combustion of a fuel equals to the negative of the heating value.

$$\Delta H^\circ{}_c = (-)\ HHV$$

Therefore, the heat of formation values of each fuel type would be calculated based on heat of combustion values of the fuel and as well as heat of formation and combustion values of individual components of the fuel.

Fuel formula for 1kgmol of coal:

$$C_aH_bO_cN_dS_e.(H_2O)_{f(s)}$$

Formation equation of fuel:

$$aC + {}^{b}/_{2}\, H_{2(g)} + {}^{c}/_{2}\, O_{2(g)} + {}^{d}/_{2}\, N_{2(g)} + eS_{(s)} + f(H_2O)_l \\ \rightarrow C_aH_bO_cN_dS_e.(H_2O)_f$$

Total combustion equation of fuel:

$$C_aH_bO_cN_dS_e.(H_2O)_{f(s)} + (a + e + {}^{b}/_{4} - {}^{c}/_{2})O_{2(g)} \\ \rightarrow\ aCO_{2(g)} +\ eSO_{2(g)} + ({}^{b}/_{2} + f)H_2O_{(g)} + {}^{d}/_{2}\, N_{2(g)}$$

Individual combustion equations of fuel components:

$C_{(s)} \quad + O_{2(g)} \qquad \rightarrow CO_{2(g)}$

$S_{(s)} \quad + O_{2(g)} \qquad \rightarrow SO_{2(g)}$

$2H_{(s)} + {}^{1}/_{2}\, O_{2(g)} \rightarrow H_2O_{(g)}$

$2N_{(s)} \qquad\qquad\quad \rightarrow N_{2(g)}$

$H_2O_{(l)} \qquad\qquad\quad \rightarrow H_2O_{(g)}$

The heat of formation of coal and biomass could be simply calculated using the equations below, since all other data and information such as heat of combustion of the fuel, heat of formation and combustion of individual components of the fuel are available in the literature (Vaysman and Lu 2012); (http://www.nrel.gov/biomass/),

Heat of formation of coal:

$$\Delta H^{\circ}{}_{f\acute{c}} = n_{(\acute{c},\acute{c})} . \Delta H^{\circ}{}_{c(\acute{c})} - \sum_{i=1}^{n} n_{(CE_i,\acute{c})} . \Delta H^{\circ}{}_{c(CE)_i}$$

Heat of formation of biomass:

$$\Delta H^{\circ}{}_{f\acute{b}} = n_{(\acute{b},\acute{b})} . \Delta H^{\circ}{}_{c(\acute{b})} - \sum_{i=1}^{n} n_{(CE_i,\acute{b})} . \Delta H^{\circ}{}_{c(CE)_i}$$

Calculating net sensible heat input and output

At this point, an attempt has been made to calculate the net enthalpy change from state1 to state 2 when the combustion reaction is occurred. In the examples of 10.4 and 10.5 in (Himmelblau and Riggs 2011), explains two fundamentals in order to obtain the net enthalpy change of a combustion reaction. As shown in the Figure 3.1, the standard heat (enthalpy) of reaction (as explained in example 10.3 (Himmelblau and Riggs 2011)) would be replaced by the heat of formation values of reactants and products (as upgraded in example 10.4 (Himmelblau and Riggs 2011)) which would make the calculation easier to apply and less susceptible to errors than the heat of reaction approach. If the combustion reaction is not complete, the material balance determines amount of fuel combusted and that would provide the exact amount of heat in and out to and from the system.

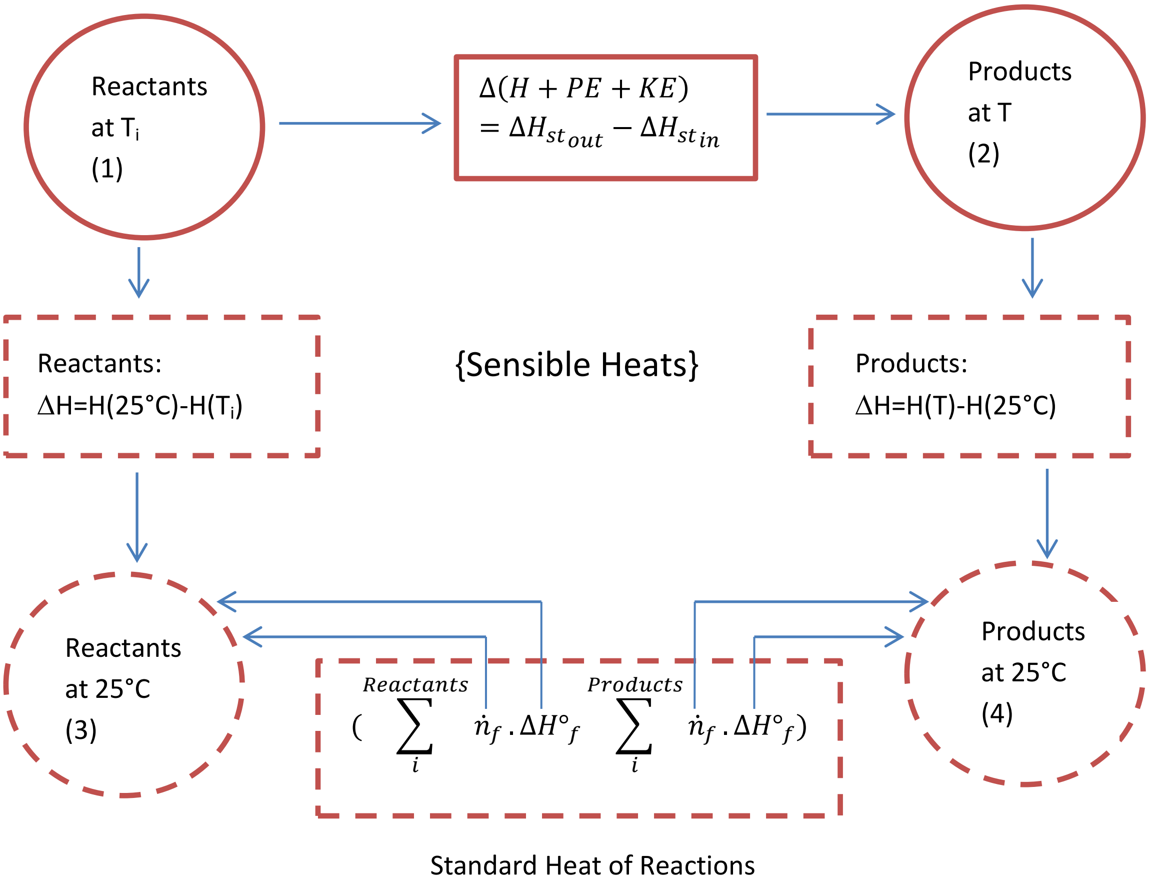


Figure 3.1 : Information flow used to calculate the net sensible heat: (Source: Figure10.4-(Himmelblau and Riggs 2011))

The sensible heat of individual component at a given temperature and pressure would be obtained by integrating the respective heat capacity equations of each component given in Appendix G - (Himmelblau and Riggs 2011).

Heat capacity equations for organic and inorganic compounds (for low pressures up to 1 atm)

Form 1: $C°_p = a + b(T) + c(T)^2 + d(T)^3$

Form 2: $C°_p = a + b(T) + c(T)^{-2}$

Sensible heat

$$\Delta\widehat{H_s} = \int_{T1=25℃}^{T2} C_p . dT$$

Then, the net sensible heat in and out to and from the system would be gained by following equations.

Net stream sensible heat input

$$\sum \Delta H_{st_{in}} = \sum \dot{n}_f . \Delta H°_f + \sum_{i=n1} \Delta\widehat{H_s} . \dot{n}_{fi} + \dot{n}_{H2O} . L$$

Net stream sensible heat output

$$\sum \Delta H_{st_{out}} = \sum_{i=n1} \dot{n}_{pi} \; (\Delta\widehat{H_s} + \Delta H°_f)$$

Consequently, the heat of reaction or the net enthalpy change of a steady state system is the difference between these two enthalpies.

$$\sum \Delta(H + PE + KE) = \sum \Delta H_{st_{out}} - \sum \Delta H_{st_{in}}$$

Theoretical Flame Temperature (TFT)

TFT would be calculated at adiabatic conditions when the net enthalpy change is equal to zero.

$$\sum \Delta(H + PE + KE) = 0$$

The change of potential energy and kinetic energy (ΔPE and ΔKE) of the reaction considered to be negligible when compared to the net enthalpy change of ΔH. Hence, it is reasonable enough to reduce the enthalpy change equation to ΔH = 0.

In order to calculate the TFT of the reaction using linear interpolation method, it is required to get two different enthalpy changes values (negative and positive) at respective outlet temperatures. Then TFT would be found when ΔH = 0 by using the equation bellow.

$$TFT = T_1 + (T2 - T1)\left[\frac{(0 - \Delta H_1)}{(\Delta H_1 - \Delta H_2)}\right]$$

Calculation of rate of boiler heat output

The TFT obtained from the previous calculation would be considered as the baseline for assuming the actual flame temperature in this stage. Therefore, the actual flame temperature would be 400°C less than the respective TFT of the fuel as mentioned in the assumptions.

Then the net stream heat of each fuel could be achieved at the assumed temperature and to end with, the rate of heat out of the boiler could be obtained at a known boiler efficiency of 85%.

Net Stream Heat – Steady-State, Open system with heat transfer at $T=T_0$

$$Q_{in} = \sum \Delta H$$

Rate of boiler heat output

$$Q_o = \eta\, Q_{in}$$

Chapter 4: Results & Discussion

This particular research is designed to analyse the combustion behaviour of biomass with diverse coal ranks in a fuel blend in terms of their energy output and GHG emissions. The 10 woody biomass species were carefully chosen from three dissimilar categories (Hard wood, soft wood and energy crops) and five of the non-woody biomass species (Agricultural waste) have considered with seven coal ranks. Summary of analysed coal, biomass and blends considered for the study are detailed in Table 4.1.

Table 4.1 : Summary of analysed coal, biomass and coal/biomass blends

Coal Ranks				**LIG**	**SUB B-B**	**SUB B-C**	**HVB -B**	**HVB -A**	**MVB**	**LVB**
				a	a	a	a	a	a	a
Biomass										
Hard wood	Eucalyptus	a		b	b	b	b	b	b	b
	Ailanthus	a		b	b	b	b	b	b	b
	Oak wood	a		b	b	b	b	b	b	b
	Black Locust	a		b	b	b	b	b	b	b
Soft wood	Spruce	a		b	b	b	b	b	b	b
	Douglas fir	a		b	b	b	b	b	b	b
	Monterey Pine	a		b	b	b	b	b	b	b
Energy crops	Willow wood	a		b	b	b	b	b	b	b
	Switch grass	a		b	b	b	b	b	b	b
	Hybrid poplar	a		b	b	b	b	b	b	b
Non woody	Barley straw	a		b	b	b	b	b	b	b
	Rice straw	a		b	b	b	b	b	b	b
	Wheat straw	a		b	b	b	b	b	b	b
	Sugarcane bagasse	a		b	b	b	b	b	b	b
	Corn stover	a		b	b	b	b	b	b	b

“**a**” – Individual fuel (Coal, Biomass) “**b**” – Coal/biomass blends

The results of the analysis have systematically been presented in a hierarchy of fuels. Consequently, coal is considered as the baseline fuel and biomass and coal-biomass blends are comparatively analysed accordingly. The reason behind that is obvious, since coal is still the major fuel source in the power generation and the attempt in this study is to provide a competitive alternative for coal which is viable. The hierarchy of calculation and results are given in Figure 4.1.

Hierarchy of the Calculation & Results:

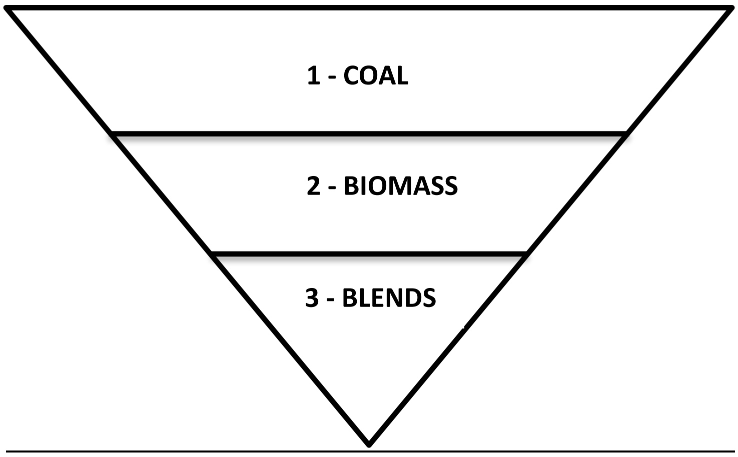


Figure 4.1 : The hierarchy of calculation and results

The respective fuel has an identical set of parameters which have been analysed in this study and the mode of demonstrating the results are detailed below.

Parameters analysed for individual fuel:

- Excess air requirement for complete combustion
- Percentage O_2 left in flue gas
- Rate of energy outputs (kWh/h)
- Rate of CO_2 emissions (for coal) or emission reductions(for biomass)(kg/h)
- Rate of SO_2 emissions(kg/h)

Specifically, the reductions, comparisons and emission factors are discussed with the fuel blend.

Parameters analysed for fuel blends:

- Percentage Reduction of energy output when co-firing
- Comparison of blend energy outputs with energy output of individual fuels
- Percentage Reduction of CO_2 emissions
- Percentage Reduction of SO_2 emissions
- Emission Reduction Factors for Coal-Biomass blends with 20% biomass by weight for boilers with 85% known efficiency (g CO_{2e}/kWh)

The ultimate outcome of the study has been to utilise the parameters in developing the carbon credits model which is detailed in the Chapter 6 of this report.

4.1. Coal combustion

Since the coal is used as the reference point for the current study, the results of the coal analysis are presented at the beginning.

4.1.1. Excess air requirements for combustion of coal

Coal has a limited range of 18 – 22% excess air need all the way through the ranks. Hence, the excess air requirement is more likely to be independant with the coal rank. However, the coal ranks which have slightly higher tendency of consuming more excess air means it has a less tendency to burn. Furthermore, it is a necessity to supply sufficient excess air for two main reasons;

1) To ensure complete combustion
2) Safe operation

The first reason has already been proven by the study results of this analysis since the excess air has been adjusted expecting the complete combustion of the fuel. Therefore, the combustion percentage of a fuel is a factor of excess air amount introduced into the system. If the air rate is too low, it could be a safety issue due to rapid buildup of carbon monoxide in the flue gas and, in extreme cases, smoke could be produced (i.e. unburnt carbon particles) (Bahadori and Vuthaluru 2010).

(Bahadori and Vuthaluru 2010) has further explained in their paper that “ the boiler efficiency is very dependent on the excess air rate. Excess air should be kept at the lowest practical level to reduce the quantity of unneeded air that is heated and exhausted at the stack temperature”.

Excess air requirement for complete combustion of varying coal ranks is presented in Figure 4.2. The coal remains in the middle of the ranking hierarchy which is “high volatile bituminous B” requires the lowest excess air whilst “low volatile bituminous” which is a high rank coal requiring the most excess air for its combustion. Basically two basic assending and decending patterns of excess air requirements can be observed with coal ranks as detailed below.

1) Decreased excess air requirement with increasing coal rank until it reaches the middle of the ranking hierarchy and achieves the minimum requirement (HVB-B).
2) Excess air requirement increases from the minimum to the maximum while shifting from middle to high grade coals.

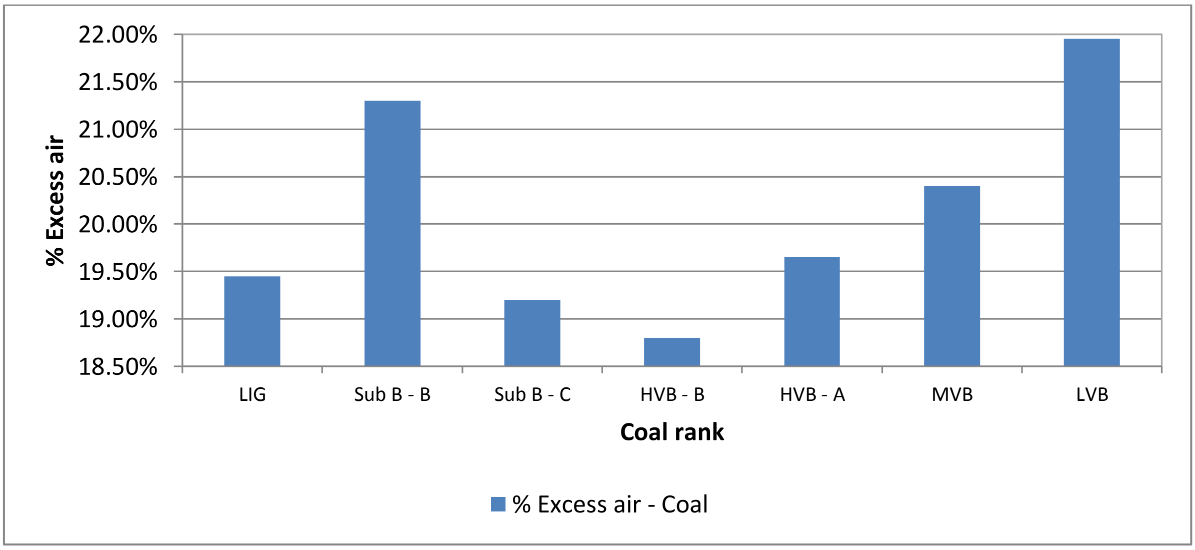


Figure 4.2 : Excess air requirement for complete combustion of coal ranks

4.1.2. Percentage O_2 in flue gas

The oxygen content in the boiler exhaust would be encountered as the flue gas oxygen. Higher the percentage of oxygen in flue gas would drain off the substantial amount of gas in the exhaust and that would potentially enhance the energy loss from the system. At the same time, low flue gas oxygen could be ended up with the waste of fuel due to incomplete combustion inside the furnace (Lingfang and Yechi 2012). For that reason, it is important to maintain a decent percentage of oxygen in the flue gas system.

In this study, the percentage oxygen remains in flue gas from coal combustion has been considered as a validating parameter by maintaining the value in the range of 4-5%. The percentage O_2 in flue gas is detailed in Table 4.2. During the combustion of low grade coals slightly higher percentage of oxygen can be observed in flue gas. This can be caused by the higher oxygen content in low grade coals itself compared to high grade coals.

Table 4.2 : Percentage O_2 in flue gas

Coal rank	% O_2 in flue gas
LIG	5.0
Sub B - B	5.0
Sub B - C	5.0
HVB - B	4.0
HVB - A	4.0
MVB	4.0
LVB	4.0

4.1.3. Rate of energy output for coal of varying ranks (kWh/h)

The rate of energy output is a key factor for any fuel kind which will enable to determine and compare the fuel types in terms of their energy efficiency under similar combustion conditions. Figure 4.3 indicates that the rate of energy output of coal is directly proportionate to its rank. At the same time, the highest (low volatile bituminous) and lowest (lignite) ranks are sitting at the two ends giving a significant range of 188 -103 kWh/h.

It is noted that the energy output values are presented in the ascending order of coal ranking system from low grade to high grade coals.

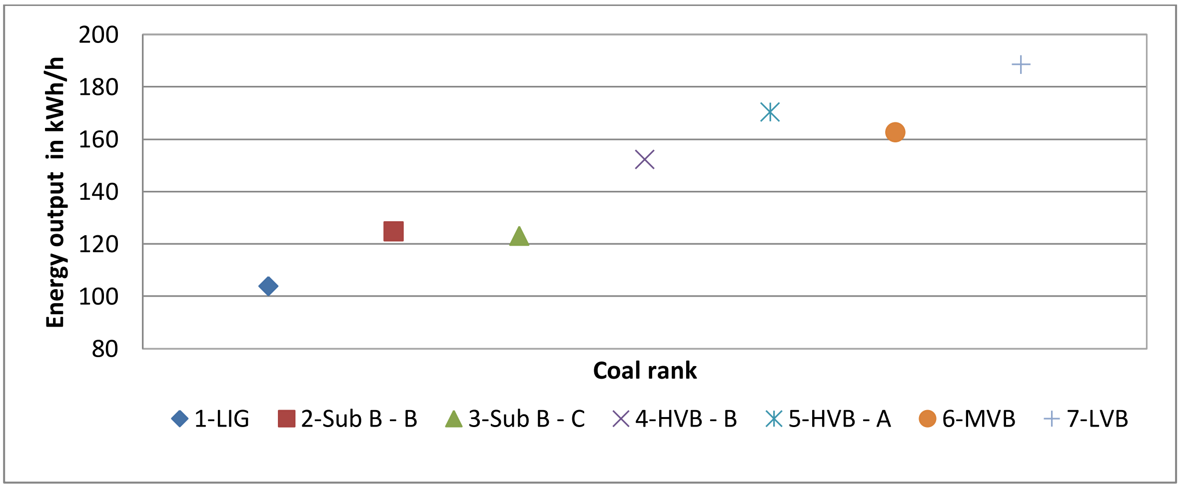


Figure 4.3 : Rate of energy outputs of varying coal ranks (kWh/h)

4.1.4. Rate of CO_2 emissions (kg/h)

Coal is the major source of CO_2 emissions in the world. And furthermore, CO_2 is the foremost Greenhouse gas on earth. Ultimately, the coal combustion accelerates the greenhouse effect and global warming which are the most debated topics in the area of coal science. As a part of this study, the highest and lowest CO_2 contributors among the coal community were able to obtain and obviously they are Low Volatile Bituminous (high rank) coals and Lignite (low rank) coals respectively. The reason behind this fact is the amount of carbon contained in the coal type and the CO_2 emission is directly proportionate to the amount of C in the fuel as shown in (Figure 4.4).

It is noted that the CO_2 emission values are presented in the ascending order of coal ranking system from low grade to high grade coals.

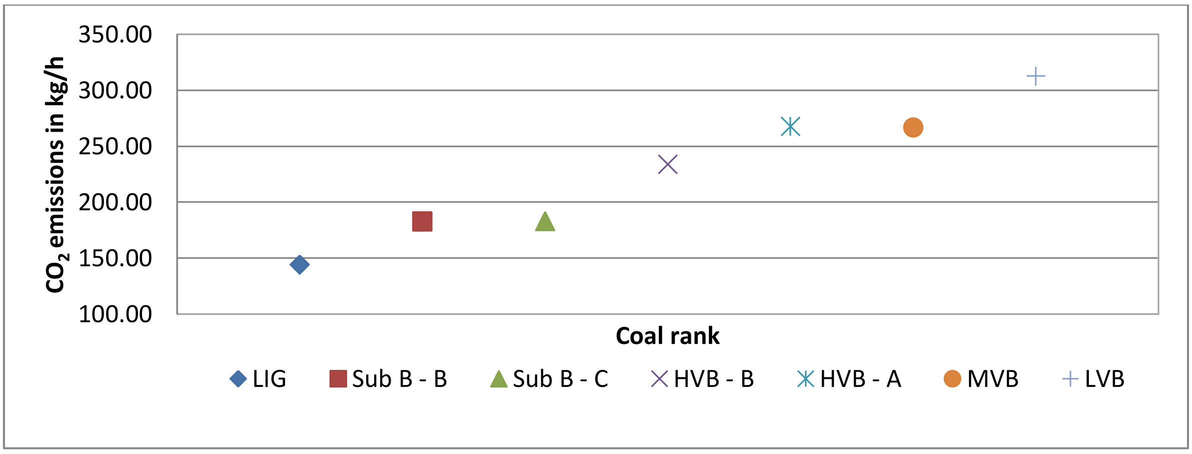


Figure 4.4 : Rate of CO_2 emissions from coal combustion (kg/h)

4.1.5. Rate of SO_2 emissions (kg/h)

The composition of S in the fuel is the main aspect which contributes the elementary S to react with oxygen producing SO_2 during combustion. Hence, it is reasonable to perform the similar comparison to find out the coal ranks with less S contents. As shown in Figure 4.5, low grade coals are primarily consistent with lower amount of sulphur compared with high grade coals. However, the low volatile bituminous (LVB) which is the highest rank of all coal types considered in the study has deviated from the pattern, emitting a substantially lower amount of SO_2

compared with other high grade coals (Figure 4.5). There are some evidences available in the literature (Moroń and Rybak 2015) where low grade coals (analysed as brown coal) produce lower amount of SO_2 emissions of 2000mg/m^3 compared to high grade coals (analysed as hard coal) of 2500mg/m^3.

It is noted that the SO_2 emission values are presented in the ascending order of coal ranking system from low grade to high grade coals.

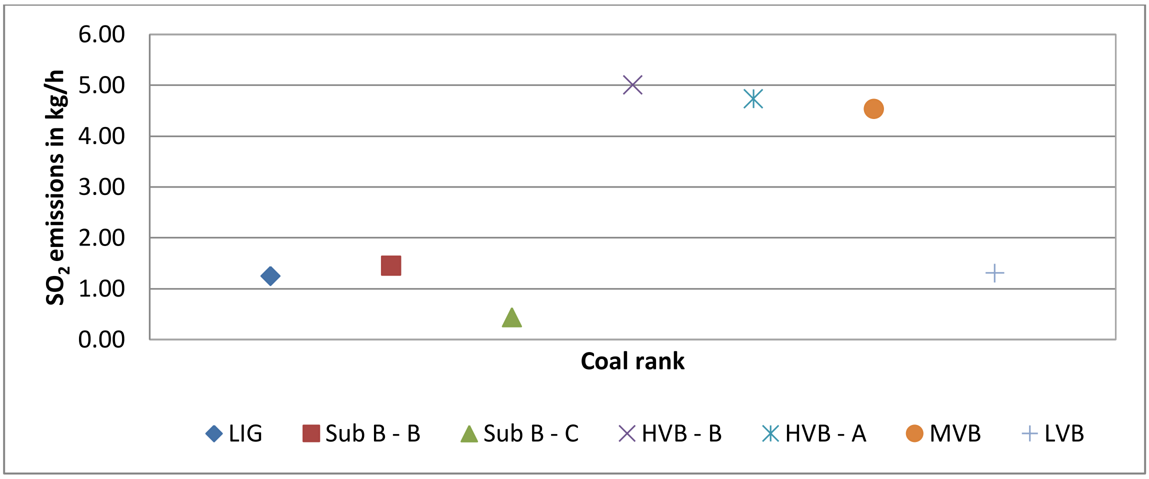


Figure 4.5 : Rate of SO_2 emissions from coal combustion (kg/h)

4.2. Biomass combustion

A study of individual biomass combustion is rather important to progress in order to understand the behaviour of coal and biomass blends during combustion. The combustion characteristics of biomass are similar to coal combustion to a certain degree since biomass is also a solid hydrocarbon fuel of similar kind. The detailed combustion characteristics of coal and biomass are compared and discussed in Chapter 2.

This study is primarily focused on fifteen different biomass species which represent few major categories among the biomass types. It should be noted that each species although has their specific features, biomass has stated their relationships by giving corresponding combustion results within the similar categories (especially the woody biomass species - Hard wood, soft wood and energy crops). This has made the analysis further easier in order to detail the results as an average basis. However, non-woody biomass has individually been analysed to prevent any misleading interpretations.

4.2.1. Excess air requirements for combustion of biomass

Despite coal, biomass has acquired higher degree of excess air need for completing their combustion with an average of 35%. This is the average value calculated according to the individual values of all biomass types considered in the study detailed in Table 4.3. Additionally, some literature evidences are available for emphasizing this value (Wang, Shao et al. 2015), reporting that the excess air requirement for hard wood species to be around 30% based on their combustion system conditions. The study results provided a common range amongst the different types of biomass about 32-41% while Barley straw being an exceptional to the others, with excess air range of coals at an approximately value of 21%. The excess air requirement for complete combustion of biomass is detailed in the Table 4.3.

Table 4.3 : Excess air requirement for complete combustion of biomass

Biomass types		% Excess air need
Hard wood	Eucalyptus	34.0
	Ailanthus	39.5
	Oak wood	34.0
	Black Locust	38.5
Soft wood	Spruce	32.9
	Douglas fir	37.5
	Monterey Pine	38.8
Energy crops	Willow wood	31.9
	Switch grass	35.4
	Hybrid poplar	40.8
Non woody	Barley straw	20.9
	Rice straw	37.8
	Wheat straw	33.0
	Sugar cane bagasse	35.2
	Corn stover	35.3

Additionally, biomass fuel is chemically composed mainly of cellulose, hemicelluloses and lignin polymers (Hydrocarbons). Other components include minerals, water, salts, and organics such as proteins, starches, nucleic acids, oils, and resins. In most fuels, cellulose is the major constituent (Sullivan and Ball 2012).

During the study of biomass combustion, the analysis has been extended in order to distinguish any of the relationships between these chemical structures of biomass with some combustion parameters such as excess air requirement for complete combustion of biomass (Table 4.4).

Table 4.4 : Effect of changes in composition of the polymer structure in biomass against excess air requirement

Polymer type	Excess air need
With Cellulose	No precise increment or decrement with amount of cellulose present in the biomass
With Hemi-cellulose	No precise increment or decrement with amount of hemi-cellulose present in the biomass
With Lignin	No precise increment or decrement with amount of lignin present in the biomass

This is a limited comparison with a single parameter however, it is considered to be most important parameter for the combustion of any fuel kind. As clearly indicated in the figures (Figure 4.6, Figure 4.7 and Figure 4.8), it should be noted that the amount of excess air required for complete combustion of biomass is autonomous with the internal polymer structure of the biomass. Furthermore, there are no evidences found in literature for analysing the effect of biomass structure for the amount of excess air required for biomass combustion.

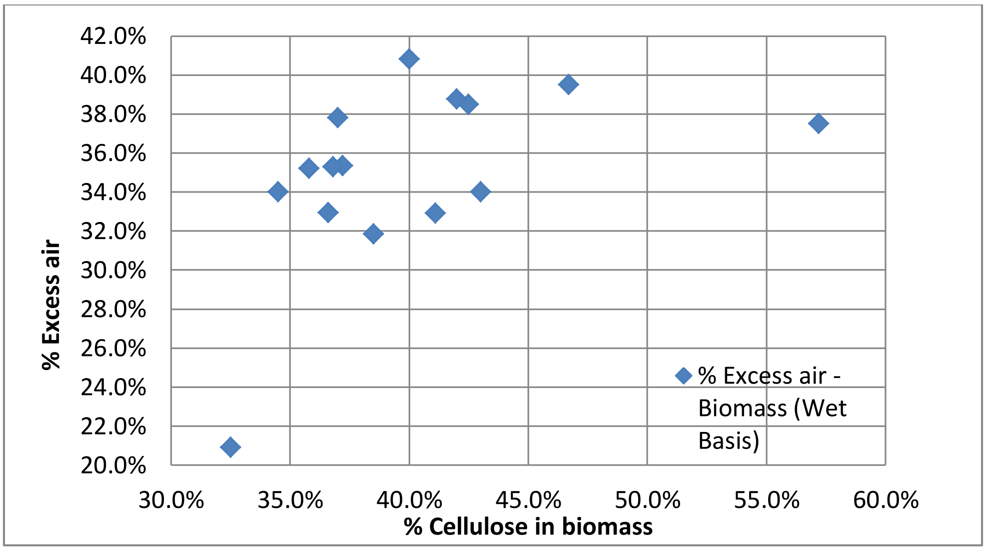


Figure 4.6 : Cellulose Vs Excess air requirement

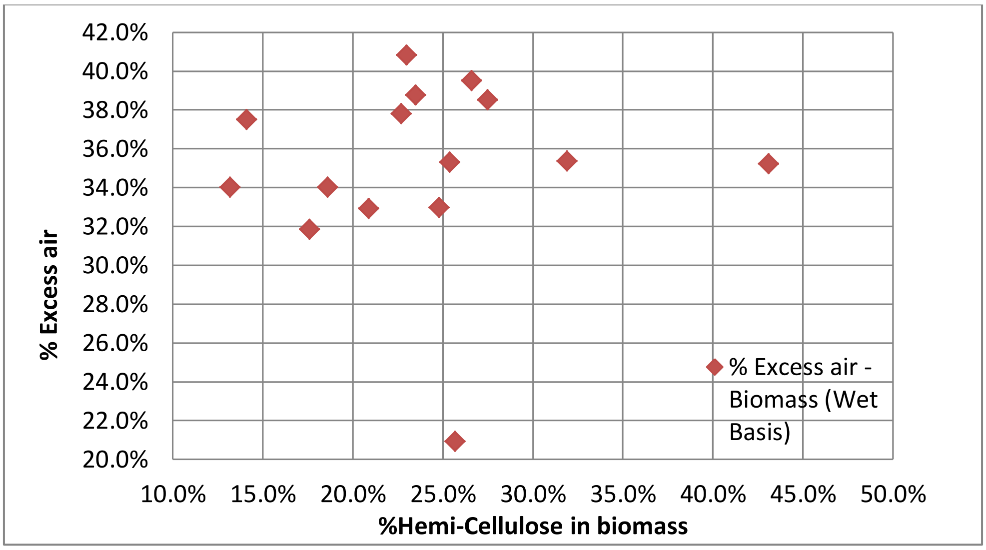


Figure 4.7 : % Hemi-cellulose Vs excess air requirement

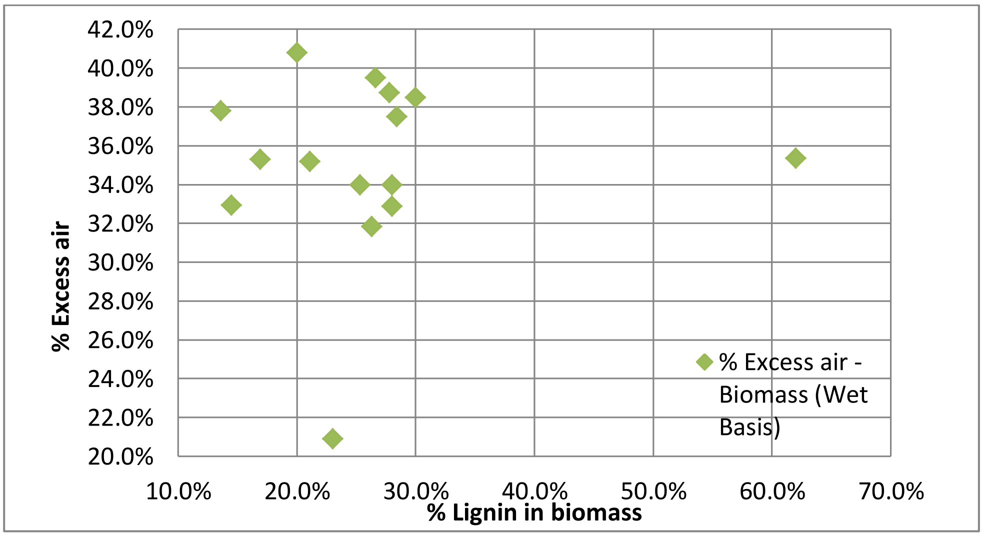


Figure 4.8 : % Lignin Vs Excess air requirement

4.2.2. Percentage O_2 in flue gas

The amount of flue gas oxygen in each biomass has a constant figure of 10% however barley straw is exceptional. As indicated in the previous section, barley straw has governed lower amount of excess air compared with other biomass types as well as it discharges slightly higher percentage of O_2 into flue gas (11%). The reason being the barley straw contains high oxygen composition of 43.13% which is higher than the average composition of other biomass types (38.5%).

4.2.3. Rate of energy output of several biomass types

The average rate of energy discharge from woody biomass has a considerably greater value than the majority energy output of non woody species. As well described in the Figure 4.9, amongst the analysed agricultural waste types, sugar cane bagasse and corn stover are the only non-woody species which have competed with the woody biomass by sitting at the range of energy crops (120-125kWh/h) in terms of their rate of energy output.

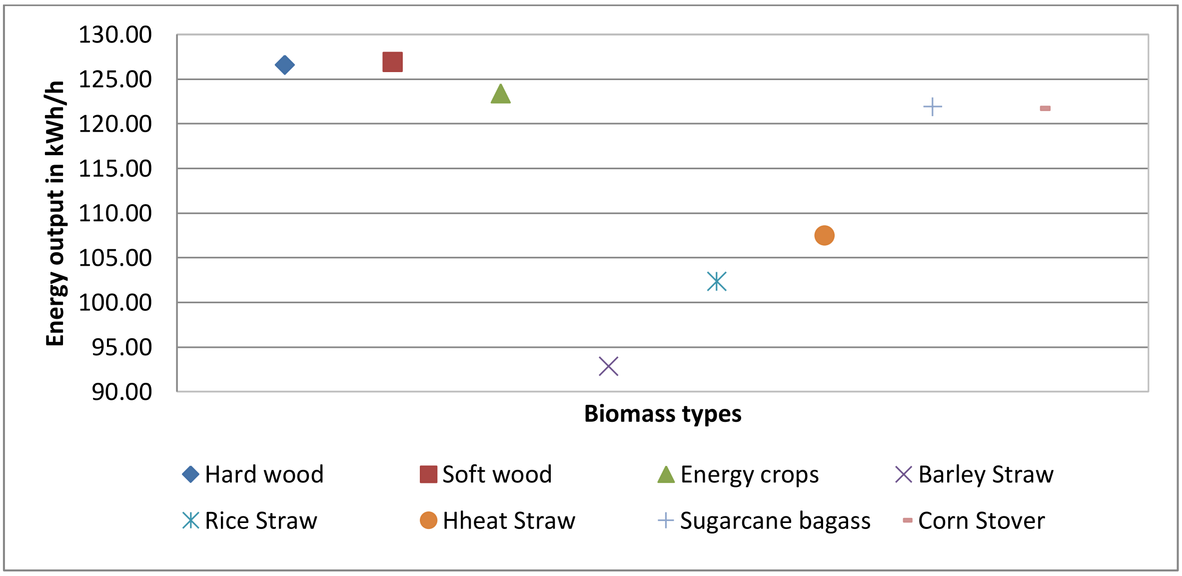


Figure 4.9 : Rate of energy output of biomass (kWh/h)

4.2.4. Reduction rate of CO_2 emissions (kg/h)

As a rule of thumb, any hydrocarbon combustion is a part and parcel of CO_2 and H_2O discharges as gaseous products of their combustion reactions. Biomass combustion has the same rule applicable in order to its combustion. However, there are some exceptions available to consider its emissions as reductions when it is sourced renewably. In this study, an attempt has been made to promote the renewable biomass harvesting and combustion by targeting carbon credits. Hence, all the CO_2 emissions associated with biomass burning could be considered as emission reductions.

The emission reduction associated with biomass burning has been detailed in the Figure 4.10. It is clearly noted that the woody biomass has achieved the highest rate while non-woody biomass having a diverse reduction approaches midst its varieties.

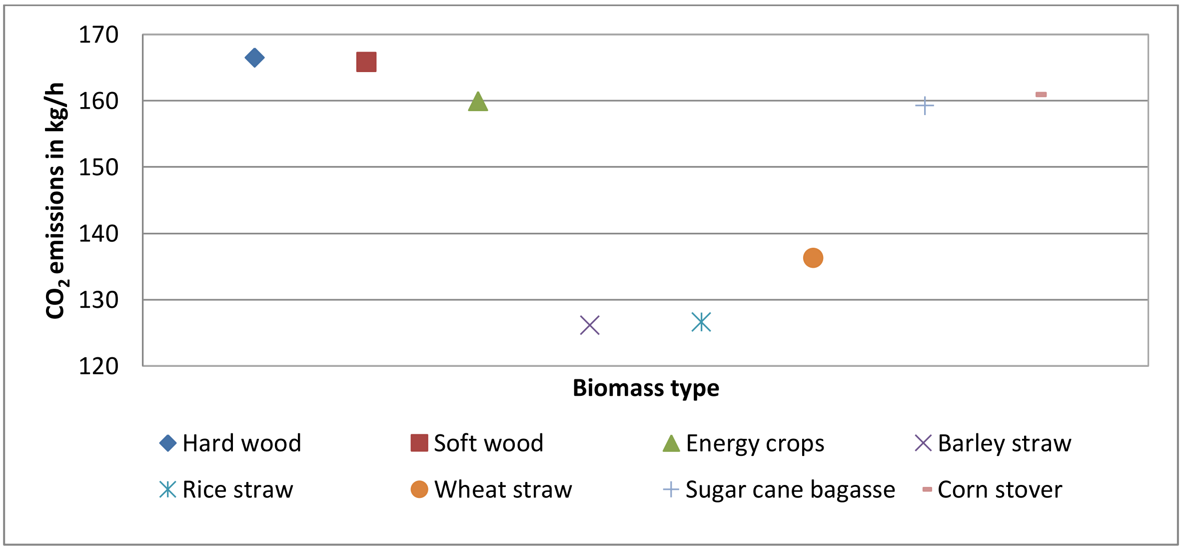


Figure 4.10 : Reduction rate of CO_2 emissions from biomass combustion (kg/h)

4.2.5. Rate of SO_2 emissions (kg/h)

The S content in biomass is directly proportionate to the SO_2 discharge as similar to the SO_2 emission in coal burning. The advantage of biomass with regards to coal is its lowest composition of S. As shown in Figure 4.11, the rate of SO_2 emissions of all sort of biomass has a value of well below 1kg/h in spite of coal has an average emissions of approximately 3kg/h.

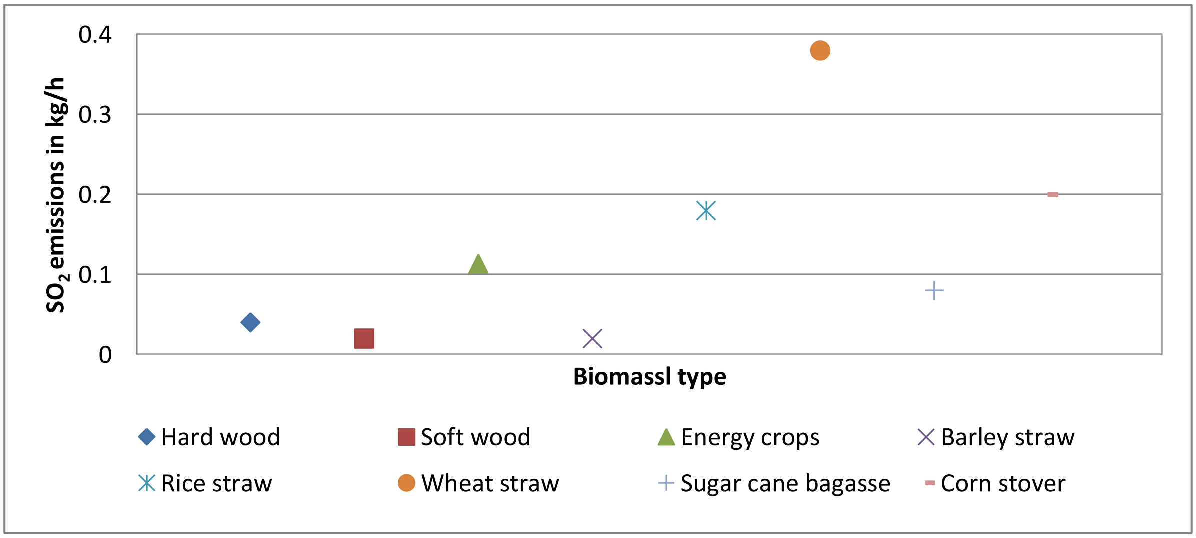


Figure 4.11 : Rate of SO_2 emissions from biomass combustion (kg/h)

4.3. Co-combustion biomass with coal

Co-firing biomass with coal would apparently be similar types of hydrocarbon burning in a same combustion chamber and hence it is reasonable to expect an outcome which is similar to individual fuel combustions in some extent. However, the effect on individual fuel in the blend is predictable. As per detailed in previous two sections individual fuel has its own combustion characteristics and it is precisely given that biomass were sitting at the lower end of coals where the low grade coals had been. The process of coalification (O'Keefe, Bechtel et al. 2013) would provide a clear reason for that further. Therefore, it is obvious that any fuel with identical features should behave equally under the same conditions. In order to have a further discussion of this correlation of fuel blend, several parameters have systematically been considered in this section.

4.3.1. Reduction of energy output during co-firing

One of the key parameters considered in this research is the reduction amount of energy output when co-firing coal and biomass which is the most important outcome to measure with any fuel kind. This is mainly due to the lower heating value of biomass and some experimental studies conducted by (Mun, Tumsa et al. 2016) provides more evidences for this.

It is noticeable that the amount of reduction is highly depending on the energy gap in between individual fuels in the blend. Hence low grade coals has quite similar rate of energy output to that of woody biomass types during individual combustion, they behave well in the blend giving rather low percentage reduction of less than 1% with Lignite and around 6% loss with Sub bituminous coal types. It should be noted that all the percentage figures have been calculated with reference to initial rate of energy output of individual coal combustion and the energy loss with reference to biomass when blend with low grade coals has considered as negligible due to lower blending ratios. Consequently, high grade coals respective for a higher energy loss during co-firing while forecasting that the low grade coals are the best fuel to blend with woody biomass (Figure 4.12).

The behavioural arrangement of non-woody biomass with coal is rather similar to that of woody biomass, however the individual behaviour of distinct biomass type(s) with coal ranks are presented in the Figure 4.13 for further details.

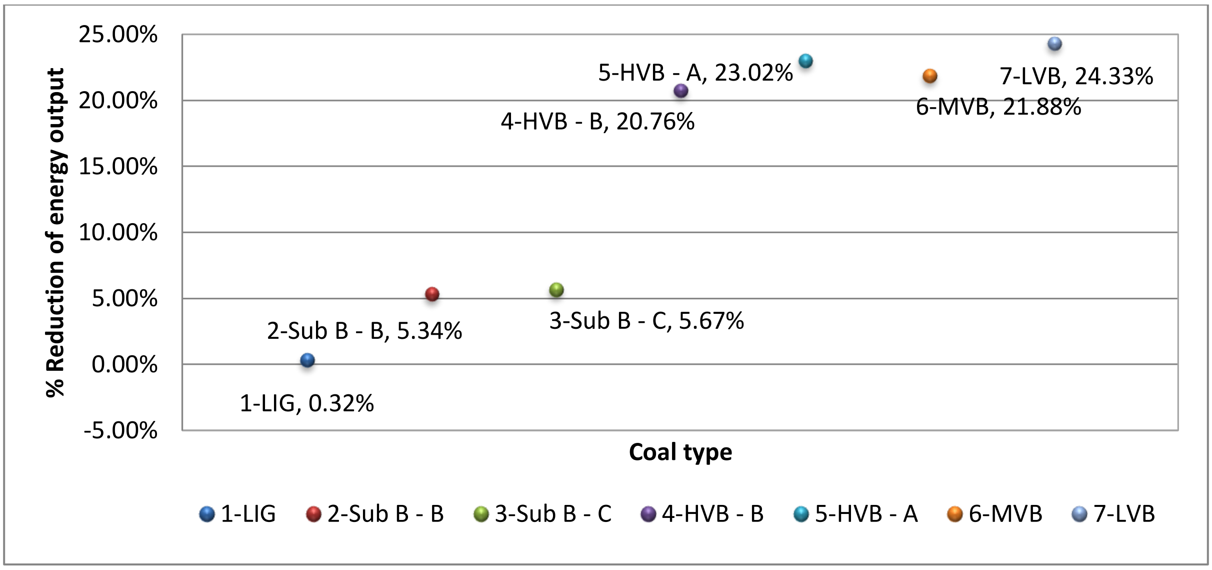


Figure 4.12 : % Reduction of energy output when woody biomass co-firing with coal

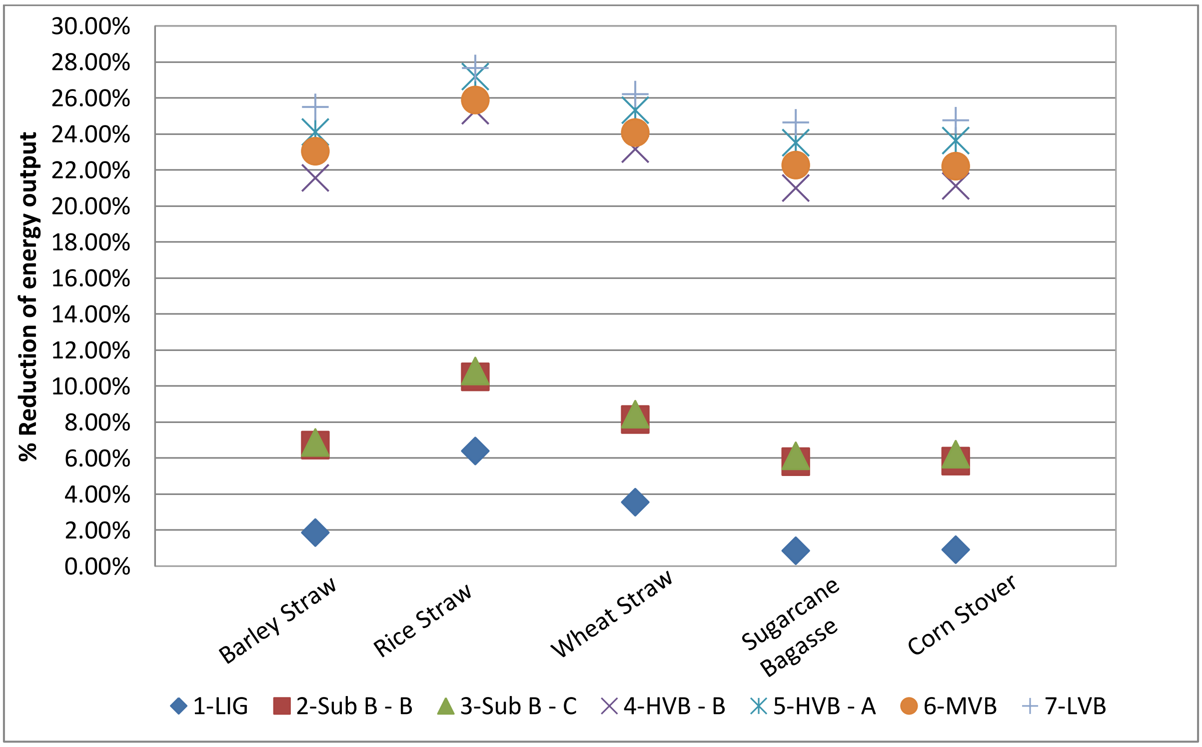


Figure 4.13 : % Reduction of energy output when non-woody biomass co-firing with coal

4.3.2. Comparison of blend energy with energy output of individual fuels

The rate of average energy output of individual fuels and the blending effect of fuels to the cumulative energy output when co-fired have already been discussed in the previous sections (4.1.3, 4.2.3 and 4.3.1). In addition, analysing all three fuels in the same axis would have precisely detailed exactly how the complete energy loss is being processed gradually (Figure 4.14 and Figure 4.15)

The average energy output of coals has spread out throughout the axis with a hierarchy of low grades to high grades (with a range of around 100-200 kWh/h). On the other hand, the entire biomass has an energy figure of well below the value of 130kWh/h. However, the majority of woody biomass species and few of non-woody biomass species such as sugar cane bagasse and corn stover have matched the range of sub bituminous coal types in terms of their energy output by placing the lignite down below their range. Furthermore, the energy output of some of the non-woody species such as rice straw and wheat straw are around the energy output range of Lignite and the worst case scenario is with Barley straw which is further down to 100kWh/h.

When the blending effect applies, the corresponding blend would have given a rate of energy output with a certain percentage loss of energy out accordingly. The percentage loss of energy output has already been discussed in the previous section (4.3.1).

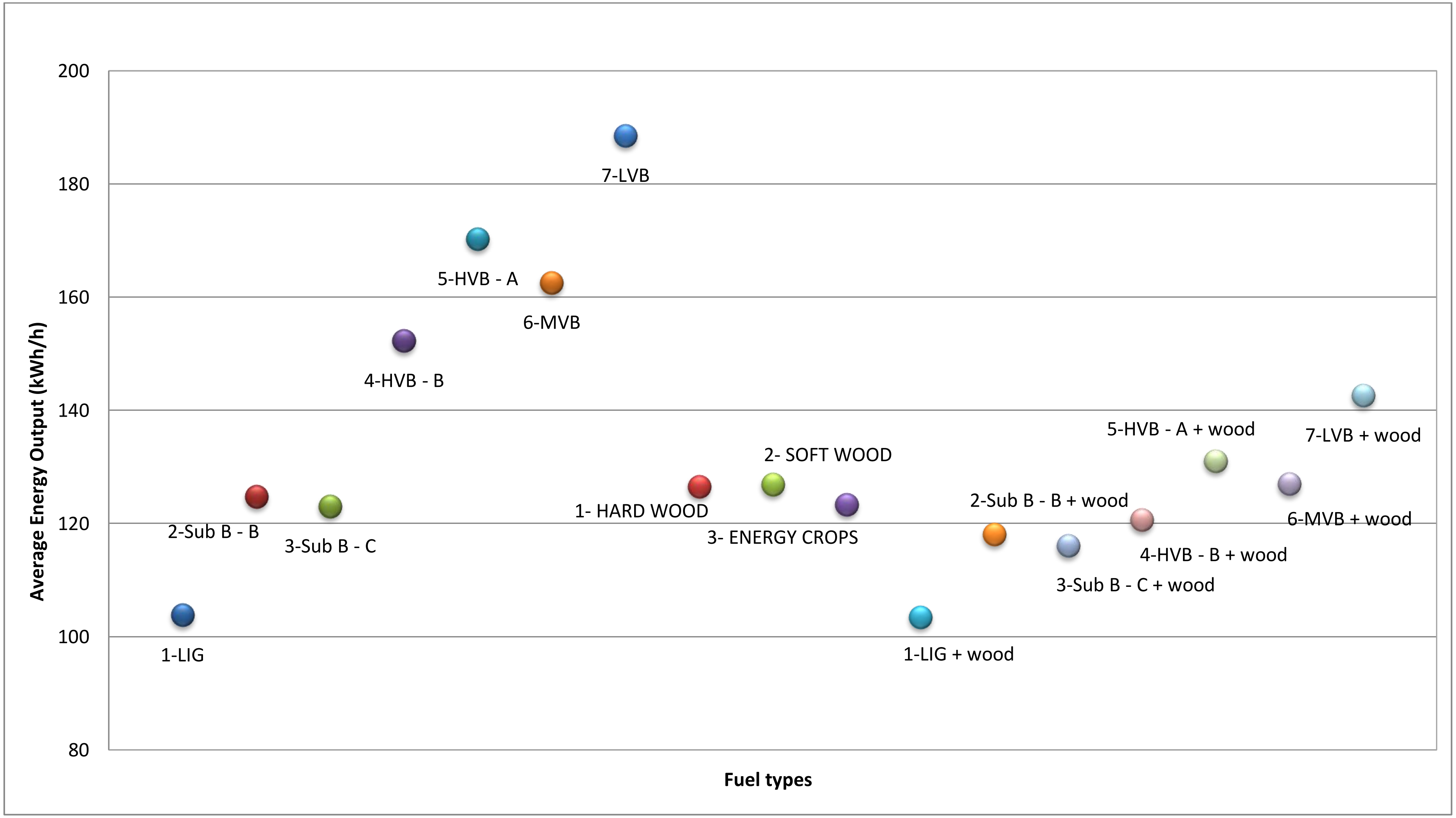


Figure 4.14 : Comparison of energy output – Coal, Woody Biomass and Coal+ Woody Biomass blend (kWh/h)

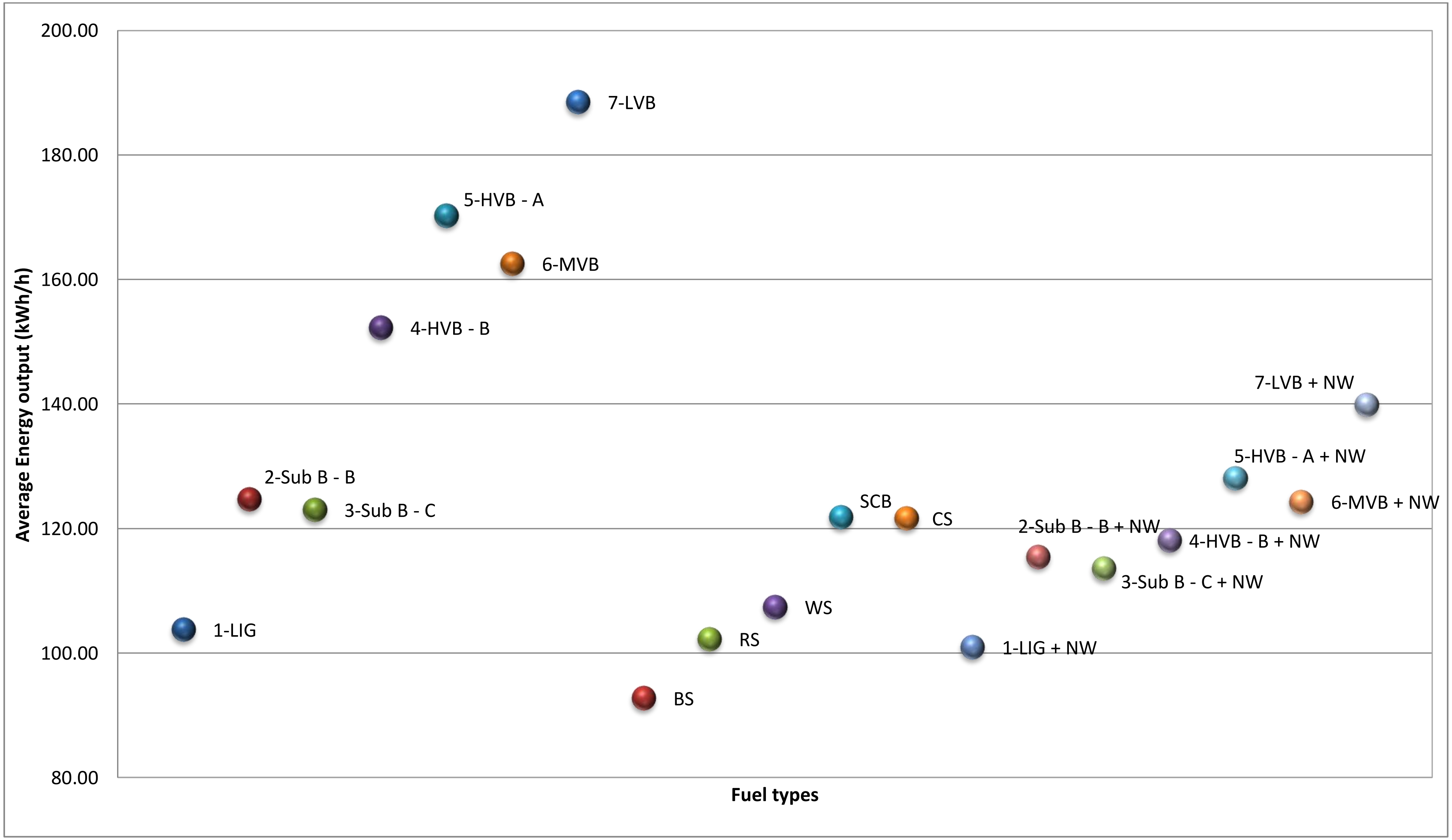


Figure 4.15 : Comparison of energy output – Coal, Non-woody Biomass and Coal-Non-woody Biomass blend (kWh/h)

4.3.3. Reduction of CO_2 emissions during co-firing

In general the amount of CO_2 reduction is directly proportionate to the blend ratio; therefore, this comparison has been carried out at a constant blend ratio of 20% biomass in order to study and compare the variation of emission reduction with different coal ranks under same combustion conditions. The individual combustion of high rank coals produces higher rates of CO_2 emissions compared to low rank coals. Hence, the percentage reduction of CO_2 emissions during co-firing will vary accordingly (lower and higher percentage reduction with high and low rank coals respectively).

As given in Figure 4.16 it is quite reasonable to consider the mean value of CO_2 reductions of woody biomass types due to the similarities in the results, nevertheless; non-woody biomass has been figured out separately for avoiding any delinquency (Figure 4.17).

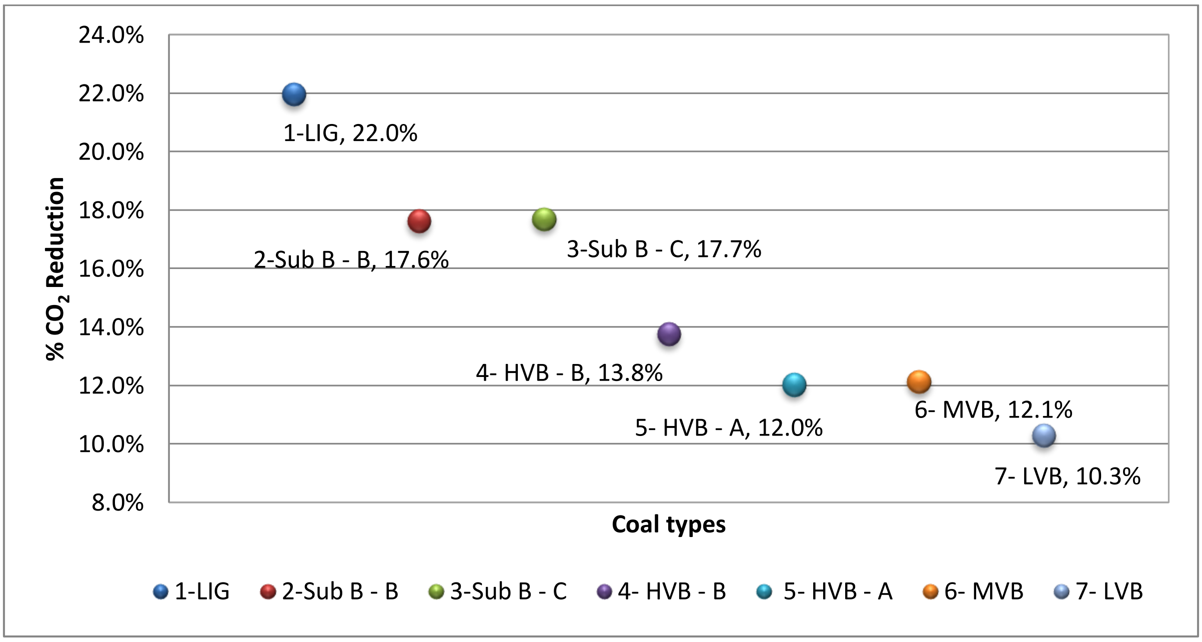


Figure 4.16 : % CO_2 reduction with woody biomass

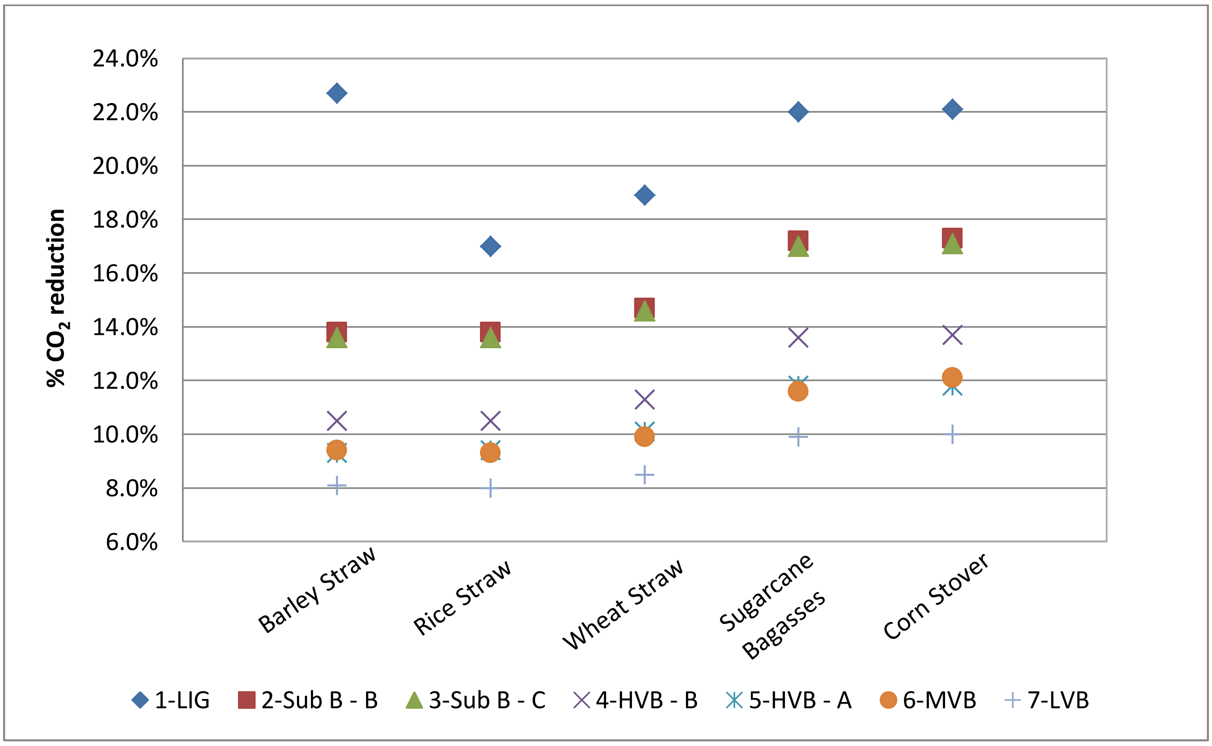


Figure 4.17 : % CO_2 reduction with non-woody biomass

4.3.4. Reduction of SO_2 emissions during co-firing

Presence of S is a mutual component in coal and biomass, although coal claims rather advanced percentage emissions compared to biomass. Consequently, that has made a way to perceive a reduction of SO_2 emissions when co-firing. Regardless of the usual behaviour of coal in terms of other factors accompanied with this study, the high grade coals accomplish greater reduction percentage of SO_2 when blend with woody and non-woody biomass species (Figure 4.18 and Figure 4.19) The reason for this behaviour is the S content in medium and high grade coals is higher to a certain extent (around 1.86%) than that of low grade coals. In spite of Low Volatile Bituminous which is nominated as the highest coal rank is an exceptional due to its high S content has given a same range of reduction percentage of SO_2 of Lowest grade coal, Lignite.

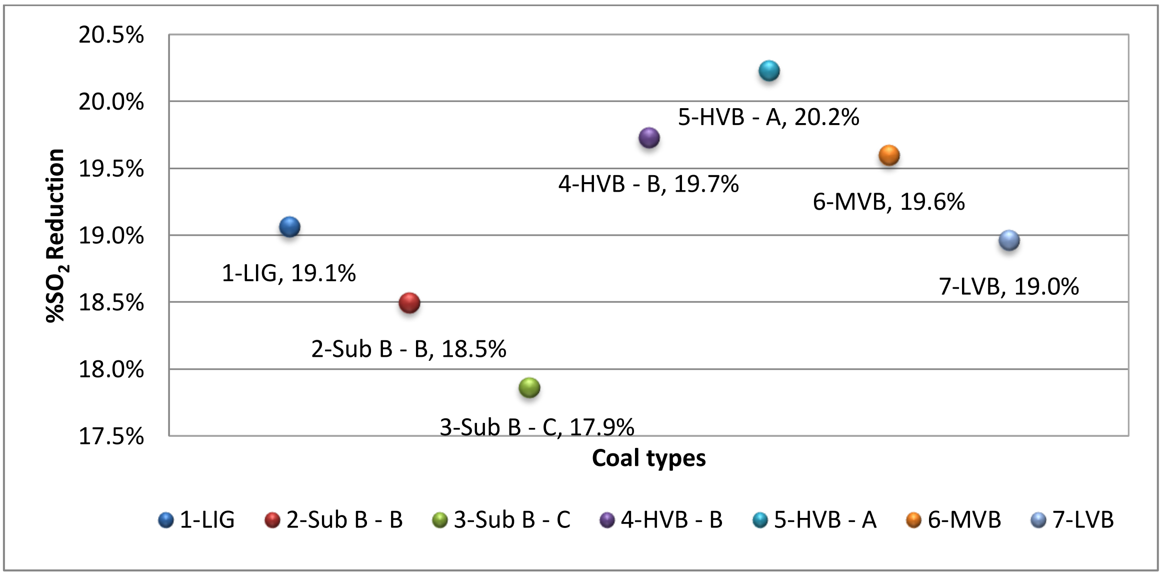


Figure 4.18 : % SO_2 reduction with woody biomass

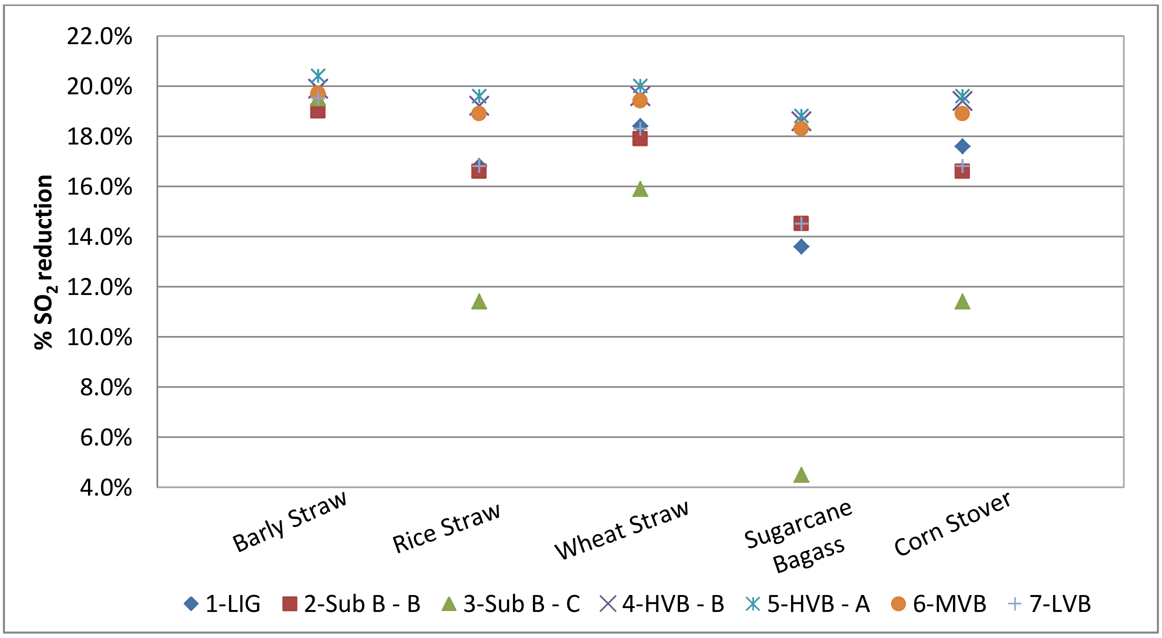


Figure 4.19 : %SO_2 reduction with non-woody biomass

4.3.5. Emission reduction factors for coal-biomass blends (gCO_{2e}/kWh)

Finally it has reached to the end of the results for predicting the emission reduction factors for co-firing biomass with coal and this is the foremost input of the carbon credits model indeed. The model development will be discussed in Chapter 6, however; a single set of emission factors at the blend ratio of 20% by weight with known boiler efficiency of 85% has been detailed in the Table 4.5.

Table 4.5 : Emission Reduction Factors for Coal-Biomass blends with 20% biomass by weight for boilers with 85% known efficiency (g CO_{2e}/kWh)

	Coal Ranks						
	LIG	**Sub B - B**	**Sub B - C**	**HVB - B**	**HVB - A**	**MVB**	**LVB**
Biomass Types							
Eucalyptus	317.62	274.89	278.10	263.45	230.42	251.99	224.29
Ailanthus	318.29	277.23	278.16	274.25	248.90	254.19	227.44
Oak wood	321.76	278.67	281.91	267.14	250.41	255.67	227.86
Black Locust	328.97	285.96	287.75	272.96	256.39	261.93	233.88
Spruce	303.02	271.46	274.96	260.49	246.27	249.14	221.73
Douglas fir	241.57	272.05	283.93	269.80	247.13	259.05	231.56
Monterey Pine	320.82	279.15	291.11	276.27	252.84	265.14	236.83
Willow wood	295.48	246.62	258.73	245.22	231.36	234.01	207.74
Switch grass	302.06	261.82	264.26	259.96	237.64	248.81	221.56
Hybrid poplar	324.11	282.64	294.13	279.35	256.00	268.69	232.05
Barley straw	320.38	216.22	217.71	205.91	192.16	199.46	179.61
Rice straw	251.85	225.86	227.11	215.99	203.90	206.07	182.84
Wheat straw	272.01	234.62	237.49	225.46	212.50	214.89	190.44
Sugar cane bagasse	308.34	267.18	269.78	264.81	242.11	244.90	218.10
Corn stover	309.79	268.34	271.00	266.25	243.41	254.84	219.37

There are a total of 105 emission factors developed for a single set as shown in the Table 4.5. Furthermore, a number of sets of emission factors (database) have been calculated during the model development and they are included in Appendix B. The each value of this table provides the amount of CO_2 eliminated by each biomass type during co-firing with coal. The database of these emission factors can be utilise in numerous ways to compare and contrast the biomass types when blended with coal targeting for maximum environmental benefits.

Chapter 5: Validation of results

This research is primarily a model based analysis, hence the evidences referred from literature has been utilized as validation parameters for verifying several important results obtained from the study. The validation parameters have been summarized below for more detail.

- **Process of coalification** – Evidence for displaying similarities in combustion characteristics of low grade coals and biomass
- **CO_2 emissions –** Comparison of calculated CO_2 emissions of respective coal ranks with available literature values
- **SO_2 emissions -** Comparison of calculated SO_2 emissions of respective coal ranks with available literature values
- **Inevitable energy loss during co-firing –** Literature evidences for predicted energy loss during co-firing

5.1. The process of coalification

The formation of coal is a process of thermal maturation of organic matter encompasses with physical and chemical changes, is defined as coalification (O'Keefe, Bechtel et al. 2013)

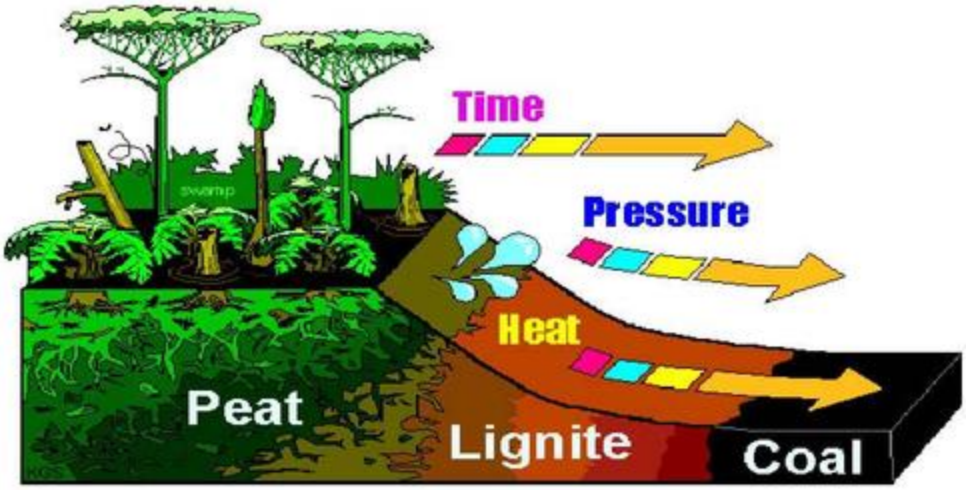


Figure 5.1 : Coalification (*https://www.quora.com/What-is-the-process-of-coalification*)

The processes of wood transformation begin with elimination of cellulose and transformation of lignin. The transformation of plant structure into coal structures through chemical formations and destructions has been carried out throughout the coalification process. It is noted that the basic plant structure of Lignin has remained unchanged up to the development of Sub-bituminous coal which is the last companion of the low grade coals (Figure 5.2and Figure 5.3). As presented in Figure 5.4. the transformation from Sub-bituminous to Bituminous (High grade coal rank) the plant structure has completely been converted into a complex and aromatic chemical structure. The aromaticity would be further increased at the formation of higher grade coals such as Semi-anthracite and Anthracite (O'Keefe, Bechtel et al. 2013). Consequently, the process of coalification has become a validating parameter of this study hence the study results have favorably displayed the similarity in combustion characteristics of low grade coals and biomass as summarised below.

- The average rate of energy output of low rank coals (lignite/sub bituminous B &C) and woody biomass (hard wood, soft wood &energy crops) has two adjacent values of 118kWh/h and 126 kWh/h respectively
- High rank coals (high volatile bituminous A&B, medium volatile bituminous and low volatile bituminous) are deviated from biomass by giving an average rate of energy output of 169 kWh/h

5.1.1. Chemical transformation of Lignin to Lignite

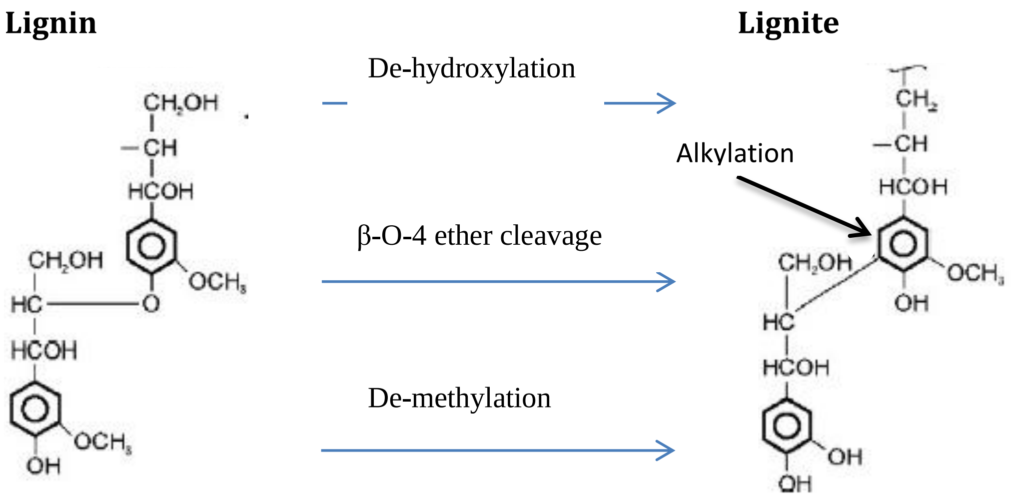


Figure 5.2 : Transformation of Lignin to Lignite (O'Keefe, Bechtel et al. 2013)

The chemical transformation of lignin to lignite is being followed with two primary cleavages of chemical bonds with alkylation of aromatic rings.

De-hydroxylation - Cleavage of aryl ether bonds (hydroxyl and methoxyl groups and β -O-4 aryl ethers)

De-methylation process - Cleavage of aryl-O bonds (methoxyl groups attached to the aromatic rings)

5.1.2. Chemical transformation of Lignite to Sub bituminous

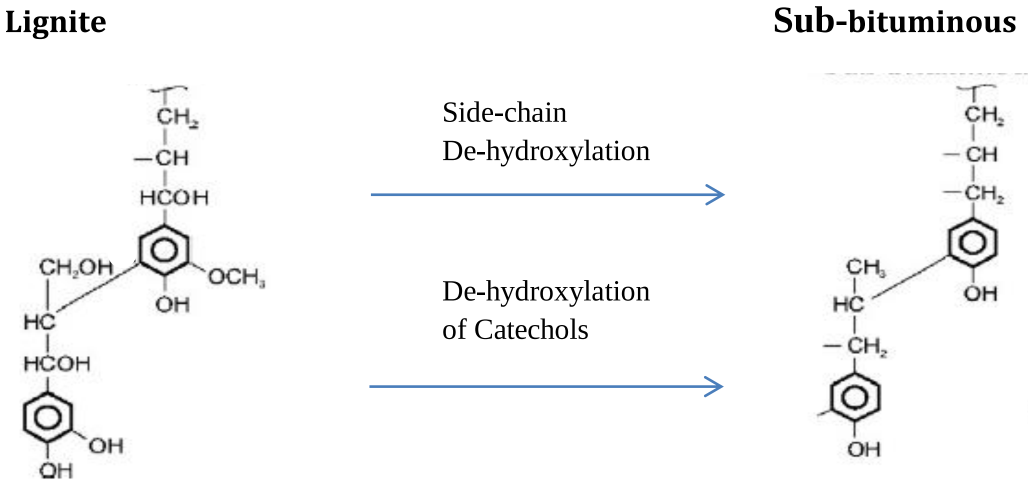


Figure 5.3 : Transformation of Lignite to Sub-bituminous (O'Keefe, Bechtel et al. 2013)

The loss of side-chain hydroxyls and de-hydroxylation of Catechols in Lignite would incline to form Sub-bituminous coal in the next step of the coalification. It is noted that the plant structure is still remained unchanged up to the formation of Sub-bituminous coal.

5.1.3. Chemical transformation of Sub bituminous to Bituminous

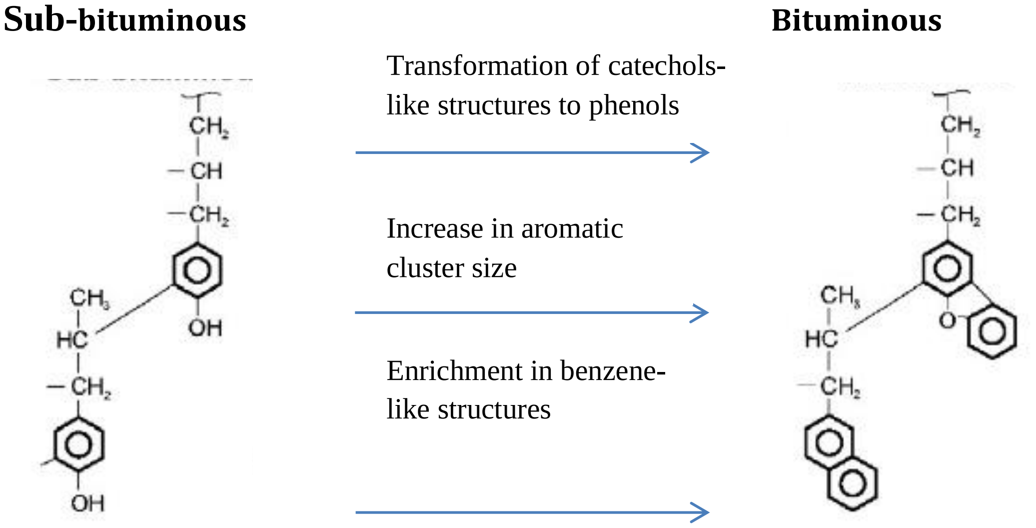


Figure 5.4 : Transformation of Sub-bituminous to Bituminous (O'Keefe, Bechtel et al. 2013)

The change of plant structure begins with progression from Sub-bituminous coal to Bituminous coal. It is possible to observe three major structural changes followed with some specific reactions as shown below.

- Transformation of catechols- like structures to phenols to form aryl ethers or dibenzofuran-like structures
- Increase in aromatic cluster size due to closure of the ring and aromatization of the alkyl side chains
- Enrichment in benzene-like structures by removing some phenolic structures forming polycyclic aromatic ring systems through condensation

Accordingly, with the increment in the coal rank the plant structure would be wiped out by complex and highly aromatic chemical structures. Though it is not highlighted in this study, the high rank coals such as Semi-anthracite and Anthracite are consistent in their highly aromatic structures.(O'Keefe, Bechtel et al. 2013).

5.2. CO_2 emissions from coal combustion

The amount of C in existence in a fuel is the primary factor which is held responsible for emitting CO_2 during its combustion. The (AP-42-Team 1995) has developed a conversion factor for calculating CO_2 emission of coal ranks per unit mass in terms of the percentage C contented in individual coal ranks. The values obtained from the study results based on the material and energy flow rates have been compared and validated with literature values.

As detailed in Table 5.1 and Table 5.2, it should be noted that the study results are realistically identical with the literature values. The percentage deviation of study results from the literature values given in Table 5.2 which indicates nonconformity of less than 1% for every coal rank.

5.2.1. Literature data of CO_2 emissions per unit mass of coal

The (AP-42-Team 1995) has specified a common conversion factor for each coal rank which is 72.6 lb CO_2/t %C. A basic formula developed for the estimation has been detailed below. The estimated values according to the formula are included in Table 5.1.

$$\frac{44\ tCO2}{12\ t\ C} \times 0.99 \times 2000 \frac{lb\ CO2}{t\ CO2} \times \frac{1}{100\%} = 72.6 \frac{lb\ CO2}{t\ \%C}$$

Where;
44 = Molecular weight of CO_2
12 = Molecular weight of C
0.99 = Fraction of the fuel oxidized during combustion

The conversion factor from lb/t to kg/t is used as 0.5.

Table 5.1 : Estimated CO_2 emissions per unit mass based on the U.S. EPA emission factor (AP-42-Team 1995)

Coal rank	% C content	kg CO_2/t coal
LIG	39.55	1435.66
Sub bituminous coal		
SUB B	50.07	1817.54
SUB C	50.23	1823.35
Bituminous coal		
HVB - B	63.75	2314.12
HVB - A	73.15	2655.34
MVB	73.39	2664.06
LVB	86.15	3127.24

5.2.2. Calculated CO_2 emissions per unit mass of coal

The material flow rates and energy flow rates obtained from the calculations have been used to evaluate the CO_2 emissions of individual coal ranks per unit mass.

Table 5.2 : Calculated CO_2 emissions per unit mass of coal (kg CO_2/tonne of coal)

Coal rank	CO_2	Q_{out} (85% boiler efficiency)	CO_2	Nonconformity with US EPA AP-42
	kg/h	kWh/h	kg/t of coal	%
LIG	144.12	103.86	1441.20	0.4%
SUB-B	182.64	124.79	1826.40	0.5%
SUB-C	183.07	123.1	1830.70	0.4%
HVB-B	233.55	152.34	2335.50	0.9%
HVB-A	267.89	170.33	2678.90	0.9%
MVB	266.71	162.62	2667.10	0.1%
LVB	312.68	188.58	3126.80	0.01%

Flow rate = 100 kg/h

5.3. SO_2 emissions from coal combustion

As highlighted in the study results, the amount of S contented in coal is directly proportionate to its SO_2 emissions. Based on this fact, the (AP-42-Team 1995) has developed an emission factor which is similarly modelled for the CO_2 emissions described in the previous section (5.2.1). In addition to that the emission factors developed by (Zhao, Wang et al. 2010) for Chinese coal power plants have also been considered for the validation of study results in terms of SO_2 emissions from coal combustion.

The percentage deviation of study results from the literature values are given in Table 5.5 has indicated the nonconformity with (AP-42-Team 1995) are comparatively lower than the percentage of nonconformity with Chinese coals. The reason is obvious that the input data of the analysis has been referred from the proximate and ultimate analysis value of US coal ranks (Vaysman and Lu 2012).

Literature data of SO_2 emissions per unit mass of coal based on the U.S. EPA emission factors:

Basically, the (AP-42-Team 1995) has declared single emission factor for Lignite coal (30S) and an emission factor range of 35S-38S for other coal ranks. With regards to the study results, the SO_2 emissions have revealed a minimum percentage of nonconformity with the emission factor of 38S and therefore this formula has been utilized for the comparison. The letter “S” is represented the amount of sulphur in coal as a percentage basis and the unit would be $lbSO_2/t$ coal. The conversion factor from lb/t to kg/t is used as 0.5.

Table 5.3 : Estimated SO_2 emissions per unit mass of coal based on the U.S. EPA emission factor (AP-42-Team 1995)

Coal rank	% S content	kg SO_2/t coal
LIG	0.63	9.4
Sub bituminous coal		
SUB-B	0.73	13.9
SUB-C	0.22	4.2
Bituminous coal		
HVB-B	2.51	47.7
HVB-A	2.36	44.8
MVB	2.29	43.5
LVB	0.66	12.5

Literature data of SO_2 emissions per unit mass of coal based on the database of emission factors for atmospheric pollutants from Chinese coal-fired power plants (Zhao, Wang et al. 2010):

The emission factor estimated for Chinese coal is 18S with the unit of kgSO_2/t coal. The developer has clearly compared their emission factors with (AP-42-Team 1995) and stated in the manuscript that the Chinese emission factors are comparatively smaller than the emission factors in US EPA AP-42 data base due to the lower heating value of Chinese coals.

Table 5.4 : SO_2 emissions per unit mass of coal of Chinese coal

Coal rank	% S content	kg SO_2/t coal
LIG	0.63	11.34
Sub bituminous coal		
SUB-B	0.73	13.14
SUB-C	0.22	3.96
Bituminous coal		
HVB-B	2.51	45.18
HVB-A	2.36	42.48
MVB	2.29	41.22
LVB	0.66	11.88

Calculated SO_2 emissions per unit mass of coal based on the current study results:

The material flow rates and energy flow rates obtained from the calculations have been used to evaluate the SO_2 emissions of individual coal ranks per unit mass.

Table 5.5 : Calculated SO_2 emissions per unit mass of coal (kg SO_2/tonne of coal)

Coal rank	**SO_2**	**Q_{out}**	**SO_2**	**Nonconformity with US EPA AP-42**	**Nonconformity with Chinese coal**
	kg/h	kWh/h	kg/t of coal		
LIG	1.25	103.86	12.5	33%	10%
SUB-B	1.45	124.79	14.5	4%	10%
SUB-C	0.44	123.1	4.4	5%	11%
HVB-B	5.01	152.34	50.1	5%	11%
HVB-A	4.74	170.33	47.4	6%	12%
MVB	4.54	162.62	45.4	4%	10%
LVB	1.31	188.58	13.1	5%	10%

Flow rate = 100 kg/h

5.4. Inevitable energy loss associated with co-firing

It is generally foreseen to experience a considerable energy loss when blending two kinds of fuels with diverse heat capacities. The fuel blend which experiences the least energy loss would be the best blend out of others if considered with other important parameters such as less environment emissions etc. However, this energy loss has been considered as a validating parameter in this study and some literature evidences would be provided as verification documents with regards to this scenario.

It is not practicable to discover same sort of fuel blends however, two types of fuel blends have been set up in Table 5.6 which are comparatively similar to two blends in the current study detailed in Table 5.7. In the current work saw dust/lignite and saw dust/bituminous blends will be compared with average value of woody biomass with same coal types and as the second comparative blend whereas rice husk will be compared with rice straw in the study with similar coal blends.

The percentage nonconformity of each blend has also been detailed in Table 5.7 both blends with bituminous coal have experienced around 60% of deviation whereas with Lignite coal is completely in the opposite characteristics where woody biomass species revealed 90% of nonconformity when rice straw has been completely in agreement with literature values.

The variation between the relative parameters of blends is mainly depending on the assumptions used in each study (in addition to the dissimilarity of biomass types). The common and additional assumptions used in the study results extracted from the literature (Mehmood, Reddy et al. 2012) and the current study has been detailed below.

The common assumptions in the both studies include:

- All components operate at steady state;
- All gases are ideal;
- Kinetic and potential energy effects are neglected;
- Ambient air is 79% nitrogen and 21% oxygen on a volume basis;

- 80% of the ash in the combusted fuel exits as fly ash, and the remainder is collected as bottom ash, which is inert;
- The bottom ash temperature is 600 °C, based on values reported for pulverized boilers with dry bottoms;
- All the carbon and sulphur in the fuel are converted to CO_2 and SO_2 respectively;
- Radiation and convective heat losses through large boilers and unburned losses due to combustibles in the ash are each 1.5% of fuel energy input;
- All the components of the steam cycle have adiabatic boundaries; and
- The isentropic efficiency for each steam turbine is 85% and for each pump is 88%.

Additional assumptions in the study results extracted from literature includes (Mehmood, Reddy et al. 2012):

- An excess air of 20% is used, based on recommendations for excess air for pulverized boilers;
- The temperature and pressure of the reference environment are 8 °C and 1.013 bar respectively;
- NO_x emissions from the combustion process are in the form of nitric oxide (NO) nitrogen dioxide (NO_2), and 96% of NO_x emissions are through the formation of NO and 4% are through NO_2 formation;
- 30% of the fuel nitrogen is converted to NO;
- 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. Fuel, thermal, and prompt NO constitute 80%, 16%, and 4% respectively of total NO formed;
- Flue gases leave the stack at 150 °C ; and
- The mechanical efficiency of each turbine and the generator efficiency are 99%, and 98% respectively.

5.4.1. Evidences from the literature for the energy loss during co-firing

The evidences for the energy loss during co-firing which obtained from the literature (Mehmood, Reddy et al. 2012) are shown in the Table 5.6. According to their results, it is precisely detailed that blend of low rank coals (lignite) with biomass (saw dust & rice husk) have a lower energy loss compared to high rank coals (bituminous) with similar types of biomass blends.

Table 5.6 : Percentage energy loss when co-firing saw dust and rice husk with lignite and bituminous coals

	Energy Output (MW)		% Energy loss	
	LIG	**Bituminous**	**LIG**	**Bituminous**
100% Coal	17.00	24.65	0%	0%
Saw dust	16.44	22.58	3%	8%
Rice husk	16.06	22.18	6%	10%

5.4.2. Predicted energy loss

The predicted energy loss according to the study results are detailed in Table 5.7. The pattern of energy loss against the type of the blends is similar to the literature evidences detailed in Table 5.6 (low ranks with lower energy loss compared to high ranks with higher energy loss) though it is not the same biomass type used for the comparison. The percentage nonconformity of each type of blend with literature values are also detailed below.

Table 5.7 : Percentage energy loss when blended with woody and non-woody biomass with coal types of Lignite & HVB-B

	Energy Output (kWh/h)		% Energy loss		% Nonconformity with literature values	
	LIG	**HVB - B**	**LIG**	**HVB-B**	**LIG**	**HVB-B**
100% Coal	103.86	152.34	0%	0%	-	-
Wood species (Average)	103.53	120.71	0.3%	21%	90%	62%
Non-woody species (Rice straw)	97.20	113.80	6%	25%	0%	60%

Chapter 6: Carbon credits model

Predicting carbon credits for PC power plants when co-fired with biomass is the ultimate objective of this current study. As per the UNFCCC definition of the carbon credits (UNFCCC 2011), One Carbon credit is equal to one tonne of CO_2e. A detail description of carbon credits and related information have been discussed in Chapter 2.

The model development was initiated with the development of emission reduction factors (ERFs - g CO_{2e}/kWh) for individual coals when co-fired with varieties of biomass species. ERFs for Coal-Biomass blends with 20% biomass by weight for boilers with 85% known efficiency have been detailed in the Table 4.5 under results and discussion. Then, series of ERFs for Coal-Biomass blends had been obtained for the range of 5-70% of biomass blend ratios. For the duration of model development a constant boiler efficiency of 85% being considered whereas the percentage blending of biomass has been used as the independent variable in order to obtain the amount of carbon credits generated per unit of energy out (tCO_2/MWh).

6.1 Model development for the prediction of carbon credits

Basically two sets of database(s) have been developed utilizing the data obtained from calculation work sheets of material and energy balances.

1) The rate of CO_2 emissions (kg/h) with the percentage variation of blend ratio of biomass with individual coal ranks
2) The rate of energy output (kWh/h) with the percentage variation of blend ratio of biomass with individual coal ranks

An example of two databases developed for the blend of biomass and Sub bituminous coal are detailed in Table 6.1 and Table 6.2 (remaining databases developed for other six biomass coal blends are included in Annex B).

The combination of these two sets of databases would be formed the required database of carbon credits per unit of energy output (tCO_2/MWh) with the percentage variation of blend ratio of biomass with individual coal ranks. An example database is given in Table 6.3 and others are included in Appendix B. It is possible to summarise this calculation into a mathematical formula as shown below.

$$\boldsymbol{CC = \frac{\dot{m}CO_2}{\dot{E}}}$$

where;

CC - Carbon credits per unit energy out (tCO_2/MWh)
$\dot{m}CO_2$ - Mass flow rate of CO_2 (kg/h or t/h)
$\dot{E}$ - Flow rate of energy output (kWh/h or MWh/h)

Table 6.1 : The database of rate of CO_2 emissions (kg/h) with the percentage variation of blend ratios of biomass with SUB B-B

	CO_2(kg/h)												
Blending-Biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
SUB B-B													
Eucalyptus	113.47	97.26	89.15	81.05	72.94	64.84	56.73	48.63	40.52	32.42	24.31	16.21	8.10
Ailanthus	114.85	98.44	90.24	82.03	73.83	65.63	57.42	49.22	41.02	32.81	24.61	16.41	8.20
Oak wood	115.99	99.42	91.14	82.85	74.57	66.28	58.00	49.71	41.43	33.14	24.86	16.57	8.29
Black Locust	117.95	101.10	92.67	84.25	75.82	67.40	58.97	50.55	42.12	33.70	25.27	16.85	8.42
Spruce	112.69	96.59	88.54	80.49	72.44	64.39	56.34	48.29	40.25	32.20	24.15	16.10	8.05
Douglas fir	113.35	97.16	89.06	80.96	72.87	64.77	56.67	48.58	40.48	32.39	24.29	16.19	8.10
Monterey Pine	115.23	98.77	90.54	82.31	74.07	65.84	57.61	49.38	41.15	32.92	24.69	16.46	8.23
Willow wood	101.01	86.58	79.37	72.15	64.94	57.72	50.51	43.29	36.08	28.86	21.65	14.43	7.22
Switch grass	107.57	92.21	84.52	76.84	69.16	61.47	53.79	46.10	38.42	30.74	23.05	15.37	7.68
Hybrid poplar	117.09	100.36	92.00	83.63	75.27	66.91	58.54	50.18	41.82	33.45	25.09	16.73	8.36
CO_2 reduction - Woody biomass avg. (kg/h)	**112.92**	**96.79**	**88.72**	**80.66**	**72.59**	**64.53**	**56.46**	**48.39**	**40.33**	**32.26**	**24.20**	**16.13**	**8.07**
Barley straw	88.11	75.52	69.23	62.93	56.64	50.35	44.05	37.76	31.47	25.17	18.88	12.59	6.29
Rice straw	88.28	75.67	69.36	63.06	56.75	50.45	44.14	37.83	31.53	25.22	18.92	12.61	6.31
Wheat straw	94.12	80.67	73.95	67.23	60.51	53.78	47.06	40.34	33.61	26.89	20.17	13.45	6.72
Sugar cane bagasse	109.93	94.22	86.37	78.52	70.67	62.82	54.96	47.11	39.26	31.41	23.56	15.70	7.85
Cone stover	110.37	94.60	86.72	78.84	70.95	63.07	55.18	47.3	39.42	31.53	23.65	15.77	7.88
CO_2 reduction - Non-woody biomass avg. (kg/h)	**98.16**	**84.14**	**77.13**	**70.12**	**63.10**	**56.09**	**49.08**	**42.07**	**35.06**	**28.04**	**21.04**	**14.02**	**7.01**

*Average values are presented in highlighted rows.

Table 6.2 : The database of rate of energy output (kWh/h) with the percentage variation of blend ratio of biomass with SUB B-B

	Rate of Energy output (kWh/h)												
Blending - biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
SUB B-B													
Eucalyptus	96.12	110.11	115.00	118.58	120.94	122.17	122.36	121.64	120.13	117.94	115.22	112.08	108.67
Ailanthus	98.79	112.23	116.86	120.19	122.31	123.31	123.30	122.39	120.69	118.35	115.49	112.25	108.74
Oak wood	96.70	111.22	116.29	120.00	122.42	123.65	123.79	122.97	121.30	118.92	115.97	112.59	108.92
Black Locust	103.90	114.79	118.47	121.05	122.60	123.19	122.92	121.87	120.15	117.85	115.09	111.97	108.61
Spruce	93.19	108.94	114.48	118.58	121.31	122.79	123.13	122.45	120.90	118.62	115.75	112.44	108.85
Douglas fir	102.60	115.28	119.56	122.56	124.36	125.06	124.76	123.57	121.63	119.06	115.99	112.55	108.88
Monterey Pine	107.90	117.43	120.55	122.64	123.78	124.04	123.49	122.23	120.34	117.93	115.10	111.95	108.59
Willow wood	93.86	108.37	113.42	117.11	119.55	120.84	121.10	120.47	119.06	117.02	114.47	111.55	108.39
Switch grass	96.90	110.60	115.30	118.69	120.86	121.92	121.98	121.16	119.59	117.41	114.74	111.72	108.47
Hybrid poplar	103.45	115.03	118.94	121.68	123.33	123.96	123.67	122.57	120.76	118.35	115.46	112.21	108.72
Energy out - Woody biomass avg. (kWh/h)	**99.34**	**112.40**	**116.89**	**120.11**	**122.15**	**123.09**	**123.05**	**122.13**	**120.46**	**118.15**	**115.33**	**112.13**	**108.68**
Barley straw	53.35	84.25	95.50	104.21	110.60	114.90	117.37	118.27	117.86	116.41	114.18	111.41	108.32
Rice straw	84.75	98.99	104.00	107.76	110.42	112.10	112.95	113.07	112.61	111.66	110.34	108.75	106.98
Wheat straw	87.23	102.67	108.09	112.13	114.92	116.58	117.24	117.05	116.12	114.61	112.63	110.31	107.76
Sugar cane bagasse	95.15	109.39	114.35	117.99	120.38	121.63	121.85	121.16	119.69	117.56	114.90	111.86	108.55
Cone stover	95.87	109.91	114.77	118.30	120.60	121.77	121.92	121.17	119.65	117.50	114.83	111.79	108.51
Energy out – Non-woody biomass avg. (kWh/h)	**83.27**	**101.04**	**107.34**	**112.08**	**115.38**	**117.40**	**118.27**	**118.14**	**117.19**	**115.55**	**113.38**	**110.82**	**108.02**

*Average values are presented in highlighted rows.

Table 6.3 : The database of carbon credits per unit energy out (tCO_2/MWh) with the percentage variation of blend ratio of biomass with SUB B-B

	Carbon credits per unit of energy out (t CO_2/MWh)												
Blending - biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
SUB B-B													
Eucalyptus	1.18	0.88	0.78	0.68	0.60	0.53	0.46	0.40	0.34	0.27	0.21	0.14	0.07
Ailanthus	1.16	0.88	0.77	0.68	0.60	0.53	0.47	0.40	0.34	0.28	0.21	0.15	0.08
Oak wood	1.20	0.89	0.78	0.69	0.61	0.54	0.47	0.40	0.34	0.28	0.21	0.15	0.08
Black Locust	1.14	0.88	0.78	0.70	0.62	0.55	0.48	0.41	0.35	0.29	0.22	0.15	0.08
Spruce	1.21	0.89	0.77	0.68	0.60	0.52	0.46	0.39	0.33	0.27	0.21	0.14	0.07
Douglas fir	1.10	0.84	0.74	0.66	0.59	0.52	0.45	0.39	0.33	0.27	0.21	0.14	0.07
Monterey Pine	1.07	0.84	0.75	0.67	0.60	0.53	0.47	0.40	0.34	0.28	0.21	0.15	0.08
Willow wood	1.08	0.80	0.70	0.62	0.54	0.48	0.42	0.36	0.30	0.25	0.19	0.13	0.07
Switch grass	1.11	0.83	0.73	0.65	0.57	0.50	0.44	0.38	0.32	0.26	0.20	0.14	0.07
Hybrid poplar	1.13	0.87	0.77	0.69	0.61	0.54	0.47	0.41	0.35	0.28	0.22	0.15	0.08
Woody biomass avg. with SUB B-B	**1.14**	**0.86**	**0.76**	**0.67**	**0.59**	**0.52**	**0.46**	**0.40**	**0.33**	**0.27**	**0.21**	**0.14**	**0.07**
Barley straw	1.65	0.90	0.72	0.60	0.51	0.44	0.38	0.32	0.27	0.22	0.17	0.11	0.06
Rice straw	1.04	0.76	0.67	0.59	0.51	0.45	0.39	0.33	0.28	0.23	0.17	0.12	0.06
Wheat straw	1.08	0.79	0.68	0.60	0.53	0.46	0.40	0.34	0.29	0.23	0.18	0.12	0.06
Sugar cane bagasse	1.16	0.86	0.76	0.67	0.59	0.52	0.45	0.39	0.33	0.27	0.21	0.14	0.07
Cone stover	1.15	0.86	0.76	0.67	0.59	0.52	0.45	0.39	0.33	0.27	0.21	0.14	0.07
Non woody biomass avg. with SUB B-B	**1.22**	**0.83**	**0.72**	**0.62**	**0.55**	**0.48**	**0.41**	**0.36**	**0.30**	**0.24**	**0.19**	**0.13**	**0.06**

*Average values are presented in highlighted rows.

In this study, an attempt has been made to create a comprehensive analysis to the interesting parties such as fuel practitioners as well as fuel planning department of utilities by developing two sets of model equations for woody and non-woody biomass species against seven coal ranks. The format of the model is a polynomial equation of degree four.

The format of the model equation:

$$y = A\,x^4 - B\,x^3 + C\,x^2 + D\,x + E$$

The A, B, C, D, E constants for woody and non-woody biomass types against coal ranks are detailed in Table 6.4 and Table 6.5 respectively.

Table 6.4 : The known constant of model equations for the blend of woody biomass and coal:

Coal rank	A	B	C	D	E
LIG	3.8003	1.6478	- 0.3868	1.6451	0.0082
SUB B-B	3.6816	2.2369	0.1110	1.3710	0.0065
SUB B-C	3.7480	2.2871	0.1389	1.3974	0.0066
HVB-B	3.3714	2.3423	- 0.0301	1.3887	0.0037
HVB-A	3.0465	2.1549	0.0206	1.2933	0.0003
MVB	3.5739	3.1659	0.4918	1.2553	0.0038
LVB	3.3135	3.3734	0.9199	1.0348	0.0045

Table 6.5 : The known constant of model equations for the blend of non-woody biomass and coal:

Coal rank	A	B	C	D	E
LIG	16.476	16.217	5.372	0.6436	0.038
SUB B-B	9.8373	9.3067	2.9788	0.8047	0.0211
SUB B-C	9.5182	8.9551	2.8552	0.8327	0.0203
HVB-B	5.4473	4.8477	1.1096	1.0635	0.0087
HVB-A	4.9493	4.6559	1.2490	0.9522	0.0078
MVB	4.8103	4.7206	1.2664	0.9816	0.0072
LVB	3.9843	4.2324	1.3869	0.8175	0.0066

6.1.1. Woody biomass with Sub bituminous coal

Either model equation or the graph is suitable for applying for the prediction of carbon credits for any of the woody biomass types for a given blend ratio (Figure 6.1).

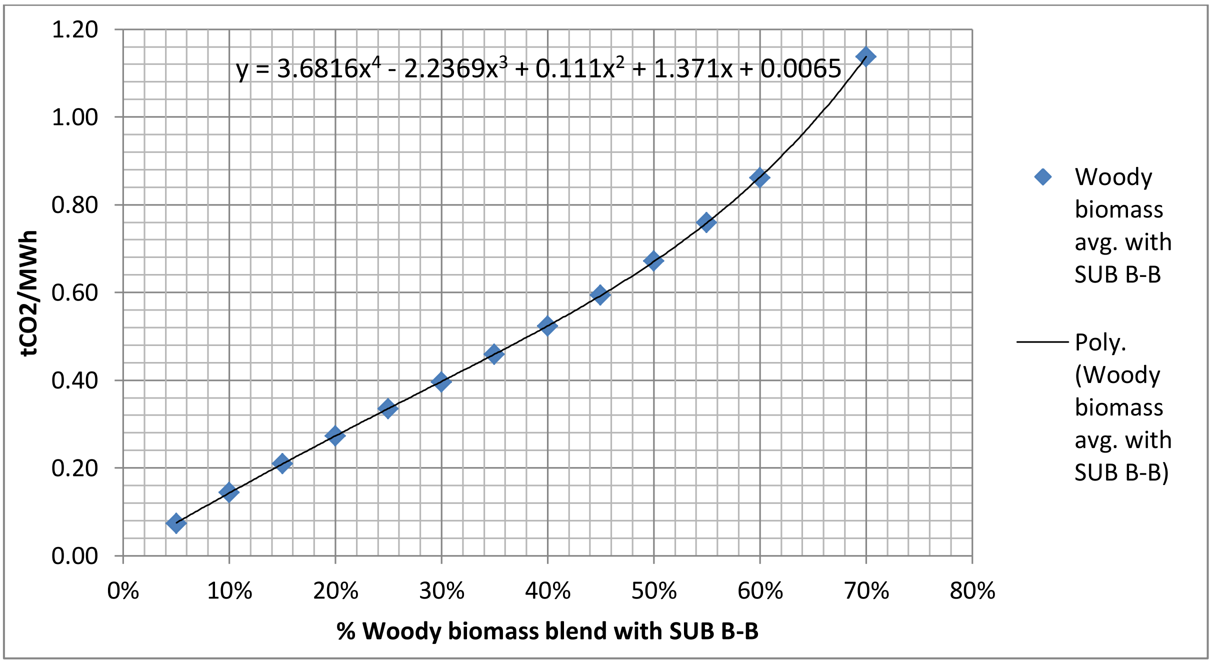


Figure 6.1 : Woody biomass with Sub bituminous–B (SUB-B)

6.1.2. Non-woody biomass with Sub bituminous coal

Hence the model equation developed for non-woody biomass was based on agricultural waste types, either the equation or the graph could be applied on predicting carbon credits for co-fired boilers which utilise any of the agricultural waste types at a given blend ratios (Figure 6.2).

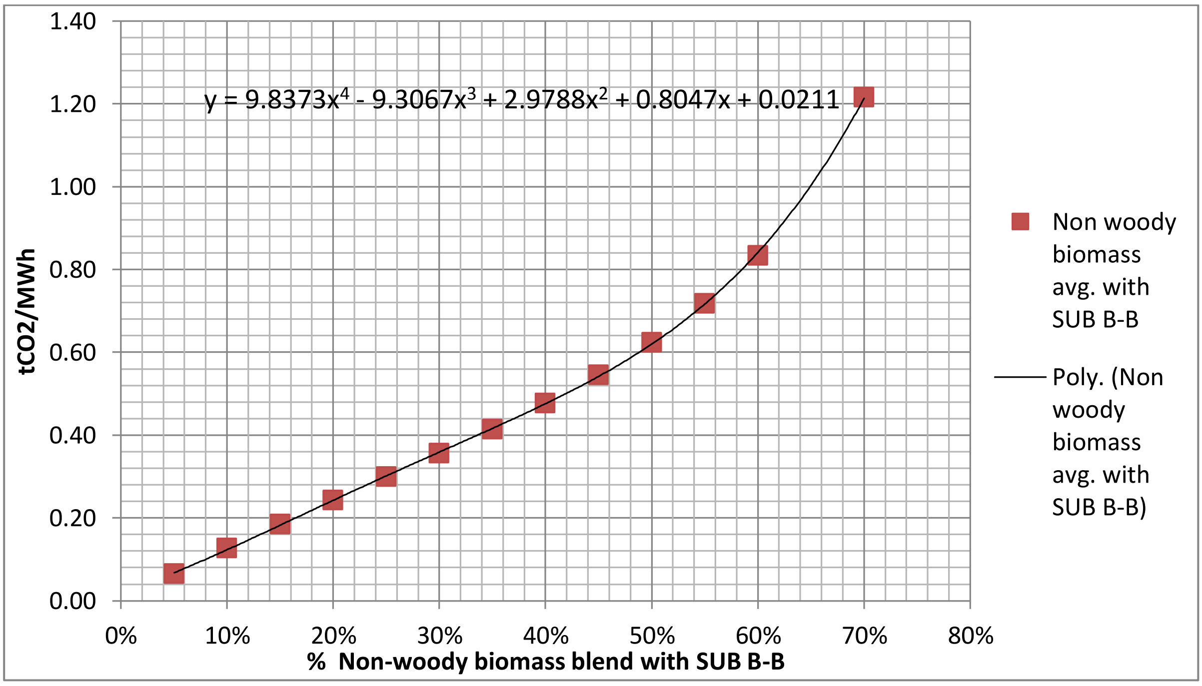


Figure 6.2 : Non-woody biomass with Sub bituminous–B (SUB-B)

It is noted that the tool is most appropriate in predicting carbon credits during the feasibility analysis stage in order to assess the project viability with or without carbon credits benefit. However, according to the UNFCCC guidelines and methodologies (UNFCCC 2011), the final carbon credits generation have to be assessed based on actual plant data and consumption values during the verification process of carbon trading techniques (CDM or JI).

6.2 Model validation

The model could be validated based on the real emissions data obtained from industry. Then the correction factors are developed accordingly.

The calculated CO_2 emissions in this study are based on seven different coal ranks. However, the correction factors are developed for coals used in two coal power plants in Queensland, Australia and South Korea.

There are some limitations are available when correlating the coals in plants with the coal ranks used in the current study. For an instance the names used for Queensland coals are specific for themselves and hence the H/C ratio being used when correlating Queensland coals with the study results. However, the secondary comparison with Korean coals is at ease since their analysis has only being based on coal types of bituminous and sub bituminous coals.

6.2.1. Correction factors for coals used in Queensland power station

The calculation of rate of CO_2 emissions (kg CO_2/MWh) in Queensland power plant being conducted based on the composition of the coal and their relative influence on combustion efficiency. These influences were mentioned in their paper as follows.

(https://www.dnrm.qld.gov.au/?a=267507)

(https://www.dnrm.qld.gov.au/?a=267503)

- Increase in coal moisture decreases combustion efficiency because of heat loss as evaporated water in the flue gas, and results in increased CO_2 emission rate for a given coal.
- Increase in ash for a given coal means that more coal must be combusted to provide the same energy output so that combustion efficiency decreases because of increased quantity of water to be evaporated (in proportion to the increased amount of coal).

- Increase in H/C ratio in the coal has a number of competing effects:
    - Boiler efficiency decreases because of the increased heat loss as water vapour from combustion of Hydrogen in the coal, thus mass flow rate of coal required increases.
    - Calorific value of the coal increases because the heat of combustion of hydrogen is much higher than the heat of combustion of carbon, thus mass flow rate of coal require decreases.
    - The relative proportion of CO_2 in the flue gas decreases.

Theoretical kgCO_2/MWh of Queensland coals detailed in Table 6.6 is based on: 20% excess combustion air, 140^0C flue gas outlet temperature, 2.5% carbon in ash, 8000MJ/MWh turbine heat rate, and 350MWe generator load.

Table 6.6 : Theoretical CO_2 emission rates from Queensland power station coals

Coal Type	H/C	kgCO_2/MWh generated
Callide	0.047	900
Curragh	0.050	830
Blackwater	0.056	830
Ipswich	0.065	825
Meandu	0.073	835
Surat	0.077	815
Moreton	0.080	835

The development of correction factors by correlating to the coals used in this study is based on the H/C ratio of each type. The H/C ratio of coal ranks used in this study is detailed in Table 6.7.

Table 6.7 : H/C ratio of coal types

Coal rank	H/C
LIG	0.069
SUB B - B	0.068
SUB B - C	0.068
HVB - B	0.071
HVB - A	0.068
MVB	0.055
LVB	0.049

The correction factors for Queensland coals are detailed in Table 6.8. According to the H/C ratio the coal types used in the plant would have more than one ranks, hence the correction factors are developed distinctly and could be used accordingly.

Table 6.8 : The correction factors for Queensland coals

The coal type in the plant	Related coal rank to the study	Correction factor
Callide	LVB	0.54
Curragh	LVB	0.50
Blackwater	MVB	0.51
Ipswich	LIG	0.59
	SUB B - B	0.56
	SUB B - C	0.55
	HVB - A	0.52
Meandu	HVB - B	0.54
Surat	HVB - B	0.53
Moreton	HVB - B	0.54

As detailed in Table 6.8 the correction factors are comparatively low for Queensland coals however the difference is mainly due to their values were based on wet coals and, the study results are based on dry coals.

It should be noted that the range of the correction factors for all coal types in Queensland power plant is a minimum value of 0.1 (from 0.5 to 0.6). Therefore; it is recommended to use any value between 0.5 and 0.6 as the correction factor for all coals in the Queensland plant at the estimation stage of the project.

6.2.2. Correction factors for coal power plants in Korea

The study conducted by (Jeon, Myeong et al. 2010) examined the characteristics of greenhouse gas emission from power plants, a major greenhouse gas source in Korea. The power plants examined use bituminous coal, anthracite, and sub-bituminous coal as fuel. For the development of correction factors for this study, only bituminous and sub-bituminous coal ranks are being considered.

As per their study, the CO_2 concentration from power plants was measured using GC–FID with methanizer. The amount of carbon, hydrogen, and calorific values in the input fuel was measured using an elemental analyzer and calorimeter.

According to their comparison with IPCC the emission factors developed in their study showed that CO_2 emission was 5.5% lower for bituminous coal, and 1.9% higher for subbituminous coal than the IPCC figures (Jeon, Myeong et al. 2010). Hence it should be noted that the correction factors would also keep this variation accordingly.

The correction factors for Korean coals are detailed in Table 6.9.

Table 6.9 : The correction factors for Korean coals

The coal rank in the plant	$kgCO_2/MWh$ from flue gas analysis	Related coal rank to the study	$kgCO_2/MWh$	Correction factor
Sub Bituminous B	295.20	SUB B - B	1463.58	0.20
Bituminous B	273.96	HVB - B	1533.08	0.18
Bituminous A	301.68	HVB - A	1572.77	0.19

The study conducted by (Jeon, Myeong et al. 2010) has completely based on the flue gas analysis and hence the correction factors for them is comparatively higher than that of Queensland coals.

Chapter 7: Practical Implications

Biomass as a fuel comprised with significant characteristics of high volatility and reactivity. Nevertheless, biomass contains comparatively less carbon (and more oxygen) and has a low heating value than fossil fuels (solids). Considering both positive and negative characteristics of biomass, it has been used as an individual fuel or blend with a primary fuel such as coal, in combustion practices. However, over the years, biomass firing technologies marked only a partial success.

The main objective of the current study is to accelerate the biomass consumption as a fuel as an alternative energy source. Burning environmental issues such as global warming and elimination of fossil resources have made a substantial influence on research and development of alternative energy fuels which are renewable.

By developing a comprehensive database of emission factors for different blends of biomass and coal types as a final outcome of this study will provide substantial information for policy makers and fuel practitioners including fuel planning department of utilities at their decision making stage of various energy projects. Additionally, some other practical implications of the study results can be summarised as shown below.

(1) For project developers who currently consume coal only and conducting some research and development on renewable alternatives will be provided with ample information to compare and contrast the energy outputs of different biomass blends.

(2) The project developers who focus on emission reduction projects in order to reduce their carbon tax and other expenses due to high emissions will be provided with substantial information of biomass types which gives higher emission reduction with lower energy loss at what percentage of blends.

(3) The other researchers, who have the study areas of coals and coal emissions, biomass and emission reductions, co-firing of biomass and coal etc., will be provided with a comprehensive database of information as and when required

Chapter 8: Conclusions & Recommendations

8.1 Conclusions

The global energy supply is primarily dependent on the fossil fuel resources. Coal holds the leadership for the power sector and its contribution is about one-third of world total primary energy supply (TPES). The risk of sole dependency on non-renewable energy sources in an unsustainable manner has been in the debate for many years. Additionally, environmental consequences due to GHG emissions during the combustion of fuels have made a turning point for conducting more research and development on sustainable energy generation at present. Among the currently available renewable energy sources such as wind, solar, hydro, nuclear energy, biomass etc., biomass has the ability to generate combined power with the existing fossil energy facilities (specially in complimenting the existing coal power plants) while incurring less capital cost. Furthermore, biomass is the world's third largest energy source after coal and oil hence, it gets more attraction than other energy sources and more research studies have been carried out for the technology advancements of biomass power generation. Moreover, biomass is a carbon neutral fuel since it is comprised with a closed loop carbon cycle. During the process of combined power generation when blending biomass with coal, it will lead to the reduction in GHG emissions and this interaction can be used for estimating carbon credits under the UNFCCC guidelines on carbon trading mechanisms.

8.1.1 Model development

The current study was focused on developing a predictive tool for estimating carbon credits in biomass-coal co-fired power plants. Ten woody biomass and five non-woody biomass blends have been considered and analysed with the seven coal ranks. Material and energy balance calculations have been carried out in order to obtain the combustion product outputs. The model development has been commenced by the development of emission reduction factors (ERFs) (Carbon credits - g CO_{2e}/kWh) for individual coals when co-fired with different types of biomass. The two main parameters have been used (the rate of CO_2 emission reduction and rate of energy output) in order to get the emission reduction factors. Then, series of ERFs for Coal-Biomass blends had been obtained for the range of 5-70% of biomass blend ratios for boilers with 85% known efficiency. These values had been used to develop the model equations for individual coals. Each coal rank has got its two model equations for woody and non-woody biomass types respectively.

8.1.2 Model results

The formulated model would allow the prediction of the potential carbon credits generated at different blend ratios of biomass during the pre-feasibility analysis stage of the project. This enable to assess the financial viability of a project with and without carbon credits benefits without further hesitation. Furthermore, the study results could be used to make a decision on selecting the most appropriate fuel blend (coal + biomass types) which gives the highest carbon credits with minimum blend energy loss. Most recommended fuel types would be discussed in the below section under the recommendations of the report.

8.1.3 Comparative results

The key results of the project was summarized in the above two sections, thus some other outputs obtained during the analysis would be concised here. Firstly, the phenomenon of energy loss when co-firing could frequently been experienced hence the blending occurred between two fuels with diverse heat capacities. However, it is noted that woody biomass had given similar range of energy output with the lower rank coals (Sub-bituminous and lignite) and thus, would end up with minimum energy loss during co-firing.

Reduction of SO_2 during co-firing was another important result obtained during co-firing. Biomass is almost free of sulphur (Contained minimum of less than 0.1%

compared to coal which contains between 0.2- 3.0%) and hence the blending would give up to 20% of SO_2 reduction.

Finally, the effect of changes in composition of the polymer structure in biomass to the amount of excess air required was analysed. The amount of Cellulose, Hemi-cellulose, and Lignite present in the biomass species are compared with the amount of excess air required during the combustion. The results showed a negative effect of the polymer structure for the air requirement.

8.1.4 Validation of results

This study is primarily a model based approach, thus the results were validated based on the previous studies which were published in the literature. The evidences were obtained from the process of coalification for verifying the similarities in combustion characteristics of low grade coals and biomass. The calculated values of CO_2 and SO_2 emissions of respective coal ranks were compared with available literature values. The highest percentage of nonconformity of the study results to the literature values obtained from US EPA AP-42 database was 0.9% for CO_2 emissions and around 4 - 6% for SO_2 emissions for all coals except lignite which has the highest difference of 33%. Furthermore, SO_2 emissions calculated in the study were compared with the emissions of Chinese coals obtained from (Zhao, Wang et al. 2010) and the nonconformity between these two values were around 10 - 12%. Additionally, previous experimental results of some of the biomass species blended with coals were provided some evidences for the inevitable energy loss when co-firing.

8.2 Recommendations

Model results indicated that lignite is the most appropriate coal type for blending with biomass since it gives the highest emission reduction (most carbon credits) of more than 20% with lowest energy loss of less than 1% with woody biomass and around 3% with non-woody types. Overall our model approach indicates that conventional boilers utilising low rank coals (Lignite and Sub bituminous) are best suited for co-firing with biomass to mitigate GHG emissions.

Furthermore, utilisation of study results would be recommended during the pre-feasibility analysis stage of the project in order to predict the potential amount of carbon credits generated for estimating the carbon credits benefits. However, it is noted that actual emission reduction units accordance with the appropriate emission trading mechanisms (in CERs under the CDM mechanism or ERUs under the JI mechanism) need to be calculated during the verification process of the carbon trading project.

Appendix - A

Case Study 01

Material balance calculation for coal - Sub Bituminous C

Data:

1) Proximate analysis

Appendix Table A.1 - Proximate analysis of coal

Components	%
C	50.23
H	3.41
O	13.55
N	0.65
S	0.22
Ash	4.50
H_2O	27.42

2) Air compositions

Appendix Table A.2 - Composition of air

Components	%
N_2	79
O_2	21

3) Molecular mass of chemical elements

Appendix Table A.3 - Molecular mass of chemical elements

Chemical element	Molecular mass
C	12.0107
H	1.0079
O	15.9994
N	14.0067
S	32.0650
H_2O	18.0152

4) Variables:

Appendix Table A.4 - Variables in the calculation

Feed rate	100	kg/h
Excess Air	19.20	%
Stack gas O_2	5	%

5) Calculation:

Appendix Table A.5 - Calculation of mole flow rates

Components	Coal (kg)	Coal (kgmol/h)	kgmol/ kg mol of coal
C	50.23	4.182	0.419
H	3.41	3.383	0.339
O	13.55	0.847	0.085
N	0.65	0.046	0.005
S	0.22	0.007	0.001
Ash	4.5		
H_2O(l)	27.42	1.522	0.152
Total	99.98	9.988	

6) Combustion reactions in the furnace

$$C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)} \quad -(1)$$
$$S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)} \quad -(2)$$
$$2H_{(s)} + {}^{1}/_{2}\, O_{2(g)} \rightarrow H_2O_{(g)} \quad -(3)$$
$$2N_{(s)} \rightarrow N_{2(g)} \quad -(4)$$
$$2O_{(s)} \rightarrow O_{2(g)} \quad -(5)$$
$$O_{2(g)} \rightarrow O_{2(g)} \quad -(6)$$

7) Stoichiometric Oxygen requirement (O_{2st})

O_2 consumption for each reaction:

Eq.(1) = Mole flow rate of C in coal = 4.182 kgmol/h

Eq.(2) = Mole flow rate of S in coal = 0.007 kgmol/h

Eq.(3) = ¼ of mole flow rate of H in coal = (3.383/4) = 0.846 kgmol/h

Eq.(4) = Zero consumption of oxygen = 0.000 kgmol/h

$$O_{2st} = \sum_{i=1}^{n} n(o_2)_{(CE)i} = (4.182 + 0.007 + 0.846 + 0.00) kgmol/h$$
$$= \mathbf{5.035\ kgmol/h}$$

8) Theoretical Oxygen requirement (O_{2req})

O_2 present in coal:

Eq.(5) = Mole flow rate of O_2 in coal = (0.847/2) = 0.424 kgmol/h

$$O_{2req} = O_{2st-} O_{2f} = (5.035 - 0.424) kgmol/h = \mathbf{4.611 kgmol/h}$$

Excess air requirement (A_{ex})

$A_{ex} = 19.20\%$

$$A_{ex} = \frac{O_{2ent-}\ O_{2req}}{O_{2req}}$$

Therefore; $O_{2ent} = \left\{(19.20\%)x\left(4.611\frac{kgmol}{h}\right)\right\} + 4.611\frac{kgmol}{h} = \mathbf{5.496 kgmol/h}$

$N_{2ent} = \left(\frac{5.496}{21}\right)x79 = \mathbf{20.675\ kgmol/h}$

9) Mass balance calculations

Nitrogen Balances:

$n_1.P = n(N_2)_f\ .FX + n(N_2)_a$

$n_1.P = \left(\frac{0.046}{2}\right)X + 20.675 \quad -(1)$

Carbon Balances:

$c_1.P = n(C)_f\ .FX$

$c_1.P = 4.182X \quad -(2)$

Sulphur Balances:

$s_1.P = n(S)_f\ .FX$

$s_1.P = 0.007X \quad -(3)$

Hydrogen Balances:

$W = n(H_2)_f\ .FX + n(H_2O)_f.F$

$W = \left(\frac{3.383}{2}\right)X + 1.522 \quad -(4)$

Oxygen Balances:

$n(O_2).P = n(O_2)_f\ .F + n(O_2)_a - nO_{2req}$

$0.05P = \left(\frac{0.847}{2}\right) + 5.496 - 4.611$

$\mathbf{P = 26.17\ kgmol/h}$

Addition of equations from (1) to (3);

$(n_1 + c_1 + s_1)P = 4.212X + 20.675$

$(1 - 0.05)x\ 26.17 = 4.212X + 20.675$

$\boldsymbol{X = 0.995}$

From eq.1: $\boldsymbol{n_1}. = \frac{\left(\frac{0.046}{2}\right)0.995+20.675}{26.17} = \boldsymbol{0.791}$

From eq.2: $\boldsymbol{c_1} = \frac{4.182\ x\ 0.995}{26.17} = \boldsymbol{0.159}$

From eq.3: $\boldsymbol{s_1} = \frac{0.007x\ 0.995}{26.17} = \boldsymbol{0.0003}$

From eq.4: $\boldsymbol{W} = \left(\frac{3.383}{2}\right)x\ 0.995 + 1.522 = \boldsymbol{3.205}$

Ash Balances:

$YR = m(AS)_f\ .F$

$YR = 4.5 \quad - (5)$

$(1 - X)F = (1 - Y)R$

$(1 - 0.995)x100 = R - YR \quad - (6)$

From eqs. (5) and (6):

$\boldsymbol{R = 5.034 kg/h}$

$\boldsymbol{Y = 0.8939}$

Energy balance calculation for coal - Sub Bituminous C

Data:

HHV of Sub Bituminous C coal = 20469 kJ/kg

Latent heat of water (L) (Hlg at 100°C and 1 atm) = 2256.1 kJ/kg = **40644.09** kJ/kgmol

Appendix Table A.6 - Standard heat of formation values of reactants and products

Reactants		
	ΔH°_f	ΔH°_c
	kJ/kgmol	kJ / kg mol
C	0	-393510
H	0	-241826
O/O_2	0	-
N/N_2	0	0
S	0	-296900
$H_2O(l)$	-285840	0
Products		
	ΔH°f	
	kJ/kgmol	
CO_2	-393510	
SO_2	-296900	
O_2	0	
N_2	0	
$H_2O(g)$	-241826	

Appendix Table A.7 - Known constant for heat capacity equations (J/mol), T in °C

Chemical element	**a**	**b**	**c**	**d**
CO_2 (g)	36.1100	4.23300×10^{-2}	$- 2.8870\times10^{-5}$	$+ 7.46400\times10^{-9}$
SO_2 (g)	38.9100	3.90400×10^{-2}	$- 3.1040\times10^{-5}$	$+ 8.60600\times10^{-9}$
O_2 (g)	29.1000	1.15800×10^{-2}	$- 0.6076\times10^{-5}$	$+ 1.31100\times10^{-9}$
N_2 (g)	29.0000	0.21990×10^{-2}	$+0.5723\times10^{-5}$	$- 2.87100\times10^{-9}$
H_2O (g)	33.4600	0.68800×10^{-2}	$+0.7604\times10^{-5}$	$+ 3.59300\times10^{-9}$
H_2O (l)	18.2964	47.2120×10^{-2}	$- 133.88\times10^{-5}$	$+ 1314.20\times10^{-9}$
H_2 (g)	28.8400	0.00765×10^{-2}	$+0.3288\times10^{-5}$	$- 0.08698x10^{-9}$
S (graphite)	15.2000	2.68000×10^{-2}	0.00000	0.00000
C (s)	11.1800	1.09500×10^{-2}	$- 4.8910\times10^{5}$	0.00000

Appendix Table A.8 - Inlet Temperatures (°C)

T°	25	°C
T_{in}	100	°C

Variables:

Appendix Table A.9 - Outlet Temperatures (°C)

T= T1	1900	°C
T= T2	2000	°C

Imported data from material balance:

kgmol per 1kg of coal = 0.0999kgmol/kg of coal

Appendix Table A.10 - Imported data from material balance

Inputs	Composition	Composition	Combusted amount (99.5%)
	kgmol/h	kgmol/kgmol coal	kgmol/h
C	4.182	0.419	4.160
H	3.383	0.339	3.365
O	0.847	0.085	0.842
N	0.046	0.005	0.046
S	0.007	0.001	0.007
H_2O(l)	1.522	0.152	1.522
O_2(air)	-	-	5.497
N_2(air)	-	-	20.678

Appendix Table A.11 -Output molar flow rate

Outputs	kgmol/h
CO_2	4.160
SO_2	0.007
O_2	1.309
N_2	20.701
H_2O(g)	3.205

Calculation:

Heat of combustion of coal

Heat of combustion of coal = (-20469) kJ/kg = (-204944) kJ/kgmol

Calculating heat of formation of coal

Fuel formula for 1kgmol of coal:

$$C_{0.419}H_{0.339}O_{0.085}N_{0.005}S_{0.001}.(H_2O)_{0.152(s)}$$

Formation equation of fuel:

$$0.419C + {}^{0.339}/_{2}\, H_{2(g)} + {}^{0.085}/_{2}\, O_{2(g)} + {}^{0.005}/_{2}\, N_{2(g)} + 0.001S_{(s)} + 0.152(H_2O)_l \rightarrow\ C_{0.419}H_{0.339}O_{0.085}N_{0.005}S_{0.001}.(H_2O)_{0.152(s)}$$

$$0.419C + 0.169H_{2(g)} + 0.042O_{2(g)} + 0.0025N_{2(g)} + 0.001S_{(s)} + 0.152(H_2O)_l \rightarrow\ C_{0.419}H_{0.339}O_{0.085}N_{0.005}S_{0.001}.(H_2O)_{0.152(s)} \quad -(1)$$

Total combustion equation of fuel:

$$C_{0.419}H_{0.339}O_{0.085}N_{0.005}S_{0.0007}.(H_2O)_{0.152(s)} + (0.419 + 0.001 + {}^{0.339}/_{4} - {}^{0.085}/_{2})O_{2(g)} \rightarrow\ 0.419CO_{2(g)} +\ 0.001SO_{2(g)} + ({}^{0.339}/_{2} + 0.152)H_2O_{(g)} + {}^{0.005}/_{2}\, N_{2(g)}$$

$$C_{0.419}H_{0.339}O_{0.085}N_{0.005}S_{0.0007}.(H_2O)_{0.152(s)} + 0.462O_{2(g)} \rightarrow\ 0.419CO_{2(g)} +\ 0.001SO_{2(g)} + 0.321H_2O_{(g)} + 0.0025N_{2(g)} \quad -(2)$$

Individual combustion equations of fuel components: - (3)

$$C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)}$$

$$S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)}$$

$$2H_{(s)} + {}^{1}/_{2}\, O_{2(g)} \rightarrow H_2O_{(g)}$$

$$2N_{(s)} \rightarrow N_{2(g)}$$

$$H_2O_{(l)} \rightarrow H_2O_{(g)}$$

Therefore; Heat of formation of coal:

From eq.(2) &(3),

$$\Delta H^{\circ}{}_{f_{\acute{c}}} = n_{(\acute{c},\acute{c})}.\Delta H^{\circ}{}_{c(\acute{c})} - \sum_{i=1}^{n} n_{(CE_i,\acute{c})} . \Delta H^{\circ}{}_{c(CE)_i}$$

$$\Delta H^{\circ}{}_{f_{\acute{c}}} = 1kgmol.(-\frac{204944kJ}{kgmol}) - \sum(\,0.419kgmolx(-393510/\text{kgmol})) + (0.001\text{kgmolx}(-296900\text{kJ/kgmol})) + ((0.169\text{kgmol})\text{x}(-241826\text{kJ/kgmol})) + ((0.0025kgmol)\text{x0kJ/kgmol}) + (0.152\text{kgmolx0kJ/kgmol})$$

$$\Delta H^{\circ}{}_{f_{\acute{c}}} = \mathbf{993.08\ kJ/kgmol}$$

Calculating sensible heats of inputs and outputs

Heat capacity equations for organic and inorganic compounds (At low pressures i.e. 1 atm)

Form 1: for CO_2, SO_2, O_2, N_2, H_2O

$$C°_p = a + b(T) + c(T)^2 + d(T)^3$$

Form 2: for C

$$C°_p = a + b(T) + c(T)^{-2}$$

E.g. Sensible heat for the formation of CO_2;

$$\Delta\widehat{H_s} = \int_{T1=25℃}^{T2} C_p . dT$$

$$\Delta\widehat{H_s} = \int_{T1=25℃}^{T2=1900℃} (a + b(T) + c(T)^2 + d(T)^3)dT$$

$$\Delta\widehat{H_s} = \int_{T1=25℃}^{T2=1900℃} (a + b(T) + c(T)^2 + d(T)^3)dT$$

$$\Delta\widehat{H_s} = \left[aT + b\left(\frac{T^2}{2}\right) + c\left(\frac{T^3}{3}\right) + d\left(\frac{T^4}{4}\right)\right]_{25}^{100}$$

Known constants from heat capacity equations for CO_2 are;

a = 36.11

$b=4.233\times10^{-2}$

$c=- 2.887\times10^{-5}$

$d=7.464\times10^{-9}$

$$\Delta\widehat{H_s} = 36.11(1900 - 25) + 4.233 \times 10^{-2}\left(\frac{(1900 - 25)^2}{2}\right) - 2.887 \times 10^{-5}\left(\frac{(1900 - 25)^3}{3}\right) + 7.464 \times 10^{-9}\left(\frac{(1900 - 25)^4}{4}\right)$$

$$\Delta\widehat{H_s} = 101742.444\ kJ/kgmol$$

Therefore sensible heat for inputs and outputs;

Appendix Table A.12 - Sensible heat of inputs

Inputs	$\Delta\widehat{H_s}$ at 100°C
	kJ/kgmol
C	7390.630
H	2163.677
O	2214.225
N	2181.967
S	1215.375
O_2	2214.225
N_2	2181.967
H_2O(l)	2522.194

Appendix Table A.13 - Sensible heat of outputs

Outputs	$\Delta\widehat{H_s}$ at 1900°C	$\Delta\widehat{H_s}$ at 2000°C
	kJ/kgmol	kJ/kgmol
CO_2	101742.444	108129.332
SO_2	99969.846	106014.283
O_2	65618.248	69441.164
N_2	61944.264	65339.418
H_2O(g)	102641.286	112694.811

Calculating net sensible heat input, output and heat of reaction at different temperatures

Net stream sensible heat input

$$\sum \Delta H_{st_{in}} = \sum \dot{n}_f \, .\Delta H°_f + \sum_{i=n1} \Delta\widehat{H_s}.\dot{n}_{fi} + \dot{n}_{H2O}.L$$

Appendix Table A.14 - Net sensible heat input

Inputs	Mole rate	ΔH_f^o	$\Delta\widehat{H_s}$ at 100°C	L	$\sum \Delta H_{st_{in}}$
	kgmol/h	kJ/kgmol	kJ/kgmol	kJ/kgmol	kJ/h
C	4.160	993.08	7390.630	0.00	48360.73
H	3.365		2163.677	0.00	
O	0.842		2214.225	0.00	
N	0.046		2181.967	0.00	
S	0.007		1215.375	0.00	
O_2	5.497	0.00	2214.225	0.00	12170.94
N_2	20.678	0.00	2181.967	0.00	45118.89
H_2O(l)	1.522	-285840.00	2522.194	40644.09	-369361.05
					-263710.489

Net stream sensible heat output at two different temperatures;

$$\sum \Delta H_{st_{out}} = \sum_{i=n1} \dot{n}_{pi} \; (\Delta \widehat{H_s} + \Delta H^{\circ}{}_f)$$

$\sum \Delta H_{st_{out}}$ at 1900°C

Appendix Table A.15 - Net sensible heat output at 1900^{0}C

Outputs	**Mole rate**	ΔH_f^o	$\Delta \widehat{H_s}$ **at 1900°C**	$\sum \Delta H_{st_{out}}$
	kgmol/h	**kJ/kgmol**	**kJ/kgmol**	**kJ/h**
CO_2	4.160	-393510.00	101742.444	-1213683.112
SO_2	0.007	-296900.00	99969.846	-1343.931
O_2	1.309	0.00	65618.248	85883.049
N_2	20.701	0.00	61944.264	1282318.207
$H_2O(g)$	3.205	-241826.00	102641.286	-446037.757
				-292863.544

$\sum \Delta H_{st_{out}}$ at 2000°C

Appendix Table A.16 - Net sensible heat output at 2000^{0}C

Outputs	**Mole rate**	ΔH_f^o	$\Delta \widehat{H_s}$ **at 2000°C**	$\sum \Delta H_{st_{out}}$
	kgmol/h	**kJ/kgmol**	**kJ/kgmol**	**kJ/h**
CO_2	4.160	-393510.00	108129.332	-1187115.189
SO_2	0.007	-296900.00	106014.283	-1302.682
O_2	1.309	0.00	69441.164	90886.591
N_2	20.701	0.00	65339.418	1352601.826
$H_2O(g)$	3.205	-241826.00	112694.811	-413819.767
				-158749.220

Heat of reaction

$$\sum \Delta(H + PE + KE) = \sum \Delta H_{st_{out}} - \sum \Delta H_{st_{in}}$$

At $T_{out} = T_1$=1900°C

$$\sum \Delta(H + PE + KE)_1 = (-292863.544 \text{ kJ/h}) - (-263710.489 \text{ kJ/h})$$

$$\sum \Delta(H + PE + KE)_1 = \boldsymbol{-29153.055 \; kJ/h}$$

When ΔPE & ΔKE are negligible;

$$\boldsymbol{\Delta H_1 = -29153.055 \; kJ/h}$$

At T_{out} = T_2=2000°C

$$\sum \Delta(H + PE + KE)_2 = (-158749.220\text{kJ/h}) - (-263710.489\text{kJ/h})$$

$$\sum \Delta(H + PE + KE)_2 = \mathbf{104961.269\ kJ/h}$$

When ΔPE & ΔKE are negligible;

$$\Delta \boldsymbol{H_2} = \mathbf{104961.269\ kJ/h}$$

Theoretical Flame temperatures

$$TFT = T_1 + (T2 - T1)\left[\frac{(0 - \Delta H_1)}{(\Delta H_1 - \Delta H_2)}\right]$$

$$TFT = 1900℃ + (2000℃ - 1900℃)\left[\frac{[0 - (-29153.055kJ/h)]}{[(-29153.055kJ/h) - (104961.269kJ/h)]}\right]$$

$$\boldsymbol{TFT} = \mathbf{1921.74}\ ℃$$

Rate of heat output

Based on the assumed actual flame temperature;

$$T_o = TFT - 400\ ℃$$
$$T_o = 1921.74℃ - 400\ ℃$$
$$\boldsymbol{T_o} = \mathbf{1521.74}℃$$
$\sum \Delta H_{st_{out}}$ at 1521.74°C

Appendix Table A.17 - Rate of heat output on actual flame temperature

Outputs	**Mole rate**	ΔH_f^o	$\Delta \widehat{H}_s$ **at 1521.74°C**	$\sum \Delta H_{st_{out}}$
	kgmol/h	**kJ/kgmol**	**kJ/kgmol**	**kJ/h**
CO_2	4.160	-393510.00	78558.932	-1310120.965
SO_2	0.007	-296900.00	78072.085	-1493.371
O_2	1.309	0.00	51379.803	67247.362
N_2	20.701	0.00	48662.868	1007377.873
H_2O(g)	3.205	-241826.00	70793.962	-548097.159
				-785086.26

Net Stream Heat – Steady-State, Open system with heat transfer at T=T$_0$

$$Q_{in} = \sum \Delta H$$

$$Q_{in} = (-785086.26 \text{ kJ/h}) - (-263710.489 \text{ kJ/h})$$

$$Q_{in} = (\mathbf{-521375.77\ kJ/h})$$

Therefore; Rate of heat output

$$Q_o = \eta \, Q_{in}$$

$$\eta = 85\%$$

$$Q_o = 85\% \, x \, (-521375.77 \text{ kJ/h})$$

$$Q_o = -443169.40 \, kJ/h$$

$$\boldsymbol{Q_o = -123.10 \, kW}$$

Appendix - B

Carbon credits model developed for the biomass blends with six other coal types (Lignite, Sub-bituminous B, High volatile bituminous A, High volatile bituminous B, Medium volatile bituminous and Low volatile bituminous) which were not included in the Chapter 6 are detailed below.

Carbon credits models developed for biomass species with LIG coal

Appendix Table B.1 - The database of rate of CO_2 emissions for biomass species with LIG coal

	CO_2(kg/h)														
Blending-biomass%	70%	60%	50%	40%	39%	38%	37%	36%	35%	30%	25%	20%	15%	10%	5%
LIG															
Eucalyptus	114.87	98.46	82.05	65.64	64.00	62.36	60.71	59.07	57.43	49.23	41.02	32.82	24.61	16.41	8.20
Ailanthus	115.51	99.00	82.50	66.00	64.35	62.70	61.05	59.40	57.75	49.50	41.25	33.00	24.75	16.50	8.25
Oak wood	117.41	100.64	83.86	67.09	65.41	63.74	62.06	60.38	58.70	50.32	41.93	33.55	25.16	16.77	8.39
Black Locust	118.86	101.88	84.90	67.92	66.22	64.52	62.83	61.13	59.43	50.94	42.45	33.96	25.47	16.98	8.49
Spruce	110.21	94.47	78.72	62.98	61.40	59.83	58.26	56.68	55.11	47.23	39.36	31.49	23.62	15.74	7.87
Douglas fir	114.26	97.94	81.61	65.29	63.66	62.03	60.39	58.76	57.13	48.97	40.81	32.65	24.48	16.32	8.16
Monterey Pine	116.06	99.48	82.90	66.32	64.66	63.00	61.34	59.69	58.03	49.74	41.45	33.16	24.87	16.58	8.29
Willow wood	106.10	90.94	75.79	60.63	59.11	57.60	56.08	54.57	53.05	45.47	37.89	30.31	22.74	15.16	7.58
Switch grass	108.73	93.20	77.66	62.13	60.58	59.02	57.47	55.92	54.36	46.60	38.83	31.07	23.30	15.53	7.77
Hybrid poplar	117.59	100.79	84.00	67.20	65.52	63.84	62.16	60.48	58.80	50.40	42.00	33.60	25.20	16.8	8.40
CO_2 reduction - Woody biomass avg. (kg/h)	**113.96**	**97.68**	**81.40**	**65.12**	**63.49**	**61.86**	**60.24**	**58.61**	**56.98**	**48.84**	**40.70**	**32.56**	**24.42**	**16.28**	**8.14**
Barley straw	88.32	75.70	63.09	50.47	49.21	47.95	46.68	45.42	44.16	37.85	31.54	25.23	18.93	12.62	6.31
Rice straw	85.69	73.45	61.21	48.97	47.74	46.52	45.30	44.07	42.85	36.73	30.60	24.48	18.36	12.24	6.12
Wheat straw	95.36	81.74	68.12	54.49	53.13	51.77	50.41	49.04	47.68	40.87	34.06	27.25	20.44	13.62	6.81
Sugar cane bagasse	111.13	95.26	79.38	63.50	61.92	60.33	58.74	57.15	55.57	47.63	39.69	31.75	23.81	15.88	7.94
Cone stover	111.57	95.63	79.69	63.75	62.16	60.57	58.97	57.38	55.79	47.82	39.85	31.88	23.91	15.94	7.97
CO_2 reduction - Non-woody biomass avg. (kg/h)	**98.41**	**84.36**	**70.30**	**56.24**	**54.83**	**53.43**	**52.02**	**50.61**	**49.21**	**42.18**	**35.15**	**28.12**	**21.09**	**14.06**	**7.03**

*Average values are in highlighted rows.

Appendix Table B.2 - The database of rate of energy out for biomass species with LIG coal

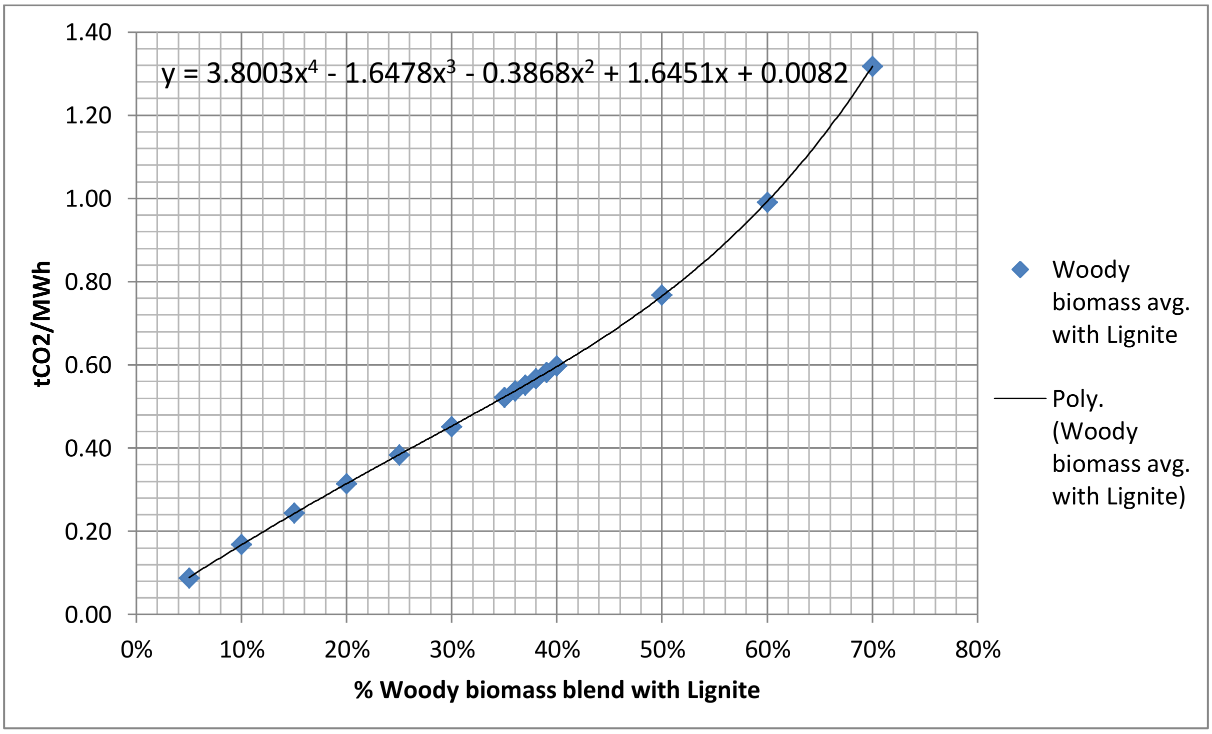
	Rate of Energy output (kWh/h)														
Blending - biomass%	70%	60%	50%	40%	39%	38%	37%	36%	35%	30%	25%	20%	15%	10%	5%
LIG															
Eucalyptus	82.87	95.95	104.27	107.99	108.12	108.21	108.26	108.27	108.23	107.48	105.81	103.33	100.14	96.38	92.17
Ailanthus	86.24	98.50	106.10	109.20	109.28	109.32	109.31	109.27	109.18	108.20	106.33	103.68	100.36	96.49	92.21
Oak wood	83.50	96.76	105.42	109.28	109.42	109.50	109.55	109.55	109.51	108.70	106.91	104.27	100.88	96.88	92.42
Black Locust	91.89	101.65	107.45	109.42	109.42	109.38	109.30	109.20	109.06	107.86	105.89	103.23	99.98	96.22	92.07
Spruce	82.49	96.33	105.09	108.96	109.09	109.18	109.22	109.22	109.17	108.34	106.56	103.92	100.57	96.64	92.29
Douglas fir	90.01	101.58	108.53	111.04	111.05	111.03	110.97	110.87	110.73	109.47	107.34	104.44	100.89	96.81	92.36
Monterey Pine	96.32	104.69	109.37	110.49	110.41	110.30	110.17	109.99	109.79	108.33	106.16	103.36	100.01	96.20	92.05
Willow wood	77.75	92.43	101.88	106.37	106.56	106.70	106.81	106.87	106.89	106.36	104.89	102.58	99.57	95.98	91.96
Switch grass	83.97	96.74	104.65	107.97	108.06	108.12	108.13	108.10	108.04	107.15	105.38	102.86	99.69	96.01	91.96
Hybrid poplar	91.48	101.80	107.94	110.05	110.05	110.02	109.94	109.84	109.69	108.46	106.42	103.67	100.3	96.43	92.18
Energy out - Woody biomass avg. (kWh/h)	**86.65**	**98.64**	**106.07**	**109.08**	**109.15**	**109.18**	**109.17**	**109.12**	**109.03**	**108.04**	**106.17**	**103.53**	**100.24**	**96.40**	**92.17**
Barley straw	35.95	66.52	87.49	99.53	100.29	100.96	101.56	102.09	102.55	103.80	103.51	101.91	99.27	95.84	91.88
Rice straw	75.15	87.68	95.52	99.26	99.43	99.57	99.67	99.75	99.79	99.56	98.66	97.20	95.27	92.97	90.40
Wheat straw	74.03	88.78	98.25	102.86	103.07	103.25	103.38	103.47	103.53	103.23	102.08	100.18	97.66	94.65	91.27
Sugar cane bagasse	82.01	95.33	103.76	107.53	107.67	107.76	107.81	107.82	107.79	107.05	105.41	102.97	99.84	96.15	92.04
Cone stover	82.77	95.87	104.11	107.70	107.82	107.90	107.93	107.93	107.88	107.08	105.39	102.91	99.76	96.08	92.00
Energy out – Non- woody biomass avg. (kWh/h)	**69.98**	**86.84**	**97.83**	**103.38**	**103.66**	**103.89**	**104.07**	**104.21**	**104.31**	**104.14**	**103.01**	**101.03**	**98.36**	**95.14**	**91.52**

*Average values are in highlighted rows.

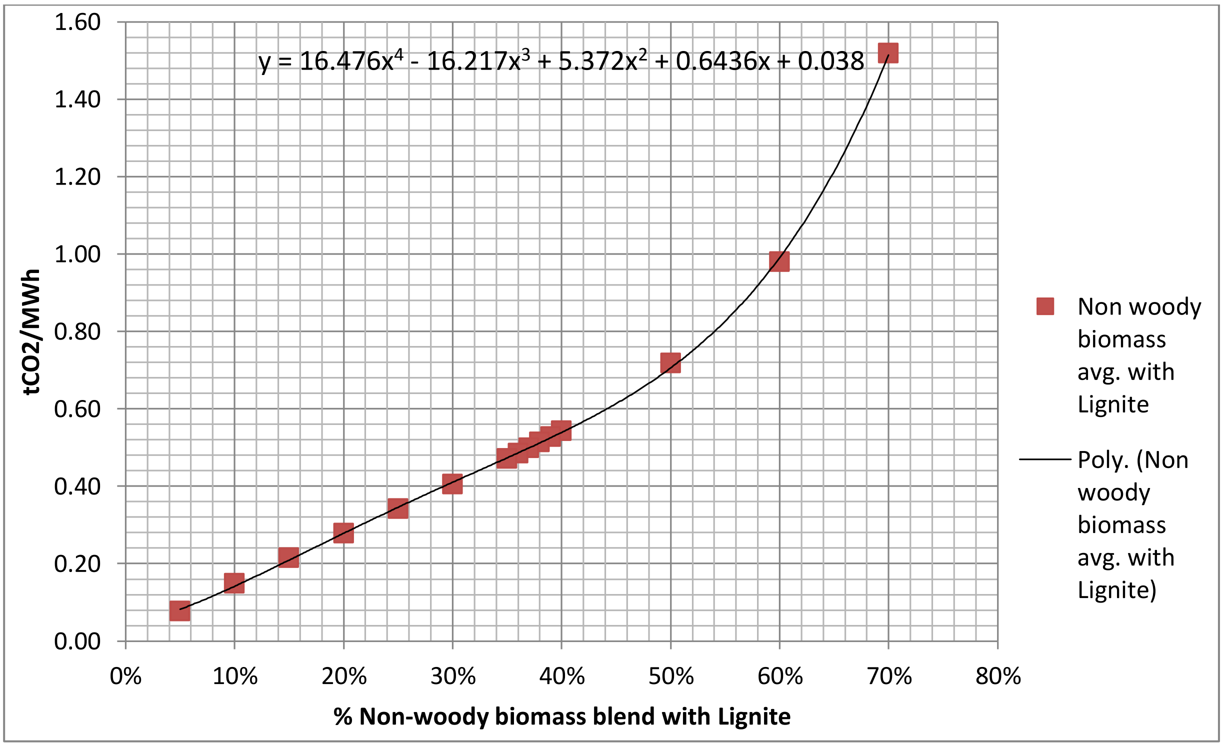
Appendix Table B.3 -The database of carbon credits per unit energy out for biomass species with LIG coal

	Carbon credits per unit of energy out (t CO_2/MWh)														
Blending-biomass%	70%	60%	50%	40%	39%	38%	37%	36%	35%	30%	25%	20%	15%	10%	5%
LIG															
Eucalyptus	1.39	1.03	0.79	0.61	0.59	0.58	0.56	0.55	0.53	0.46	0.39	0.32	0.25	0.17	0.09
Ailanthus	1.34	1.01	0.78	0.60	0.59	0.57	0.56	0.54	0.53	0.46	0.39	0.32	0.25	0.17	0.09
Oak wood	1.41	1.04	0.80	0.61	0.60	0.58	0.57	0.55	0.54	0.46	0.39	0.32	0.25	0.17	0.09
Black Locust	1.29	1.00	0.79	0.62	0.61	0.59	0.57	0.56	0.54	0.47	0.40	0.33	0.25	0.18	0.09
Spruce	1.34	0.98	0.75	0.58	0.56	0.55	0.53	0.52	0.50	0.44	0.37	0.30	0.23	0.16	0.09
Douglas fir	1.27	0.96	0.75	0.59	0.57	0.56	0.54	0.53	0.52	0.45	0.38	0.31	0.24	0.17	0.09
Monterey Pine	1.20	0.95	0.76	0.60	0.59	0.57	0.56	0.54	0.53	0.46	0.39	0.32	0.25	0.17	0.09
Willow wood	1.36	0.98	0.74	0.57	0.55	0.54	0.53	0.51	0.50	0.43	0.36	0.30	0.23	0.16	0.08
Switch grass	1.29	0.96	0.74	0.58	0.56	0.55	0.53	0.52	0.50	0.43	0.37	0.30	0.23	0.16	0.08
Hybrid poplar	1.29	0.99	0.78	0.61	0.60	0.58	0.57	0.55	0.54	0.46	0.39	0.32	0.25	0.17	0.09
Woody biomass avg. with Lignite	**1.32**	**0.99**	**0.77**	**0.60**	**0.58**	**0.57**	**0.55**	**0.54**	**0.52**	**0.45**	**0.38**	**0.31**	**0.24**	**0.17**	**0.09**
Barley straw	2.46	1.14	0.72	0.51	0.49	0.47	0.46	0.44	0.43	0.36	0.30	0.25	0.19	0.13	0.07
Rice straw	1.14	0.84	0.64	0.49	0.48	0.47	0.45	0.44	0.43	0.37	0.31	0.25	0.19	0.13	0.07
Wheat straw	1.29	0.92	0.69	0.53	0.52	0.50	0.49	0.47	0.46	0.40	0.33	0.27	0.21	0.14	0.07
Sugar cane bagasse	1.36	1.00	0.77	0.59	0.58	0.56	0.54	0.53	0.52	0.44	0.38	0.31	0.24	0.17	0.09
Cone stover	1.35	1.00	0.77	0.59	0.58	0.56	0.55	0.53	0.52	0.45	0.38	0.31	0.24	0.17	0.09
Non woody biomass avg. with Lignite	**1.52**	**0.98**	**0.72**	**0.54**	**0.53**	**0.51**	**0.50**	**0.48**	**0.47**	**0.40**	**0.34**	**0.28**	**0.21**	**0.15**	**0.08**

*Average values are in highlighted rows.



Appendix Figure B.1 -Woody biomass with Lignite (LIG)



Appendix Figure B.2 -Non-woody biomass with Lignite (LIG)

Carbon credits models developed for biomass species with SUB B-C coal

Appendix Table B.4 -The database of rate of CO_2 emissions for biomass species with SUB B-C coal

	CO_2(kg/h)												
Blending-biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
SUB B-C													
Eucalyptus	112.85	96.73	88.67	80.61	72.55	64.48	56.42	48.36	40.3	32.24	24.18	16.12	8.06
Ailanthus	113.15	96.99	88.90	80.82	72.74	64.66	56.57	48.49	40.41	32.33	24.25	16.16	8.08
Oak wood	115.33	98.85	90.62	82.38	74.14	65.90	57.66	49.43	41.19	32.95	24.71	16.48	8.24
Black Locust	116.58	99.93	91.60	83.27	74.95	66.62	58.29	49.96	41.64	33.31	24.98	16.65	8.33
Spruce	112.20	96.17	88.16	80.14	72.13	64.11	56.10	48.08	40.07	32.06	24.04	16.03	8.01
Douglas fir	116.35	99.73	91.42	83.11	74.80	66.48	58.17	49.86	41.55	33.24	24.93	16.62	8.31
Monterey Pine	118.16	101.28	92.84	84.40	75.96	67.52	59.08	50.64	42.20	33.76	25.32	16.88	8.44
Willow wood	104.31	89.41	81.96	74.51	67.06	59.61	52.16	44.71	37.25	29.80	22.35	14.9	7.45
Switch grass	106.71	91.47	83.84	76.22	68.60	60.98	53.36	45.73	38.11	30.49	22.87	15.24	7.62
Hybrid poplar	119.75	102.64	94.09	85.54	76.98	68.43	59.88	51.32	42.77	34.21	25.66	17.11	8.55
CO_2 reduction - Woody biomass avg. (kg/h)	**113.54**	**97.32**	**89.21**	**81.10**	**72.99**	**64.88**	**56.77**	**48.66**	**40.55**	**32.44**	**24.33**	**16.22**	**8.11**
Barley straw	87.35	74.87	68.63	62.39	56.15	49.91	43.67	37.43	31.20	24.96	18.72	12.48	6.24
Rice straw	87.27	74.80	68.57	62.33	56.10	49.87	43.63	37.40	31.17	24.93	18.70	12.47	6.23
Wheat straw	93.70	80.32	73.62	66.93	60.24	53.54	46.85	40.16	33.47	26.77	20.08	13.39	6.69
Sugar cane bagasse	109.10	93.51	85.72	77.93	70.14	62.34	54.55	46.76	38.96	31.17	23.38	15.59	7.79
Cone stover	109.52	93.88	86.05	78.23	70.41	62.58	54.76	46.94	39.11	31.29	23.47	15.65	7.82
CO_2 reduction - Non-woody biomass avg. (kg/h)	**97.39**	**83.48**	**76.52**	**69.56**	**62.61**	**55.65**	**48.69**	**41.74**	**34.78**	**27.82**	**20.87**	**13.92**	**6.95**

*Average values are in highlighted rows.

Appendix Table B.5 -The database of rate of energy out for biomass species with SUB B-C coal

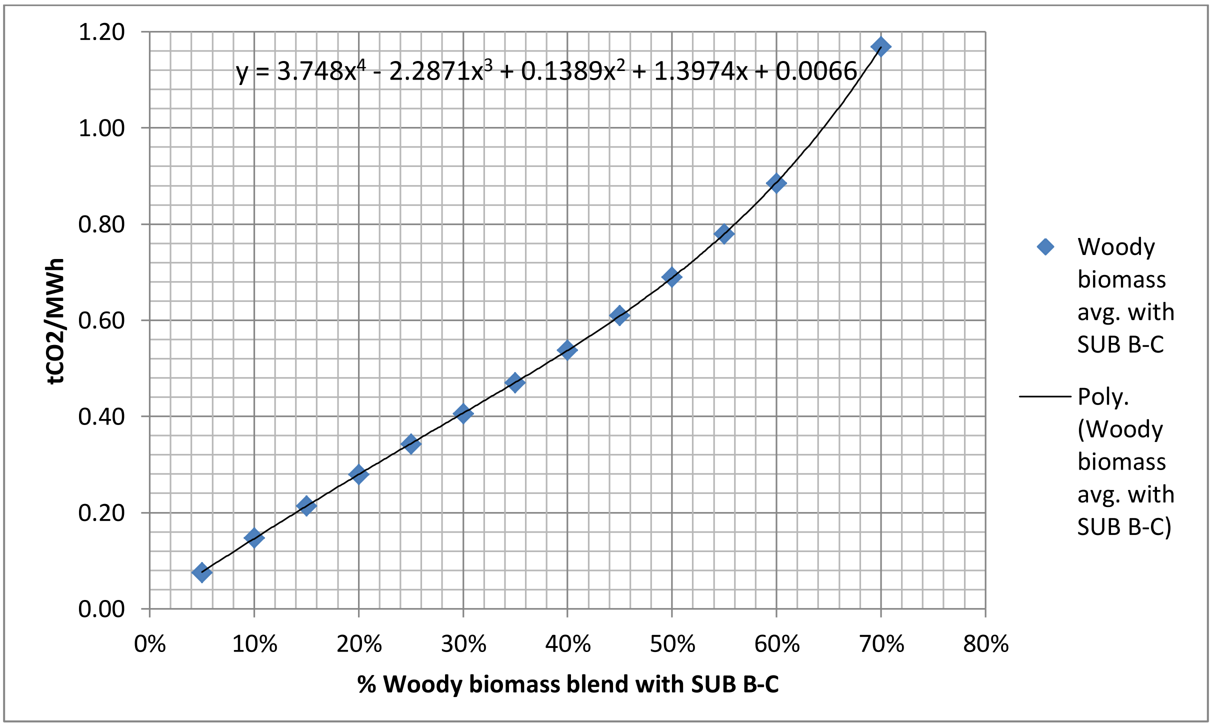
	Rate of Energy output (kWh/h)												
Blending - biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
SUB B-C													
Eucalyptus	94.77	108.21	112.91	116.37	118.66	119.86	120.08	119.42	118.00	115.93	113.33	110.33	107.05
Ailanthus	98.29	110.78	115.07	118.15	120.10	121.00	120.95	120.07	118.45	116.23	113.51	110.43	107.09
Oak wood	95.45	109.35	114.22	117.78	120.11	121.31	121.48	120.71	119.14	116.88	114.07	110.83	107.30
Black Locust	102.71	112.95	116.40	118.82	120.27	120.83	120.57	119.57	117.94	115.76	113.14	110.17	106.96
Spruce	91.93	107.08	112.42	116.38	119.03	120.48	120.84	120.22	118.77	116.60	113.86	110.69	107.23
Douglas fir	98.90	111.82	116.25	119.42	121.41	122.30	122.20	121.21	119.47	117.07	114.16	110.87	107.30
Monterey Pine	104.26	114.06	117.34	119.60	120.92	121.36	121.00	119.92	118.21	115.97	113.29	110.27	107.01
Willow wood	89.96	104.91	110.18	114.09	116.76	118.27	118.74	118.30	117.07	115.18	112.76	109.94	106.85
Switch grass	95.81	108.83	113.31	116.54	118.61	119.62	119.69	118.93	117.45	115.38	112.85	109.96	106.84
Hybrid poplar	99.83	111.6	115.64	118.54	120.35	121.17	121.07	120.16	118.54	116.31	113.60	110.50	107.13
Energy out - Woody biomass avg. (kWh/h)	**97.19**	**109.96**	**114.37**	**117.57**	**119.62**	**120.62**	**120.66**	**119.85**	**118.30**	**116.13**	**113.46**	**110.40**	**107.08**
Barley straw	53.16	83.20	94.15	102.63	108.86	113.07	115.50	116.40	116.03	114.65	112.49	109.79	106.76
Rice straw	83.88	97.45	102.23	105.83	108.39	110.04	110.88	111.04	110.64	109.77	108.55	107.06	105.38
Wheat straw	85.97	100.89	106.14	110.08	112.80	114.45	115.13	114.99	114.15	112.72	110.84	108.63	106.18
Sugar cane bagasse	94.02	107.62	112.36	115.84	118.14	119.35	119.58	118.95	117.56	115.54	113.01	110.10	106.93
Cone stover	94.77	108.13	112.77	116.14	118.34	119.47	119.62	118.93	117.50	115.46	112.93	110.03	106.88
Energy out – Non-woody biomass avg. (kWh/h)	**82.36**	**99.46**	**105.53**	**110.10**	**113.31**	**115.28**	**116.14**	**116.06**	**115.18**	**113.63**	**111.56**	**109.12**	**106.43**

*Average values are in highlighted rows.

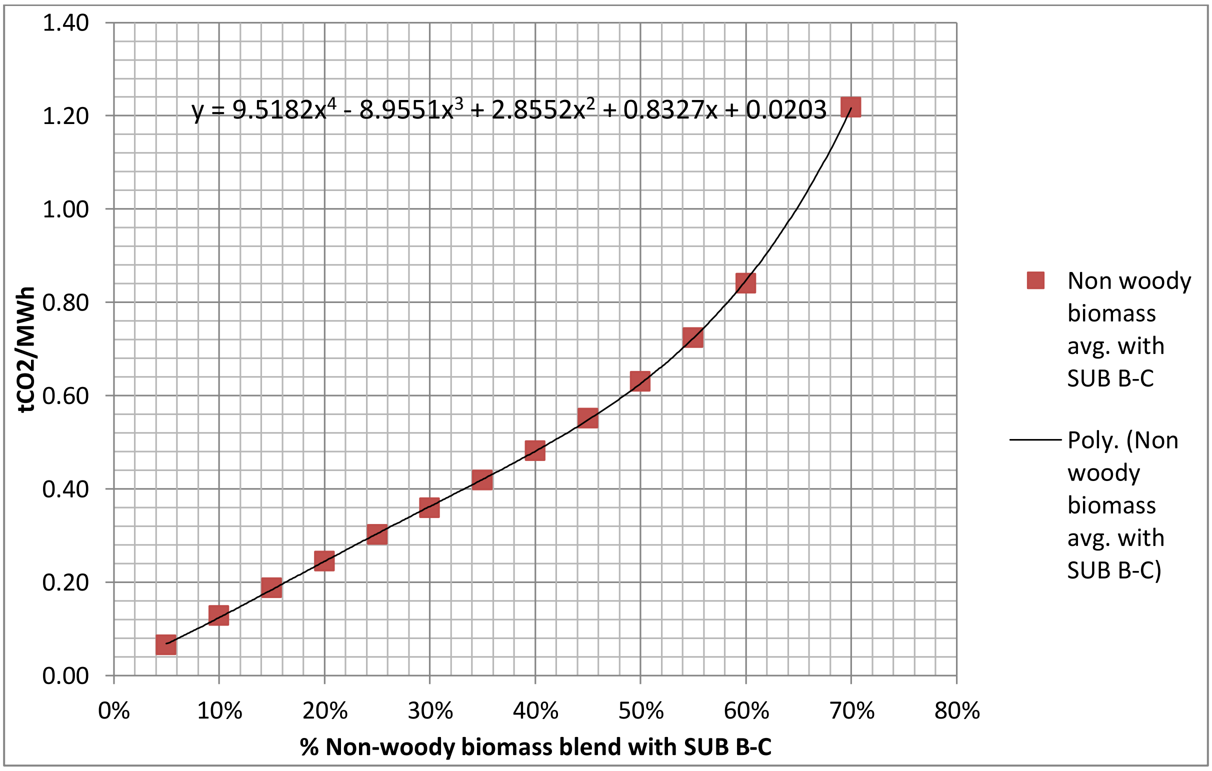
Appendix Table B.6 -The database of carbon credits per unit energy out for biomass species with SUB B-C coal

	Carbon credits per unit of energy out (t CO_2/MWh)												
Blending-biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
SUB B-C													
Eucalyptus	1.19	0.89	0.79	0.69	0.61	0.54	0.47	0.40	0.34	0.28	0.21	0.15	0.08
Ailanthus	1.15	0.88	0.77	0.68	0.61	0.53	0.47	0.40	0.34	0.28	0.21	0.15	0.08
Oak wood	1.21	0.90	0.79	0.70	0.62	0.54	0.47	0.41	0.35	0.28	0.22	0.15	0.08
Black Locust	1.14	0.88	0.79	0.70	0.62	0.55	0.48	0.42	0.35	0.29	0.22	0.15	0.08
Spruce	1.22	0.90	0.78	0.69	0.61	0.53	0.46	0.40	0.34	0.27	0.21	0.14	0.07
Douglas fir	1.18	0.89	0.79	0.70	0.62	0.54	0.48	0.41	0.35	0.28	0.22	0.15	0.08
Monterey Pine	1.13	0.89	0.79	0.71	0.63	0.56	0.49	0.42	0.36	0.29	0.22	0.15	0.08
Willow wood	1.16	0.85	0.74	0.65	0.57	0.50	0.44	0.38	0.32	0.26	0.20	0.14	0.07
Switch grass	1.11	0.84	0.74	0.65	0.58	0.51	0.45	0.38	0.32	0.26	0.20	0.14	0.07
Hybrid poplar	1.20	0.92	0.81	0.72	0.64	0.56	0.49	0.43	0.36	0.29	0.23	0.15	0.08
Woody biomass avg. with SUB B-C	**1.17**	**0.88**	**0.78**	**0.69**	**0.61**	**0.54**	**0.47**	**0.41**	**0.34**	**0.28**	**0.21**	**0.15**	**0.08**
Barley straw	1.64	0.90	0.73	0.61	0.52	0.44	0.38	0.32	0.27	0.22	0.17	0.11	0.06
Rice straw	1.04	0.77	0.67	0.59	0.52	0.45	0.39	0.34	0.28	0.23	0.17	0.12	0.06
Wheat straw	1.09	0.80	0.69	0.61	0.53	0.47	0.41	0.35	0.29	0.24	0.18	0.12	0.06
Sugar cane bagasse	1.16	0.87	0.76	0.67	0.59	0.52	0.46	0.39	0.33	0.27	0.21	0.14	0.07
Cone stover	1.16	0.87	0.76	0.67	0.59	0.52	0.46	0.39	0.33	0.27	0.21	0.14	0.07
Non woody biomass avg. with SUB B-C	**1.22**	**0.84**	**0.72**	**0.63**	**0.55**	**0.48**	**0.42**	**0.36**	**0.30**	**0.24**	**0.19**	**0.13**	**0.07**

*Average values are in highlighted rows.



Appendix Figure B.3 -Woody biomass with Sub bituminous–B (SUB B-C)



Appendix Figure B.4 -Non-woody biomass with Sub bituminous –B (SUB B-C)

Carbon credits models developed for biomass species with HVB-B coal

Appendix Table B.7 -The database of rate of CO_2 emissions for biomass species with HVB-B coal

	CO_2(kg/h)												
Blending-biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
HVB - B													
Eucalyptus	111.26	95.36	87.42	79.47	71.52	63.58	55.63	47.68	39.74	31.79	23.84	15.89	7.95
Ailanthus	115.98	99.41	91.12	82.84	74.56	66.27	57.99	49.70	41.42	33.14	24.85	16.57	8.28
Oak wood	113.70	97.46	89.33	81.21	73.09	64.97	56.85	48.73	40.61	32.49	24.36	16.24	8.12
Black Locust	114.95	98.53	90.32	82.11	73.90	65.69	57.48	49.27	41.06	32.84	24.63	16.42	8.21
Spruce	110.61	94.80	86.90	79.00	71.10	63.20	55.30	47.40	39.50	31.60	23.70	15.80	7.90
Douglas fir	114.71	98.32	90.13	81.94	73.74	65.55	57.36	49.16	40.97	32.77	24.58	16.39	8.19
Monterey Pine	116.52	99.87	91.55	83.23	74.90	66.58	58.26	49.94	41.61	33.29	24.97	16.65	8.32
Willow wood	102.84	88.14	80.80	73.45	66.11	58.76	51.42	44.07	36.73	29.38	22.04	14.69	7.35
Switch grass	109.13	93.54	85.75	77.95	70.16	62.36	54.57	46.77	38.98	31.18	23.39	15.59	7.80
Hybrid poplar	118.09	101.22	92.78	84.35	75.91	67.48	59.04	50.61	42.17	33.74	25.30	16.87	8.43
CO_2 reduction - Woody biomass avg. (kg/h)	**112.78**	**96.67**	**88.61**	**80.56**	**72.50**	**64.44**	**56.39**	**48.33**	**40.28**	**32.22**	**24.17**	**16.11**	**8.06**
Barley straw	86.08	73.79	67.64	61.49	55.34	49.19	43.04	36.89	30.74	24.60	18.45	12.30	6.15
Rice straw	86.03	73.74	67.60	61.45	55.31	49.16	43.02	36.87	30.73	24.58	18.44	12.29	6.15
Wheat straw	92.37	79.17	72.58	65.98	59.38	52.78	46.19	39.59	32.99	26.39	19.79	13.20	6.60
Sugar cane bagasse	111.54	95.60	87.64	79.67	71.70	63.74	55.77	47.80	39.83	31.87	23.90	15.93	7.97
Cone stover	111.98	95.98	87.98	79.99	71.99	63.99	55.99	47.99	39.99	31.99	24.00	16.00	8.00
CO_2 reduction - Non-woody biomass avg. (kg/h)	**97.60**	**83.66**	**76.69**	**69.72**	**62.74**	**55.77**	**48.80**	**41.83**	**34.86**	**27.89**	**20.92**	**13.94**	**6.97**

*Average values are in highlighted rows.

Appendix Table B.8 -The database of rate of energy out for biomass species with HVB-B coal

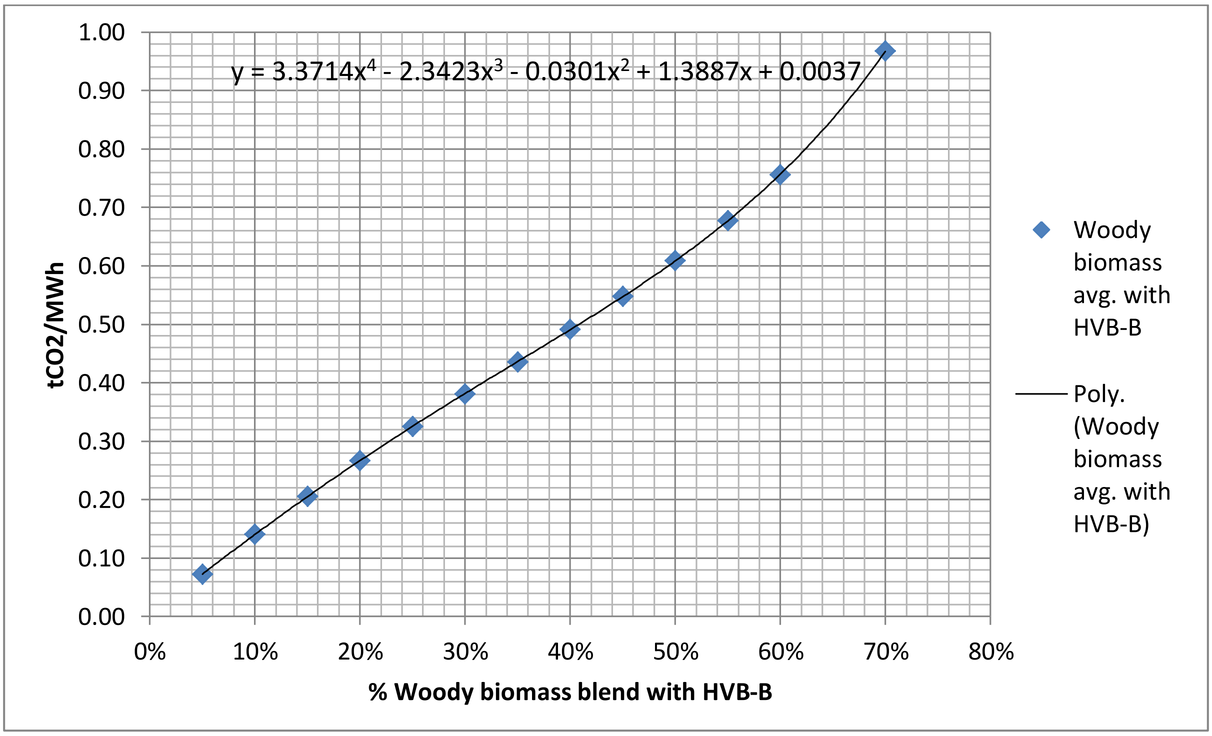
	Rate of Energy output (kWh/h)												
Blending - biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
HVB - B													
Eucalyptus	114.89	126.73	129.88	131.47	131.72	130.86	129.11	126.69	123.81	120.67	117.47	114.36	111.50
Ailanthus	115.85	127.70	130.79	132.29	132.43	131.45	129.58	127.04	124.06	120.84	117.58	114.42	111.52
Oak wood	116.28	128.55	131.80	133.42	133.63	132.66	130.74	128.12	125.01	121.62	118.16	114.80	111.70
Black Locust	120.38	129.26	131.38	132.21	131.91	130.70	128.75	126.25	123.38	120.31	117.21	114.21	111.43
Spruce	113.62	126.95	130.57	132.45	132.85	132.03	130.22	127.67	124.63	121.31	117.91	114.63	111.61
Douglas fir	119.21	130.37	133.15	134.35	134.21	132.97	130.85	128.08	124.88	121.46	118.00	114.68	111.64
Monterey Pine	121.62	130.12	132.09	132.79	132.40	131.11	129.09	126.53	123.61	120.50	117.34	114.29	111.48
Willow wood	110.91	123.97	127.53	129.43	129.93	129.27	127.70	125.45	122.75	119.81	116.80	113.91	111.27
Switch grass	113.69	125.81	128.98	130.56	130.79	129.91	128.16	125.77	122.97	119.94	116.89	113.96	111.29
Hybrid poplar	119.08	129.26	131.79	132.87	132.71	131.54	129.56	126.97	123.98	120.78	117.54	114.41	111.53
Energy out - Woody biomass avg. (kWh/h)	**116.55**	**127.87**	**130.80**	**132.18**	**132.26**	**131.25**	**129.38**	**126.86**	**123.91**	**120.72**	**117.49**	**114.37**	**111.50**
Barley straw	84.74	111.11	119.06	124.14	126.82	127.56	126.81	124.96	122.40	119.47	116.44	113.57	111.05
Rice straw	102.22	113.36	116.39	118.10	118.75	118.60	117.84	116.68	115.29	113.80	112.34	111.00	109.87
Wheat straw	106.18	118.87	122.33	124.23	124.85	124.43	123.23	121.47	119.35	117.05	114.74	112.56	110.62
Sugar cane bagasse	112.22	125.06	128.55	130.41	130.86	130.15	128.52	126.19	123.4	120.35	117.22	114.19	111.41
Cone stover	112.83	125.39	128.75	130.49	130.84	130.05	128.36	126.00	123.19	120.15	117.06	114.08	111.36
Energy out – Non-woody biomass avg. (kWh/h)	**103.64**	**118.76**	**123.02**	**125.47**	**126.42**	**126.16**	**124.95**	**123.06**	**120.73**	**118.16**	**115.56**	**113.08**	**110.86**

*Average values are in highlighted rows.

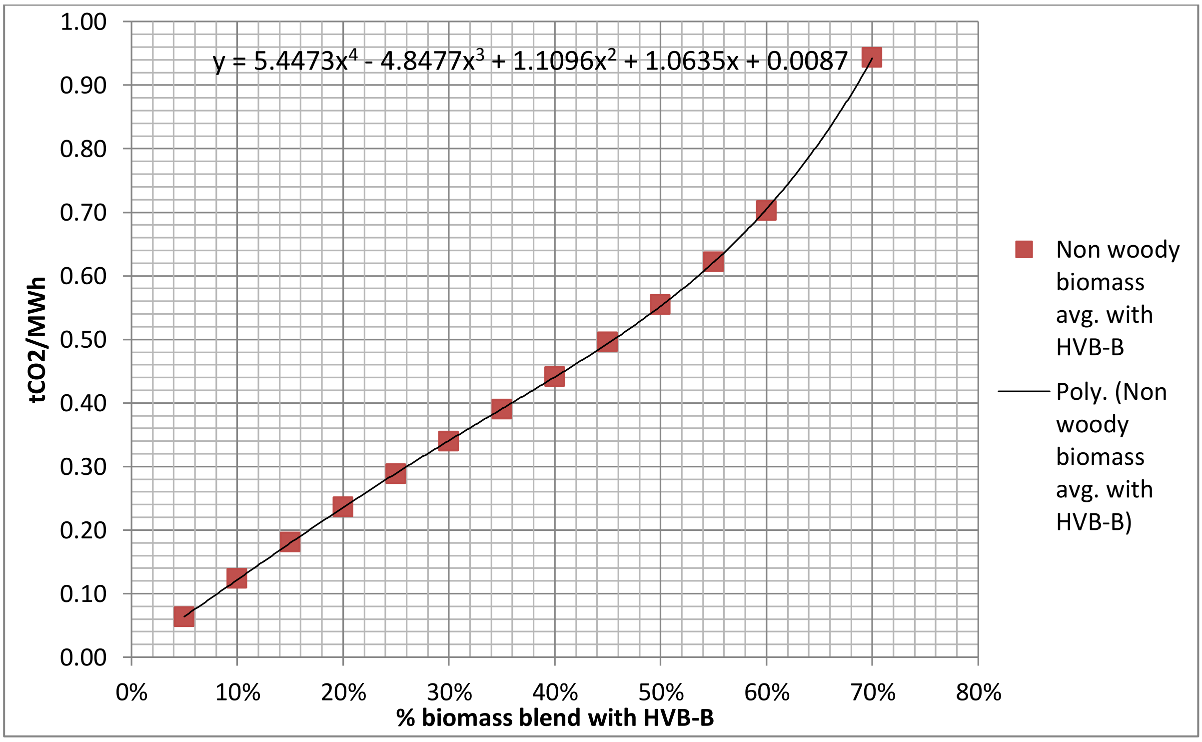
Appendix Table B.9 -The database of carbon credits per unit energy out for biomass species with HVB-B coal

	Carbon credits per unit of energy out (t CO_2/MWh)												
Blending - biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
HVB - B													
Eucalyptus	0.97	0.75	0.67	0.60	0.54	0.49	0.43	0.38	0.32	0.26	0.20	0.14	0.07
Ailanthus	1.00	0.78	0.70	0.63	0.56	0.50	0.45	0.39	0.33	0.27	0.21	0.14	0.07
Oak wood	0.98	0.76	0.68	0.61	0.55	0.49	0.43	0.38	0.32	0.27	0.21	0.14	0.07
Black Locust	0.95	0.76	0.69	0.62	0.56	0.50	0.45	0.39	0.33	0.27	0.21	0.14	0.07
Spruce	0.97	0.75	0.67	0.60	0.54	0.48	0.42	0.37	0.32	0.26	0.20	0.14	0.07
Douglas fir	0.96	0.75	0.68	0.61	0.55	0.49	0.44	0.38	0.33	0.27	0.21	0.14	0.07
Monterey Pine	0.96	0.77	0.69	0.63	0.57	0.51	0.45	0.39	0.34	0.28	0.21	0.15	0.07
Willow wood	0.93	0.71	0.63	0.57	0.51	0.45	0.40	0.35	0.30	0.25	0.19	0.13	0.07
Switch grass	0.96	0.74	0.66	0.60	0.54	0.48	0.43	0.37	0.32	0.26	0.20	0.14	0.07
Hybrid poplar	0.99	0.78	0.70	0.63	0.57	0.51	0.46	0.40	0.34	0.28	0.22	0.15	0.08
Woody biomass avg. with HVB-B	**0.97**	**0.76**	**0.68**	**0.61**	**0.55**	**0.49**	**0.44**	**0.38**	**0.33**	**0.27**	**0.21**	**0.14**	**0.07**
Barley straw	1.02	0.66	0.57	0.50	0.44	0.39	0.34	0.30	0.25	0.21	0.16	0.11	0.06
Rice straw	0.84	0.65	0.58	0.52	0.47	0.41	0.37	0.32	0.27	0.22	0.16	0.11	0.06
Wheat straw	0.87	0.67	0.59	0.53	0.48	0.42	0.37	0.33	0.28	0.23	0.17	0.12	0.06
Sugar cane bagasse	0.99	0.76	0.68	0.61	0.55	0.49	0.43	0.38	0.32	0.26	0.20	0.14	0.07
Cone stover	0.99	0.77	0.68	0.61	0.55	0.49	0.44	0.38	0.32	0.27	0.21	0.14	0.07
Non woody biomass avg. with HVB-B	**0.94**	**0.70**	**0.62**	**0.55**	**0.50**	**0.44**	**0.39**	**0.34**	**0.29**	**0.24**	**0.18**	**0.12**	**0.06**

*Average values are in highlighted rows.



Appendix Figure B.5 -Woody biomass with High volatile Bituminous–B (HVB-B)



Appendix Figure B.6 -Non-woody biomass with High volatile Bituminous–B (HVB-B)

Carbon credits models developed for biomass species with HVB-A coal

Appendix Table B.10 -The database of rate of CO_2 emissions for biomass species with HVB-A coal

	CO_2(kg/h)												
Blending-biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
HVB - A													
Eucalyptus	106.10	90.94	83.36	75.78	68.20	60.63	53.05	45.47	37.89	30.31	22.73	15.16	7.58
Ailanthus	115.01	98.58	90.36	82.15	73.93	65.72	57.50	49.29	41.07	32.86	24.64	16.43	8.21
Oak wood	116.55	99.90	91.58	83.25	74.93	66.6	58.28	49.95	41.63	33.30	24.98	16.65	8.33
Black Locust	118.24	101.35	92.90	84.46	76.01	67.57	59.12	50.67	42.23	33.78	25.34	16.89	8.45
Spruce	113.29	97.11	89.01	80.92	72.83	64.74	56.64	48.55	40.46	32.37	24.28	16.18	8.09
Douglas fir	113.64	97.41	89.29	81.17	73.06	64.94	56.82	48.70	40.59	32.47	24.35	16.23	8.12
Monterey Pine	115.48	98.98	90.73	82.48	74.24	65.99	57.74	49.49	41.24	32.99	24.75	16.50	8.25
Willow wood	105.22	90.19	82.67	75.15	67.64	60.12	52.61	45.09	37.58	37.58	22.55	15.03	7.52
Switch grass	108.01	92.58	84.86	77.15	69.43	61.72	54.00	46.29	38.57	30.86	23.14	15.43	7.71
Hybrid poplar	117.17	100.43	92.06	83.69	75.32	66.95	58.58	50.21	41.84	33.48	25.11	16.74	8.37
CO_2 reduction - Woody biomass avg. (kg/h)	**112.87**	**96.75**	**88.68**	**80.62**	**72.56**	**64.50**	**56.43**	**48.37**	**40.31**	**33.00**	**24.19**	**16.12**	**8.06**
Barley straw	86.93	74.51	68.30	62.09	55.88	49.67	43.46	37.25	31.05	24.84	18.63	12.42	6.21
Rice straw	88.51	75.86	69.54	63.22	56.90	50.58	44.25	37.93	31.61	25.29	18.97	12.64	6.32
Wheat straw	94.62	81.10	74.35	67.59	60.83	54.07	47.31	40.55	33.79	27.03	20.28	13.52	6.76
Sugar cane bagasse	110.38	94.61	86.73	78.84	70.96	63.08	55.19	47.31	39.42	31.54	23.65	15.77	7.88
Cone stover	110.82	94.99	87.07	79.16	71.24	63.33	55.41	47.50	39.58	31.66	23.75	15.83	7.92
CO_2 reduction - Non-woody biomass avg. (kg/h)	**98.25**	**84.21**	**77.20**	**70.18**	**63.16**	**56.15**	**49.12**	**42.11**	**35.09**	**28.07**	**21.06**	**14.04**	**7.02**

*Average values are in highlighted rows.

Appendix Table B.11 -The database of rate of rate of energy out for biomass species with HVB-A coal

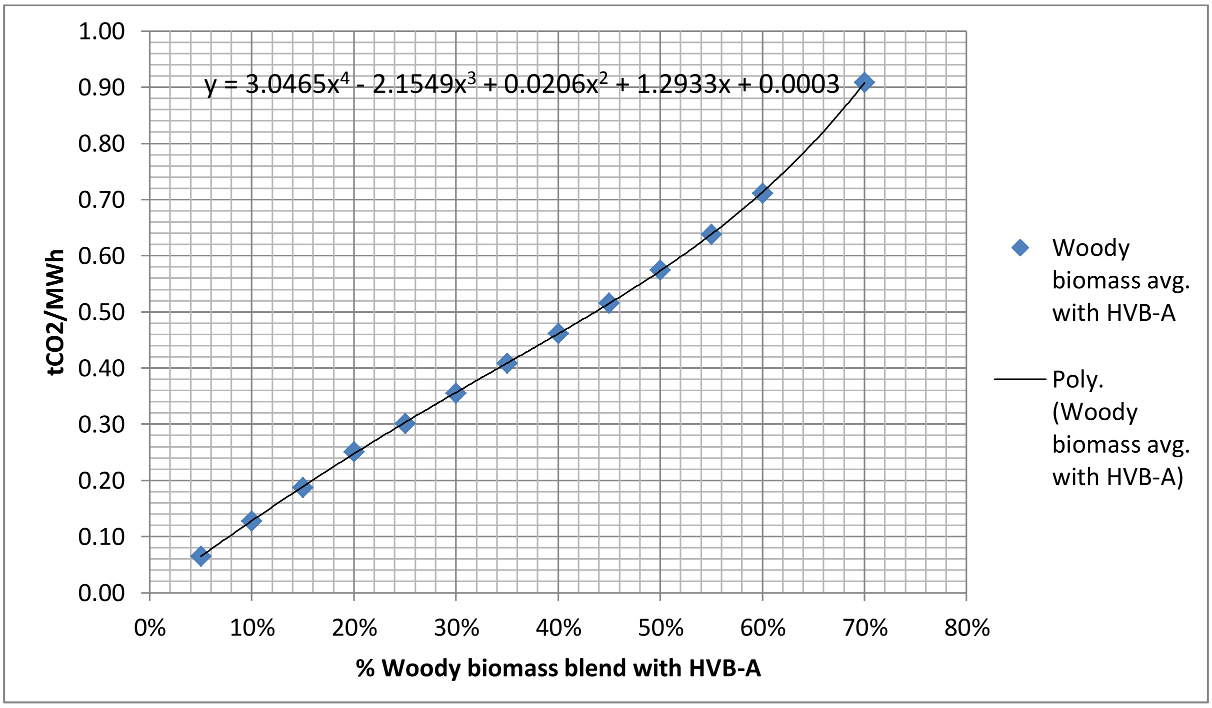
	Rate of Energy output (kWh/h)												
Blending - biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
HVB - A													
Eucalyptus	124.74	136.00	138.89	140.32	140.53	139.78	138.30	136.30	133.99	131.54	129.11	126.82	124.81
Ailanthus	123.95	136.26	139.46	141.08	141.38	140.64	139.12	137.03	134.60	132.02	129.46	127.05	124.91
Oak wood	122.61	136.29	139.99	141.98	142.54	141.94	140.45	138.31	135.75	132.98	130.19	127.53	125.14
Black Locust	126.33	136.70	139.34	140.62	140.76	139.98	138.49	136.51	134.21	131.75	129.30	126.97	124.89
Spruce	120.66	134.66	138.41	140.40	140.94	140.31	138.8	136.67	134.14	131.44	128.74	126.22	124.00
Douglas fir	127.64	138.61	141.24	142.34	142.19	141.06	139.19	136.82	134.16	131.39	128.69	126.18	123.99
Monterey Pine	129.29	137.83	139.79	140.52	140.22	139.13	137.43	135.31	132.94	130.48	128.07	125.82	123.83
Willow wood	117.95	131.56	135.24	137.25	137.89	137.46	136.21	134.40	132.24	129.93	127.63	125.50	123.66
Switch grass	122.19	134.03	137.03	138.49	138.70	137.94	136.45	134.48	132.22	129.86	127.56	125.45	123.63
Hybrid poplar	127.22	137.35	139.79	140.83	140.71	139.68	137.97	135.79	133.34	130.78	128.27	125.93	123.88
Energy out - Woody biomass avg. (kWh/h)	**124.26**	**135.93**	**138.92**	**140.38**	**140.59**	**139.79**	**138.24**	**136.16**	**133.76**	**131.22**	**128.70**	**126.35**	**124.27**
Barley straw	95.15	120.72	128.14	132.76	135.13	135.76	135.11	133.58	131.53	129.27	127.03	125.01	123.37
Rice straw	108.47	120.25	123.50	125.45	126.40	126.61	126.30	125.66	124.86	124.03	123.27	122.68	122.30
Wheat straw	113.02	126.20	129.79	131.83	132.64	132.50	131.68	130.39	128.84	127.20	125.61	124.18	123.02
Sugar cane bagasse	120.90	133.46	136.76	138.48	138.89	138.27	136.88	134.94	132.67	130.27	127.89	125.68	123.75
Cone stover	121.49	133.75	136.92	138.52	138.83	138.14	136.69	134.73	132.46	130.07	127.73	125.56	123.69
Energy out – Non-woody biomass avg. (kWh/h)	**111.81**	**126.88**	**131.02**	**133.41**	**134.38**	**134.26**	**133.33**	**131.86**	**130.07**	**128.17**	**126.31**	**124.62**	**123.23**

*Average values are in highlighted rows.

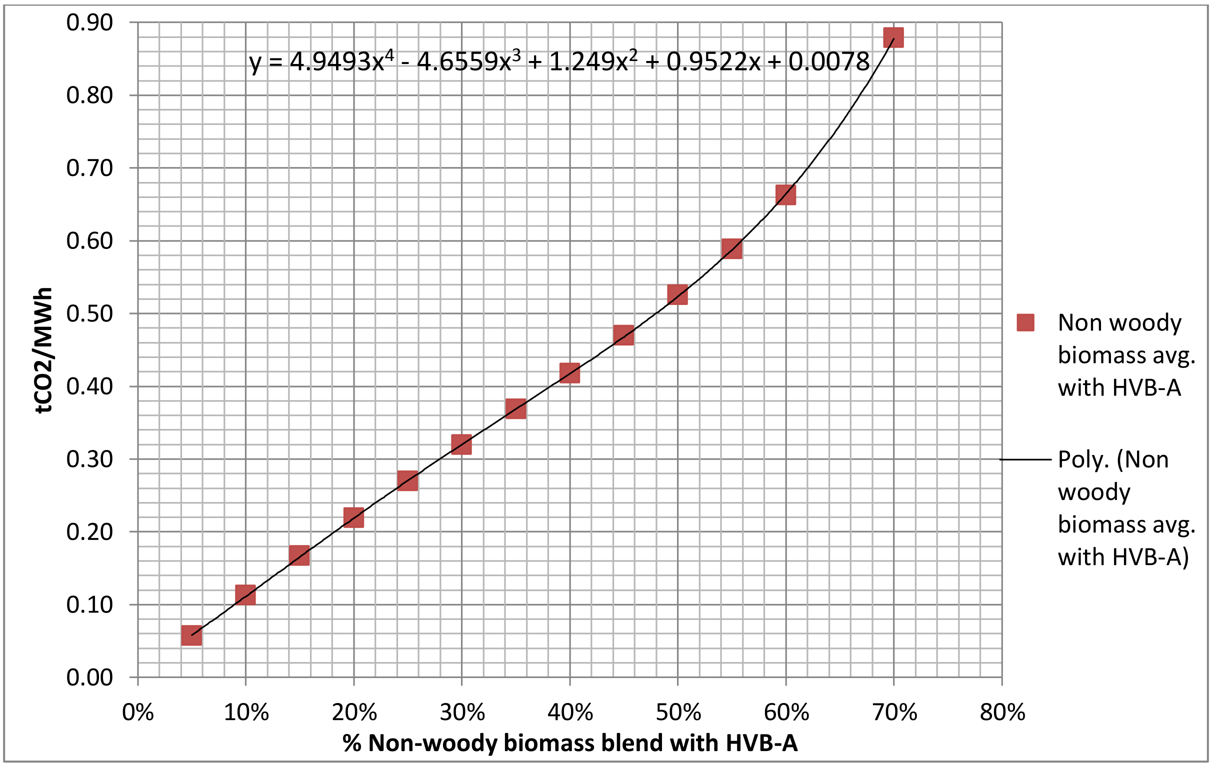
Appendix Table B.12 -The database of carbon credits per unit energy out for biomass species with HVB-A coal

	Carbon credits per unit of energy out (t CO_2/MWh)												
Blending-biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
HVB - A													
Eucalyptus	0.85	0.67	0.60	0.54	0.49	0.43	0.38	0.33	0.28	0.23	0.18	0.12	0.06
Ailanthus	0.93	0.72	0.65	0.58	0.52	0.47	0.41	0.36	0.31	0.25	0.19	0.13	0.07
Oak wood	0.95	0.73	0.65	0.59	0.53	0.47	0.41	0.36	0.31	0.25	0.19	0.13	0.07
Black Locust	0.94	0.74	0.67	0.60	0.54	0.48	0.43	0.37	0.31	0.26	0.20	0.13	0.07
Spruce	0.94	0.72	0.64	0.58	0.52	0.46	0.41	0.36	0.30	0.25	0.19	0.13	0.07
Douglas fir	0.89	0.70	0.63	0.57	0.51	0.46	0.41	0.36	0.30	0.25	0.19	0.13	0.07
Monterey Pine	0.89	0.72	0.65	0.59	0.53	0.47	0.42	0.37	0.31	0.25	0.19	0.13	0.07
Willow wood	0.89	0.69	0.61	0.55	0.49	0.44	0.39	0.34	0.28	0.29	0.18	0.12	0.06
Switch grass	0.88	0.69	0.62	0.56	0.50	0.45	0.40	0.34	0.29	0.24	0.18	0.12	0.06
Hybrid poplar	0.92	0.73	0.66	0.59	0.54	0.48	0.42	0.37	0.31	0.26	0.20	0.13	0.07
Woody biomass avg. with HVB-A	**0.91**	**0.71**	**0.64**	**0.57**	**0.52**	**0.46**	**0.41**	**0.36**	**0.30**	**0.25**	**0.19**	**0.13**	**0.06**
Barley straw	0.91	0.62	0.53	0.47	0.41	0.37	0.32	0.28	0.24	0.19	0.15	0.10	0.05
Rice straw	0.82	0.63	0.56	0.50	0.45	0.40	0.35	0.30	0.25	0.20	0.15	0.10	0.05
Wheat straw	0.84	0.64	0.57	0.51	0.46	0.41	0.36	0.31	0.26	0.21	0.16	0.11	0.05
Sugar cane bagasse	0.91	0.71	0.63	0.57	0.51	0.46	0.40	0.35	0.30	0.24	0.18	0.13	0.06
Cone stover	0.91	0.71	0.64	0.57	0.51	0.46	0.41	0.35	0.30	0.24	0.19	0.13	0.06
Non woody biomass avg. with HVB-A	**0.88**	**0.66**	**0.59**	**0.53**	**0.47**	**0.42**	**0.37**	**0.32**	**0.27**	**0.22**	**0.17**	**0.11**	**0.06**

*Average values are in highlighted rows.



Appendix Figure B.7 -Woody biomass with High volatile Bituminous–A (HVB-A)



Appendix Figure B.8 -Non-woody biomass with High volatile Bituminous–A (HVB-A)

Carbon credits models developed for biomass species with MVB coal

Appendix Table B.13 -The database of rate of CO_2 emissions for biomass species with MVB coal

	CO_2(kg/h)												
Blending-biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
MVB													
Eucalyptus	111.92	95.93	87.93	79.94	71.95	63.95	55.96	47.96	39.97	31.98	23.98	15.99	7.99
Ailanthus	113.04	96.89	88.82	80.74	72.67	64.59	56.52	48.44	40.37	32.30	24.22	16.15	8.07
Oak wood	114.39	98.05	89.88	81.71	73.54	65.37	57.20	49.03	40.86	32.68	24.51	16.34	8.17
Black Locust	116.20	99.60	91.30	83.00	74.70	66.40	58.10	49.80	41.50	33.20	24.90	16.6	8.30
Spruce	111.16	95.28	87.34	79.40	71.46	63.52	55.58	47.64	39.70	31.76	23.82	15.88	7.94
Douglas fir	115.92	99.36	91.08	82.80	74.52	66.24	57.96	49.68	41.40	33.12	24.84	16.56	8.28
Monterey Pine	117.81	100.98	92.57	84.15	75.74	67.32	58.91	50.49	42.08	33.66	25.25	16.83	8.42
Willow wood	103.22	88.47	81.10	73.73	66.35	58.98	51.61	44.24	36.86	29.49	22.12	14.75	7.37
Switch grass	109.96	94.25	86.40	78.54	70.69	62.83	54.98	47.13	39.27	31.42	23.56	15.71	7.85
Hybrid poplar	119.77	102.66	94.11	85.55	77.00	68.44	59.89	51.33	42.78	34.22	25.67	17.11	8.56
CO_2 reduction -Woody biomass avg. (kg/h)	**113.34**	**97.15**	**89.05**	**80.96**	**72.86**	**64.76**	**56.67**	**48.57**	**40.47**	**32.38**	**24.28**	**16.19**	**8.09**
Barley straw	87.35	74.87	68.63	62.39	56.15	49.91	43.68	37.44	31.20	24.96	18.72	12.48	6.24
Rice straw	86.96	74.53	68.32	62.11	55.90	49.69	43.48	37.27	31.06	24.84	18.63	12.42	6.21
Wheat straw	92.84	79.58	72.95	66.32	59.68	53.05	46.42	39.79	33.16	26.53	19.89	13.26	6.63
Sugar cane bagasse	108.37	92.88	85.14	77.40	69.66	61.92	54.18	46.44	38.70	30.96	23.22	15.48	7.74
Cone stover	112.80	96.68	88.63	80.57	72.51	64.46	56.40	48.34	40.28	32.23	24.17	16.11	8.06
CO_2 reduction - Non-woody biomass avg. (kg/h)	**97.66**	**83.70**	**76.73**	**69.75**	**62.78**	**55.80**	**48.83**	**41.85**	**34.88**	**27.90**	**20.92**	**13.95**	**6.97**

*Average values are in highlighted rows.

Appendix Table B.14 -The database of rate of energy out for biomass species with MVB coal

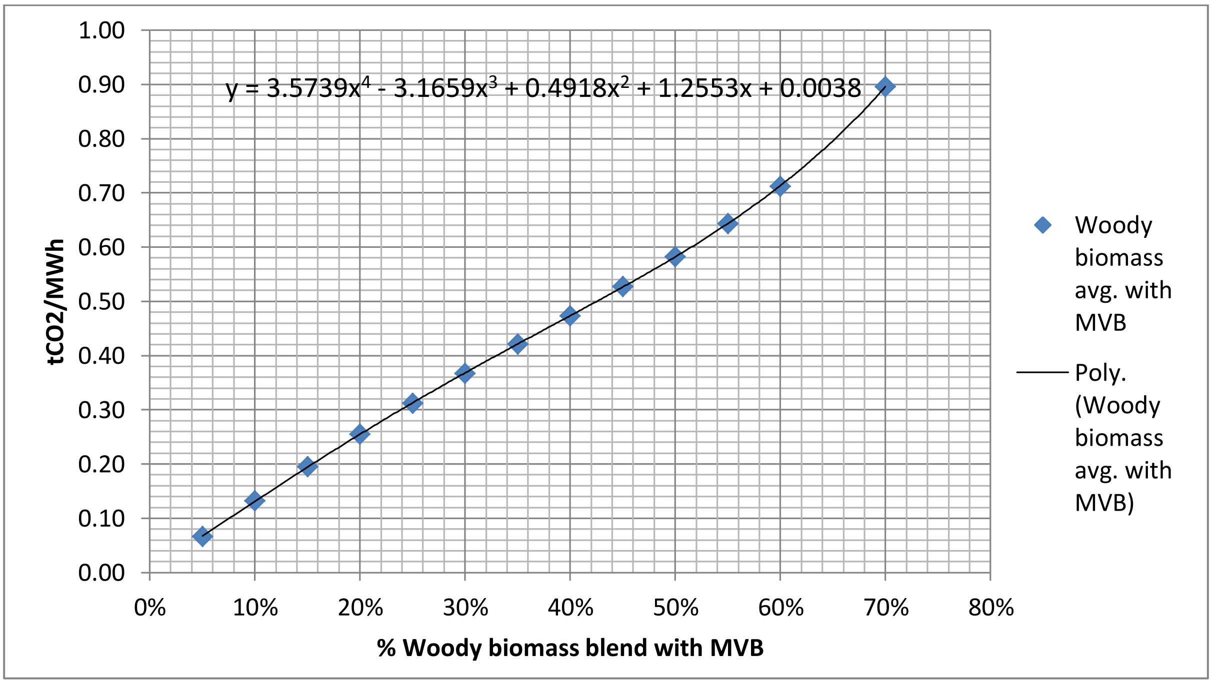
	Rate of Energy out -put (kWh/h)												
Blending - biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
MVB													
Eucalyptus	124.87	135.26	137.47	138.16	137.66	136.27	134.26	131.90	129.39	126.91	124.62	122.62	120.99
Ailanthus	127.41	137.06	138.94	139.34	138.57	136.96	134.77	132.26	129.63	127.07	124.72	122.67	121.02
Oak wood	126.57	137.39	139.67	140.33	139.73	138.17	135.95	133.34	130.56	127.82	125.26	123.02	121.18
Black Locust	129.13	136.97	138.38	138.52	137.66	136.08	133.99	131.63	129.16	126.75	124.52	122.58	120.99
Spruce	124.28	136.02	138.58	139.45	138.99	137.53	135.40	132.86	130.15	127.48	125.00	122.84	121.09
Douglas fir	128.96	138.90	140.82	141.18	140.32	138.57	136.20	133.48	130.63	127.85	125.27	123.02	121.18
Monterey Pine	130.27	137.76	139.04	139.08	138.14	136.49	134.35	131.93	129.41	126.95	124.68	122.68	121.04
Willow wood	121.25	132.62	135.15	136.09	135.79	134.59	132.77	130.60	128.29	126.02	123.95	122.17	120.77
Switch grass	123.62	134.29	136.53	137.22	136.72	135.33	133.36	131.06	128.64	126.28	124.13	122.29	120.83
Hybrid poplar	128.20	137.46	139.27	139.63	138.87	137.27	135.09	132.59	129.95	127.36	124.95	122.84	121.11
Energy out - Woody biomass avg. (kWh/h)	**126.45**	**136.37**	**138.38**	**138.9**	**138.24**	**136.72**	**134.61**	**132.16**	**129.58**	**127.04**	**124.7**	**122.67**	**121.02**
Barley straw	99.47	122.78	128.86	132.17	133.36	133.00	131.61	129.61	127.36	125.14	123.15	121.54	120.41
Rice straw	110.67	120.44	122.73	123.83	124.07	123.73	123.03	122.18	121.31	120.54	119.96	119.62	119.56
Wheat straw	115.88	126.88	129.39	130.44	130.40	129.59	128.28	126.70	125.04	123.46	122.07	120.96	120.20
Sugar cane bagasse	124.05	134.46	136.65	137.33	136.82	135.45	133.50	131.21	128.79	126.42	124.24	122.37	120.87
Cone stover	122.94	134.05	136.46	137.28	136.87	135.54	133.60	131.30	128.86	126.47	124.28	122.38	120.88
Energy out – Non-woody biomass avg. (kWh/h)	**114.60**	**127.72**	**130.81**	**132.21**	**132.30**	**131.46**	**130.00**	**128.20**	**126.27**	**124.40**	**122.74**	**121.37**	**120.38**

*Average values are in highlighted rows.

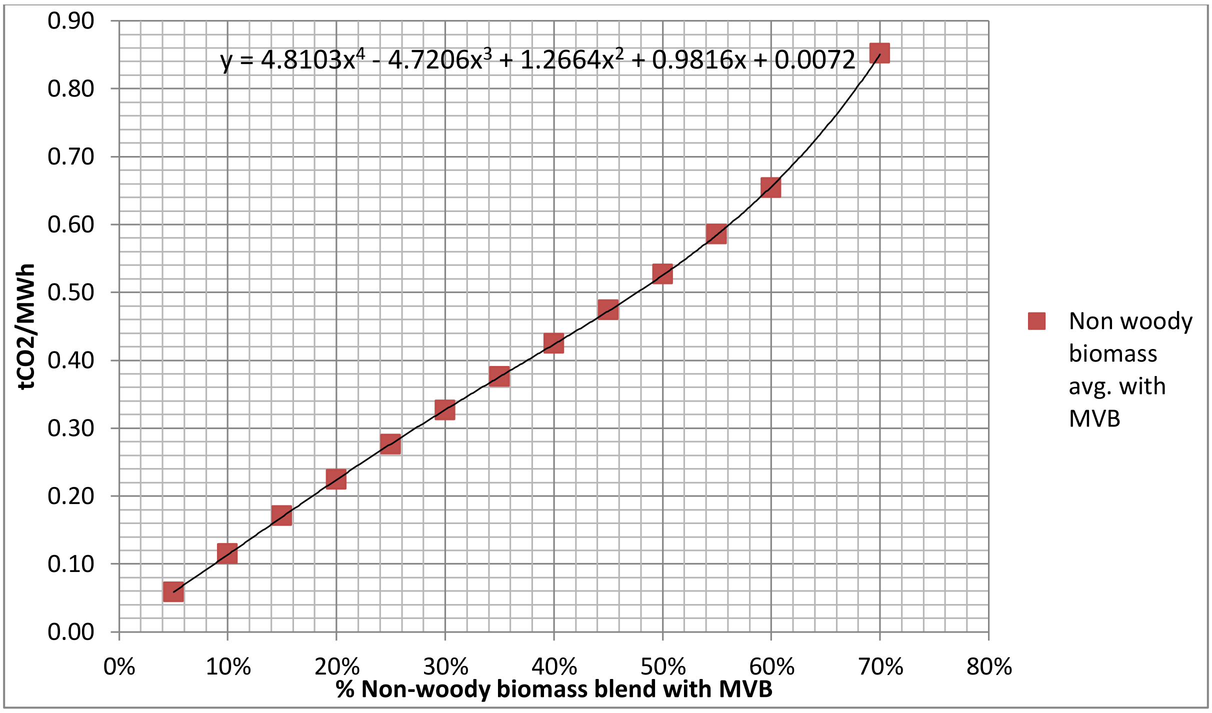
Appendix Table B.15 -The database of carbon credits per unit energy out for biomass species with MVB coal

	Carbon credits per unit of energy out (t CO_2/MWh)												
Blending – biomass %	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
MVB													
Eucalyptus	0.90	0.71	0.64	0.58	0.52	0.47	0.42	0.36	0.31	0.25	0.19	0.13	0.07
Ailanthus	0.89	0.71	0.64	0.58	0.52	0.47	0.42	0.37	0.31	0.25	0.19	0.13	0.07
Oak wood	0.90	0.71	0.64	0.58	0.53	0.47	0.42	0.37	0.31	0.26	0.20	0.13	0.07
Black Locust	0.90	0.73	0.66	0.60	0.54	0.49	0.43	0.38	0.32	0.26	0.20	0.14	0.07
Spruce	0.89	0.70	0.63	0.57	0.51	0.46	0.41	0.36	0.31	0.25	0.19	0.13	0.07
Douglas fir	0.90	0.72	0.65	0.59	0.53	0.48	0.43	0.37	0.32	0.26	0.20	0.13	0.07
Monterey Pine	0.90	0.73	0.67	0.61	0.55	0.49	0.44	0.38	0.33	0.27	0.20	0.14	0.07
Willow wood	0.85	0.67	0.60	0.54	0.49	0.44	0.39	0.34	0.29	0.23	0.18	0.12	0.06
Switch grass	0.89	0.70	0.63	0.57	0.52	0.46	0.41	0.36	0.31	0.25	0.19	0.13	0.06
Hybrid poplar	0.93	0.75	0.68	0.61	0.55	0.50	0.44	0.39	0.33	0.27	0.21	0.14	0.07
Woody biomass avg. with MVB	**0.90**	**0.71**	**0.64**	**0.58**	**0.53**	**0.47**	**0.42**	**0.37**	**0.31**	**0.25**	**0.19**	**0.13**	**0.07**
Barley straw	0.88	0.61	0.53	0.47	0.42	0.38	0.33	0.29	0.24	0.20	0.15	0.10	0.05
Rice straw	0.79	0.62	0.56	0.50	0.45	0.40	0.35	0.31	0.26	0.21	0.16	0.10	0.05
Wheat straw	0.80	0.63	0.56	0.51	0.46	0.41	0.36	0.31	0.27	0.21	0.16	0.11	0.06
Sugar cane bagasse	0.87	0.69	0.62	0.56	0.51	0.46	0.41	0.35	0.30	0.24	0.19	0.13	0.06
Cone stover	0.92	0.72	0.65	0.59	0.53	0.48	0.42	0.37	0.31	0.25	0.19	0.13	0.07
Non woody biomass avg. with MVB	**0.85**	**0.65**	**0.59**	**0.53**	**0.47**	**0.42**	**0.38**	**0.33**	**0.28**	**0.22**	**0.17**	**0.11**	**0.06**

*Average values are in highlighted rows.



Appendix Figure B.9 -Woody biomass with Medium volatile Bituminous (MVB)



Appendix Figure B.10 -Non-woody biomass with Medium volatile Bituminous (MVB)

Carbon credits models developed for biomass species with LVB coal

Appendix Table B.16 -The database of rate of CO_2 emissions for biomass species with LVB coal

	CO_2(kg/h)												
Blending-biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
LVB													
Eucalyptus	111.88	95.90	87.90	79.91	71.92	63.93	55.94	47.95	39.96	31.97	23.97	15.98	7.99
Ailanthus	113.71	97.46	89.34	81.22	73.10	64.98	56.85	48.73	40.61	32.49	24.37	16.24	8.12
Oak wood	114.37	98.03	89.86	81.69	73.52	65.35	57.19	49.02	40.85	32.68	24.51	16.34	8.17
Black Locust	116.64	99.98	91.65	83.31	74.98	66.65	58.32	49.99	41.66	33.33	24.99	16.66	8.33
Spruce	111.03	95.17	87.24	79.31	71.38	63.45	55.52	47.59	39.65	31.72	23.79	15.86	7.93
Douglas fir	116.33	99.72	91.41	83.10	74.79	66.48	58.17	49.86	41.55	33.24	24.93	16.62	8.31
Monterey Pine	118.31	101.41	92.95	84.50	76.05	67.60	59.15	50.70	42.25	33.80	25.35	16.90	8.45
Willow wood	102.98	88.27	80.92	73.56	66.20	58.85	51.49	44.14	36.78	29.42	22.07	14.71	7.36
Switch grass	110.08	94.35	86.49	78.63	70.76	62.90	55.04	47.18	39.31	31.45	23.59	15.73	7.86
Hybrid poplar	116.03	99.45	91.17	82.88	74.59	66.30	58.01	49.73	41.44	33.15	24.86	16.58	8.29
CO_2 reduction -Woody biomass avg. (kg/h)	**113.13**	**96.97**	**88.89**	**80.81**	**72.72**	**64.64**	**56.56**	**48.48**	**40.40**	**32.32**	**24.24**	**16.16**	**8.08**
Barley straw	88.29	75.68	69.37	63.06	56.76	50.45	44.14	37.84	31.53	25.23	18.92	12.61	6.31
Rice straw	87.28	74.81	68.58	62.34	56.11	49.87	43.64	37.41	31.17	24.94	18.70	12.47	6.23
Wheat straw	92.74	79.49	72.87	66.24	59.62	52.99	46.37	39.75	33.12	26.50	19.87	13.25	6.62
Sugar cane bagasse	108.47	92.98	85.23	77.48	69.73	61.99	54.24	46.49	38.74	30.99	23.24	15.5	7.75
Cone stover	108.91	93.35	85.57	77.80	70.02	62.24	54.46	46.68	38.90	31.12	23.34	15.56	7.78
CO_2 reduction - Non-woody biomass avg. (kg/h)	**97.13**	**83.26**	**76.32**	**69.38**	**62.44**	**55.50**	**48.57**	**41.63**	**34.69**	**27.75**	**20.81**	**13.87**	**6.93**

*Average values are in highlighted rows.

Appendix Table B.17 -The database of rate of rate of energy out for biomass species with LVB coal

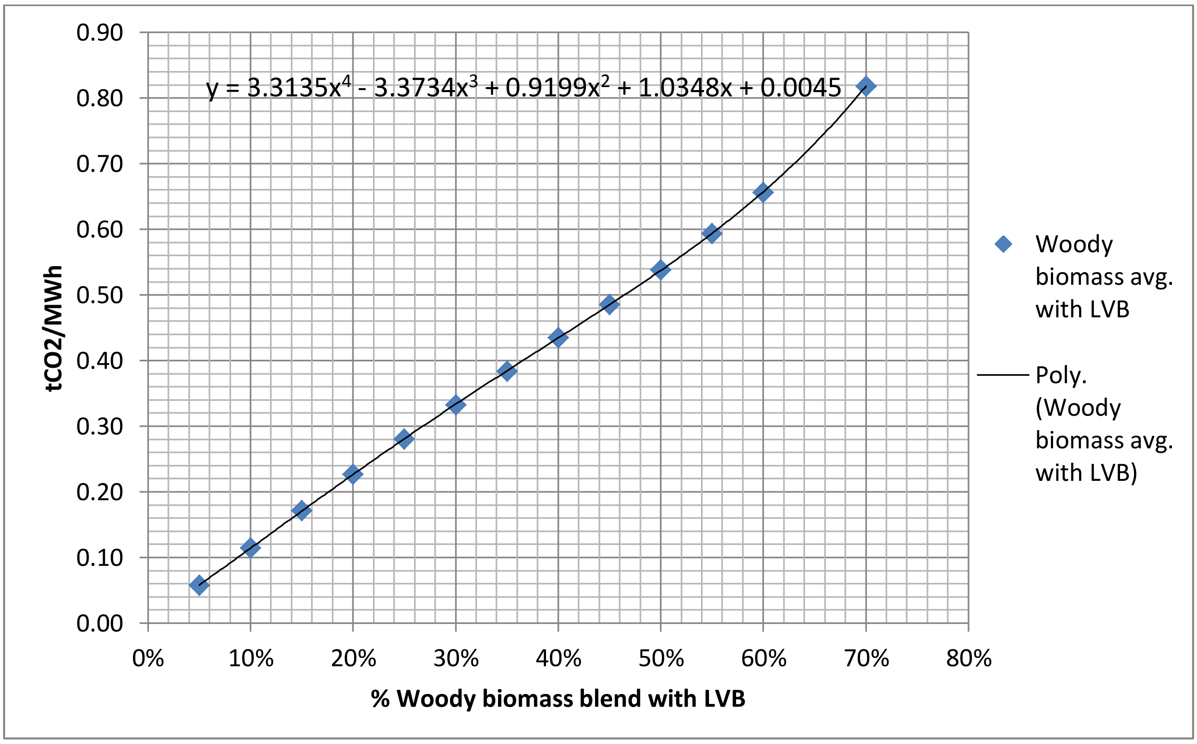
	Rate of Energy out -put (kWh/h)												
Blending - biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
LVB													
Eucalyptus	136.61	146.64	148.72	149.42	149.14	148.19	146.86	145.36	143.88	142.54	141.46	140.69	140.29
Ailanthus	138.86	148.42	150.25	150.72	150.22	149.08	147.57	145.91	144.29	142.85	141.67	140.82	140.35
Oak wood	138.62	149.03	151.11	151.74	151.30	150.14	148.56	146.79	145.03	143.42	142.08	141.08	140.47
Black Locust	140.01	147.90	149.36	149.67	149.15	148.09	146.73	145.24	143.80	142.51	141.46	140.72	140.31
Spruce	136.59	147.76	150.08	150.86	150.53	149.47	147.96	146.27	144.58	143.06	141.80	140.89	140.37
Douglas fir	140.69	150.40	152.20	152.59	151.95	150.63	148.91	147.05	145.21	143.55	142.17	141.14	140.50
Monterey Pine	141.06	148.64	149.99	150.22	149.63	148.52	147.09	145.56	144.06	142.72	141.62	140.82	140.36
Willow wood	133.17	144.00	146.33	147.24	147.16	146.41	145.28	143.99	142.73	141.62	140.77	140.24	140.06
Switch grass	135.36	145.65	147.75	148.46	148.18	147.26	145.97	144.55	143.16	141.95	141.00	140.39	140.14
Hybrid poplar	140.97	149.24	150.70	150.94	150.30	149.09	147.55	145.90	144.29	142.86	141.70	140.85	140.37
Energy out - Woody biomass avg. (kWh/h)	**138.19**	**147.76**	**149.64**	**150.18**	**149.75**	**148.68**	**147.24**	**145.66**	**144.10**	**142.70**	**141.57**	**140.76**	**140.32**
Barley straw	114.54	135.91	141.12	143.86	144.84	144.66	143.80	142.64	141.46	140.47	139.78	139.50	139.66
Rice straw	121.06	130.71	133.10	134.49	135.21	135.54	135.69	135.82	136.03	136.40	136.98	137.82	138.91
Wheat straw	127.22	137.75	140.16	141.31	141.60	141.34	140.79	140.15	139.57	139.15	138.97	139.08	139.51
Sugar cane bagasse	135.70	145.77	147.84	148.56	148.29	147.39	146.12	144.70	143.31	142.09	141.12	140.47	140.18
Cone stover	136.20	145.95	147.89	148.48	148.13	147.16	145.85	144.43	143.05	141.86	140.94	140.34	140.12
Energy out - Non - woody biomass avg. (kWh/h)	**126.94**	**139.21**	**142.02**	**143.34**	**143.61**	**143.21**	**142.45**	**141.54**	**140.68**	**139.99**	**139.55**	**139.44**	**139.67**

*Average values are in highlighted rows.

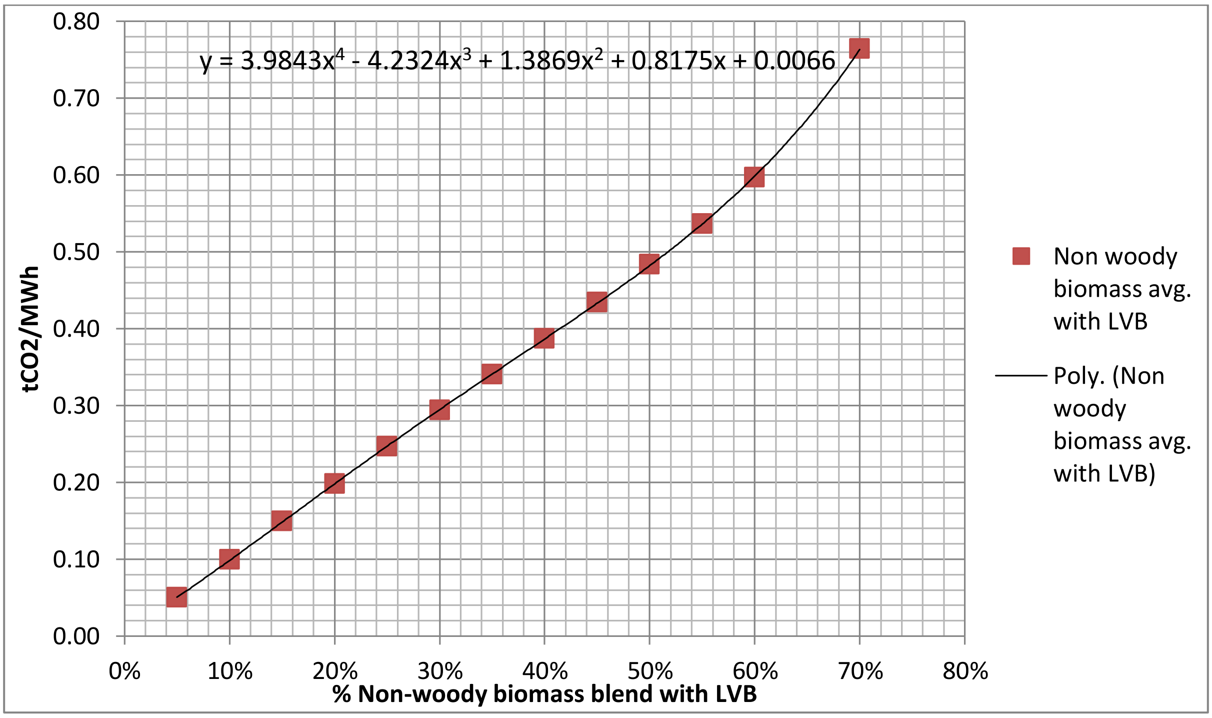
Appendix Table B.18 -The database of carbon credits per unit energy out for biomass species with LVB coal

	Carbon credits per unit of energy out (t CO_2/MWh)												
Blending – biomass%	70%	60%	55%	50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
LVB													
Eucalyptus	0.82	0.65	0.59	0.53	0.48	0.43	0.38	0.33	0.28	0.22	0.17	0.11	0.06
Ailanthus	0.82	0.66	0.59	0.54	0.49	0.44	0.39	0.33	0.28	0.23	0.17	0.12	0.06
Oak wood	0.83	0.66	0.59	0.54	0.49	0.44	0.38	0.33	0.28	0.23	0.17	0.12	0.06
Black Locust	0.83	0.68	0.61	0.56	0.50	0.45	0.40	0.34	0.29	0.23	0.18	0.12	0.06
Spruce	0.81	0.64	0.58	0.53	0.47	0.42	0.38	0.33	0.27	0.22	0.17	0.11	0.06
Douglas fir	0.83	0.66	0.60	0.54	0.49	0.44	0.39	0.34	0.29	0.23	0.18	0.12	0.06
Monterey Pine	0.84	0.68	0.62	0.56	0.51	0.46	0.40	0.35	0.29	0.24	0.18	0.12	0.06
Willow wood	0.77	0.61	0.55	0.50	0.45	0.40	0.35	0.31	0.26	0.21	0.16	0.10	0.05
Switch grass	0.81	0.65	0.59	0.53	0.48	0.43	0.38	0.33	0.27	0.22	0.17	0.11	0.06
Hybrid poplar	0.82	0.67	0.60	0.55	0.50	0.44	0.39	0.34	0.29	0.23	0.18	0.12	0.06
Woody biomass avg. with LVB	**0.82**	**0.66**	**0.59**	**0.54**	**0.49**	**0.43**	**0.38**	**0.33**	**0.28**	**0.23**	**0.17**	**0.11**	**0.06**
Barley straw	0.77	0.56	0.49	0.44	0.39	0.35	0.31	0.27	0.22	0.18	0.14	0.09	0.05
Rice straw	0.72	0.57	0.52	0.46	0.41	0.37	0.32	0.28	0.23	0.18	0.14	0.09	0.04
Wheat straw	0.73	0.58	0.52	0.47	0.42	0.37	0.33	0.28	0.24	0.19	0.14	0.10	0.05
Sugar cane bagasse	0.80	0.64	0.58	0.52	0.47	0.42	0.37	0.32	0.27	0.22	0.16	0.11	0.06
Cone stover	0.80	0.64	0.58	0.52	0.47	0.42	0.37	0.32	0.27	0.22	0.17	0.11	0.06
Non woody biomass avg. with LVB	**0.76**	**0.60**	**0.54**	**0.48**	**0.43**	**0.39**	**0.34**	**0.29**	**0.25**	**0.20**	**0.15**	**0.10**	**0.05**

*Average values are in highlighted rows.



Appendix Figure B.11 -Woody biomass with Low volatile Bituminous (LVB)



Appendix Figure B.12 -Non-woody biomass with Low volatile Bituminous (LVB)

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