ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
School of Electrical and Computer Engineering

Increased Services from the Cane Sugar Industries: Poly-generation of Heat, Power and Bio-fuel
(A Case Study at Finchaa Sugar Factory)

A Thesis Submitted to Addis Ababa Institute of Technology, School of Graduate Studies, Addis Ababa University

In partial fulfillment of the Requirement for the Degree of MASTERS OF SCIENCE IN ELECTRICAL ENGINEERING (ELECTRICAL POWER ENGINEERING)

BY

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Advisor: Getachew Bekele (Phd)

November 2014

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GSR/3541/04

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DECLARATION

I hereby declare that the work which is being presented in this thesis entitled "Increased services from the cane sugar industries: poly-generation of heat, power & bio-fuel (a case study at Finchaa sugar factory) '' is original work of my own, has not been presented for a degree in this or other universities and all sources of materials used for this thesis work have been fully acknowledged.

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This thesis has been submitted for examination with my approval as a university advisor.

Dr. Getachew Bekele ____________________

Advisor's Name Signature

Acknowledgment

Even though being a refugee and doing post graduate studies is a bit difficult, I have managed to complete my educational dream. On behalf of all the Eritrean refugees in Ethiopia, I would like to thank the government of Ethiopia in particular the Administration for Refugee & Returnee Affairs (ARRA) for giving me the opportunity to continue my education without any inconvenience that a refugee might encounter on daily basis.

I am grateful to my advisor Dr Getachew Bekele whose enthusiasm, creative ideas, assistance, suggestions and guidance were beyond my expressions during my graduate studies and thesis work.

I would also like to extend my gratitude to all the staff of Finchaa Sugar Factory who helped me in collecting the necessary data for my thesis work. Particular appreciation goes to Eng Abaynehe , technical head of the factory and Ato Ejegu head of Electrical department .

I am also indebted to the staffs of Power Engineering Stream at Addis Ababa Institute of Technology who have lectured me the necessary post graduate courses effectively which has helped me a lot during my thesis work.

I am also thankful to the secretarial staff of the Electrical Engineering Department for their warm and heartfelt support.

My compliment extends to fellow colleagues and class mates during my post graduate studies.

I would like to give my regards to my family for their life time support during my career.

And last but not least , I would like to thank Father Almighty , who gives me strength , joy , peace , happiness and success during my day to day life.

Binyam Semret

Abstract

Price of sugar in the world market is very volatile and in most cases is below the cost of production. Moreover, sustainability of the sugar industries is becoming even worse with increasing petroleum price which is resulting in high rate of cost of sugar production. This could, however be reduced, by a number of methods that would increase revenues for non-consumable products derived from cane. Bagasse, which is the fibrous material found after the cane crushing process is one of the by-products of the cane sugar industry with almost zero fuel cost. Historically, it is used in sugar industries for generating power to fulfill steam and electricity requirement of the mills. Cogeneration is the simultaneous production of electric and thermal energy from a single energy system and source. It is also known as combined heat and power (CHP) technology. Cogeneration can be based on a wide variety of fuels; however, in the sugarcane growing countries, cogeneration from bagasse is becoming increasingly important.

In this study, investigation result of the potential of co-generation process of the Ethiopian sugar industry for power generation is outlined, through analysis of a selected typical sugar mill Finchaa Sugar Factory (FSF) among the existing three sugar mills in the country and by making reference to different project case studies in different countries where the potential of the cane sugar industry has been given a boost.

The data in relation to the cane and bagasse utilization as well as turbine and boiler specification is directly obtained from FSF. The strategy used for the analysis is bagasse drying technique and RETScreen software is used for simulation purposes by changing the existing back-pressure turbine through the high pressure boiler-turbine configuration. The result from the study shows that by reducing the moisture content of bagasse up to 20 %, we are able to generate 6,311.45 Mwh of excess electrical power which could be used to supply the irrigation pump stations of the factory, part of the residences of factory and the nearby villages, where currently there is no supply of electrical power from the national grid. The cost of energy is also computed and found to be around $0.017/kwh. The simulation result also shows that through changing the existing medium pressure turbine of the factory by the high pressure, we can generate 48,279 mwh of electrical power which could be exported to the national grid while simultaneously providing 145,872.8 excess bagasse which could be pelletized and exported to foreign countries where it is used as a useful fuel for cooking gazes as well as generating electrical power.

Keywords: Bagasse, Boiler, Cane Sugar, Co-generation, Power, Pellet, RETScreen, Turbine

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Acronyms

CEST	Condensing-Extraction Steam Turbine
CHP	Combine Heat and Power
EEPCo	Ethiopian Electric Power Corporation
GEF	Global Environmental Facility
FSF	Finchaa Sugar Factory
HHV	Higher Heating Value
HVA	Hangler Vondar Amsterdam
LHV	Lower Heating Value
MSF	Metehara Sugar Factory
TCD	Ton Cane Per Day
WSSF	Wonji Shoa Sugar Factory

Notations

A	Annuity Factor
F	Moisture Content
h	Enthalpy
i	Interest Rate
I	Investment Cost
L	Loss
m	Mass Flow Rate
p	Pressure
P	Power
Q	Heat Flow Rate
r	Heat of Vaporization of Water
T	Temperature
t	Time
η	Efficiency

Subscripts

B	Boiler
d	Dry Bagasse
el	Electricity
ex	Excess
lat	Latent
me	Mechanical Power
net	Net
p/s	Process
st	Steam
t	Total Basis

Chapter One

INTRODUCTION

1.1. Background and Statement of the Problem

In recent years, globally, generation of energy from biomass has become a vital task, accounting for 7 EJ of energy in the industrialized countries and 48 EJ in the developing world [39]. Bio-energy in developing countries comes in the form of fuel wood, crop residues and animal dung and is normally used for cooking, heating and lighting purposes [40]. It is, however, used very inefficiently and is considered as a low-grade energy source but current studies indicate that its usage as an energy source contributes to a sustainable energy utilization pattern.

Sugar factories produce enormous amount of biomass energy from the cane sugar plant during the crushing process. This energy source could play a significant role in both the developed and developing countries if it is produced renewably and elevated to the level of a modern energy carrier by converting it in to electricity, gasses and processed solid fuels.

In Ethiopia, in accordance with the Growth and Transformation Period (GTP) , the government has started to expand the existing three sugar mills and is working to establish additional four new sugar factories with a total cane crushing capacity of 65,500 tons of cane per day (TCD) each having cogeneration and an ethanol plant [1]. These sugar and ethanol production processes are energy intensive, requiring both steam and electricity. The current scenario of the existing three sugar factories [Finchaa , Metehara and Wonji-Showa] reveal that cogeneration in these factories is inefficient, operating with low pressure boilers and backpressure turbines generating electric power mostly for captive power use and partial requirements of irrigation and residential houses of the factory workers [1].

Finchaa Sugar Factory (FSF) is located at 357 km from the capital city of Ethiopia and about 45 km from Finchaa hydropower plant. The factory was tested and commissioned in the year 1998 (G.C). It has an average annual production capacity of 110,000 tons of white sugar with a nominal crushing capacity of 4500 TCD [31]. A portrait of the factory is shown on figure 1.1.

Figure 1-1 Portrait of Finchaa Sugar Factory

Depending on the variety of cane crushed, method of harvesting and input applied to the cane sugar crop, the average annual amount of bagasse production reaches up to 280,000 tons per annum at a moisture content of 50 % [31]. The excess bagasse production is about 16.8 tons/day [31]. With the current situation of the factory , the excess bagasse is not used for any application, rather it is left as waste , whereby there is no proper allocation and storage for the bagasse and makes the factory field improper for employees by taking vast amount of space and area , thus making the factory vulnerable to fire . Figure 1.2 shows the bagasse generated, used for CHP and waste left at the factory and it can be seen that the excess bagasse is being stored on plastic bags and taken to the fields for disposal.

Figure 1-2 Waste Bagasse at FSF

Apart from its direct utilization as combustible in the furnaces of the sugar factory boilers for steam generation , bagasse is also used as a raw material in the paper making industry and is also used for cattle feed [17] .

1.2. Objectives of the study

The main objective of this thesis is to identify the problem associated with the energy generation and utilization of the sugar factory and to recommend possible solutions. Consequently the factory and in general the country can be benefited through:

- Minimizing resource wastage.
- Minimizing CO_2 emission.
- Exporting the surplus electricity to the national grid.
- Exploiting other energy resources.
- Getting additional profit.

And the specific objectives are:

- To survey the condition of the selected factory.
- To compute the amount of total bagasse produced and know how much is used for co-generation and how much is left as waste.
- To compute the current energy consumption of the factory.
- To analyze the feasibility of using the extra generated electrical power for irrigation purposes to power the pump stations for cultivating the cane farm.
- To analyze the feasibility of using the additional generated electrical power to nearby villages and to be able to export to the National Grid.
- To be able to produce Pellets for cooking purposes.
- To prepare a flow chart that describes the sugar manufacturing process.

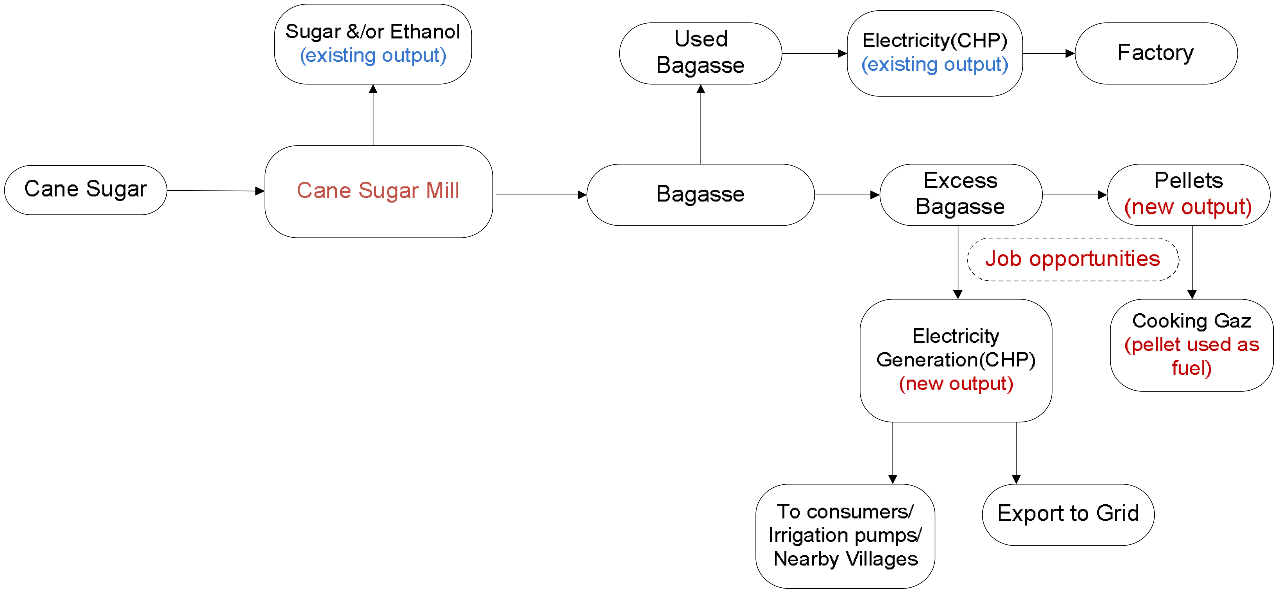


Figure 1-3 Different process flow in a sugar mill with increased output (Poly-generation)

1.3. Methodology

Site Identification

Out of the three currently operating sugar mills in Ethiopia, the selected factory for this thesis work is Finchaa Sugar Factory (FSF).

Data Collection

The necessary data for the thesis work is collected from different sources. The data’s include:

- Amount and composition of bagasse generated.
- Energy consumption.
- Energy generation capacity.
- Energy equipments.
- Energy policies.

These data are collected through:

- Conducting interviews with the respective personnel of the factory.
- Distributing questionnaires in the factory.
- Physical observation of the factory.
- Collecting data from previous papers and research documents.

Data Analysis

The collected data is analyzed quantitatively and qualitatively. After detailed analysis of the collected data and running the appropriate software for simulation purposes, then conclusion and recommendation is provided.

1.4. Related Works

Research work done by "Charles Mbohwa" [7] on bagasse energy cogeneration potential in the Zimbabwean sugar industry , where bagasse is used during the crop season and coal during the off crop season to provide electricity to the grid . The findings indicate that it is technically feasible to implement such a project but no full economic and financial feasibility has been done.

Paper done by "Scott M.,Gary Eshats , S.N.Rao,Richard Goldman and David Hess**"** [10] on promotion of biomass cogeneration with power export in the Indian Sugar Industry where Advanced Bagasse Cogeneration (ABC) is used to promote year round cogeneration in Indian sugar mills with power export using only biomass as a fuel. A study done by "Eyerusalem B." [13] at FSF on investigation result of the potential of the Ethiopian cane sugar industry for power generation. In her study, she considered only the feasibility study on the energy potential of bagasse and in addition used only the method of bagasse drying for generating additional power and the analysis is done without any computer tool.

Yohannes B. [17] studied the energy assessment, generation and utilization efficiency in the

Ethiopian sugar factories, the study addresses the problems encountered by the sugar factories with respect to energy starting from the resources up to the end users of the factory's machineries, the study focuses in improving the total efficiency of the sugar factory and does not include the potential of generating and exporting electrical power to the grid.

1.5. Organization of the Thesis

This thesis is organized in to six chapters. The first chapter is about the background of the study, statement of the problem, objective, methodology and related works to this thesis. The second chapter presents the basic theory of the cane sugar industries by showing the sugar production process, it also covers the general overview of the existing Ethiopian cane sugar industry, this chapter also shows the chemical and physical composition of bagasse, the various technologies of bagasse burning for power generation and the use of pellets. The third chapter gives the data collection steps and analysis and shows the application of RETScreen in the cane sugar industries. Chapter four is all about the simulation result and discussion. The fifth chapter gives the economic analysis of the study and the sixth chapter brings to an end of the research with conclusion and recommendations.

Chapter Two

THE SUGAR CANE INDUSTRY

2.1 Cane Sugar

Cane Sugar is a kind of grass with big stems similar to bamboo cane with some of its forms growing up to 6 m but mostly when it is harvested it has a height of about 3m [29]. Figure 2.1 illustrates the percentage distribution of biomass on the cane sugar plant. Here it is seen that out of the total biomass 60% is millable cane.

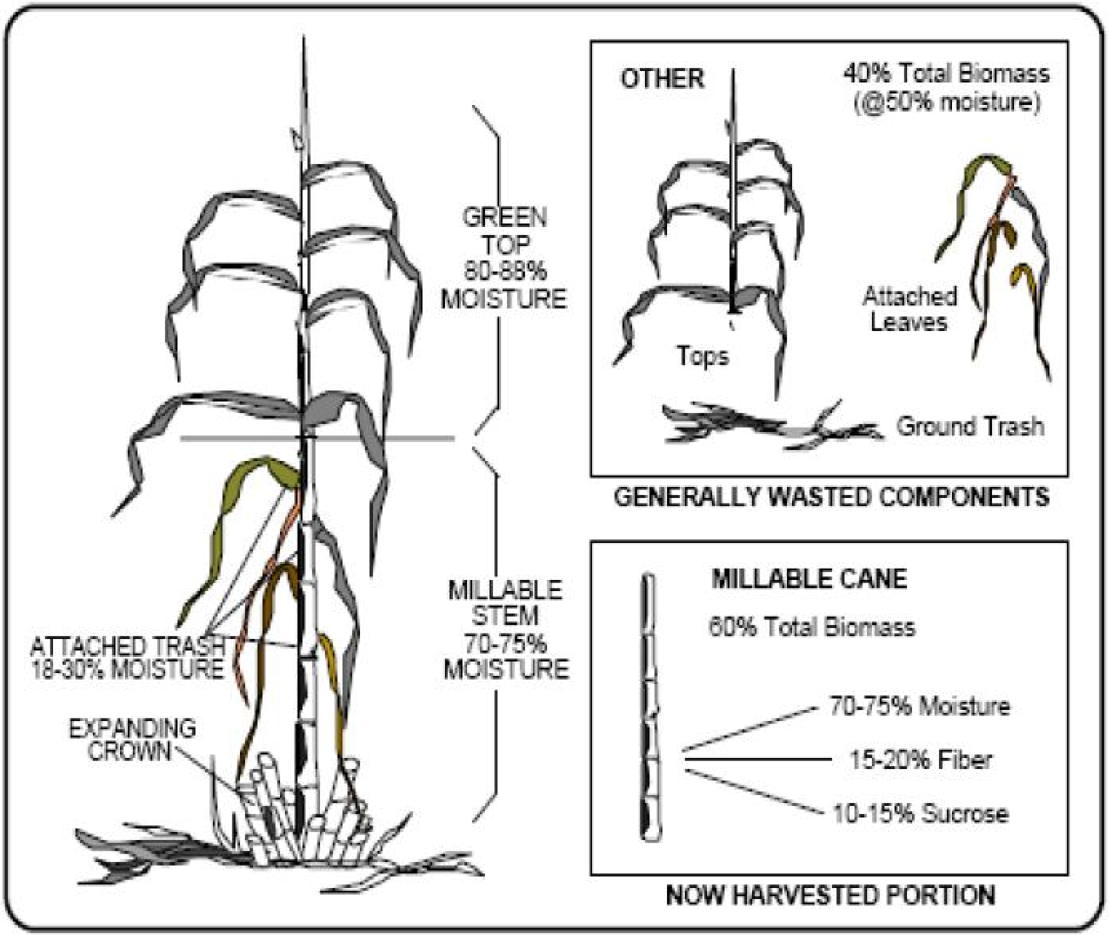


Figure 2-1 The percentage distribution of biomass on cane sugar plant [33]

Cane sugar is mostly grown in sub-tropical and tropical countries where there is plenty of sunshine and rainfall [29]. Mostly, a rainfall range of 750 – 1200 mm and temperatures below 50^{o}C and above 20^{o}C are suitable for its healthy growth. Harvesting of cane sugar is done with the aim of preparing the cane to the mill with the minimum amount of trash and it is carried out during dry seasons with prior irrigation of the field [29]. It is done by chopping the stems without touching the roots to enable re-growth (green harvesting) or field burning in the case of traditional harvesting. The duration of the harvesting can take between 2.5 – 11 months [29]. The method of harvesting includes hand cutting or mechanical racking [8]. Currently about 70 % of the world's sugar production comes from cane sugar and the rest of the production comes from sugar beet [29]. Figure 2.2 depicts the places where cane & beet sugar grow in the world. As shown in the figure the larger portion of sugar production comes from cane sugar, as compared to sugar beet.

Figure 2-2 An interactive world map of sugar production [29]

The three largest sugarcane growers in the world in terms of production are Brazil, India and China, yielding between them more than half of the total sugar production worldwide. Table 2.1 and Figure 2.3 compare production and yield figures for the top 11 sugar-growing countries [16].

Table 2-1Main cane sugar producing countries in the world [16]

	Area Harvested (Ha)	Production Ranking	Yield (tones/ha)	Production (tones)
Brazil	5,303,560	1	73.83	386,232,000
India	4,300,000	2	67.44	290,000,000
China	1,328,000	3	70.71	93,900,000
Thailand	970,000	4	76.36	74,071,952
Pakistan	1,086,000	5	47.93	52,055,800
Mexico	639,061	6	70.61	45,126,500
Colombia	435,000	7	84.14	36,600,000
Australia	423,000	8	85.13	36,012,000
Cuba	1,041,200	9	33.33	34,700,000
USA	403,390	10	77.29	31,178,130
Philippines	385,000	11	67.10	25,835,000
Other	4,091,132			244,581,738
TOTAL	20,405,343			1,350,293,120
Average			68.53	

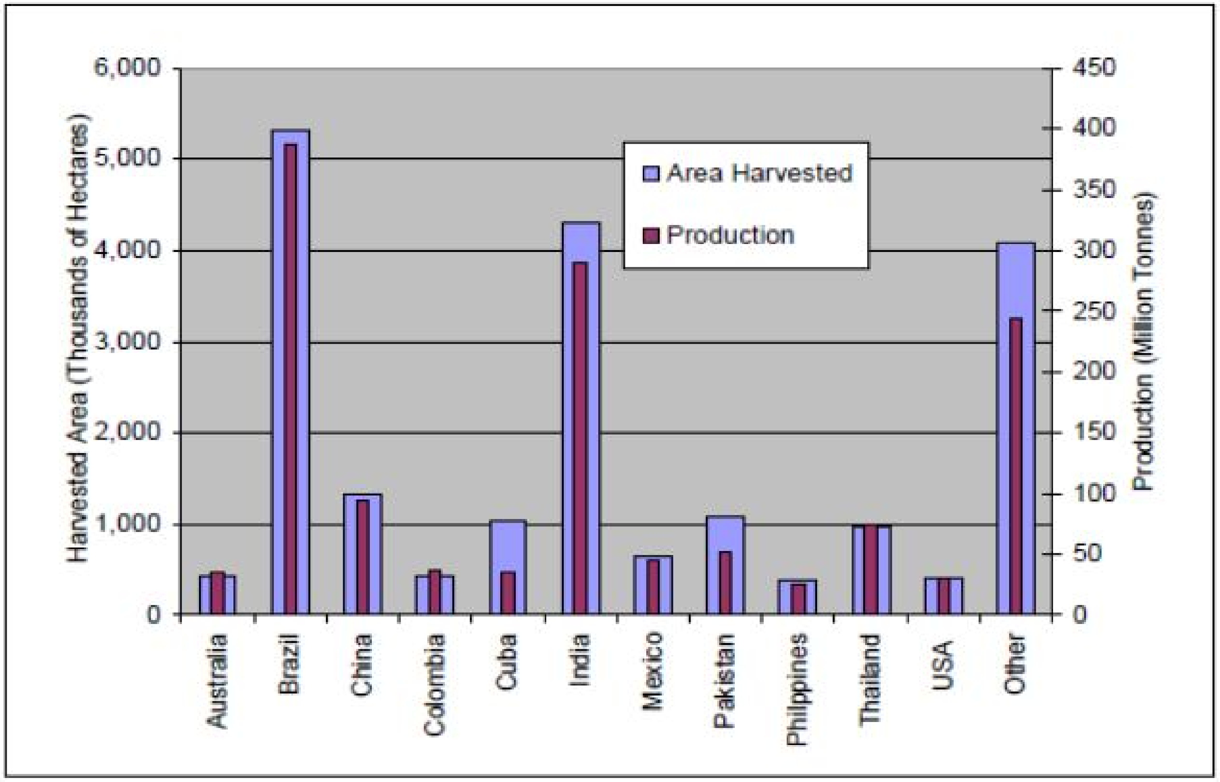


Figure 2-3 Sugar cane production by country [16]

2.2 Cane Sugar Potential for Electrical Power Generation

There is a vast amount of potential for electrical power generation from the cane sugar industry by-products of like bagasse. In many sugar industries especially in industries found in developing countries, bagasse is used in an inefficient way [4]. This is due to the fact that previously bagasse was burned as means of solid waste disposal. However, increased cost of fossil fuels and electricity, forced bagasse to be regarded as a useful energy source rather than waste. Moreover, researches and experiences have proved that bagasse is an environmentally friendly sustainable fuel source if it is burned making use of an appropriate technology [8]. Globally, about 1.2 billion tons of cane sugar is harvested every year and this corresponds to a global electricity production potential of 40 GW or 300 Twh per year in the eighty cane sugar growing countries [11].

Power co-generation from bagasse is not a new idea for the cane sugar industries as most of them satisfy their internal heat and power consumption by burning bagasse in their boilers. Most sugar mills are designed to meet their power demands without generating excess electricity to the grid, however; only few mills now make use of higher steam parameters in order to produce excess electrical power. The idea of producing excess electricity for sales to the grid stemmed from the fact that there is an increasing global energy demand and hence better utilization of bagasse to get excess electrical power has become a viable approach [9]. On the other hand, the contribution of the potential to the energy balance is pronounced greatly in countries like Cuba, Brazil, India, Thailand, Pakistan, Colombia, Mexico and The Philippines. The potential in these countries accounts for 70 % of the global cane production [12]. The production of the African cane sugar industry amounts to 8.3 million tons of sugar and cane production of 83 million tons. Hence it is estimated that the potential of surplus electricity export can reach up to 8300 Gwh [15].

2.3 Sugar Production Process

The production process of sugar from cane sugar involves the separation of the sucrose from the rest of the components of the cane. Tables 2.2 and 2.3 describe the production process of brown and white sugar making respectively and figure 2.4 illustrates these processes diagrammatically.

Table 2-2 Production process of brown sugar from cane sugar [12]

Process Type	Process Description For Brown Sugar Production
Harvesting	Involves chopping down of the stems without touching the roots (green harvesting) or field burning (traditional harvesting)
Crushing	Initial milling of the cane
Juice Extraction	Extraction of the sucrose juice from the pulp (fibrous cane sugar residue) called Bagasse
Juice Filtration	Separation of the juice from the Bagasse
Juice Treatment	S_2O and lime are added to the juice and heating of the alkaline juice by steam is done afterwards
Clarification	Separation of impurities from the juice by adding flocculants which will react with organic material and precipitation of non-sugar debris (mud) will follow. The clarified juice will be filtered further.
Evaporation	The filtered juice will be concentrated to form syrup called molasses by heating it with low pressure steam in the evaporators.
Crystallization	Formation of crystals from the syrup takes place in simple effect vacuum evaporators.
Centrifugation	Separation of the crystals from the molasses is carried out to get raw inedible sugar
Drying	Before packing the raw sugar it is dried for suitable storage and to inhibit micro-organism development

Table 2-3Production process of white sugar from cane sugar [12]

Process Type	Process Description For Sugar Refining (White Sugar Production)
Affination	Removal of the outer layer of molasses from the crystals by adding syrup and then centrifugation to separate the molasses-free crystals. These are then dissolved in water
Carbonation	Chalk or lime is added to the dissolved liquor and $CaCO_3$ will form to which solid impurities attach then the liquor is separated through filtration
Decolourization	Addition of Granular Activated Carbon (GAC) by which small impurities are absorbed leaving the liquor white
Evaporation	Concentration of the white liquor to form crystals
Crystallization	Formation of crystals from the liquor
Centrifugation	Separation of the crystals from the mother liquor. White refined sugar crystals are obtained hereafter
Drying	Before packing the raw sugar it is dried for suitable storage and to inhibit micro-organism development

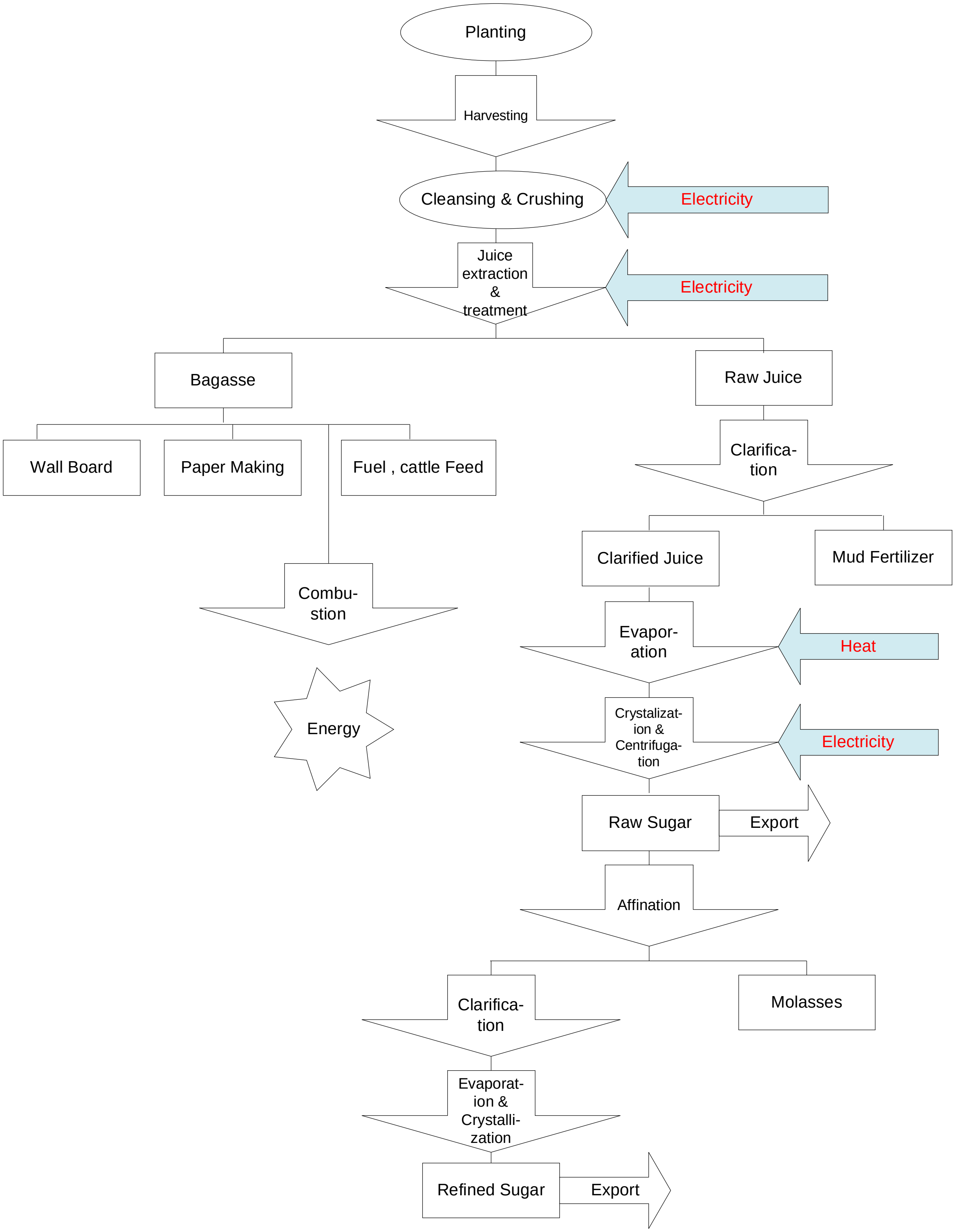


Figure 2-4 Flow chart of sugar processing from sugarcane [12]

2.3.1 By-products of Sugar Production Process from Cane Sugar

Besides bagasse, sugar mills also produce other by-products such as filter mud and molasses. The purpose and use of each by-product is outlined below.

Molasses

Molasses is the by-product of the sugar industry that is obtained in the form of liquid after sugar separation process by centrifugation. One important application area of molasses is its usage in the processing of alcohol. The major process steps in the production of alcohol are: raw material preparation, fermentation, and distillation. Ethanol has different uses such as raw material for food industries, fuel for vehicles and other application areas.

Filter Mud

Filter Mud is obtained after the raw juice clarification process and is usually known as Filter cake in the production process. The main use of the filter cake is as a fertilizer for the cane plantation.

Bagasse

Bagasse accounts for about ¼ th on weight of fresh cane & approximately 1/3rd of the cane's energy content [22]. It is primarily used in the boilers of sugar mills for steam generation. This steam is used both for electrical power generation and for the evaporators. Bagasse consists of water, fiber and certain soluble solid materials. Its composition and heating value vary depending on the climate, type of soil where the cane is grown, type of cane sugar, method of harvesting, and how the sugar is milled. Table 2.4 shows the different properties of Bagasse.

Table 2-4 Properties of Bagasse [12]

Property	Amount
Water Content [% on total basis]	46 – 52
Fibre Content [% on total basis]	43 – 52
Soluble Solids [% on total basis]	2 – 6
Average Density [dry-basis , kg/m^3]	150
Lower Heating Value (LHV) [wet-basis , MJ/Kg]	7.45
Higher Heating Value (HHV) [dry-basis , MJ/Kg]	17

Apart from this, bagasse has several other applications: fuel for lime kilns, used in paper industries & cattle feed [30]. In order to exploit the potential of bagasse efficiently, investigation of combined heat and power (CHP) systems in sugar factories is important. Also assessment of the possible optimization places in the sugar factory like boilers and turbo-generators will help the investigation process.

2.3.2 Energy Requirement of Cane Sugar Industries

Cane sugar industries are energy intensive requiring both steam and electricity. Sugar industries can get part of their power from the national grid or they can export power to the grid depending on meteorological conditions and the availability of downstream units such as alcohol distilleries, biogas plants, and chemical plants etc which contribute to increased demand of power [12]. Moreover, production of surplus electricity from excess bagasse will enable sugar mills to export electricity to the national grid. Table 2.5 outlines typical steam power plant parameters in a sugar mill [12].

Table 2-5 Typical steam parameters in a sugar mill [12]

Parameters	Value
Live steam pressure from Boiler	15 – 30 bar
Live steam temperature from Boiler	300^{o} C
Steam consumption	350 – 500 Kg/t millable cane
Electricity production	15 – 25 Kwh/t millable cane
Exhaust steam pressure delivered from turbine [back-pressure]	4 bar

The heat demand in cane sugar industries is mainly for the Evaporation, Crystallization, Drying and Distillation (if alcohol production is available as downstream unit) processes and the electricity requirement is for the Juice extraction (milling process), Conveyor belts, Centrifuges , Pumps and other auxiliary equipments.

2.4 Cane sugar industry in Ethiopia

Ethiopia is a country located in the horn of Africa with a land area of about 1.14 million km^2 having a climatic condition of tropical monsoon and wide topographic-induced variation [34].

The country has plenty of sunshine for long months of the year with the rainy season occurring from mid-June to mid-September and preceded by intermittent showers from February to March.

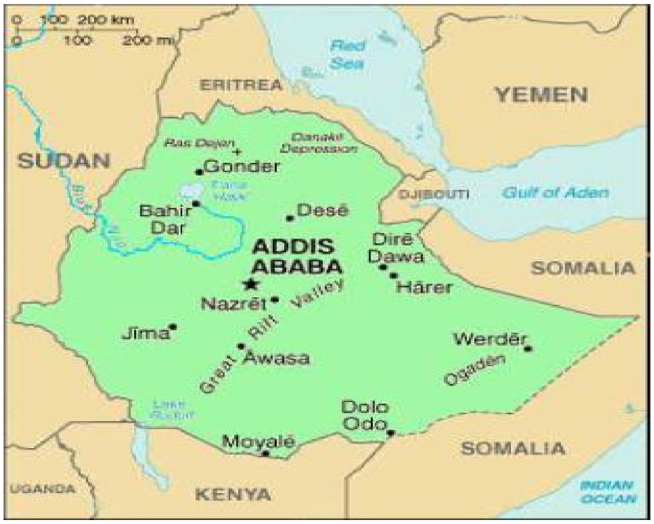


Figure 2-5 Geographical Map of Ethiopia [34]

The topography of the country is a massive highland with many mountains and dissected plateaus that are divided by Rift Valley from southwest to northeast part of the country.

2.4.1 Energy situation of the country

Ethiopia is endowed with plenty of energy resources including hydropower, biomass, solar power, and geothermal energy .Table 2.6 presents the mix of energy resources in the country [5]. These energy sources are not sufficiently exploited yet and among this biomass is one of the dominating natural resource. Biomass is the main source of fuel for cooking and heating during colder nights for many Ethiopian households having a share of about 90% [15] in the energy sector.

Table 2-6 Ethiopia's energy mix [5]

Source	**Exploitable reserves**	**Units**	**Exploited percent (%)**
Hydro power	30,000	MW	7
Solar insolation	5 – 3	Kwh/m2	0.25
Wind speed	3.5 – 5.5	m/s	0.5
Geo-thermal	4,000	Mw	1.2
Wood	1,120	Million tons	50
Agricultural waste	15 – 20	Million tons	30

2.4.2 Electricity generation situation

The majority of the country's electricity generation comes from hydropower which accounts for 97.5% of the electrical energy produced. Diesel and geothermal energy contribute the remaining percent. Less than 6% of the country's population and less than 0.5% of the towns have access to electricity [15], [16]. A state owned enterprise called Ethiopian Electric Power Corporation (EEPCo) owns the Ethiopian power sector. The corporation controls the generation, transmission and distribution of power in the country. The current total installed capacity of the corporation is 2 GW and the corporation has a long term plan of exporting power to neighboring countries by 2020, when the construction of the countries big hydropower plants is completed. Regarding the grid system, the main power grid is the Interconnected System (ICS) and this connects the different hydropower plants to main towns. The current electricity tariff in Ethiopia is on average in the range US$50-55/MWh and has been unchanged for the past 10 years [35].

2.5 General Overview of the Ethiopian Cane Sugar Industry

Sugar industry in Ethiopia was pioneered by the Dutch management and consultancy firm called **HVA International** in the early 1950s. This firm established the three sugar mills of Ethiopia, namely Wonji, Shoa and Metahara in 1954, 1960 and 1968 respectively [18]. When built, the sugar factories had a combined milling capacity of 6500 TCD and a total cane plantation area of 13,000 ha. Ethiopia has also another sugar mill called Finchaa Sugar Factory that was built in 1998 [31]. Wonji and Shoa sugar factories are now merged under one management institute. All of the three factories employ cogeneration technology to get heat and power for the sugar processing. In addition, the mills obtain national grid power for irrigation pump stations and domestic purposes. Table 2.7 shows the different capacities of the four plants.

Table 2-7 Annual production capacities of the sugar mills in Ethiopia [18]

Sugar factory name	Production capacity [ton of white sugar]
Finchaa	85,000
Metehara	120,000
Wonji-Shoa	70,000

The general description of the above mentioned Ethiopian sugar mills is presented in the sections below with more detailed approach to Finchaa sugar Factory (FSF) which for the purpose of this thesis work , is selected as the typical sugar mill of Ethiopia.

2.5.1 Wonji-Shoa Sugar Factory (WSSF)

WSSF is a public enterprise agro-industry that produces cane sugar. WSSF consists of two sugar factories Wonji and Shoa and it has a total sugar plantation farm of about 7,022 ha. Wonji sugar factory was commissioned in 1954, with a capacity of 1,450 TCD and Shoa sugar factory was commissioned in 1962 with a capacity of 1,650 TCD [15]. Due to long years of operation and obsolete technology, the performance of the WSSF is not satisfactory hence feasibility studies were conducted with the aim of investigating the possibility of long-term operation, rehabilitation, and expansion of the plant for maximum sugar output [15]. The study results have not yet been implemented. WSSF has a milling season of about 220 days with duration from October to May. Table 2.8 shows the nominal annual production capacities of the two plants [15].

Table 2-8 Annual production capacity of WSSF [18]

Factory	Nominal Crushing Capacity [TCD]	Annual Production Capacity		
		Sugar [tons]	Cane [tons]	Plantation [ha]
Wonji	1450	70,000	593,000	7,022
Shoa	1650			

Bagasse production at WSSF

Bagasse is co-generated for the internal electrical power generation of the sugar mills. Research studies show that the estimated production of bagasse at WSSF to be around 30.29 % of the cane crushed [15].

Table 2-9 Bagasse and Cane composition at WSSF [15]

Component	Parameter	Amount
Bagasse	Humidity [% on total basis]	50
	Fiber [% on total basis]	46.9
Cane	Fiber [% on total basis]	14.2
	Bagasse [%]	30.29

Table 2.10 shows the production of bagasse for three consecutive years for WSSF. Currently, about 15,000 tons of excess bagasse is produced from WSSF mills. This amount is expected to increase by three folds when the expansion programme is implemented and this might cause disposal problems unless utilization of the excess bagasse for extra electricity generation which could be sold to the national grid is considered.

Table 2-10 Annual Bagasse production at WSSF, 2001/02 [15]

	Wonji			Shoa		
	2010/11	2011/12	2012/13	2010/11	2011/12	2012/13
Cane Crushed [tons]	270,943	272,803	270,359	325,575	326,163	305,558
Bagasse Produced [tons]	82,989	83,069	82,324	101,869	100,863	96,273

2.5.2 Metehara Sugar Factory (MSF)

MSF is located at about 220 km from the capital city of Ethiopia, Addis Ababa and about 100 km below Awash Hydropower Plant. The factory was built in 1968 and it has a crushing capacity of 5,000 TCD [19] and a production capacity of 120,000 ton white sugar per annum with a plantation area of about 8507 ha [15]. Process steam is produced by bagasse burning in the four boilers of the factory that have a total capacity of 125 t/hr of steam which is supplemented by fuel oil burning [19] .

2.5.3 Finchaa Sugar Factory (FSF)

Being located near EEPCO's Finchaa hydro electric power plant station, FSF is connected for 10 MVA, 66kV from this hydropower plant. Unlike the rest of the sugar mills in the country during its cropping season, FSF supplies part of the irrigation system and the surrounding villages and town with electricity through two main net stations : (3 MVA – 66/55 kV) and (7 MVA – 66/15 kV). [31]

The factory has the capacity of producing 8 million liters of ethanol per year and, up until december, 2011 it had been the only factory in the country that produces ethanol. Table 2.11 shows the annual production capacity of the factory.

Table 2-11 Annual production capacity of FSF

Nominal Crushing Capacity(TCD)	**Annual Production Capacity**				
	Sugar (Ton)	Ethanol (Litres)	Cultivation (Ha)	Cane (Ton)	Harvest (Ha)
4500	110,000	8,000,000	6800	1,012,500	4010

Bagasse Production at FSF

The boilers at the factory are able to burn both fuel oil and bagasse. The bagasse generation and consumption in terms of flow rate and the required steam flow rate are outlined in table 2.12.

Table 2-12 Steam flow rate data at FSF

	Description	**Quantity**	**Source**
1	Ton of cane crushed per hour	183.22	Nominal design
2	Preventive maintenance in hours	180	Nominal design
3	Bagasse available from cane per kg per hour	51,367.94	Nominal design
4	Moisture at 50 % of Bagasse	47.54	Factory lab report
5	Kg of steam per Kg of Bagasse burnt	2.23	Nominal design
6	Kg/hr of steam generating 1 MWe power	8,940	Nominal design
7	Kg of steam generated per litre of fuel oil	11.98	Nominal design
8	Nominal capacity of boilers(2 * 65 ton steam/hr)	130	Nominal design
9	Temperature of live steam in ^{o}C	400	Nominal design

10	Pressure of live steam [bar]	30	Nominal design

Steam and Electricity generation at FSF

Steam generation facility: There are two boilers each capable of generating 65 ton of steam per hour operating with a pressure and temperature of 30 bar and 400 ^{0}C respectively. The boilers have total capacity of accommodating about 5250 TCD.

Electricity generation facility: The power plant is equipped with 2 x 3.5 kV turbo-generators with installed capacity of 7 MW, 3.3 kV line of EEPCO utility grid for power requirements during off-crop season, and 3 x 500 kW, 380 Volts diesel generators as stand by units.

Sugar Production Process at FSF

Harvesting of cane sugar: The harvesting is done manually after burning the cane field and leafy trash and green tops are left over as wastes from the harvesting process and are burned in the field.

Cane preparation units: After transporting the canes from the field to the factory the canes are washed and prepared for crushing. The cane preparation units are equipped with two heavy-duty cane cutting machines that are installed in series. These are meant for cutting the cane into pieces that are further shredded in a heavy-duty shredder into smaller sizes. The shredding is done for easier pressing of the cane and extract as much juice as possible.

Milling section: The milling section is equipped with 4 sets of roller mills through which the prepared cane passes and the juice in the cane is extracted by means of applying hydraulic pressure on top of the milling rollers. Bagasse is obtained from the milling process after extraction of the juice and to enable more extraction of the juice, imbibition water is spread on the bagasse in the last roller mill.

Then a mixture of the extracted juice (called “mixed juice”) from the different steps of set of the roller mills is obtained and mixed together in a trough. The Bagasse obtained after the last set of roller mill is known as "**Mill Wet Bagasse**". The amount of bagasse produced is about 1,280 ton per day.

The processed bagasse which has a fiber content of 48 to 50 % and about 1 to 3% sugar is taken to the boiler plant for the purpose of generating steam to steam turbines of the milling plant, of the boiler feed water pumps and of the power generators. The steam exiting the turbines is brought to the sugar process before returning to the boilers. The energy (both steam and electricity) requirement depends on various factors but on the average the exhaust steam required is about 0.4 ton per ton of cane processed.

Evaporation of mixed juice: The evaporation of mixed juice is done with the objective of concentrating the mixed juice. The steam after the turbines in the milling and power generation plants is used as process steam for concentration and evaporation of the juice.

Clarification of juice: The clarification of juice is done with the objective of clarifying the juice from impurities and the CO_2 obtained from the boiler flue gases can be used for carbonization of cane sugar juice. The precipitate (known as mud or filter cake) found from the clarification process is heated with the juice so that it settles easily.

Filtration of mud : The filtration of mud is done by making use of vacuum filter which filters the precipitate from the clarifier to separate the remaining juice from the filter mud (filter cake) obtained after the filtration process. This is deposited outside the factory and the juice obtained after this filtration process is called filter juice.

Evaporation of filter juice: Evaporation of filter juice is done to further concentrate the filter juice and the clear juice from the clarifier. The heat for the evaporation process is obtained from the steam turbine section. The evaporation process is done in a multiple effect evaporator under vacuum to obtain syrup of at least 60 % solids content.

Crystallization: Crystallization is done in vacuum pans to concentrate (increase the percentage of sugar in the syrup) the syrup and form sugar crystals through continued boiling. The liquid portion of the solution having sugar crystals is called mother liquor " the sugar crystal massecuite ’’. When the desired size of the sugar crystals is obtained the boiling is stopped and the massecuite is sent to a centrifuge.

Centrifugation: Centrifugation is done to separate the mother liquor from the sugar crystals and to get a refined sugar. This involves washing of the sugar crystals using a jet of superheated steam in order to remove thin films of molasses covering the crystals and dry the sugar crystals. The dried crystals are then packed and distributed to the market. After centrifugation process molasses is obtained which still contains some sugar which can be further crystallized. To do this, the molasses is heated in a vacuum pan to get more sugar crystals and the final molasses is sent to storage and it serves as a raw material for alcohol production.

Boiler section: The bagasse is used as a fuel source in the boiler section and the excess bagasse is left in the field outside the factory. The wet bagasse obtained from the last set of roller mills and having a moisture content of about 50% is sent directly to the boiler without prior treatment process. The combustion technology employs suspension burning at the combustion chamber.

The two boilers of the factory are designed with a maximum pressure capacity of 40 bars with both having economizer and air pre-heater which makes the plant more efficient than other boilers in the rest of the sugar mills in Ethiopia. The live steam (super heated steam) has a pressure of about 30 bars and a temperature of $400^{o}C$. Each boiler generates 65 t/hr of live steam at these pressure and temperature.

After the combustion process the flue gases leaving the boiler contain about 12 to 14% CO_2 having a temperature range of 93 ^{o}C to 260 ^{o}C . There is also a wet scrubber system to remove the fly ash for flue gas filtration.

Boiler feed water and air preheating: Preheating of boiler feed water and air is done by making use of the heat contained in the high temperature of the flue gases from the boiler.

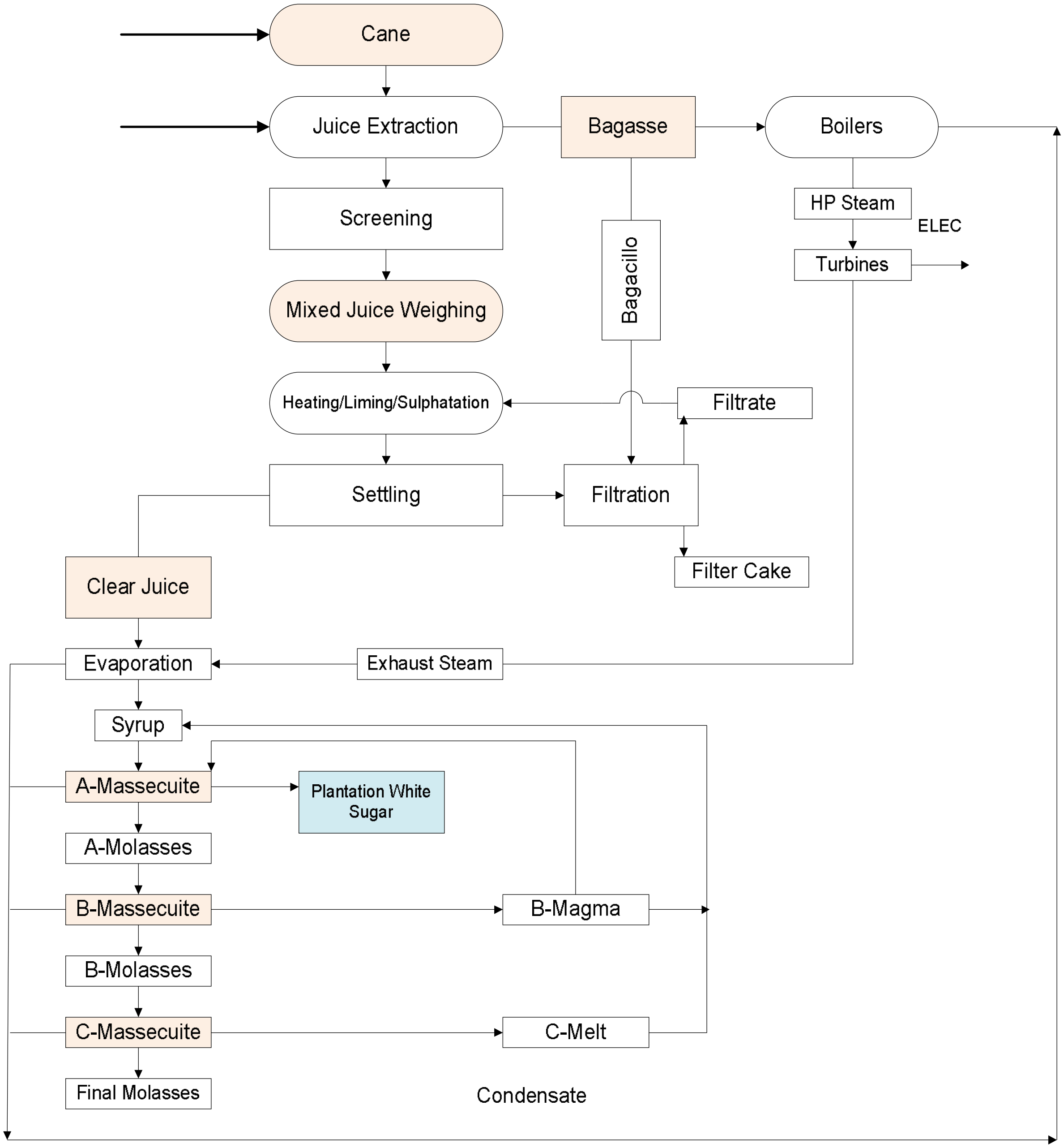


Figure 2-6 Process flow diagram for plantation white sugar production at FSF

2.6 Bagasse

Bagasse consists of water, fibres and relatively small quantities of soluble solids. Its composition varies according to the variety of cane, its maturity, the method of harvesting, and the efficiency of the milling plant [6]. The estimated composition of bagasse is outlined on Table 2.13

Table 2-13 Estimated Composition of Bagasse [6]

Bagasse Composition	Amount
Moisture	46 % - 52 % [av. 49 %]
Fiber	43 % - 52 % [av. 48.7 %]
Soluble solids	2 % - 6 % [av. 2.3 %]

The value of bagasse as a fuel depends largely on its calorific value, which in turn is affected by its composition, especially with respect to water content and to the calorific value of the sugarcane crop, which depends mainly on its sucrose content. Every tonne of sugar has an energy potential equivalent to that of 1.2 barrels of petroleum [12].

About one third of the bagasse produced in a mill can provide enough steam and electricity for the mill's requirements. Table 2.14 summarises the typical energy requirements of cane sugar mills [20]

Table 2-14 Steam and Power demands of a typical sugar mill, Per ton of cane crushed [12]

Sugar Mill Efficiency	Low-to-High
Steam requirement	500 kg (low & high efficiency)
Electricity requirement	15 kwh (low) to 34.5 kwh (high)

2.6.1 Calorific Value of Bagasse

Many formulas have been proposed to determine the calorific value of bagasse; amongst the better known the more reliable are that of Pritzelwitz van der Horst of Java and that of Hessey of Australia [6] .

(a) Pritzelwitz van der Horst:

Gross calorific value: $4550 – 10\ S\% – 45.5\ W\%$ in kcal/kg
Net calorific value: $4250 – 10\ S\% – 48.0\ W\%$ in kcal/kg

(b) Hessey:

Gross calorific value: $4636 – 12.3\ S\% – 46.46\ W\%$ in kcal/kg

Net calorific value: 4324 – 12.3 S% – 49.04 W% in kcal/kg

Both formulae are expressed in kcal/kg , where W is the moisture in the bagasse , and S the soluble solids (mainly sugar) expressed as percentages.

On average the calorific value of Bagasse can be taken as:

Gross calorific value: 2340 kcal/kg (4200 BTU/lb.)
= 9769.2kJ/kg

Net calorific value: 1920 kcal/kg (3450 BTU/lb.)
= 8027.7kJ/kg

The net calorific value takes into account the impossibility in practice of cooling; hence the net calorific value is a more realistic measure of the heating power of the fuel considered [6]. Table 2.15 shows the proximate and ultimate analysis of bagasse. The fuel substitutes for bagasse are generally fuel oil or coal, occasionally natural gas and even more rarely wood. The calorific value of these substitutes is given in Tables 2.16.

Table 2-15 Energy property of Bagasse [6]

Proximate Analysis		**Ultimate Analysis**	
Fixed Carbon	7.0 % by weight	Carbon	23.7 % by weight
Volatiles	42.5 %	Hydrogen	3.0 %
Moisture	49.0 %	Oxygen	22.8 %
Ash	1.5 %	Moisture	49.0 %
		Ash	1.5 %

Table 2-16 Calorific value of Bagasse substitutes resources [6]

Type of Fuel	Gros Cal. Value	Net Cal. Value
Fuel oil	10,000 Kcal/kg	9,300 Kcal/kg
Bituminous coal (avg.)	6,700 Kcal/kg	6,500 Kcal/kg
Natural gas	12,250 Kcal/kg	11,200 Kcal/kg
Wood (green) = 30 % moisture	3,255 Kcal/kg	2,800 Kcal/kg
Wood (air-dried) = 15 % moisture	3,990 Kcal/kg	3,600 Kcal/kg

Different bagasse furnaces are used in different Sugar factories , among which the most basic type are : The step grate ; The horse shoe ; The ward and The spreader stoker . The efficiency of these bagasse furnaces is outlined on Table 2.17 .

Table 2-17 Common Bagasse Furnaces [6]

	Step grate	**Horse shoe**	**Ward**	**Spreader stoker**
G.C.V of bagasse(kcal/kg)	2340	2340	2340	2340
N.C.V of Bagasse(kcal/kg)	1920	1920	1920	1920
Exit temp. Feed water (^{o}C)	180	180	180	180
Inlet temp. Feed water (^{o}C)	85	85	85	85
Excess air required (%)	80	70	40	30
Losses : (as % of G.C.V) Moisture in fuel loss (%) Flue gases loss (%) Unburned fuel loss (%) Radiation & Unaccounted (%)	 18 13.2 4 6	 18 13 2.5 4	 18 11 2 2.5	 18 10.4 2 2.5
Boiler efficiency Based on G.C.V Based on N.C.V	 58.8 71.6	 62.5 76.1	 66.5 81	 67.1 81.7
Kg steam/ kg bagasse 7 kg/cm , saturated 10 kg/cm , 250 c 20 kg/cm , 300 c 40 kg/cm , 350 c	 2.39 2.23 2.16 2.04	 2.45 2.37 2.3 2.17	 2.7 2.52 2.45 2.31	 2.72 2.54 2.47 2.33

The fuel replacement value of bagasse calculated based on the energy content of the fuels, amount of energy that can be extracted from the fuels and the cost of fuel is given as:

0.18 tone of fuel oil
0.28 tone of bituminous coal
0.15 ton of natural gas
0.55 ton of wood (air dry) is equivalent to 1 ton of bagasse [6].

2.6.2 Availability of Bagasse at FSF

For convenience and uniformity, quantitative measurements of bagasse are generally expressed either in terms of mill run bagasse (approx. 49% moisture) or in terms of bone dry bagasse weight. Surplus bagasse is rarely weighed at the factory, hence unless the bagasse is baled; weight estimates of loose bagasse are often unreliable.

2.6.3 Storage of Bagasse at FSF

The cost of bagasse, whether it is to be sold on a calorific value basis or on a purely surplus basis, has generally to be determined by the cost of handling, storage and transportation. Apart from its direct utilization as combustible in the furnaces of the sugar factory boilers for steam generation , bagasse is also used as raw material in the paper making industry and is also used for cattle feed . Its low density and relative in-flammability makes it a bulky and costly material to handle and transport.

2.6.4 Experiences of Foreign Sugar Factories in Using Bagasse

Over the years, cane sugar factories around the world and more specifically those found in the islands of Hawaii and Mauritius, devoid of any fossil fuel resources, have invested in energy efficient equipment and adopted energy conservation measures with the objective of reducing energy demand in cane processing and maximizing energy export in the form of electricity to the public grid [21].

In the islands of Mauritius , a factory with a cane crushing capacity of 300 ton cane per hour equipped with 2 x 140t/h boiler and producing steam at a pressure and temperature of 82 bar & 525°C respectively is fed to 2x35mw condensing extraction turbo-alternator . The net electricity exported by this factory reaches 110kwh/tone cane which means that a cane sugar factory processing around 1 million tons of cane can accommodate a power plant generation of 440 GWH [21].

By investing in mill efficiency and giving attention to this important energy resource, “Bagasse”, Mauritius had a positive outcome where significant improvements were made in energy use and conservation in cane processing. In addition to generating energy for the whole process of sugar manufacturing, bagasse based power plants are also available in different countries of the world, table 2.18 shows bagasse based power plant in Mauritius up to the year 2010. Energy generation and export from excess bagasse is at this time a favourable activity in addition to sugar manufacturing in many countries. Current studies show that Hawaii’s largest sugar producer converts around 250,000 ton of bagasse to electricity and exports about 100,000 Kwh to utility grid [21].

Table 2-18 Bagasse based power plants in Mauritius [21]

Factory Name	Ton cane per hour	Type	Units from Bagasse (Gwh)	Units from coal (Gwh)	Total units from Bagasse & coal (Gwh)
Fuel	270	F	60	115	175
Deep River Beau champ	270	F	70	85	155
Belle Vue	210	F	105	220	325
Medline	190	C	20	-	20
Mon Tresor Mon Desert	105	C	14	-	14
Union St Aubin	150	C	16	-	16
Riche en Eau	130	C	17	-	17
Savannah	135	C	20	-	20
Mon Loisir	165	C	20	-	20
Mon Desert Alma	170	C	18	-	18

F – Firm or Bagasse during crop & Coal during non-crop season
C – Continuous or Bagasse during crop season only

2.7 Technologies of bagasse burning for power generation

Bagasse burning has been carried out traditionally to fuel boilers with the aim of meeting the heat and electricity demands of the sugar industries from which it is produced. Current developments in technology make use of different conversion technologies to convert bagasse to electricity or heat in a more efficient and environmentally friendly manner. More over such modern technologies have contributed to creating the opportunity to export power to the power grid. This section will discuss in brief some of the conversion technologies of bagasse for electrical power generation. The technologies include Biomass-fired steam-Rankin cycle for cogeneration using Condensing-Extraction Steam Turbine (CEST), Biomass integrated gas turbine combined cycle (BIG/GTCC) and fluidized bed combustion cycle (FBC).

2.7.1 Biomass fired steam cycle using condensing extraction steam turbine (CEST)

Most sugar mills use backpressure turbines where the steam exiting the turbine is brought to process. This technology is advantageous compared to the CEST technology when it comes to total efficiency of the power plant where the process heat rate need is fixed. However, the back-pressure system has very low efficiency during off-season, and therefore reduces the possibility of producing only electricity. The CEST cycle consists of direct combustion of bagasse in a boiler to raise steam, which is then expanded through a turbine. It involves boiling pressurized water with the resulting steam expanding to drive a turbo-generator and then condensing back to water for partial or full recycling to the boiler. It is a well-known technology but the cogeneration units are of low efficiency and not competitive as compared to other power generation technologies [22]. A schematic diagram of such combustion technology is shown in figure 2.7.

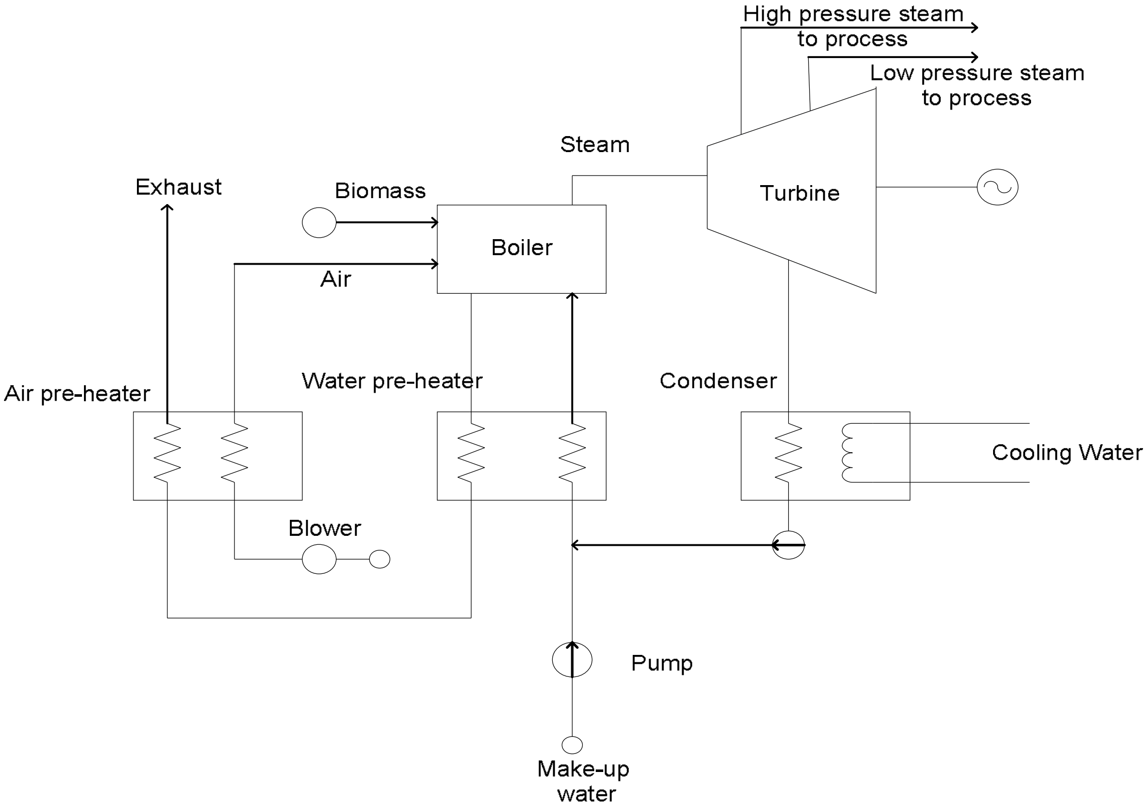


Figure 2-7 Schematic diagram of biomass-fired steam cycle for cogeneration using a condensing extraction steam turbine [22]

2.7.2 Biomass integrated gas turbine combined cycle BIG/GTCC

The atmospheric-pressure of the BIG/GTCC process for systems involving power generation or cogeneration of heat and power (CHP) is comprised of processes like fuel preparation, air blown gasification in an atmospheric pressure CFB reactor, tar cracking, product gas cooling and cleaning, multiple-stage compression, gas combustion and expansion in a gas turbine-generator and gas turbine exhaust heat recovery using a steam turbine generator. The BIG/GTCC, regardless of its wide advantages as a combined cycle technology, is not yet commercialized. The BIG/GTCC combined cycle technologies for co-generation or stand alone power generation will provide a low cost generation of electricity as compared to most alternative technologies. Moreover it is an environmentally friendly technology with near zero net CO_2 emission [23]. For sugar industries in developing countries that produce sugar and alcohol, this technology is promising. Figure 2.8 depicts the schematic diagram of BIG/GTCC process.

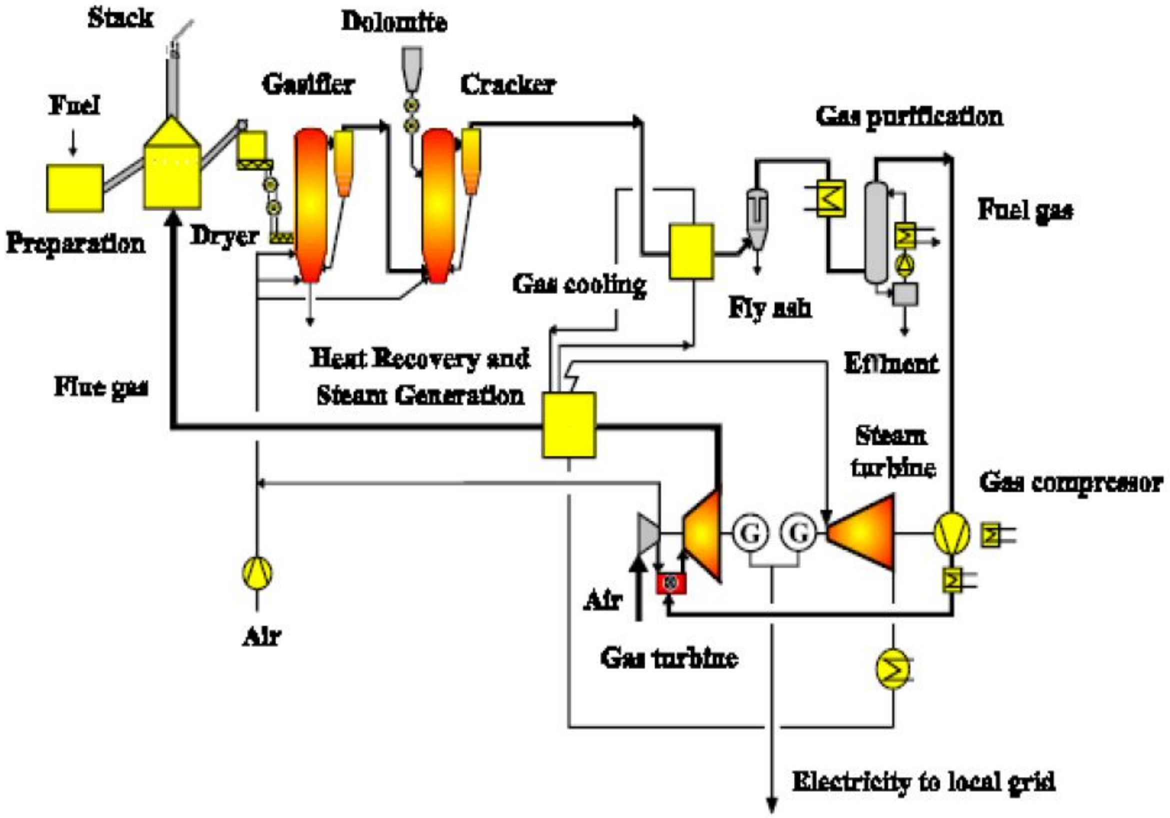


Figure 2-8 Schematic diagram of BIG/GTCC process flow [23]

2.7.3 Fluidized bed gasification

Fluidized bed gasification involves fluidization of fuel particles due to air introduction into the chamber and presence of sand bed (usually silica sand and dolomite) in the chamber which is used to physically abrade the fuel particles. This scrubbing action constantly exposes fresh surfaces for volatilization of the gas. The sand represents a large hot mass and has thus a damping function for temperature fluctuations caused by fuel heterogeneity. In this type of gasifiers, the prepared fuel is gasified at 800 to 900°C in a fluidized bed. Introduction of fluidizing air through the nozzle tray creates the fluidized bed [23]. If air flow is further increased so that the bed material fills out the entire reactor, cyclone is used to separate heavy particles from the light ones and gas. Return of inert material to the bed is also carried out. This type of fluidized bed is called Circulating Fluidized Bed (CFB) [23].

2.8 Pellets

Bagasse is powdery by its nature and is hard to handle and manage especially when produced in excess and when no storage place is available, thus for convenience, Pellet mill is used to compress the powdery material in to firm and uniformly shaped granules called Pellets. Pellets are dust free thus reducing dust explosion potential and minimizing particle emission during combustion [24]. At Finchaa Sugar Factory, the excess produced bagasse is simply left at the field and it is not pelletized, hence using proper type of pellet mill the extra generated bagasse can be pelletized and stored properly and used as a valuable fuel. Bagasse pelletizing has many advantages and are mentioned below:

- It minimizes problems of reclaiming or disposing of dust, powders, residues or other hard to handle materials.
- It reduces cost for shipping, storage and handling.
- It densifies waste materials.
- It converts combustible energy resources in to more efficiently consumed, cleaner burning fuel [25].

Chapter Three

DATA COLLECTION AND ANALYSIS

3.1 Data Collected

Different kinds of data have been collected while doing the research work at Finchaa sugar factory. These data have been collected from many sources and for ease of study have been divided by the researcher in to two major types: one is the primary data and the other the secondary data.

Primary data is obtained by the researcher and is the result of own studies of the Problem. It includes the collection of information through direct observation of the factory auxiliary and major operating equipments, through distributing questionnaires to the technical and management staff of the factory and through conducting personal conversations and interviews. The secondary data, on the other hand, is the result of other people's research in the same problem area, or from other related problem areas. It includes the study of documents and archival records obtained from the factory, web-sites and other historical and documentary records relevant for the research. Tables 3.1 & 3.2 show the data collected in relation to the Cane and Bagasse production and utilization while Tables 3.3 up to 3.5 outline the technical specifications of the Turbines , Boilers and Generators at Finchaa Sugar Factory .

Cane sugar is planted throughout the year and the average harvest period at FSF extends from the month of October up to the month of June, in figure this on average amounts to 7 and a half months which is equivalent to 225 days . The harvest period may vary from season to season depending on the length of the winter season where by rainfall usually occurs between the months of June and September.

During the milling season, the factory operates 24 hours a day and 7 days a week, there are three shifts per day whereby each shift operates for 8 hours a day. During the off-milling season, the factory shuts down and maintenance and repairing is done on the evaporators, distillers, turbines, boilers and other auxiliary parts of the factory.

For co-generation purposes, bagasse is the fuel that is used at the Boilers for the generation of steam & electricity. The total amount of bagasse that is produced during the milling season on average reaches up to 287,820 tons. Investigation done by the researcher show that not all of the bagasse that is produced at the factory is used for steam generation, rather ample amount is left as waste. The data collected shows that out of the total bagasse that is produced 284,040 ton are used for steam generation and the remaining 3,780 ton is left as waste on the field at the factory.

The conventional turbine technology deployed at Finchaa Sugar Factory is the back-pressure type; these turbines have relatively poor conversion efficiency in the range of 55 % to 65 % [31]. The actual steam rate for the turbines per kwh equals to 9 kg. The turbines operate at medium pressure and temperature of 30 bars and $400^{o}C$ respectively.

The manufacturer of the boiler at FSF is Zurn of Germany. The design performance data that is obtained from the manufacturer considers only one moisture content, i.e., 50 %. The boilers also operate at medium pressure and temperature.

Table 3-1 Cane base data at FSF [5]

		Data 1 : FSF	**Data 2 : Prof. W.Ghiorgis**
Cane	**Harvest period**		
	Planted cane [months]	12	
	Average harvest period [months]	7.5 (October – June)	
	Hrs/shift	8	8
	Shifts/day	3	3
	Days/month [Eth Calendar]	30	30
	Months/year	7.5	
	Days/year	225	
	Cane Milling Capacity		
	ton-cane/hr	187.5	183.3
	ton-cane/day [TCD]	4500	4400
	ton-cane/day [maximum capacity]	5500	
	ton-cane/day [actual running capacity]	4500	
	Energy requirement		
	Kg steam / ton-cane	400	
	Electricity [MWe]	6	
	Electricity [kwh/toncane]	20	
	Property		
	Fiber content (%)	14.6	
	Milling Power requirement		
	Milling efficiency (%)	70	
	Milling season [days/year]	225	
	Peak power [MWe]	6.8	
	During milling season [MW]	5.2	
	During off-season [MW]	0.4	

Table 3-2 Bagasse base data at FSF [5]

		Data 1 : FSF	**Data 2 : Prof. W.Ghiorgis**
Bagasse	**Production capacity [*Total Bagasse]***		
	ton/hour	53.3	54.7
	ton/day	1279.2	1312.8
	ton/year	287,820	295,380
	Used Bagasse (CHP)		
	ton/hour	52.6	54.2
	ton/day	1262.4	1300.8
	ton/year	284,040	292,680
	Excess Bagasse		
	ton/hour	0.7	0.5
	ton/day	16.8	12
	ton/year	3,780	2700
	Property		
	Soluble Solids (%)	2	
	Dry matter (%)	48	
	Moisture content (%)	50	47.54
	Density[kg/m^3]	150	
	Fiber Content [%]	47	
	Heating Value		
	LHV [Kcal/Kg]		
	Dry	17,800	
	Wet	13,500	
	HHV [Kcal/Kg]	4000	
	Steam generation		
	Kg steam / kg bagasse	2.2	2.23
	Heat & Power production		
	MW per day	5	

Table 3-3Turbine (T/A) specification at FSF [5]

		Data 1 : FSF	**Data 2 : Prof. W.Ghiorgis**
Turbine (T/A)	**For factory power production**		
	Qty	2	2
	Type	Back-Pressure	Back - Pressure
	Production Capacity		
	Electricity [MWe]	3.5 * 2 = 7	3.5 * 2 = 7
	Steam Data		
	Pressure [bar]	30	30
	Temperature [^{o}C]	400	400
	Steam consumption for power generation		
	Actual Steam rate [Kg/kwh]	9	8.94
	Steam flow [ton steam/hr]	41.3	
	Back Pressure[bar]	1.25	
	Steam turbine efficiency	66	
	Return temperature[^{o}c]	125	
	Heat rate [KJ/Kwh]	8000	
	Enthalpy[KJ/KG](check)	2713.75	
	For Milling power production		
	Qty	4	
	Production capacity		
	Power [KW]	525 - 750	
	For shredding power production		
	Qty	1	
	Production capacity		
	Power [kw]	850	
	Power [kw/t fibre-hr]	40	
	Power [kw/t cane-hr]	584	
	Process Steam (going to evaporators ,distillers etc)		
	Pressure [bar]	1.25	
	Temperature [^{o}C]	125 - 140	

Table 3-4 Boiler specification at FSF [5]

		Data 1 : FSF	**Data 2 : Prof. W.Ghiorgis**
Boiler	**Qty**	2	
	Production Capacity		
	Steam [ton/hr] ; Peak	72 * 2 = 144	65 * 2 = 130
	Steam [ton/h r]; ambient	65 * 2 = 130	65 * 2 = 130
	Live Steam data		
	Pressure [bar]	30	30
	Temperature[^{o}C]	400	400
	Peak steam data		
	Pressure [bars]	40	
	Temperature [^{O}C]	450	
	Water data		
	Pressure [bars]	60	
	Efficiency (%) check	66	
	Flue gas		
	Temperature (^{O}C)	200	
	Ash		
	Combustion type	Suspension burning	
	Enthalpy[KJ/Kg]		
	Live Steam (check)	3231.6	
	Feed Water (at the output to the Boiler)	521.31	

Table 3-5 Generator specification at FSF [5]

	Data 1 : FSF	**Data 2 : Prof. W.Ghiorgis**
Diesel Generator Set		
Qty	3	
Production capacity		
Power [kw]	3 * 512	3 * 512
Electricity consumption from grid		
Milling [kw]	450	

3.2 Data Analysis

The factory operates at medium pressure and temperature of 30 bar and 400°C respectively. The steam on cane consumption of the factory reaches at 40 % [(i.e.) 400 kg of steam per ton cane]. The configuration of the existing turbine/boiler lay out is shown on figure 3.1.

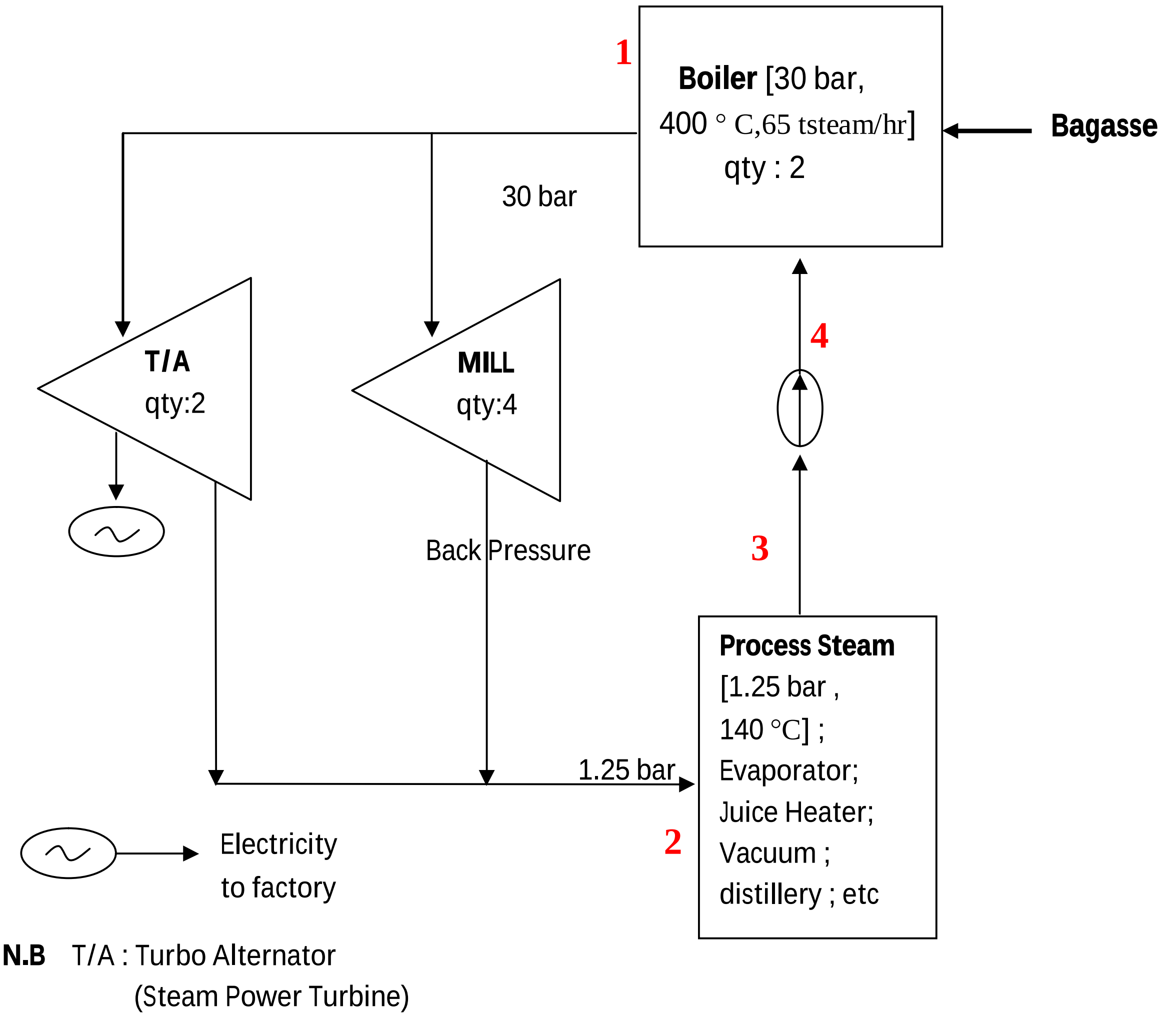


Figure 3-1 Current Turbine/Boiler configuration of FSF

The steam generated at medium pressure and temperature from the boiler feeds both the milling section and the turbo-alternators. There are 4 mills at the factory which are used to crush the cane sugar and extract the juice from the cane. The turbo-alternators are of 2 in quantity and they are used to generate electricity to supply the factory. The turbo-alternators and the mills have extraction ports which outputs steam at a pressure of 1.25 bar and 140 ^{o}C and this steam is used to operate the evaporators, juice heaters, distilleries etc. In doing the research work, two different analysis strategies are done and compared with each other, one is to use bagasse drying strategy for different moisture contents of the bagasse, the idea behind this strategy is through reduction of the moisture content of bagasse whereby its heating value will be enhanced and eventually the combustion temperature will increase, this will result in the production of excess bagasse and hence excess electrical power. For the bagasse drying strategy, the heat energy from the boiler flue gas is considered to be used. The second strategy is to change the configuration of the turbine-boiler arrangement and use a high pressure and temperature turbine & boiler and compute the generated bagasse and electrical power using the RETScreen simulation software.

3.2.1 Bagasse Drying

By reducing the moisture content of bagasse, Boiler efficiency can be greatly improved resulting in excess bagasse being available for storage for off season energy needs. More over this process can result in enhanced level of electricity export to the grid. Bagasse drying by using flue gas is widely applicable in many sugar countries like Cuba, Australia, India, Brazil and USA [26].

In addition to energy efficiency, bagasse drying will also improve sugar recovery efficiency of the mill because of the fact that the mill operators will concentrate fully on the amount of sucrose extraction rather than on the bagasse moisture content only [26].

The standard moisture content of the bagasse at FSF is 50% and for calculation purposes this will be taken as the base case, the initial values for the calculation of the different parameters used are taken from the information obtained from the sugar factory under consideration. Typical bagasse dryer and bagasse dryer arrangement are shown in the following figures.

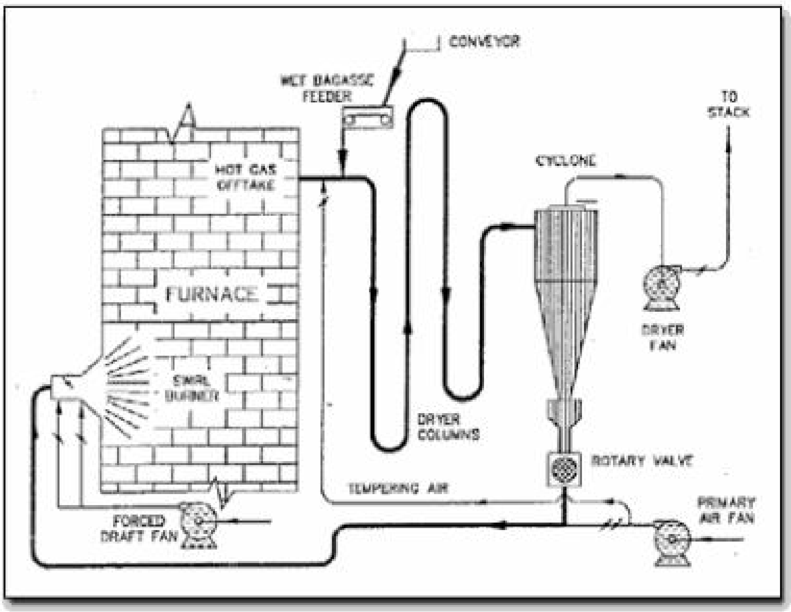


Figure 3-2 Bagasse dryer [26]

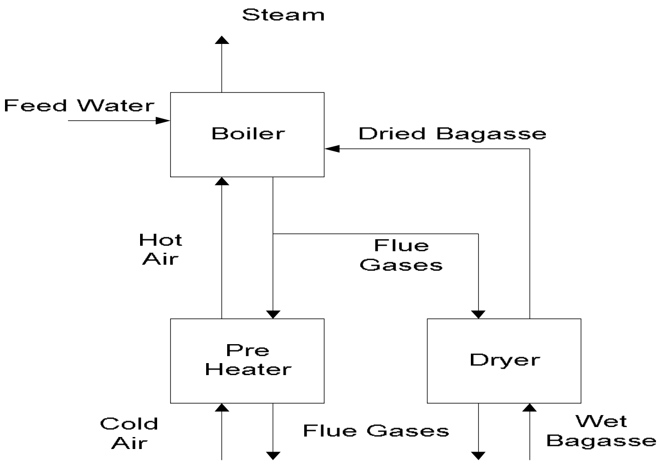


Figure 3-3 Bagasse dryer arrangement [26]

The mass and energy balance for the bagasse and steam flow is analyzed and for computation purposes the block diagram of figure 3.1 is used, the subscripts used in the different parameters are taken from the corresponding labels in the figure.

Mass Balance

From the data obtained from FSF, the total mass flow rate of bagasse at 50% moisture content is:

$M_{Bagse,total}$= 53.3 [ton/hr] = 14.81[kg/s] (table 3.2 , bagasse base data)

Mass flow rate of excess bagasse at 50% moisture content equals:

$M_{Bagse,excess}$ = 0.7 [ton/hr] = 0.19 [kg/s] (table 3.2 , bagasse base data)

The used or net mass flow rate of bagasse fed to the boilers will be equal to the difference between the total and excess flow rate:

$M_{Bagse,net} = M_{Bagse,total} - M_{Bagse,excess}$ [kg/s] ……………………………….(1)

=14.81 – 0.19 [kg/s] = 14.61[kg/s]

Mass flow rate of steam through existing electrical power turbines:

$M_{steam,1-2,electral}$ = 41.3 [ton steam / hr] = 11.48 [kg/s] (table 3.3 , turbine base data)

From the block diagram of figure 3.1 , the mass flow rate of steam through the mill turbines will equal to:

$M_{steam,1-2,mech} = M_{steam,total} - M_{steam,1-2,electral}$ [kg/s] ……………………….(2)

The total mass flow rate of steam generated $M_{steam,total}$ can be calculated from the Energy balance of the cycle .

Energy Balance

In doing the calculation for the energy balance, we assume that there is no enthalpy change before and after the pump. Lower heating value of bagasse on total basis is given as [28]:

$LHV\text{tot} = LHV\text{dry} * (1 - f)$ [kJ/kg]; where “f” is moisture content of bagasse and LHV_{dry} is the lower heating value of bagasse on dry basis which is obtained from factory….... (3)

The power input to the cycle is given as [37] :

$P_{input} = M_{Bagse,net} * LHV_{tot}$ [MW] ....(4)

Mass flow rate of the total steam [37]

$M_{steam,total} = (P_{input} * \eta cycle)/(h_1-h_4)$[kg/s]..(5)
where : ῃ = efficiency of the system (%)

P_{input} = power input (MW)
h_1 & h_4 = enthalpy changes (kJ/kg)

Electrical power output from the existing electrical power turbines

$P_{electcal,1\text{-}2} = M_{steam,1\text{-}2,electral} * (h_1 – h_2)$ [MW] …...(6)
where : h_1 , h_2 = enthalpy changes (kJ/kg)

Mechanical power output from the existing mill turbines

$P_{mech,1\text{-}2} = M_{steam,1\text{-}2,mech} * (h_1 – h_2)$ [MW] ....(7)
where : h_1 , h_2 = enthalpy changes (kJ/kg)

Heat flow for the process

$Q_{processs,2\text{-}3} = M_{steam,total} * (h_2 – h_3)$ [MW] ....(8)
where : h_2 , h_3 = enthalpy changes (kJ/kg)

Total heat and power of the cycle

$P_{output} = P_{electcal,1\text{-}2} + P_{mech,1\text{-}2} + Q_{processs,2\text{-}3}$ [MW]..(9)

Total efficiency of the cycle

$\eta_{cycle} = P_{output} / P_{input}$ [%] ....(10)

<u>Production of Excess Bagasse</u>

The net bagasse flow rate will be reduced due to the improved heating value, thus excess bagasse will be produced in addition to the one that is left on the field while producing the same amount of heat and power as in the base case. The steam flow rate remains at a constant amount for all the different moisture contents as there will not be more steam generated. From the mass balance equations obtained above, we obtain the following results: (N.B detailed calculation is presented on Appendix I.1)

Mass flow rate of steam through existing electrical power turbines:

$M_{stm,\ 1\text{-}2,\ electl} = 11.48$[kg/s] (table 3.3, turbine base data)

Total mass flow rate of steam through Boiler:

$M_{steamtotal} = 107.1$ [ton/hr] = 29.75 [kg/s] (from equation 5 & taken from appendix I)

Mass flow rate of steam used for mechanical power generation:

$M_{steam,1\text{-}2mech} = 29.75 - 11.48 = 18.27$[kg/s] (from equation 2 & taken from appendix I)

From the energy balance equations, following results are generated .From equation 5 above, boiler power output is given as:

$P_{outpt} = M_{steamtotal} * (h_1 - h_4)$ [mw]

where; h_1 , h_4 = change in enthalpy (kJ/kg)

Fuel power input to the cycle

$$P_{input,cycle} = P_{outpt} / \eta_{boiler} \qquad (11)$$

where ; ῇ = efficiency (%)

Mass flow rate of total bagasse at different moisture contents [37]

$$Mf,t,b = P_{output}/LHV_t\ [\frac{kg}{s}] \qquad (12)$$

where ; P_{output}=output power (Mw)

LHVt = lower heating value on total basis (kJ/kg)

Mass flow rate of dry bagasse at different moisture contents [37]

$$Mf,d,b = Mf,t,b * (1 - F)[\frac{kg}{s}] \qquad (13)$$

where ; F = moisture content (%)

Mass flow rate of dry excess bagasse production [37]

$$Mf,d,ex,b@f\% = Mf,d,b@50\% - ,Mf,d,b@f\%[\frac{kg}{s}] \qquad (14)$$

Total annual mass of excess dry bagasse produced [37]

$$Mf,d,ex,b\left[\frac{t}{yr}\right] = Mf,d,ex,b * \left(\frac{3600\left[\frac{s}{hr}\right]*24\left[\frac{hr}{d}\right]*225[\frac{d}{yr}]}{1000[\frac{kg}{t}]}\right)[\frac{t}{yr}] \qquad (15)$$

Annual fuel power of excess dry bagasse produced [37]

$$Qf,d,ex,b = Mf,d,ex,b * LHV_{dry}[MW] \qquad (16)$$

Annual energy potential of bagasse [37]

$$Q_{e,b} = Mf,d,ex,b\left[\frac{t}{yr}\right] * LHV_{dry}[mw] * 1000\left[\frac{kg}{t}\right] * 277.78 * 10^{-6}\left[\frac{mwh}{mJ}\right][\frac{mwh}{yr}] \qquad (17)$$

The amount of excess bagasse produced due to bagasse drying is calculated using the above formulas and detailed computation is done on Appendix II of this study. The obtained result from the calculation is presented on the table below for moisture contents of 50%, 40%, 30% and 20% respectively.

Table 3-6 Excess bagasse amount generated due to bagasse drying procedure

F	LHVt [kJ/kg]	$M_{st,tot}$ [Kg/s]	$M_{st,elt}$ [Kg/s]	$M_{st,mec}$ [kg/s]	P_{el} [mw]	P_{mec} [mw]	Q_{prcs} [mw]	P_{in} [mw]	P_{out} [mw]	η %	$M_{f,t,b}$ [kg/s]	$M_{f,d,b}$ [kg/s]	$M_{f,t,ex,b}$ [kg/s]	$M_{f,d,exb}$ [kg/s]	$M_{f,d,ex,b}$ [kt/yr]
20	14,240	29.75	11.47	18.27	5.9	9.4	65.22	110.5	80.63	73	7.75	6.21	6.86	1.1	21.38
30	12,460	29.75	11.47	18.27	5.9	9.4	65.22	115.2	80.63	70	9.25	6.47	5.36	0.84	16.33
40	10,680	29.75	11.47	18.27	5.9	9.4	65.22	122.2	80.63	66	11.44	6.864	3.17	0.446	8.67
50	8900	29.75	11.47	18.27	5.9	9.4	65.22	130.1	80.63	62	14.61	7.31	0.19	0.095	1.85

As can be seen, when the moisture content of the bagasse is decreased from its value, the amount of bagasse that is generated in excess increases, but it is not feasible to continuously decrease the moisture content beyond limit since the maximum power generation capacity of the existing turbines is set to 7.5 MW and hence the least possible value that can be used is set at 20 % .

Boiler efficiency calculation

The calculation of the boiler efficiency is based on the information provided by the FSF's boiler manufacturer "Zurn". The design performance data that is obtained from the manufacturer considers only one moisture content, i.e., 50%. For the bagasse drying strategy, consideration of different moisture contents is necessary. Therefore, making use of the information provided in the manufacturer's boiler design performance data as a starting point, corresponding values of the boiler efficiency are calculated for the different moisture contents of the bagasse. The calculation procedure is shown below and the detailed calculation is shown on appendix III , the calculated values are summarized on table III.1 of appendix III.

Lower heating value

The heating value on total basis is calculated from equation 4; the lower heating value on dry basis is taken directly from the factory and is tabulated on table 3.2 and equals to 17,800 kJ/kg .

Higher heating value

The higher heating value of the bagasse is calculated as below [28]:

$$LHV = HHV - r_{h2o} * (8.92*H_2 + F)\ [MJ/kg] \ldots\ldots (18)$$

where the mean value for the heat of vaporization, r_{h2o} at 25°C is taken as 2440 kJ/Kg [28].

The boiler efficiency is calculated by deducting the different losses that occur at the boiler and these losses are summarized below:

Flue gas loss on dry basis (L_{fg})

The flue gas loss is calculated using "Siegerts" formula [28]

$$L_{fg} = K * (t_{fg} - 25) / [CO_2]_d\ [\%] \ldots\ldots (19)$$

The flue gas temperature is taken as an average value and is estimated as 200°C [31]. For the estimation of the value of CO_2 on dry basis, figure III.1 in appendix III is used , moreover, for the estimation of the value of k , figure III.2 in appendix III is used with the CO_2 value obtained and the moisture content for wood equal to zero[28].

Loss due to heating of water vapor from vaporization temperature up to stack temperature ($L_{h20,\ sens}$) [28]

$$L_{h20,\ sens} = \Delta h * (F + 8.92 * H_{2t} * (1-F)) / HHV*100\ [\%] \ldots\ldots (20)$$

where ; Δh = enthalpy change (kJ/kg)
F = moisture content (%)
HHV = higher heating value (kJ/kg)
H_{2t} = hydrogen on total basis (%)

Loss due to vaporization of water during combustion [28]

$$L_{h20,\ Lat} = r_{h20} * (F + 8.92 * H_{2t} * (1-F)) / HHV*100\ [\%] \ldots\ldots (21)$$

where ; F = moisture content (%)
H_{2t} = hydrogen on total basis (%)

HHV = higher heating value (kJ/kg)
r_{h2o} = mean value for the heat of vaporization at 25°C = 2440 kJ/Kg [28]

Other indirect losses (which account to a value of 5.3) are directly taken from the Boilers manufacturers design performance data (ZURN) and are assumed to be unchanged [31] ; hence the total formula is given as follows [28]:

$$\eta_{boiler} = 100 - (L_{fg} + L_{h20,sens} + L_{h20,Lat} + L_{indirect})[\%]\ldots\ldots\ldots\ldots(22)$$

3.2.2 High Pressure Boiler

The next analysis in doing the project work is to use a high pressure boiler and turbine instead of the existing medium pressure boiler and run the RetScreen simulation software to obtain the desired output. In doing so the selected and available type of high pressure turbine and boiler in the market operate at a pressure of 70 bar and a temperature of 500 °C . In this new setup , all the data obtained from the factory except for the Turbine and Boiler remain the same and the condition of the exhaust steam from the new turbine is maintained at 30 bars and 400 °C as in the base case so that the production of heat and power for the base case is unaffected while the steam flow rate of the turbine is changed from 41.3 ton/hr to 65 ton/hr as obtained from the supplier , moreover the steam parameters for the old mills is assumed to be unchanged as in the base case .The new type of configuration together with the changed Boiler and Turbine is shown on figure 3.4 .

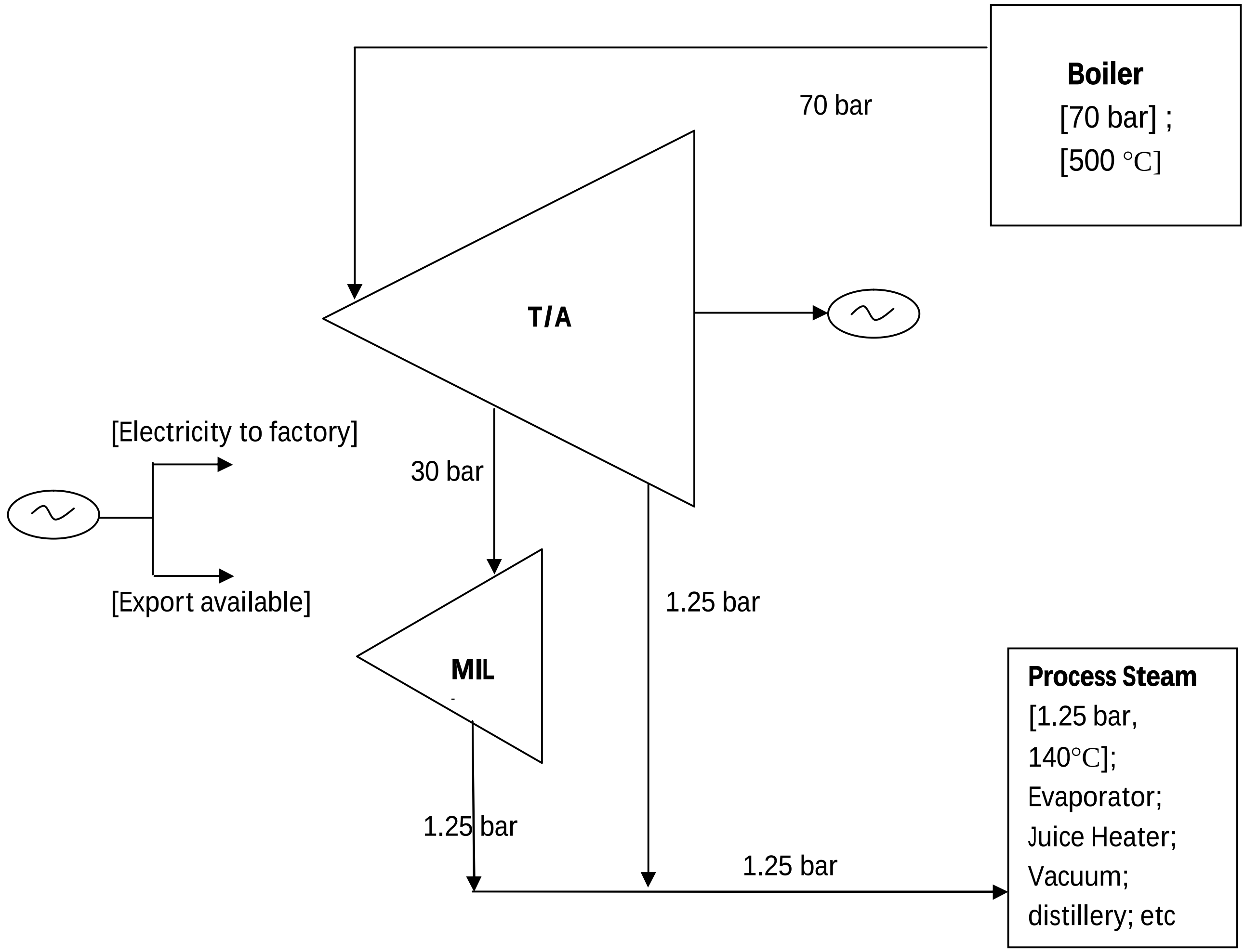
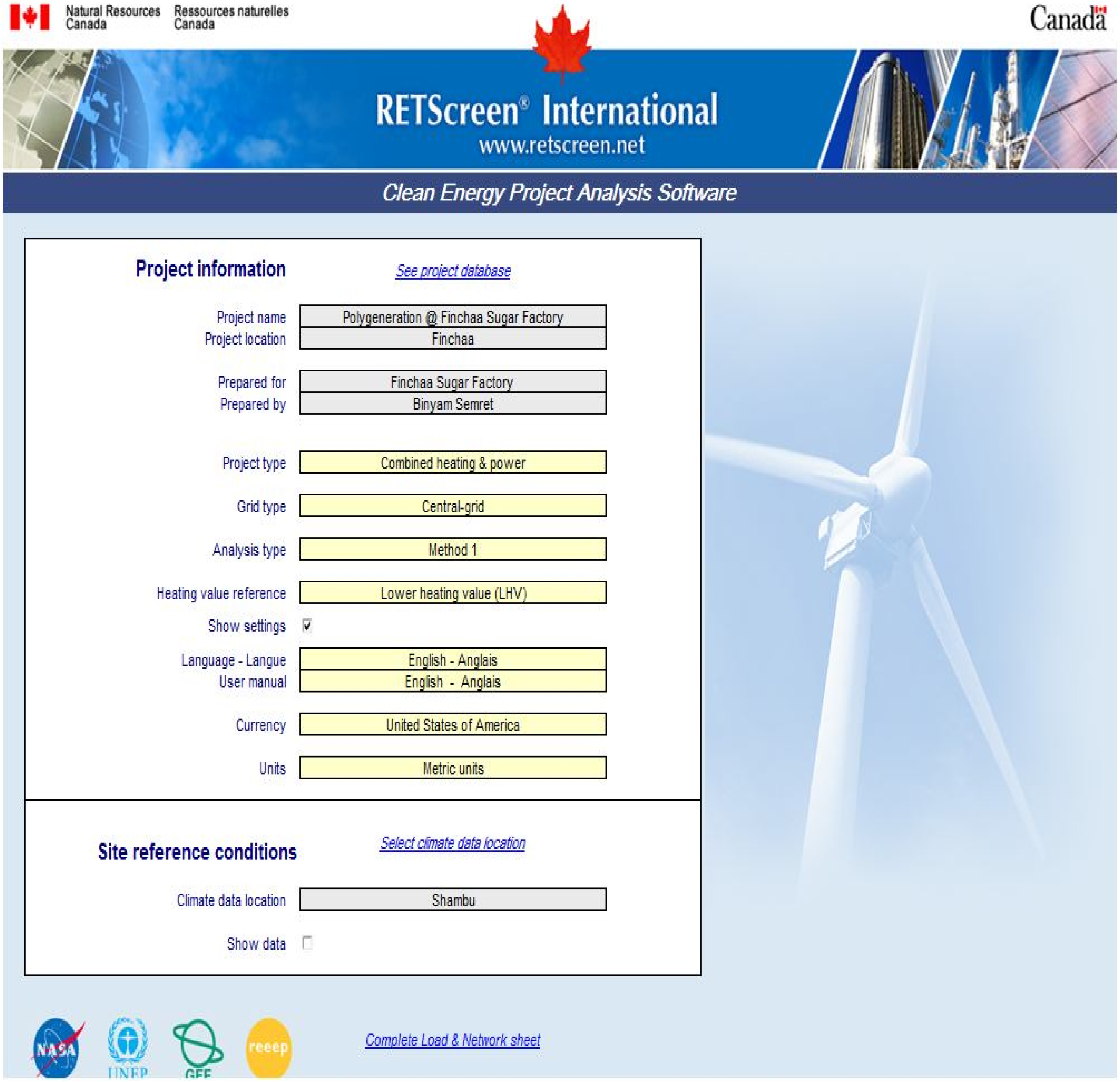


Figure 3-4 New Turbine/Boiler configuration of FSF

The steam generated from the high pressure and temperature boiler feeds the stand alone high pressure Turbo-Alternator at a pressure of 70 bar and a temperature of 500 ^{o}C . The output from the exhaust valve of the Turbo-Alternator feeds all the existing mills at the standard existing pressure of 30 bars and temperature of 400 ^{o}C each. The output steam pressure from the backpressure port of the Turbo-alternator and that of the mills remains the same at 1.25 bar, this steam is then used for process at the factory. RETScreen software is fed with the changed parameters of the boiler and turbine to compute the electrical power generated and the amount of bagasse produced and used.

3.2.3 RETScreen

RETScreen® International is a clean energy awareness, decision-support and capacity building tool. The core of the tool consists of a standardised and integrated clean energy Project analysis software that can be used world-wide to evaluate the energy production, Life-cycle costs and greenhouse gas emission reductions for various types of energy efficient and renewable energy technologies (RETs). Each RETScreen technology model is developed within an individual Microsoft® Excel spreadsheet "Workbook" file. The Workbook file is in-turn composed of a series of worksheets. These worksheets have a common look and follow a standard approach for all RETScreen models [27]. Figure 3.5 shows the input on to RETScreen for simulating the data obtained from FSF.



Project information

Project name: Polygeneration @ Finchaa Sugar Factory
Project location: Finchaa

Prepared for: Finchaa Sugar Factory
Prepared by: Binyam Semret

Project type: Combined heating & power
Grid type: Central-grid
Analysis type: Method 1
Heating value reference: Lower heating value (LHV)
Show settings: ☑
Language - Langue: English - Anglais
User manual: English - Anglais
Currency: United States of America
Units: Metric units

Site reference conditions

Climate data location: Shambu
Show data: ☐

Figure 3-5 RETScreen Graphic User Interface (GUI) for FSF

Load & Network Design

The Load & Network Design in RETScreen is used to estimate the heating, cooling &/or power loads for the base case and proposed case systems. This worksheet is also used to prepare a preliminary design and cost estimate for the district heating &/or cooling networks [27]. The annual system load characteristic for the factory is presented on table 3.7 below:

Table 3-7 RETScreen, gross monthly average power load

Month	**Power gross average load (kw)**
January	5,555
February	5,760
March	5,600
April	5,482
May	5,400
June	2,300
July	250
August	255
September	247
October	2,450
November	5,730
December	5,815
Peak load - annual	5,815

The factory operates under full load from the months of November to May and under half load on the months of June and October. During the months of July to September the factory shuts down due to weather conditions and maintenance purposes, hence the power load highly decreases and supply is needed only for the auxiliary parts of the factory. The graphical representation of the power gross average load is shown on figure 3.6.

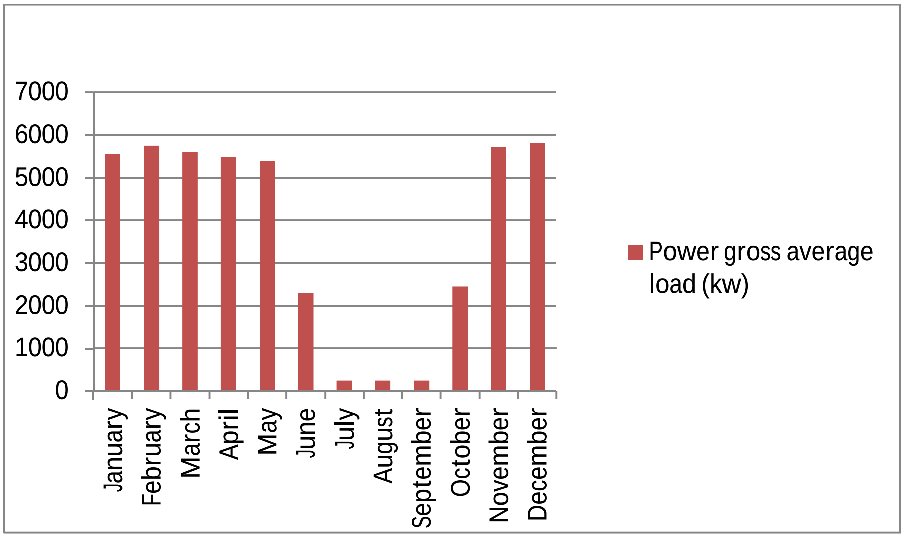


Figure 3-6 Chart, Power gross average load

The varying power loads obtained from the factory on monthly basis throughout the year presented on the table above is fed on to RETScreen for calculation purposes and the peak load – annual value is calculated by the model automatically.

Energy Model

The Energy model in RETScreen is used to evaluate the proposed case system [27]. Feeding the data obtained for the existing system and new configuration, output is generated in this worksheet. Table 3.8 shows the input on to the software. The system selection for the desired design is the base load system and the technology used for the CHP system is the steam turbine with 67% availability, which shows the accessibility of the power system in terms of percent of hours per year and as the factory doesn't operate the whole year, the above value is used. The

Table 3-8 RETScreen, Input data

Proposed case power system		
System selection	Base load system	
Base load power system		
Technology	Steam turbine	
Availability	67	%
Fuel selection method	Single fuel	
Fuel type	Bagasse	

Fuel rate (USD/t)	0.000	
Steam turbine		
Steam flow	65,000	Kg/h
Operating pressure	70	Bar
Super heated temperature	500	°C
Extraction port	Yes	
Maximum extraction	5	%
Extraction pressure	400	Kpa
Back pressure	125	Kpa
Steam turbine efficiency	70	%
Minimum capacity	40.0	%
Seasonal efficiency	75	%
Return temperature	90	°C

type of fuel used is bagasse and as it is obtained from the factory there is no cost associated with it and hence the fuel rate is considered to equal zero . The steam flow rate for the selected steam turbine as obtained from the supplier is 65 ton/hr as compared to the existing which is about 41.3 ton/hr . The selected high pressure steam turbine for optimal performance from the market operates at a temperature of 500 °C and a pressure of 70 bar, it has an extraction port available with maximum extraction of 5 %. The extracted pressure from the turbine equals 4 bar with back pressure output of 1.25 bar . The minimum capacity value is the amount of power that the power equipment can operate at as a percentage of the total power capacity and for the selected steam turbine it is taken at 40%. The seasonal efficiency is based on seasonal basis and is generally lower than the steady-state efficiency and the selected steam turbine has a 75 % seasonal efficiency. The return temperature of the steam turbine corresponds with the temperature of the condensed steam at the back pressure and extraction port. With this parameters entered on to RETScreen, output is generated by the software and it is tabulated on table 3.9. The model calculates the steam saturation temperature at 286 °C, which is the boiling point at the selected steam operating pressure. The enthalpy and entropy values for the steam turbine is also

Table 3-9 RETScreen, output data

Steam turbine		
Saturation temperature	286	°C
Enthalpy	3,437	kJ/kg
Entropy	6.84	kJ/kg/k
Extraction port		

Extraction	3,250	Kg/h
Temperature	144	°C
Mixture quality	0.92	
Enthalpy	2,713	kJ/kg
Theoretical steam rate (TSR)	4.97	Kg/kwh
Back pressure		
Temperature	106	°C
Mixture quality	0.92	
Enthalpy	2,515	kJ/kg
Theoretical steam rate (TSR)	3.9	Kg/kwh
Actual steam rate (ASR)	5.65	Kg/kwh
Summary		
Power capacity – with extraction	11,496	kw
Power capacity – without extraction	11,654	kw
Electricity delivered to load	22,977	mwh
Electricity delivered to grid	48,279	mwh
Fuel required	265.2	GJ/h
Heating capacity – without extraction	41,670.5	kw
Heating capacity – with extraction	41,696	kw

calculated by the software , similarly for the extraction port of the turbine , the amount of steam that can be extracted based on the maximum extraction and the steam flow is computed at 3,250 kg/h . The temperature of the extracted steam at the extraction pressure is also obtained. The steam mixture quality determines the amount of water that the steam contains and acceptable values for a typical steam turbine range from 0.9 to 0.95 [27] . The theoretical steam rate (TSR) of the extracted steam which represents the theoretical amount of steam necessary to produce 1 Kwh of power at the extraction port comes out to a value of 4.97. In a similar way the different values calculated by the model for the back pressure port are outlined , the additional data is the actual steam rate (ASR) which is the actual amount of steam necessary to produce a Kwh of power . A summary is generated by the model showing the power capacity available with and without extraction ports, the amount of electricity delivered to the load and the grid is also computed.

The energy model worksheet in RETScreen based on the proposed case power system also computes and outputs the different operating strategies and the optimal operating strategy for the design is selected. Table 3.10 shows the different operating strategies generated by the model.

Table 3-10 RETScreen , operating strategy

Operating strategy	Electricity delivered to load (Mwh)	Electricity exported to grid (Mwh)	Remaining electricity required (Mwh)	Heat recovered (Mwh)	Remaining heat required (Mwh)	Power system fuel (Mwh)	Efficiency (%)
Full power capacity – without extraction	**22,977**	**48,279**	**9,941**	**163,681**	**142,013**	**450,435**	**52.2**
Full power capacity – with extraction	22,977	47,713	9,941	163,772	141,922	450,435	52.1
Power load following – without extraction	20,208	0	12,710	72,260	233,434	127,745	72.4
Power load following – with extraction	19,935	0	12,983	3,657	302,037	127,745	18.5
Heating load following	20,208	21,101	12,710	149,826	155,868	264,708	72.2

The most suitable operating strategy is selected based on the efficiency of the system and in the output of the simulation the maximum efficiency is obtained at 52.2 %. This efficiency shows the ratio of the useful energy (i.e) electricity delivered to load, electricity exported to grid and heat recovered to the energy input or power system fuel. Hence the full power capacity – without extraction is best appropriate for the selected design parameter. Finally the Energy model in RETScreen presents the proposed case system summary for the selected design by giving the total amount of fuel/bagasse used for both the power and heating load, together with the generated electricity and energy delivered. These data's are tabulated on table 3.11.

Table 3-11 RETScreen, Proposed case system summary

Proposed case system summary	**Fuel type**	**Fuel consumption unit**	**Fuel consumption**	**Capacity (Kw)**	**Energy delivered (Mwh)**
Power					
Base load	Bagasse	ton	92,820	11,654	22,977
Peak load	User-	kg	4,765,988	7,000	9,941

	defined fuel				
Electricity exported to grid					48,279
Total				18,654	81,197
Heating					
Base load	Recovered heat			41,670	163,681
Peak load	User-defined fuel	kg	44,361,844	55,500	142,013
Total				97,170	305,694

The data generated on the proposed case system summary for the high pressure boiler configuration is analyzed and compared with the data obtained from the factory for the existing configuration. The analysis proceeds as below:

Adding the total amount of fuel used from the proposed case system for the new configuration for the base and peak load we obtain

- Total Bagasse = 92,820 ton + 4765.98 ton + 44,361.84 ton
  =**141,947.82** ton/year

The amount of electricity/energy generated from the simulation equals

- electricity = 11.6 MW
- energy = 22,977 Mwh

The electrical power to be exported to the grid by the system comes out to be

- electricity exported to grid = 48,279 Mwh

The data obtained from the factory and listed on table 3.2 of section 3.1 for the current existing system for the amount of bagasse/fuel used is tabulated below:

- generated bagasse = **287,820** ton/yr
- used bagasse for CHP = **284,040** ton/yr
- excess bagasse = **3780** ton/yr

The result from RETScreen simulation after changing the turbine/boiler configuration to a high pressure and temperature and using the parameters obtained from the factory equals

- used bagasse = **141,947.82** ton/yr

The generated bagasse for the factory remains the same regardless of the change in the configuration of the system, hence as can be seen using the data obtained from the factory and changing the configuration of the system, the result from the simulation shows that there remains extra bagasse which equals to

- excess bagasse = used bagasse from existing – used bagasse obtained from RetScreen
  = 284,040 ton/yr – 141,947.2 ton/yr
  = 142,092.8 ton/yr

Chapter Four

SIMULATION RESULT AND DISCUSSION

This research analyzes two different cases for supreme operation of the cane sugar factory at Finchaa. The result for both the cases (i.e.) bagasse drying strategy and high boiler configuration are compared and contrasted with each other.

Case I: Bagasse drying.

Boiler efficiency

Table 4.1 gives a summary of the calculated boiler efficiencies for the corresponding moisture contents. The detailed result is outlined in table III.1 of appendix III. As the results in the table indicate, the efficiency of the boiler improves with the decrease in the moisture content. This is the result of the increased heating value of the bagasse with the drying procedure thus enhancing combustion process in the boiler.

Table 4-1Summary of boiler efficiency for different moisture contents

Moisture content[%]	η**boiler**
20	74
30	72
40	69
50	66

Excess bagasse obtained from bagasse drying

From the result obtained on Table 3.6 of section 3.2.1 of this thesis, typical values of steam parameters are selected to show the variation of the excess bagasse production and the total plant efficiency with different moisture contents and it is summarized and shown on the table below:

Table 4-2 Excess bagasse amount

F	LHVt [kJ/kg]	$M_{f,d,ex,b}$ [kg/s]	η %
20	14240	1.1	73
30	12460	0.84	70
40	10680	0.446	66
50	8900	0.194	62

It can be seen that for moisture content of 20% the plant efficiency is increased to 73% and the mass flow rate of the extra bagasse rises to 1.1 kg/s .This is presented graphically on figure 4.1 by showing the variation of the excess bagasse flow with moisture content and its effect on plant efficiency.

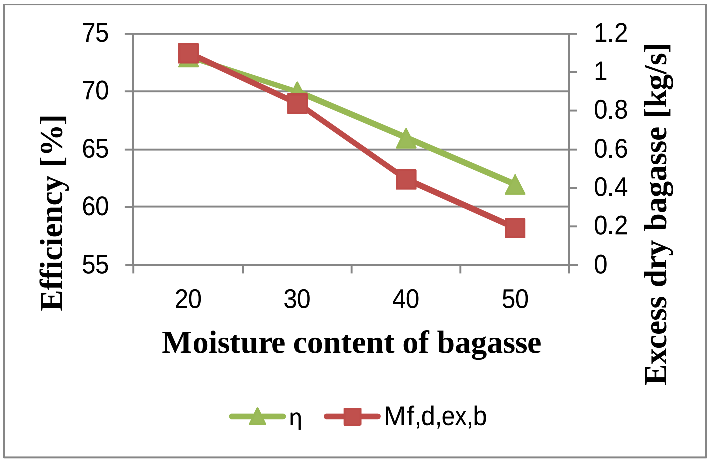


Figure 4-1 Moisture content vs excess bagasse

As shown on the figure , as the moisture content of bagasse decreases more bagasse is generated and also the plant efficiency is improved which implies that by drying the bagasse it is possible to meet the factory's internal demand while producing excess bagasse for other possible applications. The amount of excess bagasse on yearly basis and the corresponding energy potential in Mwh is shown on Table 4.3 and this is plotted graphically on figure 4.2. The chart shows the variation of the excess bagasse amount with moisture content and as shown by drying the bagasse up to 20% moisture content the total yearly energy potential can be increased to as high as 105,713.06 mwh from 18,690.14 mwh energy potential of bagasse which corresponds to 50% moisture content of the bagasse.

Table 4-3 Summary table for total annual excess bagasse and the corresponding energy potential

Moisture content [%]	$M_{f,d,ex,b}$ [t/yr]	LHV_{dry} [MJ/kg]	$Q_{E,b}$ [Mwh/yr]
20	21380	17.8	105713.06
30	16330	17.8	80743.42
40	8670	17.8	42868.67
50	3780	17.8	18690.14

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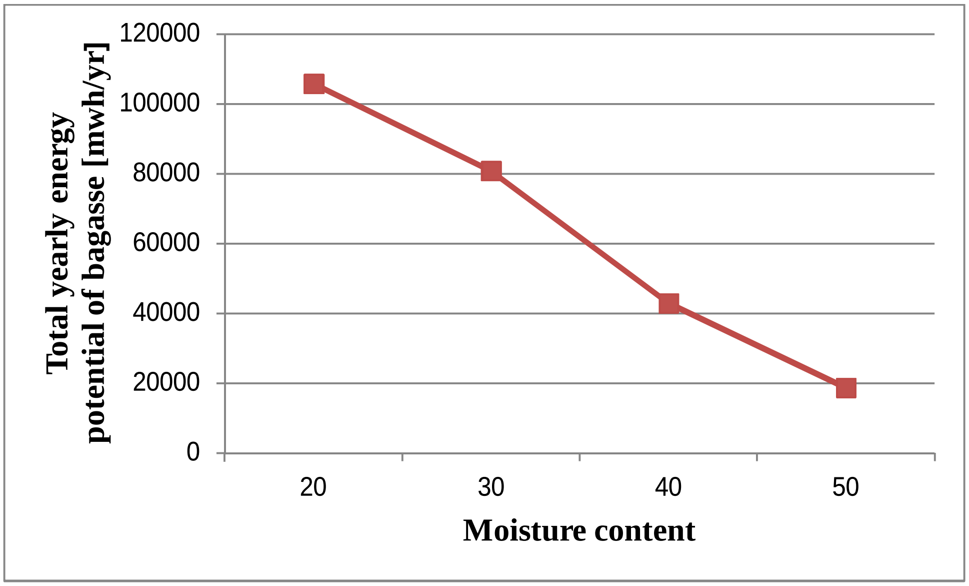

Figure 4-2 Total yearly energy potential of bagasse Vs moisture content of bagasse

Electricity generation from the surplus bagasse

The amount of surplus bagasse from the bagasse drying process at a moisture content of 20% is taken for optimum performance and it equals to 21,380 ton/yr. The excess amount that is being generated from the factory without any enhancement to the process as obtained directly from the factory equals to 3,780 ton/yr. Hence the total amount of bagasse that is obtained equals to the sum of the two:

21,380 + 3,780 = **25,160** ton/yr.

This amount of excess bagasse can be used to generate additional electricity using the existing facility of the factory. From literature and data obtained from factory 1kg of bagasse produces 2.2kg of steam [12] and therefore the amount of steam to be generated by using this surplus bagasse is

$$25{,}160 * 2.2 = \mathbf{55{,}352}\ tonsteam.$$

This generated steam is converted in to the per hour consumption:

$55{,}352/(365 * 24)$= **6.32** tonstm/hr ; throughout the year .

Again from literature one ton of steam produces 114kwh of energy [12] and hence the generated steam will produce:

6.32tonstm/hr * 114kwh/tonstm = **720.48** Kw .
= **0.721** Mw of electrical power.

The Kwh energy throughout the year equals to

720.48*365*24 = **6,311,404.8 kwh**
= **6,311.41 Mwh**

This is the amount of electricity that can be generated from the total surplus bagasse obtained from bagasse drying by using the existing energy facilities of the factory. This extra generated electricity will be used to supply the water pumps for irrigation purposes and part of the factory residences where most of the low paid employees working on harvesting and cane cutting reside without any electrical power currently.

Case II: Excess bagasse obtained from high pressure Boiler/Turbine.

From the data collected from the factory in section 3.1 of this thesis, the excess amount of bagasse that is left as waste equals to:

- excess bagasse from data obtained from factory = **3,780** ton/yr

From RetScreen simulation for the new configuration, the excess bagasse that is obtained equals to:

- excess bagasse for new configuration obtained from RetScreen = **142,092.8** ton/yr

The total amount of bagasse available from this new setup will be the sum of the two:

- Total available bagasse = 3,780 + 142,092.8

  = **145,872.8** ton/yr

Again from the simulation result in the proposed case system summary of section 3.2.3, the electricity generated at 11.6 mw is enough to supply the factory as compared to the current power generation and consumption of the factory. Besides providing the factory with the necessary electrical power for its operation and excess bagasse production, the new setup will also be able to export **48,279** Mwh of electrical power to the national grid.

The excess **145,872.8** ton of bagasse will be pelletized using a Pelleting machine and kept in a structured hard solid form (Pellets) and can be:

- Used as a fuel for pellet based cooking gazes.
- Exported to foreign countries for fulfilling energy needs.
- Can be used to fulfill energy needs of the factory during the off milling season.

Figure 4-3 Bagasse in Pellet Forms [25]

Chapter Five

ECONOMIC ANALYSIS

In the case of bagasse drying, since the maximum output of the turbine at 7.5 Mwe should not be exceeded and the current output is below 6 Mwe, the costs related to the modified plant will be associated with the installation of the dryer only and the existing facilities of the factory will be unchanged and used for co-generation. For optimal operation, the moisture content of bagasse that is considered will be at 20%. In the case where a high pressure boiler-turbine is used for the study, the cost considered will be with the purchase of the high pressure boiler, turbine and pelletizing machine, here also all the existing facilities besides the boiler and the turbine will be used for computation purposes.

<u>Case I – Bagasse drying</u>

Investment cost

<u>Dryer</u> – for bagasse drying purposes a rotary dryer is selected from potential manufacturers and suppliers and the capital cost for a factory having a capacity of 5000 TCD is estimated around $ 80,000 dollars (this price is taken from personal communication through email with Ms Lily Qin of Henan Yuhang Heavy Machineries on Alibaba.com) the factory are experienced bagasse dryer installers in many sugar factories like Brazil , Cuba , Mauritius etc .

<u>Useful life</u> – The supplier for the bagasse dryer assures 15 years operation life time.

<u>Customs duty</u> – It is believed that the equipment will be imported duty free due to energy economy measures that the factory and consequently the country makes.

Cost of Energy (COE)

For co-generation purpose, from section 4 above, the kwh energy generated by the extra bagasse is calculated to be :

=**6,311,404.8kwh**

This is the amount of electricity that can be generated using only bagasse and the existing energy facilities of the factory.

The cost of the dryer neglecting transportation cost as obtained from the supplier equals $80,000 [taking the birr versus U.S. dollar price from eth commercial bank, $1 = 19.65 birr] ,we have : $80,000 = 1,572,000 birr .

For calculation purposes, we assume 5% for maintenance [31] and depreciation of the existing boiler plant with respect to the increased steam production for co-generation, again we will consider additional labor cost, since the excess bagasse must be balled and stored for the off milling season, there will be cost of balling and storing.

The average milling season days of the factory is 225, then the bagasse balled and stored will be

$$\frac{(365-225)*25{,}160}{225} = 15{,}655.1\ ton$$

We consider the current cost of balling and storing bagasse on average to be birr25/ton [31] and the total cost will equal to: 15,655.1 ton * birr 25 = 391,377.5 birr .

Again by considering the labour cost for supervision at the boilers, turbo-alternators and evaporators to be birr 30/hr [31] due to the extra steam generated. Then 30/hr * 24 * 225 = 162,000 birr per year. Assuming other indirect costs due to the increase in steam production to equal 5%, we get:

*= 0.05 *(391,377.5 + 162,000)*
= 27,668.875 birr

Then the total cost incurred will be equal to:

=1,572,000 + 391,377.5 +162,000 + 27,668.875
=2,153,046.375 birr

The cost of generating electricity can be calculated as follows:
(Generating cost) * (amount of energy generated) = total cost
(Generating cost) * (6,311,404.8kwh) = 2,153,046.375 birr
Generating cost = 0.34 birr per kwh
= 34 cents/kwh

The current electricity tariff from EEPCO for industrial use is around \$0.035/Kwh or when converted to local currency it equals birr 0.7/Kwh and when compared to the birr 0.34/Kwh generation from the cogeneration unit, the factory will be beneficial by selling the additional generated electrical power.

Case II – High pressure boiler

Investment cost

Pelletizer – for an excess dry bagasse production of 27 t/hr (i.e by dividing sum of existing 3780 t/yr plus additional of 142,092.8 t/yr with 225 operating days) the cost of pelletizer is estimated at about \$100,000 dollars (this price is obtained through email contact with Ms Mary Wang of the wood pellet mill manufacturers – www.woodpelletmill.net) .

High pressure boiler – the cost of the high pressure boiler operating at a temperature of 500^{o}C and a pressure of 70 bar as obtained from the supplier is \$1000,000 dollars (the price is obtained through email communication with Ms Daisy Iv. of Taishan Group). Since we will be using 2 boilers the total price will be \$2,000,000 .

High pressure turbine – the cost of the high pressure turbine operating at a pressure of 70 bar and steam flow of 65,000 kg/hr is \$1,200,000 dollar (the price is obtained through email communication with Ms Tina Ma) . The number of turbines used is 2 and the total price will be \$2,400,000.

Operation & Maintenance cost – for the pelletizer the cost of operation is estimated at \$5/tone [31] and when multiplied with the total excess production of 145,872.8 ton/yr , the cost will be 729,364 \$/yr . For the changed turbines and boilers it is assumed that the existing man power will be used.

Useful life – The estimated life time of the equipments as obtained from the suppliers is around 20 years.

Customs duty – It is believed that the equipments will be imported duty free and the transportation cost as compared to the cost of the equipments is neglected.

For computation purposes the general formula for the annuity of the investment is taken and it is given as [38] .

$A = \text{Annuity factor} = \left[1 - \frac{1}{(1+i)^n}\right]\frac{1}{i}$ *[1/yr] where i is the interest rate per period and n is the number of payments... (22)*

The present value of the annuity is obtained by multiplying the annuity factor with the payment made during each period [38] .

*P = I * A [$/yr] where I is the total cost of investment & A the annuity factor …………..(23)*

The payback period is obtained using the formula [ref] :

Payback period = $\frac{I}{I.C - O\&M cost}$ *[yr] where I is the total investment cost, I.C is the tot.9al income and O&M is the operation and maintenance cost .... (24)*

Income

The income in the case of using a high pressure turbine-boiler comes from two options (i.e) from the sale of pellets and that of electric power. For obtaining maximum income from the sale of pellets, the export of pelletized bagasse to abroad is considered where demand for the product is high. The selling price of the bagasse is estimated at $70/ton (the price is obtained through email communication with Ms Mary : mary@vietnambiomass.com) .

- *Pellet income = $70/ton * 145,872.8 ton/yr*
  = 10,211,096 $/yr

The income for the sale of electricity is calculated based on the electric tariff for industries in Ethiopia which is $0.048/kwh [36] . The kwhel surplus produced is obtained from section 3.2.3 of this thesis and it is 48,279 Mwh .

- *Electricity income = $0.048/kwh * 48,279 Mwh*
  = $ 2,317,392

The economic analysis is tabulated on Table 5.1 and the detailed calculation is presented on Appendix III.2

Table 5-1Summary of economic analysis for high pressure boiler

i [%]	**I** [$\$10^6$]	**n** [yr]	**A** [1/yr]	**Present value** [$/yr,$10^6$]	**O&M** [$/yr,$10^6$]	**Income** [$/yr$10^6$]	**Payback period** [yr]
15	4.5	20	4.48	20.16	0.729	12.52	0.38

Chapter Six

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Every countries economic development is dependent directly or indirectly on its energy generation and usage, hence efficient use of available energy resources is vital for increased energy production. Sugar factories in many countries contribute remarkable amount of energy in to the mix of generation, moreover for the factories to be competent in the international market they should utilize each and every by-product effectively and efficiently. This study focuses on the use of bagasse for co-generation purposes by considering two analytic strategies (i.e.) bagasse drying and use of high pressure boiler. Based on the analysis, problems are identified and possible solutions towards energy generation and utilization efficiencies are suggested.

Bagasse drying

In the bagasse drying strategy, the production of excess bagasse during the milling season is considered. In this strategy, the factory will be able to save additional amount of 21,380 tons of bagasse from bagasse drying. This saved bagasse together with the additional that is obtained from the factory equals to 25,160 ton/yr. This amount of bagasse is able to produce electricity of about 6,311.41 Mwh/yr. A preliminary economical analysis gives the cost of generation at about 34 cents/Kwh which is less than EEPCO's tariff. This generated electrical power can be used to supply the irrigation pump stations as well as to power up residences of the factory and nearby villages where currently the villagers don't get power from the national grid. The strategy is simple and could generate additional income to the factory.

High pressure boiler

In the case where high pressure boiler and turbine is used in place of the existing medium pressure turbine, based on the data collected from the factory , the RetScreen simulation software gives the amount of saved bagasse which equals to 142,092.8 ton/yr . This together with the excess bagasse that is being produced at the factory equals to 145,872.8ton/yr. The result also shows that we are able to produce 11.6 mw of power to supply the factory while still obtaining export of 48,279 Mwh to the national grid. The remaining bagasse can be pelletized using a pelletizing machine and exported to western countries where demand for biomass is very high. Part of the pelletized bagasse can also be sold to the local community to be used as a fuel for cooking gazes and this needs further investigation. The payback period is calculated to be around 5 months.

6.2 Recommendation

***** This study focuses only on one sugar factory in Ethiopia, and it doesn't cover the remaining sugar factories. The study also focuses on one energy resource from cane that is "bagasse", it doesn't consider the energy available from using the leaves and tops of cane sugar plant.

* Despite the huge hydroelectric potential of Ethiopia, severe power cuts in recent years have a heavy impact on the country's economy. Hence getting additional power from the sugar factories to the national grid will increase the mix of energy availability.

* Electrical power generation from bagasse is environmental friendly and no concern on green house gases and pollution should be made.

7. REFERENCES

[1] Belay Dechassa : challenges and prospects of cogeneration and energy efficiency improvement in Ethiopian Sugar Industry.

[2] Rick W.M. Cogeneration challenges & opportunities: meeting cogeneration targets in the market place. Exxonobil Power and Gas Services Incl.,

[3] Kassiap D. 2005 : Sugarcane bagasse energy cogeneration : lessons from Mauritius. Paper Presented to Parliamentarian Forum on Energy Legislation and Sustainable Development, Cape town , South Africa .

[4] SWECO,Consulting Engineers,Architects and Economists : 1985 Power from cane sugar bagasse .

[5] Wolde-Ghiorgis, W. : (2005) AFREPREN Occasional Paper 24: The Potential Contribution of renewable in Ethiopia's energy sector – an analysis of geo-thermal & cogeneration technologies , Nairobi , AFREPREN .

[6] Maurice Paturau : by products of the cane sugar industry an introduction to their industrial utilization , Port Louis Mauritius , 1969 .

[7] Charles Mbohwa : bagasse energy cogeneration potential in the Zimbabwean sugar industry

[8] U.S.EPA ,U.S. Environmental Protection Agency: 2006 **,** Bagasse Combustion in Sugar mills .

[9] Catharina Erlich ;Öhman Marcus ; Björnbom Emilia ; Fransson Torsten H. : 2005 thermochemical characteristics of sugar cane bagasse , Science direct; ISSN 0016-2361, No.5,pp,569-575 .

[10]Scott M. Smouse , Gary E. Staats , S.N Rao Richard Goldman , David Hess : promotion biomass cogeneration with power export in the Indian sugar industry .

[11]L. Waldheim & M. Morris and M. Regis Lima Verde Leal : 2000 Biomass power generation : Cane sugar bagasse & trash ; paper presented at progress in thermo-chemical biomass conversion , Austria .

[12]WADE, World Alliance for Decentralized Energy: 2004 Bagasse cogeneration global review and potential .

[13]Eyerusalem Birru : Investigation of the potential of cane sugar industry in Ethiopia – a case study .

[14]Pickering, S. : (2000). Sugarcane: Offering Australia a Sweet Power Alternative, in Refocus

[15]UNEP & AFREPREN/FWD : 2006 COGENERATION PROJECT FOR AFRICA – country study : Ethiopia .

[16]FAO : FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS data base ; 2006 .

[17]Yohannes Berhane : (2007) Energy assessment , generation and utilization efficiency in Ethiopian sugar factories – a case study in Metehara sugar factory .

[18]HVA, World Agricultural Development : 2006 Sugar Prodcution

[19]Joint UNDP/World Bank Energy Sector Management Assistance Program

[20]Casten, T : (2004). The DG Revolution – A Second Indian Miracle

[21]S. Ramajatun, J GUkhool and D. Seebaluk : optimization of power generation in the local cane sugar factories , Mauritius 1999 .

[22]UNFCCC : 2004 Project design document .

[23]TPS : 2006

[24]**Pellets 2002**: the first world conference on pellets Johan Vinterba¨ ck
[25]**Francesco Cariello,ETA-Florence,Italy :** 2006 Advanced Pelleting Technology,Modern biotechnologies & sustainable development .
[26]**V.E Baikow:** manufacturing and refining of row can sugar, Amsterdam, 1982 .
[27]**RETScreen® International :** Clean Energy Decision Support Centre .
[28]**Sustainable Power Generation :** Applied Heat and Power Technology , Equations, diagrams & tables .
[29]**Skil (sugar knowledge international) :** 2006 .
[30]**S.Rahjutun . J. Gukhool and Seebaluck :** 1999 Optimizatin of power generation in the local cane sugar factories ; science & technology – research journal – vol.3 – university of mauritius , reduit , Mauritius .
[31]**Finchaa Sugar Factory Data :** collected during the year 2013 .
[32]**Aurelie M. 2004 : bagasse cogeneration , global review and potential , World Alliance** For Decentralized Energy – WADE .
[33]**Shleser, R. 1994 :** Processes , feedstock's and current economic feasibility of fuel grade ethanol production in Hawaii .
[34]**UNDP(United Nations Development Program) :** website accessed on the year 2014 .
[35]**World bank :** Ethiopia accelerated electricity access rural expansion project .
[36]**EEPCO :** Ethiopian electric power co-operation
[37]**Kent GA :** Estimating Bagasse Production , Queens land university of Technology,Brisbane
[38]**Annuities :**
[39] **Linnhoff , B.D , D.W Townsend ,:** A user guide on process integration for the efficient use of Energy .
[40] **Floudass , C.A , A.R. Cirac and I.E Grossmann ,:** Automatic synthesis of optimum Network configurations of Energy .

8. APPENDICES

Appendix I : Mass & Energy Balance Calculations

The mass and Energy balance for the Bagasse and Steam flow is calculated and analyzed as follows:

Mass Balance

$M_{bagse,tot}$ = 53.3 ton/hr = 14.805 kg/s (from table 3.2 of section 3.1)

$M_{bagse.exces}$ =0.7 ton/hr = 0.195 kg/s (from table 3.2 of section 3.1)

$M_{bagse,net}$ = 14.805 – 0.195 = 14.611 kg/s (from equation 1 of section 3.2.1)

$M_{stm,1\text{-}2,electl}$ = 41.3 tonsteam/hr = 11.48 kg/s (from table 3.3 of section 3.1)

Energy Balance

F = 50% (default moisture content of bagasse as taken from factory)

P_1 = 30 bars, $T_1 = 400^oC$ (from block diagram of fig 3.1 of section 3.2)

P_2 = 1.25 bars , P_{atm} = 1 bar , P_{2tot} = 1 + 1.25 = 2.25 bars (P_{atm} , atmospheric pressure)

$P_2=P_3$=2.25 bars (neglecting enthalpy change before and after the pump)

P_4 = 40 bars (max boiler pressure from fig 3.1 of section 3.2)

From equation (3) of section 3.2.1

$LHV_t = LHV_d * (1 – F)$[kJ/kg]
= 17,800 * (1 – 0.5)[kJ/kg] (from table 3.2 of section 3.1)
= 8900 kj/kg

From equation (4) of section 3.2.1

$P_{input} = LHV_t * M_{bagse,net}$ [mw]
= 8900 * 14.611 [mw]
= 130.037 mw

From equation (5) of section 3.2.1

$M_{steamtotal} = (P_{input} * \eta) / (h_1 – h_4)$ [kg/s]
= (130.037 * 0.62) / (3231.57 -521.31) [kg/s]
= 29.74 kg/s

From equation (2) of section3.2.1

$M_{steam,1\text{-}2,mech} = M_{steam,total} - M_{steam,1\text{-}2,eletcl}$[kg/s]
= 29.74 – 11.48 [kg/s]

$= 18.26$ [kg/s]

$P_{elect,1\text{-}2} = M_{steam,1\text{-}2,eletcl} * (h_1 - h_2)$[mw]
$= 11.48 * (3231.57 - 2713.75)$ [mw]
$= 5.9$ mw

From equation (7) of section 3.2.1

$P_{mech,1\text{-}2} = M_{steam,1\text{-}2mech} * (h_1 - h_2)$
$= 18.26 * (3231.57 - 2713.75)$ [mw]
$= 9.45$ mw

From equation (8) of section 3.2.1

$Q_{process,2\text{-}3} = M_{steamtotal} * (h_2 - h_3)$
$= 29.74 * (2713.75 - 521.31)$[mw]
$= 65.203$ mw

From equation (9) of section 3.2.1

$P_{total} = P_{electl,1\text{-}2} + P_{mech,1\text{-}2} + Q_{process,2\text{-}3}$[mw]
$= 5.9 + 9.45 + 65.203$ [mw]
$= 80.53$ mw

From equation (10) of section 3.2.1

$\eta = P_{total} / Q_{cycle} * 100\ \%$
$= 80.53 / 130.037 * 100\ \%$
$= 62\ \%$

Appendix II : Excess Bagasse and Excess Power Calculations

The different moisture contents that are considered for the bagasse drying procedure are 50% , 40% , 30% and 20 % respectively . The boiler efficiencies that are used in the calculations is taken such that the maximum power generating capacity of the existing turbines (i.e) 7.5MW is not exceeded. The calculations results are done as follows:

***For F = 50 % moisture content*:**

LHVt = (LHV)dry * [1 – F] ; $M_{stm,total} =$ 29.75 Kg/s (from appdix 1,fixed for all moisture contents)
= 17,800 * [1 – 0.5] ; $M_{stm,eletcl} =$ 11.47 Kg/s (>> >> >> >> >>)
= 8900 KJ/Kg = 8.9 MJ/Kg ; $M_{stm,mech} =$ 18.27 Kg/s (>> >> >> >> >>)

$P_{output} = M_{stm,total} * (h1 - h4)$; P_{eltcal} = 5.9 MW (from appdix 1, fixed all F values)

= 29.75 * (3231.5 – 521.31) ; P_{mech} = 9.4 MW (>> >> >> >> >>)

= 80.62 MW (fixed for all F value) ; $Q_{process}$ = 65.22 MW (>> >> >>)

$P_{input} = \frac{Poutput}{\eta,50\%}$; $\eta_{50\%}$=62% (from table 3.4, section 3.1)

$= \frac{80.62}{62\%}$

= 130.04 MW

$Mf,t,b = \frac{Pinput}{LHVt}$ (mass flow rate of total bagasse ; section 3.2.1 , eqn 12)

$= \frac{130.04MW}{8900KJ/Kg}$

= 14.61 Kg/s

$Mf,d,b = Mf,t,b * [1 - F]$ (mass flow rate of dry bagasse ; section 3.2.1 , eqn 13)

= 14.61 Kg/s * [1 – 0.5]

= 7.305 Kg/s

Mf,t,ex,b @ 50% = 0.19 Kg/s (mass flow of excess bagasse @ 50 % , bagasse base data)

Mf,d,ex,b @ 50% = 0.095 Kg/s (mass flow rate of dry excess bagasse @ 50 % , bagasse base data)

$Mf,d,ex,b\,[ton/yr] = Mf,d,ex,b\left[\frac{Kg}{s}\right] * \left(\frac{3600[\frac{s}{hr}]*24[\frac{hr}{d}]*225[\frac{d}{yr}]}{1000[\frac{kg}{t}]}\right)[\frac{t}{yr}]$; total annual mass of excess dry bagasse produced .

$$Mf,d,ex,b\,@50\%\,[ton/yr] = 0.095\left[\frac{Kg}{s}\right] * \left(\frac{3600\left[\frac{s}{hr}\right] * 24\left[\frac{hr}{d}\right] * 225[\frac{d}{yr}]}{1000[\frac{kg}{t}]}\right)[\frac{t}{yr}]$$

= 1.846 Kton/yr

<u>For F = 40 % moisture content</u>:

LHVt = (LHV)dry * [1 – F] ; $M_{stm,total}$ = 29.75 Kg/s (from appdix 1,fixed for all moisture contents)

= 17,800 * [1 – 0.4] ; $M_{stm,eletcl}$ = 11.47 Kg/s (>> >> >> >> >>)

= 10680 KJ/Kg = 10.68 MJ/Kg ; $M_{stm,mech}$ = 18.27 Kg/s (>> >> >> >> >>)

$P_{output} = M_{stm,total} * (h1 - h4)$; P_{eltcal} = 5.9 MW (from appdix 1, fixed all F values)
$= 29.75 * (3231.5 - 521.31)$; P_{mech} = 9.4 MW (>> >> >> >> >>)
= 80.63 MW (fixed for all F value) ; $Q_{process}$ = 65.22 MW (>> >> >>)

$P_{input} = \frac{Poutput}{\eta,40\%}$; η40% =66% (from appdix 3)
$= \frac{80.63}{66\%}$
= 122.2 MW

$Mf,t,b = \frac{Pinput}{LHVt}$ (mass flow rate of total bagasse @40% ; section 3.2.1 , eqn 22)
$= \frac{122.2MW}{10680KJ/Kg}$
= 11.44 Kg/s

$Mf,d,b = Mf,t,b * [1 - F]$ (mass flow rate of dry bagasse @40% ; section 4.2.1 , eqn 23)
= 11.44 Kg/s * [1 – 0.4]
= 6.864 Kg/s

Mf,t,ex,b @ 40% = Mf,t,b @50% $-$ Mf,t,b @40%$[\frac{Kg}{s}]$ (mass flow of excess bagasse @ 40 %)
= 14.61 – 11.44 [Kg/s]
= 3.17 Kg/s

Mf,d,ex,b @ 40% = Mf,d,b @50 % $-$ M,f,d,b @40%(mass flow rate of dry excess bagasse @50%)
= 7.31 – 6.864 [Kg/s]
= 0.446 Kg/s

The calculation for the rest of the moisture contents proceeds with the same procedure as above and the obtained values are listed on the table below:

F	LHVt [kJ/kg]	$M_{st,tot}$ [Kg/s]	$M_{st,elt}$ [Kg/s]	$M_{st,mec}$ [kg/s]	P_{el} [mw]	P_{mec} [mw]	Q_{prcs} [mw]	P_{in} [mw]	P_{out} [mw]	$M_{f,t,b}$ [kg/s]	$M_{f,d,b}$ [kg/s]	$M_{f,t,ex,b}$ [kg/s]	$M_{f,d,exb}$ [kg/s]	$M_{f,d,ex,b}$ [kt/yr]
20	14240	29.75	11.47	18.27	5.9	9.4	65.22	110.5	80.63	7.75	6.21	6.86	1.1	21.38
30	12460	29.75	11.47	18.27	5.9	9.4	65.22	115.2	80.63	9.25	6.47	5.36	0.84	16.33
40	10680	29.75	11.47	18.27	5.9	9.4	65.22	122.2	80.63	11.44	6.864	3.17	0.446	8.67
50	8900	29.75	11.47	18.27	5.9	9.4	65.22	130.1	80.63	14.61	7.31	0.19	0.095	1.85

Table (II.1) Excess bagasse amount generated due to bagasse drying procedure

Appendix III : Boiler Efficiency Calculation

From Equation (22) of section 3.2.1 , we have the formula for calculating the boiler efficiency : ηboiler = 100 – (L_{fg} + $L_{h20,sens}$ + $L_{h20,Lat}$ + $L_{indirect}$)[%] ; where $L_{indirect}$ is directly taken from the Boilers manufacturers design performance data [Zurn] and equals to 5.3 and is assumed unchanged .

Equation (19) of section 3.2.1 gives the flue gas loss:

$L_{fg} = K * (t_{fg} – 25) / [CO_2]_d$ [%] ; where t_{fg}=200(FSF) , $[CO_2]_d$ =0.148 is calculated to be similar for all moisture content (taken from appendix table I.1 - I.4) , K=0.797 is read from the diagram on figure II.2 and thus $L_{fg} = 0.797 * (200 -25) / 14.8 = 9.42$.

From Equation (20) of section 3.2.1 , the formula for loss due to vaporization of water vapour is $Lh20, sens = \Delta h * \frac{(F + 8.92 * H2t * (1-F))}{HHV*100}$; where F=0.5 for 50% moisture content, H_{2t} = 3.27 for 50 % moisture content, $\Delta h = h - h^{l}$ = 2875.47 – 2675.77 kJ/kg =199.7[kJ/kg] is fixed for all moisture content and HHV = 10.83 for 50% moisture content . Thus $Lh20, sens$ = 1.46 at 50 % moisture content.

Similarly from equation (21) of section 3.2.1 , we have the formula for the loss due to combustion as $Lh20, Lat = rh20 * \frac{(F + 8.92 * H2t * (1-F))}{HHV*100}$; where F=0.5 for 50% moisture content , H2t=3.27 for 50 % moisture content , $rh20$ = 2440 kJ/kg is fixed for all moisture content and HHV = 10.83 for 50% moisture content . Thus $Lh20, Lat$ = 17.83 at 50% moisture content. Therefore the overall loss at 50% moisture equals to:

$$\eta\text{boiler} = 100 - 9.42 - 1.16 - 17.83 - 5.3$$

$$\eta\text{boiler} = 66\ \%$$

The computation for the rest of the moisture contents that is for 40% , 30% and 20% is similar to the above and the obtained values are listed on the table below :

Table (III.1) Boiler efficiency values for different moisture contents

F[%]	LHV[MJ/kg]	HHV[MJ/kg]	L_{fg}	$L_{h20,sens}$	$L_{h20,Lat}$	$L_{indirect}$	η_{boiler}
50	8.9	10.83	9.4	1.46	17.83	5.3	66
40	10.68	12.37	9.4	1.21	14.8	5.3	69
30	12.46	13.9	9.4	0.94	11.43	5.3	72
20	14.24	15.44	9.4	0.86	10.54	5.3	74

Figure (III.1) CO_2 & O_2 contents in flue gas as a function of air excess factor [28]

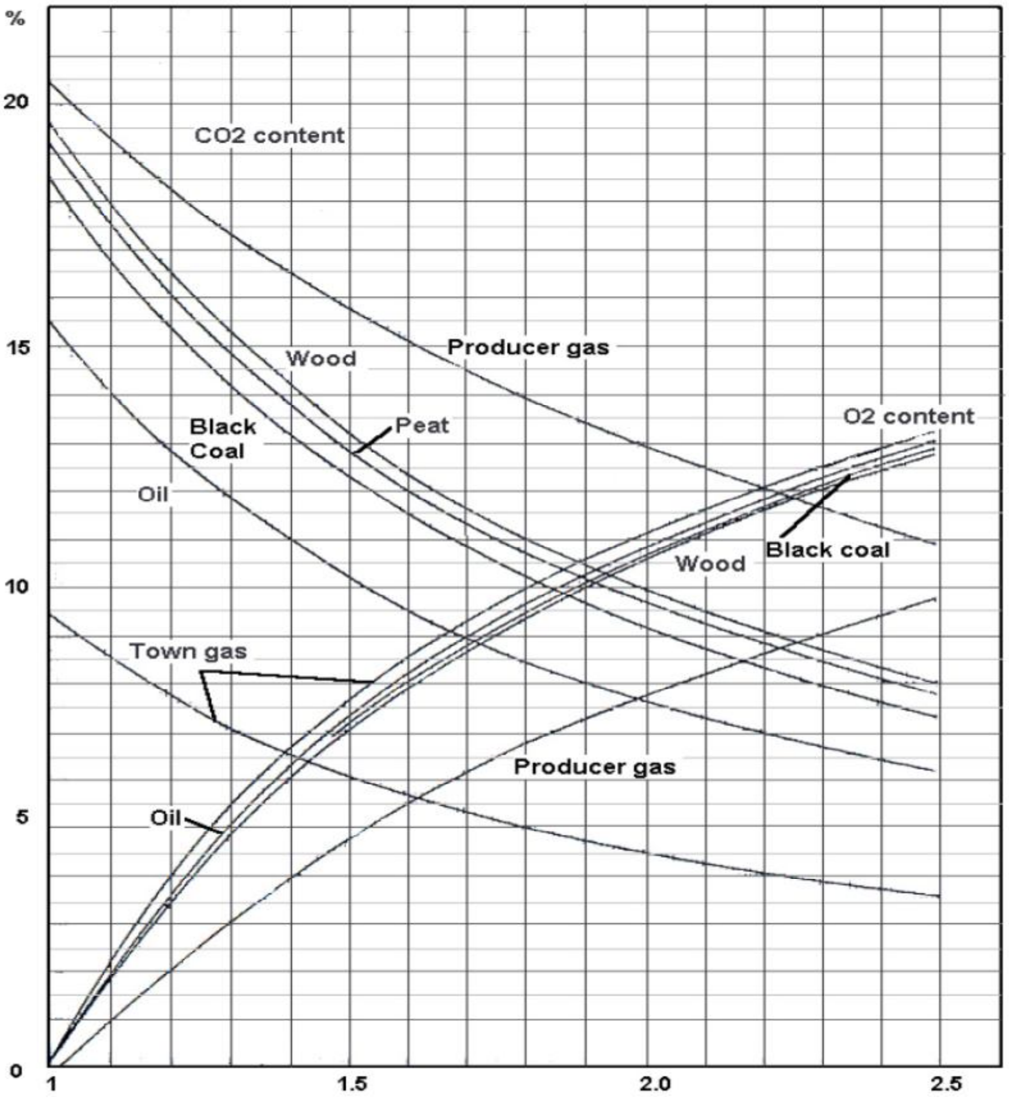

Figure (III.2) Coefficient K in siegerts formula [28]

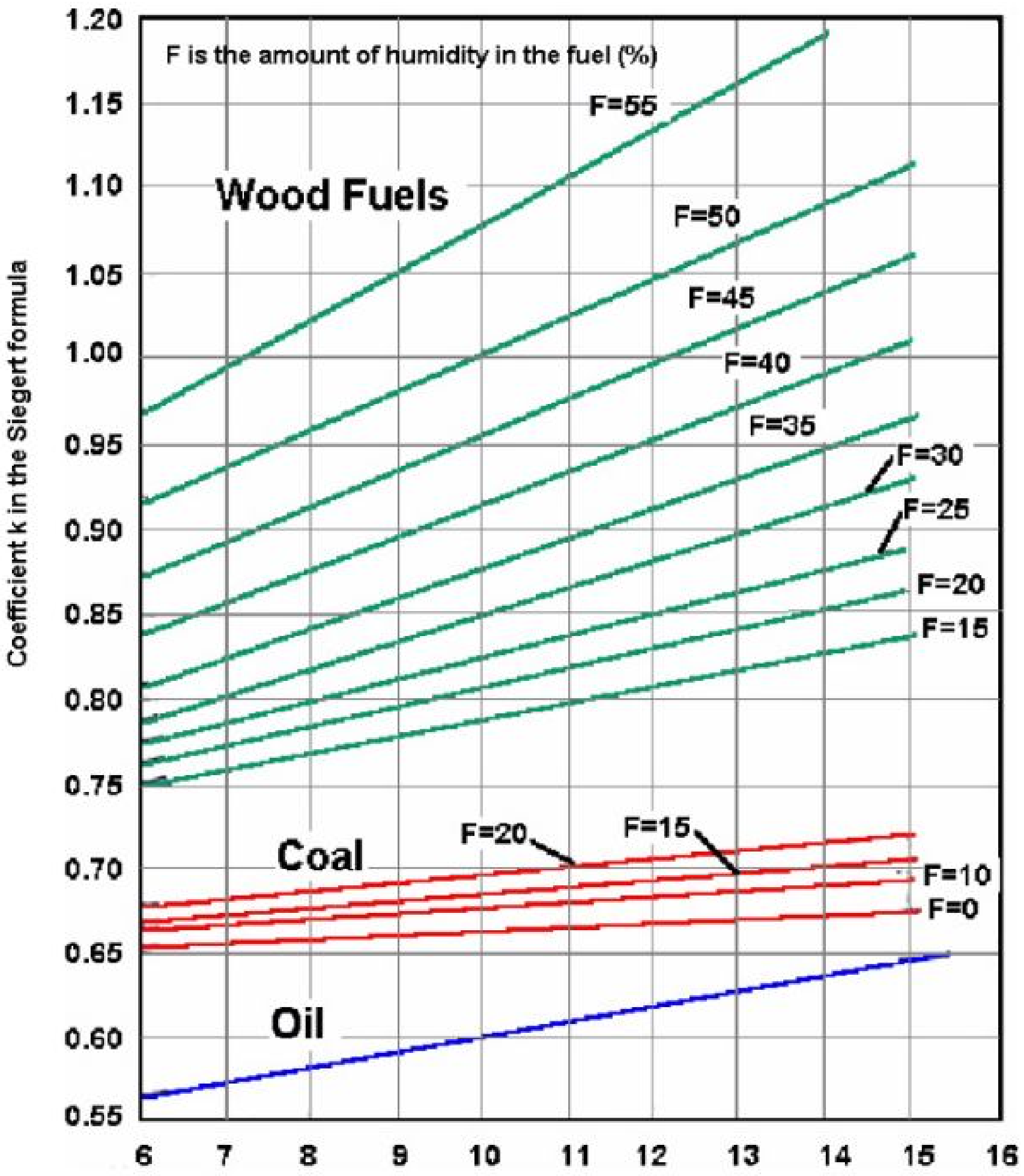

Table (III.2) New Turbine specification as obtained from supplier

	Specifications	
	Qty	2
	Type	High – Pressure
	Produciton Capacity	

High Pressure Turbine	Electricity [Mwe]	6.5 * 2 = 13
	Steam Data	
	Pressure [bar]	70
	Temperature [^{o}C]	500
	Steam consumption for power generation	
	Actual Steam rate [kg/kwh]	9
	Steam flow [ton stm /hr]	65
	Extraction port	Yes
	Extraction pressure[bar]	4
	Back pressure [bar]	1.25
	Return Temperature [^{o}C]	90
	Seasonal Efficiency [%]	75

Appendix IV : Combustion tables

To calculate the amount of flue gas per kg of bagasse burnt, we consider the bagasse fuel composition on total basis at 50% moisture content which is obtained directly from the boiler manufacturer’s document and we use the following formulae to calculate the composition on different moisture contents: [28]

a% C , b% O_2 , c% H_2 , d% S , e% N_2 , f % humidity(H_2O) , g % ash such that :

a+b+c+d+e+f+g = 100 %. And in our case it corresponds to:

23.62 % C + 22.11 % O2 + 3.27 % H2 + 50 % humidity+ 1 % ash = 100 % @ 50 % moisture content obtained from boiler manufacturer document. The first step is to convert the content of the different elements in to moles:

Element	Molar mass (g/mol)	Analysis (g/kg bagasse)	Analysis (mol/kg bagasse)
C	12	a*10=23.62*10=236.2	a*10/12=236.2/12=19.68
O_2	32	b*10=22.11*10=221.1	b*10/32=221.1/32=6.91
H_2	2	c*10=3.27*10=32.7	c*10/2=32.7/2=16.35
S	32	-	-
N_2	28	-	-
H_2O	18	f*10=50*10=500	f*10/18=500/18=27.8
Ash	-	-	

Elemental combustion reactions

$$C + O_2 = CO_2$$

$$S + O_2 = SO_2$$

$$H_2 + 0.5\ O_2 = H_2O$$

Needed air supply according to the elemental reactions:

Element	Analysis (mol/kg bagasse)	Oxygen needed (mol/kg bagasse)
C	a*10/12	a*10/12
O_2	b*10/32	- b*10/32
H_2	c*10/2	0.5* c*10/2
S	-	-
N_2	-	-
H_2O	f*10/18	-

Oxygen needed [O_2] = a*10/12 - b*10/32 + 0.5* c*10/2 [mol/kg bagasse]. Since air is most often used for combustion, N_2 has to be included in the analysis:

Nitrogen in air: [N_2] = 3.76 * [O_2] mol/kg bagasse

From the set of elemental reactions, the gases produced which constitute the flue gas are also obtained:

Element	Analysis(mol/kg bagasse)	H_2O	CO_2	SO_2	N_2	O_2
C	a*10/12		a*10/12			
O_2	b*10/32					
H_2	c*10/2	c*10/2				
S	-			-		
N_2	-				-	
H_2O	f*10/18	f*10/18				
N_2 in air					[N_2]	

The dry basis composition of the fuel is obtained from the total basis @ 50 % based on the formula from equation 12 of section 3.2.1

Carbon

From equation (12) in section 3.2.1

C_d=23.62% / (1 – 0.5) = 47.24 %

Hydrogen

From equation (13) in section 3.2.1

H_{2d} = 3.27% / (1 – 0.5) = 6.54%

Oxygen

From equation (14) of section 3.2.1

O_{2d} = 22.11 % / (1 – 0.5) = 44.22 %

Ash

From equation (15) of section 3.2.1

Ash = 1% / (1 – 0.5) = 2%

The values obtained on dry basis are used for the calculation of the fuel composition on total for the different moisture contents; this together with the calculation of the flue gas amount is summarized in the following tables.

Table (IV.1) Combustion table for moisture content of 50 %

Molar Weight		Analysis		Oxygen		Flue gases (mol/kg bagasse)				
Content	g/mol	g/kg bagasse	mol/kg bagasse	mol/kg bagasse		H_2O	CO_2	N_2	SO_2	O_2
C	12	236.2	19.67	19.67			19.67			
H_2	2	32.7	16.19	8.09		16.19				
O_2	32	221.1	6.91	-6.91						
N_2	28		0							
S	32		0							
Ash		10	-	-						
Water	18	500	27.75			27.75				
	Sum	1000	Sum O_2	20.85		43.94	19.67			
Nitrogen in air	3.77 * O2			78.61				78.61		

Table(IV.2) Combustion table for moisture content of 40 %

Molar Weight		Analysis		Oxygen		Flue gases (mol/kg bagasse)				
Content	g/mol	g/kg bagasse	Content	g/mol		H_2O	CO_2	N_2	SO_2	O_2
C	12	283.4	C	12			23.6			
H_2	2	39.24	H_2	2		19.62				
O_2	32	265.32	O_2	32						
N_2	28		N_2	28						
S	32		S	32						
Ash		12	Ash							
Water	18	400	Water	18		22.22				
	Sum	1000		Sum		41.84	23.6			
Nitrogen in air	3.77 * O2		Nitrogen in air	3.77 * O2				94.702		

Table (IV.3) for moisture content of 30 %

Molar Weight		Analysis		Oxygen		Flue gases (mol/kg bagasse)				
Content	g/mol	g/kg bagasse	mol/kg bagasse	mol/kg bagasse		H_2O	CO_2	N_2	SO_2	O_2
C	12	330.68	27.56	27.56			27.56			
H_2	2	45.78	22.89	11.44		22.89				
O_2	32	309.54	9.67	-9.67						
N_2	28		0							
S	32		0							
Ash		14								
Water	18	300	16.67			16.67				
	Sum	1000	Sum O_2	29.36		39.56	27.56			
Nitrogen in air	3.77 * O2			110.6				110.6		

Table (IV.4) for moisture content of 20 %

Molar Weight		Analysis		Oxygen		Flue gases (mol/kg bagasse)				
Content	g/mol	g/kg bagasse	mol/kg bagasse	mol/kg bagasse		H_2O	CO_2	N_2	SO_2	O_2
C	12	330.68	27.56	27.56			27.56			
H_2	2	45.78	22.89	11.44		22.89				
O_2	32	309.54	9.67	-9.67						
N_2	28		0							
S	32		0							
Ash		14								
Water	18	200	16.67			16.67				
	Sum	1000	Sum O_2	29.36		39.56	27.56			
Nitrogen in air	3.77 * O2			110.6				110.6		