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Investigation of small scale power generation and briquette production from biomass, involving cases from Bolivia

Thesis submitted for examination for the degree of Master of Science in Technology

Espoo 16.11.2016

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Abstract of master's thesis

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Abstract

Fossil fuels are still the major source of power in the world. The unabated increase in greenhouse gas (GHG) emissions over the years has accelerated climate change. Various international agreements and treaties like the Paris Agreement in 2015 have aimed at reduction of emissions. But to effectively combat climate change, collective efforts at every scale are required. On the other hand, there are communities who are financially insecure and suffer from energy poverty. Incidentally, many of these communities are also the people who are most prone to the effects of climate change. Providing renewable power to these communities will make communities more resilient and also create opportunities for financial and social development.

The focus of the work in this thesis has been the investigation of production of decentralised power and briquettes in the context of settler communities living on the edge of the Bolivian Amazon forest. The needs of such communities are oftentimes ignored by institutions, and the challenging geographic conditions further complicate matters. Agroforestry plantations have been established as a means for reforestation and poverty alleviation. The residues available from local forestry plantations are considered as the feedstock. Different biomass energy conversion pathways were examined and compared. A CHP plant of 50 kW electric output and a briquetting facility of 200 kg/hour capacity have been proposed. Gasification and combustion with ORC turbine were found to be technologically feasible and commercially available for a plant of this scale.

The technical parameters, performance characteristics and economics of a plant based on both selected conversion methods were analysed. The overall electric efficiency for a gasifier power plant was higher at 21 % compared to 10% for an ORC power plant. However, the recovered heat is higher in an ORC plant, leading to a total efficiency of 73%. The gasifier plant was slightly deficient in terms of providing the thermal energy needed for drying, hence the output of briquettes was lower. The daily biomass consumption (at 40% MC) for briquetting, and power production for gasifier and ORC based plants, were about 3.5 tons and 4.2 tons respectively. According to estimates, the biomass supply requirement is easily met from the plantations, and leaves potential for scaling up of operations.

The total investment cost, annual recurring costs and revenues earned for both systems were computed. The indicators of NPV, IRR and discounted payback period were utilised to compare the economic feasibility. The initial costs associated with a gasifier powered plant was lower. At a small scale, the gasifier option seems to be an economically suitable option. However, on an operational and performance basis, ORC systems are more reliable. The economic feasibility was found to be heavily reliant on the selling price of briquettes. By ensuring an appropriate selling price for briquettes, both the ORC and gasifier configurations of the plant are economically feasible.

A plant like this is expected to provide employment and alternative economic benefits to the local communities which can lead to positive change in society and development of services. Moreover, the project will lead to savings of over 1000 tons of CO_2 equivalent GHG emissions over a 20-year lifespan.

There exist certain barriers in the path of such projects, especially due to low prices of electricity and fossil fuels. The government is in the process of developing policies and regulations to support renewable energy production which can incentivise such projects and decrease the payback period.

Keywords biomass, CHP, briquetting, Bolivia, gasification, ORC, techno-economic analysis, feasibility, cost estimation

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Saurav Kalita

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Symbols and Units

\$	US dollar
$\dot{m}$	Mass flow rate
˚C	degree Celsius
€	Euro
C	Carbon
$C_{biomass}$	Annual cost for biomass
C_c	Annual costs
C_{labour}	Annual labour cost
C_{misc}	Annual miscellaneous cost
CO	Carbon Monoxide
C_o	Total investment cost
C_{om}	Annual operation and maintenance cost
C_r	Annual revenues
C_t	Net annual cash flow
$C_{transport}$	Annual transportation cost
D	Depreciation
EJ	Exajoule
$gmCO_2$	Grams of carbon-dioxide
GWh	Giga-watt hour
H	Hydrogen
i	Interest rate
kg	kilogramme
kg/h	kilogram per hour
km	kilometre
km^2	square kilometres
ktoe	kiloton of oil equivalent
kW	kilowatt
kW_{el}	kilowatt of electricity
kWh	Kilo-watt hour
kWh_e	kilowatt-hour of electricity
kW_{th}	kilowatt of heat
l	litre
ln	natural logarithm
m	meter
m^2	square meters
MJ/kg	Mega joule per kilogram
mm	millimetre
Mtoe	Million tonnes of oil equivalent
MW	Megawatt
MW_{el}	Megawatt of electricity
MWh	Mega-watt hour

n	Time period
Nm^3	Newton cubic metre
NO_x	Nitric Oxides
O	Oxygen
P_{el}	Electric power output
P_{th}	Heat power output
Q_b	Fuel power input
Q_{th}	Thermal output of boiler
r	taxation rate
SO_x	Sulphur Oxides
T	Annual Tax
tCO_2	Tonnes of carbon-dioxide
T_{dp}	Discounted payback period
T-s	Temperature – entropy
US$	United States dollar
W	watt
γ	Ratio of thermal output to electricity output
η_b	Thermal efficiency of boiler
η_{chp}	Combined heat and power efficiency
η_{el}	Electric efficiency
η_l	Heat loss factor
η_{orc}	Electric efficiency of ORC module

Abbreviations

AD	Anaerobic Digestion
APL	ALL Power Labs
BOB	Bolivian Boliviano
CCHP	Combined Cooling Heat and Power
CHP	Combined Heat and Power
CIA	Central Intelligence Agency
CSP	Concentrated Solar Power
DC	Direct Cost
ENDE	*Empresa Nacional de Electricidad*
ENPOGEN	Energy, Poverty and Gender in Rural China
EPRI	Electric Power Research Institute
ESMAP	Energy Sector Management Assistance Program
EU	European Union
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GEFC	Gross Final Energy Consumption
GHG	Greenhouse gas
GIS	Geographic Information System
GNI	Gross National Income
HDI	Human Development Index
HH	Household
HHV	Higher Heating Value
IC	Indirect Cost
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
KTH	Kungliga Tekniska Högskolan
LAC	Latin America and Caribbean
LHV	Lower Heating Value
MC	Moisture Content
MSW	Municipal Solid Waste
NASA	National Aeronautics and Space Administration
NBP	Energy Sector Management Assistance Program
NOAA	National Oceanic and Atmospheric Administration
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
OFSC	Off-site costs
ONSC	On-site costs
ORC	Organic Rankine Cycle

PEC	Purchased Equipment Cost
PPP	Purchasing Power Parity
PV	Photovoltaic
SA	*Sistemas Aislados* (Isolated Systems)
SIC	Specific Investment Cost
SIN	*Sistema Interconnectado Nacional* (National Interconnected System)
TIC	Total Investment Cost
TPES	Total Primary Energy Supply
TRL	Technology Readiness Level
UK	United Kingdom
UNDP	United Nations Development Program
US	United States
USA	United States of America

1 Introduction

The scientists at NASA's Goddard Institute for Space Studies have reported that the average global temperature has increased by 0.8 ˚C since 1880. The alarming fact is that two-thirds of the warming has occurred since 1975. This indicates that the rate of temperature increase is accelerating with passage of time.[1] Figure 1 displays the annual temperature anomaly from observations by NASA, NOAA, the Japan Meteorological Agency and the Met Office Hadley Centre (UK). From these worldwide observations it is evident that global temperatures are increasing rapidly.[2]

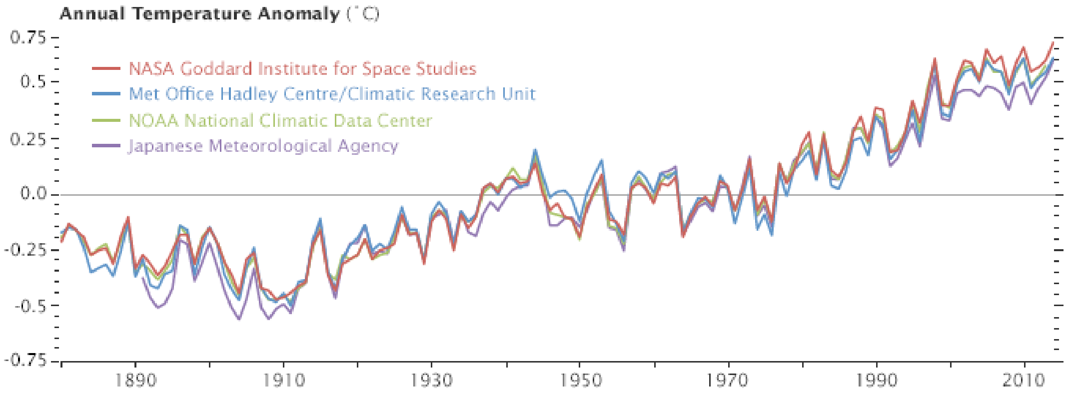


Figure 1 Annual temperature anomaly as reported by various organizations [2]

It is widely acknowledged by academics and scientists that accumulation of GHGs in the atmosphere is the major cause of global temperature increase. The rapid industrialization of the world fuelled by fossil fuels have led to alarming levels of GHG emissions. In figure 2, it is clearly evident how levels of GHG concentrations in the atmosphere has increased dramatically in the last century alone. According to studies by IPCC, more than 50% of anthropogenic GHG emissions are caused by consumption of fossil fuels.[3] The limited reserves and uneven distribution of fossil fuels have led to further complications. There has been a great deal of focus towards replacing fossil fuel energy with cleaner and renewable sources in an attempt to control GHG emissions.

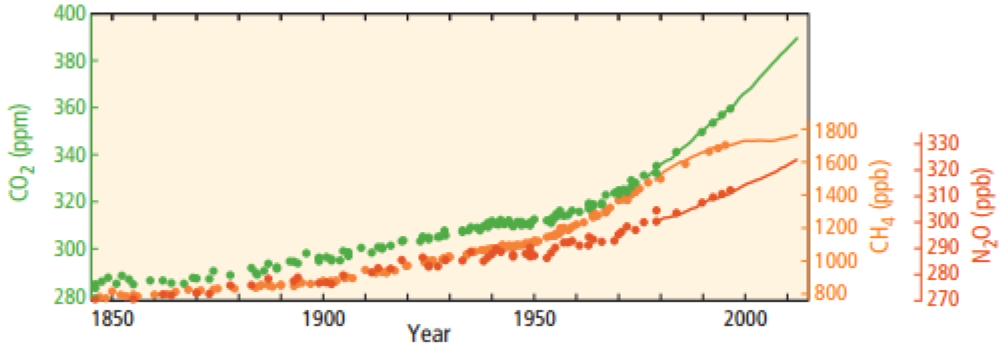


Figure 2 Global average of atmospheric GHG concentrations - CO_2 (green), CH_4 (orange), and N_2O (red) [3]

Fossil fuels dominate the current energy scenario of the world. Although the share of renewable energy has increased over the years, still more than 80% of global TPES is fulfilled by fossil fuels as of 2014.[4] The share of renewables in global gross final energy consumption

(GFEC) has grown from 17.6% in 2000 to 18.3% in 2013. The GEFC takes into account the energy commodities utilised by end sectors for energy.[5] Thus the relative growth in use of renewables has been steady, but the rate of growth has been very modest.

At the same time, a significant amount of the world population suffers from energy poverty - lacking access to electricity and clean cooking fuels. This problem is more acute in rural areas of the world. As of 2012, 28% of the global rural population still lack access to electricity. The statistics vary wildly from 1.2% in Burundi to 100% in EU and North America.[6] The access to affordable and clean energy is one of the 17 Sustainable development goals (SDGs) defined by the United Nations as shown in figure 3. The SDGs are a part of the '2030 Agenda for Sustainable Development' which was accepted by world leaders in September 2015.[7] Also the access to clean and affordable energy directly and indirectly influences the attainment of several of the SDGs. It is widely accepted that addressing the inequalities in electricity access is essential in alleviation of poverty and attainment of a decent standard of living. [8]

Figure 3 The sustainable development goals defined by the United Nations [7]

Biomass has been used as a fuel since mankind learned to harness fire. It is considered a carbon neutral fuel and can be a significant contributor to clean energy through sustainable utilization. The local availability of biomass also reduces the cost of transport. The field of energy generation from biomass has received considerable interest in recent times.

By definition, biomass refers to all forms of natural organic matter derived from living organisms. Bioenergy is the term used to define the energy that can be obtained by utilization of biomass for energy. Various types of biomass are available for bioenergy: residues from agriculture, livestock and forestry; energy crops; short-rotation forestry plantations; and waste from municipal and organic streams. Through various conversion pathways the chemical energy stored in the biomass can be converted into higher forms of energy like electricity and heat. They can also be converted to solid, liquid or gaseous fuels. [9]

Biomass has the unique advantage among renewable sources of being available continuously unlike intermittent sources like solar and wind energy. Biomass can be collected and by proper methods can be stored for future needs. This makes bioenergy suited for both centralized and de-centralized applications.

Bioenergy is the most widely utilized renewable energy source. In 2013, biomass made up 57.7 EJ out of the 78.1 EJ from renewables in global TPES. The most widespread use of biomass for energy is through traditional methods for providing heat for cooking and other processes. Traditional use of biomass is widely prevalent in poorer and developing countries. The difference in transformation of biomass from primary to final energy in the different continents is quite evident from figure 4. In Europe, the biomass is entirely transformed to heat and electricity. On the other hand, in Africa the conversion is to other forms like charcoal.[5]

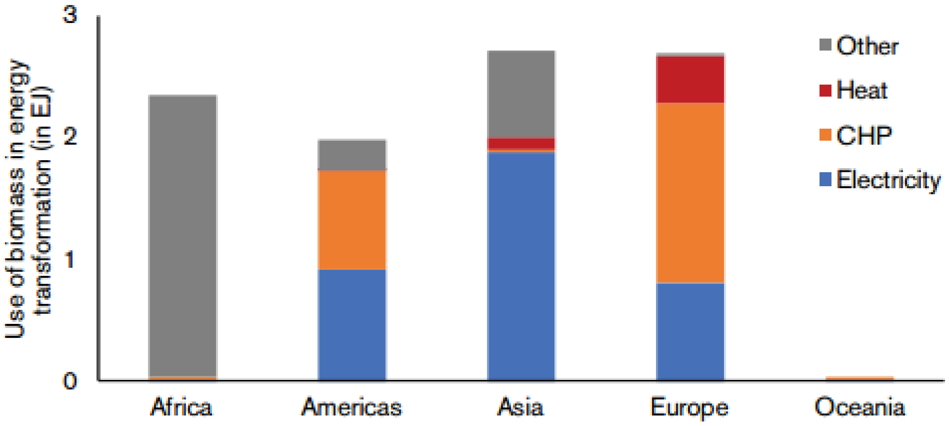


Figure 4 The distribution of biomass according to transformation in the different continents [5]

The region of focus in this study is Bolivia, specifically settler communities on the fringes of the Amazon rainforest. Bolivia is one of the least developed countries in the Latin American and Caribbean (LAC) region [10], [11]. Years of stagnant economic growth and political conflicts have led to very slow development and high inequality. Much of the poverty and inequality is concentrated among the indigenous population. It has been argued that past reforms have rarely benefitted the indigenous population. The collapse of the mining sector and dwindling arable land in the highland areas has led to migration of people to the fringes of the low-lying rainforests. Improper management, lack of knowledge, bureaucratic inefficiency and corruption has led to unsustainable exploitation of the rainforest. Bolivia is blessed with tremendous bio-diversity, and more than half the country is covered by Amazonian forest. Despite this, the forestry sector is under developed and the rainforest is severely threatened. The settler communities in the peripheries of the rainforest often lack access to basic services like electricity. Their remote location and poverty levels further aggravate the situation. The presence of the dense rainforest presents as a lucrative potential resource. The sustainable management and efficient utilization of this resource can lead to poverty alleviation and protection of the rainforest as well.

1.1 Objective of thesis

The central theme of the study was to devise a solution for utilization of biomass for generation of power and other products in the context of a community located in the Bolivian Amazon. The specific sub objectives were:

a. To assess the prevalent conditions in the country as a whole and in the area of interest. The understanding of prevalent conditions is important in decision making.
b. To create a system model by estimating the energy requirements and market opportunities for products.
c. To investigate alternatives for generation of power and selection based on real-world availability for further study.
d. To estimate the performance, costs and revenues of system based on selected technologies. The economic feasibility of the alternatives is assessed.
e. To identify the social and environmental impacts of the project and to suggest steps for future progress.

1.2 Significance of study

The study is important in identifying the feasible technology options which can be implemented sustainably in rural low-income scenarios. It provides information on sizing, technology selection and biomass processing for power generation, as well as revenue generation via briquetting. In tackling poverty, the importance needs to be on income generation through energy access. The results and discussions presented can be adapted to different regions and also be scaled to different sizes. This study will help in further planning, design and decision making for projects on utilization of renewable biomass feedstock like forestry residue.

1.3 Brief introduction of the company

The opportunity to conduct this study was provided by Renetech AB and Swedish Bioenergy Association (SVEBIO). ArBolivia was the partner operating in Bolivia, which wanted to explore the options of utilising biomass for small scale decentralised power generation and possible processing into fuels. The technical and economic aspects of power and briquette production was prepared with consideration of the geographical location of ArBolivia projects.

Renetech AB, established in 2005, operates in the domains of project development, research and consultancy in the field of renewable energy and sustainability. Renetech AB has offices in Stockholm and Dublin. They have been a part of several projects in the EU, Africa and Vietnam involving solar energy, hydropower, biomass and bioenergy.

SVEBIO is a consortium of about 300 companies involved in the various stages and processes in the biomass and biofuels industry. SVEBIO has played a pivotal role in development of the bioenergy sector since 1980, by advocating increased bioenergy use in a sustainable and economically optimal way. SVEBIO plays an important and active role in all major political decisions regarding bioenergy and its related matters in Sweden. SVEBIO is headquartered in Stockholm

2 Bolivia

The Plurinational State of Bolivia is a land-locked country located in west-central South America. Bolivia was named after the Simon Bolivar, one of the most important military and political leaders of the Spanish American Revolution. It is bordered by Brazil to the north and east, Argentina in the south, Peru and Chile in the west, and Paraguay to the south-east as seen in figure 5. It covers an area of 1,098,581 km^2, which makes it the 28th largest country in the world. The constitutional capital of Bolivia is Sucre, although the administrative capital is La Paz. The country is very diverse in its geography with tropical Amazonian forests in the east to the high-altitude Andes mountains towards the west.

Figure 5 Map of Bolivia [12]

2.1 The Land

Bolivia can be divided into three major geographic regions from the west to the east [10], [13]:

a. **Altiplano**: Altiplano is the high-plateau of the Andes located in the western part of the country. The area lies at high elevations between 3,650 m to 3,800 m. The area is prone to extreme temperature differences between day and night, and is drought prone. Lake Titicaca, which is the world’s highest navigable lake, is located in the northern Altiplano and La Paz is situated close to it. The southern Altiplano has a desert climate and not suited for human habitation. Although is it rich in mineral deposits.
b. **Yungas**: The Altiplano descent to the Yungas, which translates to “Warm Valleys”. It is a densely forested and hot and humid belt with rugged terrain. There is considerable rainfall and the area is composed of fertile valleys and mountain basins. The

rugged terrain has impeded its agricultural exploitation. Cochabamba and the capital Sucre are located in this region.

c. **Oriente**: Further to the east lies the Oriente, which is an extension the Amazon basin. This low-lying area is composed of alluvial plains, swampy areas, open grasslands and tropical forests. The area receives very heavy rainfall in the three-month long rainy season. But remains hot and dry during other periods. The largest city of Bolivia, Santa Cruz is located there.

Figure 6 represents the land use in Bolivia as of 2011 data by FAO [14]. A little over half of the country is covered by forests, although the number has been decreasing over the years. 34% of the total land area is used for agricultural activities, of which majority are pastures.

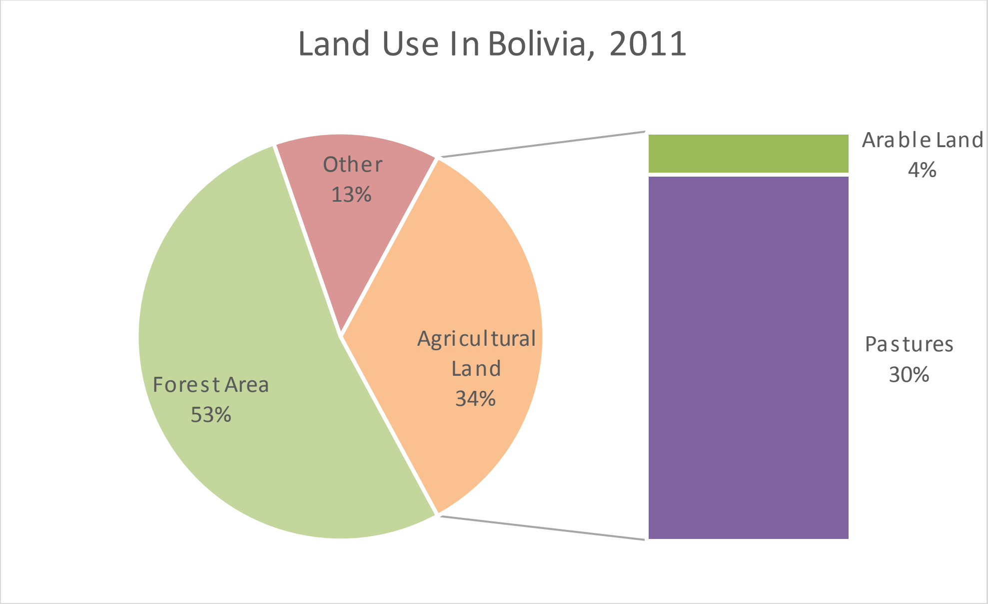


Figure 6 Land use in Bolivia adapted from FAO [14]

2.2 Social and Political Aspects

The population of Bolivia is projected to be 11,410,651 by *Instituto Nacional de Estadística* (National Statistics Institute) of Bolivia [15]. The three major ethnic groups are Indigenous natives, Mestizo (mixed European and Amerindian ancestry) and European (mostly Spanish descent). Over the years there has been considerable intermixing, but the majority of the population (about three-fifths) identify themselves as Indigenous. [10]

A large proportion of the population suffers from moderate poverty (less than $2 per day). According to data from *Instituto Nacional de Estadística*, the national moderate poverty levels have decreased from 66% in 2000, to 39% in 2014, although the percentage is 57.6% in the rural areas [16]. The income inequality is high in Bolivia with a GINI rating of 48.4 as of 2014, which puts Bolivia in the top 25 bracket of income inequality [17].

Bolivia is culturally very rich, with 36 indigenous languages besides Spanish being designated as official languages. Roman Catholicism is the major religion, which more than three-quarters of the population identifying as such. [10]

Bolivia is one of the less developed LAC countries. Table 2-2 exemplifies how Bolivia compares with LAC and World averages on various indicators [18].

Table 2-1 Comparison of Bolivia with LAC and World averages for selected indicators

Indicator	Bolivia	LAC	World
HDI	0.662	0.748	0.711
Life Expectancy at Birth (years)	68.3	75	71.5
GNI per capita (2005 PPP US$)	5,760	14,242	14,301

Bolivia is a young country with 52.5 % of the population being under 25 years of age. Majority of the Bolivian population reside in urban areas, with 31.5% of the population living in rural areas as of 2015.

2.3 Economy

After years of uneven growth, the economy of Bolivia has grown steadily at an average of 4.9% from 2004 to 2014. The GDP has grown from $8.4 billion in 2000 to $33.2 billion in 2015. Figure 7 displays how the GDP per capita has changed in Bolivia since 1990, with strong growth since 2005.[19]

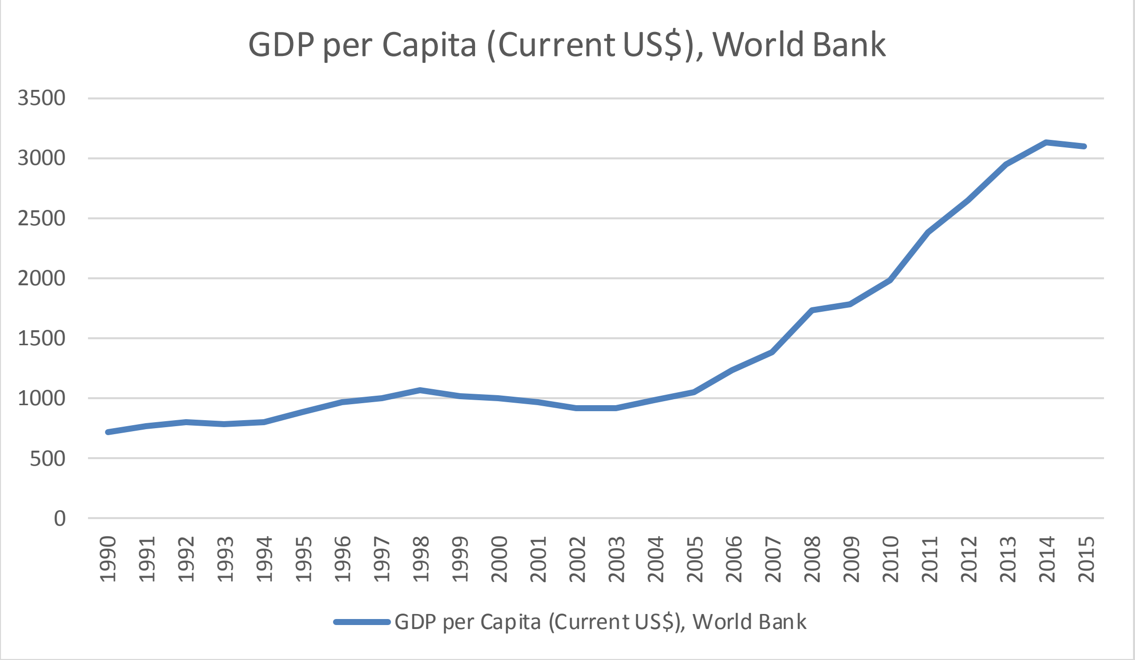


Figure 7 GDP per capita of Bolivia (1990-2015) [19]

Bolivia is rich in natural resources. There are significant deposits of various minerals and hydrocarbons (petroleum and natural gas). Also it has renewable natural resources in the form of agricultural and forest products. Historically, the economy has been focussed on a single commodity, which had made it vulnerable to changes in global demand. For example, a decrease in demand in 1980s caused the state-owned mining corporation to lay off almost 70% of the work force. In recent years, the natural gas exports have dominated the Bolivian economy by accounting for approximately 50% of the exports. The Bolivian economy has been one of the strongest performers in South America during the last global recession period. The fiscal savings are 25% of GDP and public debt is less than 40% of GDP. Although the state nationalization policy has deterred external investment, which poses as one of the biggest challenges to the economy. The slump in global petroleum prices in 2014 has led to a decrease in the GDP growth rate and government revenue in 2015. [10], [20], [21]

The government approved the National Economic and Social Development Plan 2016-2020 with an aim to maintain an average growth of 5%, and decrease extreme poverty to 10% between 2016-2020.[20]

2.3.1 Agriculture and Forestry

Agriculture contributes a little over 13% to GDP, and 32% of the labour force [21]. The major agricultural products are soybeans, meat and poultry, sugarcane, rice, potatoes and maize. Besides these major products, large variety of other vegetables, fruits, cash crops, and grains are produced throughout the country. [22]

Bolivia has the highest number of certified natural tropical forests, according to the guidelines laid down by the Forest Stewardship Council (FSC). There are more than 2,000 varieties of trees and shrubs that have been identified in Bolivia. There is a lack of detailed reliable data about the forestry sector, and its full-scale impact.[23] According to the FAO, the forestry sector employed 9,000 people directly (0.2% of labour force), and contributed 2.2% to GDP in 2011.[24] It has to be taken into consideration that the actual contribution will be higher, as informal, indirect and unreported are not included. [25]

2.3.2 Industry

The industry contributes 38.3% to GDP as of 2014. The mining sector has been the backbone of the Bolivian economy. The discovery of large natural gas reserves in Bolivia has led policies focussing on utilization and export of gas. Natural gas revenue is expected to fund more than 50% of its 2015 budget.[21]

It is also a major producer of tin and gold. Most of the mining was in the hand of small companies, which have been nationalized under the present government. There are large deposits of lithium in Bolivia, but are located in sensitive areas. Currently discussion regarding safety and feasibility of lithium production is ongoing.[10]

The manufacturing and processing of foods, beverages, tobacco and textiles are the other major industries. Growth has been slow and steady in these sectors. Most of the products are for regional use and only a small proportion is exported. [10]

2.3.3 Services

The services sector accounts for 48.5% of the GDP and employs 47.9% of the labour force [21]. Banking and Finance is closely controlled by the government. After years of fluctuating performance, the banks are performing steadily. The privatization of some financial services has bolstered the economy [20].

Tourism is a rapidly growing sector in Bolivia. The natural and cultural resources have been attracting large number of foreign visitors. This has provided an impetus to the hospitality sector. [10]

2.4 Energy

In terms of primary energy, Bolivia is a net energy exporter. The total energy production is 23.16 Mtoe, of which 15.87 Mtoe is exported. The exported energy is almost entirely in the form of natural gas exports. About 81% of the natural gas produced is exported. Figure 8 represents the total energy production in Bolivia from the various sources according to IEA. It can be clearly seen from the graph that there was a big leap in energy production with exploitation of the natural gas reserves in the late nineties.[26]

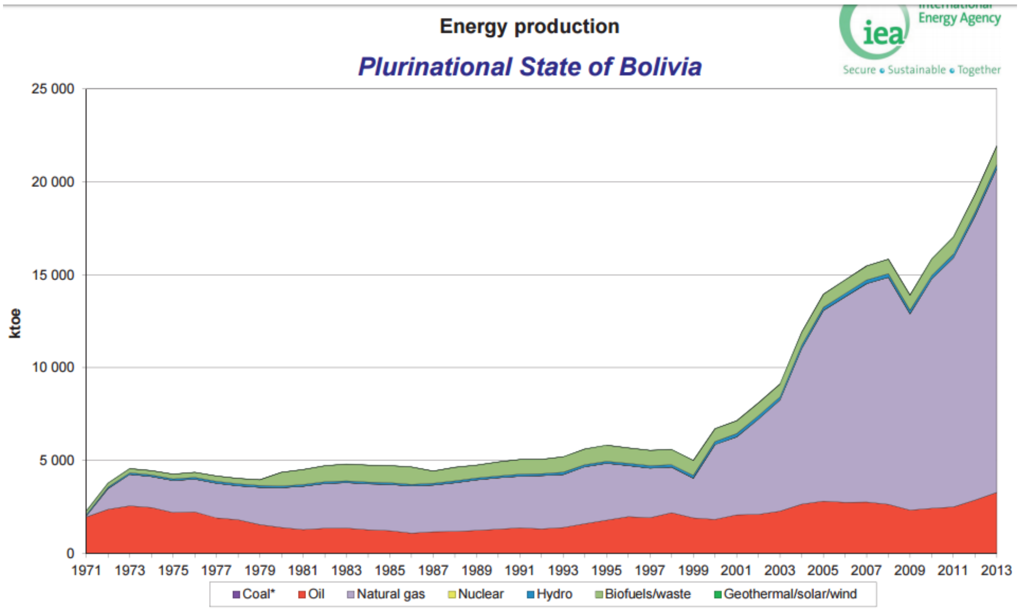


Figure 8 Energy production in Bolivia by source [27]

The TPES is 8.33 Mtoe, and the total final consumption is 6.55 Mtoe in 2014 as of IEA Energy Statistics [26]. Figure 9 below represents the consumption of final energy between the different sectors and the share of each energy type. The transport sector is the largest consumer of energy at 2,455 ktoe. All the energy for transport comes from fossil fuels – petroleum and natural gas. The industry sector relies heavily on natural gas, biofuels and waste for energy. The overall residential consumption of energy is 1,173 ktoe. There is no significant use of coal within the country. Energy from biomass is used mostly in the residential and industry sectors. Three-quarters of the energy needs of the country are satisfied by fossil fuels. [26]

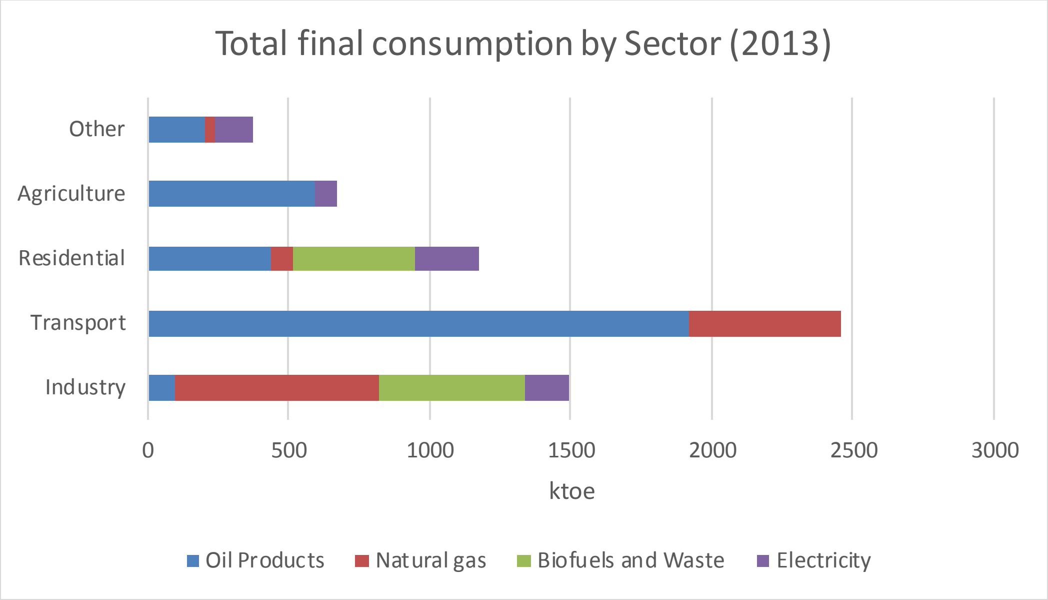


Figure 9 Total final energy consumption by sector and source of energy, adapted from IEA energy statistics[26]

Bolivia produced a total of 8,036 GWh of electricity in 2013 [28]. The per capita electricity consumption is 0.69 MWh/capita, much below the world average of 3.03 MWh/capita [29]. Figure 10 represents the electricity production according to source in 2013. 5,321 GWh of the electricity is generated using gas. The next major source is hydro, with 2,535 GWh of production. Biofuels account for only 1% of the electricity production. In total, 32% of the electricity is generated from renewable sources. [28]

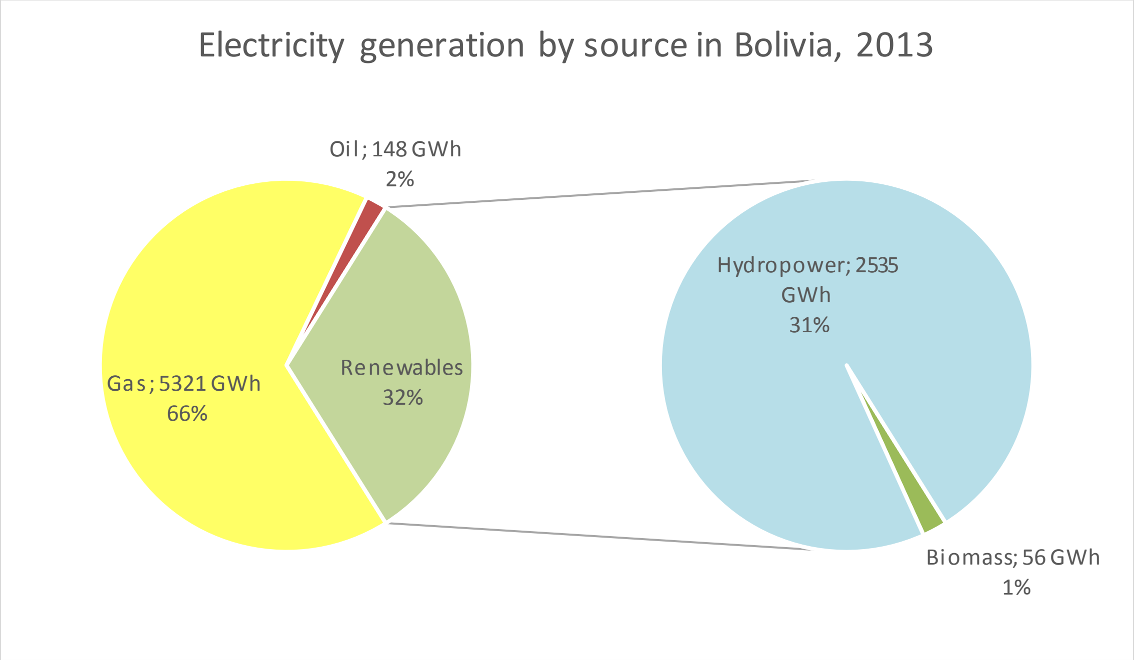


Figure 10 Sources of electricity production in Bolivia [28]

According to 2012 estimates, Bolivia has an installed electricity generation capacity of 1,650 MW [21]. IRENA estimates that Bolivia has an installed capacity of about 555 MW of renewable electricity [30]. Table 2-2 presents the breakdown of renewable power capacity by source.

Table 2-2 Installed Renewable Energy Capacity in Bolivia based on data from IRENA [30].

Technology	Capacity in 2015 (MW)
Large Hydropower	416.0
Medium Hydropower	77.2
Solid Biomass	52.0
Solar PV	6.9
Onshore Wind	3.0
Total	555.1

The electricity distribution system in Bolivia is composed of the *Sistema Interconnectado Nacional* (SIN), which is the national grid; and the *Sistemas Aislados* (SA), which consists the off grid systems. At present the state-owned ENDE corporation is responsible for about 80% of existing distribution infrastructure in the SIN [31]. Figure 11 shows the SIN grid system in Bolivia. The national grid is operational in the areas of higher population density, while the eastern part is unconnected to the grid.

Figure 11 National Electricity Grid of Bolivia [31]

The *Sistemas Aislados* supply electricity through small grids in the departments of La Paz, Beni, Pando, Tarija and Santa Cruz. They operate mostly on gas or diesel fired generator systems, with a small amount of hydropower. There are a number of operators within the system and generally they are vertically integrated.[31]

The diesel fuel used in the SA power generation systems is subsidised by the government at US$ 0.16 per litre. In spite of subsidized diesel, the average electricity tariffs in the SA are US$ 0.14/kWh, compared to US$ 0.08/kWh in the SIN as of 2013. In many parts of the SA, the electricity supply is intermittent, which negatively affects productive activities and services. [32] The electricity tariff varies to a large extent from system to system. The government is making efforts to set a universal tariff rate, although disparities still exist.

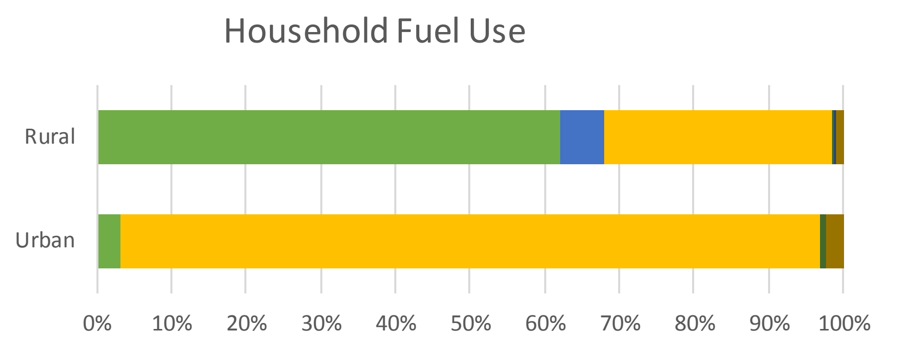
The prices of gasoline (petrol) and diesel in Bolivia are one of the lowest in the world. The prices have not been updated over time and present a significant problem for the government. Efforts to increase prices have failed in recent years because of lack of proper planning and implementation. Gasoline price in Bolivia is 0.48 €/litre and diesel price is 0.49 €/litre. [33], [34]

2.4.1 Electricity access and energy use in households

The right to access to basic services such as electricity is defined as one of the basic rights in the Constitution of Bolivia [32]. The household electricity access in Bolivia has increased from 64.4 % in 2001 to 82.3% in 2012. However, the rural electricity access rate is still only 57.48%, compared to 95.56% in urban areas. The major challenge lies in providing electricity to rural areas which are remote and not easy to access. There were still approximately 500,000 households without access to electricity as of 2012 national census.[35]

Besides electricity, the other fuels and energy sources used in rural and urban households are documented from data available from the national census. Figure 12 is created from this data to better visualise the fuel usage. [35]

The major use of these fuels is for cooking. A clear divide between rural and urban households in the types of fuel used can be seen. 94% of urban households use gas compared to 30.71% of rural households. Firewood is the main fuel in rural areas, with 62.26% of households being dependent on it. The high use of firewood for cooking and heating in rural areas can be attributed to unavailability and unaffordability of gas [36].



	Urban	Rural
🟩 Firewood	3.05%	62.26%
🟦 Dung/Excrement	0.05%	5.68%
🟨 Gas	94.00%	30.71%
🟩 Electricity	0.82%	0.28%
🟦 Other	0.14%	0.22%
🟫 Does not use	2.25%	1.00%

Figure 12 Types of fuels used in Bolivian households – adapted from national census data [35]

2.4.2 Energy Policy

Since 2009, the government of Bolivia has followed a policy of nationalization of many private entities in the basic services sectors. There was an increase of 97 MW annually and investments in the power sector increased [31].

The program '*Electricidad para Vivir con Dignidad'*(Electricity to live with dignity) aims for universal electricity access in Bolivia by 2025 [31]. The government is engaging in rapid expansion of the national grid to provide better access. Policies and schemes have been enacted in an effort to battle wealth disparity by making power expenses cheaper for poorer consumers. Under the '*Tarifa Dignidad'* (Dignity tariff) consumers with a monthly consumption equal or less than 70 kWh are given a discount of 25% on their power bill [31].

In recent years Bolivia is making efforts to increase the share of renewable and sustainable energy. Under Article 379 of the new constitution adopted in 2009, the state is obligated to 'develop and promote alternative energy in an environmentally sound way'. According to the Bolivia Electric Plan 2025, the country aims to add 183 MW of renewable electricity generation by 2025. Large hydropower above 2 MW are not considered for this target. [37]

The Policies for Renewable Energy in the Electric Sector was laid down in 2011, and prescribes action through four programmes [37]:

a. Deployment of renewable energy
b. Rural Electrification
c. Development of regulatory framework
d. Research & development

New laws and regulations regarding renewable energy and its promotion is under development. It is expected to include financial mechanisms and import tax exemptions for equipment which is not locally available. A feed-in tariff is also under development. Concessional loans from international donors, fiscal incentives, and support for feasibility studies regarding renewable energy is provided on the government on a case-by-case basis. Most small scale renewable energy generators up to 500kW are exempt from environmental impact assessments. In conclusion, many policies and incentives are under development which are expected to boost the renewable energy sector in Bolivia in the future. [37], [38]

2.4.3 Energy Potential

Bolivia has a variety of potential renewable energy sources. The geographic distribution of the potential energy sources can be seen in the map in figure 13 [39], and are discussed below.

a. It can be seen that there is solar potential in about one-third of the country. The majority of these regions are located in high elevation regions in the Altiplano, which receive high intensity solar radiation.
b. Bolivia has considerable geothermal resources along the Andes mountain range. Exploitable resources are located in the regions of Sajama, Exempa river valleys and along the southern lagoons. Many studies establishing the potential have been completed since the 1970s. Over time several projects to tap into the geothermal projects had been proposed but none have been completed to date[40]. The National Development Plan of 2007 aimed at installing 120 MW of geothermal power, but the goal was not pursued [37].
c. The perennial rivers of Bolivia with strong flow present a great hydro potential in Bolivia. Although much of the hydropower potential has been tapped, the hydropower utilization is much lower than the average in the LAC region. The government considers hydropower plants above 2 MW as conventional, and as such do not qualify for meeting renewable energy targets [37].
d. The wind energy atlas of Bolivia estimates that wind energy potential exists around the area of Santa Cruz, and between the shores of Lake Titicaca and Oruro.
e. The abundance of forests and lush vegetation endows Bolivia with a huge biomass potential. More than half of the country has potential for sustainable biomass conversion. Most of the biomass in the country is utilized through traditional methods. Through proper planning and management of biomass resources and application of modern efficient methods, biomass can have a very significant contribution in providing clean power in Bolivia.

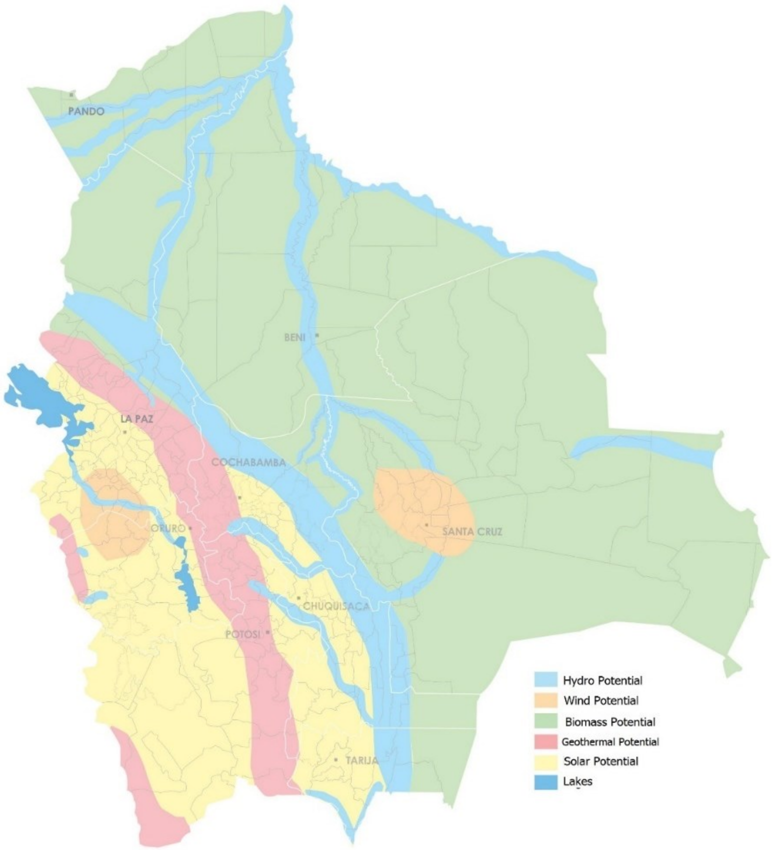


Figure 13 Distribution map of renewable energy potential in Bolivia [39]

2.5 Project Area

In this section, the area of interest and the conditions prevalent in the area are discussed. The study area is region around the small town of San Carlos, about 110 km to the west of Santa Cruz as marked in figure 14. The area falls under the administrative department of Santa Cruz. The client ArBolivia operates a small sawmill in San Carlos. The wood from the plantations established in the region is harvested and processed into planks of timber for commercial use. The plantations are owned by farmers who receive investments and knowledge to take care and maintain the trees and the land. Predominantly indigenous hardwood trees are grown in these plantations.

Figure 14 The location of San Carlos within Bolivia

ArBolivia presents a business model which allows collaboration between local smallholders and foreign investors. The project aims at reforestation activities by helping establishment of forestry plantations. The investments are used for management and operation of plantations and training of the owners. The profits from the timber are shared equally between the landowners and investors, which makes the approach sustainable and scalable.

The majority of the plantations are in settler communities in the Bolivian Amazon. These settler communities were created by migration from Altiplano and High Valley areas due to the decline of mining, loss of agricultural lands and increasing poverty. These settlers were awarded with 25-30 hectares of land on the fringes of the Amazon, but from a lack of capital and knowledge many of them had resorted to slash and burn farming. They were also given concessions for harvesting rainforest for timber. The inefficient logging practices by companies led to low gains from logging, leading to further felling of trees. These unsustainable and inefficient methods led to depreciation of the land and deforestation of the rainforest. As a part of the project by ArBolivia, the farmers have access to capital, and they are provided knowledge of techniques and advice on maintaining the plantations as well as the whole farm. By involving the farmers as equal partners, it improves their financial conditions which discourages them from slash and burn farming.

The significant economic benefits would be enjoyed in the long term when the tree plantations become mature. In the short term, the community is enjoying benefits from the community saw mill. They get better prices for their sawn timber, and the processing is more efficient. The saw mill also provides employment for community members.

From GIS data available from ArBolivia, the number of plantations under management in the area around San Carlos can be visualised in figure 15. There are more than 1,000 plantations in a 30 km radius from the location. The size of individual plantations varied from more than 2.5 hectares in size to about 0.2 hectares.

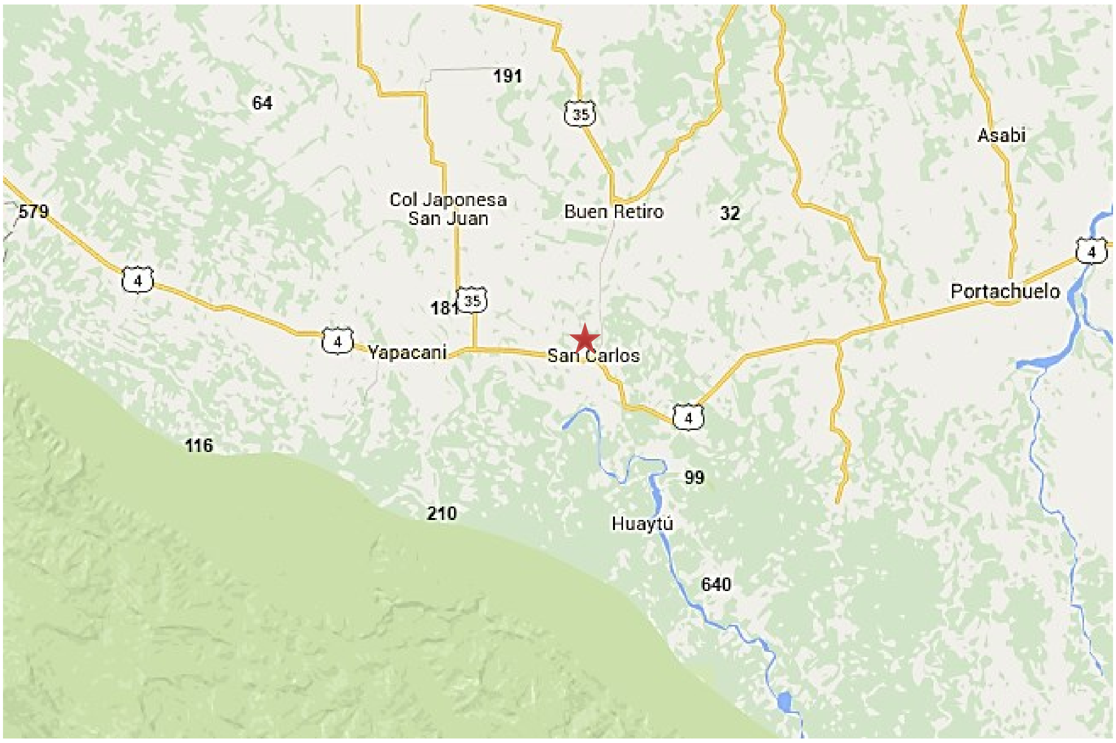


Figure 15 The number of plantations under the ArBolivia program around San Carlos

To determine the average plantation size, a sample size of plantations was selected. The sample size was calculated with an online sample size calculator tool from [41]. A population size of 1,000, confidence level of 85% and a margin of error of 10% was used to calculate the sample size. A sample size of 50 was obtained. Thus, 50 plantations were selected at random near San Carlos, and their sizes were noted. The average size of plantation based on the sample size was found to be 1 hectare.

The project area falls in the Oriente region of Bolivia, which has a hot and humid climate. There is heavy rainfall in the rainy season, but rest of the year it can be dry. Climate change is leading to variation of rainfall, which has significant impacts on such communities.

3 Methodology

This section lays down the steps and methods used to collect data, analyse and arrive at results and conclusions in this study.

3.1 Literature review

The first step in tackling the objective of this thesis was to carry a literature review. It is an essential step in carrying out any study. The literature review allows to create a theoretical framework and constitutes the foundation of the study. The latest knowledge available on the topics of interest is summarized, and the methods used in previous research on the topic are identified. This knowledge assists in identifying the direction of the study and to compare the work with previous studies. Literature on technological aspects, social and economic aspects, policies, current and future development scenarios, economic potential, and commercial aspects were studied. The relevant information on Bolivia and specifically the target area is presented in chapter 2. The technological and economic data on the conversion pathways are used and presented in chapters 4, 5, 6 and 7.

3.2 Boundaries, energy demand estimation and biomass properties

To define the direction and scope of the study, the boundaries of the system are defined. The subjects defined within the boundaries are studied and investigated further in the appropriate sections.

The energy demand for the project area based on client inputs and studies is estimated. Estimation of energy demand is necessary for sizing of the power generation system. A part of the energy is used for the client's operations and activities while the rest is sold for revenue. The assumptions and estimates regarding the collection, harvest and utilization of biomass is also laid down in this section.

This information is required to proceed to further detailed studies with reliability. Chapter 4 deals with this part of study.

3.3 Technology selection and performance

In chapter 5 depending on the knowledge obtained from literature review, the different technological pathways available were studied. The power generation technologies taken into consideration were combustion with Stirling engine, combustion with ORC, combustion with screw-type engine, and gasification coupled with generator.

The parameters on which the technological options were judged in decreasing order of importance are:

i. Maturity and commercial status
ii. Efficiency
iii. Feedstock requirements
iv. Operational characteristics
v. Scalability

A comparison of technologies based on these indicators are presented in Summary section of chapter 5.

The technologies which were found to be relevant for application in the project area were considered for further study. The thermodynamic performance and biomass feed requirements of the selected conversion pathways were calculated.

3.4 Secondary biomass use

Alternate use for biomass for briquette production is considered in the study as a means of revenue generation. Briquette production will provide an impetus to the local economy by creation of employment and income generation opportunities. The sizing, performance calculation and costs for a briquetting plant was carried out. The briquette production unit is considered to be combined with the power plant unit in the form of a consolidated plant.

3.5 Economic analysis

The total investment costs and annual costs for the systems are estimated based on literature and manufacturer sources. The indicators utilized to evaluate and compare the economic feasibility of the systems are described below:

Net Present Value

Net present value (NPV) is a method of analysing the profitability of an investment. It is the calculated by subtraction of present values of cash outflows from cash inflows for the determined time period of the project. It accounts for the time value of money and gives a direct indication of the value of investment. [42] The NPV is calculated according to the following formula:

$$NPV = C_t \left[\frac{(1+i)^n - 1}{i \times (1+i)^n} \right] - C_o$$

Where C_t is the net annual cash flow, C_o is the total investment cost, i refers to the discount rate and n is the time period of the project in years. The current central bank discount rate is 4.5% in Bolivia, which is used for the calculations as well [43]. The value of n was assumed to be 20 years for the projects.

If NPV is less than zero, the investment is not profitable and may be rejected. For comparison of multiple projects, the time period and interest rate should be common. Higher NPV indicates to higher profitability of project.

Internal rate of return

Internal rate of return (IRR) is another parameter to quantify profitability of an investment. The IRR is the discount rate at which the NPV becomes zero; which means that the present value of all net cash flows becomes equal to the capital investment. IRR is calculated according to the same formula as NPV, by setting the NPV as zero and solving for i. A higher value of IRR indicates higher profitability for the investment. The rate of growth a project can generate can be visualised through IRR. [44]

Discounted payback period

The discounted payback period (T_{dp}) gives the time period required to break-even from the initial capital investment, by discounting future cash flows [45]. The advantage over simple payback period is that the time value of money is taken into account. The mathematical formula to calculate discounted payback period (T_{dp}) is shown in equation below.

$$T_{dp} = \frac{\ln C_t - \ln(C_t - i \times C_o)}{\ln(1 + i)}$$

If $C_t < i \times C_o$, the investment will not payback. The discounted payback period must be lower than useful lifetime of the investment.

3.6 Impact on the environment and society

The social and environmental impacts of the project, specifically relevant to the community are studied. The savings in GHG emissions comparison to conventional grid based power is calculated. The barriers in the path of implementation of the project are also outlined.

4 Definition of study parameters and framework

4.1 Boundaries of the study

In this study, we are dealing with a rural scenario in Bolivia situated in sub-tropical lowlands of the Amazon basin. The biomass to be used as feedstock is from several small plantations of mostly native tree species. A suitable conversion pathway for this mixed forest feedstock will be examined. The products from the conversion will be utilised in a CHP co-generation unit to produce heat and electricity as products. A briquetting system to utilise the residues from the plantations is also analysed.

The boundaries defined will take into consideration the transportation of feedstock to the plant, processing of the feedstock, technological aspects of the conversion pathways, generation of electricity and heat, the briquetting plant, and the final products produced. An economic analysis will be undertaken to determine the capital costs, recurring annual costs, and revenues earned. The boundaries and limitations of the study are explained below and pictorially represented in figure 16.

- It is assumed that the biomass from individual plantations in a five kilometre radius is collected in a local community centre. The costs involved in transportation of biomass from plantations to the local centre are assumed to be small and not taken into account in the final calculations.
- The transportation of feedstock from local collection centre to the central plant, processing and transformation of biomass to power and briquettes is considered inside the system boundaries.
- The distribution of power and briquettes, to the end users and markets through the appropriate delivery systems is not taken into account in the study. The delivery and supply of the products to markets can be the subject of a future study.

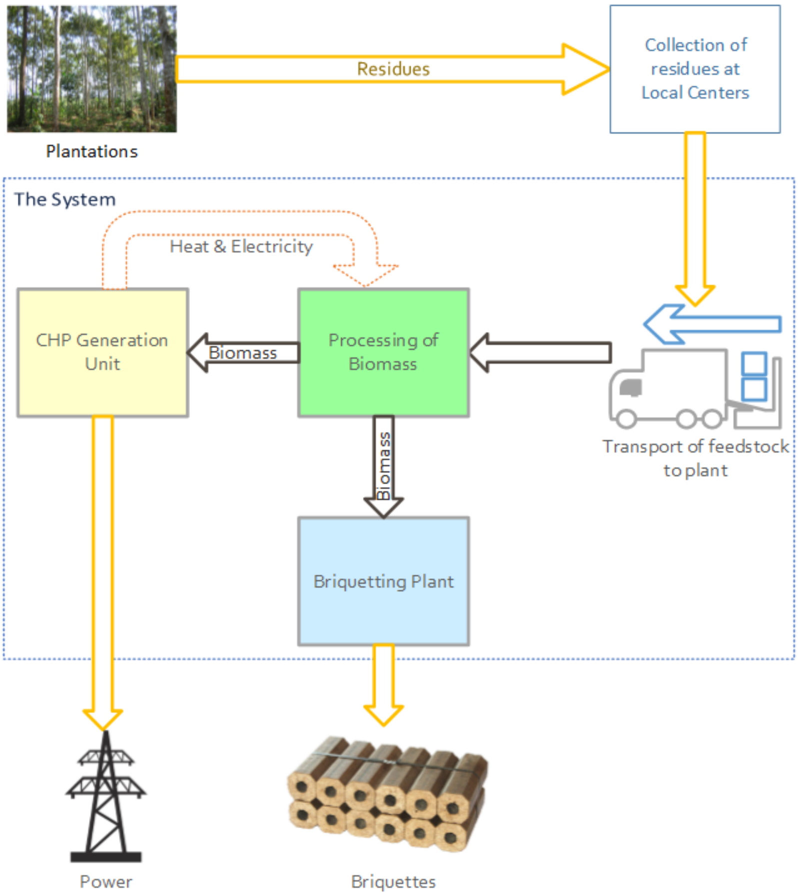


Figure 16 System diagram with defined boundaries of study

4.2 Estimation of energy demand

The estimation of energy demand is necessary for sizing of the energy generation system. Energy demand is separated into two classes – residential energy and non-residential energy. They are discussed briefly here.

4.2.1 Residential Energy Demand

It is estimated there are about 30 households in the rural community to which electricity is to be supplied.

The residential energy demand is estimated based on lighting and other household appliances. In Bolivia, the most common use of electricity in rural households besides lighting was for entertainment. In a survey of more than 300 households, 63.5% owned a TV and/or a radio [46].

A field study as a part of a collaboration between The Royal Institute of Technology in Stockholm (KTH) and Universidad Mayor de San Simón in Cochabamba was useful in providing some insights into the living conditions and energy use by rural communities. In the Oriente region, there is a demand for indoor cooling which is mostly satisfied by using fans. A refrigerator is also a desired appliance, but many rural families cannot afford it. In most households, the peak of energy usage was in the evening, when it was time for household activities, illumination and recreation. In the morning, the family members would head out for activities, which would lead to minimal energy demand during that time. [13]

Based on the knowledge gathered from different sources, and discussions, the typical electricity usage pattern for a household was estimated. A typical household was assumed to use the appliances and devices in table 4-1. The time of usage of each appliance is estimated, and based on these parameters the daily average household demand is calculated. From the daily household demand, the total residential energy demand for 30 households of the community is calculated.

Table 4-1 Estimated residential energy demand

Appliance	Power (W)	Numbers	Duration of usage (hours)	Energy consumed (kWh)
Energy efficient lights	20	4	5	0.4
Fans	75	2	16	2.4
Colour TV	150	1	4	0.6
Cell Phone Charger	5	2	2	0.02
Small Kitchen Appliance	300	1	0.17	0.05
Radio/Music Player	50	1	2	0.1
Daily Energy demand of 1 household (kWh)				3.57
Daily Energy demand of 30 households (kWh)				**107**

The power demand curve for residential energy is displayed in figure 17. It can be seen that peak residential power demand is about 12 kW. The breakdown of the power demand used to create the power curve is presented in Appendix I.

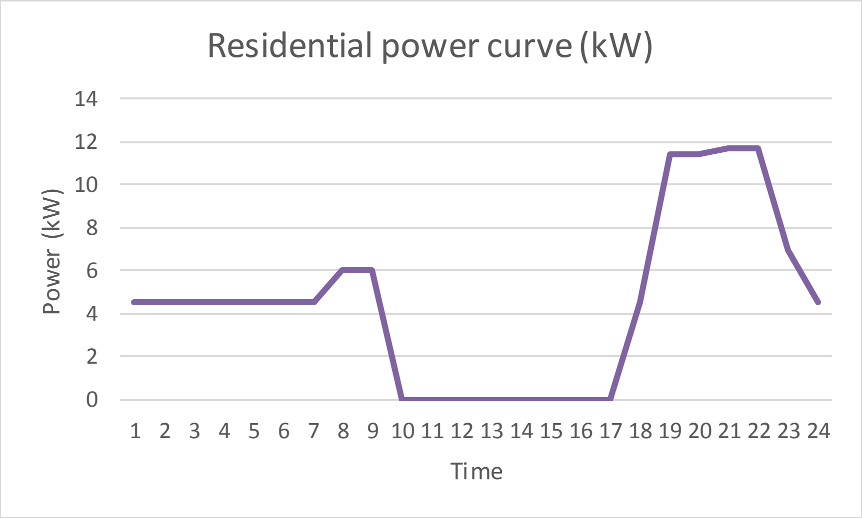


Figure 17 Residential power demand curve

4.2.2 Non-Residential Energy Demand

The non-residential energy demand is based on supplying electricity for timber processing, briquette production, water supply via electrical pump and electricity for a community center.

The energy demand for timber processing is expected to come from operation of sawmill and power tools. The briquetting plant will need electricity for running a biomass shredder, briquette press, drying fan and other auxiliary systems. The power requirement and usage of the equipment was based on estimations from reports and examples of other similarly sized systems.

The non-residential power usage and the daily energy demand is shown in table 4-2.

Table 4-2 Estimated non-residential energy demand

Commercial Activities	Power(kW)	Duration of operation (hours)	Energy Consumption (kWh)
Timer Sawmill	11	5	66
Wood Drying	1	24	24
Power tools for Processing	3	5	18
Shredder	15	10	150
Briquette Press	18.5	8	148
Aux systems	1	8	8
Water Pump	2	3	6
TV + Speakers for Hall	0.5	4	2
Daily non-residential demand (kWh)			**422**

Figure 18 shows the power demand curve for non-residential usage. The estimated peak non-residential power demand is 50 kW. The breakdown of the power demand used to create the curve is presented in Appendix I.

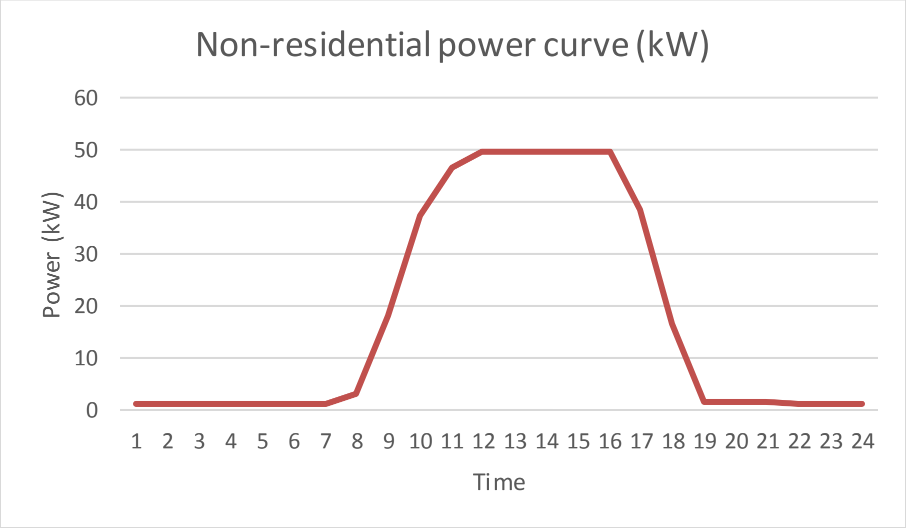


Figure 18 Non-residential power demand curve

4.2.3 Peak power and annual energy demand

The power demand for residential and non-residential sectors are combined and represented in figure 19. It is seen that the peak power demand is approximately 50 kW. The electricity generation system is designed on this estimate.

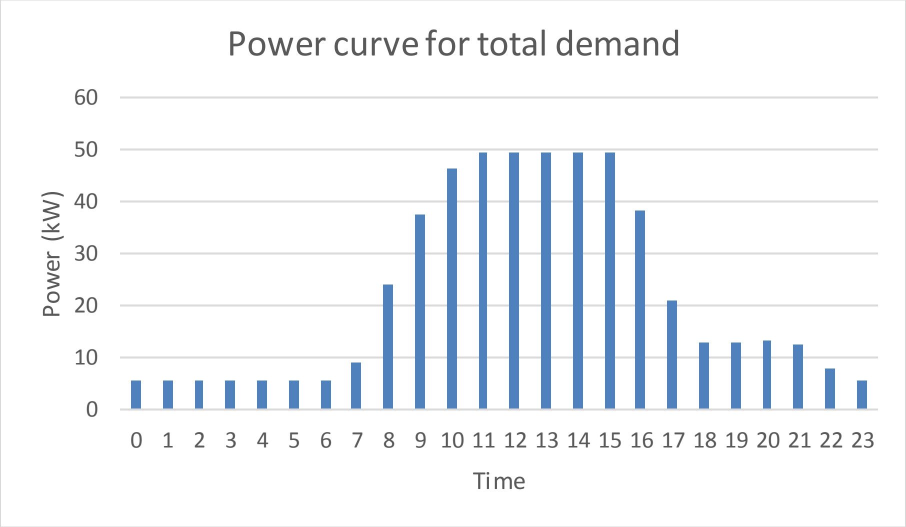


Figure 19 Combined power curve

The estimation of the annual electricity supply is based on the assumption that the system is available for 85% of the year. The daily and annual electricity energy supply is presented in table 4-3. The electricity used in the wood processing and briquette production is considered as internal demand as that energy is used by the system owner, and does not contribute to revenues. The net available energy is the part which is supplied to customers and revenue is generated from its sale.

Table 4-3 Daily and Annual energy demand estimates

	Daily energy demand (kWh)	**Annual energy demand (kW)**
Residential Energy	107	33,228
Non-Residential Energy	422	130,926
Gross Energy	**529**	**164,153**
Internal Use	306	94,937
Net available energy	**223**	**69,217**

4.3 Biomass feed properties

To support the tremendous biodiversity in Bolivian forests and prevent creation of green deserts, monoculture is discouraged. Under ArBolivia's program, 10 native hardwood species and teak is grown in the timber plantations. The variability of source means that to know the exact biomass characteristics, samples from the plantations have to be collected and tested. In the absence of such data, average values for woody biomass and forestry residue characteristics have been assumed from several sources. Such data enables to perform the system calculations with sufficient accuracy.

The assumptions regarding the forest residue biomass used in this study are as follows:

- The yield of forest residue is dependent on a large extent on factors like geographical conditions, weather, cultivation methods and practices. The forest residue yield was found to vary from 2.9 tons/hectare to about 6 tons/hectare. In the warm and humid climate of the Amazon, the growth rate is expected to be higher. Hence it is assumed that a sustainable yield of 4 tons/hectare at 30% MC is obtained annually.
- The moisture content of freshly harvested residues can range from 50-70%. Moisture is lost during collection and storage before transportation via proper storage methods. It is assumed that the biomass arriving at the processing center is at 40% MC.
- The variation of calorific value (LHV) of some biomass sources with moisture content is displayed in figure 20 based on values based on Biomass Energy Center, UK [47]. The average heating value of processed and dried biomass is considered as 16 MJ/kg at 10% MC.

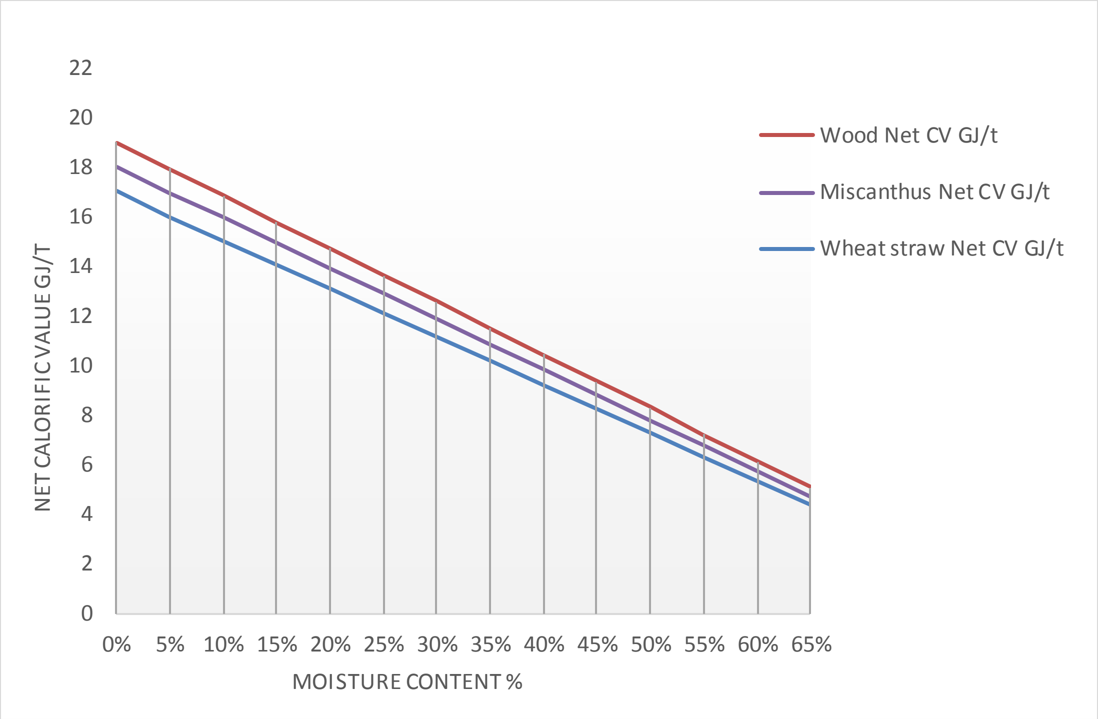


Figure 20 Net calorific value versus moisture content [47]

5 Evaluation of conversion technologies

There are three major energy pathways for the conversion of biomass: thermochemical, biochemical and physical. The selection of appropriate conversion pathway depends mainly on the type of biomass feedstock, end-use application, scale of operations, and economic conditions [48], [49]. The major types of technologies and the end products are shown in figure 21.

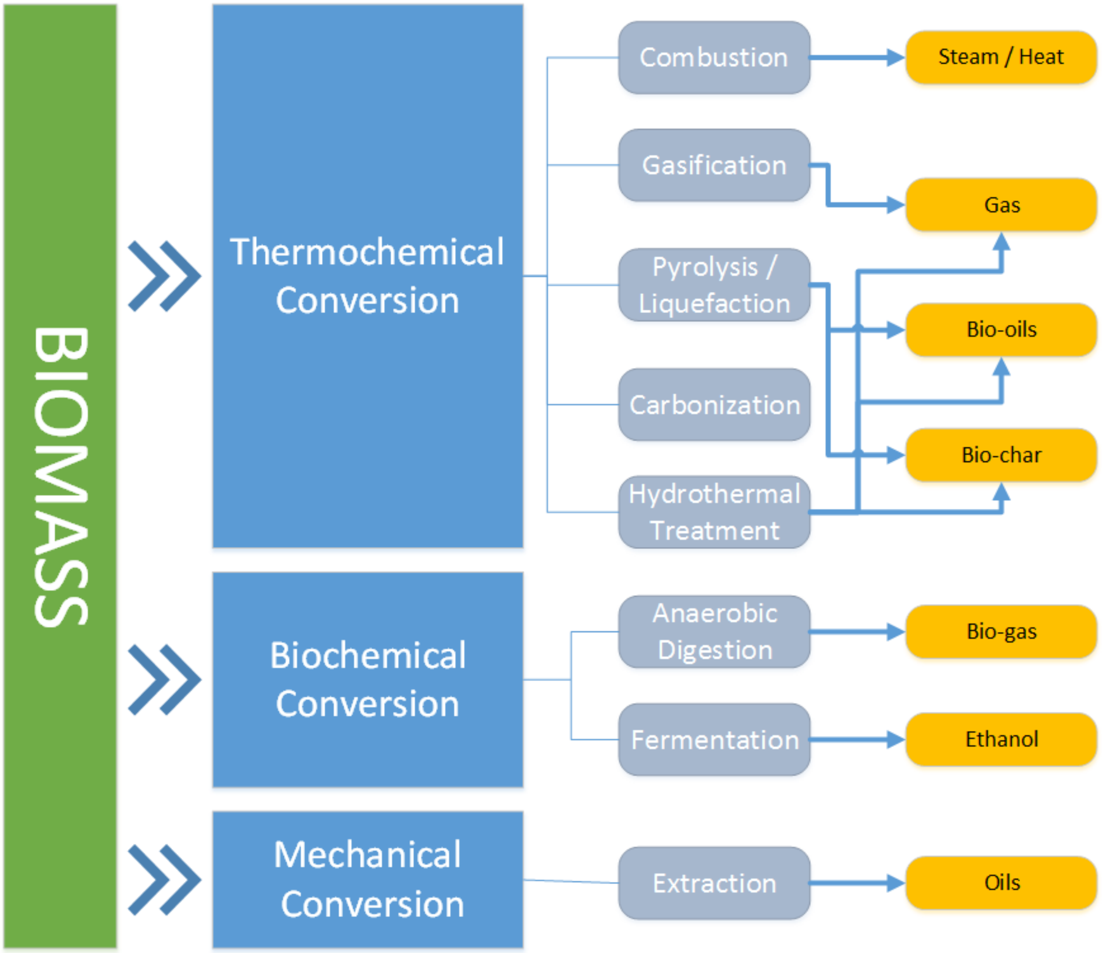


Figure 21 Biomass energy conversion pathways and products

The different end products of the conversion pathways can be utilised in three different ways – for power/heat generation, production of biofuels, or as chemical feedstock. For power generation, either thermochemical or biochemical conversion pathways are used. The mechanical extraction of oils from biomass is usually done for making biofuels or other chemical products.[48]

There are two major biochemical processes – fermentation and anaerobic digestion. Fermentation is usually used to break down carbohydrates from sugar and starch rich crops to produce ethanol. The ethanol is generally used for biofuel production. Anaerobic digestion (AD) is an effective and simple method for producing bio-gas by action of micro-organisms. The biogas can be used as a fuel to produce power or for other energy needs. AD is promoted in many rural areas of the world to produce biogas for cooking.[48] AD requires considerable capital for establishment of the required infrastructure and processes. It also needs significant pre and post processing, and has a high water requirement. The whole digestion process needs to be closely monitored for high and steady production of biogas.[50] AD was analysed as a technology taking into consideration the complications associated with AD, and the requirements of this project.

The main factors in the project area affecting the selection of appropriate technology can be enumerated as follows:

- Electrical power output of 50 kW
- Ability to utilise a feedstock arising from mixed biomass source
- Easy commercial availability
- Easy to set-up, operate and maintain

The thermochemical processes most utilised for a small-scale system are direct combustion and gasification. The end product of these primary technologies are converted through a suitable secondary technology to electricity. The primary technology, intermediate product and appropriate secondary technologies are listed in table 5-1.

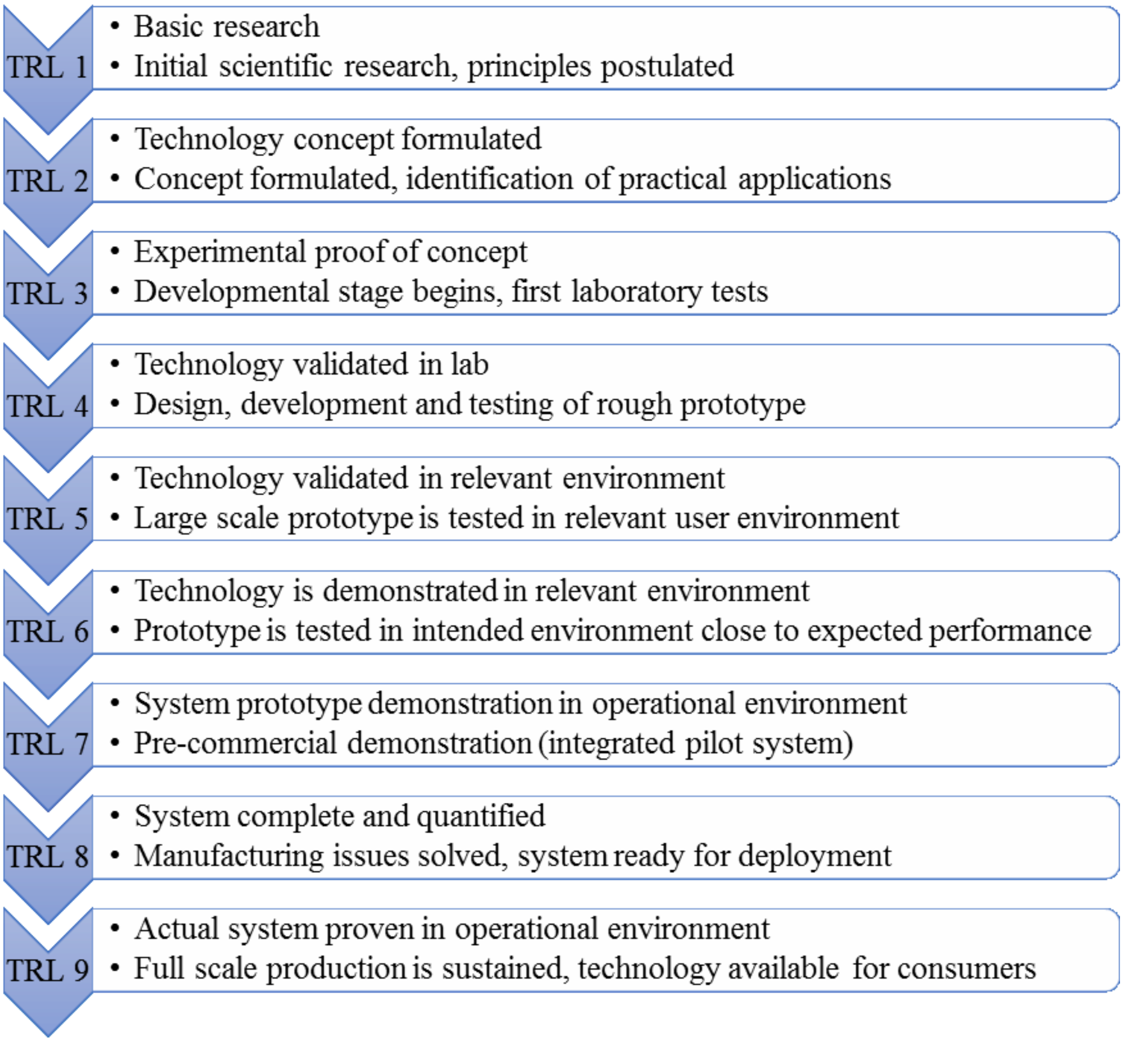
Table 5-1 Technology conversion pathways

Primary Technology	Intermediate Product	Secondary Technology
Combustion	Steam / Hot water/ Hot gases	Steam turbine, ORC, Stirling Engine, steam engine, screw engine
Gasification	Combustible gases	ICE, gas turbine, micro turbine

The most common method for power generation from direct combustion is production of heat (usually steam) which is passed through an expander like a turbine to move a generator to produce electricity. In gasification, the combustible gases are used as a fuel in an ICE or gas turbine to generate electricity. The primary and secondary technologies are discussed in detail in the upcoming sections.

The technological readiness level (TRL) is a method to assess the technological maturity of components or systems. It provides a scheme to compare different developing technologies to understand their technological maturity. A high level of TRL is proportional to a high level of technological maturity. This system of 9 levels of technological development was initially developed by NASA. Since then, they have been adapted by various organizations and bodies, and have been modified according to the field of application.[51], [52]

The TRL is classified into nine levels from TRL 1 to TRL 9, which are described very briefly in figure 22. These descriptions are adapted to the definitions specified in the Horizon 2020 Work Program 2016-2017 by the European Commission [53].



TRL 1
- Basic research
- Initial scientific research, principles postulated

TRL 2
- Technology concept formulated
- Concept formulated, identification of practical applications

TRL 3
- Experimental proof of concept
- Developmental stage begins, first laboratory tests

TRL 4
- Technology validated in lab
- Design, development and testing of rough prototype

TRL 5
- Technology validated in relevant environment
- Large scale prototype is tested in relevant user environment

TRL 6
- Technology is demonstrated in relevant environment
- Prototype is tested in intended environment close to expected performance

TRL 7
- System prototype demonstration in operational environment
- Pre-commercial demonstration (integrated pilot system)

TRL 8
- System complete and quantified
- Manufacturing issues solved, system ready for deployment

TRL 9
- Actual system proven in operational environment
- Full scale production is sustained, technology available for consumers

Figure 22 Brief definitions of Technology Readiness Levels (TRL) [51]–[53]

From the information collected for the various power generation concepts considered in the study, their technological maturity is represented in the form of TRL. This helps in easier understanding and comparison of the maturity of the technologies. The TRL of the power generation configurations for small scale power production from solid biomass are presented in figure 23. Majority of the different conversion technologies evaluated have high TRL values in the range of 8-9, except for Stirling engines, with an average TRL of 6. It is difficult to attach a fixed vale of TRL as the application base is very broad, hence they are represented as ranges. [54],[55]

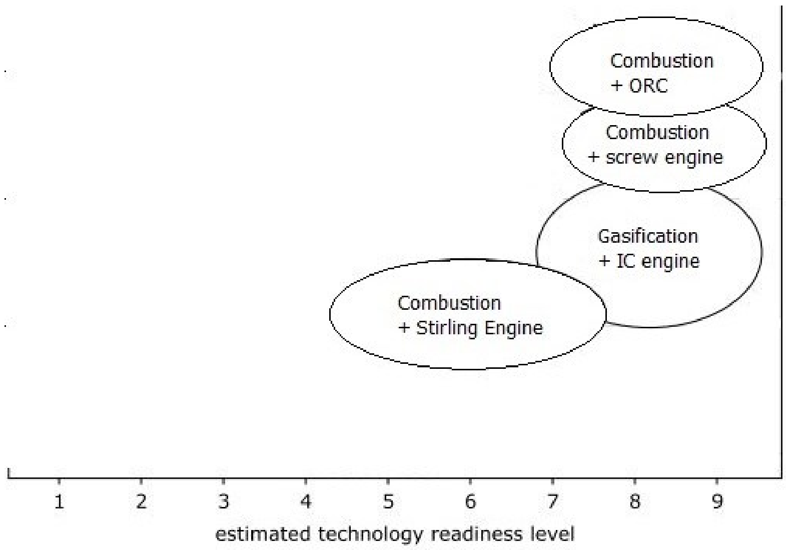


Figure 23 TRL of the biomass power generation concepts being compared adapted from [54]

5.1 Direct Combustion

Combustion is the main energy conversion pathway for utilizing biomass. It is estimated that more than 90% of bioenergy contribution is through some form of combustion [56]. In combustion, the oxidation of the organic compounds in biomass takes place. The chemical energy is converted to heat, which results in production of flue gases in temperatures of 800-1000 ˚C [48]. Carbon dioxide and water vapour are the major products of combustion. Besides them, oxides of other elements like nitrogen and sulphur are also formed. The proportion of these other products depend on the chemical composition of the biomass and the combustion conditions. The unburnt matter in combustion is left behind as ash. The ash is generally disposed or treated depending on its composition. The basic combustion equation through empirical formula of cellulose $(C_6H_{10}O_5)_n$ is exemplified by the following chemical reaction:

$$(C_6H_{10}0_5)_n + 6n0_2 \rightarrow 6nCO_2 + 5nH_2O$$

Biomass combustion has a relatively high tolerance of moisture content in feedstock, enabling feedstocks with up to 50% moisture to be utilised [48]. Figure 24 exemplifies the steps involved in combustion of a solid particle [57]. It is possible for several stages to progress simultaneously during combustion. As the particle gets heated up, it undergoes drying by evaporation of water. Biomass has higher percentage of volatiles compared to coal, and in addition they are released at lower temperatures. The volatiles mix with air and burn, releasing heat. The remaining charcoal in the particle undergoes combustion at higher temperatures and at a slower rate compared to volatile gases. The unburnt matter is left behind as ash.

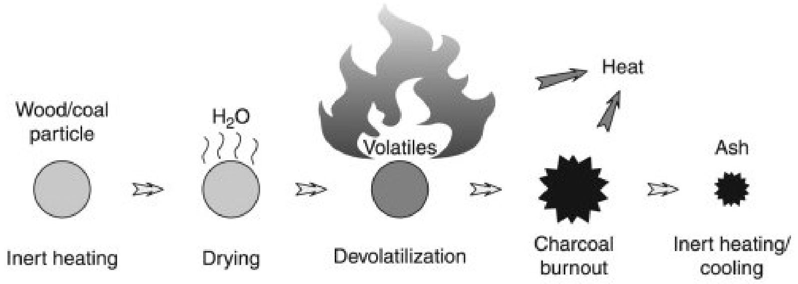


Figure 24 The combustion route of a solid particle[57]

The simplest combustion system is a furnace that burns the biomass feedstock in a chamber. Combustion is a mature technology and boilers ranging from a few kilowatts to hundreds of megawatts are commercially available [56].

Direct combustion paired with a steam turbine is the most common power generation method [58]. Steam turbines are utilised in medium to large scale power plants, and offer good efficiencies in the range of megawatts. Hence, they are not suitable for a small-scale CHP system. The suitable combustion technologies for small scale power generation are discussed here.

5.1.1 Stirling Engine

The Stirling engine is an old concept; in fact, it was designed 70 years before Otto engines [59]. Stirling engine is a closed-cycle engine which operates on cyclic compression and expansion of the working fluid.

The working of the Stirling engine can be visualised through sequence of diagrams in figure 25. The four phases are briefly explained [60]:

1. The piston is at the maximum displacement on the hot side. Heating of the gas occurs through heat transfer with the hot side. Due to heating, the gas expands and moves to the cold cylinder.
2. As the gas moves into the cold cylinder, it gets cooled and pressure is reduced. Due to the flywheel momentum, upstroke in the hot cylinder takes places and its volume reduces.
3. Almost all the gas is present in the cold cylinder and further cooling of gas takes place. This leads to further reduction of the pressure and the cold cylinder piston starts to compress.
4. Expansion of the hot cylinder takes place, and the cycle repeats itself.

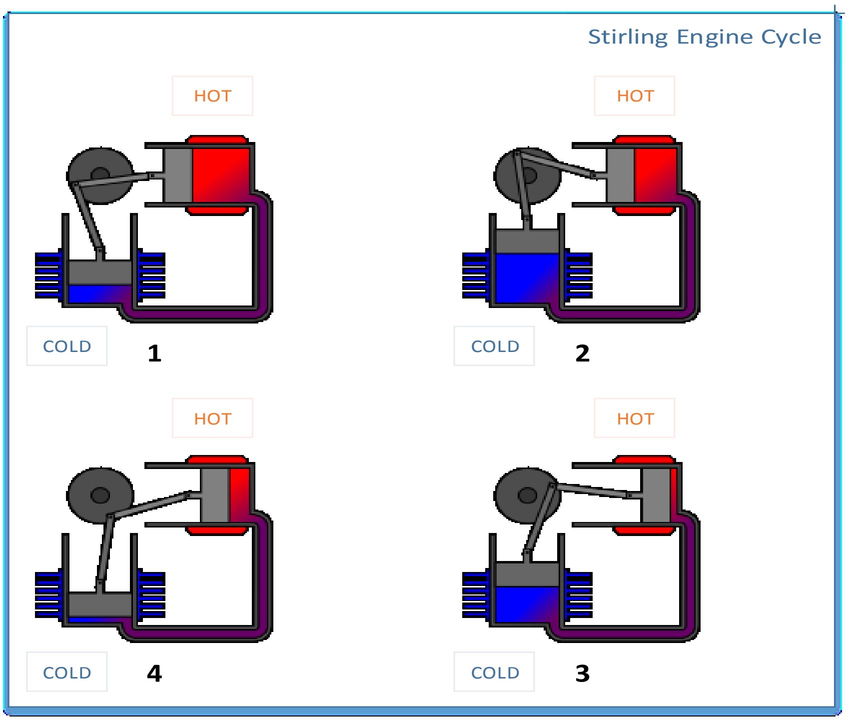


Figure 25 Stirling engine phases [61]

The Stirling Engine is an externally combustion engine, as such the heat for the process comes from outside the system. This enables the Stirling Engine to utilise any heat source to generate power. The hot and cold spaces need to be maintained at constant temperatures. The greater the temperature difference, higher is the efficiency of the engine. The external combustion of fuel allows for more controlled and efficient burning, which leads to lower emissions, lower noise and vibrations compared to a conventional ICE.

The main components if a Stirling engine are the engine piston, an exchanger piston, and three heat exchangers – a heater, a cooler and a regenerator [62]. The engine piston is responsible for conversion of gas pressure to mechanical power, and exchanges piston moves the working fluid between hot and cold regions. For efficient working, the engine requires fast and efficient heat exchange. On the basis of their mechanical configurations, Stirling engines can be classified as alpha, beta and gamma types [59].

- Alpha type: The pistons are mechanically linked together and move with fixed lag. The working gas moves from hot to cold cylinder via regenerator.
- Beta type: The engine and exchanger piston are in line with each other.
- Gamma type: The two pistons are in separate cylinders in this case.

5.1.1.1 Technical parameters and performance

Stirling engines have been widely studied and theoretically they are very well suited for small scale power generation. Engines in a wide range of electricity generation capacities ranging from 1 W to 1 MW have been developed and studied [62]. The ability of Stirling engines to operate on a wide variety of fuels also it favourable for use in biomass CHP systems. The electric efficiencies of Stirling engines are reported in the range of 25-40%. [63], [64]

Figure 26 presents a simple schematic of a biomass powered CHP plant based on a Stirling engine[65]. The biomass is combusted in a furnace and hot flue gases are produced. Through heat exchangers, part of the energy in hot flue gases is transferred to the engine. Heat is recovered from the residual heat in flue gases and from cold side heat exchanger of Stirling engine.

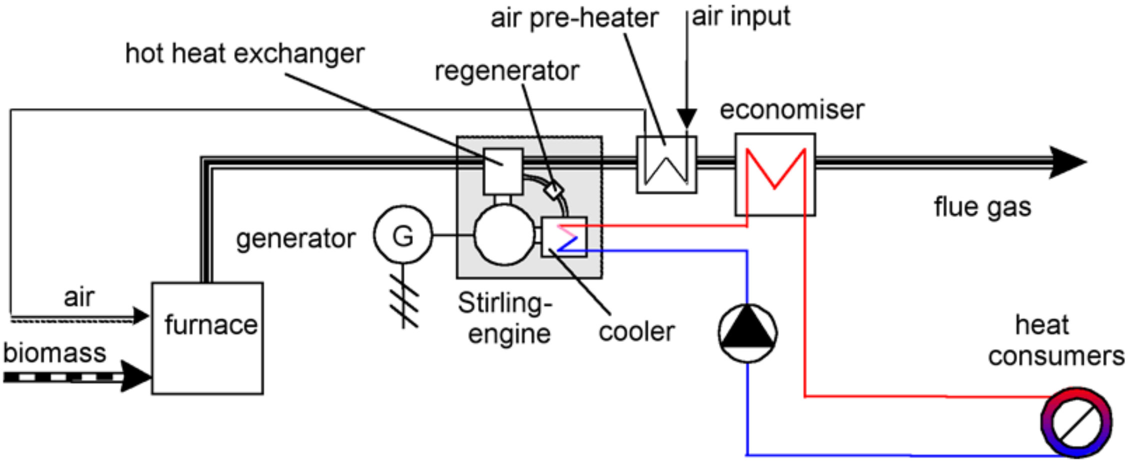


Figure 26 Schematic of biomass Stirling CHP plant [65]

In the process of several R&D projects between BIOS Bioenergiesysteme GmbH, MAW-ERA Holzfeuerungsanlagen GesmbH and the Technical University of Denmark developed and optimised biomass-powered CHP system with Stirling engines[66], [63], [67]. Stirling engines of nominal electric outputs of 35 kW$_{el}$ and 70 kW$_{el}$ were developed [68]. The fully automated pilot plant was operated in excess of 5,000 hours, using wood chips as fuel. The Stirling engine was designed at the Technical University of Denmark. The 35 kW$_{el}$ and 70 kW$_{el}$ engines were operated for 12,000 and 7,000 hours respectively. The main technical and performance parameters for the two systems are presented in table 5-2 as reported in [67]. The emissions from the CHP plants were low and further optimization to improve the electric efficiency were being carried out. The 70 kW$_{el}$ CHP plant set-up can be seen in figure 27.

Table 5-2 Reported specifications of 35 kW$_{el}$ and 70 kw$_{el}$ Stirling CHP plants [67]

Electric Power output - Stirling Engine (kW)	35	70
Working gas	Helium	Helium
Engine Weight (kg)	1,600	3,500
Thermal output - Stirling Engine (kW)	105	210
Thermal output - CHP Plant (kW)	230	460
Fuel Power Input (kW)	300	600
Electric Efficiency – Stirling Engine	25%	25%
Overall electric efficiency – CHP Plant	11.7%	11.7%
Overall efficiency – CHP Plant	88.3%	88.3%

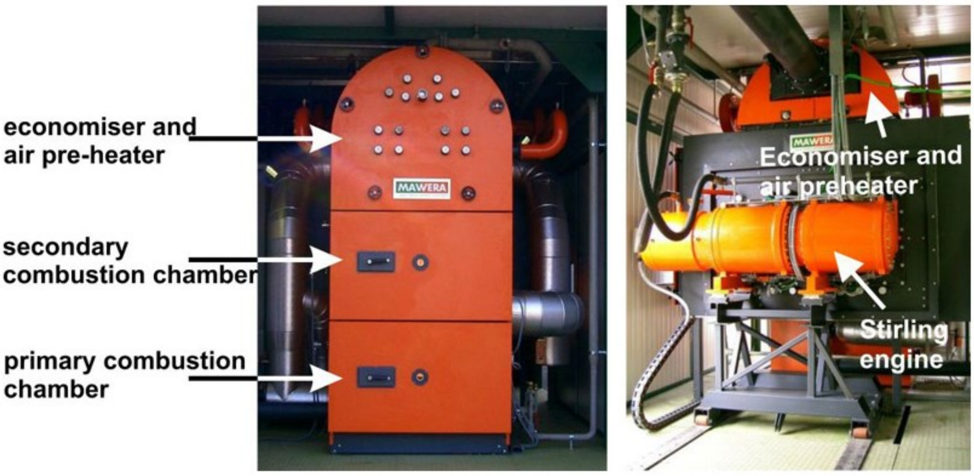


Figure 27 The 70kW$_{el}$ Stirling engine CHP plant [67]

The technology was expected to be available commercially by end of 2008 [66]. But in reality, the market has been very reluctant in adopting Stirling engine technologies. The company Stirling DK was offering the biomass powered Stirling engine. But it went bankrupt in 2013 and went out of business [69].

Some of the limitations faced by Stirling engines are [59], [70], [71]:

1. Due to the requirements of efficient heat exchangers, Stirling engines are bigger and heavier than an ICE of the same capacity. Thus the weight-to-power ratio for a Stirling engine is high, which increases material cost and makes them bulky.
2. Stirling engines are slow to load variations. Dynamic operation with prompt response is difficult to achieve.
3. The cost of Stirling engines is also estimated to be higher than other available technologies. It is estimated that ORC systems cost 60% less in comparison to Stirling engines [70].
4. Although in theory Stirling engines are simple, in reality there are practical issues in construction of Stirling engines which has hampered their marketability [59].

At present, some companies and research groups are involved in establishing a commercial biomass powered Stirling engine. But as of now, no commercial model of Stirling engine operated on biomass were found in the range of the project. The major current use of Stirling engines is in naval systems, power generation from heat recovery, and micro-scale power generation (less than 1 kW$_{el}$) [72], [73]. Due to the commercial non-availability of Stirling engines which meet the requirements of the project, this technology was not considered further in the evaluation.

5.1.2 Screw type engine

The screw type engine is an alternative to the conventional steam turbine. It operates on a Rankine cycle and is used as the expander for pressurised steam [74]. The expander is connected to a generator which produces electricity. It is based on the principle of screw compressor.

Screw engines are displacement rotary engines which have a closed working chamber. The engine consists of a male rotor, female rotor, casing, steam inlet and exhaust port [75]. The rotor is mounted on a shaft connected to a generator by a system of gears, and has appropriate seals to prevent leakage. Figure 28 presents the section view of a screw-type engine with the following parts: 1 - steam inlet, 2 - exhaust outlet, 3 - male rotor, 4 - shaft seal, 5 - synchronisation gearwheels, 6 - friction bearing, and 7 – output shaft.

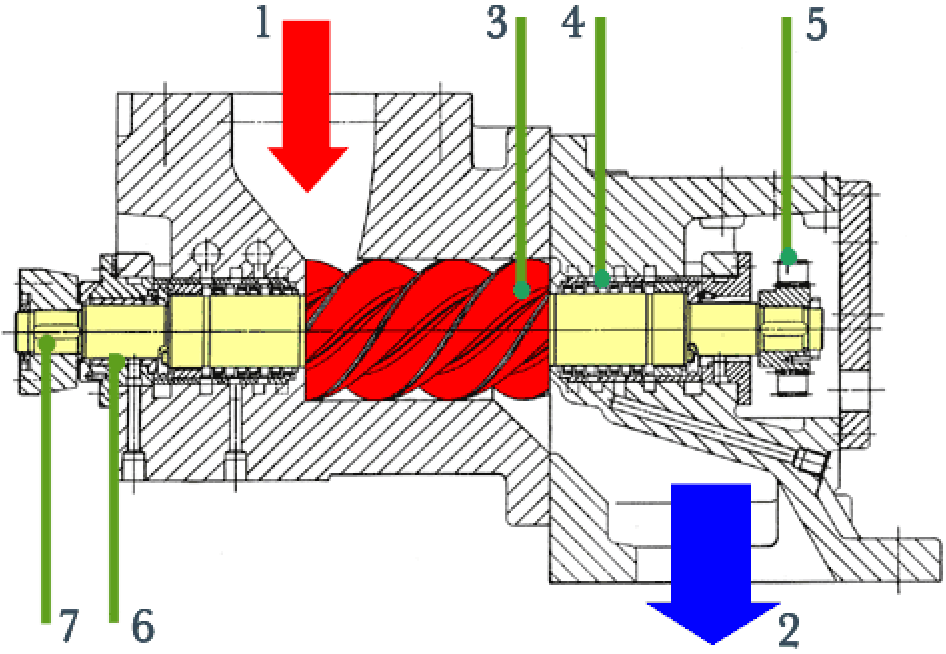


Figure 28 Section drawing of Screw-type engine [74]

The steam enters through the inlet into the casing. The rotor moves due to pressure exerted on the screw, and the volume expands cyclically. With the rotation, the volume increases while the energy contained in the steam decreases. This proceeds till the steam reaches the outlet and escapes from the chamber. After exiting the engine, energy in the form of heat is extracted in condenser to be used as process heat.

The screw-type engines offer several advantages compared with conventional steam technologies [74]:

1. The greatest advantage over steam turbines is that screw engines are insensitive to steam quality. On the other hand, turbine blades are corroded by wet steam.
2. It has very good partial load efficiency. It is able to operate efficiently between 30-100% of nominal electric load.
3. It offers high electric efficiency for small units.
4. It is compact in size and robust.

5.1.2.1 Technical parameters and performance

A CHP plant operating on screw-type engine and with biomass as fuel was commissioned in Hartberg, Austria in 2003 [75]. The plant had an electric output of 730 kW_{el} and a thermal output of 4,800 kW_{th}. The CHP plant was integrated into an existing district heating plant. An electric efficiency of 12.6% was obtained at nominal loads. The technical maturity of the technology was effectively demonstrated. Figure 29 represents the process flow diagram of the CHP plant.

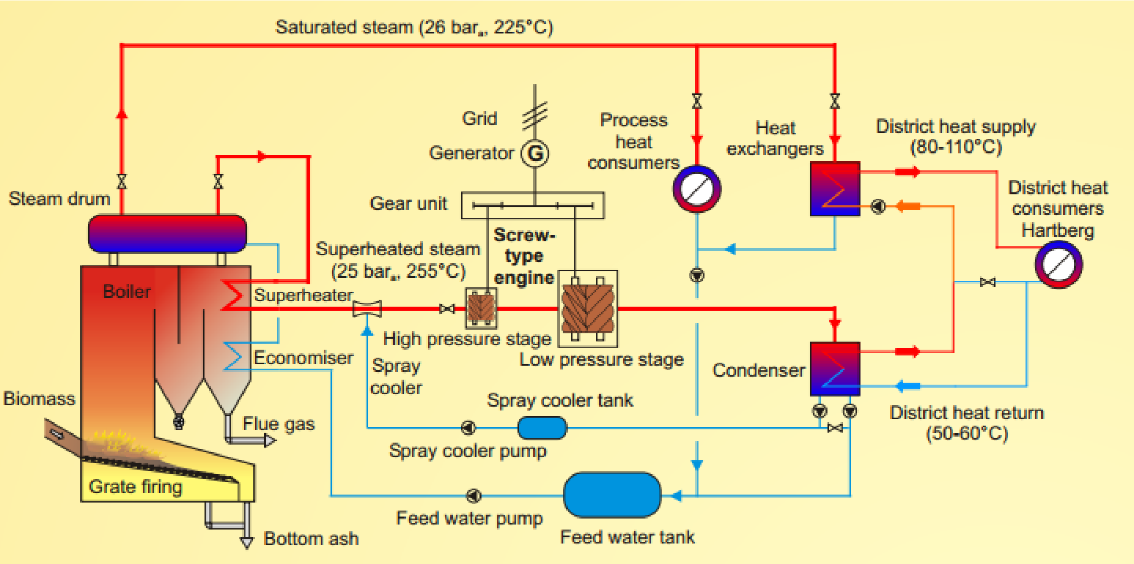


Figure 29 Process flow diagram of Stirling engine biomass CHP Plant at Hartberg [76]

At present, the screw engines in the range of 200 kW_{el} to 5 MW_{el} are being offered by manufacturers [77], [78]. The main application areas are utilization of residual steam and hot gases in process industries, or as an alternative to small steam turbines. Unfortunately, there were no systems available below 100 kW_{el} which would be suitable for the project. As a result, this technology was not considered further.

5.1.3 ORC turbine system

The Rankine cycle is a mathematical model of a heat engine which converts heat to mechanical work. The Organic Rankine Cycle is a variant of the Rankine Cycle with an organic, high-molecular mass working fluid in place of water [79]. The organic fluids used have a lower boiling point compared to water, hence heat from low-temperature sources can be utilized in an ORC turbine. The use of organic fluids has several advantages over water. In many cases, superheating of the fluid is not required. They can be used for low to medium temperatures, and lower pressures while yielding competitive or even higher efficiencies than conventional steam cycles.

The advantages arise from the fact that the organic fluids are dry fluids, which mean they have a positive slope of the saturated vapour curve in the temperature-entropy (T-s) diagram. When expansion takes place in the expander, the organic fluid is still in the vapour region, and thus there is no condensation and formation of droplets. On the other hand, water is a wet fluid and has a negative slope. It has to be superheated to inhibit droplet formation in the final expansion stages in the turbine. These differences can be visualised through the two T-s diagrams in figure 30. The T-s chart on the left is for an organic fluid, Isopentane and on the right is water.[80]

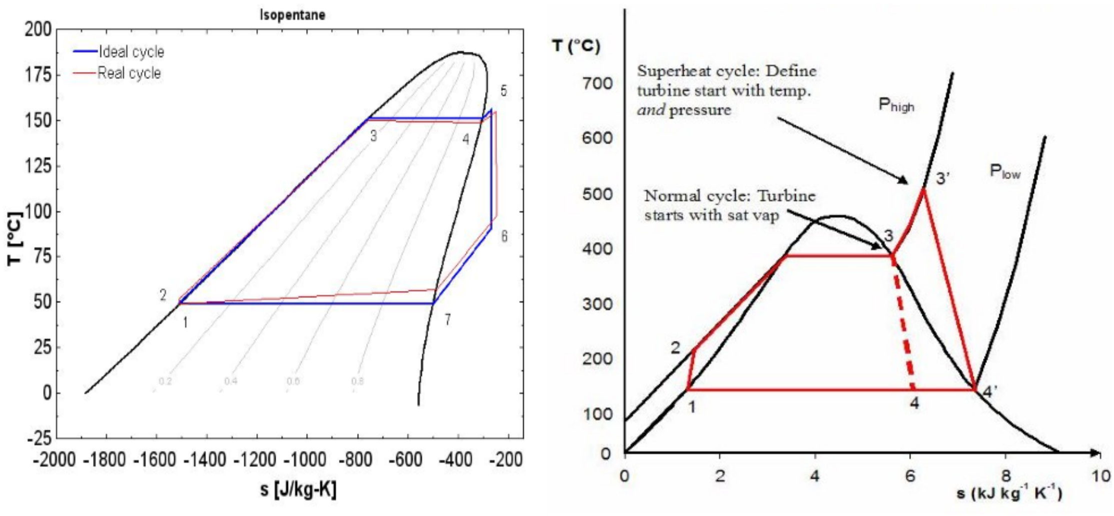


Figure 30 T-s diagram for organic fluid Isopentane (left) and water (right)

Furthermore, organic fluids have densities almost ten times higher to water which contributes to compact turbine sizes. The heat of evaporation of organic fluids is also about much smaller, which leads to high mass flow rates in ORC systems. This means that feed pumps in ORC systems are much larger than a comparative steam turbine system. [80]

An ORC power system comprises of similar components as a steam cycle, a boiler, a turbine, a condenser and a pump. The heat produced by combustion of fuel is transferred to the working organic fluid directly, or through a secondary heat exchange circuit. The heat is used to vaporize the working fluid at high pressure in the evaporator. The high pressure vapour is injected in a turbine, which converts the energy to mechanical work. The turbine is couple to a generator which process electricity. The expanded fluid is cooled down in a condenser, which extracts thermal energy to be used as process heat. Feed pumps pump the fluid back to evaporator, completing the circuit. The ORC unit is a closed system, as the working fluid is recirculated in the system. Figure 31 shows the possible schematic of a biomass powered furnace couple to an ORC system for power generation.[81]

The heat input comes from a separate boiler in biomass ORC systems, which enables a variability in feedstock type and quality. Boilers can be optimised for the feedstock which is widely available and they usually can combust biomass with up to 50% moisture.

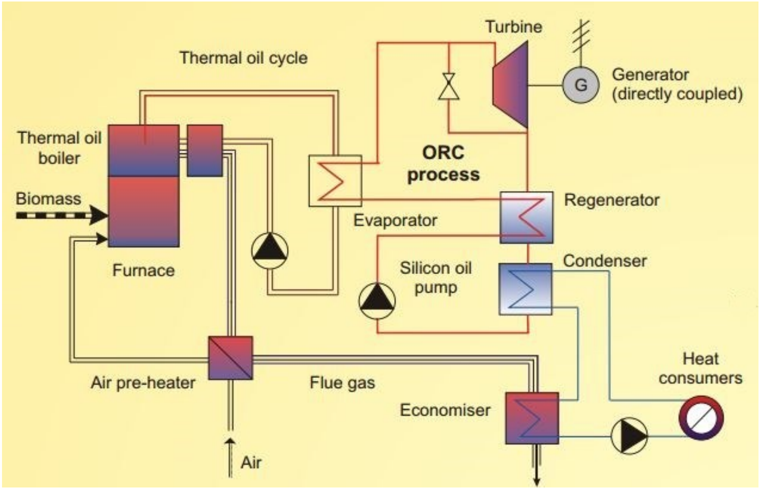


Figure 31 Schematic of a biomass powered ORC power system

5.1.3.1 Technical parameters and performance

The principle of ORC systems has been well known for a long time. Systems ranging in size of a few kilowatts to a few megawatts have been developed and tested. Up to the late 1980s, the ORC systems were in the mostly in prototype stage and with limited market scope. At present, the ORC utilization is expanding with more than 200 plants located in Europe alone.[79]

The thermal efficiencies of ORC systems are usually in the range below 20%, but their ability to utilise low temperature heat make them suitable for a range of applications. ORC systems are widely used in biomass CHP, geothermal, heat recovery applications and solar CSP applications [81], [82]. In figure 32 the installed capacity per year for per application can be seen from a review of the ORC market [83]. In the last 15 years, there has been a tremendous growth in added capacity per annum. The major application of ORCs has been in the production of heat and power from geothermal as they are ideally suited to utilise low temperature heat.

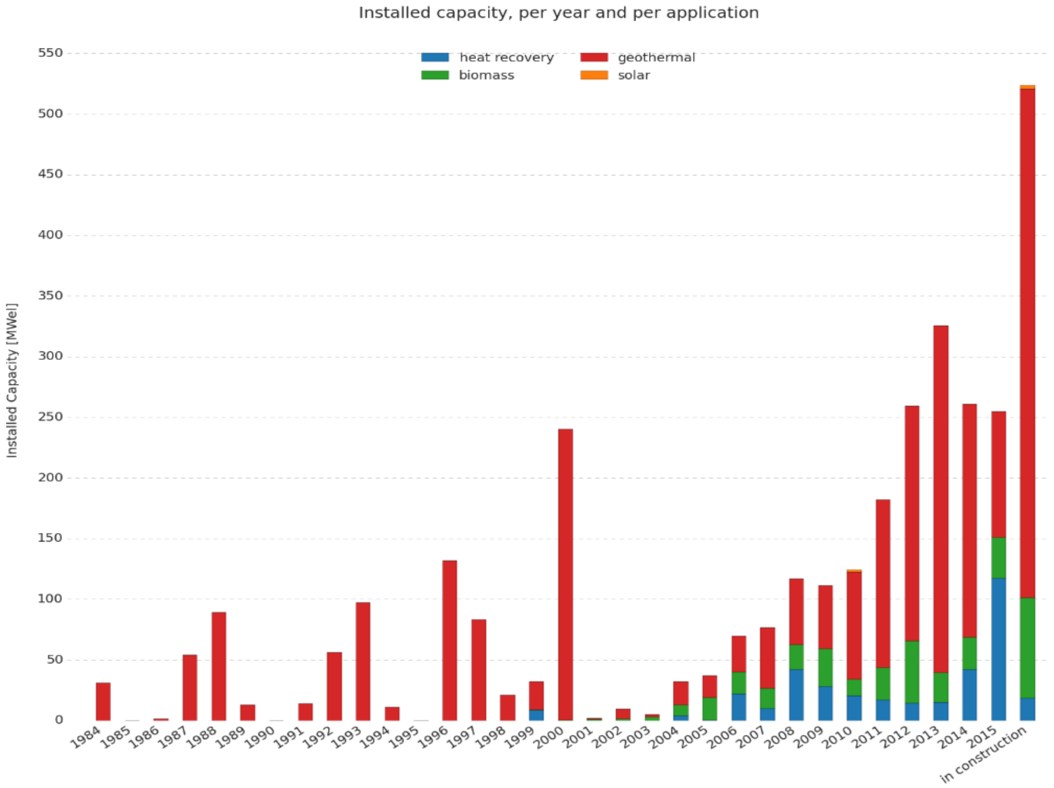


Figure 32 Installed capacity of ORC units, per year and per application [83]

There are currently about 340 ORC plants operating on biomass in the world. Figure 33 shows the location of the biomass ORC plants compiled from different sources [83]. It is clearly seen that almost all the units are located in Europe. Out of these plants, there are 33 in the capacity below 250 kW_{el}. The small scale biomass ORC plants- have been recently established and long term operational and economic data is not available.

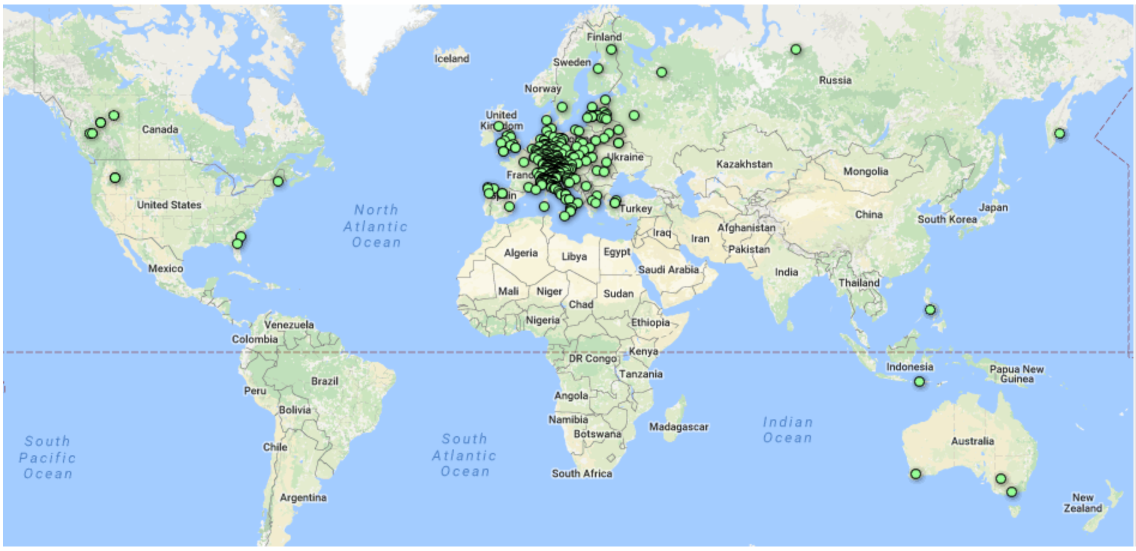


Figure 33 Global distribution of biomass ORC plants

The electrical efficiency of ORC systems depends on size of plant and heat source. Efficiencies range from about 7% for low-temperature systems to more than 20% for larger high-temperature systems. Biomass CHP power plants operating on ORC cycles in the electrical range of 200 kW-1.5 MW have been successfully demonstrated in the last decade. They have high uptimes of more than 97% and lifetimes of more than 20 years as observed from experience with geothermal plants. [84], [70]

The thermodynamic properties of organic fluid also lead to higher turbine efficiency in both full load and partial load conditions. This is exemplified from the operational data of biomass CHP plant at Lienz, Austria [85]. At 40% of net electric capacity, the electric efficiency is 85% of nominal value.

The operating temperatures and pressures in ORC systems are lower compared to steam cycles, which means that the thermal stresses are much lower and safety requirements are simpler and installation costs are lower. This also means that the need for licensed operators is eliminated, who are required for high pressure steam systems in many countries. [79], [86]

A wide variety of commercial ORC systems are available at present. Systems in the range of 30 kW_e-2 MW_e are widely available and being implemented widely in Europe, where the demand for heat and cost of power make them favourable [71]. More interest has been shown in development of medium to larger systems. Biomass ORC systems in the range below 100kW are possible, and have been established [79]. But detailed economic analysis and costs for small systems were not available.

The application of ORCs to produce power from biomass is seen in a range starting from 100 kW at present. The Triogen ORC system from Netherlands has seen wide application in Europe in recent years for a number of biomass applications. Figure 34 shows a Triogen ORC power system operating on biomass in Propopulo, Slovakia [87]. The plant utilises saw dust from a sawmill, and has an electric capacity of 130kW and thermal capacity of 660 kW. The overall efficiency of the plant is about 12%. The heat and electricity produced are utilised in the plant and offices. The surplus electricity generated is sold back to the grid.

Figure 34 Furnace (left) and Triogen ORC (right) installed in Slovakia

A significant factor to be considered for ORC systems is the organic fluid used as the organic medium. The selection of organic fluid depends on the heat source and the working temperatures for which the system is designed. Table 5-3 details the common classes of organic fluids used for different temperature ranges and the usual application areas.[79]

Table 5-3 Common working fluids for ORC systems

Temperature Range	Working Fluid	Usual Applications
80-140 ˚C	Refrigerants (R245fa, R134a)	Low temperature waste heat
150-250 ˚C	Hydrocarbon fluids	Flue gases, Process heat
250-350 ˚C	Silicon oils	Biomass combustion

The major considerations regarding the organic working fluids are [79], [88]:

1. The working fluid must be stable in the temperature range of the system. The breakdown temperature of the organic fluid should be higher than maximum operating temperature of the system.
2. The fluid and its decomposition products should preferably be non-toxic, carcinogenic or explosive. The systems have to be designed and manufactured carefully such that there is no escape of the organic fluid.
3. The fluid should also be relatively easily available at a reasonable cost. Otherwise the capital cost can be very high.

ORC units combined with biomass combustion are a promising technology in small scale power systems. It is a mature and commercially available technology. The ORC system will be further considered in the study as a viable alternative for heat and power generation.

5.2 Gasification

Gasification is a process of conversion of organic carbonaceous matter to combustible gases. It comprises heating the organic matter at high temperatures, usually 800-900 ˚C in the presence of a gasifying agent like air or steam. In gasification, controlled partial oxidation of the organic matter takes place, which produces a mix of combustible gases. This mix of gases is commonly known as syngas or producer gas. Some amount of tar and char are produced as by-products during the process. The quality of the syngas and tar products depends on the process type, operating conditions, and feedstock composition.[48], [89]

The gas mixture can be utilised in ICEs, gas turbines and boilers, after appropriate cleaning and condition for production of heat and power. For small-scale power generation, ICEs are favoured as they are easily available, have low capital cost, and qualified maintenance personnel are readily available [84].

Gasification has had a long history of application. In the 19th century, many towns and cities relied on town gas for heating and lighting needs. Town gas was produced by gasification of coal. With the increasing prevalence of electricity and natural gas, the need for coal gasification decreased. In the fuel crisis of World War 2, small gasification units were used widely, mainly for transport. It is estimated that in this period, about a million gasifier units were in use. Figure 35 shows a World War 2-era modified Adler Limousine running on wood as fuel. In recent years, the interest and utilization of gasification has increased as a means of producing renewable power from biomass. [90]

Figure 35 Adler Limousine converted to use wood as fuel [91]

The heating value of the product gas obtained depends on a large extent on the gasifying agent used. The main gasifying agents are air, steam and oxygen. Table 5-4 shows the typical heating values of the producer gas according to gasifying agent. Utilizing air produces gas of lowest heating value due to dilution by nitrogen present in atmospheric air. If steam is used, the product gas has a higher hydrogen to carbon ratio. And use of oxygen produces more carbon based compounds like CO and CO_2. Despite low heating value producer gas, air is the most widely utilized gasifying agent as it results in a simpler and more economical system.[92]

Table 5-4 Heating values of product gas according to gasifying medium[92]

Medium	**Heating Value (MJ/Nm^3)**
Air	4–7
Steam	10–18
Oxygen	12–28

A schematic of a biomass CHP gasifier system is shown in figure 36. The biomass of appropriate size and quality is fed into the gasifier and air is utilized as gasifying agent. The producer gas is cleaned and fed into an ICE. The mechanical work generated by engine is transformed into electricity by a generator. The heat in the flue gases is recovered through a heat exchanger and supplied to meet the needs.

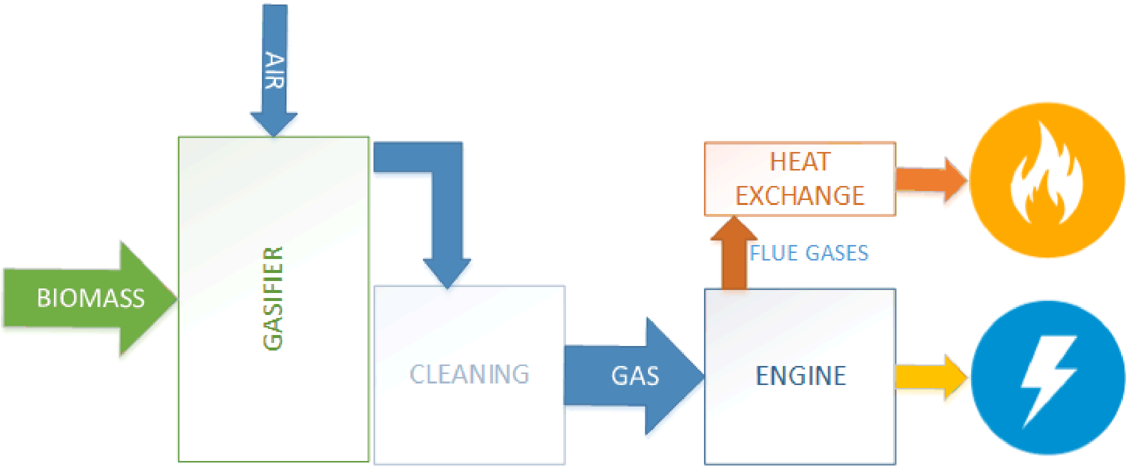


Figure 36 Schematic of a biomass gasifier CHP system

Technology status

Biomass gasification is a mature technology owing to decades of operational history. They have been implemented and are commercially available in a range from a few kilowatts to several megawatts [93]. The electric efficiencies of gasifier systems are usually higher than direct combustion in lower capacities. The electric efficiency is in the range of 20-35% [94], [95]. From specialised applications, gasification is moving towards more widespread applications with larger plants being built and operated.

A large number of small scale biomass gasifier units utilising waste biomass and residues have been established for generation of electricity. Figure 37 shows a commercially available model of a gasifier-generator model offered by ALL Power Labs, California [96]. Such models are designed for 20 kW_e peak electrical capacity and operate on a variety of biomass feedstocks. Such systems have reported overall electric efficiencies of about 20%, although real-life operational efficiencies depend on a large extent on feedstock quality.

Figure 37 Biomass gasifier-generator set from ALL Power Labs

From the information presented above, it can be seen that gasification technology for small scale power generation from biomass is well developed and suited for our case. Although long term operational and economic data is not extensive and problems with gas quality are factors to be considered.

5.3 Summary of evaluated technologies

Based on the discussion of the conversion technologies, a summary has been prepared as represented in table 5-5. The comparison is based on the indicators specified on the left. As discussed in the preceding sections in this chapter, ORC turbine and gasification are the two technologies considered for application in the project. These two conversion pathways are the most suitable based on the indicators. The green coloured boxes represent the most favourable technology in each indicator.

Table 5-5 Comparison chart of conversion technologies based on selected indicators

Indicator	Stirling Engine	Screw Type Engine	ORC turbine	Gasification
Maturity & Commercial Status	TRL of 6-7. Mature technology but not commercially widespread. Used in some specialised cases.	TRL of 7-9. Mature technology, but not currently used in medium scale operations	TRL of 8-9. Mature technology and is commercially available in a wide range. Small and micro scale application in recent years.	TRL of 8-9. Mature and Commercially available technology.
Electric Efficiency	20 -25%	12-15%	10-20%	~20%
Feedstock requirements	Biomass boiler is primary conversion technology. Feedstock quality depends on boiler type – usually tolerant to a range of feed qualities.			Generally sensitive to fuel quality. Low moisture and low ash feed required.
Operational characteristics	Large size, slow response to load variation	Compact, good partial load operation and insensitive to steam quality.	Efficient and reliable performance at low temperature difference.	Relatively good performance, long term operational data is not established.
Scalability	Is reported to be advantageous in small applications. Limitations due to complexity.	Hard to define as not many cases were found.	Systems ranging from 20kw to few MW have been implemented.	Flexible to needs. Different configurations according to capacity available.

6 Briquetting

Briquetting is a method of compaction of loose feedstock into a product of high density. Almost any solid biomass feedstock can be processed to form briquettes. Some briquettes made from a variety of feedstocks are shown in figure 38. Loose biomass has low bulk density, which makes the storage and transport cumbersome. At the same time, the calorific value of biomass is low, which leads to low energy density. The uneven physiochemical characteristics, variability in moisture content and hygroscopic properties of primary biomass makes its utilization for energy difficult. [97]

Briquetting enables to utilize the biomass feedstocks for energy which otherwise are considered as wastes. The residues with poor energy characteristics can be converted into briquettes which are a replacement for firewood and charcoal. This helps in combating deforestation from over utilization of forests for firewood and charcoal. [98]

Briquettes offer the following advantages over unprocessed biomass [99], [100], [101]:

- The bulk density is immensely improved and moisture content is decreased. Thus the concentration of energy per unit volume increases.
- Briquettes are of uniform size and quality, which makes the transport and storage very convenient.
- Due to uniform composition and density, combustion of briquettes is very uniform and clean. This leads to reduced pollution levels, lower particulate matter and higher thermal efficiency.
- Briquetting adds value to raw biomass as briquettes are a good alternative to firewood and charcoal.

Sawdust Briquette

Wood Shavings / Sawdust Mixture

Shredded Straw Briquette

Shredded Paper Briquette

MDF Briquette

Pine Briquette

Mahogany Briquette

Cardboard Briquette

Figure 38 Briquettes from various feedstocks [102]

6.1 Processes of briquette production

The processes involved in creation of briquettes from biomass feedstock are described briefly below:

1. **Size reduction**: the biomass undergoes mechanical breakdown into smaller particles. A hammer mill or shredder is used for size reduction of feedstock. A particle size of 6-8 mm with 10-20% powdery material generally gives best results. Over-

sized particles can cause clogging and jamming in the machines. And large proportion of fine particles are not suitable as they are very cohesive and do not flow freely.[97], [99]

2. **Drying**: The moisture content of feedstock is a critical factor in briquette production. Drying is necessary for wet feedstocks and might not be required is feedstock is already very dry. The appropriate quantity of water in feedstock is essential for development of self-bonding properties under high pressure and temperature in briquette press. A moisture content of about 10-15% is suitable for briquetting. If moisture content is high, the briquette structure is weak and they break easily. It is necessary to maintain optimum moisture content for good quality briquettes.[97], [99]
3. **Densification**: A briquette presses densifies the processed feedstock into briquettes. The loose material is compacted and the material agglomerates under high pressure and elevated temperature. There might be external heating or heat produced by friction to keep the temperature in the optimum range of 280-290°C. There are three main technologies for briquette presses – hydraulic press, screw press and piston press. Hydraulic presses operate at lower pressures and usually used for lower production capacities below 200 kg/h. Hydraulic presses are not widely used. Screw presses require drier biomass (8-12% moisture) but produce better quality briquettes. Piston presses are the most cost effective and widely used briquette presses, although the briquettes are of lower quality than screw presses. The basic working scheme of piston and screw press can be visualized from figure 39. The piston press has a reciprocating motion, while the screw presses produces a continuous briquette. [97], [99]

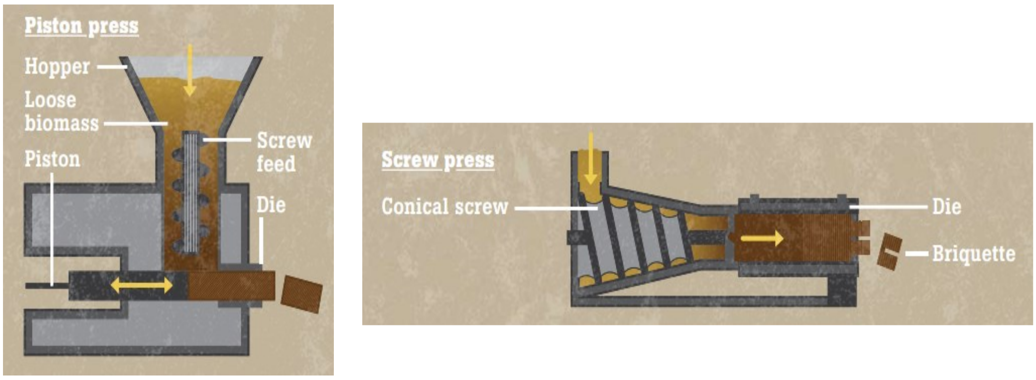


Figure 39 Working of piston press and screw press [103]

6.2 Briquettes utilization

Briquettes can be combusted in any wood and coal burning appliances, but some degree of modification in operation is required. Biomass briquettes being denser than firewood, need a higher supply of air for combustion. Hollow briquettes have better combustion properties as the central hole provides larger surface area and better air circulation. The char left after combustion of briquettes is about twice the density of firewood char and burns slower. These qualities mean that briquettes retain heat for a longer period and maintain a steady temperature.[97]

For use in cook stoves, solid briquettes need to be broken into smaller pieces for better burning [97]. Hollow screw pressed briquettes are comparably easier to burn. The specific air requirement for briquette combustion is approximately 1.6 Nm^3/hour for each kWh of heat.

Thus it should be ensured that there is appropriate air circulation by provision of entry holes for secondary air. For small stoves, this can be ensured by providing appropriate air inlets, while for large stoves a fan system can be utilized. Examples of small and large scale briquette stoves can be seen in figure 40. The large stoves are well suited for institutional and commercial use.

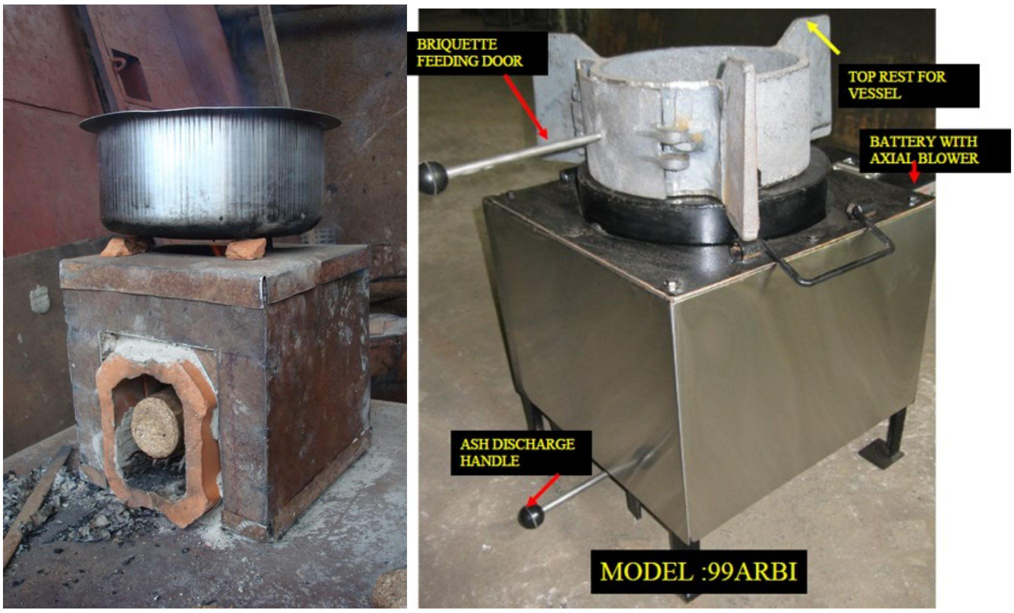


Figure 40 Small (left) [104] **and Large (right)** [105]**scale briquette stove**

Briquettes can also readily replace wood and coal in industrial scale furnaces for a wide range of applications. Similarly, as for stoves, the air supply has to be modified for optimum burning. The power density of briquettes is also much higher. Roy and Corscadden [106] tested 15 different varieties of biomass briquettes in a Drolet XV EPA residential wood stove and reported combustion efficiencies of 71.07% to 76.75% based on HHV. The NO_x and SO_x emissions were dependent on briquette composition, while particulate matter was much lesser for hardwood briquettes compared to softwood briquettes.

6.3 Market situation

The marketability and success of biomass briquettes in local markets depend on a large extent on conditions of the population and their willingness to adapt.

The briquette market and utilization is at a developmental stage in South America. The possibility of briquette and pellet production for both local markets and export to North America, Europe and eastern Asia are being investigated. Felfli et al [98] have reported in their study in Brazil that the market base is not related to production capacity of briquettes. Some large manufacturers are solely supplying the local market, while some small producers are exporting to foreign markets. Also the cost of briquettes per ton vary in a large extent depending of customer, order size and delivery distance.

Eco-K Internacional operates a briquette plant in Bolivia at Beni. Pruning collected from Santa Cruz are pressed into briquettes and sold at supermarkets and butchers. As of 2014, the production capacity was 20 tons per week. The briquettes were sold by volume in bags of approximately 3 kg at 15 BOB each. The same quantity of charcoal was being sold at 15-20 BOB. The company was moving to second phase of project and expanding the distribution to markets in Tarija, Beni and La Paz. The price for the bags would vary from 20 BOB in Tarija to BOB 35 in La Paz. Export of the product to Chile, Peru, USA and Europe was also being explored. Thus, the market in Bolivia is being established at present and judging from the case of Eco-K Internacional SRL, the prospects seem promising. [107]

6.4 Factors affecting demand for briquettes

Drivers for briquette demand:

1. Briquettes are a strong alternative to charcoal used for low intensity heat applications like cooking. The cost for briquettes is lower than charcoal and the burn time is longer. They are smokeless and well suited to indoor use. [97]
2. Some customers might be willing to spend extra money to avoid inconvenience of collection and storage of firewood, as seen in the case of a rural briquette producer in Kenya [108]. In such cases, the appropriate pricing is essential.
3. The extensive dependency of rural industries on biomass for energy is a huge potential market. As of 2005, rural industries in Bolivia were using an equivalent of half a million tons of firewood in biomass [109]. Briquettes would be a higher quality alternative with steady supply.
4. Institutions like schools, hospitals, poultry farms and restaurants utilizing a large quantity of fuel daily for heat and cooking are potentially large customer bases. In a case study from Kampala in Uganda, briquettes were very successful as a replacement for firewood and charcoal in institutional kitchens [110]. The workers greatly appreciated the smoke free and steady operation with briquettes.
5. A small number of consumers could also be willing to pay additional price for a cleaner and more sustainable source.

Challenges for adoption of briquettes:

1. About 68 % of rural households in Bolivia are using firewood and dung for energy. It is difficult to replace these sources if they are easily obtained and available for free.
2. Some customers might not have compatible stoves for briquettes. Institutional users can sometimes be hesitant to make changes in equipment to utilize a different fuel. [108]
3. Briquettes take a longer time to burn and provide a lower and consistent heat compared to fuels like kerosene or gas. [108]
4. There is low awareness about briquettes and effective utilization of biomass.
5. The low price of fossil fuels in Bolivia is a major drawback.

6.5 Biomass Use by Rural Industries

The Energy Sector Management Assistance Program (ESMAP) has provided the finances for several projects under the National Biomass Program (NBP) for development of the biomass energy sector in Bolivia [109]. The program was executed by the World Bank via a US$ 2.66 million grant by the Netherlands. The rural industries could be classified into two sectors – producing building materials (bricks, gypsum) or traditional products (maize beer, pottery). It was established that annual biomass consumption by rural industries was equivalent to 500,000 tons of firewood, comparable to approximately 80,000 hectares of forest.

The data on the six major rural industrial sectors and their respective biomass usage is presented in table 6-1[109]. The biomass was almost entirely provided via commercial channels and the utilization efficiency was poor, attributed to lack of technological development and knowledge. The supply of biomass was affected by low production in highland areas, lack of regulations governing access and exploitation of forestry for energy, leading to unsustainable conditions.

The economic effects of this biomass consumption in rural industries were:

1. The rural industries were spending about 16% of their annual sales for acquiring biomass – the percentage was considerably greater than the industry sector average.
2. The biomass expenditure was reflected in total cost of product and ranged from 2% for bakeries to 69% for lime production.

Table 6-1 Six major rural industries and respective biomass usage for energy [109]

Rural Industry	**Number of identified establishments**			**Estimated Consumption of type of biomass (tons/year)**		
	Santa Cruz	Cochabamba	Bolivia (total)	Firewood	Sawdust	Dung
Bricks	544	530	1,732	124,632		
Gypsum		150	581	30,508		
Chica (Maize Beer)		477	477	13,782		
Pottery			355		1,199	13
Rice	97		97	18,263		
Chancaca (Raw Sugar)	41		89	10,862		

6.6 Proposed briquette plant

The proposed layout of the briquetting unit is seen in figure 41. As processed biomass is required for both the power plant and briquette press, the steps involved in processing of the incoming feed is common to both. The incoming biomass first passed through a crusher for size reduction. The size reduction increases the surface area of particles, which aids in faster drying. The crushed biomass is stored in a dryer, where heat recovered from CHP unit is used to dry the biomass. A filter ensures that the particles are of required size, which ensures uniform quality of briquettes. As the briquette market is at a developing stage, an average production capacity of 200kg/hour for the briquette press is suggested. Depending on future market conditions, the output can be increased by attaching additional briquetting unit.

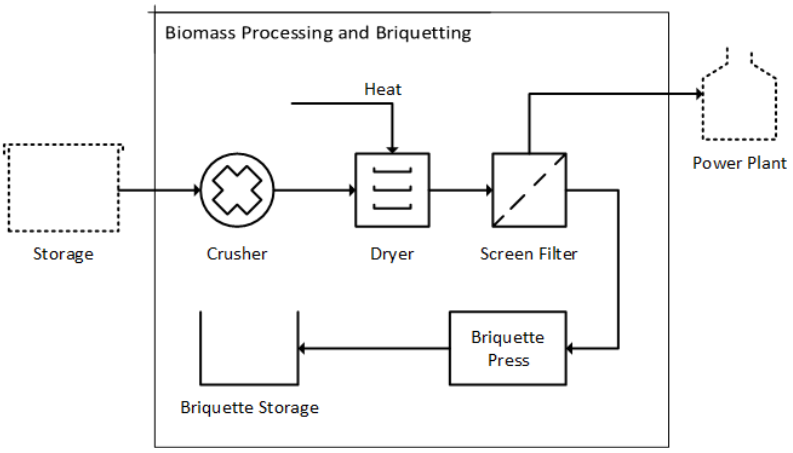


Figure 41 Layout of proposed briquetting unit

7 Analysis and results

7.1 Theory and equations for thermodynamic calculations

The methods used to calculate the thermodynamic performance of the ORC and gasifier systems are detailed here. Figure 42 outlines the basic schematic for the ORC and Gasifier generator on the left and right respectively. The associated energy flows with each system are also marked in the figure.

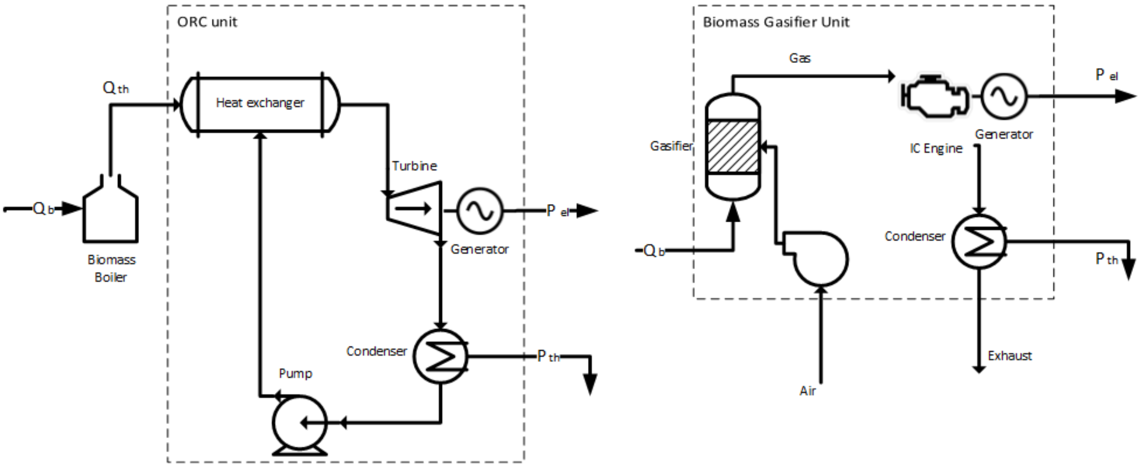


Figure 42 ORC (left) and Gasifier (right) CHP plant schematic

Efficiency of Conversion

The overall electric efficiency (η_{el}) of a power plant is defined as the electric power output(P_{el}) divided by the power input in the form of fuel (Q_b). The CHP efficiency (η_{chp}) is sum of electric power and heat output (P_{th}) of the system divided by fuel power(Q_b). The power in the fuel is the product of the mass flow rate of fuel ($\dot{m}$) and LHV of fuel.

$$\eta_{el} = \frac{P_{el}}{Q_b}$$

$$\eta_{chp} = \frac{P_{el} + P_{th}}{Q_b}$$

$$Q_b = \dot{m} \times LHV_{fuel}$$

The ratio of heat output (P_{th}) to electric output (P_{el}) is denoted by γ as shown in the equation below. The ratio is used to calculate the daily heat energy production by multiplying with the daily electricity demand.

$$\gamma = P_{th}/P_{el}$$

The gasifier system is available as a single unit comprising of the gasifier and the ICE generator. On the other hand, the ORC generation system is typically composed of two distinct parts, the biomass boiler and the ORC unit. The energy analysis of the ORC system is further described below.

The performance of biomass boiler is expressed in terms of its thermal efficiency. The thermal efficiency of boiler is represented as:

$$\eta_b = \frac{Q_{th}}{Q_b}$$

Where Q_{th} is the thermal energy supplied by the biomass boiler to the ORC cycle after combustion. The thermal energy supplied to the ORC unit is converted to electric power output (P_{el}) as per the following equation:

$$P_{el} = \eta_{orc} \times Q_{th}$$

The efficiency of electric power generation is represented by η_{orc}. The heat losses in the system is denoted by η_l . Hence, the thermal power output (P_{th}) from the ORC unit is described as

$$P_{th} = (1 - \eta_l) \times (Q_{th} - P_{el})$$

Drying Capacity from thermal output

The thermal output from the power plant is used for drying of the incoming biomass feedstock. The effectiveness of heat for evaporation of moisture in biomass is represented by η_{dry} and is assumed to be 45% for small scale drying as discussed in preceding sections. The latent heat of evaporation of water is 2.26 MJ/kg.

The heat required for drying the biomass is calculated by the following equation,

$$Heat\ required\ for\ drying = \frac{L \times \Delta M}{\eta_{dry}}$$

Where ΔM denotes the difference in weight of biomass before and after drying.

7.2 ORC Power system

7.2.1 Technical overview and performance estimation

A small scale CHP unit based on ORC turbine has the following major components:

Biomass Boiler: The biomass feedstock is fed into the boiler, where it is combusted and heat released as a result is transferred to a transport medium. Depending on the ORC plant utilized, it can be a secondary loop for heat transfer, or direct transfer to the organic fluid.

The biomass boiler is a mature technology and has existed for many years. There have been improvements in efficiency, emissions and degree of automation. The efficiency of small biomass boilers (below 1.5 MW) has improved from about 65-75% in 2000 to 80-90% at present. Various models are commercially available ranging from simple furnaces to fully automated systems with capacities from few kW to more than 100 MW. On the basis of operation, there are three broad classes of technologies [111], [112]:

- Fixed bed combustion
- Fluidized bed combustion
- Pulverized bed combustion

The fluidized bed technology is used for applications above 20MW_{th} and pulverized bed is generally used in range of 2-8 MW. Hence they are above the capacity of the system.

There are numerous technologies under fixed bed combustion systems. The basic principle is that the primary air passes along a fixed bed, and the stages of drying, gasification and char combustion take place. Figure 43 represents the basic combustion progress in a fixed bed system. The fuel combustion takes place in the form of a gradually progressing ignition front. [57], [111] The effective combustion and utilization of biomass depends on proper distribution of primary and secondary air, and effective mixing of feedstock. Heat pockets and overheating need to be prevented to ensure longer life. The boiler has to be suited to the feedstock characteristics.

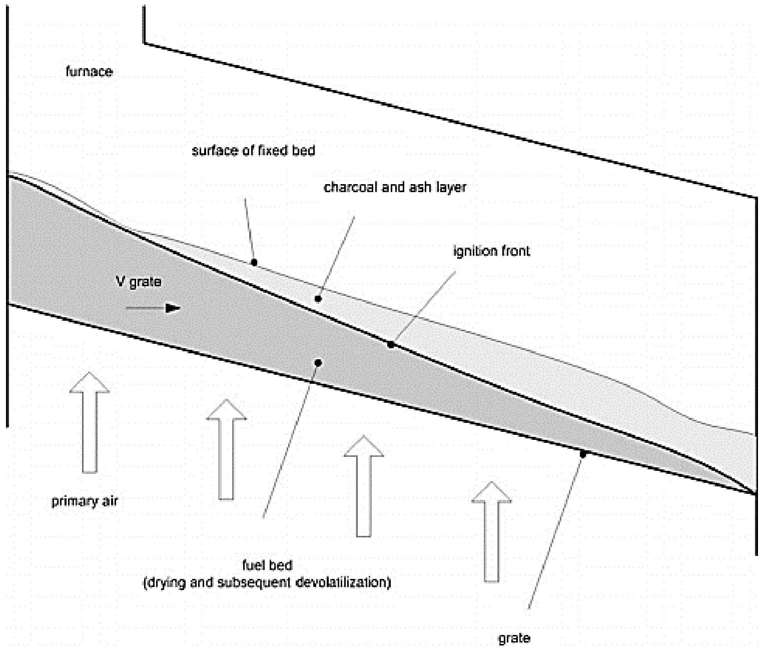


Figure 43 Combustion process scheme in fixed bed [111]

In table 7-1 the most frequently used for small scale systems and the associated typical fuel characteristics are described [112]. It can be seen that moving grate furnace type boilers can handle a wide range of biomass feedstocks.

Table 7-1 Types of biomass furnaces and fuel characteristics in applicable capacity range [112]

Furnace Type	**Typical Capacity**	**Typical Fuel types**	**Moisture Content**	**Ash content**
Understoker Furnace	20 kW – 2.5 MW	Wood chips and residues	5% - 50%	<2%
Moving grate Furnace	150 kW – 15 MW	Most biomasses	5% - 60%	<50%
Pre-oven with Grate	20 kW – 1.5 MW	Dry wood and residues	5% - 35%	<5%

Manufacturers claim efficiencies of close to 90% for modern small boilers operated on standard wood pellets and dry biomass [113]. Tests carried out by Tomberlin for NREL [114] on a biomass boiler of $300kW_{th}$ capacity on an average boiler load of 45% yielded an efficiency of 85.6%. The fuel used in the tests were pellets with a HHV of 19 MJ/kg. Thus modern small scale biomass boilers are found to be highly efficient, and for the purpose of this study, the thermal efficiency of biomass boiler was taken to be 80%.

ORC turbine generator system:

ORC units producing electricity and heat are commercially available in the market today. They need to be connected to a heat source which can be a biomass boiler, waste heat processes, or hot water from solar panels. The minimum required temperature of the heat source depends on the working fluid of the system. In high-temperature systems with capacities of 200kW$_{el}$, common working fluids are toluene or pentane. Traditionally, ORCs less than 200kW$_{e}$ use hydrocarbons as working fluid and were used mostly for heat recovery applications.[71]

The energy from hot flue gases is transferred to working organic fluid directly or via a thermal oil loop. In biomass combustion applications, the working fluid evaporates at a temperature slightly lower than 300˚C [115]. After expansion in turbine, the fluid is condensed at around 90˚C in the condenser. The heat is generally extracted in the form of hot water. The basic schematic of ORC cycle is displayed in figure 44.

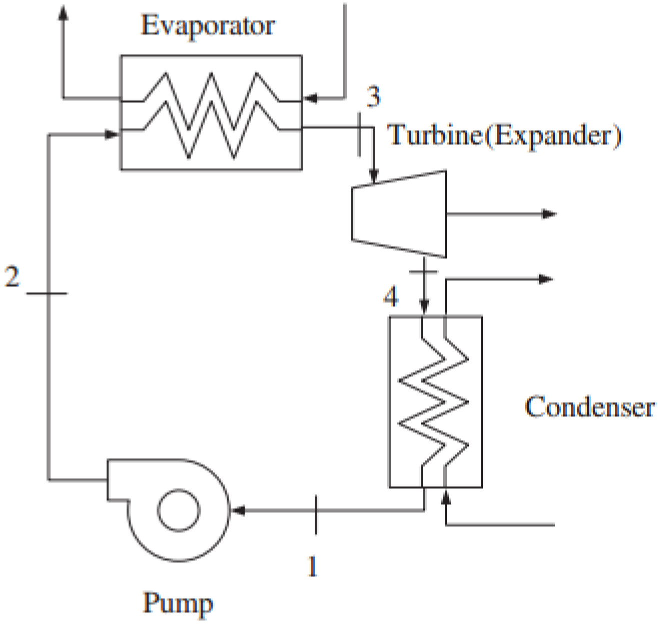


Figure 44 Simple schematic of ORC cycle

The electric efficiency of ORC system usually ranges from about 8% for small and low-temperature systems to about 23% for large and modern systems [71].

The electric efficiency of ORC unit depends on the temperature of heat source, and the temperature difference available between the hot side and the cold side. Higher the temperature and greater the temperature difference, higher is the electric efficiency of the system.[79]

One of the leaders in biomass ORC systems, Turboden reports electrical efficiency from thermal oil as 24 % for large systems above 1.2 MW and overall efficiency of 16% from biomass [116]. A 1.67 MW ORC plant in Ostrow Wielkopolski was showing an operational electric efficiency of 16.7% from thermal input [117].

Recent research and developments in production of power from biomass using ORC has led to improvements in electric efficiency for small systems. There is much interest on small and micro scale ORC systems for generation of power from sources generally considered as waste.

Based on several sources, the electric efficiencies for small ORC systems is observed to be from 7 % to 16 % in the range of 2kW-1000kW. The overall efficiency is reported to be from 85% to 92%. [118]

For the ORC, the efficiency for conversion of thermal energy to electricity was assumed to be 10%, 13% and 14% for a 20 kW_{el}, 50 kW_{el} and 100 kw_{el} system respectively. A 10% loss in recoverable heat from exhaust stream was also considered. The results of the performance calculations are represented in Table 7-2.

Table 7-2 Estimated performance of ORC and Boiler system according to own calculations.

Estimated Performance				
Electric Power output, P_{el}	kW_{el}	20	50	100
Electric Efficiency, η_{orc}		10%	13%	14%
Thermal Power Input, Q_{th}	kW_{th}	200	400	714
Thermal Output				
Losses assumed, η_l		10%	10%	10%
Heat output, P_{th}	kW_{th}	162	315	553
Biomass Power Input				
Boiler Efficiency, η_b		80%	80%	80%
Biomass Power Input, Q_b	kW_{th}	250	500	893
Overall Efficiency				
Electric Efficiency, η_{el}		8.0%	10.0%	11.2%
CHP Efficiency, η_{chp}		72.8%	73.0%	73.1%

Waste Products

The major waste product after combustion of the solid biomass is ash. The ash can be classified into two types – bottom ash and fly ash. The bottom ash is present in the primary combustion chamber and gets collected on the grate. It consists of heavier and larger particles. The finer particles are carried away by the flue gases and removed as fly ash. The ash contains many of the plant nutrients from the solid biomass combustion. Hence if the ash is from uncontaminated biomass combustion, it can be utilised as a soil conditioner. The fly ash has been shown to contain higher proportion of heavy metals compared to bottom ash, as such it cannot be directly used as a fertilizer. The fly ash might be mixed in low ratios to bottom ash to prepare a suitable fertilizer mixture. The presence of oxides of alkaline metals such as calcium and potassium makes the ash alkaline. Therefore, soil pH has to be taken into account for using the ash. [119], [120]

7.2.2 Cost Estimation

The cost of the two major components, the boiler and the ORC module based on literature and some vendor claims are discussed in the forthcoming section. Based on the specific investment cost for both components, the overall cost of the ORC system with a biomass boiler is estimated. As the specific investment cost varies to a great extent because of economy of scale, the attempt is to investigate systems which are of similar scale as far as possible.

Boiler Cost

The costs of boiler depend on various factors such as degree of automation, emission control system and multi-fuel capacity. The costs from literature and both manufacturers were collected and are presented in table 7-3. The costs were standardised into euros and adjusted for inflation where necessary.

Based on the different sources, the average specific investment cost for biomass boilers was estimated to be 604 €/kW$_{th}$. For the purpose of the study, it was rounded off to 600€/kW$_{th}$. Modern combustion systems are also available in container solutions which make them very quick and easy to install.

Table 7-3 The cost associated with capacity according to source

Source	Capacity (kW)	Cost (€)	SIC (€/kW)
Biomass Boilers Sales, UK [121]	190	141,743	743.5
Wood Biomass for Energy (2004), Forest Products Laboratory [122]	300 (input)	57,600-86,400	275-412
Boiler Project at the Ketchikan [114]	300	405,000	1350
Biomass Heating Upgrade to Galena Air Base [123]	1250	450,000-625,000	360-500
TSS Consultants [124]	12000	7,891,000	585

ORC module cost

As mentioned before, biomass ORC systems below 200 kW are a newly commercialised system, hence detailed economic studies on operational plants were difficult to find.

The SIC costs of biomass ORC module based on different sources were analysed and a distribution chart was created as seen in figure 45. Detailed information on costs regarding ORC modules and projects are relatively scarce [125]. Not all sources reporting ORC costs have been considered for cost estimation. Some sources do not mention the power capacity of the system, while some other sources mention the costs in terms of €/kWh. Such estimates were not taken into consideration. The different sources based on which the price distribution figure is created are detailed in Appendix 2.

The costs for systems below 100 kW are relatively quite high at the moment, estimated to be about 2,800-5,000 €/kW. But with increased interest in small scale power generation and higher manufacturing rates, the investment costs are decreasing. It is also observed that the specific cost decreases substantially with increase in scale of system.

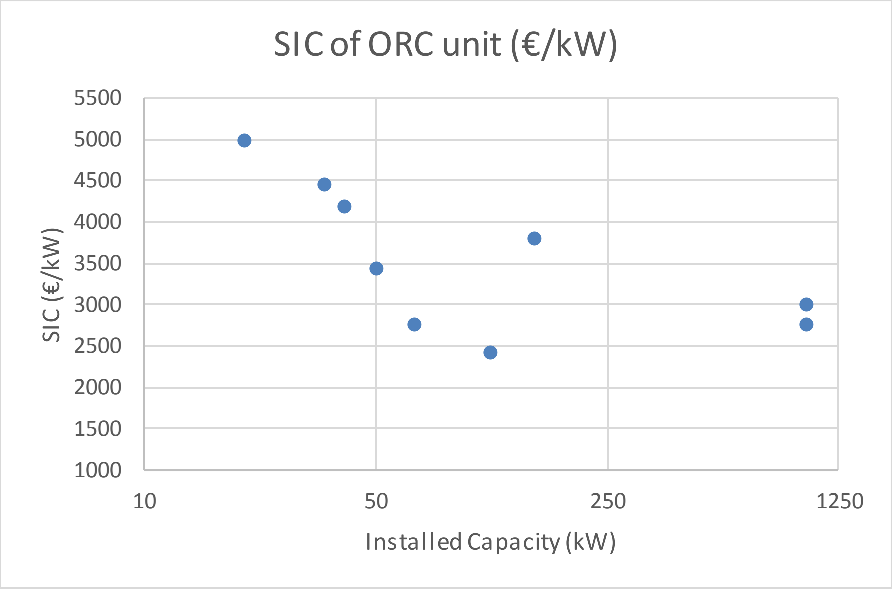


Figure 45 SIC costs of small scale ORC – distribution based on various sources [118], [125]–[127]

Based on the study of boiler systems and ORC systems, the cost of systems in capacities of 20, 50, and 100 kW_{el} were estimated. The SIC for ORC module was assumed to decrease with increasing capacity of system. The cost estimation is presented in Table 7-4.

Table 7-4 Estimated equipment cost of ORC system components based on own calculations

El Power output	**kW_{el}**	20	50	100
Estimated ORC SIC	**€/kW_{el}**	4,000	3,500	3,300
ORC Cost	**€**	80,000	175,000	330,000
Boiler thermal capacity	**kW_{th}**	250	400	850
Estimated Boiler SIC	**€/kW_{th}**	600	600	600
Boiler Cost	**€**	150,000	240,000	510,000
Estimated System Cost	**€**	230,000	415,000	840,000

7.3 Gasifier Power system

7.3.1 Technical overview and performance

Gasification process is carried out in a reactor called gasifier. Depending on the gas-solid interaction mode, gasifier reactors are divided into three primary types: fixed bed gasifiers, moving bed (or fluidized bed gasifiers) and entrained flow gasifiers [128]. One of the greatest advantages of gasification is variety in gasification technology, which has led to the availability of commercial gasifiers in a wide operation range [129].

Each type of gasifier operates with specific capacity range. The fixed bed (updraft and downdraft) type typically operates in smaller units, such as 10 kW- 10 MW. Fluidized bed type is appropriate for medium to large capacity units in between the range of 5 MW-100 MW. For very high capacity and syngas production, entrained flow is substantially used with a capacity greater than 50 MW. Different gasification technology capacity ranges are shown in figure 46.[130], [128]

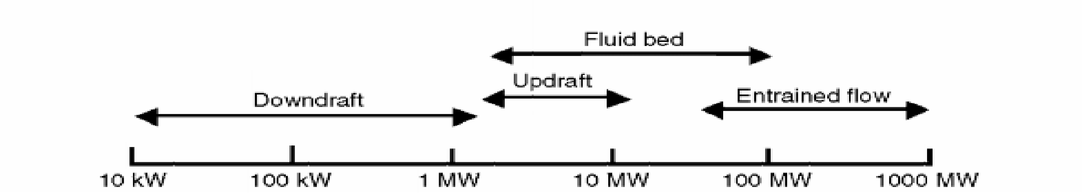


Figure 46. Capacities range of typical biomass gasifiers [128]

According to literature study, downdraft type gasifier is the most appropriate type of technology for the capacity range of the power plant in the study. In this gasifier system, the gasifying medium is introduced into the reactor from the middle part and the biomass is fed from the top of the reactor vessel. The injected medium and feedstock move co-currently downwards in downdraft gasifier. The fuel goes through different reactions as it passes along the zones of drying, pyrolysis, oxidation and reduction as seen in figure 47.

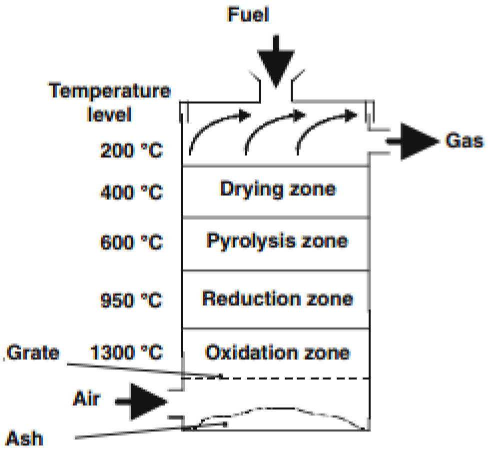


Figure 47 Zones in a downdraft gasifier [131]

The steps involved in gasification are described briefly here [131], [132]:

1. **Drying**: The feedstock loses moisture in the drying zone as the temperature of feedstock begins to increase. High moisture in the feedstock leads to high energy consumption in drying and leads to production of low calorific value and unclean gas,
2. **Pyrolysis**: With increase in temperature, the biomass begins to decompose into volatile gases, liquids and solid char.
3. **Combustion**: The incoming air leads to combustion of some of the biomass products leading to high temperatures. The high temperatures help to break down the tars in a process called as cracking. The heat produced by combustion provides the energy to drive the other processes. In a downdraft the optimization of combustion is the main method for control of tars.

4. **Reduction**: The combustion products and hot char reacts leading to formation of CO and H_2. The gases exit from the bottom of gasifier leading to coining of the name ‘downdraft’ gasifier.

The gas passes through appropriate filters and cleaning system before being fed to the engine. The typical characteristics of downdraft type gasifiers based on literature [58], [131] are as follows:

- Cold gas efficiency of about 80%. There is unconverted carbon in the ash.
- Tar content in gas is around 100mg/m^3, which is much lower compared to updraft systems. This is the greatest advantage of downdraft systems.
- Higher temperatures lead to greater affinity towards slag formation, which puts a limit of about 6% on ash content of fuel.
- The syngas is of relatively high quality which allows it to be used in engines without significant cleaning.
- It is sensitive to fuel quality. The biomass should be dry, with moisture less than 20%.

The secondary conversion technology typically paired with small gasifiers is the ICE. It is a technology which is well-proven and very widely used. They have low capital costs and good part load performance. ICEs can also be operated on multiple fuels which make the integration of a back-up fuel simpler. Although ICEs generally do not have high efficiency, alternative conversion technologies are not yet suitable for small scale application. [129]

The overall electric efficiencies of gasifier systems combined with ICEs have been relatively well studied and investigated. The performance of systems smaller than 200kW$_e$ output were investigated from different sources and are summarized in table 7-5. It is seen than even at this small scale, the average electric efficiency is 21.35%, which is relatively higher than current typical conversion technologies at this range. The total efficiency for useful heat and electricity is seen to vary considerably from system to system. The electric efficiency was assumed as 21% and the total efficiency was assumed as 61%.

Table 7-5 Compilation of biomass gasifier systems and their efficiencies based on various sources

Source	**Electric output (kW$_{el}$)**	**Electric efficiency (η_{el})**	**Total efficiency (η_{chp})**	**Fuel**
Ahrenfeldt et al. [133]	18.55	25.10%	93%	wood chips
Centre Tecnològic Forestal de Catalunya [134]	20	25%	74%	forest residue
Lee, Balu and Chung. [135]	28	20.60%		red oak
Lee, Balu and Chung. [135]	28	23%		pine wood
Warren, Poulter and Parfitt. [136]	30	20%	60%	wood chips
Assanee & Boonwan. [137]	100	17.72%		wood chips
Dasappa et al.[138]	120	18%	81%	wood chips
All Power Labs PP 20 [139]	18	20%	35%	Various biomass
Burkhardt Wood Gasifier V 4.50 [140]	50	25%	80%	Standardised wood pellets
Average electric efficiency		**21.35%**		

The biomass consumption is reported to vary from 0.8kg/kWh to 1.2 kg/kWh of electric energy [139], [140]. For the purpose of calculations, a value of 1.4kg/kWh was assumed. The performance calculations were performed for the gasifier power plant for sizes of 20 kW_{el}, 50kW_{el} and 100kW_{el} for comparison purposes and are summarized in table 7-6.

Table 7-6 Performance of gasifier unit based on own calculations

Electric Output, P_{el}	kW_{el}	20	50	100
Electric efficiency, η_{el}		21%	21%	21%
CHP efficiency, η_{chp}		61%	61%	61%
Thermal output, P_{th}	kW_{th}	37.6	94	188.1
Biomass Power Input, Q_b	kW	95	238	476
Biomass flow rate, $\dot{m}$	Kg/hour	24	60	120

Waste products

The main solid by-products from a gasifier system are bio-char and ash and are produced in the range of 10-15% according to studies. It is suggested by some gasifier manufacturers that the char can be used as a cooking fuel, char briquettes and as a soil supplement [141]. The heavier bottom ash also has the potential of being used as a fertilizer as it contains calcium and potassium oxides. A study under Makerere University in Uganda has observed that plants show improved growth due to bio-char [142]. The tars removed in cooling water was found to be potentially toxic. Hence, care has to be taken in disposing of the tars and fly ash to prevent contamination of surrounding areas.

7.3.2 Cost estimation

Simple manually operated gasifiers have been used in India for many years. Although majority of these systems lack any degree of automation and use wet gas cleaning systems. The stricter regulations in European countries has led to evolution of fully automated systems with elaborate gas cleaning. Most of these systems operate on standard pellets or wood chips in Europe. Hence, there are both advanced systems with higher system costs, and basic simple setups with low initial costs. [131]

Studies on financial evaluation of gasifier systems in the scale below 100kW of electric output were investigated to identify the costs associated with them. Costs available from manufacturers of gasifier power plants were also taken into account. The costs from the respective sources are detailed in Appendix 3. The specific investment cost per kilowatt of electric output was calculated from these references. From this data, a plot between SIC and plant electric capapcity was created as shown in figure 48. It was observed that the SIC for gasifier-generator assembly lies in the range between 1,200 €/kW to 3,400 €/kW. The average value of SIC was calculated to be 1,814 €/kW and this value was used for further calculations regarding cost estimation.

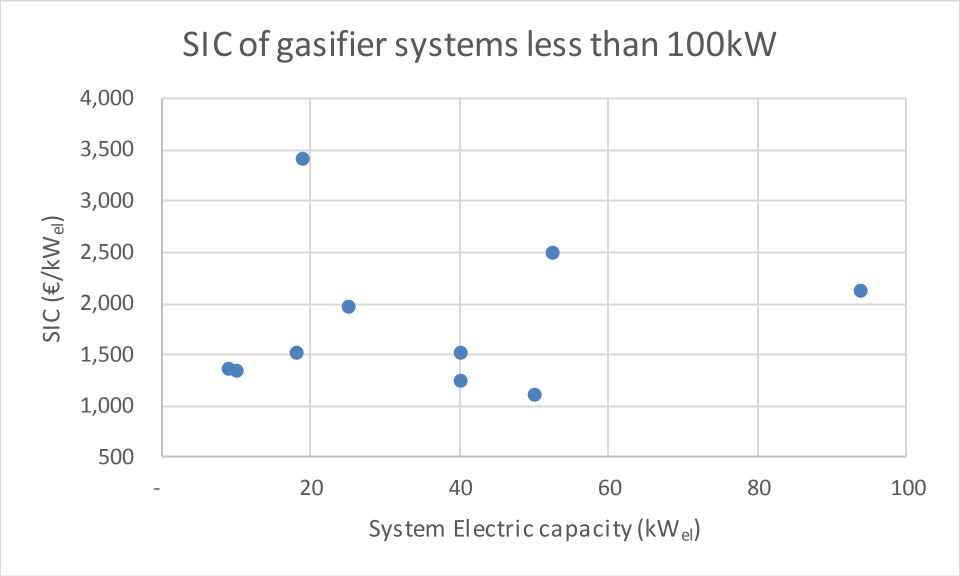


Figure 48 Representation of SIC for Biomass gasifier-ICE power plant [143]–[148]

The cost of the CHP module for heat recovery from flue gases was assumed be 20% of the combined gasifier and ICE module. The calculations were performed and the obtained estimated costs are summarized in table 7-7.

Table 7-7 The calculated equipment cost for Gasifier-ICE CHP system

Electric Output (kW_{el})	20	50	100
SIC for Gasifier ICE power system (€/kW_{el})	1,814	1,814	1,814
Equipment cost			
Gasifier ICE power system (€)	36,279	90,698	181,395
CHP Module (€)	7,256	18,140	36,279
Estimated net equipment cost (€)	43,535	108,837	217,674

7.4 Biomass processing and briquetting plant

The main purpose of biomass processing is to improve feedstock characteristics for further utilization in briquette production and power generation. In the first step, the biomass is fed into a shredder for size reduction. It is then stored in a drying storage chamber where heat from the power plant is circulated to accelerate the drying process. The dried and shredded biomass is finally fed to briquette press and power plant. The process flow is illustrated through figure 49.

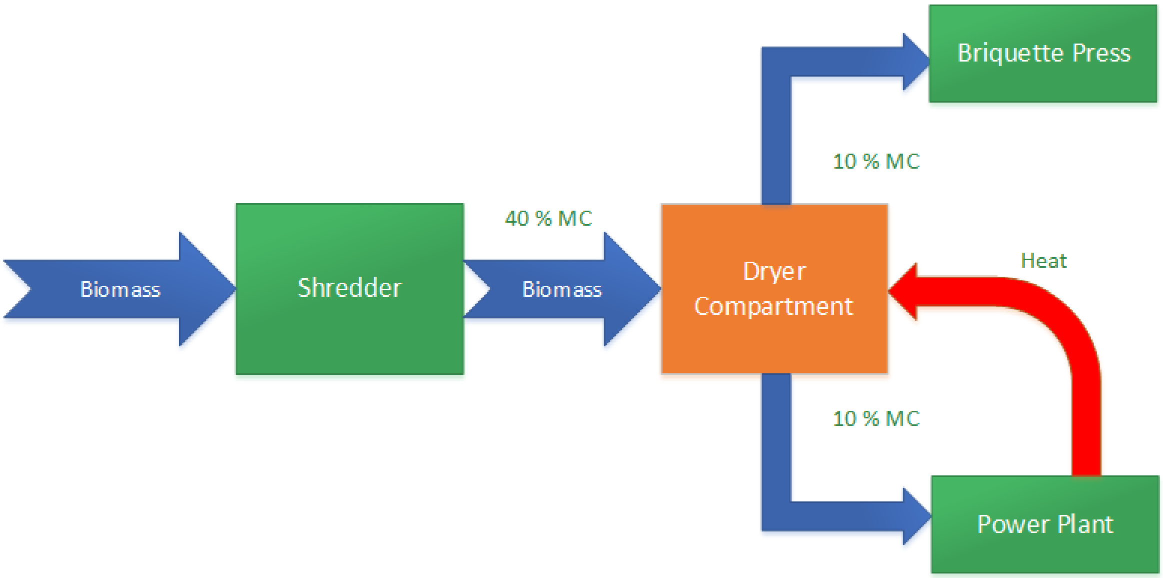


Figure 49 Process flow diagram of biomass processing

7.4.1 Shredder

The size-reduction of biomass is an important pre-processing step in biomass utilization for energy, pulp and paper and for bio-chemical industries. The size reduction is by use of a shredder or grinder which mechanically breaks the biomass being fed into smaller pieces. The desired size of biomass depends on its method of utilization. There are various kinds of machines to attain the requisite particle size. There are three prevalent machinery types based on the grinding mechanism [149], [150] :

- Chippers – The grinding takes place by cutting of the biomass and fairly similar sized particles are produced. The cutting device are knives attached to a heavy rotating disc or drums.
- Hammer mills – Hammer mills have blunt hammers mounted on a rotating drum, which crush the incoming biomass. The particles are irregular in shape and size. This type of machinery is more tolerant to sand and stones, which can cause sharp blades of chippers to blunt. The different mechanism of operation of chipper and hammer mill is illustrated in figure 50.
- Combination type – The third group of machinery combines both features pf chippers and hammer mills. They have knives mounted on rotors, but the knives are not as sharp as chippers. They can grind and shred a wide variety of materials at a high feed rate, but are more expensive.

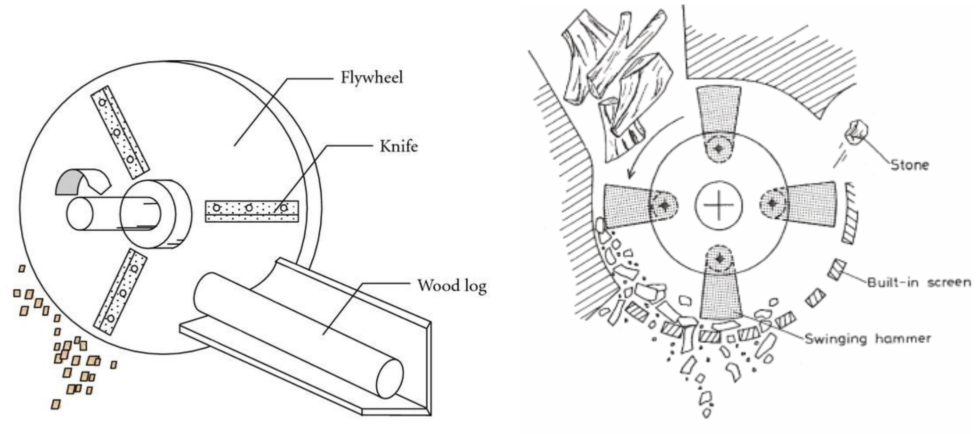


Figure 50 Working principle of chipper (left) and hammer mill (right) [149]

The hammer mill type is well-suited for producing particles for briquetting as irregular sizes help in improved binding under pressure.

To meet the daily biomass requirement, the requisite shredder capacity is 400-500 kg/hour. The cost of such equipment was obtained by quotations from two manufacturers. The quotations were obtained through private communication by email, and the names of the manufacturers have been kept confidential. Manufacturer A provides a more robust machine with advanced technology capable of shredding a wide variety and size of material. This is reflected in a higher cost price for the equipment. Manufacturer B offers a hammer mill customised for shredding small biomass less than 30mm in diameter and are equipped with a cyclone separator. The models offered by Manufacturer B are significantly lower in cost. The shredders also have screens to filter particles of correct size. Another shredder available from an online power equipment seller is also included as a reference. The costs associated with the models of shredder are shown in Table 7-8. The average cost of shredder from these references was calculated to be € 5,292. This was taken as the cost of the shredder for further cost estimation.

Table 7-8 Cost of shredder as quoted by source

Source	Cost(€)
Manufacturer A Model I	14,900
Manufacturer B Model I	833
Manufacturer B Model II	936
DR Power Equipment [151]	4,500
Average	5,292

7.4.2 Briquette Press

The briquette press applies high pressure to the shredded and dried biomass feedstock to produce dense briquettes. The biomass particles are closer by a gradually increasing pressure gradient. The shearing forces and friction within the biomass, and with the walls causes an increase in temperature. Some briquette presses also incorporate a heating element which helps in smooth extrusion of briquette.

The assumed output of the briquette press is 200 kg/hour. The cost of briquette press depends on a great extent on the country of application. The estimated cost of a briquette press varies from approximately 7,000 € - 14,000 € in India to almost 34,000 € in Europe. The names of the manufacturers from which costs have been obtained by private communication have been kept confidential. Manufacturers in China and India quote lower prices for briquette presses as the production volumes are high and degree of automation is generally low. Stringent rules and regulations drives up the cost of equipment in developed countries. The cost of briquette press from literary sources and equipment manufacturers were computed and are presented in Table 7-9. Based on all these sources, the average cost of a briquette press is calculated to be 16,694 €, which is taken as the cost of the briquette press for further economic analysis.

Table 7-9 Cost of Briquette press according to different references

Source	Cost (€)
Ashden [103]	7,079
The briquetting of agricultural wastes for fuel [99]	17,510
FAO biomass briquetting and practices [97]	14,141
Manufacturer A Model I	33,480
Manufacturer A Model II	33,980
Manufacturer B Model I	5,985
Manufacturer B Model II	4,680
Average	16,694

7.4.3 Drying

The drying of biomass is perhaps the most important step in improving the quality of feedstock as a fuel. The moisture content and calorific value of fuels are inversely related to each other [152]. During combustion process, the latent heat for evaporation of the water contained is provided at expense of overall heat released by combustion. This leads to higher temperatures during combustion which promotes better heat transfer to working fluid and better combustion of feedstock. More complete combustion leads to reduced emissions of CO and tars. Thus, dry fuels have much better combustion characteristics than wet fuels. Moreover, wet fuels promote degradation by providing favourable conditions for fungal growth. The briquetting of the feedstock also requires moisture levels of 10-15% as discussed in previous sections.

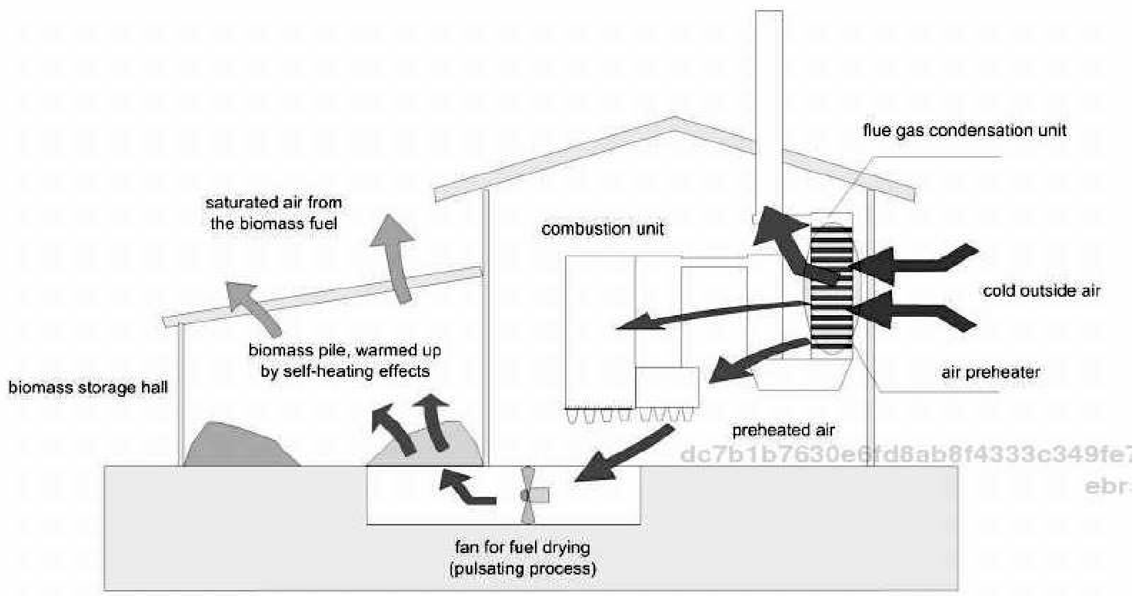
There are two broad classifications of drying – passive drying and active drying. Passive drying relies on ambient temperatures and air flow for drying of biomass. While in active drying assisted flow of air is used to accelerate the drying process. Active drying is more energy intensive, but much faster. Proper optimization is required in active drying so that energy requirement is balanced with the improvement in biomass quality. [153]

The moisture level of green biomass is about 60%. The moisture during collection or harvest depends on a great extent on external factors like weather conditions. By employing proper methods of field storage during collection of biomass, it is possible to dry biomass to about 30% moisture content effectively. [152]

In the system model, it is assumed that low-cost methods are employed when storing the collected biomass. This reduces the moisture content of the green biomass to 40%, which is delivered to the plant for further processing. The biomass received at the plant undergoes size reduction before the active drying stage. The breakdown of large pieces to smaller ones increase the surface area of the particles exponentially. The increased surface area aides in faster drying of the biomass, but can also provide surfaces for mould to grow. For this reason, it was chosen to shred the biomass before the active drying to reduce the moisture content to 10%. [152]

Converted trailers and buildings with fans to circulate air are often used for small scale drying. Specialised drying equipment are generally used for large industrial scale operations which have a high energy and infrastructure demand. The suggested system for drying is a purpose-built drying house where the heat from CHP power plant would be utilised to aid the drying of the feedstock. [153] Figure 51 pictorially describes such a system where heat from flue gas condensation is utilised to dry biomass piles. There are three major requirements for a drying system:

- A heat source
- Method to remove evaporated water through proper air circulation
- Agitation to expose new material and for uniform drying



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ebr

Figure 51 Biomass drying using heat from flue gas condensation [152]

The details on small to medium scale drying are not easily available. Studies by Francescato et al.[154] report drying of chips to 30% moisture in 2-3 days using heated air at 80˚C, but energy or financial costs are not provided. In trials in Norway, chips were dried from 66-52% to 9.6-6.9% in about 550 hours by using waste heat and a 4kW fan [155]. A review of studies on various methods of drying suggests that green biomass can be dried to around 25-30% reasonably rapidly in 2-3 days. Drying proceeds in a linear rate in the beginning and then deaccelerates as internal moisture evaporation requires more time. The further decrease of moisture below 20% necessitates longer drying times of about 6 days or higher energy input [153]. Hence, a drying time of 10 days is assumed in the drying chamber to ensure moisture reduction to 10% in our case.

To ensure uniform drying, stirring of the biomass is required. This can be achieved by using stirring devices like a sweep auger. It also enables for greater depth of pile of about 2-2.5 m. Recirculating bin dryers are such a suitable type of technology. The sweep auger is activated by temperature or moisture sensors to mix the biomass until target conditions are satisfied. Figure 52 illustrates a recirculating bin dryer used for high temperature drying. Such technologies are widely used in drying of grains.[156]

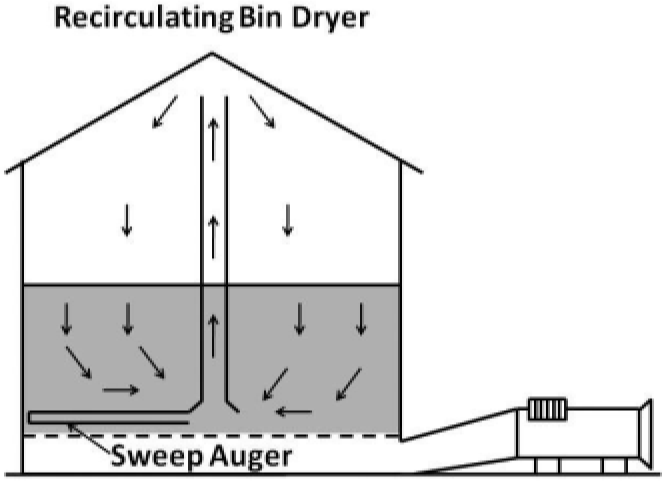

Figure 52 A bin dryer with recirculation by a sweep auger [156]

For drying of shredded biomass, the proposed solution is construction of a storage bin through which fans will circulate heated air. A mechanism is provided to ensure adequate mixing of the biomass contained within.

Table 7-10 Specifications for suggested grain dryer storage

Buffer capacity (days)	10
Pile height (m)	2
Floor Area (m^2)	100
Maximum Capacity (tons)	50
Average moisture content of incoming biomass	40%
Average moisture content of outgoing biomass	10%

7.4.3.1 Cost estimation of biomass drying

According to a report by La Tourette et al. the approximate cost of construction of storage shed for biomass is \$ 9/ft^2, which is equivalent to € 90/m^2. The cost of the dryer storage bin is calculated on the basis of this value and the selected floor area. The costs for the blower mechanism is assumed to be 20% of the combined equipment cost of briquette press and biomass shredder, which is calculated to be €4,397. The summation of the cost estimation is presented in Table 7-11.

Table 7-11 Cost calculation of dryer storage

Cost per unit area of storage(€/m^2)	90
Floor area of dryer storage (m^2)	100
Cost of storage construction (m^2)	9,000
Cost of blower mechanism (€)	4,397

7.5 Transportation of feed

7.5.1 Logistics Model

To estimate the costs involved with transportation of biomass to the plant, a simplified logistics model is considered. The model will be explained in this section. The distribution of plantation in a 30 km radius of San Carlos (the red pin) are visualised in figure 53 with the image of a tree representing a plantation. As discussed before, there are about 1,000 plantations according to GIS data from ArBolivia. The shading in the image is provided to visualise the distribution in a 10 km and 20 km radius as well. It can be clearly seen that the distribution of plantations is concentrated in certain areas. There are few plantations in the northern regions. It will be economical to collect residues from areas where the concentration of plantations is higher compared to isolated plantations.

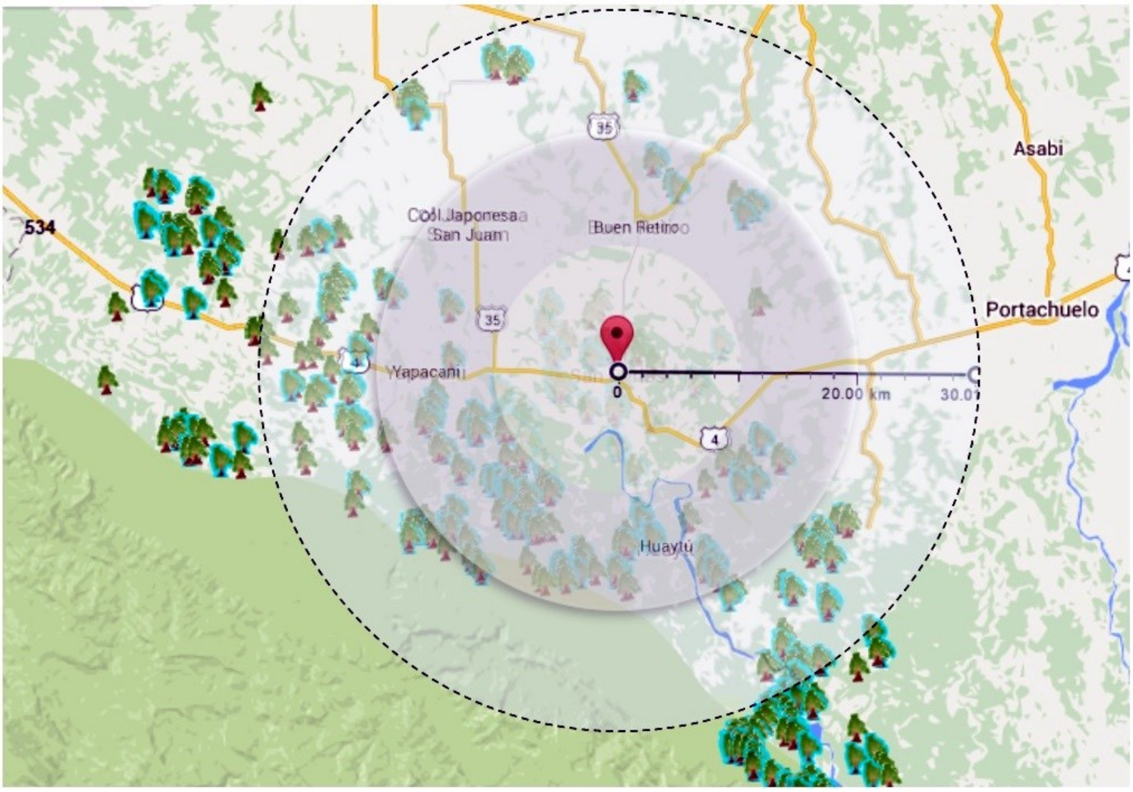

Figure 53 Segregation of the area in 10 km, 20 km, and 30 km circles.

As discussed in section 2.5, there are more than 1,000 plantations in an area of 30 km radius around San Carlos. Based on the distribution map, the region is divided into sectors of 5 km radii each as shown in figure 54. The black circle represents the central sector to which the biomass from the surrounding sectors (green) are transported to. It is assumed that biomass is collected from 50 suitable plantations within each sector. Each sector is assumed to have a local collection centre where the biomass from the plantations within the sector are transported and stored for further movement to the plant. Trucks are used to transport the collected biomass to the plant at regular intervals. This model can be visualised through figure 55. The internal transportation within the sector is not taken into consideration for calculation as the distance of plantations from the local distribution centre varies greatly and the volumes of material transported are small. For accurate and precise logistics, ground studies would have to be conducted.

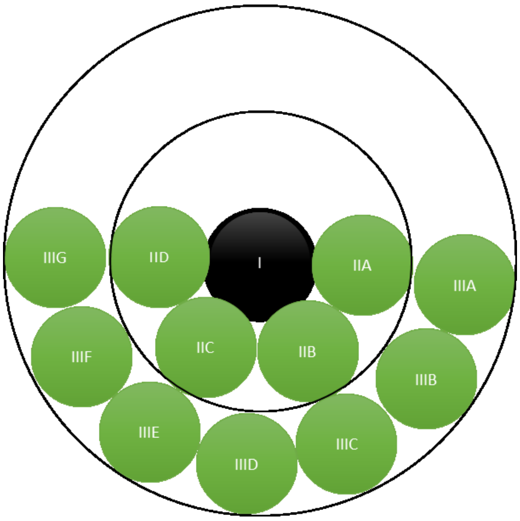

Figure 54 The division of the area into sectors of 5 km radii each

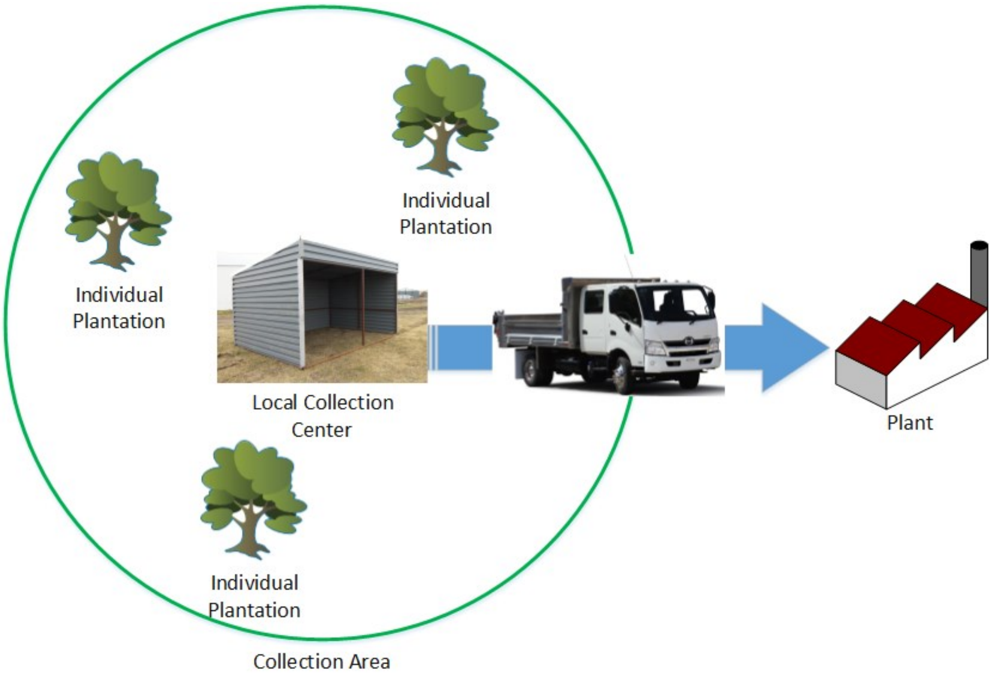

Figure 55 The simplified logistics model

7.5.2 Costs associated with transportation

Commonly available medium duty trucks are assumed to be used to transport the biomass from local collection centre to the plant. The trucks are considered to be of Class 5 category according to gross vehicle weight rating system used in the US. The typical specifications associated with a truck of this category are presented in table 7-12, along with the fuel cost per unit distance. [152]–[155]

Table 7-12 Specifications of a Class 5 Truck and fuel cost [157]–[160]

Gross weight range (kg)	7,258-8,845
Empty weight range (kg)	4,309-4,900
Typical payload capacity (kg)	3,946
Typical Fuel economy (km/l)	3.5
Cost of fuel in Bolivia (€/l)	0.49
Fuel cost per unit distance (€/km)	0.14

In previous sections, it has been described that the annual yield of forest residue is 4 tons/hectare at 30% moisture content and the average plantation size is one hectare in size. This is equivalent to an annual biomass yield of 5.33 tons per plantation. It is calculated that for each sector, the equivalent daily biomass yield is 752 kg at 40% MC. This means that in about 5 days, enough biomass is collected to fill a Class 5 truck. These results are presented in table 7-13.

Table 7-13 Forest residue collection estimation

Annual biomass yield per plantation at 40% MC	5.33 tons
Daily biomass yield per plantation at 40% MC	15 kg
Number of plantations per sector	50
Daily biomass yield per sector at 40% MC	752 kg
Load capacity of Class 5 truck	3,900 kg
Days needed to fill one truck	5
Number of trips in one year	60

From the previous sections, it is clear that the biomass feed requirement for the ORC operated system is higher compared to the gasifier operated system. The biomass feed needed for ORC and gasification based system are 4,225 kg and 3,511 kg respectively. To meet this need, the ORC system requires biomass from 6 sectors and the gasification system requires feed from 5 sectors. The straight distance between the local centre and power plant is multiplied by a factor of 1.5 to simulate actual travelled distance. The calculations provide yearly fuel costs for transportation as € 1,997 for ORC based system and € 1,498 for gasifier based system. The breakdown of fuel costs is shown in table 7-14.

Table 7-14 Calculated annual fuel cost for transportation of biomass feed

Sector	Trip distance (km)	Fuel cost per unit distance (€/km)	No of trips per year	Annual fuel cost for each sector (€)
I	0	0.14	60	0
IIA	45	0.14	60	375
IIB	45	0.14	60	375
IIC	45	0.14	60	375
IID	45	0.14	60	375
IIIA	60	0.14	60	499

7.6 Economic Analysis

The economic analysis enables us to determine the feasibility of carrying out a project on the basis of financial terms. It provides us with a comparison between competing technologies to help decide which alternative is more economically feasible.

7.6.1 Total Investment Cost

The total investment cost (TIC) is a fixed one-time cost which consists of direct cost (DC), indirect cost (IC) and other outlays. The costs for other outlays are not taken into account in the calculations. The direct cost takes into account the costs involved with resources such as equipment, materials, labour involved in the set-up of the facility. While the indirect costs account for the various services like engineering, supervision and contactors fees.

$$TCI = DC + IC$$

The major difference between the two alternatives being considered in this study is in the biomass conversion technology. One operates on a gasifier-ICE setup, while the other utilizes a boiler-ORC turbine combination. Besides the power block, the rest of the set-up involving the biomass processing, briquetting plant, storage and other facilities are mutual for both systems. The ORC system is denoted as Project A and the gasifier powered system as Project B.

The most accurate methods for estimating the costs for the equipment, installation, construction and services required for set-up of the plant is through quotations from suppliers, manufacturers and service providers. As such quotations are not easily available and require significant time and effort to prepare detailed costs, the various associated costs are estimated as percentages of equipment cost or direct costs as suggested by literature and other references. As both systems are similar to each other except for the purchased equipment, the assumptions for the dependant costs are taken in a manner to obtain equivalent values. Due to significantly higher equipment cost of ORC system, using the same assumption for both systems would lead to very high costs for the ORC system.

DIRECT COSTS (DC)

The purchased equipment cost (PEC) takes into account the costs for main equipment consisting of the ORC or gasifier power block, biomass shredder, briquette press and drying system. The estimation of the individual equipment has already been discussed in the previous sections. The PEC for both the systems are presented in Table 7-15.

Table 7-15 Purchased equipment cost for the two systems

System A		**System B**	
Equipment	Cost	Equipment	Cost
ORC power system	420,000	Gasifier power system	108,837
Shredder	5,292	Shredder	5,292
Briquette press	16,694	Briquette press	16,694
Drying System	4,397	Drying System	4,397
Total PEC	446,383	**Total PEC**	135,220

The equipment installation costs accounts for the transportation, costs of handling, construction and other expenses related to setting up of the equipment and establishing necessary connections.[161]

The cost for Piping, instrumentation and control includes the costs for the electronics, control, and piping of the plant. With higher degree of automation, the instrumentation and control costs increase. Most modern systems have some degree of automation and electronic processing pre-installed in the system. As such, with further development these costs are decreasing. Electrical equipment and material cost represent the cost of equipment, materials and labour of the electrical lines, switch gears, emergency power supply, lighting and other electrical set-up of the whole system. [161]

The systems being modelled in our case are relatively of small generation capacity. Moreover, from the specifications of most of the equipment considered, it is seen that they are designed for easy installation and have a degree of automation incorporated. This results in lower associated costs with the equipment.

The offsite costs (OFSC) include the cost for land, civil works and service (or auxiliary) facilities. The cost of land in the project region was reported to be 1,600-2,500 € per hectare [162]. The maximum amount of land required for setting up the plant for both systems was estimated to be half a hectare. Taking the higher land value for the purpose of calculation, the cost of land was found to be 1,250 €.

The major civil and structural works are the construction of the housing for the power module, shredding and briquetting machines and two large storages. The two storage systems are both assumed to have a floor area of 100m^2. Using the value of 90€/m^2 of storage as reported in [163], the construction cost for both storage units is € 18,000. The rest of the construction and civil works costs are assumed as a percentage of PEC.

INDIRECT COST (IC)

The indirect costs can also be projected as percentages of the purchased equipment cost or capital cost. The indirect cost comprises the cost for engineering and supervision, construction costs and contingencies. The engineering and supervision cost is used to estimate the fees paid for engineering of plant, supervision of activities, administration, travel and consultation services. The construction costs include the expenses for facilities, operation and personnel at the construction site, as well as the contractor's profit. The contingencies are used to account for unexpected events like bad weather, work stoppage, price change, and change in design. Thus it is used to attach a monetary value to uncertainties that may arise. [161]

The calculated values for direct cost, indirect cost and total investment cost for both systems A and B are represented in table 7-16. The estimates used to calculate the individual costs for either system are also indicated.

Table 7-16 The breakdown of the TIC based on calculation and assumptions

	System A		System B	
Cost element		Cost (€)		Cost (€)
Onsite Costs (ONSC)				
Purchased Equipment Cost (PEC)		446,383		135,220
Equipment Installation	10% of PEC	44,638	15% of PEC	20,283
Piping, Instrumentation and controls	10% of PEC	35,711	10% of PEC	13,522
Electrical materials and equipment	5% of PEC	22,319	10% of PEC	13,522
Offsite Costs(OFSC)				
Land		1,250		1,250
Civil, structural and architectural work	Storage	18,000	Storage	18,000
	15% of PEC	66,957	30% of PEC	40,566
Service facilities	3% of PEC	13,391	8% of PEC	10,818
Direct Costs (DC)		619,685		253,180
Engineering and Supervision	5% of DC	30,984	10% of DC	25,318
Construction costs	3% of DC	18,591	5% of DC	12,659
Contingencies	10% of sum of engineering and construction cost	4,957	10% of sum of engineering and construction cost	3,798
Indirect Costs (IC)		54,532		41,775
Total Investment Cost (TIC)		674,217		294,995

7.6.2 Annual recurring costs

The annually recurring costs represents the yearly spending on fuel, maintenance, transportation and labour involved with the project. These costs are incurred every year due to operation of the plant.

The annual operation and maintenance cost (C_{om}) comprises the value of labour (C_{labour}), purchase of biomass ($C_{biomass}$), transportation of feed ($C_{transport}$) and other miscellaneous requirements (C_{misc}) as represented by the equation below.[161]

$$O\&M\ Cost\ (C_{om}) = C_{labor} + C_{biomass} + C_{transport} + C_{misc}$$

Regular maintenance of the equipment according to the manufacturer's instructions is essential to prolong longevity and to ensure there are minimal breakdowns and replacement of parts. The labour and miscellaneous cost are considered as fixed costs, which stay constant irrespective of plant output. The biomass required and its transportation depends on the output of the plant, hence the associated costs are variable costs.

The assumptions used to calculate these costs are:

- Based on studies and recommendations for a plant of this size, it is assumed that maximum of 3 workers are required for the operation of the plant. The minimum monthly wage in Bolivia has been set as 1,805 Bolivianos as of 2016 [164], which is equivalent to about € 237. The monthly wage of the employed labour is assumed to be € 300 for the purpose of calculations. The workers are mainly required for the briquette production and biomass processing units.
- The cost of biomass is assumed to be € 6 per ton. This incentive will encourage the plantation owners to collect the residues for the plant. At the same time, it will prove them additional income to these marginal groups.
- The miscellaneous additional costs were estimated as 3% of PEC for the gasifier operated system and 1% of PEC for the ORC system. From literature sources, it has been established that ORC systems have significantly lower operational costs compared to other systems, hence the lower assumption.

Based on these assumptions, the annual recurring costs for both systems are calculated, and presented in table 7-17.

Table 7-17 Annual operation and maintenance cost

Annual Costs		System A	System B
Labour cost (€/year)	C_{labour}	10,800	10,800
Biomass purchase cost (€/year)	$C_{biomass}$	7,866	6,536
Transportation cost (€/year)	$C_{transport}$	1,997	1,498
Miscellaneous/ other costs (€/year)	C_{misc}	4,464	4,057
Total (€/year)	C_{om}	25,127	22,891

7.6.3 Annual Revenues

There are three products generated which can be are sold to generate revenues – electricity, heat and briquettes. At present the electricity tariff varies from 0.08 €/kWh in most areas, to a high of 0.21 €/kWh in some isolated systems [13], [165]. Based on the values for electricity tariff throughout the country, a value of 0.10 €/kWh was selected for estimating revenue from electricity sale which are summarized in table 7-18.

Table 7-18 Estimated annual revenue from sale of electricity

	Cost of Electricity (€/kWh)	**Annual units of electricity sold (kWh)**	**Revenue from electricity (€)**
System A	0.10	69,217	6,922
System B	0.10	69,217	6,922

The cost of briquettes globally varies from about € 80-100 per ton in India [103], [105] to € 133-340 per ton in the EU [166]. The briquette market in Bolivia is in its developmental stage and there are a few manufacturers. Eco-K Internacional SRL from Beni, Bolivia sells briquettes in bags of about 3kg in the market [107]. These bags fetch a price of about 15 BOB, which is equivalent to € 644 per ton of briquettes. The actual bulk selling price for briquettes would be much lower. A study on sawdust briquette factory in Paraguay suggested a selling price of € 272 per ton of briquettes, which can be considered as a guide for briquette prices in Bolivia as the economic and environmental conditions are similar in these neighbouring countries. Two briquette selling prices were considered for revenue estimation to understand the effect of price variability and to reflect the uncertainty in selling prices. The low price was selected as € 100 per ton, and the high price as € 250 per ton. The revenue generated from briquette sale are represented in table 7-19 below. It is seen that the briquettes contribute the largest share of income generation. The selection of a low and high value of briquette selling price enables to visualize the sensitivity of the economic feasibility of the projects. This leads to creation of two scenarios – a low revenue scenario and a high revenue scenario.

Table 7-19 Estimated annual revenue from sale of briquettes

	Selling Price of Briquettes (€/ton)		**Annual Briquette Production (tons)**	**Revenue from Briquettes (€)**	
	Low	High		Low	High
System A	100	250	496	49,640	124,100
System B			455	45,451	113,629

The cost estimation of the heat revenue is difficult as there is no district heating system in Bolivia and references establishing the cost of heat are not available readily. According to IPCC report on cost and performance parameters for renewable energy, the heat revenue from CHP ORC plants is about 0.07€/kWh and for CHP gasification plants is 0.01-0.04 €/kWh [94]. The average cost of district heating in Sweden is about 0.07€/kWh [167]. In the previous sections it has been established that only the ORC system produces enough heat which can be sold to generate income. Bolivia is a developing country and the domestic heating demand in the region of operation is not well established, a selling price of 0.03

€/kWh was assumed for calculation of revenue. The table 7-20 shows the calculated revenue from sale of the heat based on the assumptions.

Table 7-20 Calculated revenue earned from heat sales

	Annual Heat available (MWh)	Cost of heat (€/kWh)	Revenue from heat (€)
System A	425	0.03	12,737
System B	0	-	0

The gross annual revenue generated from sale of electricity, heat and briquettes for both the systems are summarized in table 7-21. It is evident that the greatest impact on yearly revenues is from the selling price of briquettes, and thus it will play a significant role in feasibility of the project.

Table 7-21 Total annual revenue summarized for both systems

	Revenue from electricity (€)	Revenue from heat (€)	Revenue from Briquettes (€)		Total revenue (€)	
			Low	High	Low	High
System A	6,922	12,737	49,640	124,100	69,298	143,758
System B	6,922	0	45,451	113,629	52,373	120,550

Net Cash Flow

The annual net cash flow (C_t) is calculated by subtracting the annual costs (C_c) and tax (T) from the annual revenues (C_r). The annual tax is computed by assuming a taxation rate (r) of 20% and depreciation (D) of the plant. Depreciation is an accounting method to attach a monetary value to the wear and tear of the plant. The depreciation is calculated as the total investment cost (C_o) divided by the useful life of the plant (n). The equations describing these relations are shown below. [161], [168]

$$Depreciation, D = \frac{C_o}{n}$$

$$Annual\ Tax, T = r \times (C_r - D)$$

$$Net\ Cash\ Flow, C_t = C_r - T - C_c$$

The net cash flow for both systems, based on the assumptions and equations are calculated and the results are presented in table 7-22. The net cash flow for System A operating on ORC cycle is higher as the associated revenue is higher due to greater briquette production and extra heat available for sale.

Table 7-22 Calculated net cash flow for the systems

	Revenue Before Tax (€)		Annual costs (€)	Depreciation (€)	Tax (€)		Net Cash flow (€)	
	Low	High			Low	High	Low	High
System A	69,298	143,758	25,127	33,711	7,118	22,010	37,054	111,514
System B	52,373	120,550	22,891	14,748	7,525	21,161	21,957	90,135

7.6.4 Economic Feasibility

The selection of two selling prices of the briquettes gives rise to a low revenue model and a high revenue model. In the low scenario, the discounted payback period is 38.8 years for the ORC operated system and 21.1 years for the gasifier operated system. The NPV values are also negative for both systems in the low scenario. The IRR value is negative in case of system A, and below the discount rate for system B. Hence, the systems are not economically feasible at the current revenue model at low briquette selling price.

In the high revenue model, the discounted payback time is calculated as 7.2 years for system A and 3.6 years for system B. The NPV was positive for both systems, but higher for system B. The IRR also improves significantly in this scenario, with the IRR for System B being almost double. Thus, in the high revenue model, both systems are economically feasible with promising values for the economic indicators. System B indicates higher profitability compared to system A, which makes the gasifier operated system more favourable. The results of the economic feasibility analysis are summarized in table 7-23.

Table 7-23 Summarised values of feasibility indicators for both systems

	Discounted Payback Period (years)		NPV (€)		IRR	
	Low	High	Low	High	Low	High
System A	38.8	7.2	-192,220	776,351	-2%	14%
System B	21.1	3.6	-9,334	877,510	4%	30%

7.7 Social and Environmental impacts

This section discusses the social and environmental impacts of the proposed project. The main focus is on identification of factors which contribute to poverty reduction through energy based on research and case studies.

The ENPOGEN project in China, Indonesia and Sri Lanka have inferred that energy access has a pivotal role in income generation and poverty alleviation when supporting conditions are present [169]. Access to electricity alone is insufficient in poverty reduction. Focus on income generating and asset building is required. It is suggested that microcredit options are helpful in enabling the communities to utilise the energy access for income generation activities. This is especially true for improvement of income and creation of employment among poorer groups.

The development of rural economies is expected to stimulate growth of existing sectors and also emergence of new enterprises as well [170]. This is a cyclic process, as the energy access can stimulate economic growth, leading to increased wealth and demand, which in turn leads to further increase in energy demand. Diversification of income generation is associated with diversification in energy services. The influence of electricity access on agriculture was in the replacement of manual labour for processing and water pumping. In agricultural areas new technologies were readily implemented on a community scale and households have reported increase in incomes. Women also seem to have more time for relaxation and other activities.[46]

Small enterprises targeting local markets can cooperate in procuring and sharing of appliances as a method of sharing expenses. Appliances for carpentry, metalworks, cooling facilities for storage of perishables are some examples of appliances which allow shared use [169]. Studies in several locations by Kooijman-van Dijk and Clancy [46] have shown that that the major effect of electricity has been towards the improvement of working conditions. The use of electric appliances leads to lower noise, lower pollution, and better time and work management. Work can also be performed at night due to lighting and establishments have longer opening hours.

The effect of energy access in remote and sparsely populated regions was found to be lower as the opportunities to utilize power for diverse activities is low. The main benefit in such situations is from lighting [169]. The project area in our case has the advantage of being situated close to Santa Cruz, which is the most populous city in Bolivia and is also close to major roads. There are also other smaller towns in the proximity which means there is a potential market base for goods and services. Along with proximity to markets and roads, the location close to exploitable resources like agricultural land, tourism is also significant [46].

The project is estimated to generate direct employment for 3 workers, while several indirect opportunities for employment are created in the biomass supply chain and supply of goods and services. This is significant change for small communities in which employment is highly seasonal and agriculture based. Many people venture out to nearby larger towns and cities in search of employment, Availability of stable power together with financing options can stimulate entrepreneurial enterprises. The sale of biomass residues also supplements the income of the plantation owners. Evidence also suggests that electricity access have strong impact on non-financial facets of poverty through development of products and services [46]. Improvements in facilities like communication, healthcare and recreational activities are also a result of electricity access. Thus, there is expected overall development when the focus is on economic growth by taking into account the factors like market development and financing opportunities along with energy access.

As mentioned in earlier sections the by-products also have potential value for utilisation. The ash can be distributed among the plantation owners as a low-value fertiliser which will replace lost nutrients from the soil and lead to increased yields. The bio-char can also be sold as a low-cost fuel in rural markets. At present there is a lot of interest on bio-char as a soil conditioner. It could also be further processed and sold to urban markets as a high value product, which create more jobs and income.

There are three main products from the system – electricity, heat and briquettes. While ash and char in varying quantities are produced according to the system selected. The direct savings in GHG emissions is from the electricity generated by the system as about 68% of the electricity in Bolivia is generated from fossil fuels. The emissions for the annual electricity output as provided by biomass and from the grid is calculated. Life-cycle GHG emission values provided in Annex II of IPCC Special report on Renewable Energy Sources and Climate Change Mitigation (SRREN)[94] for electricity generation from different energy sources are used for calculation purposes. Life-cycle emissions take into account the global warming potential from the different steps and processes involved in the generation of per unit of electricity from a source. Although sources like biomass and nuclear are assumed to be carbon neutral while energy production, there are emissions from infrastructure, transportation and other processes. The values from the 50th percentile obtained from almost 300 selected references were chosen. For the purpose of comparison of GHG emissions, an average lifecycle emission value for the electricity in Bolivia is calculated based on the energy sources as shown in Table 7-24. The life cycle emission value of the national energy mix is calculated as 327.8 $gmCO_2/kWh_e$.

Table 7-24 Weighted average of life cycle emissions for Bolivia electricity mix

Generation Technology	**Life Cycle GHG Emission [94] ($gmCO_2/kWh_e$)**	**Share in electricity generation [28]**
Natural Gas	469	66%
Hydropower	4	31%
Oil	840	2%
Biomass	18	1%
Weighted Average of life cycle emissions	**327.8**	

The annual production of electricity as shown in section 4.2 is 164,153 kWh. The lifecycle GHG emissions to provide this electricity from biomass and from the national energy mix is calculated and shown in table 7-25. The biomass operated system offers significant savings of 50.85 tons of CO_2 equivalent emissions compared to the average emissions from the national electricity mix.

Table 7-25 Calculated lice-cycle emissions from biomass and national energy mix annually

Electricity Source	**Annual electricity production (kWh_e)**	**Life Cycle GHG Emission ($gmCO_2/kWh_e$)**	**Total GHG emissions (tCO_2/year)**
Biomass	164,153	18	2.95
National Energy Mix	164,153	327.8	53.80

The cumulative GHG emissions over the assumed lifetime of 20 years of the project from the electricity generated from biomass and the calculated value for the national energy mix are displayed in figure 56. The avoided life cycle CO_2 equivalent emissions by use of biomass over the 20-year life amounts to approximately 1,017 tons, which is equivalent to CO_2 emission from 2,365 barrels of oil [171].

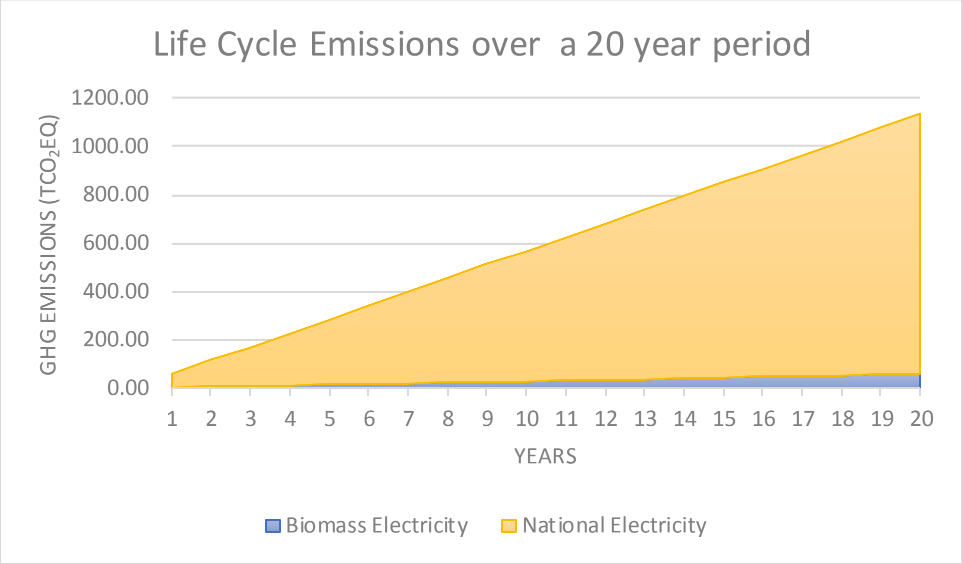

Figure 56 Cumulative life cycle emissions for electricity from the biomass and national energy mix

The heat and briquette use also can provide savings in GHG emissions if they are used to replace fossil or high emission energy sources. From the current scenario in Bolivia and the characteristics of briquettes discussed in previous sections, they are expected to replace existing biomass energy sources like charcoal and firewood. Hence the GHG emissions are expected to be the similar from their utilization, but they are a sustainable source which prevents overuse of firewood. There are potential GHG savings, water and land savings from the briquettes as residues are being utilised. But to quantify these savings much detailed and localised studies would be required.

7.8 Operational differences and uncertainties associated with the systems

From the results of the economic analysis, it is seen that System B based on a gasifier as the power generation unit is the more economically attractive option. It has lower capital investment, higher NPV, lower discounted payback time and higher IRR compared to the ORC powered system. But in practicality, there are operational restrictions, and risks and uncertainties associated with a gasifier system. These are described as follows:

- Gasifiers are sensitive to fuel quality. Most gasifiers are limited to certain fuel types, and subject to strict controls overs size, moisture and ash content in the feed. The use of lower quality fuel will lead to damage of the engine and the gasifier. This means that the range of suitable feedstocks are limited for gasifiers and they are highly sensitive to fuel quality. On the other hand, the use of a boiler as the primary conversion system in ORC system gives much greater flexibility in utilization of feedstocks. Typically, boilers can burn a wide variety of feeds, and have higher tolerance for ash and moisture content. Boilers to burn even wastes like MSW and plastics are available, which can rarely be utilised in small gasifiers. [172], [57]
- Higher ash content can lead to aggravated corrosion and deposit formation, which reduces the life of the parts and increase maintenance time and cost for both boilers

and gasifiers. Although the tolerance limit is about 5-8% in fixed bed gasifiers, and higher in boilers. Woody biomass with the exception of bark has low ash contents, but agricultural residues like straw and husk have higher contents of ash. The higher flexibility in feed offered by boiler is an advantage in future expansion of the project, as it enables the utilisation of agricultural and other waste streams.[119]

- The power module in an ORC system is a closed system, which means that there is very minimal maintenance required and the risk of severe damage is very limited. While gasifiers have been reported to suffer from operational issues. In some cases, the gasifiers were not performing to the stated standards and were suffering from breakdowns. This lead to a decrease in availability of the system. In small-scale rural bioenergy projects in China, gasifier equipment was found to be getting jammed by tar formation [173]. It was difficult and time consuming to remove the tars once they had coagulated on internal surfaces.
- Biomass gasifiers might require frequent cleaning due to tar formation, which provides as a hindrance to flow of syngas. In a study on operation of a gasifier operated on maize cobs and coffee husks in Uganda [142], servicing of constricted parts was required every 18 hours of operation. The high tar formation also creates a problem for disposing of scrubber water from the gas cleaning unit as it contains high amount of dissolved organic compounds.

7.9 Barriers to successful implementation

The major obstacles to implementation of decentralised alternative power generation technologies in Bolivia are identified as follows:

- The government traditionally has been focussed on exploiting hydrocarbons for power. The availability of cheap fossil fuels in Bolivia is a hindrance to development of alternative technologies. This has also led to black marketing of diesel and petrol, which are smuggled to neighbouring countries to be sold at higher prices. Fuel prices are controlled by the government and have heavy subsidies for several years. The poor planning and implementation in price increase by the government has led to nationwide protests when the prices have been increased in recent years, which has forced the government to keep the prices low. Instead to rapid increase in fuel cost, long term planning is required to gradually increase the prices and reduce the government spending on subsidies.[33], [174]
- The historic bias in energy policy of the government has been towards extension of the central grid. The central grid is able to provide power at cheaper subsidised rates which appeal to the rural poor. The lower subsidised tariffs hamper the development of alternative power generation options and creates market imbalance. Drinkward et al. [175] have also established that government projects have higher costs because of inefficient construction practices and the bureaucracy. The potential and need of rural markets are also not studied properly or ignored in some cases. Tariff adjustment to keep pace with inflation is a dire need in Bolivia for local projects to survive and flourish without constant external aid.
- There is a lack of knowledge and understanding of renewable energy among the actors in the electricity sector which has led to slow progress in development of renewable energy sources and design of appropriate regulatory frameworks [175]. Only hydropower has been developed for electricity generation, while other sources remain virtually untapped. Compared to other LAC countries, the number of renewable energy policies are lower in Bolivia, although the government is making efforts to

implement new policies [38]. A study on micro hydro projects reported that local communities often lack the appropriate technical capability and knowledge about the plant and its maintenance [175]. This can be attributed to improper transfer of knowledge to the local operators. This also led to heavy reliance on engineers who had to be brought in from cities to the remote areas, increasing downtime and costs.

- The poorer communities do not have the financial means to afford modern energy appliances and machines to improve their working conditions or increase the output of goods and services. In many cases it has been seen that it is the relatively wealthier sections of society which benefit the most while the poorer sections hardly enjoy monetary benefits [169]. Majority of rural entrepreneurs also lack the knowledge of the role modern energy access can play and market opportunities can be developed.

8 Conclusion and Future Work

8.1 Conclusion

The focus of the study was evaluation and analysis of potential methods for power generation and value-added products in the form of briquettes from the residual biomass available from the plantations. The appropriate technology options for the case in Bolivia were arrived at through the study. The main conclusions that could be drawn from the project work are listed here:

- The peak power requirement for the case study was estimated to be 50 kW. A system of this size will be able to power the operations of the client, 30 households, a new briquette plant, and other facilities and services. The power requirement is high during working hours in the daytime, but is below 20 kW between 1700-0800 hours. Thus, the power generation system can potentially provide higher levels of energy. This would require higher biomass input and processing, which can be investigated in further studies according to client requirements. The power generation unit can also be composed of 2 sub-units of 25 kW each. During periods of low demand, one unit can be turned off.
- There is sufficient residual biomass from the number of forestry plantations available in the project area, based on an estimated yield of 4 tons/hectare per annum. In the study, only the forest residues were considered to be utilized. The average size of the forest plantations was assessed to be 1 hectare, while the total land owned by each owner is around 25 hectares. Further examination can help to identify and select other residues for use. This will give the option of expanding the size of operation in the future and provides great potential for establishment of a bio-economy in the region.
- The briquette market in Bolivia is at a developmental stage. Biomass usage is high in rural enterprises. Unsustainable biomass exploitation has caused serious damage to forests. Sustainably produced briquettes may be a suitable alternative, with a potential of being a successful product in the market. Another briquette manufacturer, Eco-K Internacional, with an output of 20 tons per week has enjoyed success in the market, and is in the process of expansion of operations. Thus there already exists an emerging market for briquettes in the region, which potentially will expand further in the future. The presence of rich biomass reserves and the shifting focus of government policy from fossil fuels are positive factors towards development of biomass industry.
- A gasifier coupled with an ICE, and a boiler coupled with an ORC unit, respectively, are the two suitable technologies for a power capacity of 50 kW. Stirling engines display great potential in micro and small scale systems utilizing biomass, but their commercialization has not been successful until now. Stirling engines have high efficiency and are theoretically very well suited to small scale power generation. But complex construction, bulky size, high costs and slow load variability have prevented their wide-scale implementation. Ongoing efforts on cost reduction, and solving practical operational and construction issues can lead to emergence of Stirling Engines as the most viable option for micro to small scale application.
- A consolidated plant is considered which has a CHP unit, and a briquette manufacturing unit. The biomass processing system is common for both units. The heat from the CHP unit is used to dry the incoming biomass. The potentially income generating outputs from the plant are electricity, heat and briquettes.

- The briquetting unit is designed for an average output of 200 kg/hour. The cost of the briquette press is estimated to be € 16,694. The price of the briquetting equipment was seen to vary considerably according to area of manufacture. It is suggested that local procurement of the press can lead to low costs. To assess the sensitivity of feasibility of project on briquette selling price, two selling prices were assumed – a low price of € 100/ton and a high price of € 250/ton.
- Cost analysis revealed that the PEC for an ORC power generation system is 3.85 times the PEC for a gasifier power generation system of same power capacity. The high cost for ORC system can be attributed to the fact that a separate boiler for combustion and an ORC cycle needs to be assembled for the complete power unit. On the other hand, gasifier units with an incorporated ICE are easily available, which reduces their cost. The complexity of ORC cycle unit and the special organic working fluid contributes towards higher costs. ICEs are relatively simpler in construction and the technology is much widely used and available, leading to low costs.
- Owing to lower electric efficiency of ORC relative to gasifier unit, the biomass consumption per unit of electricity is about 64% greater for the ORC unit. On the other hand, the thermal output of the ORC system is about 3 times higher compared to the gasifier unit. The heat can also be recovered at a higher temperature from ORC unit. This leads to a total CHP efficiency of 73% for ORC power generation system and 61% for gasifier generation system.
- The costs of the plant based on the two selected conversion technologies are presented in table 8-1. The higher cost of ORC unit contributes to an overall increase in total investment cost of plant. Although the annual recurring costs for operation and maintenance of the plant are similar for both systems.

Table 8-1 Total investment and annual recurring costs for the plant configurations

	Plant with ORC unit	Plant with Gasifier unit
Total Investment Cost (€)	674,217	294,995
Annual Recurring Cost (€)	25,127	22,891

- The calculated annual revenues from the ORC based system was higher on account to greater heat output. The thermal energy recovered from the gasifier system is not sufficient to meet the estimated heat requirement for drying of the biomass during processing stage, which leads to a decrease in total briquette production. The ORC system on the other hand produces more than the required amount of thermal energy for drying, and the excess is assumed to be utilized for revenue generation. The most significant contribution to yearly revenues is from the selling of briquettes. The expected revenues from electricity sales is low because of the low energy prices in Bolivia.
- At the lower briquette selling price of € 100/ton, the discounted payback period for both systems is greater than the assumed operational life of 20 years. Hence, neither system design is economically feasible at this low revenue scenario. In the high revenue scenario with a briquette selling price of € 250/ton, both systems are economically feasible with payback period of 3.6 years for the gasifier operated system and 7.2 years for the ORC operated system.

- The two systems were examined on the basis of the economic feasibility indicators of NPV, payback period, and IRR. Based on these parameters alone, the system based on gasifier operated system is financially more viable. The lower capital investment for the gasifier system, in spite of lower yearly revenue contributes to the greater financial viability.
- Due to difference in technology there are operational differences between the ORC and gasifier power system – leading to certain advantages and disadvantages for both systems. The main advantages of the gasifier power system are easy installation, higher electrical efficiency, lower capital cost and relatively wider application. In application, gasifiers are sensitive to fuel quality, and face problems due to formation of tars and ash content of fuels. This necessitates frequent maintenance of the equipment. The use of a boiler for utilization of biomass in an ORC system means that a wide variety and quality of feeds can be utilized with significantly fewer problems. The ORC unit itself is low maintenance and potentially can be operated continuously and has a longer life compared to gasifier system.
- The lifecycle GHG emissions from electricity production was 2.95 tCO_2 equivalent per annum. This is only 5.5% of the equivalent GHG emissions if the electricity is provided from the national grid. Moreover, the use of forest residues helps to decrease the unsustainable exploitation of forests for firewood and charcoal.
- A multitude of social benefits can arise from implementation of a project as outlined. The plant will lead to direct and indirect economic opportunities to the communities from stable power supply, creation of jobs and extra income for sale of forest residues. The project is suitable for integration into the already existing forestry plantation scheme of the client. Also, many sub-industries and services can develop in the future as a result. An emerging bio-economy will greatly improve the economic and social conditions for the communities.
- One of the most significant barriers for the success of the project is the low price of electricity and fossil fuels in Bolivia, which hinders the development of alternate technologies. The lack of funds and low incomes in the rural communities further complicate this issue. There is also a lack of knowledge at both local and governmental levels. The government is trying to make changes in policy and regulations to encourage renewable energy use. A feed-in tariff is under development. With support from the government and proper management, such rural biomass based projects have a great potential for success in Bolivia.

8.2 Recommendations for future work

There was a general lack of specific information and studies which focused on production of power and other products from biomass in the Bolivian context. It is a strong suggestion to perform ground studies to attain more site-specific information to aid in decision making and design of projects. Some suggested studies are:

- To determine the characteristics and estimated quantities of biomass available in the region, to identify the suitable types for power generation and other uses.
- Assessment of the energy needs, markets and activities at the local scale to adapt the outputs of the plant and to make best use of the conditions.

From the estimates, it seems that there could be large amount of residues present in the region. If they can be collected and transported at a low cost, the output of the plant can be increased which will reduce the per unit cost for the outputs. If the briquette prices are sufficiently low, their adoption will be easier and the market base will also expand.

The government of Bolivia is in the process of developing a feed-in tariff for renewable energy, and is expected to bring more policies to support renewable energy. In face of positive conditions, a plant of higher capacity should be envisioned. The specific investment for the power conversion technologies especially for ORC systems, decreases significantly with increased size.

The major focus should be on development of local economy in a sustainable way, which will help the local communities as well as prevent the degradation of the precious rainforest.

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Appendices

Appendix 1 Power demand estimation – 3 pages

Appendix 2 Cost of ORC modules – 1 page

Appendix 3 Cost of gasifier and ICE power system – 2 pages

Appendix 1 Power demand estimation

The appliances used in an average household in the community and the usage pattern in a period of 24 hours are shown in table 1. Based on the distribution pattern for one household, the peak power demand was found to be 390 watts and daily energy consumption was 3.57 kWh. For a community consisting of 30 households, the combined peak demand was 12 kW and daily energy consumption was 107.1 kWh.

Similarly, the consumption and usage pattern by non-residential activities are listed in table 2. The peak power demand is 49.5 kW and daily energy consumption is 422 kWh. The activities marked in yellow in the table represent internal electricity consumption in the plant. By combining the power demand and energy consumption for both residential and non-residential usage, the overall distribution is obtained.

Total daily energy consumption = 529 kWh
Internal consumption = 306 kWh
Daily electricity available for sale = (529-306) kWh = 223 kWh

Considering annual availability of 85 % for the system,

Annual electricity production = 164,153 kWh
Annual electricity sales = 69,217 kWh

Table 1 Residential electricity usage distribution pattern

Household Appliance	Power (W)	Number	Net Power (W)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Hours	Total Energy (kWh)
Energy efficient lights	20	4	80																			80	80	80	80	80		5	0.4
Fans	75	2	150	150	150	150	150	150	150	150	150	150									150	150	150	150	150	150	150	16	2.4
Colour TV	150	1	150																			150	150	150	150			4	0.6
Cell Phone Charger	5	2	10																					10	10			2	0.02
Small Kitchen Appliance	300	1	300																									0.17	0.05
Radio/Music Player	50	1	50								50	50																2	0.1
	Power Demand (w)		1 HH	150	150	150	150	150	150	150	200	200	0	0	0	0	0	0	0	0	150	380	380	390	390	230	150		**3.57**
	Power Demand (kW)		30 HH	4.5	4.5	4.5	4.5	4.5	4.5	4.5	6	6	0	0	0	0	0	0	0	0	4.5	11	11	12	12	6.9	4.5		**107.1**

Table 2 Non-residential electricity usage distribution pattern

Non-Residential Activities	Power (kW)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Hours	Total Energy (kWh)
Timer Sawmill	11											11	11	11	11	11	11									5	66
Wood Drying	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	24	24
Power tools for Processing	3												3	3	3	3	3	3								5	18
Shredder	15									15	15	15	15	15	15	15	15	15	15							10	150
Briquette Press	18.5										18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5								8	148
Aux systems	1										1	1	1	1	1	1	1	1								8	8
Water Pump	2								2	2	2															3	6
TV + Speakers for Hall	0.5																		0.5	0.5	0.5	0.5				4	2
Power Demand (kW)		1	1	1	1	1	1	1	3	18	37.5	46.5	49.5	49.5	49.5	49.5	49.5	38.5	16.5	1.5	1.5	1.5	1	1	1		**422**

Appendix 2 Cost of ORC modules

Sources for credible and reliable cost estimates for ORC modules were scarce. Table 3 lists the sources from which the equipment cost of ORC modules was collected. ElectraTherm and Againity are two manufacturers of small scale ORC units. In some sources, the total cost of unit was specified, which was divided by the capacity of unit to arrive at the specific investment cost. A distribution chart was created of the variation between specific investment cost with size.

Table 3 Reported costs of ORC units

Reference/Source	Size (kW)	Total Cost (€)	Specific Investment Cost (€/kW)
ElectraTherm, Nevada [126]	65	180,651	2,779
ElectraTherm, Nevada [126]	35	156,228	4,464
ElectraTherm, Nevada [126]	110	267,480	2,432
Againity AB, Sweden	20	100,000	5,000
Rentizelas, A. et al. [118]	1,000		2,760
Alaska Center for Energy and Power [127]	50	173,350	3,447
Lemmens, S. [125]	1,000	-	3,000
Lemmens, S. [125]	40	-	4,200
Lemmens, S. [125]	150	-	3,800

Appendix 3 Cost of Gasifier and ICE power system

The most common and widespread method of micro and small scale power generation from gasification is the combination of gasifier with an ICE. The syngas produced by gasification is utilized in an ICE to provide mechanical power. A generator converts the mechanical motion to electricity. The costs of such systems below 100 kW_{el} output were analyzed from different literature sources and from manufacturers. The costs associated are presented in table 4. It was seen that most manufacturers offer a basic model of biomass gasifier-generator. Extra add-ons like auto-feed system can be added for higher degree of automation albeit at a cost. In the instances where cost of feeding system and other auxiliaries were not available directly, they were considered to be 10% of the cost of the basic unit. The specific investment cost in €/kW_{el} was calculated from the combined cost of basic unit and auto feed system.

Some manufacturers like APL are offering an add-on CHP unit for heat recovery. With success of micro and small scale gasifier units for heat and power in Europe, manufacturers are designing and planning to release more gasifier CHP units. There are also integrated gasifier CHP plants with high efficiency and low pollutants from manufacturers like Entrade and Burkhardt. Although they are high in cost and required standardized pellets for operation. this makes such systems unsuitable in their current state in the project area.

Table 4 Reported costs of Gasifier ICE units below 100 kWel capacity

	Source										
	STAK [143]	BETPL [148]			Vulcan Gasifier [144]	Nouni et. Al. (2007) [145]				APL [139]	Entrade [147]
Peak Net power (kW)	50	19	53	94	25	40	40	9	10	18	25
Gasifier + Gen-set Basic Unit (€)	49,300	64,080	119,434	189,079	45,000	55,072	45,309	11,241	12,257	24,256	-
Feeding and Auxiliary Systems (€)	6,186	-	11,282	11,282	4,500	5,507	4,531	1,124	1,226	3,150	-
Combined cost of Basic unit + Auto feed (€)	55,486	64,080	130,716	200,361	49,500	60,579	49,840	12,365	13,483	27,406	-
SIC (€/kW_{el})	1,110	3,418	2,490	2,137	1,980	1,514	1,246	1,374	1,348	1,523	-
CHP Module										4,500	-
Overall system cost										31,906	143,100