CO-FIRING BIOMASS WITH COAL IN PULVERIZED COAL FIRED BOILERS

Shami Ridma Himanthaka Mudunkotuwa

(118680F)

Degree of Master of Science

Department of Electrical Engineering

University of Moratuwa
Sri Lanka

April 2016

CO-FIRING BIOMASS WITH COAL
IN PULVERIZED COAL FIRED BOILERS

Shami Ridma Himanthaka Mudunkotuwa

(118680F)

Thesis submitted in partial fulfillment of the requirements for the degree
Master of Science

Department of Electrical Engineering

University of Moratuwa
Sri Lanka

April 2016

DECLERATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: Date:

The above candidate has carried out research for the Masters thesis under my supervision.

Signature of the supervisor: Date:

DEDICATION

I would like to dedicate this thesis to my mother, father, all teachers who educated me and to my wife.

ACKNOWLEDGEMENT

First of all, I am very grateful to my supervisor, Eng. (Mr.) Anura Wijayapala, for his guidance and support throughout the period of the research. I would also like to thank Dr. Rohan Fernando and Mr. Parakrama Jayasinghe for their time and valuable suggestions given to aid my progress. I would also like to express my great appreciations to the Head of the Department and all the staff of the Department of Electrical Engineering, Faculty of Engineering, University of Moratuwa for their assistance and support. Lastly and the most importantly, I would also like to thank my family for their support and encouragement throughout the entire process.

ABSTRACT

Power generation using pulverized coal power technology is a very mature and extremely popular technical trend in the global scenario. The first coal fired power plant complex in Sri Lanka, Lakvijaya Power Station employs the same technology. For a country like Sri Lanka, import of coal will cost a lot of foreign exchange since it has no coal reserves within the country. Also, as a nation, it is strategically advantageous to rely on multiple fuels which reduces energy imports in to the country. Biomass co-firing is successfully being demonstrated around the world. There are several co-firing technologies and the pulverized coal fired plants can retrofit the technology very easily. By doing so, there are many benefits that a nation can achieve. The amount of fuel can be conserved while substituting it with a suitable type of available biomass. Hence, a direct nationwide economic benefit can be achieved. Also, with the global climatic changes, the world is currently looking for way to reduce and compensate to green house gas emissions. Biomass co-firing is also beneficial in that manner since a significant amount of fossil fuels will be substituted with carbon neutral biomass. When introducing co-firing technology, there are many other aspects to be considered. They are of technical, economical and social of nature, and hence can impact national economy in various ways. As a nation whose future generation plan is coal dominant, it is vital that Sri Lanka consider this particular concept seriously.

In this thesis, glerecedia is considered as the candidate biomass option which will be mixed with coal to be fired within the same boiler. An extensive analysis is carried out and elaborated in this thesis in regard to technical, economical and other concerns arising when co-firing is introduced to an existing pulverized coal fired installation. As a case study Lakvijaya Power Station Complex is considered. It is concluded that the introduction of direct co-firing techniques and subsequently addressing minor concerns related to it, can be demonstrated in a commercial scale successfully. It is recommended to carry out initial trials up to a co-firing ratio of 5%. This report will focus on the design of co-firing arrangement up to a maximum of 5% as it is the globally established benchmark for direct co-firing strategy.

TABLE OF CONTENTS

2. Methodology

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	**Description**
CFR	Co-firing Ratio
BM	Biomass
GCV	Gross Calorific Value
NCV	Net Calorific Value

LIST OF APPENDICES

Chapter 1

Introduction

Co-firing is the process of burning two different types of fuels in the same or different boilers to generate power. The main idea is to replace the main fuel with another one to achieve any benefits involved. In the current global context, the two fuels are coal and biomass in most of the cases. Co-firing should not be confused with the combustion of multiple fuels in boilers designed especially for burning of multiple fuels [3]. The basic difference between such a type of combustion and co-firing is that co-firing is achieved in a boiler originally designed to burn only a specific kind of fuel which is coal in most of the cases. In simple terms, biomass co-firing with coal can be thought of as the process of partial supplementing of coal with biomass in coal-fired boilers. The term co-firing ratio is defined as the ratio between coal and biomass which is blended by weight or energy for combustion [2].

Co-firing is a promising technology which offers many advantages. The most significant feature in co-firing is that one can carry out co-firing in an existing coal-fired installation. This means that the co-firing is retrofit able to any existing installation. This can be done in a very short time and with an investment which is significantly smaller [2]. Hence, it is a faster, easier and extremely economical way to increase the percentage of renewable power generated in any sector. Also, by employing co-firing, would contribute negatively to the green house effect by cutting down on CO_2 emissions on a mass scale. In addition, it will also cut down other emissions such as NO_x & SO_x [1]. It is also a fact that co-firing is proven to be one of the cheapest measures to mitigate green house gas emission. Being a tropical country which has favorable environmental conditions for plantations, Sri Lanka can benefit a lot by adhering to co-firing. Specially, in securing the biomass supply needed to fulfill the demand. When doing so, on one hand, the rural communities can be made growers to secure supply throughout the year and on the other hand, the foreign exchange spent on importing coal will be saved and will be spent on rural farmers. The rural communities around the isle will be empowered and they can be encouraged to grow more. The benefits are further accelerated with time, as the generation sector is now moving towards coal power generation in the long run. Another key feature in co-firing is that the unit flexibility in switching between 100% coal and biomass co-firing maximum ratio depending on the seasonal availability of biomass [9].

1.1 Global Status of Co-firing

Biomass co-firing began in the 1980s in Europe and USA and currently it has acquired a wide popularity among the countries all over the world. Among the global leaders, many plants in USA, Finland, Denmark, Germany, Belgium, The Netherlands, Poland, Austria, Spain, Australia, Japan and Great Britain are now successfully demonstrating co-firing biomass with coal [10]. As at end of 2004, there are about 220 plants worldwide that are running on a commercial level [2]. Figure 1.1 shows the global distribution of the biomass co-fired coal power plants.

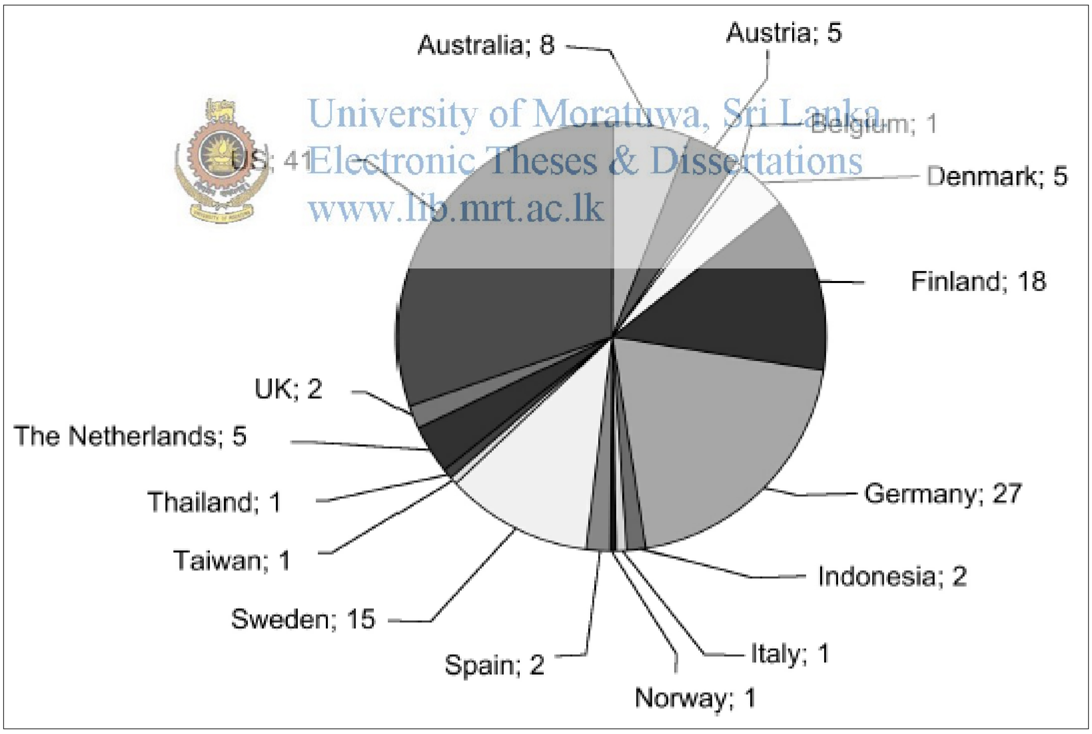


Figure 1.1 : Coal Power Plants Experienced Biomass Co-firing [1]

It is also noted that co-firing has been employed using all types of boiler available. Bubbling and circulating fluidized bed boilers and stoker boilers have been utilized, but most of the boilers involved in the co-firing are pulverized coal boilers, including tangentially-fired, wall-fired, and cyclone units. As of 2004, more than 50% of the boilers utilized in co-firing were of the pulverized fuel type [1]. All the types of boilers that have successfully carried out co-firing have fired a wide range of biomass types with various attributes.

1.2 Properties : Coal vs Biomass

There are many attributes, factors and parameters to compare fuels. If those parameters are considered, biomass and coal has some significant differences. The type of biomass is selected for the co-firing scenario and it is called Glerecedia. The reason for selection is explained in detailed in Chapter 2. A comprehensive comparison of chemical and thermal parameters between coal and Glerecedia is given in tables 1.1 and 1.2 respectively. The values are based on the results obtained by carrying out tests on Glerecedia.

Parameter	**Coal (Bituminous)**	**Biomass (Glerecedia)**
Gross Calorific Value (kcal/kg)	5800 – 6900	4400 – 5250
Moisture Content (w/w %)	8 – 16	10 – 23
Ash Content (w/w %)	4.5 – 16	1 – 10
Volatile Matter (w/w %)	20 – 40	50 – 80
Ash Fusion Temperature (°C)	1250 – 1800	1400 – 1900

Table 1.1 : Thermal Properties of Coal and Biomass

Parameter	**Coal (Bituminous)**	**Biomass (Glerecedia)**
Carbon (w/w %)	42 – 57	40 – 50
Oxygen (w/w %)	6 – 12	15 – 25
Hydrogen (w/w %)	3 – 4	5 – 10
Sulphur (w/w %)	0.2 – 0.7	0.1 – 0.4
Nitrogen (w/w %)	1 – 2	0.5 – 1.5
Chlorene (w/w %)	N/A	0.3 – 0.7
Sodium (w/w %)	N/A	0.1 – 0.5
Calcium (w/w %)	N/A	2 – 3

Table 1.2 : Chemical Properties of Coal and Biomass

Some major differences between the two can be clearly identified by looking at the above tables. The most significant differences are that the gross calorific value (GCV) and moisture content. The GCV is less and moisture is higher in biomass than in coal. The lesser amounts of ash in biomass is a positive factor towards co-firing, since it means that less amount of slagging and fouling inside boiler due to biomass [10]. The ash fusion temperatures are roughly in the same range and shall not cause any instability in the furnace.

Chemically, the carbon amount is less than biomass and it is reflected in the less number in GCV. Fewer amounts of Nitrogen and Sulphur in biomass is a favorable factor since it will emit less SO_x and NO_x. The Sulphur and Chlorine in biomass will impose a threat in causing corrosion inside the boiler and shall be taken care of. The amount of Sulphur is lesser in biomass so it is better than coal when it comes to corrosion.

As it is clearly seen, there are some changes and gaps between the two as fuels. The challenge is to bridge the gaps between the two, so that biomass can be used to replace coal. After successfully accounting for parameters only, one can use biomass to co-fire with coal. The main methodology which can help to bridge the gap between coal and biomass is biomass pre-treatment. The pre-treatment technologies used on biomass plays a major role in improving attributes in biomass as a fuel. Pretreatment process and plant will be explained in detail in chapters to come.

1.3 Technology Options for Co-firing

There are many technical options available for co-firing and almost all of them have been successfully used around the world. There are three basic technology options which are different in their nature [1].

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

1.3.1 Direct co-firing

The basic concept in this is that both fuels are combusted in the same furnace. This is the most commonly applied and proven as the most economical co-firing configuration. Depending on the biomass fuel characteristics, the same or separate mills and burners can be used. In direct co-firing, there are four options which can be employed depending on various characteristics and parameters. All of these four options can be implemented and sometimes retrofitted to pulverized coal fired boilers.

The first option suggests that the biomass and coal are mixed with each other in the fuel hand ling systems and then this blend is fed into the furnace. This is the most straightforward and least expensive option. However, this option can only be accomplished at low percentages of co-firing ratios such as 5% maximum. This option is suitable only for conventional wall or corner-fired boilers [1]. Biomass types such as fire woods, coconut shells, sawdust, etc can be successfully co-fired with coal while some other different types of biomass causes many problems during feeding and sizing.

The second option involves the separate milling of biomass, but the pulverized biomass is injected in to the existing pulverized coal pipe work either upstream of the burner or at the burners. This approach involves higher investment than option one, but will allow going for higher co-firing ratios [4].

In the third option, it also involves separate biomass milling, but two separate feeding lines are constructed to feed coal and biomass separately in to the boiler. Coal is injected using original injection system, whereas biomass is injected through the dedicated burners in the lower furnace. With compared to other two options in direct co-firing, this option involves the highest capital for construction.

Figure 1.2 below summarizes all three options available for direct co-firing method.

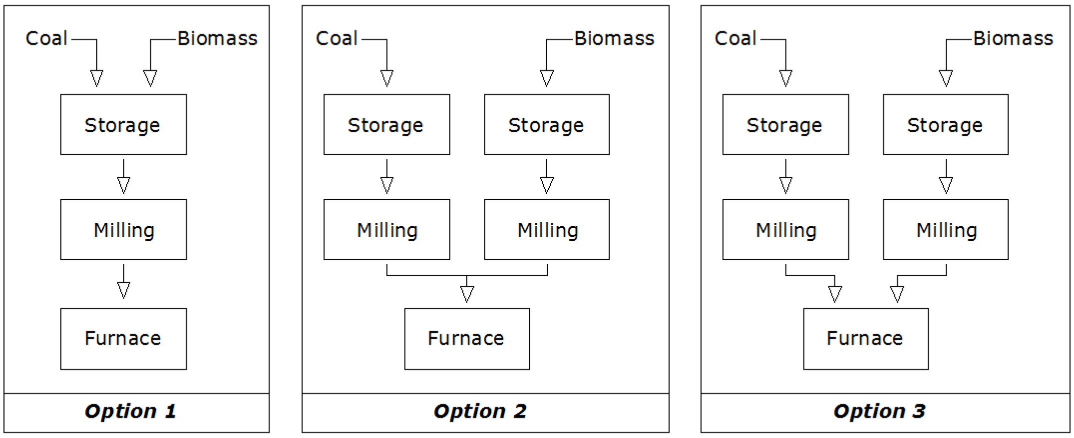


Figure 1.2 : Options Available for Direct co-firing

1.3.2 Indirect co-firing

In this type of co-firing, the solid biomass is gasified separately and the produced gas is combusted in the furnace of existing coal-fired boiler. This method has a significantly high investment costs [9][6]. However, through this method, wider range of biomass types can be used since it is the synthesis gas that matters at the end of the day. Also, the Chlorides can be prevented from entering in to the furnace. This is advantageous since Chlorides cause tube corrosion in the boiler. The fly ash will be pure just as coal is the only solid fuel which is combusted in the furnace.

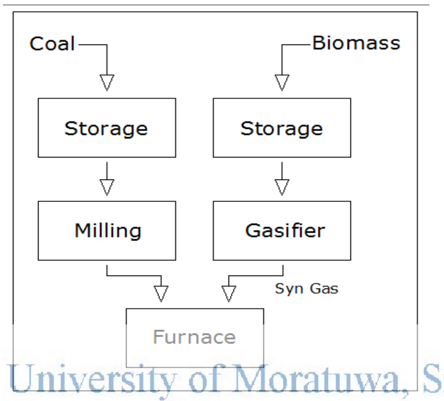


Figure 1.3 : Schematic Diagram for In-direct co-firing

1.3.3 Parallel co-firing

Parallel co-firing suggests that biomass is combusted in a separate boiler to produce steam to be utilization in the coal-fired power plant. The steam is added to the same cycle. The investment in parallel co-firing installations is higher than direct co-firing [1].

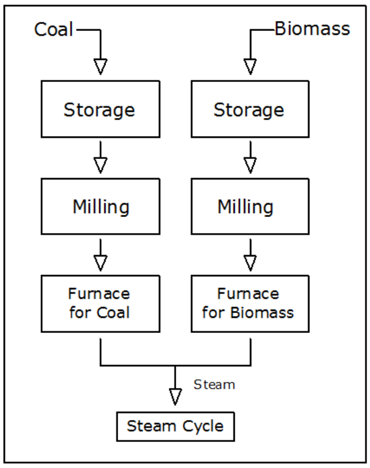


Figure 1.4 : Schematic Diagram for Parallel co-firing

1.4 Pulverized Coal Power Technology and Co-firing

By principle, pulverized coal fired power generation technology explains one of the most common and oldest ways to generate electricity with coal as the primary source of energy. As the name explains, the coal is transformed in to pulverized physical form from its original nature. Although, by definition, it seems to be a fundamental concept, it has a vast area of technical aspects in various subcomponents of the technology [11].

A coal power station obviously follows the slightly modified Steam cycle with one or more reheat stages and the four basic components exist as boiler, turbine, condenser and feed pump. By means of the four main components, the specialty of pulverized coal fired station can be recognized mainly from the boiler. Typical arrangement of a conventional pulverized coal fired power plant is shown in Fig. 1.5.

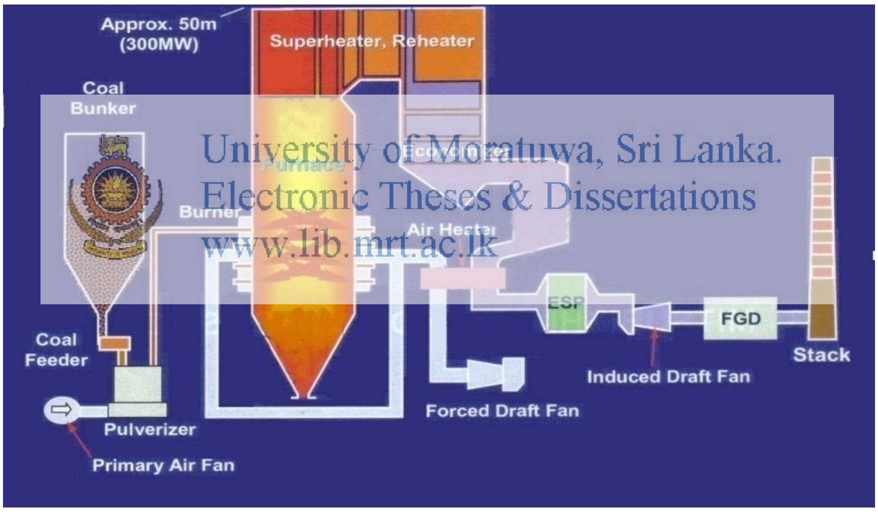


Figure 1.5 : Typical Arrangement of a Pulverized Coal Fired Power Station [2]

The process explanation of a pulverized coal power station can be started from the coal handling system. The coal handling system is responsible for following functions [1];

- Pre-treating raw coal by reducing sizes to suit the boiler pulverizers
- Transporting coal from storage yard to bunkers
- Minimizing environmental effects by extracting dust in coal

After the coal arriving in to boiler, they are stored in bunkers attached to pulverizers. The pulberizers then pulverize the coal chunks in to an air suspendable form of dust. The primary air supplied by the primary air fan carries the pulverized coal dust in to the furnace where combustion is taking place. The furnace arrangement is done in such a way that coal dust mixed air is injected from corners of the boiler and it happens in several layers as shown in Fig. 1.6. Also, the coal injecting guns are directed in to the furnace space in such a manner that the coal injection in done in a tangential manner in to the furnace [12]. The Fig 1.7 shows the view when looking from above inside the boiler when tangential firing takes place.

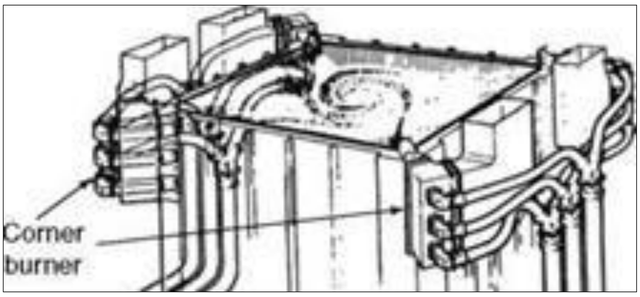


Figure 1.6 : Corner and Multilayer Firing [3]

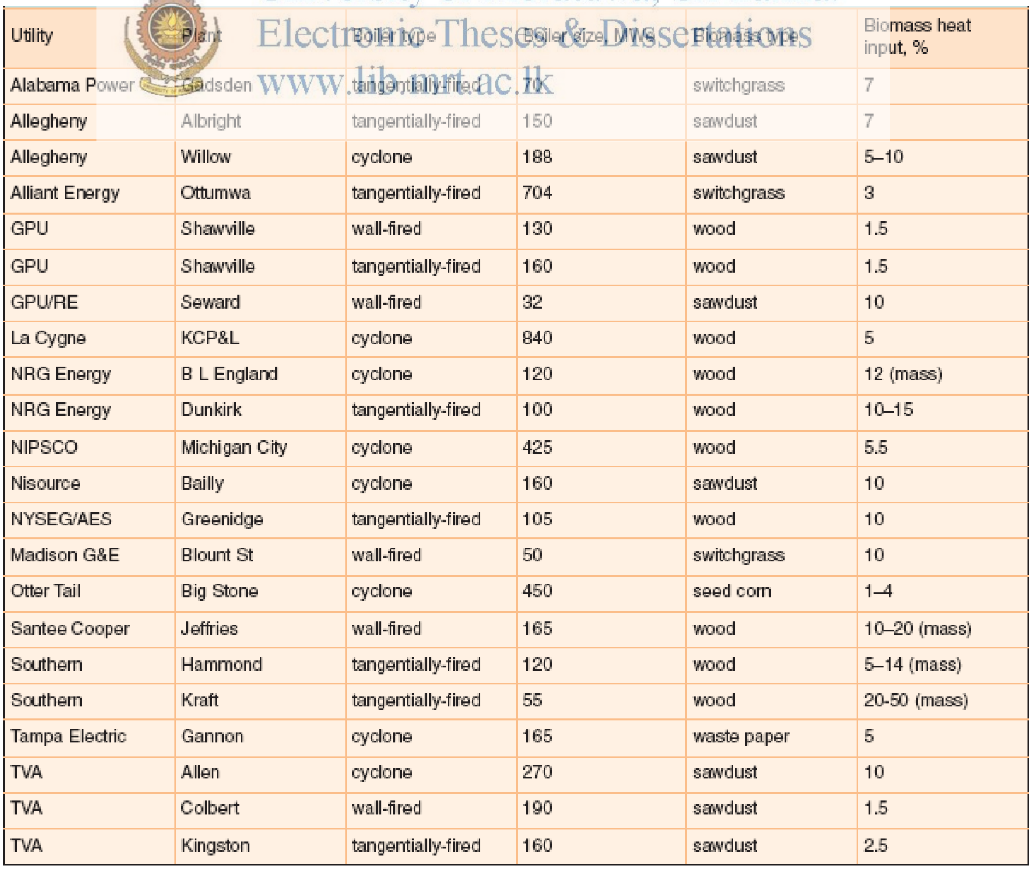
Figure 1.7 : Tangential Firing [3]

The significance in layered corner and tangential firing method is that the resulting efficiency in combustion and low emissions [12]. During the combustion, the tangential firing effect will create a literal rotating fireball due to the airflow in mixed with the fuel. This fireball when in stable operation, will suck in the new coal dust mixed air injected in to the chamber from corners in the boiler, in to the fireball [12]. With this, the complete combustion of fuel is guaranteed, hence the majority of the energy of the fuel is released in to the chamber. In addition, the layer combustion improves the flame stability and again the efficiency is enhanced. From the air system side, while the forced draft fan pushes preheated air coming through air pre-heater air in to furnace while the induced draft fan creates an opposite pull [1]. As a result, a balanced draft is created along the boiler interior and the flue gas is travelled following the draft. On its way, the flue gas exchanges it’s heat to water walls and various other tubes, panels which carries water or vapor, to form super heated steam.

When employing co-firing of biomass in to such boiler, there are three main technology options that can be employed as mentioned in a subsection before and they have many other combinations of sub-options with many technical variations within them. Each of these technological options shall be carefully analyzed in terms of technicalities, economical concerns, not forgetting environmental concerns and also in terms of commercial aspects. After a careful, in depth analysis the most suitable technological option can be selected to be employed for co-firing biomass in a pulverized coal fired boiler. The detailed methodology is discussed in chapter 2.

1.5 Co-firing Ratio

Co-firing ratio suggests that the amount of weight or energy added in mix with coal substituting the same. The definition of course differs based on the co-firing option. Generally, in global context, 100% co-firing ratio had been achieved for various co-firing options. Which means that, coal fired boilers are completely converted to biomass boilers. In between the extreme case of 100%, there are many global examples where much different number of co-firing ratios is achieved with different co-firing options used in pulverized coal power stations. Table 1.3 below summarizes many examples about the variation of co-firing ratios. These variations occur due to various factors such as technology of combustion, fuel type and it's availability, unit size, etc. Throughout this report, 5% maximum co-firing ratio will be considered for design purposes as it is the current practically tested global benchmark to stay within safety region for biomass varieties that has around 18-20MJ/kg heating values[1].



Utility	Plant	Boiler type	Boiler size, MWe	Biomass type	Biomass heat input, %
Alabama Power	Gadsden	tangentially-fired	70	switchgrass	7
Allegheny	Albright	tangentially-fired	150	sawdust	7
Allegheny	Willow	cyclone	188	sawdust	5–10
Alliant Energy	Ottumwa	tangentially-fired	704	switchgrass	3
GPU	Shawville	wall-fired	130	wood	1.5
GPU	Shawville	tangentially-fired	160	wood	1.5
GPU/RE	Seward	wall-fired	32	sawdust	10
La Cygne	KCP&L	cyclone	840	wood	5
NRG Energy	B L England	cyclone	120	wood	12 (mass)
NRG Energy	Dunkirk	tangentially-fired	100	wood	10–15
NIPSCO	Michigan City	cyclone	425	wood	5.5
Nisource	Bailly	cyclone	160	sawdust	10
NYSEG/AES	Greenidge	tangentially-fired	105	wood	10
Madison G&E	Blount St	wall-fired	50	switchgrass	10
Otter Tail	Big Stone	cyclone	450	seed corn	1–4
Santee Cooper	Jeffries	wall-fired	165	wood	10–20 (mass)
Southern	Hammond	tangentially-fired	120	wood	5–14 (mass)
Southern	Kraft	tangentially-fired	55	wood	20-50 (mass)
Tampa Electric	Gannon	cyclone	165	waste paper	5
TVA	Allen	cyclone	270	sawdust	10
TVA	Colbert	wall-fired	190	sawdust	1.5
TVA	Kingston	tangentially-fired	160	sawdust	2.5

Table 1.3 : Co-firing Ratios of Various Pulverized Coal Fired Power Stations [4]

Chapter 2

Methodology

When attempting to retrofit co-firing to an existing pulverized coal power station, there are many initial steps involved in it before even beginning the initial major design stages. First and foremost, the decision on the biomass type to be employed for co-firing process shall be taken. There are very specific reasons behind that being the first step for the process. There are number of factors to be considered such as possibility of pretreatment arrangements and security of supply in the long run. The type of biomass should possess several unique attributes in order to become a successful candidate for co-firing. They will be discussed in the following section in details.

After selecting what will be burnt to replace coal, it is required to come up with a suitable proposal for a biomass pretreatment plant. As discussed in comparison in the previous chapter, there are noticeable differences between coal and biomass as a fuel. Pretreatment process can help majorly to improve the attributes of the biomass as a fuel. There are many ways to pre-treat a biomass and the most suitable process types are to be selected based on technical and economic feasibility of the process combinations.

Finally, it is up to the designer to decide on the most suitable co-firing option for the pretreated specific biomass type. As we are retrofitting co-firing to an existing pulverized coal fired installation, the first priority is to conserve the performance and minimize all risks imposed on the existing installation. The performance and attributes of the ongoing process is not to be compromised while trying to retrofit co-firing. Therefore, when selecting the co-firing option, the designer shall be mindful to select an option where significant system alterations are not carried out and it shall also facilitate the maximum designed co-firing ratio (5%) without reducing boiler performance significantly. The selected option also shall be technically feasible and shall be economical in the long run.

After considering and deciding on all of the above, then it comes to the final detailed design for the overall system. The design shall include every detail ranging from pretreatment process to boiler modifications. The overall process is shown below in Fig. 2.1. For the study and for the analysis, Lakvijaya Power Station Complex is taken as the case study when required.

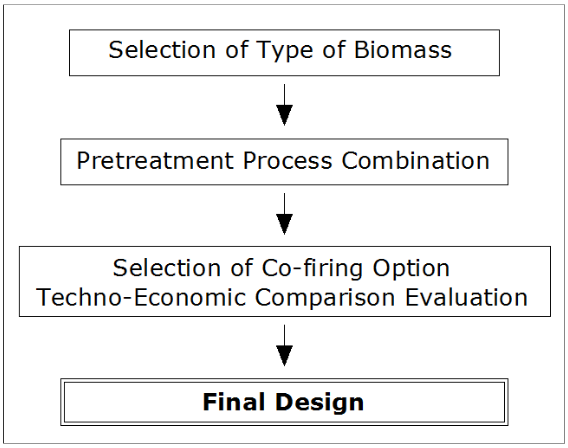


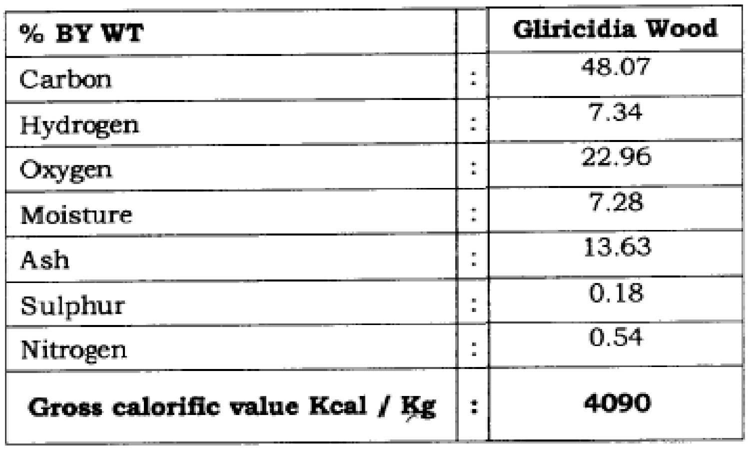
Fig. 2.1 :Co-firing Design Process

2.1 Selection of Biomass Type

Sri Lanka is a tropical country with quite a lot of plantations and variety of crops. If biomass co-firing is to be carried out in Sri Lanka, there are many suitable types of plants, which can be suitable candidates for the purpose. There are specific set of attributes that the biomass type should bear in order to become successful crop to be grown in large scale and to be used for co-firing. They are as follows.

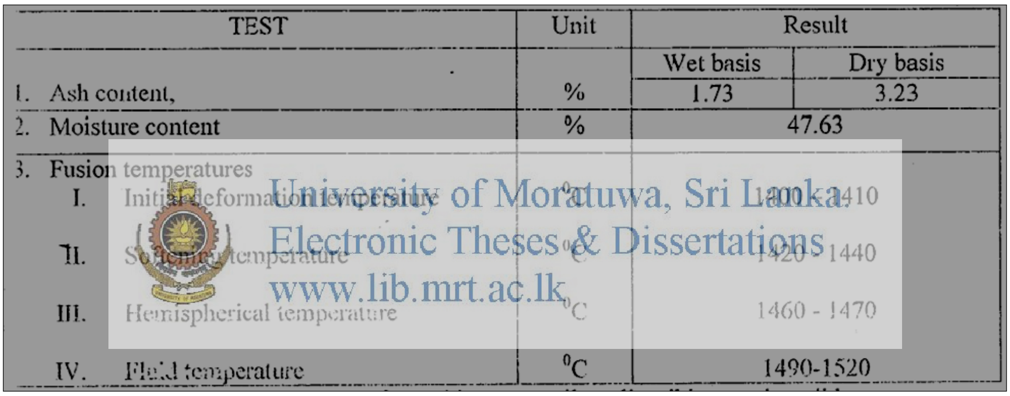
1) High Calorific Value
2) Ease of Moisture Removal
3) Favorable Growth Conditions
4) High Growth Rate (Easy Propagation)
5) Ease of Harvesting and Transportation
6) Security of Supply
7) Chemical Composition

After considering all above conditions, the best choice for a local biomass co-firing project is glerecedia. In Sri Lanka, the most popular energy crop for decades now had been glerecedia. The dedicated glerecedia plantations had been growing for the last 25 years due to its demand for some of the industry maintained small-scale boilers. It also becomes the most suitable local candidate for co-firing due to its satisfactory performance in all the above criteria. A test sampling has been carried out on glerecedia samples and the reports are shown below in Fig. 2.2, 2.3 and Fig. 2.4. Test sample is extracted from Marawila, Sri Lanka.



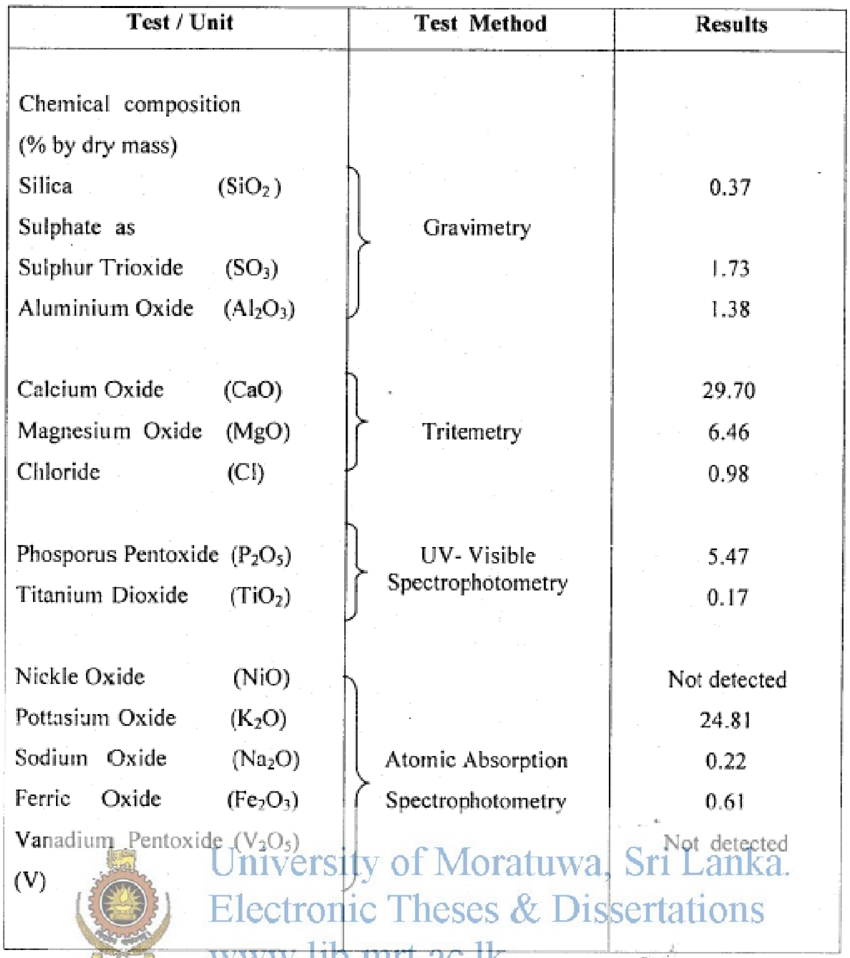
% BY WT		Gliricidia Wood
Carbon	:	48.07
Hydrogen	:	7.34
Oxygen	:	22.96
Moisture	:	7.28
Ash	:	13.63
Sulphur	:	0.18
Nitrogen	:	0.54
Gross calorific value Kcal / Kg	**:**	**4090**

Fig. 2.2 : Ultimate Analysis of Glerecedia Sample (dry basis)



TEST	Unit	Result	
		Wet basis	Dry basis
1. Ash content,	%	1.73	3.23
2. Moisture content	%	47.63	
3. Fusion temperatures			
I. Initial deformation temperature	^{0}C	1400 - 1410	
II. Softening temperature	^{0}C	1420 - 1440	
III. Hemispherical temperature	^{0}C	1460 - 1470	
IV. Fluid temperature	^{0}C	1490-1520	

Fig. 2.3 : Analysis of Glerecedia Sample (As received)



Test / Unit	Test Method	Results
Chemical composition (% by dry mass)		
Silica (SiO_2)	Gravimetry	0.37
Sulphate as Sulphur Trioxide (SO_3)		1.73
Aluminium Oxide (Al_2O_3)		1.38
Calcium Oxide (CaO)	Tritemetry	29.70
Magnesium Oxide (MgO)		6.46
Chloride (Cl)		0.98
Phosporus Pentoxide (P_2O_5)	UV- Visible Spectrophotometry	5.47
Titanium Dioxide (TiO_2)		0.17
Nickle Oxide (NiO)	Atomic Absorption Spectrophotometry	Not detected
Pottasium Oxide (K_2O)		24.81
Sodium Oxide (Na_2O)		0.22
Ferric Oxide (Fe_2O_3)		0.61
Vanadium Pentoxide (V_2O_5) (V)		Not detected

Fig. 2.4 : Chemical Analysis of Glerecedia Sample

1) <u>High Calorific Value :</u>

   As a fuel, the most important factor is the calorific value of the biomass type. There are two instances where the gross and net calorific values are measured. The net calorific value (NCV) is calculated when moisture is present in the fuel and is obviously less than gross calorific value (GCV). According to one of the sample tests carried out on samples received from Sri Lankan glerecedia plantations (Fig 2.2), the GCV is found to be within the range 4000 ~ 4300 kcal/kg (16.7 MJ/kg ~ 18 MJ/kg). When compared with thermal grade coal which carries 26 MJ/kg it is about 30% drop in calorific value. In order to account to this, about 45% more weight of biomass is to be added to the furnace for heat compensation. When compared with other biomass fuels available in Sri Lanka, glerecedia is far more ahead in terms of calorific value.

2) <u>Ease of Moisture Removal :</u>

Biomass, by its nature, packs quite a lot of moisture inside them in raw form. As the original test report says (Fig 2.3), on as arrived basis, the particular raw biomass sample of glerecedia carried 47.63% of moisture. According to sample tests, depending on the crop zone, the amount of biomass in glerecedia can vary within the range 25% ~ 60%. The amount of moisture must be reduced as much as possible to make biomass suitable to be fed to the co-firing with biomass. The drying trials carried out on biomass samples have proven the effective ways of moisture removal.

Usually the glerecedia are grown as tall sticks of about 2 ~ 5 m in length (Fig 2.5). The original form of existence will limit the ability to get rid of moisture. Therefore, the original sticks must be converted in to cut chips which will also split them (Fig 2.6).

Fig. 2.5 : Sticks of Glerecedia

Fig. 2.6 : Chopped Sticks of Glerecedia

Drying trials carried out on sticks and on the chopped, split (husked) sticks have proven that the efficiency and rate of moisture removal is significantly higher in split sticks (Fig 2.7). The source of drying for the trials was on natural basis. If forced drying is used, the rate of drying will significantly improve [13].

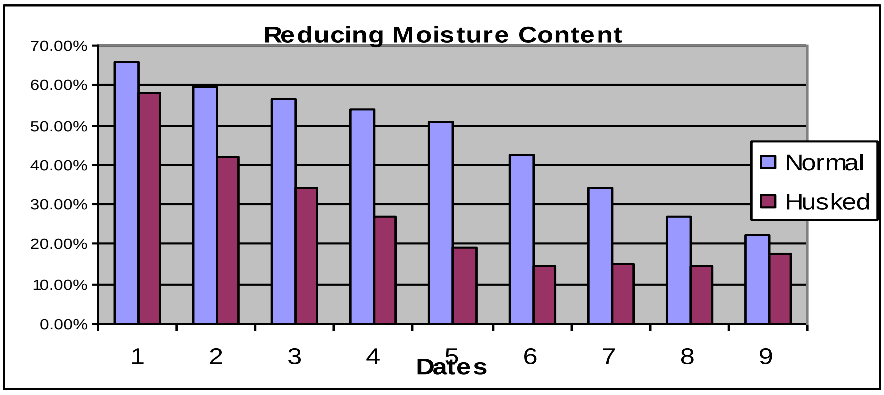


Fig. 2.7 : Moisture reduction with time for Glerecedia Raw Sticks & Husked Sticks

Based on these trails, the following conclusions are made.

- The biomass shall be husked and/or split for efficient drying
- Forced drying improves the rate of drying significantly

3) Favorable Growth Conditions, Ease of Harvesting and Transportation and Security of Supply :

The environmental conditions, rainfall, temperature, average soil, etc is favorable for growth of glerecedia in almost all parts of the country. The plantations come under dedicated plantations and also equally popular as intercropped plantations with coconut, tea and rubber. Once the plant nurseries are done, the propagation is done quite easily using grown sticks. The growth rate is very high and can yield 50t/year/ha as a dedicated crop, and 15t/year/ha as an intercrop. As it is grown in sticks spanning up to about 4m above ground, it is easy to harvest with manual labor. The transportation is also trouble free and can accommodate a large stock at a single turn because of the nature of the harvested raw biomass. The security of supply is an extremely important aspect when it comes to biomass co-firing in the long run. The local rural communities have already proven their capacity to supply a promising amount of glerecedia for existing small scale boilers. The intercrop agreements between grower and buyer are popular among large scale coconut planters since the intercropping glerecedia with coconut has many extra benefits as well. The intercropping has zero bad side effects on the main plant and have benefits such as protection to main crop against harmful deceases and insects, supply nutrients such as nitrogen to soil. Therefore, by promoting these intercrop agreements further the supply security can be improved significantly.

4) Chemical Composition :

The chemical composition of the type of biomass used is extremely important due to two reasons. The biomass being combusted in the furnace can pose threats to the lifetime and operation of the boiler [13]. There are few concerns which can affect the operations and the lifetime of the boiler.

I. Corrosive agents and/or catalysts

II. Ash content

The test report on sample of glerecedia Fig. 2.8 and 2.9 shows the chemical elements found in the biomass sample. Among the elements a two corrosive agents for metal can be identified. They are sulphur (as S and SO_3) and chlorine (as Cl). Suphur can take form of sulphuric acid (H_2SO_4) in the furnace since moisture and high temperatures are available [15]. Chloerene can form hydrochloric acid (HCl) inside. Both of these acids can be detrimental to the boiler internal metallic structure such as water walls, reheater panels, super heaters and other convective panels [18]. The high temperatures inside will accelerate the acidic corrosive reactions. From the test report, the amounts can be identified as about 0.5% for total sulphur and 0.98% for Cl. The boilers are designed to burn coal which are having certain amount of sulphur. For example, the boiler of Lakvijaya Power Station is designed to burn coal which contains sulphur in range 0.3% - 0.8%. With compared to that, the amount of sulphur present in the biomass sample is permissible. Although the amount of Cl permissible for boilers is not usually specified, it is found that if the sulphur to chlorine ratio exceeds 5 inside the boiler, the corrosive impact from chlorine gets neutralized due to sulphation mechanisms inside the boiler [4]. With the addition of majority of sulphur from coal, the total amount of sulphur exceeds way more than ratio of 1:5 against chlorine. Hence, the corrosion from chlorine is minimized and will be under control naturally.

The ash content is critical since it can cause unnecessary ash deposits on heat transfer surfaces inside boiler. This will reduce the boiler heat transfer functions and can lead to many boiler operational problems. The boiler manufacturer specifies a percentage of permissible ash content that can contain in the fuel that is being combusted in its furnace. For Lakvijaya Power Station the permissible range is 4.5% - 16% [12]. The biomass test report in Fig. 2.8 says that the amount of ash in the sample is 13.63%. It is seen that the amount of ash is comparatively low in biomass. Hence, the total fly ash output will be lower when replacing high ash content of coal with low ash content of biomass. Therefore, it is clear that the chemical composition of biomass is not detrimental to the boiler and other related equipment.

2.2 Pretreatment Plant Design

The main function of the pretreatment plant is to transform raw form of Glerecedia in to a fuel which is suitable to be sent to the furnace for co-firing with coal. The pretreatment plant has two main purposes. They are removal of moisture in biomass and reduction of particle size of biomass. When it comes to removal of moisture, the physical attributes of the biomass matters to large degree [14]. In the previous section, the relationship between the rate of moisture removal and the physical form of biomass was discussed. It was seen that the husked biomass removes their moisture faster than the non-husked raw form. Therefore, the first step in pretreatment is to alter the physical form of biomass to facilitate the comfortable reduction of moisture. For this, the chipping method is applied on Glerecedia sticks. Disc type wood chippers are used for the purpose. After converting in to suitable size, the biomass pieces are ready to get dry. The chipped sticks will be dried using a rotary type drier. The dryer will get rid of the majority of the moisture in the Glerecedia wood chips. After passing the drier, since the moisture is less in chips, they can be easily crushed to make wood dust. The dried wood chips will be crushed using a crusher to form wood dust since the fuel must be in dust form to be fed in to the boiler. After crushing, the wood dust will be stored in a silo to be conveyed in to furnace chamber using conveying air. The process flow design for the pretreatment plant is given below. An overall rate of 10t/h is to be maintained in processing biomass to match with the feeding rate of approximately 8 t/h. There are many intermediate conveyers connecting each step in the pre-treatment process. To increase process reliability, the cross conveying systems are also provided. The path of the process can be selected based on the available equipment at any given time.

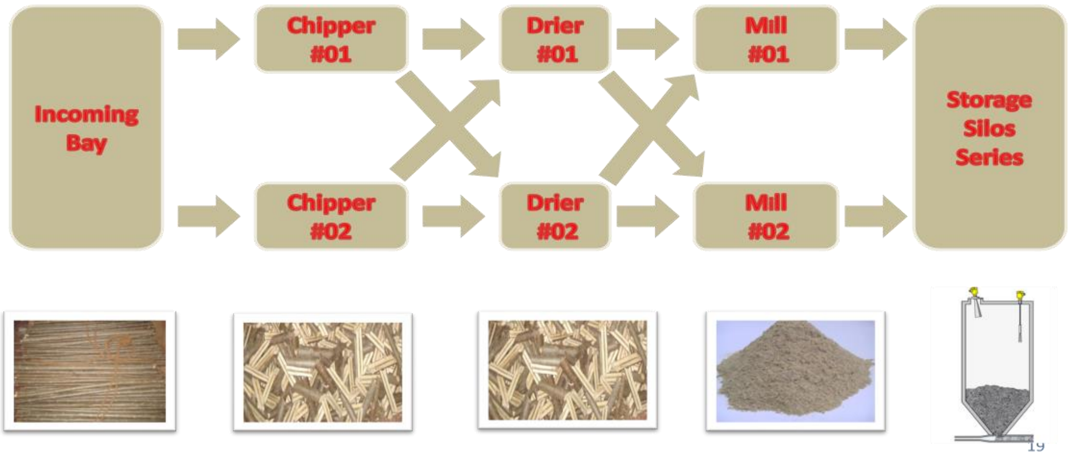


Fig. 2.8 : Process Flow Diagram for Pretreatment Plant

2.2.1 Incoming Bay

Incoming bay is designed to be the point of reception for incoming raw biomass. It is basically a semi outdoor facility which can accommodate 300t of incoming biomass when fully utilized. Usually the biomass sticks has dimensions ranging from 1 ~ 2.5m in length and 2 ~ 4cm in diameter. Light weight bulk handling equipment will be used to handle biomass. Manual labor will be used when needed to handle biomass as well. At this point, the moisture content in biomass can be as high as 50% depending on the environmental conditions [17]. The measures will be taken to reduce the storage time for biomass in this area in order to minimize further absorption of moisture. The materials will be handled on FIFO (first in, first out) basis. The raw biomass sticks will be fed in to the first stage in pretreatment system which is the chipper by manually using manual labor.

2.2.2 Chipper Stage

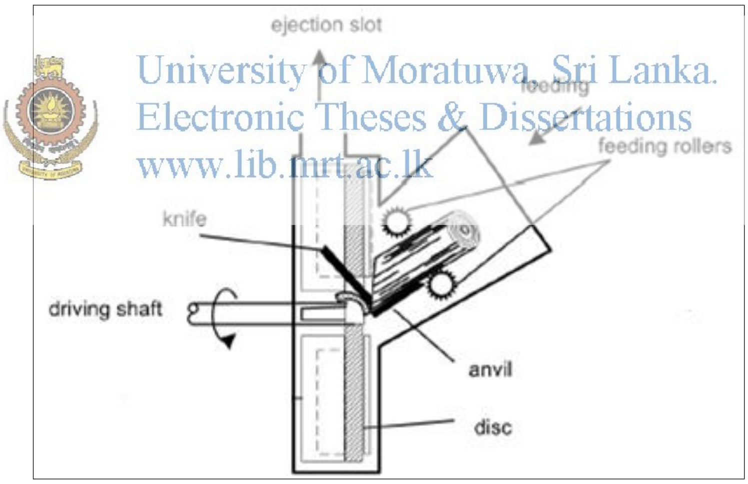


Fig. 2.9 : Operation of a disc chipper for wood

After feeding raw biomass to the conveyer from the incoming bay, the first stage is the chipping stage. Biomass having the raw form of sticks will be fed in to the chipper and the chipping disc parameters are adjusted to obtain average 20mm sized chips from them. The significance and important in chipping is that this process split opens the biomass exposing the interior of it which carries most of the moisture. Therefore, this process facilitates removal of moisture in the coming steps of pre-treatment. The disc type chipper is employed due to its ruggedness, reliability and low maintenance.

2.2.3 Dryer Stage

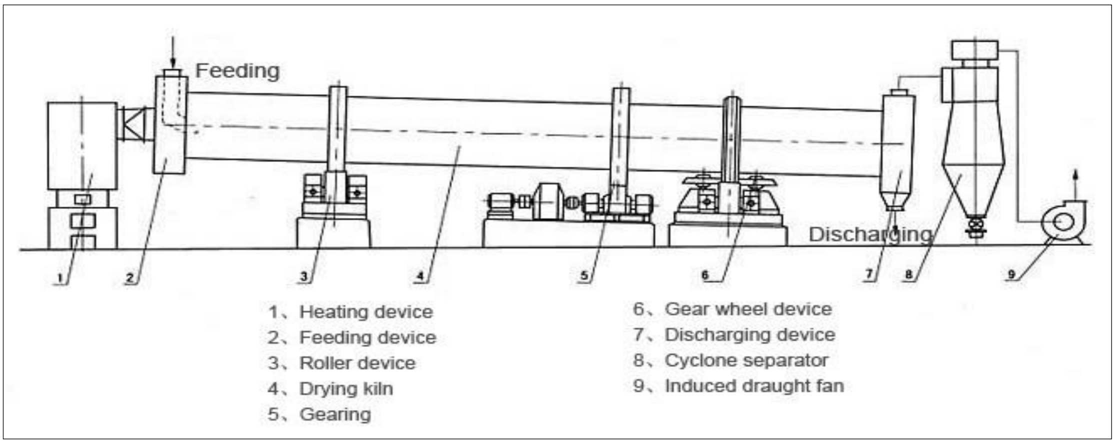


Fig. 2.10 : Operation of a rotary dryer

The cut chips are then conveyed in to the dryer for the removal of moisture. After drying, the biomass is expected to lose the majority of it’s’ moisture and become effective for the pulverizing process. The fig. 2.10 shows the parts of the dryer. The heating device consists of a heating element made of copper tubes which carries blow down superheated steam generated in the plant which acts as the source of heat. A force draft fan blows air through the heat exchanger and generates the hot gas which will then traverse in to rotary dryer kiln. The induced draft fan on the other end would support the travelling of flue gas at an efficient rate. The biomass is fed from the top corner of the kiln and due to the angle of the rotary kiln the biomass chips would travel downstream at a rate of 10 t/h. While they travel inside the biomass will absorb the heat of the flue gas and will evaporate the moisture in them.

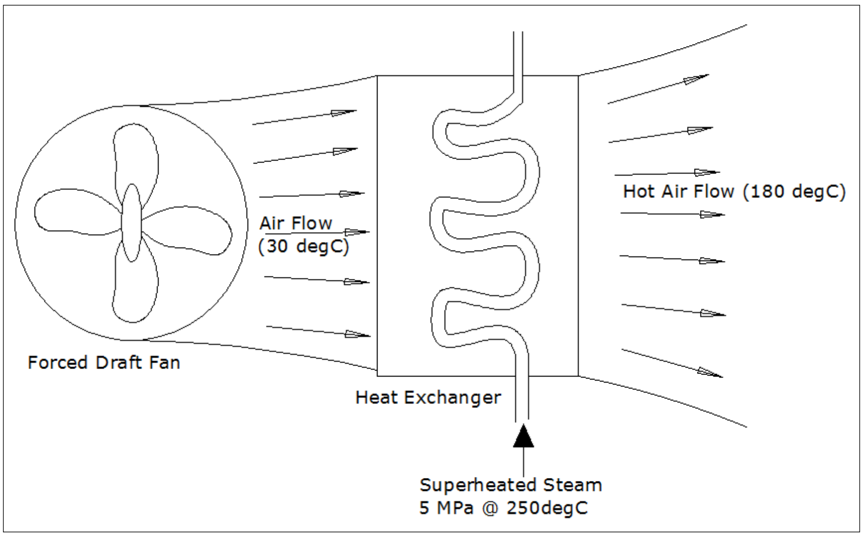


Fig. 2.11 : Dryer Heating Device

The dryer is designed to reduce 20% of the moisture from the biomass which is being processed inside. The design calculation for the heating device is as follows.

Output biomass feed rate from dryer = 10 t/h
Moisture removal percentage = 20%
The rate of moisture removal = 2 t/h

Heat energy rate required to evaporate moisture out from biomass =
Energy rate to heat up to evaporation temperature + Energy rate to evaporate

Energy rate to heat up = $\frac{mc\theta}{t}$

m = Mass c = Specific heat capacity θ = Increase in temperature t = Time

Energy rate to evaporate = $\frac{mC_e}{t}$

m = Mass C_e = Specific heat of evaporation

Total heat rate required to evaporate water @ 2 t/h = $\frac{mc\theta}{t} + mC_e$

= [(2000 kg/h) x (4186 J/kg/°C) x (70°C)] + [(2000 kg/h) x (2.26 x 10^6 J/kg)]

$\dot{Q}$= 5,106.04 MJ/h

Steam at 5 MPa pressure and 250°C used for heat exchanger. According to steam tables the specific heat capacity (h_g) for steam at above state is 2792.9 kJ/kg.

Since the heat rate shall be derived from steam to air, the following equation can be written.

$$\dot{m}_s h_g = \dot{Q} = \dot{m}_a C_a(\Delta T)$$

Where ;
$\dot{m}_s$ = Steam rate (kg/h)
h_g = Specific heat of steam (kJ/kg)
$\dot{Q}$= Total heat rate required to evaporate water
$\dot{m}_a$= Air flow rate (kg/h)
C_a= Specific heat capacity of air (kJ/kg/°C)
ΔT= Difference in temperature in air

Required air flow rate ($\dot{m}_a$) = (5,106.04 x 10^6) / (1005 x 150) kg/s

= 9.4 kg/s

Required steam rate ($\dot{m}_s$) = (2553.02 x 10^3) / (2792.9) kg/h

= 1,828.2 kg/h

The heat exchanger is designed to have ambient air at the inlet and the temperature of the heating air is increased to 180°C using the superheated blow down steam at 5 MPa and 250°C. The required airflow and steam flow rates shall be maintained to yield desired biomass rate (10t/h) at the desired average moisture output (20%).

2.2.4 Crusher Stage

After removing moisture, the biomass pieces become easier to crush with the increase of dryness. The crushers are design to crush the larger size pieces (20mm average at input) in to particles of the 1mm size. There are several reasons behind the selection of particle size to be 1mm. The main reason is the ease of conveying in to the boiler. Smaller particle sizes are harder to achieve but provides easier conveying due to low weight. Bigger particle sizes are easier to achieve in crushing processes but they weigh more and will have difficulties in conveying and there is a tendency to cause pipe clogging. The rated rate of production per crusher is 10t/h. The crusher is a hammer type mill which has several multi diameter crushing wheels (multi stage) to achieve the desired particle size. The crusher also includes an airlock system and a cyclone blower which enables separation of proper size particles. If not for the multi stage crushing system, the average output particle size of 1mm cannot be achieved. This arrangement is to make sure that none of the oversized particles get carried to the silo other than 1m sized ones. The fig. 2.12 shows a multistage hammer mill crusher with airlock and cyclone separator which has a process rate of 5t/h.

Fig. 2.12 : Crusher Mill with Airlock and Cyclone Separator [11]

2.2.5 Silo Storage

The crushed biomass is now forwarded to the silo storage. The silo is designed to act as short term storage (<1.5 hours) for pretreated biomass. The silo storage consist of four silos whose individual capacity is 15t. The total storage capacity is 60t.

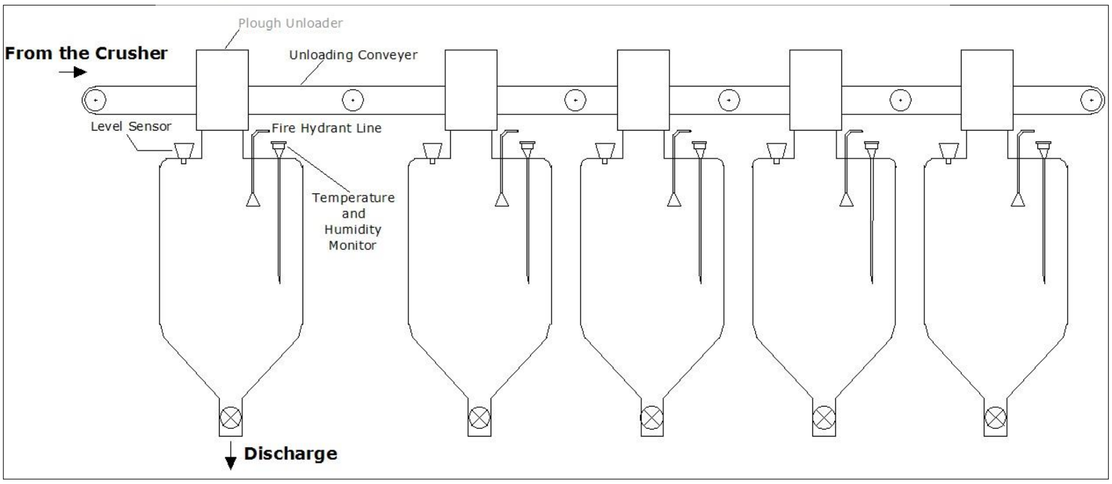


Fig. 2.13 : Silo Storage System

The crushed biomass is conveyed to the silo bay using a conveyer. Each silo has its own plough unloader. The unloading operations are semi-autonomously done based on the material level in each silo. A silo also has the level monitoring system, fire detection and extinguishing system and real time humidity monitoring system of the biomass stored inside the silo.

2.3 Selection of Co-firing Technology Option: Technical Evaluation

Three main co-firing options were introduced in last chapter. They are direct, indirect and parallel. In this section, only a technical evaluation will be carried out giving technical drawbacks and discussing other technical related concerns.

2.3.1 Direct Co-firing

Direct co-firing method involves feeding biomass materials directly to the combustion chamber in their original form of existence, but after treating suitably. There are three separate methods to do so and are described below.

2.3.1.1 Direct Co-firing : Method 1

Mix and load the treated bio fuel to the coal carrying conveyers on their way to the coal bunkers. After that, the mixture is stored and co-milled together before sending in to the furnace (Fig. 2.15). The weight of bio fuel is loaded to the conveyers based on the designed co-firing ratio. For example, since the co-firing ratio is 5%, the mass of bio fuel supplied should be able to provide 5% of the energy provided by total amount of coal. The calculation can be carried out as follows;

Average gross calorific value of bituminous coal = 26 MJ/kg

Average gross calorific value of biomass (glerecedia) = 18 MJ/kg

At 5% Co-firing, energy to be provided by biomass = 114 x 26000 x 0.05 MJ/h

Biomass feed rate to boiler for 300MW = $\frac{(114 \times 26000 \times 0.05)}{(18000)}$ t/h

Biomass feed rate per 300 MW unit = 8.234 t/h

As seen from the calculation, when one unit is running, to replace 5% weight or energy of coal, a biomass rate of 8.234 t/h shall be maintained parallel to the balance energy feeding rate. In method 1, the biomass particles will be mixed with coal feeding conveyers. Fig. 2.14 shows an example how the biomass is mixed with coal at the conveyer.

Fig. 2.14 :Mixing Biomass with coal under 1st Method of Direct Co-firing [1]

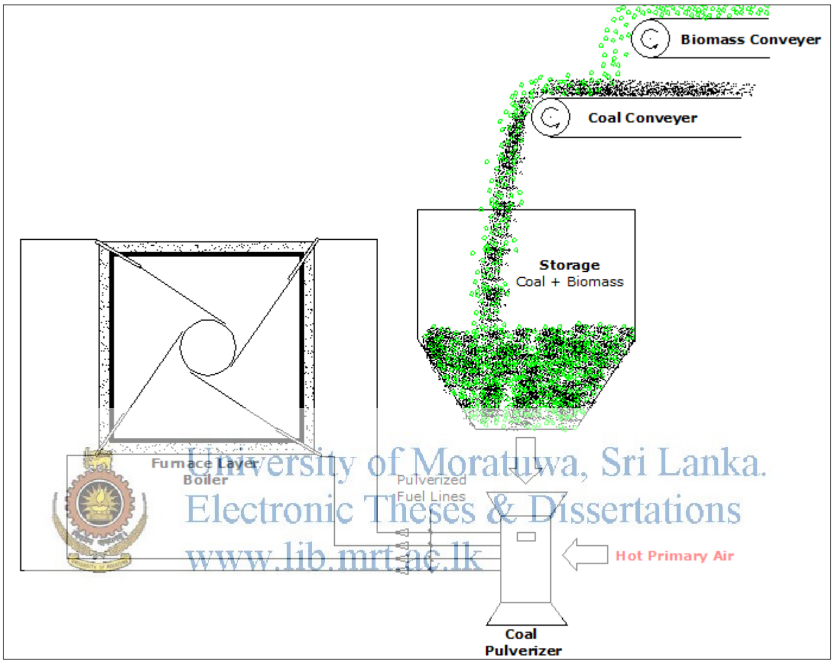


Fig. 2.15 : 1st Method of Direct Co-firing Process Schematic

This mixture will be conveyed in to a set of bunkers where the mixture will be stored before fed in to the pulverizer. The storage time may differ based on design, and can range from few hours to few days. In the pulverizer, the mixture is milled together to form a mixture of pulverized coal and biomass. The mixture is conveyed to the boiler furnace after mixing with hot primary air, using existing pipelines.

Advantages :

- Lowest amount of investment, design and construction involved [1]

Disadvantages :

- Non-uniformity of the mixture when fed to the boiler
- Risk of fire due to long term storage of biomass with coal in bunkers/silos [17]
- High possibility of mill overload

- High possibility of mill clogging and line clogging

Although, the amounts of construction work involved are minimum, there are some serious drawbacks in this method which involves risks that cannot be neglected. It is important that the 5% ratio is maintained in the combustion chamber. Since both coal and biomass are fed in to the same storage silo, it is impossible to predict whether the two materials are packed inside the storage in a uniform manner. The usual case is that they are packed in a random manner and when they are being released from the bottom, the mixture ratio can be changed significantly. If the mass ratio is not properly maintained within limits of 5%, the combustion chamber dynamics, heat zones will be altered in unimaginable ways and will also result in flame instability. These phenomena would affect the steam generation process in a larger scale and can demolish the balance achieved within the steam cycle. As a result, not only many operational malfunctions can occur, but also there is a possibility of an accident. So, this method, since the mixture ratio is not properly maintained, can result the above explained case. The air system modifications are not required as the mixture is blown through the mill itself using the ordinary hot primary air supply which is supplied to the mills.

Apart from that, owing to the high amount of volatile matter in biomass than in coal, there is a higher risk of silo fire. The special case is found to be dangerous when both coal and biomass is stored as a mixture [1]. There had been some similar fire accidents in the global scenario as well.

Finally, since the mills and lines will be shared by biomass, there is an obvious risk of clogging. Usually coal pulverizers are designed to grind coal under a certain specified grind ability index. Biomass, unlike coal is less brittle and less grind able even if the moisture is fully removed during pretreatment phase. Therefore, using coal grinders to grind biomass to form dust will not yield expected result as for coal and also will provide extra loading for mills. The ungrinded large biomass particles will block and clog the output lines which carry coal dust mixed with hot air. This way, it will provide additional issues while trying to co-fire biomass. With a moderately high biomass feed rate of 8.234 t/h, there is a high probability that these issues will only become serious with the long term operations [12].

2.3.1.2 Direct Co-firing : Method 2

Under the 2nd method, biomass and coal are stored, milled separately and the pulverized biomass is injected in to the existing pulverized coal pipe work either upstream of the burner or at the burners. The simplified process schematic is shown in Fig. 2.16.

At 5% co-firing ratio when the unit is running at full load, the rate of biomass that will be added to the pulverized coal stream is 8.234 t/h in total. Usually, there are four pulverized coal lines conveying to each boiler layer corner. So, there should be four individual biomass feeding lines connecting to four pulverized coal pipes travelling to four corners in the same layer in the boiler. Since there are four mills (out of the five) running during full load operation, there are a total of 20 lines running to boiler out of which 16 lines carry biomass since 4 pulverisers are in operation when operated full load. The total biomass feed rate is to be divided in to four before conveying after mixing with air. Therefore, the biomass feed rate for one line is about 0.52 t/h. This way, the total biomass flow is uniformly distributed within the four corners (16 lines total) of a single layer and will be the same for all layers. It will help greatly towards retaining the flame stability, since two types of fuels are being combusted.

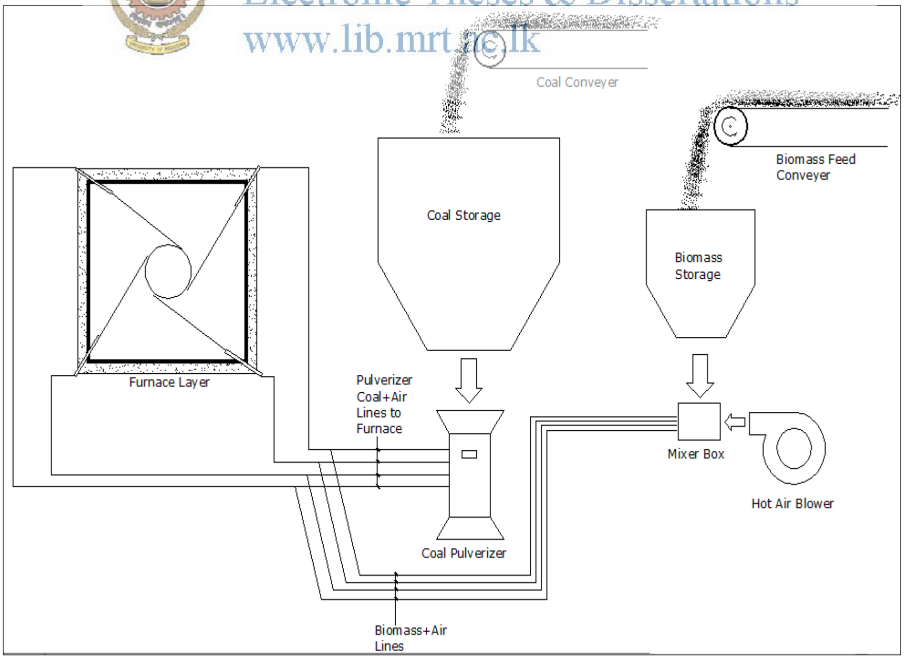


Fig. 2.16 :2nd Method of Direct Co-firing Process Schematic (feeding to single layer)

When biomass feed rate in a single line is 0.52 t/h, the pulverized coal flow on the same line is about 6.785 t/h. While improving the flame stability, more importantly it will decrease the effect on existing heat zones within the boiler. However, generally, in similar power stations which are now in operation, only single layer is used for injecting biomass and they seem to work without an issue [1].

The advantages and disadvantages of the method can be listed as follows.

Advantages :

- No mill overload and clogging
- Less fire risk in silo storage
- Line clogging can be made minimum
- Operational flexibility (ratio assurance and variability) [12]

Disadvantages :

- Line clogging still exist in smaller proportions

This method addresses several major drawbacks existed in method 1 and can be clearly distinguished as an improved version of the same. The most noticeable improvement is the achievement of co-firing ratio controllability. With the current setup, the co-firing ratio can be adjusted to any value between 0~5% at any given instance during operation. The air side modifications are required for biomass feed. A separate hot air blowing system is required for biomass system with the option of diverging a part of primary hot air in to the biomass mixer box. The hot primary air flow should be reduced from the coal side and the very same amount shall be added from biomass blower side. The temperature is also should be kept at the same value as hot primary air. This is essential since the total primary airflow in to the furnace needs to be kept constant. Usually, a fuel to air ratio greater than or equal to 1:2.5 is to be maintained in the pulverizer system.

Mill overloading, clogging and fire risk is overcome using separate storage and milling. The line clogging drawback is still at large due to the nature of biomass and since the pulverized coal lines are lengthy. But it can be minimized by injecting pulverized biomass in to the pulverized coal pipeline near to the burner in boiler.

2.3.1.3 Direct Co-firing : Method 3

The major difference in this method with compared to the above two is that the pulverized biomass is not mixed with pulverized coal before feeding to the boiler. Here, biomass is fed to boiler using a separate pipeline without mixing to pulverized coal pipes. Therefore, at least a single separate layer is to be constructed with four corner injecting nozzles dedicated to biomass. For a co-firing ratio of 5%, only one additional layer is enough for a single unit of 300 MW, since the total amount of biomass to be injected is as small as 8.234 t/h with compared to coal injection rate of over 100 t/h. As the process schematic shown in Fig. 2.17 clearly indicates, the biomass is being fed to the separate layer above the coal layer. The biomass layer may be added to anywhere as the designer prefers. It can be top, bottom or middle of the existing coal guns. Another significance of this method is that the biomass feeding system operates completely independent from the coal feeding system without any connection to it.

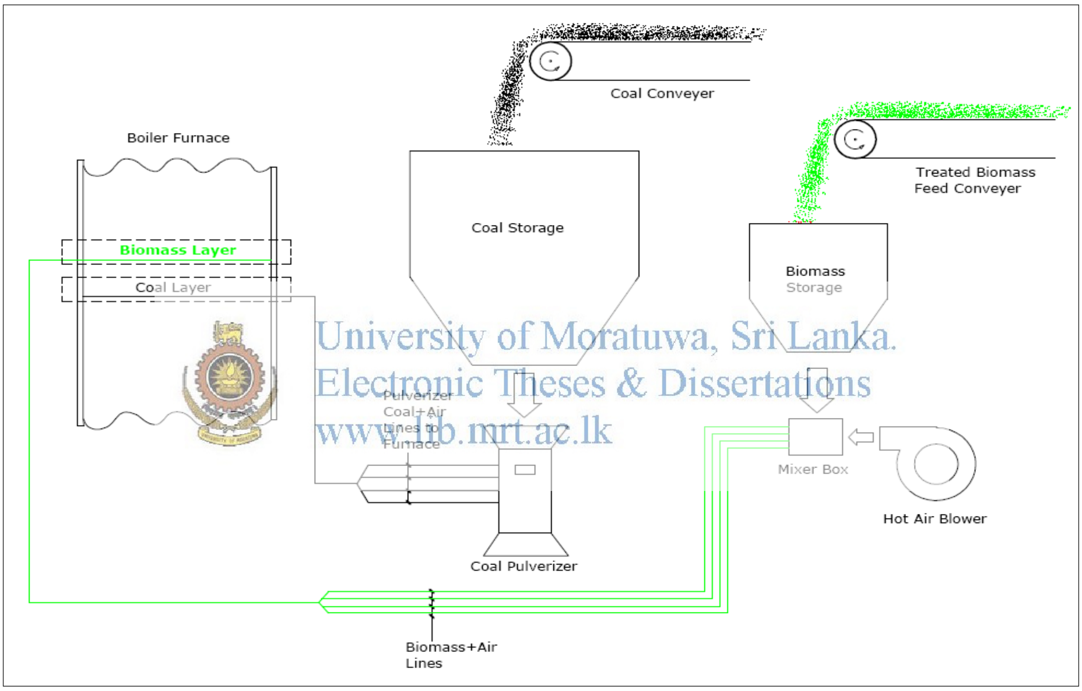


Fig. 2.17 : 3rd Method of Direct Co-firing Process Schematic

Advantages:

- No mill overload and clogging
- Less fire risk in silo storage
- Zero line clogging in coal pipelines
- Operational flexibility (ratio assurance and variability)

Disadvantages:

- Serious alteration in furnace internal dynamics and heat zones
- Higher amount of construction work to be done

Further improvements to method 2 can be noticed in method 3 due to overcoming the line clogging issue in coal pipelines. As the two feeding systems coal and biomass now operated independently, no mill or line clogging will occur in coal feeding system. This adds more reliability in to the whole plant as the coal feeding system now operates in a hassle free. The advantages present in method 2, the fewer fire risks and the operational flexibility are also present in method 3.The air side modifications in method 2 are also required in method 3. The same logic applies to air flow adjustments on biomass and coal sides.

The most important point in this method is the disadvantage that can be strongly noticed and cannot be neglected at all when attempting to retrofit to an existing unit.

2.3.2 Indirect Co-firing

The indirect co-firing option involves gasification of biomass. The fuel gas produced by the gasification is directly injected. The option is considered to be a more complex one compared to others due to several reasons. There are no particular advantages compared to other methods discussed. The complexities and disadvantages involved with the method are listed below.

- The exact attributes of output fuel (syn gas) product from the gasification is unpredictable. Calorific value is generally low and the variation is possible depending on the moisture content of biomass. The cleaning is required to remove undesirable debris from the gas.[1]
- Unlike other options, the co-firing fuel is a gaseous substance and the combustion dynamics can vary drastically depending on the fuel quality. [2] Separate specialized study need to be carried out on the aspect before trails.
- Major capital cost component is added to the overall cost with the addition of gasifier hence the investment return incurs a major delay (approximately fifteen times) with compared to cheapest direct co-fired options which can deliver same energy amount.
- Sulphur content can be increased during gasification hence can increase SO_x emissions. [9]

2.3.3 Parallel Co-firing

The parallel co-firing option involves installation of a separate combustor and a boiler for biomass. The steam produced from the biomass boiler steam cycle will be used in the coal fired power plant steam circuit. When compared with others, this method requires the highest capital costs of all due to heavy installations involved [1]. The total capital investment can be as high as up to thirty times as a directly co-fired option. But, it is proven to be advantageous if the biomass fuel available is hard to burn and contains heavy alkali metals, chlorine, etc [2]. This way, the corrosion of the boiler, slagging and fouling inside the main coal fired boiler can be overcome completely. In terms of technicalities, the method involves a lot of technical considerations and a separate detailed study needs to be carried to find out the exact aspects in design.

2.3.4 Conclusion

It is clear that in technical aspects, as mentioned above the indirect co-firing method needs to be reviewed in further details in order to decide whether it is a viable candidate on a local context. Out of the remaining candidates, the parallel co-firing option is technically advanced and also needs a detailed study before approving. Hence, as this research is concerned, only the three direct co-firing options are available for the conclusion, as for which option to be used for the co-firing with coal in the same boiler.

Usually, a pulverized coal fired unit has several coal layers and the number of layers depends on the capacity. A typical 300MW unit has 5 layers, but only 4 layers are fired in full capacity to reach full load and the other layer and it’s mill is kept as redundant. The orientation of layers can be seen in the second sub figure in Fig. 2.18. Under option 3, an additional layer dedicated to biomass is added to the boiler furnace area as shown in the first figure in Fig. 2.6. The addition of the new layer can be done at any place within 5 layers of coal. If reviewed in detail, the addition of the separate biomass layer can affect the original boiler design in various ways.

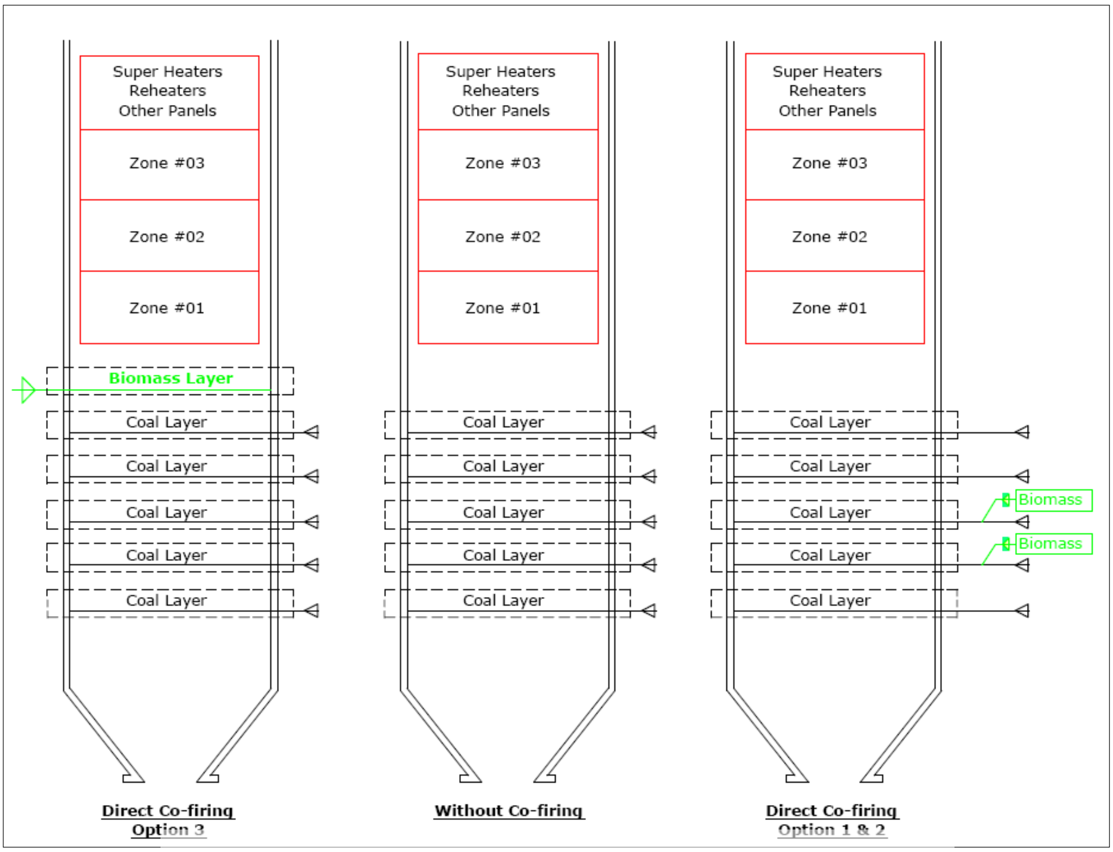


Fig. 2.18 : Comparison of all three options (section view of boiler)

1) <u>Extension of combustion area</u> : -

As clearly shown in the Fig. 2.18, the 3rd method will extend the combustion chamber volume. In addition, the new areas will combust a fuel with about 30% lower calorific value than coal [13]. While all four layers of coal combust the original designed fuel, the dedicated layer would fire biomass among them. Generally this will alter the original intended heat zone design inside the boiler (Fig. 2.18), temperature gradients, etc in the boiler. The reason for this is that the drop in calorific value is significant when fired in a dedicated layer, rather than mixing with coal and firing in a coal layer. As a result, the heat absorption assemblies in the boiler such as super heaters, re-heaters, economizers, etc will not be able to maintain their designed temperatures and steam pressures [15]. This will lead to a major change in the various stages of the steam cycle and may lead to unpredictable dangerous consequences of the unit. The first and second methods do not have such effects on boiler since both of them won't alter combustion chamber volume. On the contrary, they will only replace a relatively small amount of coal with biomass while keeping all other important parameters such as total air flow, air temperature, pressure, etc almost constant and/or within acceptable range.

2) Addition of a New Primary Air Injection Port :-

Originally, a 300MW pulverized coal fired boiler is designed to have five layers which will inject hot primary air mixed with coal in to the furnace at a specified rate. Out of the five layers, any four layers will inject coal at a time during full load operation. When running at full load, a typical 300 MW unit consumes 114 t/h of coal. When running at full load with 5% co-firing, the four layers burning coal will have to cut down on coal. As a result, in order to conserve the 1:2.5 ratio, the air flow will also have to be cut down in all four layers. On the other hand, the biomass layer would need an air flow rate. The calculations can be carried out as follows.

When not co-firing the coal flow in to a single layer = 114 / 4 t/h
= 28.5 t/h

The total air flow in to a single coal layer = 28.5 x 2.5 t/h
= **71.25 t/h - - - - (1)**

Assuming 5% Co-firing rate : -

Total biomass rate @ 5% CFR = 8.234 t/h

The drop in coal flow due to injection of biomass = $\frac{(8.234 \times 18)}{26}$
= 5.7 t/h

Total coal flow in to the furnace (4 layers) = (114 – 5.7) t/h
= 108.3 t/h

Total coal injection at a single layer = 27.08 t/h

Total air flow in to the furnace through single layer = 27.08 x 2.5 t/h
= **67.7 t/h - - - - (2)**

Air flow in to the furnace through biomass layer = **20.59 t/h - - - - (3)**

As per the calculations, the air flow rates have now altered for every level and an additional layer has been added which was not there before (Fig. 2.19). It is very clear from the figure, that using the existing coal lines for biomass injection is very much the best option compared to option 3 which uses a separate injection port. The simple reason is that the original airflow arrangement is best conserved in it.

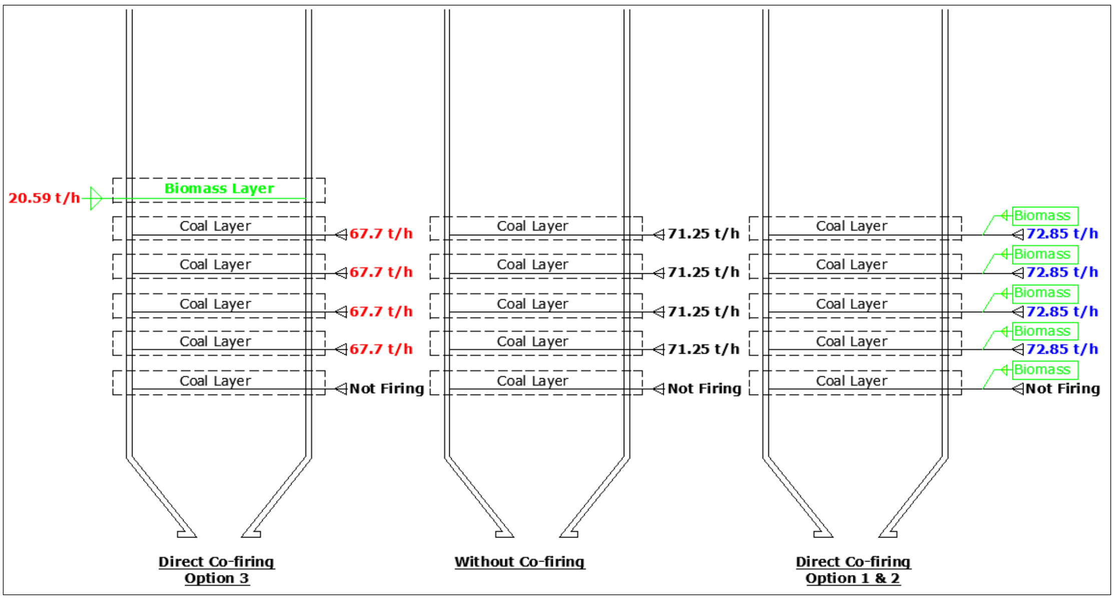


Fig. 2.19 :Air flow rates in to furnace during all Direct Options

Further, adding an extra layer causes injection velocities to lower on all coal layers while there is an extra velocity component which wasn't there before. The major catastrophe that can occur due to this is that change in particle resident time changes. Due to lower injection velocities, the fuel particle resident times will be slightly higher and the low velocities of flue gas will occur. These phenomena will create an anomaly in the furnace interior.

Therefore, it is clear that the 3rd option of direct co-firing is not technically suitable for the application. Out of the two options left (Direct Co-firing : Option 1 & 2), the advantages and disadvantages can be listed out as shown below.

Direct Co-firing : Option 1		**Direct Co-firing : Option 2**	
Advantages	***Disadvantages***	***Advantages***	***Disadvantages***
• Lowest amount of investment, design and construction involved	• Non-uniformity of the mixture and non-grind ability	• No mill overload and clogging	• Line clogging still exist in smaller proportions
	• Risk of fire due to long term storage of biomass with coal in bunkers/silos	• Less fire risk in silo storage	
	• High possibility of mill overload	• Line clogging can be made minimum	
	• High possibility of mill clogging and line clogging	• Operational flexibility (ratio assurance and variability)	

Table 2.1 : Comparison between Direct Co-firing Options 1 & 2

By comparing the options given in table 2.1, the following can be deduced.

- *Option 1 has the most number of technical disadvantages with compared to option 2.These technical disadvantages cannot be overcome easily with the current type of biomass.*
    - Non uniformity of the mixture, non-grind ability, clogging and overload :

      The packing patterns of biomass and coal cannot be controlled when inside the bunker. Owing to that, the co-firing ratio cannot be control and it will vary unpredictably resulting undesired phenomenon in the furnace. The pulverized coal power stations mostly use the bowl mills which are designed to grind coal having HGI (Hargrove Grindability Index) of 45 - 70. The equivalent index for biomass under normal physical conditions is usually below 20 [5]. Therefore, the co-milling of glerecedia with coal cannot be done in pulverized coal power stations. If attempted, mill overloading and clogging can occur.
    - Bunker Fire risk :

      The coal and biomass will be stored in the same bunker. The storage time for a single particle can range from 8 – 9 hours, depending on the plant dispatch pattern. Coal has a higher calorific value than biomass and both fuels have a significant amount of volatile matter. Apart from that, since biomass is handled and stored for several days, they emit methane in small amounts when stored in silos [4]. Due to all these phenomena and prolonged storage, with air trapped inside, the probability of a bunker fire gets increased. Due to the temperature increase in the surroundings, the risk gets further increased.

- *Option 2 overcomes the majority of the technical disadvantages found in the option 1.The only technical disadvantage present in option 2 can be considered as a minor one and can be overcome by adopting necessary technical measures.*
    - No mill overload and mill clogging :

      Since the glerecedia is pretreated by other methods, the mill usage is not required. Therefore mill overload and mill clogging is not present.

- Reduced fire risk :

  A dedicated storage is designed for biomass (no mixing with coal). The residence time is reduced to 3 hours by making the silo smaller in order to reduce the fire risk further.
- Achieving Control over co-firing ratio :

  Now that the biomass and coal are being prepared separately and injected at two separate places, the energy ratio between biomass and coal fed to the boiler can be controlled in real time operations. Therefore all operational and safety objectives can be achieved with the same.
- The line clogging can be minimized :

  Since the biomass injection is done to existing coal pipelines, biomass can clog lines in small proportions. This can be further minimized, by finding the closest possible place to the coal gun to install the biomass injectors. This point will be calculated, designed and decided during final design stage and is discussed in the final design stage.

Based on above technical justifications, it can be concluded that the direct co-firing option 2 is the most technically viable option for co-firing glerecedia as biomass in a pulverized coal fired boiler system. Among all other options, this method is the easiest to implement and can be retrofitted to the existing system without raising much technical concerns.

2.4 Final Design

2.4.1 Introduction

From the co-firing option detailed comparison, it was concluded that the direct co-firing option 2 is the technically most viable to implement as a retrofit option on an existing pulverized coal fired power station. The overall process schematic for the selected option is shown in fig. 2.20. The indicated technical aspects shall be addressed and solutions shall be designed to technical issues encountered. After addressing all of them, the final design can be yielded.

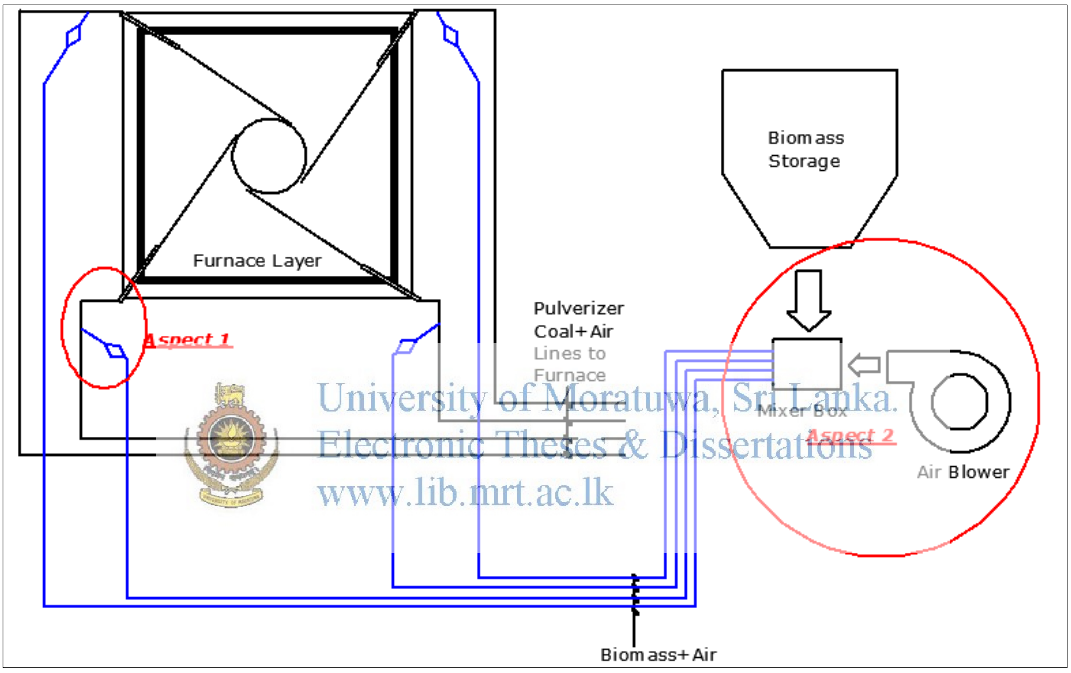


Fig. 2.20 : Overall Process Design Schematic

2.4.2 Design Aspects

Several aspects can be identified as individual technical problems that shall be addressed separately. The overall process design schematic for direct co-firing option 2 is shown in fig. 2.20 shows two separate problems as such. Each of these are to be analyzed separately and develop a solution to overcome all concerns involved. The two can be briefly described as follows. It is also noticed that these aspects must be addressed in the exact given order due to their interdependent nature. Finally, the control system logic for the whole system will be implemented using ladder logic.

1) *Aspect 1 : Injection Mechanism for Biomass*

In this co-firing option, the biomass mixed with air is to be injected in to the exiting coal pipelines running to the boiler. There are several technical parameters to be preserved when doing so. If the injection system is not designed to preserve those parameters, it will affect the boiler operational stability at that instance.

2) *Aspect 2 : Biomass Feeding & Conveying System Design*

The feeding system shall be designed to facilitate proper conveying of biomass up to the injection point and also to mix biomass evenly with air. All of these shall be properly addressed under this aspect, to achieve success in co-firing.

2.4.2.1 Injection Mechanism for Biomass

When injecting biomass in to the existing coal conveying pipeline, there are several parameters to be preserved and to be considered. The ideal objective is to mix coal and biomass mixtures to form a uniform mixture which will traverse to the combustion chamber. The following requirement must be met when designing the injection system.

1) The flow velocities of the mixture before and after injection shall be within acceptable limits (5% as incoming) [7]

The existing coal conveying system pipeline poses the following parameters.

- Pipe Internal Diameter : 0.53 m
- Pipe Thickness : 0.01 m
- Coal with Air Flow : 24.93 t/h @ Full Load
- Average Flow Velocity : 24– 29m/s @ Full Load

The flow calculations for coal and biomass can be done as follows. There are 16 total coal lines conveying coal in to the furnace and each line is injected with glerecedia. Hence, there is a total of 16 biomass lines.

When co-firing glerecedia at 5% co-firing ratio;

Total Coal amount replaced by biomass (4 layers/16 lines) = 114 x 0.05 t/h
= 5.7 t/h

Amount of coal to be conveyed per line (1/16 lines) = (114 – 5.7)/16 t/h
= 6.769 t/h

Air quantity required for complete combustion & conveying (1:2.5 fuel to air ratio)
= 16.923 t/h

The above amount of coal (GCV 26 MJ/kg) is to be replaced with Glerecedia (GCV 18 MJ/kg)

Total amount of biomass replacing the same coal amount = 5.7 x (26/18) t/h
= 8.234 t/h
Amount of biomass to be conveyed per line (1/16 lines) = 8.234/16 t/h
= 0.515 t/h
Air quantity required for complete combustion & conveying (1:2.5 fuel to air ratio)
= 1.288 t/h
Total flow (air + biomass) from Biomass injection side = 1.803 t/h
Total flow (air + coal) from coal conveying side (per line) = 23.692 t/h

The typical arrangement for biomass injection for the above system at 5% co-firing is shown in fig. 2.21. The flow parameter calculated above and some of the related technical parameters are also shown in the same.

Fig. 2.21 : Glerecedia Injection Point

The two key parameters (D & Q) are to be optimally decided while keeping the two main requirements satisfied.

D : The diameter of the glerecedia injection pipe

Q : Angle of Injection for glerecedia flow

2.4.2.1.1 Deciding Optimum Values for D & Q

There are some important relationships involving D & Q, at the point of injection, that need to be understood in order to decide on best values for D & Q. Under the requirements, the flow velocities after and before injection are to be kept almost constant without a major deviation. The velocities at the point of injection can be represented as shown in fig. 2.22.

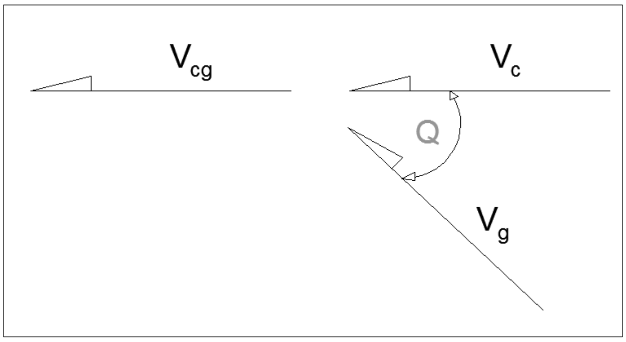


Fig. 2.22 : Representation of Velocity Components at the Point of Injection

V_c : Velocity of particles in coal flow before injection
V_g : Velocity of particles in glerecedia flow before injection
V_{cg} : Velocity of particles in coal and glerecedia mixed flow after injection

The relationship between the components can be written as ;

$$V_{cg} = V_c + V_g[\mathrm{Cos}(Q)]$$

In order to satisfy the first requirement, the deviation between V_{cg} and V_c should not exceed 5%. From the above equation, it is clearly seen that the velocity of the mixture after the injection will be a much higher value than the original and exceed 5% mark. Therefore, both parameters D & Q shall be selected to minimize V_{cg}.

Glerecedia injection pipe diameter (D) is directly proportional to V_g. By maximizing the diameter, the injection velocity can be minimized. Since the coal pipe internal diameter is 0.53m, the maximum possible diameter that agrees with the practical construction is 0.5m. So it can be decided that the optimum value for D is 0.5m.

Another measure can be taken to minimize the effective injection velocity by varying the injection angle (Q). Ideally, Q can be varied within the range of 0° - 180°. As per the variation of the cosine value of the angle, the value 90° will cancel the effect of injection velocity component. Angle less than that will add the effect, which will increase the velocity after injection and any angle more than 90° will give a negative effect to the velocity after injection, which will decrease the overall velocity after injection. This is also not meet with the velocity requirement at the point of injection. Therefore, the 90° is the best value for angle of glerecedia injection (Q).

Therefore the best possible value for Q & D are as follows.

$$Q = 90° \qquad D = 0.5\ \mathrm{m}$$

The criteria, the scenario was modeled in 3D space with actual flow parameter and simulated using Solidworks 2014 CFD. The model is shown in fig. 2.23.

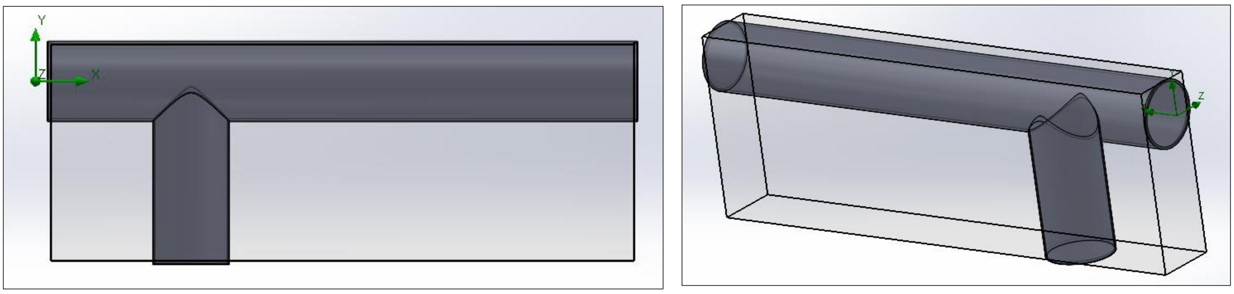


Fig. 2.23 : Solid Works 3D CFD Flow Analysis Model for Velocity Simulation

The results showed that the velocities are still comparatively higher and the criteria doesnot satify the velocity requirement for the design (Fig. 2.24). As per the plots, the average velocity after injection reaches an average of 31.2 m/s which is about 15% more of the original incoming velocity 27 m/s, and it doesnot satisfy the requirement.

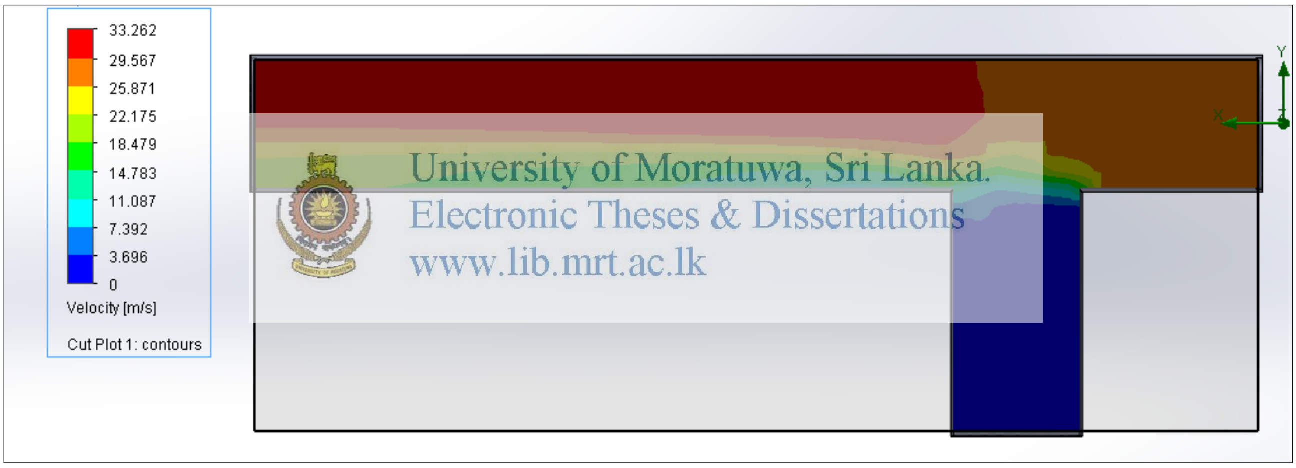


Fig. 2.24 : Pipe front plane section Results for Velocity Analysis

Therefore, the model arrangements must be redesigned, so that the original velocity will remain within the safety margins after injection.

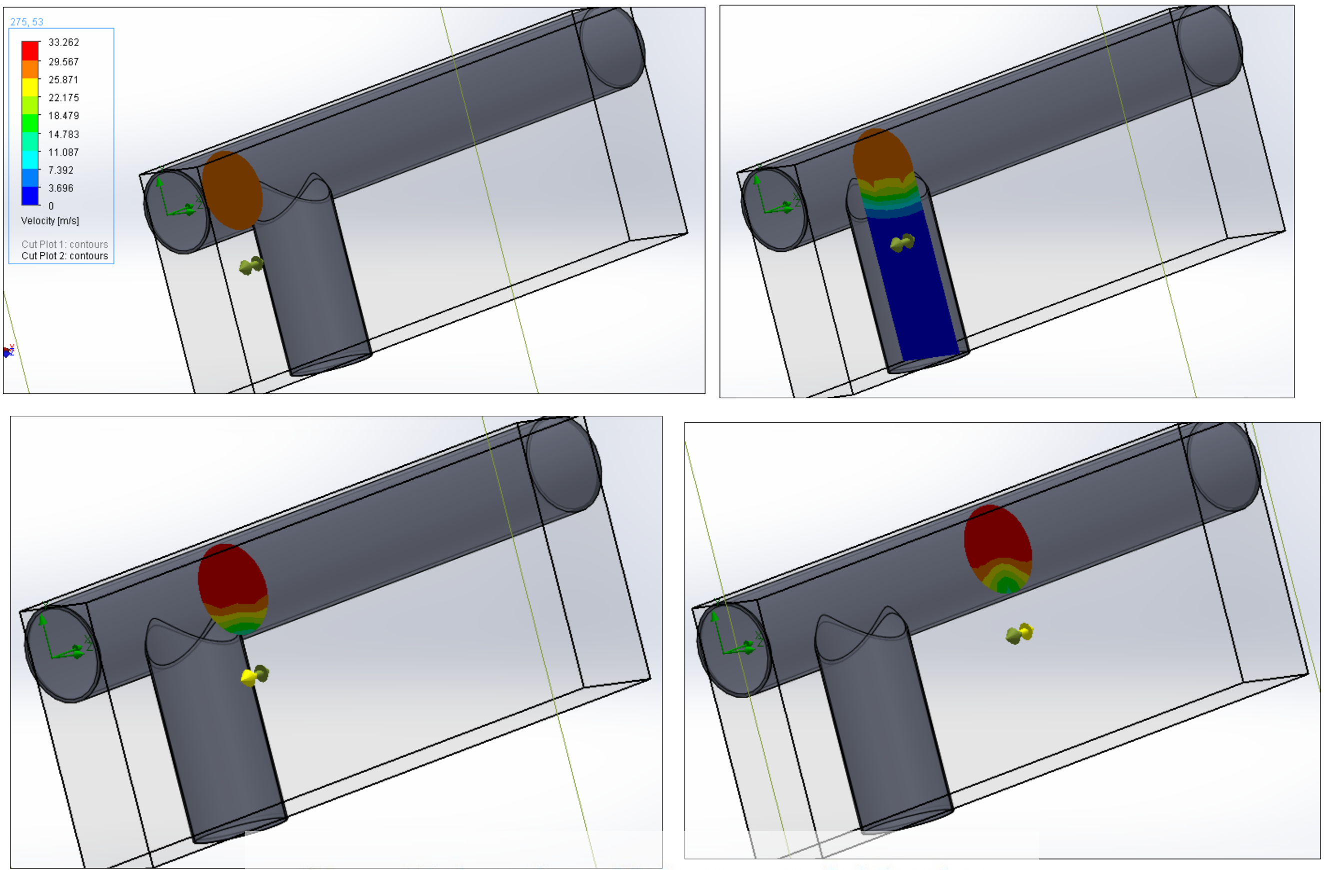


Fig. 2.25 : Velocity Cut Plots along the pipe cross section

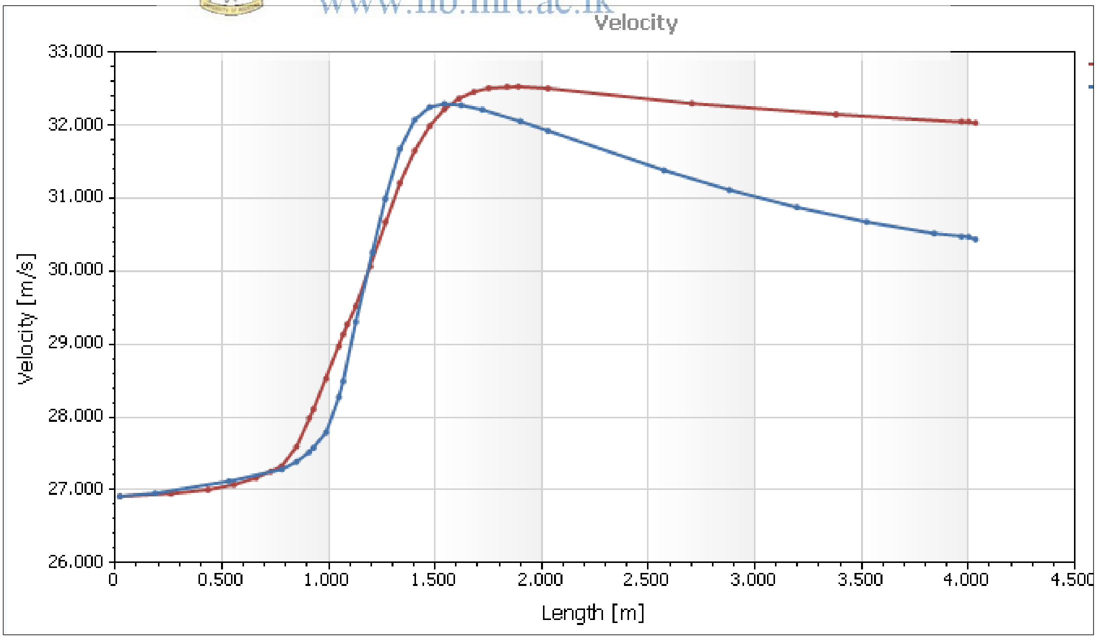


Fig. 2.26 : Velocity Plots Along the Length of the Pipe

To over the velocity increase problem, an expander is added to the main pipeline after the point of injection (Fig. 2.25).

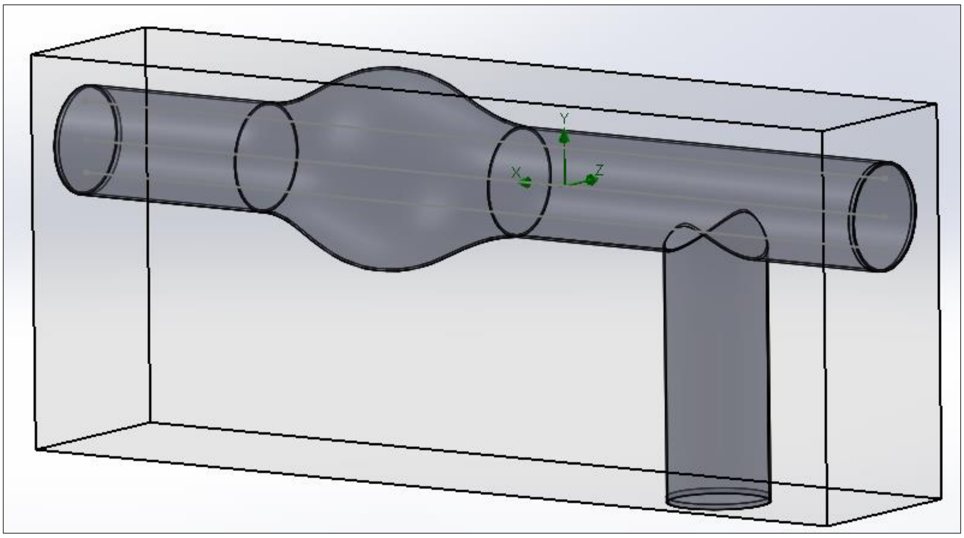


Fig. 2.27 : Modified Flow Analysis Injection Model with Expander

The modified model was resimulated using Solidworks 2014 CFD tool. The velocities were reanalysed after the simulation.

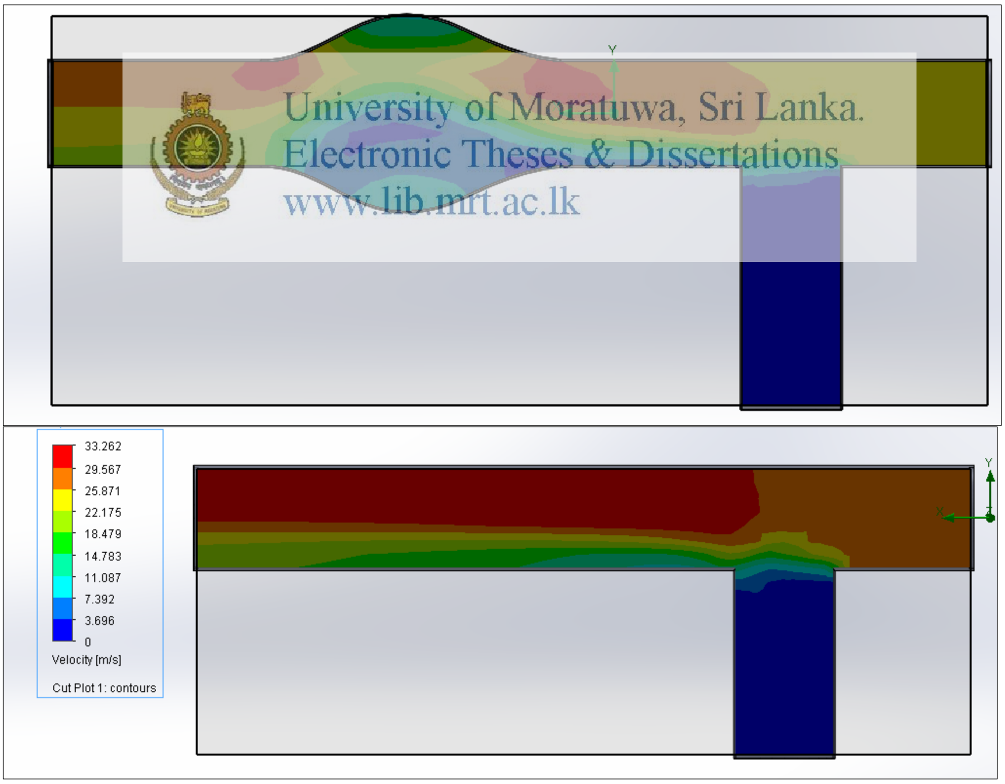


Fig. 2.28 : Pipe front plane section Results for Velocity Analysis with Expander (above) & Comparison with the case without expander

After the simulation was done on the modified model, the results showed a considerable improvement when compared to the scenario before (Fig. 2.16). The velocities are now decreased due to the addition of expander. The velocity plot shows that now the average velocity after injection reaches a value of 26.8 m/s while the value before injection is about 26.9 m/s. The results clearly show that the addition of expander has led to achieving the targeted velocity targets since the velocities before and after injection are now almost the same (Fig. 2.29). Hence, it can be concluded that the injection of biomass in to existing coal pipelines is successful when expanders are introduced.

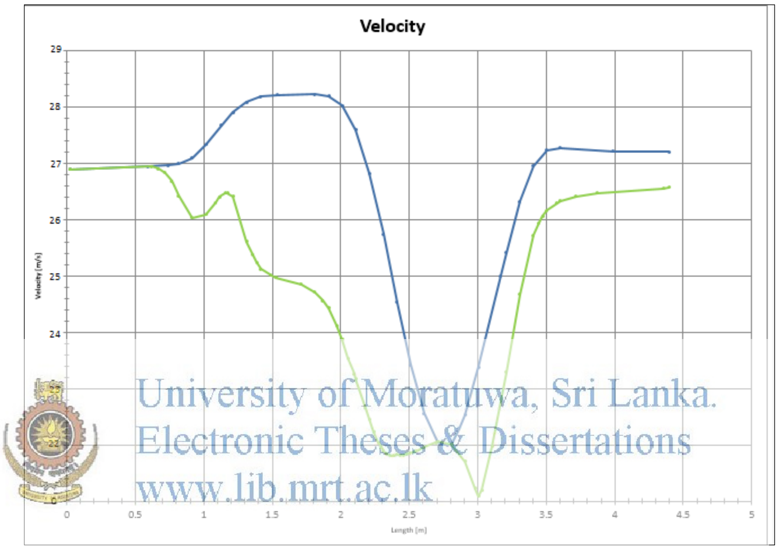


Fig. 2.29 : Velocity Plots along the Length of the Pipe after adding Expander

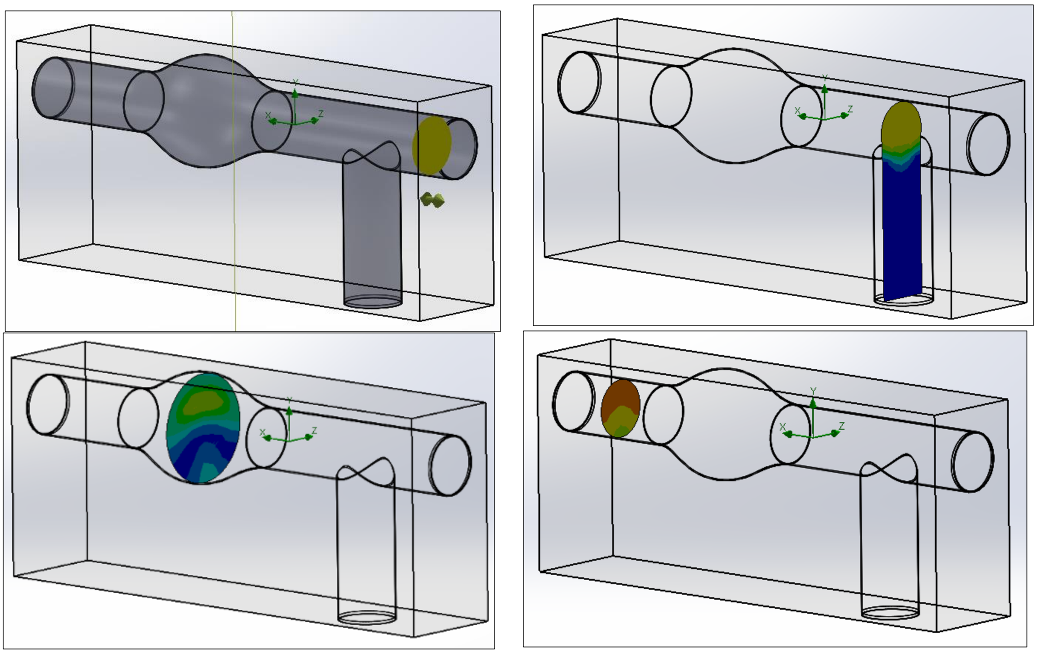


Fig. 2.30 : Velocity Cut Plots along the pipe cross section with Expander

2.4.2.2 Biomass Feeding and Conveying System Design

The biomass conveying system shall be designed to achieve proper conveying of biomass after mixing with air from the mixer up to the point of injection. The pre-treated biomass is stored in five silos. Each silo will have a feeder which feeds the pre-treated biomass to the conveying air system. The feeder will also measure the biomass feeding rate and will keep it within the operator setting accordingly for the preset co-firing ratio. After the feeder, the biomass is directed to the air manifold using a tree conveying arrangement which will divide the biomass flow in to four equal flows (Fig. 2.32). The four identical biomass flows are to be mixed with the four air flow pipes going to the point of injection (four corners). The tree arrangement surface is subjected to vibration using mini vibrator devices in order to ease the traveling down of biomass through the pipes with the support of gravity.

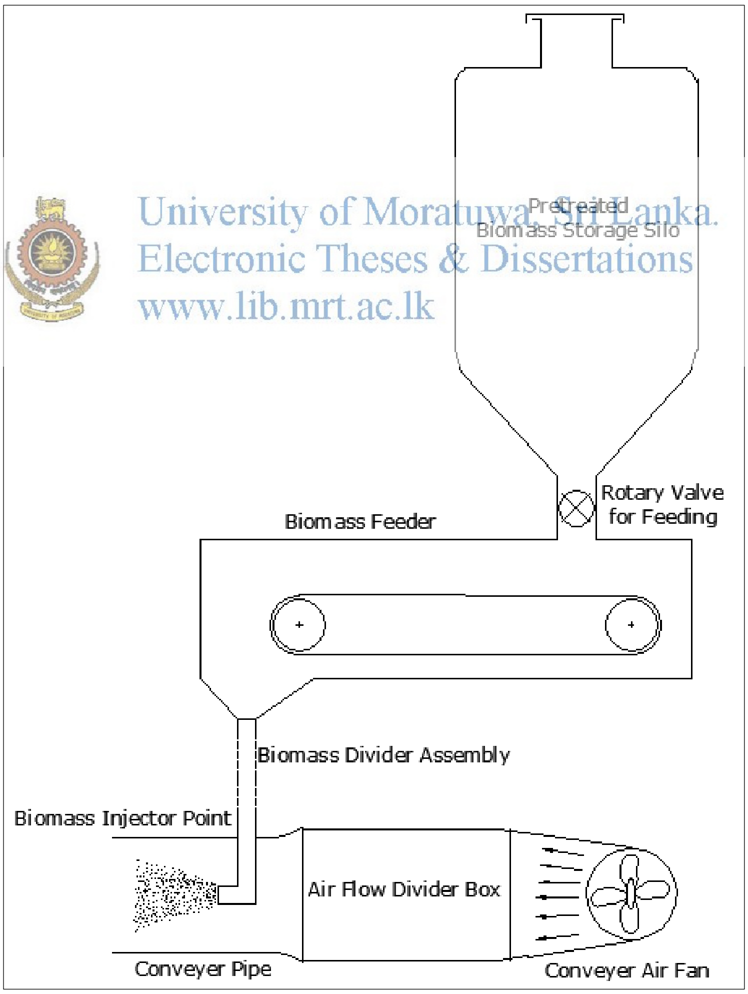


Fig. 2.31 : Silo and Feeding System

After reaching the pipe, the biomass will be released to the air flow of the air conveying pipe (Fig. 2.31). Through this method the biomass will be mixed with air in a uniform manner. This phenomenon is equal to what happens in a fuel carburetor used in automobiles.

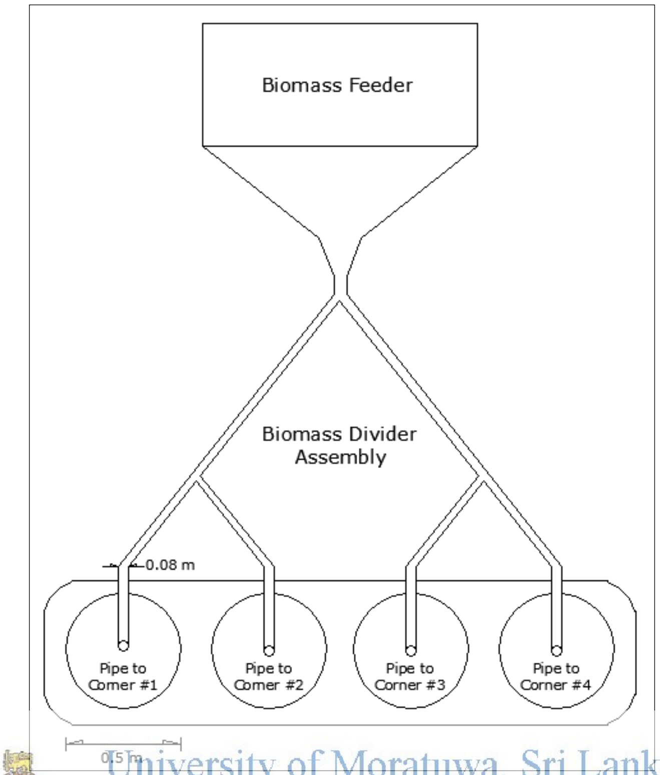


Fig. 2.32 : Biomass Feeding Tree for Pipelines

Air flows allocation is done as follows.

At 5% co-firing ratio;

Air flow per pipe (from injection criteria design calculations) = 1.288 t/h

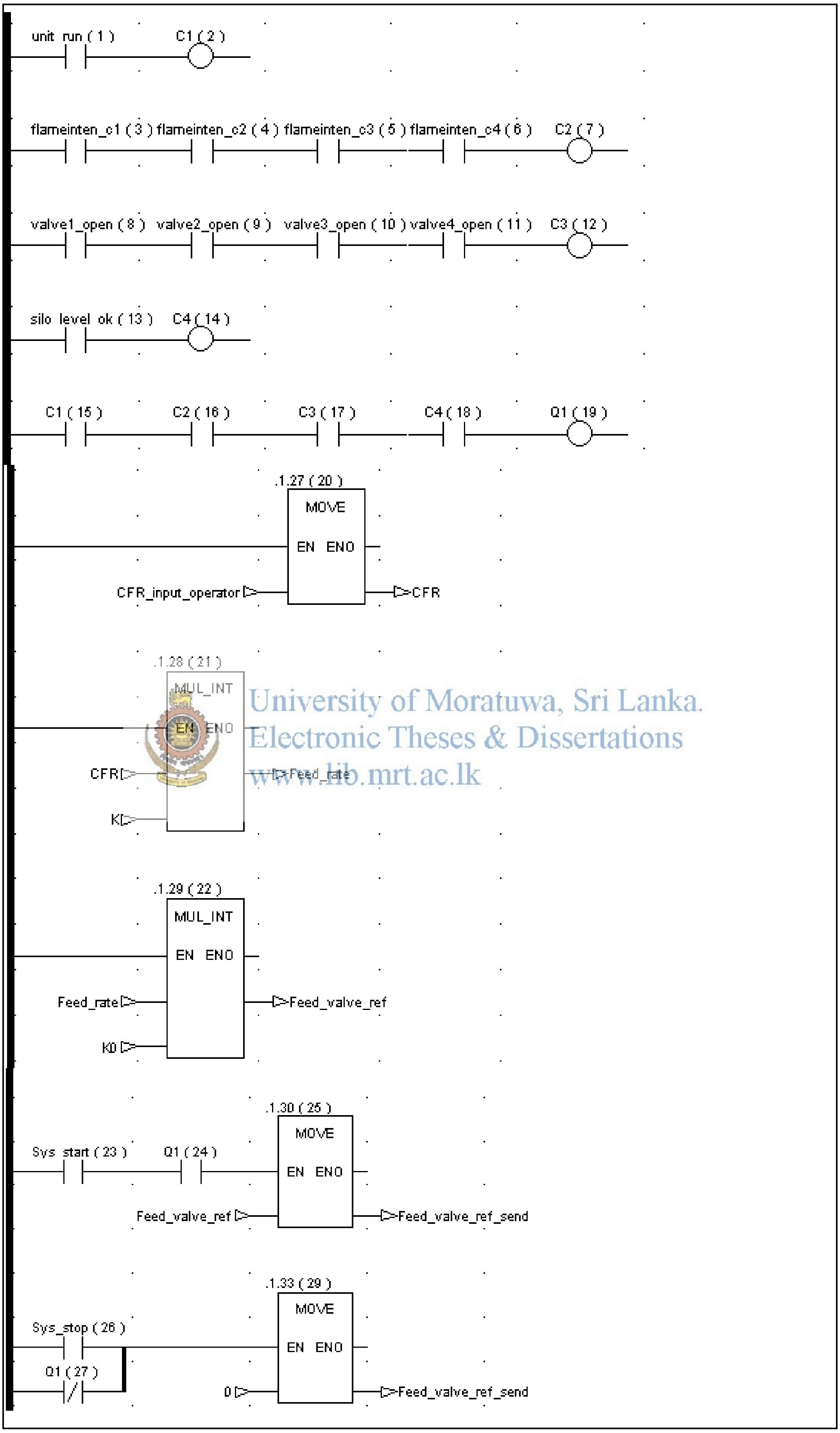
Total air flow provided by the fan (4 x pipes) = 1.288 x 4 t/h

= 5.152 t/h

The axial fan capacity should be more than 5.152 t/h and the available lowest is the 5.5 t/h capacity.

2.4.2.3 Control Logic for Injection System

A control logic shall be realized using industry standard IEC 61131-3 ladder logic programming language in order to monitor & control the entire biomass injection system. All possible safety precautions and interlocks also must be added to the same to ensure safe operation of the unit and the system. The drawn logic ladder is given in the next page and is explained afterwards.


unit run (1)
C1 (2)
flameinten_c1 (3)
flameinten_c2 (4)
flameinten_c3 (5)
flameinten_c4 (6)
C2 (7)
valve1_open (8)
valve2_open (9)
valve3_open (10)
valve4_open (11)
C3 (12)
silo level ok (13)
C4 (14)
C1 (15)
C2 (16)
C3 (17)
C4 (18)
Q1 (19)
.1.27 (20)
MOVE
EN ENO
CFR_input_operator
CFR
.1.28 (21)
MUL_INT
EN ENO
CFR
Feed_rate
K
.1.29 (22)
MUL_INT
EN ENO
Feed_rate
Feed_valve_ref
K0
.1.30 (25)
MOVE
Sys start (23)
Q1 (24)
EN ENO
Feed_valve_ref
Feed_valve_ref_send
.1.33 (29)
MOVE
Sys_stop (26)
EN ENO
Q1 (27)
0
Feed_valve_ref_send

There are four separate conditions to be satisfied, in order start the biomass co-firing injection system.

1) The unit must run and the load should be more than 220 MW –**[Coil C1]**

   At coal supply rates corresponding to 220 MW, the unit stability is higher to introduce biomass co-firing since the unit is only running on coal. At low loads, the oil guns are also in operation in parallel to coal guns and hence the coal rates are lower. In that case, the possibility and risk of system instability occurrence is higher. So, for the safety of the unit, the minimum load should be 220 MW to introduce biomass in to the boiler.

2) All flame intensities of the corresponding layer must be stable – **[Coil C2]**

   The flame intensity of the coal gun indicates the flame stability of the burning corners. If the flame intensities are below 50% it is not suitable for biomass injection since the intensity below 30% during 4 seconds delay for a single layer will trip the unit instantly for the boiler safety. Therefore, all the flame intensities shall be above and stable at 80% in order to safely start biomass injection.

3) All valves at injection port shall be open – **[Coil C3]**

   All the valves at the biomass injection port shall be open in order start injection.

4) Biomass Silo Level must be high enough – **[Coil C4]**

   When fully filled, the biomass silo level is 15 m. At least 8 m level shall be available in order to start injection using the same silo. This is to make sure that the continuous uninterrupted feeding is guaranteed.

When all of the above conditions are satisfied, the system can be started. In the rest of the logic, the user can set the co-firing ratio and the feeding valve will be operated accordingly. Start up and stop can be done by the operator at his own will.

2.4.3 Design Finalization

Bringing together all the above discussed subtopics will form the major overall design for the whole system. Details such as dimension of structures also can be determined and shown clearly in relevant occasions. However, some of the minor details are not discussed in the design above since they are accounted for when the economic evaluation is done. Details such as structural mountings, supports, control boxes, power panels, etc have not been discussed or illustrated. Apart from those, all the major design issues are addressed above.

2.5 Economics Evaluation

2.5.1 Introduction

The technical comparative evaluation above yielded that the direct co-firing method 2 is technically most suitable and viable option when co-firing glerecedia with coal in a pulverized coal fired boiler. The technical evaluation alone is insufficient when it comes to finalizing the decision whether it is feasible to go for co-firing biomass. It must be verified financially whether it is going to work out in the short run as well as in long run. In making the final decision, the economics behind all installations shall be taken in to account. In other words, the project return must be verified after all costs, benefits are taken in to account. The significance in economic evaluation lies among several key indicators related. Some of the below points are measurable in value and some can be immeasurable. The components related can be listed as follows.

Cost Components	Income/Return Components
Capitals Costs	Return from Fuel Saving
Operational Costs	
Maintenance Costs	Social Benefits
Social Cost	
Environmental Cost	Environmental Benefits

Table 2.2 : Costs and Income Components

2.5.2 Cost Components : Capital Costs

There are number of new structures and systems to be built for enabling the project. All those come under the category of capital investments. The total capital can be divided among the sub systems as follows.

1. Biomass Pretreatment Plant
2. Feeding and Injection System
3. Other Modifications

1) <u>Biomass Pretreatment Plant</u>

   The pretreatment plant was discussed in details in section 2.3. The cost breakdown for each stage components is given in table 2.3.

Index	*Component/Subsystem*	*Cost (LKR)*	*Remarks*
1	Incoming Yard	5,000,000	Two parallel bays
2	Intermediate Storage	6,000,000	300t capacity
3	Chippers	21,000,000	02 nos x 10 t/h each
4	Dryers	40,000,000	02 nos x 10 t/h each Including heating subsystem
5	Crushers	19,000,000	02 nos x 10 t/h each
6	Silo System	5,000,000	5 nos x 15 t each
7	Conveyers	16,000,000	800 m in total length 10 t/h capacity (20,000 LKR/m)
8	Other (Misc.)	14,000,000	Supporting structures, electrical and instrumentation controls
Total Cost (LKR)		**126,000,000**	

Table 2.3 : Cost Breakdown for Pretreatment Plant

2) <u>Feeding and Injection System</u>

The fuel feeding system and injecting system is also a new addition. The modification of coal pipeline also comes under the same. The cost breakdowns are given in table 2.4.

Index	*Component/Subsystem*	*Cost (LKR)*	*Remarks*
1	Feeder with accessories	45,000,000	04 nos (2.5 t/h each) Including injector assembly
2	Axial Blower Fan with Manifold	10,000,000	01 nos (5.5 t/h capacity) Including all Electrical and Mechanical accessories
3	Pipelines	15,400,000	Average line length – 35m 20 lines (22,000 LKR/m)
4	Modification at Point of Injection	20,000,000	20 nos of expanders and welding jobs
5	Electrical Installation	14,000,000	350 A capacity installation with all inclusive

6	Control System	6,000,000	All inclusive hardware & software
7	Other (Misc.)	15,000,000	Steel supports, hangings, minor concrete support structures, etc
Total Cost (LKR)		**125,400,000**	

Table 2.4 : Cost Breakdown for Feeding & Injection System

The total capital cost (pretreatment plant & feeding and injection system) add up to a value of LKR 251,400,000.

2.5.3 Cost Components : Operation, Maintenance & Other Costs

In order to keep the co-firing system operating reliably and without any failures, there are several other costs to be bared by the operator. They are as follows.

1) Cost of Electricity :

In the run, the Electrical equipment incurs a cost due to Electricity consumption. The number of units of monthly consumption can be estimated as follows.

Total power capacity of pretreatment plant

[2 x Chippers + 2 x Dryers + 2 x Dryer blowers + 2 x Crushers + All conveyers]

= (65kW x 2) + (20 kW x 2) + (5 kW x 2) + (60kW x 2) + (200kW)

= 500 kW

Units consumed = 500 x 24 x 30 x 0.75 kWh = 270,000 kWh/month

Monthly bill amount under the current structure (Government Rate #3)

= [270,000 x 14.35] + [500/0.86 x 1000] + 3000

= LKR 4,458,895/-

Average annual electricity cost = **LKR 53,506,740/-**

2) Cost of Maintenance

Usually, the first three years shall have no breakdowns in the system and hence, no parts replacements required. Nevertheless, a mandatory spares list shall be procured and maintained in store so that they can be used in case of a breakdown. Apart from that, the routine maintenance such as greasing motors, rollers and general cleaning shall be carried out.

Index	**Item**	**Amount (LKR)**
01	Mandatory Spares (Annual)	
	- Motors (05 nos)	250,000/-
	- Blades, rotors, fans, bearings, etc (Mechanical Spares)	400,000/-
	- Conveyer Rollers	65,000/-
	- Heat Element	100,000/-
02	Routine maintenance Materials (Annual)	150,000/-
Total Cost of Maintenance		**965,000/-**

Table 2.5 : Cost Breakdown for Plant Maintenance (as at 2016)

3) Administrative costs

Administrative costs basically include the salaries of workers who are allocated for the work in pretreatment plant. Workers must be allocated for the incoming bay (02 nos), process operators (02 nos) and other purposes (02 nos). Each will be paid a salary of LKR 30,000. Therefore the annual admin cost is (30,000 x 6 x 12) **LKR 2,160,000/-**.

4) Social costs

The social cost component usually quantifies the cost incurred by the society or the impact of the project on the society at large. The following justifications clearly indicate that there is no social cost involved. Instead, many social benefits are gained by the society.

- The biomass planting community is promoted with direct income.
- The saving of the fuel goes to the community and the general public at large.

5) Environmental costs

The environmental cost component usually quantifies the cost incurred on the environment. The environmental impact of the project is attempted to quantify. The following justifications clearly indicate that there are no environmental costs involved. Instead, many environmental benefits are gained by the implementation of the project.

- The SO_x & NO_x emissions are cut down by about 5% from each category.
- Since biomass is carbon neutral, 5% of the CO_2 emissions is also considered as cut down and results a reduced carbon foot print.
- Due to the less amount of coal usage, the dust accumulation is lower. It leads to better worker, public health & safety.

2.5.4 Revenue Components : Saving from Fuel

The saving gained by switching to biomass is the major income component considered under the cost benefit analysis for the project. Simply speaking, the biomass is cheaper than coal and will deliver a saving and supposed to be profitable in long term.

The cost of production and delivery of biomass to plant should be determined firsthand in order to calculate the overall saving in co-firing. It can be derived as follows;

Total Cost of Biomass (LKR/kg) =

Purchase rate (LKR/kg) + Cost of Transportation (LKR/kg)

Purchase rate of unit weight of biomass is the direct fee paid to the grower for growing biomass. According to current coconut grower intercrop agreements, the current rate of purchase range from LKR 1.50/kg to 2.00/kg based on the amount moisture (> or < 30%). The average can be taken as LKR 1.75/kg.

Cost of transportation is calculated using the scenario that a 10t carrier is used to transport biomass from average distance of 250km. The value of 250km is taken considering the current and projected distribution of coconut intercrop fields in the country. The destination is selected as the Lakvijaya Coal Power Station. Usually the 10t carrier charges LKR 140/km. Therefore total cost of transportation for the average distance is (140 x 250) LKR 35,000/-. The transportation charge per unit weight is (35,000/10,000) LKR 3.50/kg.

Hence, the total cost of biomass unit weight when it reaches the plant premises is (1.75 + 3.50) LKR 5.25/kg.

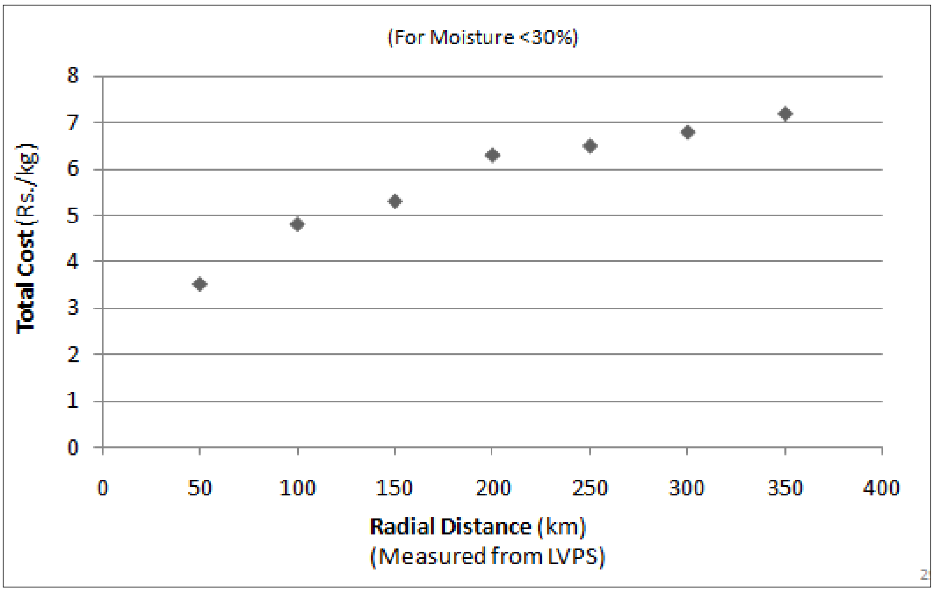


Fig. 2.34 : Total Cost of Biomass vs Distance Traversed

The saving calculation can be continued further as follows.

The coal rate to be replaced with biomass co-fired at 5% = 5.7 t/h
(per single unit 300MW)
The rate of biomass to be fed when co-fired at 5% = 8.23 t/h
Saving achieved by reducing coal consumption = 5.7 x 12,000
(Price of coal considered as LKR 12,000/t, using 5 year average in South African Coal export price index [8]) = LKR 68,400/h
Annual saving by cutting down coal (75% plant factor) = 68,400 x 24 x 365 x 0.75
= LKR 449,388,000/year
Hourly expenditure for biomass (LKR 5250/t) = 8.23 x 5,250
= LKR 43,207.50/h
Annual expenditure for biomass (75% plant factor) = 43,207.50x24 x365 x 0.75
= LKR 283,873,275/year
Annual net saving by replacing coal with biomass = **<u>LKR 165,514,725/year</u>**

The annual net saving calculated above is the main source of income.

2.5.5 Revenue Components : Social and Environmental Benefits

Except for the fuel saving figures which can be quantified in monetary terms, there are many social and environmental benefits, which cannot be expressed in the same way.

Social Benefits

- Rural Community Empowerment :

  Through this project, the central government can cut down on foreign trade through reduction of coal imports. It will have an impact on national economy since it will limit the foreign exchange transactions. Instead, through procurement of energy crops from local communities, the foreign exchange saving is invested and divided among the grower communities spread throughout the country. Usually, these communities consist of low income families who do not have a fixed, reliable source of income. This move will generate long term employment opportunities for them. According to the generation expansion plan, thousands of MWs of coal power are to be added to the grid. Through introducing co-firing to those during the construction stage, extra unwanted costs can be avoided and the grower communities will be benefitted on a national scale. Through doing so, huge amounts of investment will be made in the area, accelerating the community response further. The actual benefits enjoyed by them cannot be quantified in cash terms. The project contributes to the long term sustainable economic development in two ways. That is, while promoting grower agreements among communities, the energy crop supply security can be enhanced and on the other hand the long term benefits for the very same communities can be guaranteed.

Environmental Benefits

- Cut Down on Emissions :

  Biomass is considered as a carbon neutral fuel when it comes to emissions. Since 5% of energy generated by coal is now generated using biomass, approximately 5% of the emissions are directly cut (emissions are generally directly proportional to energy). The main gas included in the emissions category is CO_2. The cut down of CO_2 would give way to reduce carbon foot print and also enables the eligibility to claim carbon credits. Further, CO, SO_x and NO_x also will be cut down by 5% reducing on the potential impacts.

2.5.6 Overall Economic Evaluation

After identifying the income and expenditure components, the final evaluation shall be carried out in order to check project's long term feasibility. The lifetime of the plant is around 30 years.

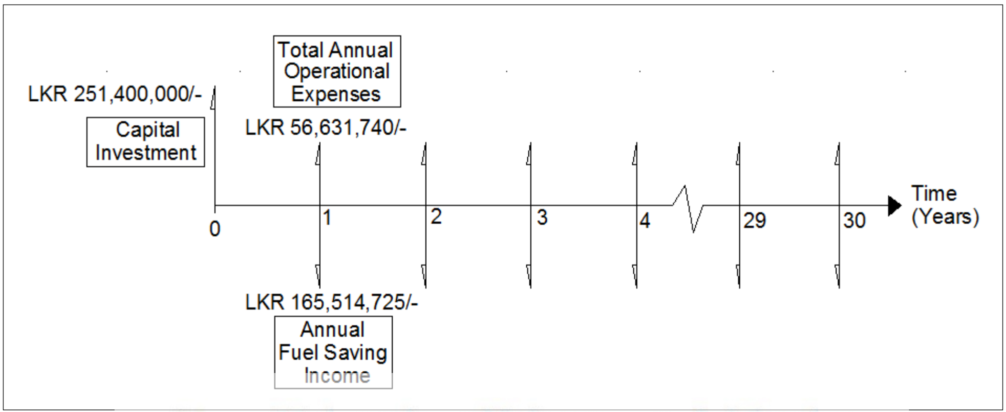


Fig. 2.35 : Summary of Project Capital, Income and Expenditure over the time

Project capital, income and expenditure components which were discussed in detail are summarized in Fig. 2.35. On the upper side of the timeline, capital investment and total operational expenses are mentioned. The total operational expenses include all expenses such as The figure elaborates that a total annual profit of LKR 108,882,985 is incurred annually operationally (difference between Total Annual Operational expense and fuel saving income). Using simple payback period to check on the return on investment it is seen that, within about 2.5 years the total investment is recovered (Capital/Net Profit). After recovering full investment (within 2.5 years), each year, a net profit of LKR 108,882,985 is achieved. Therefore, it is clearly seen that the project is financially viable to implement.

2.5.7 Conclusion

From the financial evaluation done in section 2.6.6, it can be clearly justified that the project is financially viable to implement. In addition to the long term guaranteed profits obtained after the capital is recovered, the social and environmental benefits will continue to pump in benefits to the respective sectors.

Chapter 3

Conclusion and Recommendations

Many countries around the world have already employed biomass co-firing with coal to gain benefits involved. As a developing country with a tropical nature, Sri Lanka has quite a lot of potential to try out this technology. The long term generation expansion plan has forecasted many coal power stations to be added within the next 10 years. If the proper frameworks and policy decisions are made right away, the cultivation of benefits will enable a massive economic boom in the energy sector.

The three main technological options for co-firing were discussed in detail in Chapter 2. The direct, indirect and parallel co-firing options were introduced. Indirect and parallel co-firing options were not considered in detail as a possible option since the complexities found in those options were unfavorable to pulverized coal power stations. According to available information and global experiences, if employed, the two options have a high possibility of disproving technical and financial viability of the whole project in overall. To get to a solid conclusion on the exact technical and economic feasibility of these two options, more in depth research has to be done unlike the first option which is direct co-firing option. Therefore, it is recommended to carry out in depth research separately on employing biomass indirect and parallel co-firing in to a pulverized coal power station.

The direct co-firing option is analyzed in detail in connection to pulverized coal fired stations. The exact specifications of the boiler were mentioned in Chapter 1. The three sub-options coming under direct co-firing were analyzed individually. Finally, the 2nd option was selected as the most technically and economically viable option. The detailed design of all aspects connected to the co-firing system installation was carried out. After the design, the detailed budget is worked out and so is the financial viability. It yielded that within 2.5 years the capital will be recovered and a net profit of LKR 108,882,985 is earned each year afterwards. Hence, the financial viability of the total installation is out of the question.

Since the technical and financial viability is now being verified, it is recommended to carryout trials on a pulverized coal fired boiler. Initially, the co-firing should be started with a lower co-firing ratio and measure the performance of the boiler and generation. While monitoring the unit critical parameters closely, the co-firing ratio is to be increased up to the maximum design value of 5%.

If co-firing ratios of more than 5% need to be achieved, a scaled down model (Fig. 3.1) of the exact boiler should be constructed so that the trials exceeding 5% co-firing ratio can be carried out [10]. Also, it is an excellent way to verify all possible side effects as a result of the proposed co-firing.

Fig. 3.1 : Scaled Down Model of a boiler used to conduct co-firing trials

REFERENCES

[1] S. V. Loo and J. Koppejan, *“The Handbook of Biomass Combustion and Cofirirng”* London, UK: Earthscan, 2008

[2] Clean Coal Co., (2011). *Clean Coal Technology* [Online].
Available : http://www.cleancoal.org/cleantech/cofire

[3] Energy Efficiency Asia Co. (2012) *Combustion Technologies* [Online].
Available : http://www.energyefficiencyasia.com/comtech

[4] Rohan Fernando, *“Fuels for Biomass Co-firing”* CCC/102, IEA Clean Coal Centre, December 2011

[5] Lei Shang Lars Bach, *“Physical & Chemical Changes in Biomass when Torrefied”*, World Sustainability Energy Days 2012, Beijing, China

[6] Isaac Emery and Nathan Moiser, *“Emission of Methane from Biomass Feedstocks”*, GCB Bioenergy, 2014

[7] China Machinery Engineering Corporation, *“Aero Dynamic Calibration Test Report for Furnace”*, Harbin, China, 2011

[8] Coal South African Export Coal Price Index (2016) [Online].
Available : http://www.indexmundi.com/coalglobal

[9] Xiangmei MENG, *“Biomass gasification : the understanding of sulfur, tar and char reaction in Fluidized Bed Gasifiers”* M.S. thesis, Dept. Mechanical Engineering, Tianjin Univ., China, 2012.

[10] Rohan Fernando, *“Co-firing High Ratios of Biomass with Coal”* CCC/194, IEA Clean Coal Centre, January 2012

[11] Shoaib Mehmood, *”Energy and Exergy Analysis of Biomass Co-firing Based Pulverised Coal Power Generation”* M.S. thesis, Dept. Mechanical Engineering, Univ of Ontario, Canada, 2011

[12] China Machinery Engineering Corporation, *“Operations Regulations for Pulverised Coal Fired Boilers”*, Harbin Boiler Company, Harbin, China, 2011

[13] Biomass Energy Data Book (2011) [Online] Available : http://cta.ornl.gov/bedb

[14] Doosan Babcock Energy, *"Biomass Firing and co-firing in Large Coal Fired Utility Boilers"*, W R Levinstin Coal Research Centre, Leeds, UK, 2010

[15] VGB Powertech, *"Advantages and Limitations of Biomass Co-combustion in Fossil Fuel Fired Boilers"*, Powertech Research Centre, USA, 2012

[16] Thomas Nussbaumer, *"Combustion and Co-combustion of Biomass: Fundamentals, Technologies, and Primary Measures for Emission Reduction"*, Verenum, Langmauerstrasse, Zurich, Switzerland, 2003

[17] International Renewable Energy Agency (IRENA), *"Biomass Co-firing technology brief"*, Energy Technology Systems Analysis Program, 2013

[18] David Tillman, Richard Conn, Dao Duong, *"Coal Characteristics and Biomass Co-firing in Pulverised Coal Boilers"*, Electric Power Baltimore, Clinton, NJ, USA 2010

APPENDIX – A :
Power Plant and Other Data Used for Calculations

- Unit Size : 300 MW
- Coal Feed Rate at Full Load : 114 t/h
- Plant Factor Considered : 75 %
- Gross Calorific Value for Coal : 26 MJ/kg
- Gross Calorific Value for Glerecedia : 18 MJ/kg
- Considered co-firing ratio : 5 %
- Rate of feed for Glerecedia : 8.234 t/h
- Power Factor assumed for Motors : 0.86 lag