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AGRICULTURAL RESIDUE AS A RENEWABLE ENERGY RESOURCE

Utilisation of Agricultural Residue in the Greater Gariep Agricultural Area as a Renewable Energy Resource

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Utilisation of Agricultural Residue in the Greater Gariep Agricultural Area as a Renewable Energy Resource

Thesis presented in partial fulfilment of the requirements for the Masters of Engineering (Mechanical) degree in Renewable and Sustainable Energy at Stellenbosch University.

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ABSTRACT

In the Greater Gariep agricultural area adjacent to the Orange River between Prieska and the Vanderkloof dam alone an estimated 311 000 ton/yr of maize and wheat straw is available. These agricultural residues have an energy equivalent of 196 000 ton of coal per year and should be utilised as a renewable energy resource.

A technical and financial evaluation on the collection and transport of agricultural residue showed that the Hopetown area has the highest concentration of agricultural residue in the Greater Gariep agricultural area with approximately 68 000 ton/yr that is spread out over 76 km^2.

Briquetting, combustion, pyrolysis and gasification were identified as the technologies with the highest potential to convert agricultural residue into a higher grade energy product in this area. The expected overall energy conversion efficiency for a plant capacity between 5 000 to 100 000 ton/yr is 98.9%, 10-25%, 25-30% and 28-36% for the briquetting, combustion, pyrolysis and gasification plants respectively.

A financial evaluation based on the internal rate of return and the net present value of investment showed that the briquetting plant is financially feasible and the most profitable for capacities between 25 000 and 60 000 ton/yr while the pyrolysis plant was financially feasible and the most profitable technology for capacities greater than 60 000 ton/yr.

A sensitivity and risk analysis done on the proposed briquetting and pyrolysis plants to evaluate the impact of market fluctuations on the profitability of the power plants exposed the briquetting plant as a very high risk investment, mainly because of the sensitivity to the selling price of fuel briquettes and the high maintenance cost associated with the briquetting equipment. Although the proposed pyrolysis plant is sensitive to variation in the electricity price, the risks associated with the market conditions for the pyrolysis plant is very low and an internal rate of return of 15% is still projected at the minimum expected electricity price.

From the study it is clear that the utilisation of agricultural residue available in the Greater Gariep agricultural area is technically and financially viable.

OPSOMMING

In die Groter Gariep landbougebied langs die Oranjerivier, tussen Prieska en die Vanderkloof Dam is daar jaarliks 'n beraamde 311 000 ton mielie- en koringstrooi beskikbaar. Hierdie landbou-reste het die energie-ekwivalent van 196 000 ton steenkool per jaar en behoort as hernubare energiebron benut te word.

'n Tegniese en finansiële evaluasie van die versamel en vervoer van landbou-reste het getoon dat die Hopetown-area die hoogste konsentrasie landbou-reste in die Groter Gariep landbougebied het met ongeveer 68 000 ton/jaar wat versprei is oor 76 km^2.

Brikettering, verbranding, pirolise en vergassing is geïdentifiseer as die tegnologieë met die hoogste potensiaal om landbou-reste te omskep in 'n hoër graad energieproduk vir hierdie gebied. Die verwagte totale energie-omsettingseffektiwiteit vir 'n aanlegkapasiteit van tussen 5 000 tot 10 000 ton/jaar is onderskeidelik 98.9%, 10-25%, 25-30% en 28-36% vir die brikettering, verbranding, pirolise en vergassingsaanlegte.

'n Finansiële evaluasie gebaseer op die opbrengs op aanvangskoste en die netto huidige waarde van die belegging het getoon dat die briketteringsaanleg finansieel lewensvatbaar is en die winsgewendste is vir 'n aanlegkapasiteit tussen 25 000 en 60 000 ton/jaar terwyl die pirolise-aanleg finansieel lewensvatbaar is en die winsgewendste tegnologie is vir kapasiteite van groter as 60 000 ton/jaar.

'n Sensitiwiteits- en risiko-analise is op die voorgestelde brikettings- en pirolise-aanlegte gedoen om die impak van markskommelings op die winsgewendheid van die aanlegte te evalueer. Die resultate het getoon dat die briketteringsaanleg 'n baie hoë-risiko belegging is as gevolg van die sensitiwiteit op die verkoopprys van brikette en die hoë onderhoudskoste van briketteringstoerusting. Alhoewel die voorgenome pirolise-aanleg sensitief is vir skommelings in die elektrisiteitsprys, is die risiko's wat met die marktoestande vir die pirolise-aanleg gepaardgaan, baie laag en 'n opbrengs op aanvangskoste van 15% word steeds voorspel teen die minimum verwagte verkoopsprys van elektrisiteit.

Vanuit die studie blyk dit duidelik dat die gebruik van landbou-reste wat beskikbaar is in die Groter Gariep landbougebied, tegnies en finansieel lewensvatbaar is as hernubare energiebron.

PLAGIARISM DECLARATION

I know that plagiarism is wrong.

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NOMENCLATURE

Cap = Capacity of bio-energy plant based on feedstock
$C_{Material}$ = Material cost of agricultural residue on the farm
$C_{Resource}$ = Cost of agricultural residue resource
$C_{Transport}$ = Transport cost of agricultural residue to the bio-energy plant
$C_{C.PT}$ = Capital cost pre-treatment
$C_{C.Briq}$ = Capital cost briquetting
$C_{C.Comb}$ = Capital cost combustion
$C_{C.Steam}$ = Capital cost steam cycle
D_{Ave} = Average distance of agricultural residue from processing plant
E_{Diesel} = Energy value of diesel
$E_{Resource}$ = Energy input per ton of resource
EB = Energy balance of fossil fuel input to renewable energy out
F_{Cons} = Fuel consumption of the truck
$F_{Resource}$ = Fuel usage per ton of resource
L_{max} = Maximum allowable mass load per truck
T_{eff} = Effective transport rate
T_{rate} = Transport rate
V_{max} = Maximum volumetric load per truck
ρ_{bulk} = Bulk density of baled residue
η = Energy conversion efficiency

1. INTRODUCTION

1.1. Background

Every year, millions of tons of agricultural residue, mainly corn and wheat stover, are burned and the energy wasted on the fields in order to reduce the biomass before ploughing and preparing the soil for the next crop. The biggest drawback for the majority of these agricultural residues to be utilised as a renewable energy resource is the low concentration of the residues as it is spread out over vast areas of land.

Agricultural residue from irrigated land where very high crop yields are achieved is concentrated around the water source. Agricultural residue produced in these areas has higher potential as a renewable energy resource than rain-fed agricultural areas because of the higher concentration of available biomass.

The agricultural area to be investigated in this research project is the Greater Gariep agricultural area next to the Orange River from the Vanderkloof Dam to Prieska. This area produces very high crop and biomass yields and because of the favourable climate and abundant water sources, double cropping is practiced in this area that further increases the amount and concentration of biomass produced.

Many proven technologies exist to convert these agricultural residues into a more useful form of energy. The challenge lies in selecting, sizing and applying these technologies correctly and in new ways to make agricultural residue a feasible and attractive renewable energy resource. For each specific resource, location and situation there is an optimum solution that must be found that will ensure economic viability as well as the sustainability of the specific development. The systems engineering of the application is becoming more and more important with very little research being focused on this aspect of renewable energy technologies.

Before evaluating the potential of agricultural residue and the application of different biomass conversion technologies in the Greater Gariep agricultural area, it is important to have a good understanding of the current global and South African energy situation as well as other available energy resources.

1.2. The Current Energy Situation

“World marketed energy consumption is projected to increase by 44 percent from 2006 to 2030. Total energy demand in the non-OECD countries increases by 73 percent, compared with an increase of 15 percent in the OECD countries” this is according to the reference case scenario presented in the International Energy Outlook report of 2009 (EIA, 2009).

In 2007, South Africa’s energy supply could not meet its energy demand leading to the current South African energy crisis. In order to overcome the shortfall in energy supply as well as to make provision for the forecasted growth in energy demand to sustain the economic growth in the country, the government needs to establish very clear and decisive energy policies to guide the growth and development of the South African energy market towards a sustainable future. These policies however can only create a favourable environment for the development of the energy market, but it will take a collaborative effort between the public sector, private sector and each individual to meet this challenge and ensure a sustainable energy future.

The energy sector will need to make a paradigm shift away from only large coal-fired power stations feeding electricity to the grid to an energy sector where allowances are made for smaller independent power producers to participate, develop and implement new and innovative technologies and solutions to energy supply.

In 2004, 87.5 percent of South Africa's energy supply was based on fossil fuels, mainly coal and oil. Only 9.5 percent were from renewable resources, mainly biomass and hydro energy (DME, 2006). In order for the South African energy supply to become sustainable, the energy mix needs to change from a fossil fuel based supply to a renewable energy based supply. The government's vision for the role of renewable energy in the South African energy economy as outlined in the White Paper for Renewable Energy is:

"An energy economy in which modern renewable energy increase its share of energy consumed and provides affordable access to energy throughout South Africa, thus contributing to sustainable development and environmental conservation" (DME, 2003).

In line with the government's vision for renewable energy in South Africa, the purpose of this research project is to develop agricultural residue (biomass) as a renewable energy resource in the rural South Africa by proposing and evaluating solutions that are based on proven technologies and robust financial models.

1.3. Global and South African Energy Resources

When looking at energy resources, it is important to differentiate between and clearly understand the difference between renewable and non-renewable energy resources. It is difficult to compare the two as renewable energy can be expressed on a rate basis whereas non-renewable resources are finite and there is only a specific amount left that has been discovered or that can be harnessed economically given the technologies available at the time.

An illustration of the potential of the different non-renewable and renewable energy resources relative to the current world energy consumption is provided in Figure 1-1 below. From this comparison it is clear that renewable energy has a far greater potential than non-renewable energy resources and is more than capable to meet the world energy demand now and in the future.

The non-renewable energy resource base consists mainly of coal, oil, natural gas and uranium, thus fossil fuels and nuclear energy, whereas the renewable energy resource base consists mainly of solar, wind, hydro and biomass energy. Other minor resources are tidal, wave and OTEC energy. Each of these resources and technologies that exploit these resources are briefly discussed in this section.

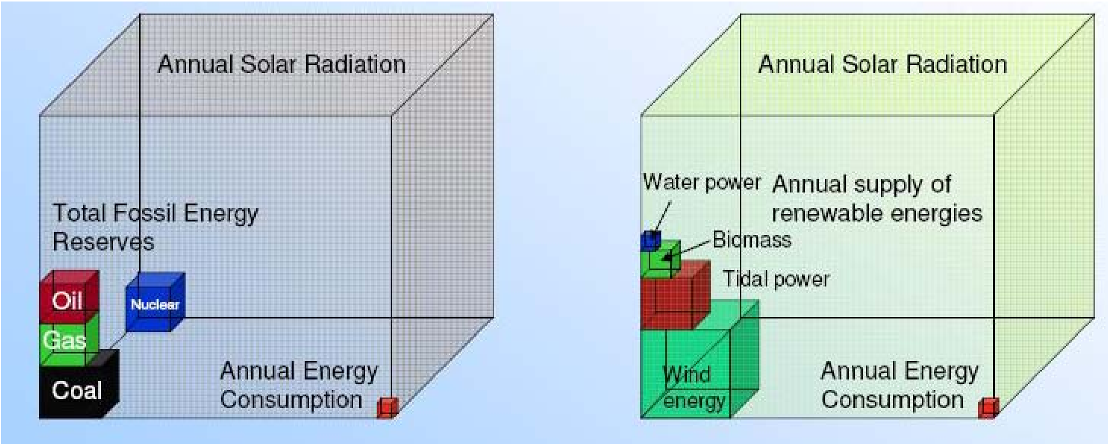


Figure 1-1: Energy resources compared to annual consumption (Swanepoel, 2007)

Coal

Coal is the fuel that started and spearheaded the industrial revolution before it was overtaken by oil. The proven recoverable amount of coal still available in 2005 was 847 billion tons (WEC, 2007), equivalent to approximately 22 870 EJ.

The ratio of South Africa's non-renewable resources is vastly different to the global non-renewable energy mix in that coal completely dominates South Africa's reserves. The South African energy resources as estimated in the integrated energy plan of 2003 are given as energy resources that are available, and then as energy reserves that are currently economically exploitable.

South Africa's estimated coal resources and reserves in 2003 were 115 billion tons and 55 billion tons respectively (DME, 2003), equivalent to 2 530 EJ and 1 210 EJ respectively.

Oil

Crude oil soon overtook coal as the number one energy resource driving the industrial revolution and continued to be the number one energy resource fuelling our current economy. The proven recoverable oil reserves, including crude, shale natural bitumen and heavy oils in 2005 was 4 347 billion barrels (WEC, 2007), equivalent to approximately 26 517 EJ.

South Africa's estimated oil resources and reserves in 2003 were 5 billion barrels and 0.4 billion barrels respectively (DME, 2003), equivalent to 30.5 EJ and 2.4 EJ.

Natural Gas

Natural gas is the "cleanest" resource of the fossil fuel family. The world's proven recoverable reserves are on the increase since 1980 and new reserves are still being found. In 2005 the proven recoverable natural gas reserves were 176 trillion cubic meters (WEC, 2007), equivalent to approximately 6 741 EJ.

South Africa's estimated natural gas resources and reserves in 2003 were 20 trillion cubic foot and 5 trillion cubic foot respectively (DME, 2003), equivalent to 21.7 EJ and 5.4 EJ.

Nuclear

Nuclear power is another big contributor to the global electricity supply. Nuclear energy is mainly derived from uranium and the global nuclear resource potential is measured based on the availability of uranium. In 2005 the proven recoverable uranium reserves were 2 397 thousand tons with the 2005 production of uranium being 41.7 thousand tons.

South Africa's estimated uranium resources are 261 thousand tons (DME, 2003).

Solar

The sun is the most abundant and reliable source of energy supplying the earth and strictly speaking indirectly responsible for wind, wave, biomass and hydro resources as well. For the purpose of this study, solar energy only refers to the direct conversion of solar energy to heat or electricity. The average annual solar radiation onto the earth is more that 7 500 times the global primary energy consumption of 450 EJ in 2005 (WEC, 2007) all of which is obviously not exploitable, but only 0.015% has to be exploited to meet the world's current energy demand.

South Africa has some of the highest solar energy potentials in the world with an average daily solar radiation between 4.5 and 6.5 kWh/m^2 (DME, 2003). The extent to which solar resources can be used depends on the technology. The potential for solar water heating in South Africa is estimated to be 5 900 GWh that will be measured in saving of electricity (DME, 2003). The potential for Photovoltaic panels are in small standalone off-the-grid units in remote locations, it can also be used for domestic electricity supply when installed on rooftops or alternatively compete with large solar thermal plants to supply electricity to the grid. The area with sufficient radiation potential for solar thermal power plants in South Africa is estimated at 194 000 km^2. If only one percent of this area is used, South Africa can install 64.6 GW of solar thermal power plants (DME, 2003).

Wind

Wind along with solar resources are the world's two most abundant energy resources. Very good progress is being made in mapping and determining the real potential of wind as renewable energy resource.

The global wind resource is estimated at around 70 TW that can be exploited and is at least 30 times the present world electricity consumption (Swanepoel, 2007).

South Africa's wind resources are concentrated around the coastline with a conservative estimated upper limit potential of 3 GW (DME, 2003). This estimate excludes the offshore potential which is also substantial.

Hydro

Hydro electricity is currently the largest contributor to the global renewable energy supply with nearly 778 GW of installed capacity globally in 2005. Hydro electricity is also the cheapest form of renewable energy. The global hydro electricity potential that is technically exploitable is estimated to be 4.6 TW (WEC, 2007).

Even though South Africa is a water scarce country with relatively low hydro electricity potential compared to the rest of the world, hydro electricity is currently the biggest renewable contributor to the electricity grid with an installed hydro electricity capacity of 687 MW. It is estimated that an additional 5 160 MW can be installed in South Africa (DME, 2003).

Biomass

Biomass is carbon based materials derived from living organisms or organisms that recently lived, thus mainly plant materials, but also animal and human waste. There are many different types of biomass, but the main biomass resources are: wood and forest residues, agricultural crops, agricultural residue, sugarcane bagasse, sewage, municipal solid waste and algae.

The global biomass potential can be estimated with many different models. One such model is to estimate the amount of photosynthetic carbon captured in terrestrial biomass every year that gives the net primary productivity (NPP). The NPP was estimated as 489 g carbon/m^2 on vegetated land and is equivalent to 1 665 EJ of primary energy captured in biomass on an annual basis (WEC, 2007). This however includes biomass that is produced for food and does not represent the amount that is realistically available for bio-energy. With recent developments in genetically engineered crops that are drought resistant or designed to grow under specific climatic conditions, the total biomass produced can be increased significantly. The development of algae reactors with the potential to produce very high yields of biomass per square meter will also increase the potential of biomass in the near future as the technology matures.

The potential of biomass in South Africa is estimated at 1 834 PJ/yr and is discussed in more detail in section 2.1.

Tidal, Wave and OTEC

Although the potential of tidal, wave and OTEC energy is significant, the technologies to exploit these resources are still in very early stages of development and the associated cost thereof is still very high.

South Africa’s wave energy resource is estimated at 40 kW/m along the South West Coast, and between 18 and 23 kW/m along the rest of the coastline (Joubert, 2008).

1.4. Motivation and Objectives

The motivation of this research project is to develop agricultural residue as a technically and financially viable renewable energy resource in the Greater Gariep agricultural area.

This will be done by evaluating the potential of agricultural residue as renewable energy resource in the Greater Gariep agricultural area and evaluating the technical and financial feasibility of different existing biomass conversion technologies to convert these agricultural residues into a useful form of renewable energy.

In order to meet the objectives, the following questions will be answered through this investigation:

- What is the potential of agricultural residue in the Greater Gariep agricultural area?
- Is agricultural residue produced in the Greater Gariep agricultural area a technically and financially viable renewable energy resource?
- Which proven biomass conversion technologies can best be utilised to convert agricultural residue into a more useful form of energy?
- What renewable energy product or intermediate product can be produced from the agricultural residue in a financially viable and environmentally sustainable way?

1.5. Scope of Investigation

The investigation was divided into three main sections: biomass resource, conversion technology and renewable energy products. The research for this investigation was done within the following boundaries so that the scope and limits of this study is clearly defined:

- Biomass resource
    - Evaluate the potential of agricultural residue in the Greater Gariep agricultural area next to the Orange River between Vanderkloof and Prieska as an energy resource;
    - Develop an energy balance and financial model to evaluate the technical and financial viability of agricultural residue in this area as renewable energy resource.
- Biomass conversion technology
    - Do a high-level evaluation of biomass conversion technologies and select a minimum of three technologies with the highest potential;
    - Do a literature review and technical evaluation of the selected technologies;
    - Evaluate the capital and operating cost associated with the selected technologies.
- Renewable energy product
    - Investigate the demand and offset potential of the renewable energy products or intermediate products produced from the agricultural residue;
    - Evaluate the revenue potential of the different renewable energy products.

Besides these three main sections, a final combined evaluation will be done taking into account the resource, technology and product to determine the overall energy efficiency and financial viability of the proposed solutions.

2. BIOMASS RESOURCE

Bio-energy refers to the conversion of biomass into a useful form of energy. Many different technologies exist to convert different types of biomass into different forms of useful energy, for example soybeans to biodiesel, corn to ethanol, wood to electricity, etc. The potential of biomass as renewable energy resource refers to the combined energy value of all the different types of biomass available that can realistically be converted into bio-energy. Currently the potential of biomass as renewable energy resource exceeds the annual primary energy consumption of the world.

In this section, a high level investigation of the potential of biomass as a renewable energy resource in South Africa will be done. This was followed by an in-depth research and evaluation of the potential and viability of agricultural residue as renewable energy resource in the Greater Gariep agricultural area next to the Orange River between Vanderkloof and Prieska.

2.1. Potential of Biomass as Energy Resource in South Africa

The total potential of biomass as renewable energy resource in South Africa is estimated to be 1 834 PJ/yr as summarised in Table 2-1 below (values from Table 2-2 to Table 2-5).

Table 2-1: Primary energy potential from available biomass in South Africa

Description	Primary Energy Value PJ/yr
Wood and Forest Residue	267.9
Energy Crops	1 170.0
Agricultural Residue	225.3
Sugarcane Bagasse	126.2
Sewage	4.1
Municipal Solid Waste	40.5
Total	**1 834.0**

2.1.1. Wood and Forest Residues

Woody, forest or lignocellulosic material is typically composed of 40-60% cellulose, 20-40% hemicellulose, 10-25% lignin and also small amounts of salts, minerals and acids (Chirwa, et al., 2007). The main sources of woody biomass is commercial plantations, sawmill processes, pulp and paper industry, alien vegetation and residues from agricultural crops. For the purpose of this study, residues from agricultural crops are investigated separately and not as part of this section. The South African Renewable Resource Database published a map indicating the biomass potential of South Africa in energy potential per hectare per year. This model is based on the potential of wood, agricultural residues and grass as shown in Figure 2-1 below.

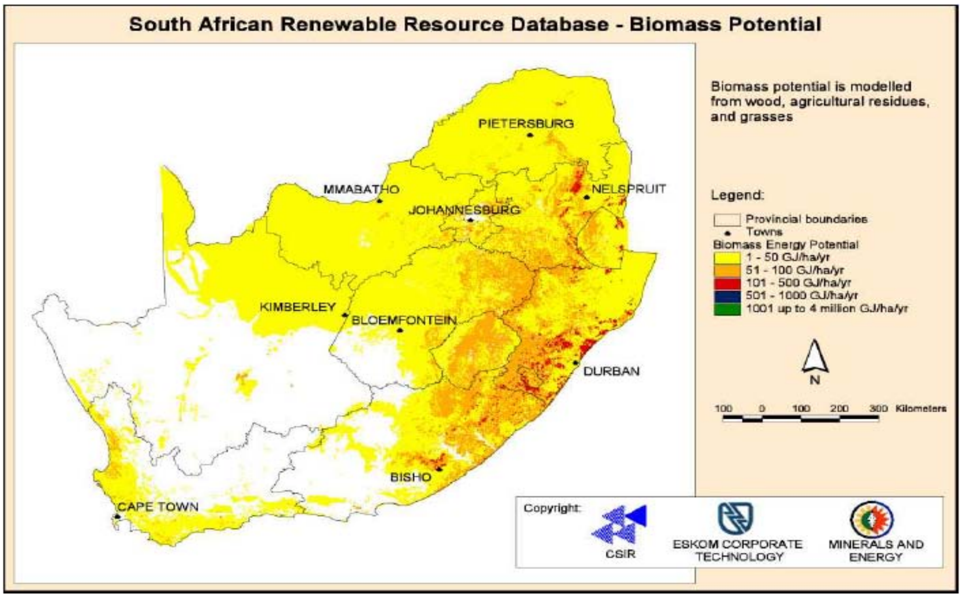


Figure 2-1: South African renewable resource database – Biomass (DME, 2003)

The primary energy potential of the biomass from the forest residue, sawmill operation, pulp and paper industry and alien vegetation is estimated at 267.9 PJ/yr as detailed in Table 2-2 below.

Table 2-2: Primary energy potential from the wood and paper industries

Description	Mass [Mton/yr]	Energy Value [MJ/kg]	Energy Value [PJ/yr]	Reference / Comments
Biomass left in forest	4.0	17.3	69.0	(Lynd, et al., 2004)
Biomass from sawmill operation	1.6	17.8	27.9	(DME, 2003)
Biomass from pulp industry	1.0	20.0	20.0	(DME, 2003)
Invasive plant species	8.7	17.4	151.0	(Lynd, et al., 2004)
Total wood and forest biomass	**15.3**	17.5	**267.9**	

2.1.2. Agricultural Crops

Energy derived from agricultural crops includes biodiesel from sunflowers, soybeans, and other oil crops as well as ethanol from maize. The energy potential of these crops is significantly higher than the current primary energy demand of South Africa. One of the biggest problems in utilising this potential is the Food vs. Fuel debate and the ethical issues around using food crops to produce energy while people are starving in some countries.

An alternative to cereal crops are energy crops that differ from cereal crops mainly in that they are planted primarily as energy resource and not for food and most importantly that they have to be planted on marginal land that is not used for food production. The production of energy crops should not compete in any way with food production, not for land, water, fertilisers or markets.

The potential of energy crops utilising only 10% of available land in excess to the land required for the production of food crops is estimated at 67 million ton/yr with a primary energy equivalent of 1 170 PJ/yr (Lynd, et al., 2004).

2.1.3. Agricultural Residue

Agricultural residues are produced as a waste product from food crops such as maize, wheat, sunflowers, etc. Currently small amounts of these residues are being used by farmers as feed for livestock and the rest of these are ploughed back into the soil or burned to get rid of the huge volumes of biomass before planting the next crop. The biggest advantage of utilising agricultural residues is that it does not compete with the production of food, and if it can become a by-product that can be utilised economically for the production of energy, it will result in lower food prices.

It is estimated that roughly one ton of residue is produced for every ton of grain harvested (Lynd, et al., 2004). Using the average production of maize, wheat, sunflowers and grain sorghum of the last five years, the primary energy potential from agricultural residues in South Africa is estimated at 225.3 PJ/yr as detailed in Table 2-3 below.

Table 2-3: Primary energy potential of agricultural residues

Description	Mass	Energy Value		Reference /
	[Mton/yr]	[MJ/kg]	[PJ/yr]	Comments
Maize residue	10.4	17.0	176.0	(Directorate Agricultural Statistics, 2010)
Wheat residue	2.0	17.0	34.1	(Directorate Agricultural Statistics, 2010)
Sunflower residue	0.6	17.0	11.0	(Directorate Agricultural Statistics, 2010)
Grain Sorghum residue	0.2	17.0	4.2	(Directorate Agricultural Statistics, 2010)
Total Residues	**13.3**		**225.3**	

2.1.4. Sugarcane Bagasse

Sugarcane bagasse is the by- or waste product that is left after the processing of sugar cane for the extraction of sugar. In 1998 South Africa had 412 000 ha of productive sugarcane plantations concentrated in the KwaZulu-Natal coastlands and Mpumalanga lowveld (Kleynhans, 2007). The estimated primary energy potential of sugarcane bagasse is 126.2 PJ/yr as calculated in Table 2-4 below.

Table 2-4: Primary energy potential of sugarcane bagasse in South Africa

Description	Value	Units	Reference / Comments
Hectares of productive sugarcane	412 000	ha	(Kleynhans, 2007)
Sugarcane yield	52.5	ton/ha/yr	(DME, 2003)
Bagasse yield	17.5	ton/ha/yr	(DME, 2003)
Tons of sugarcane	21 630 000	ton/yr	
Ton of bagasse	7 210 000	ton/yr	(DME, 2003)
Calorific value of bagasse	17.5	MJ/kg	
Energy potential per hectare	306.3	GJ/ha/yr	
Annual primary energy potential	**126.2**	**PJ/yr**	**Primary Energy**

2.1.5. Sewage

Sewage can be treated with an anaerobic biological process in an anaerobic digester that produces biogas as by-product. This biogas consists typically of 50-70% methane, 30-40%

carbon dioxide, 5-10% hydrogen and 1-3% of other gasses depending on the type of carbon source and nutrients that are being digested. The maximum primary energy potential of sewage in South Africa was calculated based on the assumptions as detailed in Table 2-5 below as 4.1 PJ/yr.

Table 2-5: Primary energy potential from sewage in South Africa

Description	Value	Units	Reference / Comments
Population in South Africa	49.99	million	(Stats SA, 2010)
Biogas potential per capita	3.8	m^3/person/yr	(Stafford, et al., 2007)
Biogas potential from sewage	189.8	GL/yr	
Energy value of biogas	21.6	MJ/m^3	(Stafford, et al., 2007)
Total primary energy potential from sewage	**4.1**	**PJ/yr**	

Other advantages of the anaerobic digestion of sewage are that the product water is very rich in nutrients and can be used for irrigation purposes, and the sludge that is produced can be stabilised and used as compost.

2.1.6. Municipal Solid Waste

Most of South Africa's domestic solid waste as well as the industrial solid waste are being discharged into landfill sites. Anaerobic digestion of the organic materials occurs naturally inside these landfills and produce significant amounts of biogas. It is estimated that the primary energy value of the domestic and industrial waste discharged into landfill sites in South Africa amounts to 40.5 PJ/yr (DME, 2003).

2.1.7. Algae / Oilgae

Algae, or oilgae as the oil producing strains of algae is referred to, is a second generation biodiesel feedstock and is different to other energy crops in two very important ways: oilgae can be grown in any place as long as there is enough sunshine available for photosynthesis, even in saline water, thus it does not compete with food crops as other energy crops do; secondly, the potential yield of oil per hectare is estimated to be more than 200 times that of the best performing vegetable oils (Becker, et al., 2007). Unfortunately this has only been achieved on lab and pilot scale and the commercialisation of this technology is still under development.

2.2. The Greater Gariep Agricultural Area

2.2.1. Boundaries of the Area Investigated

There are many different agricultural areas in South Africa each with its unique climate, soil and water resources that determine the type of crops planted and the yields produced in that area. One of the most important factors determining the potential of biomass as a renewable energy resource is its availability and the concentration or energy density of the biomass. The lower the concentration and energy density of the biomass, the more energy is required to collect and transport it to the renewable energy plant and the higher the cost of the resource making it environmentally and financially unattractive.

For the purpose of this research project, only the potential of existing agricultural residues were investigated and not the potential of cultivating energy crops for the production of biomass. Thus there can be no argument against it from a food vs. fuel perspective as it does not compete with food crops. In fact the additional revenue from the residue will make the production of food crops more competitive and could lead to lower food prices in the long term.

The Greater Gariep agricultural area next to the Orange River between the Vanderkloof Dam and Prieska were evaluated for this research project as shown in Figure 2-2. This area was chosen because of the following reasons:

- The agricultural land is concentrated next to the Orange River, a permanent water source from where the crops can be irrigated. As a result the crop yields produced are less dependent on the weather conditions making this area a reliable source of agricultural residue.

- Very high yields of maize (11 to 14 ton/ha) and wheat (5 to 8 ton/ha) are produced in this area. These high yields can be ascribed to a combination of fertile soil, favourable climate and the permanent water resource available for irrigation.

- The climatic conditions and permanent water supply allow for the practice of double cropping in this area, thus more than one crop can be produced on the same land in one year. This further increases the amount of agricultural residues produced per hectare per year. A general crop rotation system is followed in this area where typically two crops of maize and one crop of wheat is produced in 24 months allowing the soil to rest for 6 months out of the 24. From time to time, as required, the production of maize and wheat are rotated with legumes to maintain or increase the fertility of the soil.

- As a result of the double cropping practice and very high yields, the agricultural residue produced is too much to be ploughed back into the soil before planting the next crop, thus it is burned on the field to reduce the biomass before preparing the soil to plant the next crop.

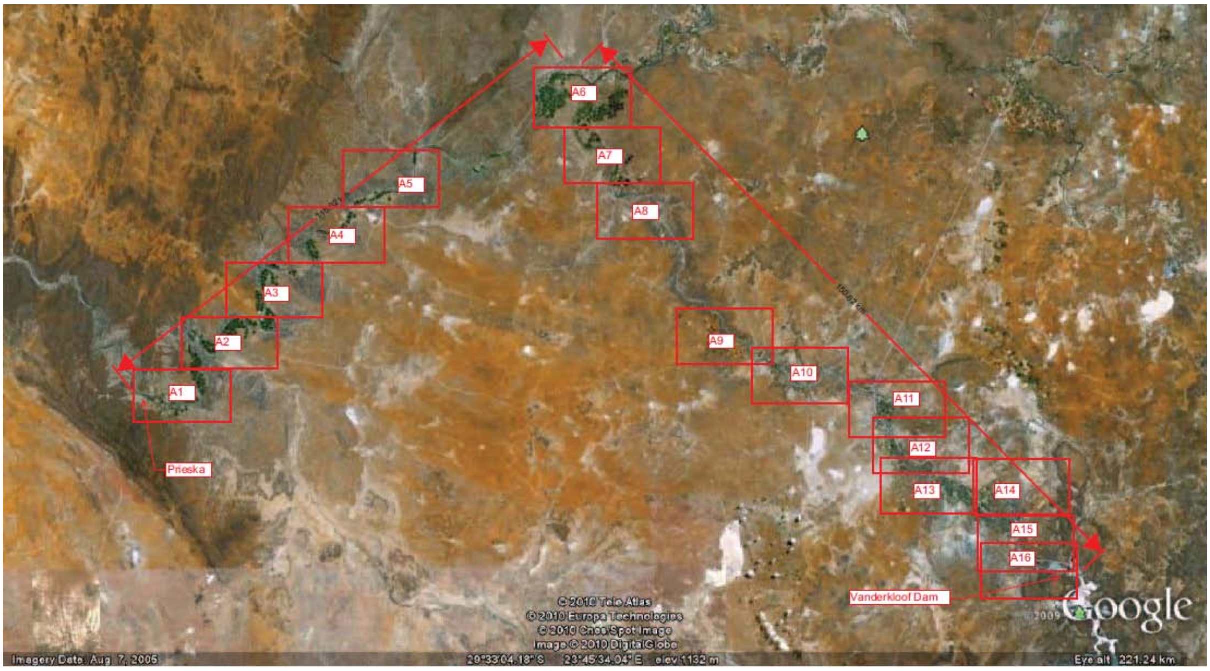


Figure 2-2: Overview of the Greater Gariep agricultural area

It is not in the scope of this project to evaluate and compare the potential of all the different agricultural areas in South Africa, thus there might be many other areas that also have a high concentration and energy density of agricultural residue that can be utilised.

The area investigated stretches for approximately 150 km (straight line distance) next to the Orange River from the Vanderkloof Dam to Douglas where the Vaal River meets the Orange River. From Douglas it stretches for approximately another 115 km (straight line distance) to Prieska. The majority of the fields are located within 2.5 km to 3 km from the river to minimise pumping cost, thus the fields with potential to produce agricultural residue as renewable energy resource are located in an area that is approximately 265 km long and 6 km wide.

2.2.2. Agricultural Residue Produced in this Area

In order to determine the agricultural residue produced in this area, the actual area under irrigation had to be determined first. This was calculated by counting and measuring the area of the fields under irrigation off satellite images from Google Earth.

As shown in Figure 2-2, the area under investigation was divided into sixteen separate areas (A1 -A16) to measure and calculate the areas under irrigation. Only the fields irrigated with pivot irrigation systems (circles) were measured as maize can only be planted under pivot systems. More than a thousand fields in this area were counted and measured.

Maize and wheat are the main crops produced in this area and only the residue from these crops will be considered as renewable energy resource from this area. Although other crops are planted from time to time, the residues from these (typically legume) crops are very little compared to maize and wheat residue and it is more valuable as animal feed or natural nitrogen and phosphate source to the soil and is used accordingly.

The assumptions used to estimate the agricultural residue available as renewable energy resource is given in Table 2-6 below.

Table 2-6: Assumptions used to estimate the tons of agricultural residue available

#	Description	Units	Value	Reference / Comments
1	Fields not planted with maize or wheat	%	30%	Assumption
2	Maize crops planted per year on a field	Maize crops	1	Rotational crop practices in the area
3	Wheat crops planted per year on a field	Wheat crops	0.5	Rotational crop practices in the area
4	Maize yield per hectare	ton/ha	11.6	(Grain SA, 2010)
5	Wheat yield per hectare	ton/ha	6.3	(Grain SA, 2010)
6	Residue to cereal ratio	kg/kg	1	(Lynd, et al., 2004)
7	Recoverable biomass	%	75%	Assumption

Based on the assumptions listed in Table 2-6, the estimated amount of agricultural residue available as renewable energy resource from this area is 371 951 ton/yr as detailed in Table 2-7 below.

Table 2-7: Summary of agricultural residue available

Area	Fields Measured	Total Area	Available Area	Residue			
				Maize	Wheat	Total	Exploitable
#	#	ha	ha	ton/yr	ton/yr	ton/yr	ton/yr
A1	73	2 789	1 952	22 648	6 150	28 798	21 599
A2	83	3 772	2 641	30 631	8 318	38 949	29 211
A3	56	1 886	1 320	15 315	4 159	19 474	14 606
A4	28	1 212	849	9 843	2 673	12 516	9 387
A5	18	721	505	5 855	1 590	7 445	5 584
A6	147	6 182	4 328	50 201	13 632	63 834	47 875
A7	44	1 637	1 146	13 292	3 609	16 901	12 676
A8	19	903	632	7 329	1 990	9 319	6 990
A9	105	4 549	3 185	36 941	10 032	46 973	35 230
A10	75	4 261	2 983	34 603	9 396	43 999	32 999
A11	70	2 515	1 761	20 422	5 546	25 967	19 476
A12	58	2 427	1 699	19 705	5 351	25 056	18 792
A13	58	2 427	1 699	19 705	5 351	25 056	18 792
A14	70	1 961	1 372	15 920	4 323	20 243	15 182
A15	97	2 152	1 506	17 475	4 745	22 221	16 666
A16	22	860	602	6 981	1 896	8 877	6 657
Total	**1 023**	**40 254**	**28 178**	**326 866**	**88 761**	**415 627**	**311 720**

Comparing the available agricultural residue with the overview of the area it becomes clear that there are four distinct areas where the biomass is concentrated that can be evaluated separately. These areas are:

- Areas A1 to A5 (around Prieska) 80 386 ton/yr
- Areas A6 to A8 (around Douglas) 67 541 ton/yr
- Areas A9 to A10 (around Hopetown) 68 229 ton/yr
- Areas A11 to A16 (from Orania to Vanderkloof) 95 564 ton/yr

This comprises approximately 2.6% of the total estimated agricultural residue from maize and wheat available in South Africa.

2.3. Energy Potential of the Agricultural Residue Produced in this Area

The total primary energy potential of the agricultural residue from this area is estimated at 5 362 TJ/yr or the energy equivalent of 179 000 tons of bituminous coal per year. In order to estimate the primary energy potential of the agricultural residue, some assumptions were made regarding the energy value of maize and wheat residue. These assumptions are listed in Table 2-8 and the energy potential for each area and group can be seen in Table 2-9 below.

From these estimates it is clear that all four groups have enough agricultural residues available for a number of small- to medium-scale bio-energy plants. A thorough investigation of the various technologies available and the optimum scale for each technology can be justified.

Table 2-8: Assumptions regarding the energy value of agricultural residue

#	Description	Units	Value	Source
1	It is assumed that the energy value of maize and wheat residue is the same	N/A	N/A	N/A
2	Average energy value of maize and wheat residue measured on a LHV basis	MJ/kg	17.2	Average
	Maize	MJ/kg	17.6	(Lynd, et al., 2004)
	Wheat	MJ/kg	17.5	(Lynd, et al., 2004)
	Maize	MJ/kg	16.4	(Potgieter, 2004)

Table 2-9: Energy potential of the agricultural residue produced in this area

Area	Group	Exploitable Biomass		Primary Energy Potential			
		Area	Group	Area		Group	
#		ton/yr	ton/yr	TJ/yr	MW (LHV)	TJ/yr	MW (LHV)
A1	Prieska	21 599	80 386	371	11.8	1 383	43.8
A2		29 211		502	15.9		
A3		14 606		251	8.0		
A4		9 387		161	5.1		
A5		5 584		96	3.0		
A6	Douglas	47 875	67 541	823	26.1	1 162	36.8
A7		12 676		218	6.9		
A8		6 990		120	3.8		
A9	Hopetown	35 230	68 229	606	19.2	1 174	37.2
A10		32 999		568	18.0		
A11	Orania to Vanderkloof	19 476	95 564	335	10.6	1 644	52.1
A12		18 792		323	10.2		
A13		18 792		323	10.2		
A14		15 182		261	8.3		
A15		16 666		287	9.1		
A16		6 657		115	3.6		
Total		**311 720**	**311 720**	**5 362**	**170.0**	**5 362**	**170.0**

2.4. Agricultural Residue Concentration Model

The concentration of agricultural residues that are available in the four areas identified in section 2.3 was estimated and used to develop a model to estimate the average distance that the agricultural residue need to be transported from the field to the bio-energy plant. This model will be used to determine the transport cost and also the energy efficiency of the resource collection in section 2.5.

The concentration of agricultural residue depends mainly on the geographical factors of the area over which it is spread out. The satellite images used to estimate the area under irrigation in the four areas identified were also used to estimate the area over which the agricultural residues are spread out. The crops are generally concentrated next to the Orange River, thus a model was used taking into account the length of the river through the area and the width of the developed agricultural land perpendicular to the river.

The following was determined for each of the four areas:

- Agricultural area profile for each area;
- Concentration of agricultural residue in each area;
- Available agricultural residue within a certain transport radius from one central bio-energy plant;
- Average distance that the agricultural residue needs to be transported to the plant versus the capacity of the bio-energy plant.

2.4.1. Prieska Area

The agricultural area profile for the Prieska area is shown in Figure 2-3 below.

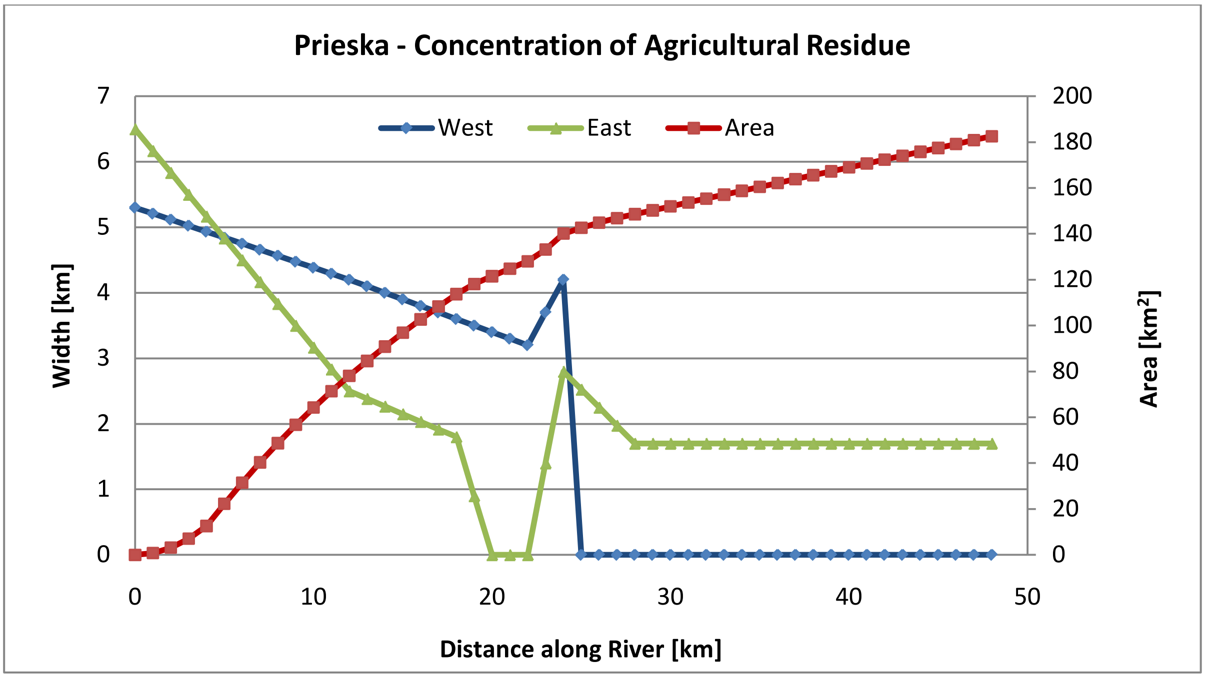


Figure 2-3: Profile of agricultural area around Prieska

Based on the available agricultural residue in the area and the area that this residue is spread out over according to Figure 2-3, the concentration of available agricultural residue in the Prieska area is 440 ton/km^2/yr.

The average distance of the agricultural residue from the bio-energy plant is plotted against the capacity of the bio-energy plant in order to evaluate the effect of capacity on transport efficiency and is shown in Figure 2-4 below.

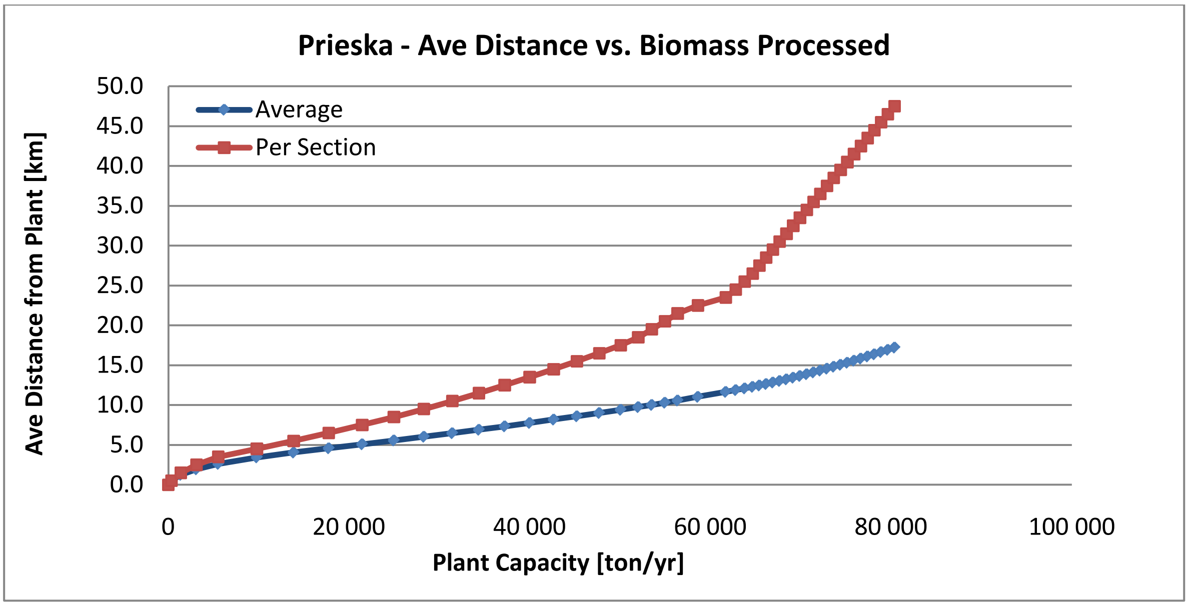


Figure 2-4: Average distance from bio-energy plant

The average distance plotted in Figure 2-4 will be used in the transport costing and energy balance models and it is thus necessary to fit the average distance as a function of plant capacity. From the geographical layout of the agricultural area around Prieska, the average distance of the agricultural residue from the bio-energy plant can be divided into two sections. The first section around the bio-energy plant is best fitted with a power function while the expansion along the river is best fitted with an exponential function.

The function fitted to the first section from 0 to 31 000 ton/yr is:

$$D_{Ave} = 0.02243 \times Cap^{0.5467} \qquad (2.1)$$

The function fitted to the second section from 31 000 to 80 000 ton/yr is:

$$D_{Ave} = 3.527e^{1.949\times10^{-5}\times Cap} \qquad (2.2)$$

2.4.2. Douglas Area

The agricultural area profile for the Douglas area is shown in Figure 2-5.

Based on the available agricultural residue in the area and the area that this residue is spread out over according to Figure 2-5, the concentration of biomass in the Douglas area is 611 ton/km^2/yr.

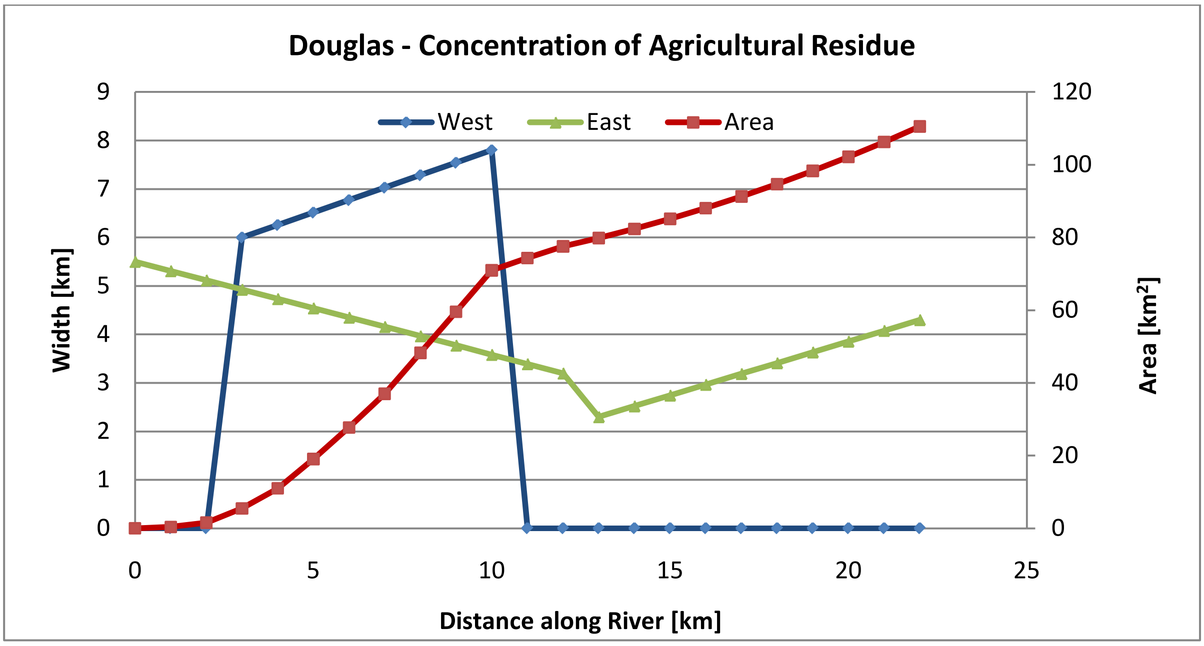


Figure 2-5: Profile of agricultural area around Douglas

The average distance of the agricultural residue from the bio-energy plant is plotted against the capacity of the bio-energy plant in order to evaluate the effect of plant capacity on transport efficiency. The results are shown in Figure 2-6 below.

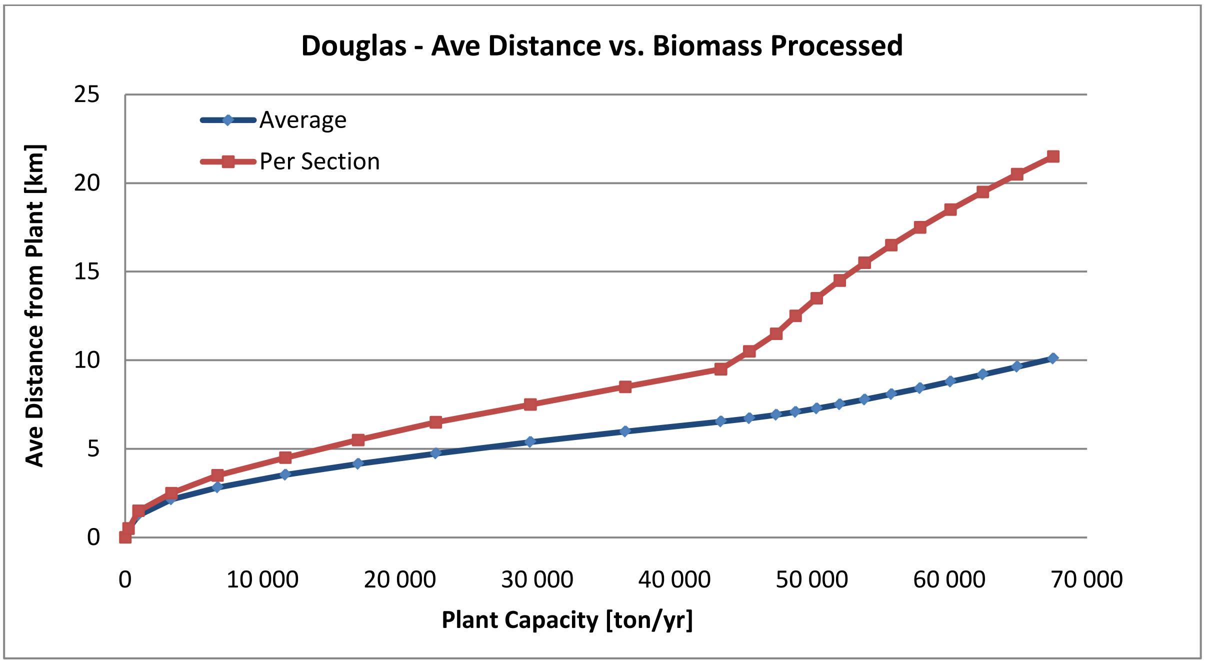


Figure 2-6: Average distance from bio-energy plant

From the geographical layout of the agricultural area around Douglas, the average distance of the agricultural residue from the bio-energy plant can be divided into two sections. The first section around the bio-energy plant is best fitted with a power function while the expansion along the river is best fitted with an exponential function.

The function fitted to the first section from 0 to 45 000 ton/yr is:

$$D_{Ave} = 0.04335 \times Cap^{0.4706} \quad (2.3)$$

The function fitted to the second section from 45 000 to 67 000 ton/yr is:

$$D_{Ave} = 2.833e^{1.882\times10^{-5}\times Cap} \quad (2.4)$$

2.4.3. Hopetown Area

The agricultural area profile for the Hopetown area is shown in Figure 2-7.

Based on the available agricultural residue in the area and the area that this residue is spread out over according to Figure 2-7, the concentration of biomass in the Hopetown area is 893 ton/km^2/yr.

The average distance of the agricultural residue from the bio-energy plant is plotted against the capacity of the bio-energy plant in order to evaluate the effect of bio-energy plant capacity on transport efficiency and is shown in Figure 2-8.

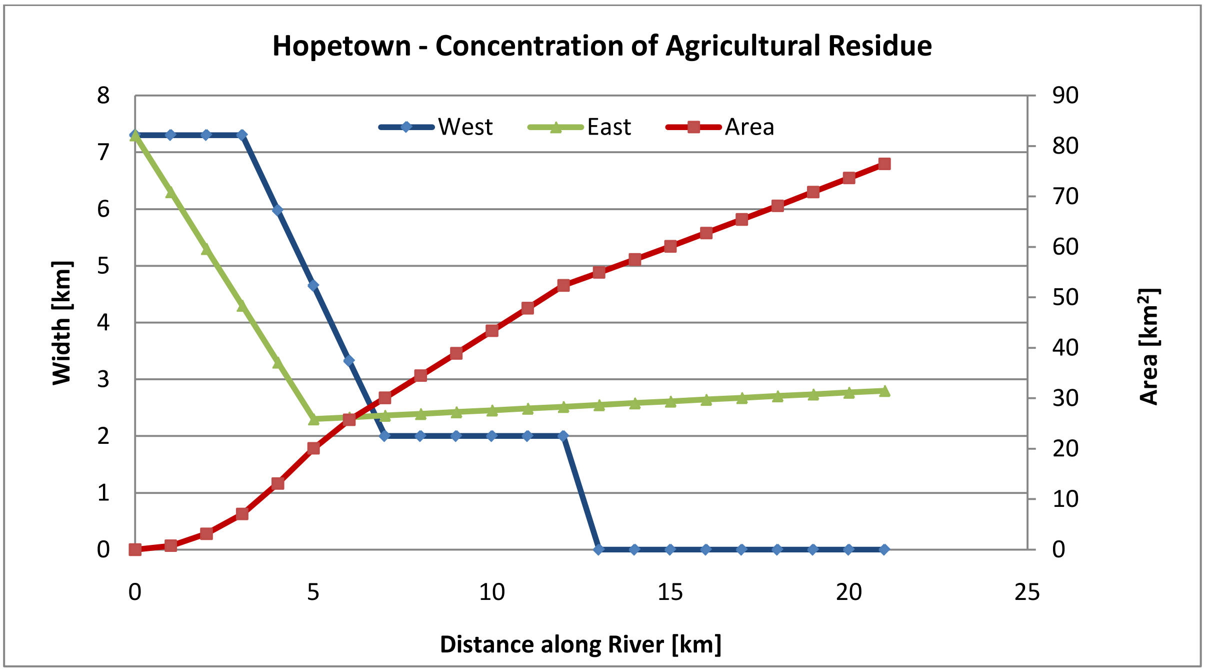


Figure 2-7: Profile of agricultural area around Hopetown

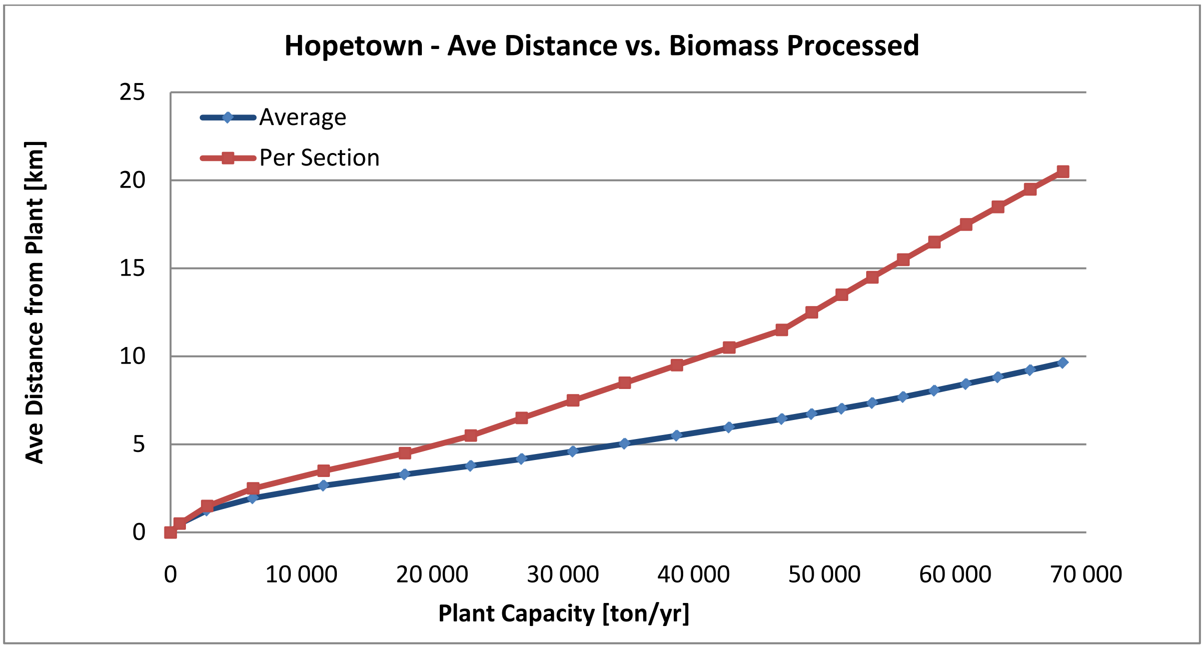


Figure 2-8: Average distance from bio-energy plant

From the geographical layout of the agricultural area around Hopetown, the average distance of the agricultural residue from the bio-energy plant can be divided into two sections. The first section around the bio-energy plant is best fitted with a power function while the expansion along the river is best fitted with an exponential function.

The function fitted to the first section from 0 to 31 000 ton/yr is:

$$D_{Ave} = 0.01257 \times Cap^{0.5709} \quad (2.5)$$

The function fitted to the second section from 31 000 to 68 000 ton/yr is:

$$D_{Ave} = 2.568e^{1.955\times10^{-5}\times Cap} \quad (2.6)$$

2.4.4. Orania to Vanderkloof Area

The agricultural area profile for the Orania to Vanderkloof area is shown in Figure 2-9.

Based on the available agricultural residue in the area and the area that this residue is spread out over according to Figure 2-9, the concentration of biomass in the Orania to Vanderkloof area is 576 ton/km^2/yr.

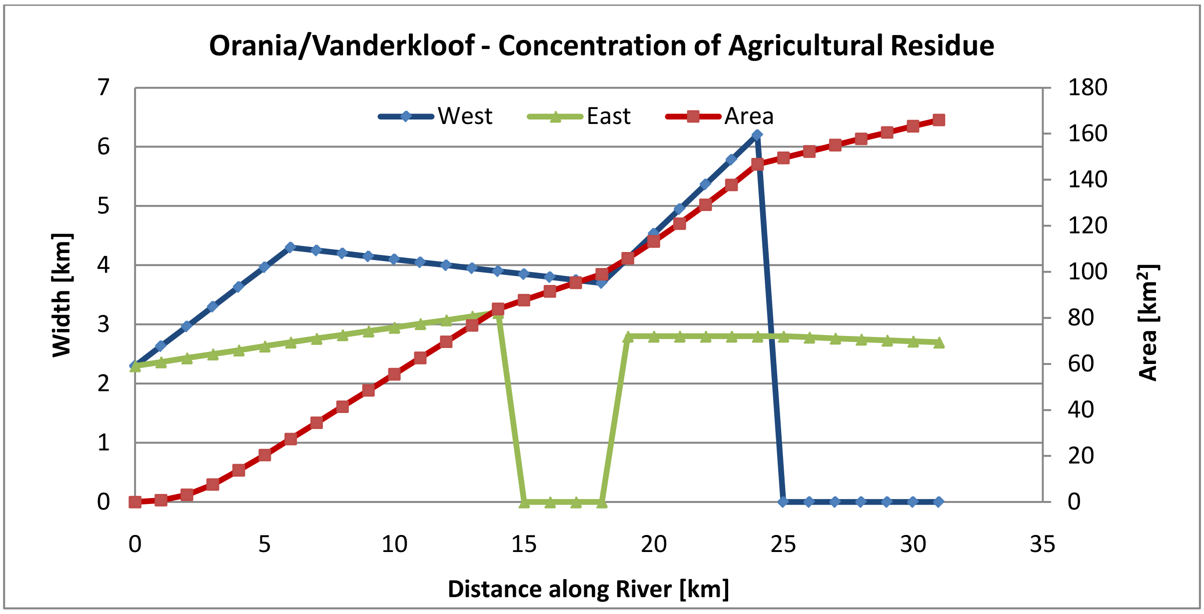


Figure 2-9: Profile of agricultural area between Orania and Vanderkloof

The average distance of the agricultural residue from the bio-energy plant is plotted against the capacity of the bio-energy plant in order to evaluate the effect of bio-energy plant capacity on transport efficiency and is shown in Figure 2-10 below.

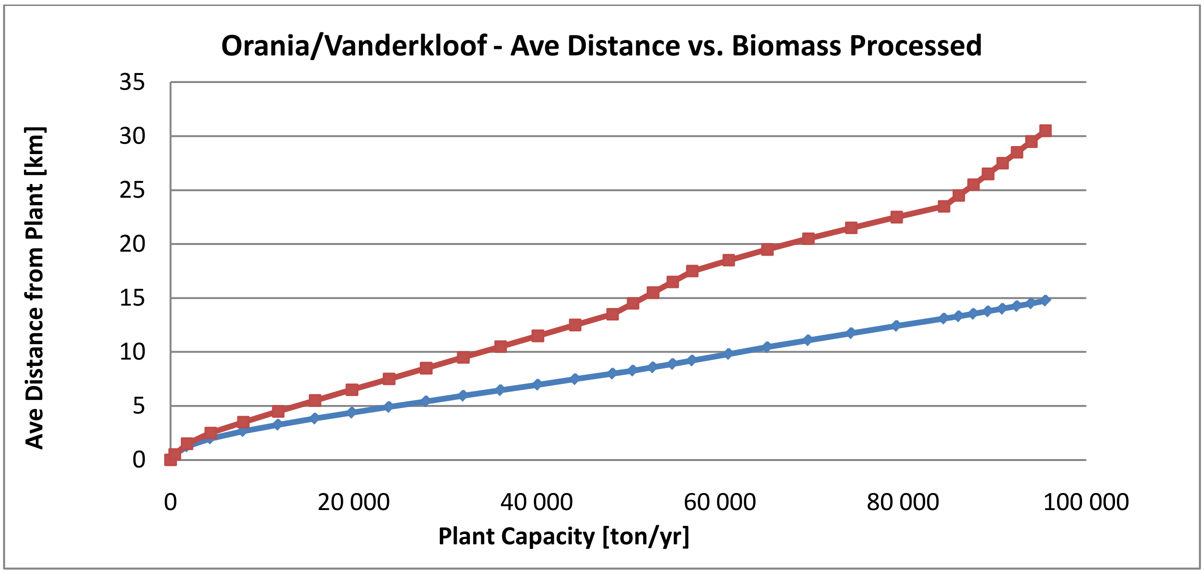


Figure 2-10: Average distance from bio-energy plant

From the geographical layout of the agricultural between Orania and Vanderkloof, the average distance of the agricultural residue from the bio-energy plant can be divided into two sections. The first section around the bio-energy plant is best fitted with a power function while the expansion along the river is best fitted with a linear function and not exponential like the other areas.

The function fitted to the first section from 0 ton/yr to 40 000 ton/yr is:

$$D_{Ave} = 0.01624 \times Cap^{0.5686} \tag{2.7}$$

The function fitted to the second section from 40 000 ton/yr to 95 000 ton/yr is:

$$D_{Ave} = 1.411 \times 10^{-4} \times Cap + 1.208 \tag{2.8}$$

2.5. Cost and Energy Balance of Agricultural Residue Resource

The cost of transportation and the energy required to collect and deliver huge amounts of agricultural residue to a bio-energy processing plant is one of the biggest factors determining the financial and environmental feasibility of agricultural residue as renewable energy resource.

The efficiency and cost of transportation associated with the collection thereof and transportation to a central processing plant depend on many different independent variables:

- The concentration factor (section 2.4);
- The capacity of the bio-energy plant;
- The location of the bio-energy plant;
- The density of the biomass transported;
- The mode of transport used to collect the biomass.

The concentration factor – The concentration factor for each area was investigated in detail in section 2.4 and is given as a function of plant capacity in equation 2.1 to 2.8.

Capacity of the bio-energy plant – For the transport model, the full range of agricultural residues available in each area was used to evaluate and plot the increasing transport requirements with increasing capacity.

Location of the bio-energy plant – The location of the bio-energy plant for each area was selected by visual inspection of the area from the satellite images based on available land, road access and proximity to the available agricultural residue in the area.

Density of biomass transported – It was assumed that the agricultural residue will be baled for transportation to the processing plant. The bulk density of these bales typically varies between 80 kg/m^3 and 200 kg/m^3. A bulk density of 150 kg/m^3 was used for the purpose of this study.

The mode of transport used to collect the agricultural residues – It was assumed that general six-axle trucks with volume and weight limitation of (12 x 2.4 x 2.6) 75 m^3 and 32 ton will be used to transport the baled agricultural residues (Road Freight Association, 2010).

Based on the variables and selections above, a model was developed to estimate the total cost of agricultural residues as well as the energy efficiency and input required to get the agricultural residues to the bio-energy plant.

2.5.1. Biomass Resource Cost Estimate

The cost of agricultural residue can be divided into two portions. Firstly the cost of the biomass, and secondly the cost associated with the transportation of the biomass to the bio-energy plant.

Currently there is not an existing market for agricultural residue in South Africa, thus the value of this type of biomass is not established yet. This poses a major risk, but also potential reward to the investors and the development of agricultural residue as renewable energy resource as the demand and price will be determined by the renewable energy sector until a more diverse demand for agricultural residues has developed. The cost of the biomass is independent of the capacity of the bio-energy plant, the concentration of the agricultural residue or the conversion technology used in the bio-energy plant. This cost will cover as a minimum all the cost incurred by the farmer to collect and bale the residue to get it ready for transportation. None of the production cost is included as part of the agricultural residue cost as it is assumed that all the production costs will be covered by the income from the actual crops. The residue is a waste product that currently does not posses a value.

The cost of transportation is generally quoted as R/ton/km and depends on the transport market. For the type of truck that was assumed to be used for transportation of the agricultural residue, the current cost is R0.85/ton/km (Road Freight Association, 2010). As a result of the low bulk density of the agricultural residue, this cost needs to be adjusted based on the maximum volume that this truck can carry and the bulk density of the agricultural residue. From the above discussion the total cost of resources can be simplified and expressed as a function of the material cost, transport rate, bulk density, concentration factor of the area, and plant capacity as given in equation 2.9.

$$C_{Resource} = C_{Material} + C_{Transport} \quad (2.9)$$

$$C_{Transport} = T_{rate} \times \frac{L_{max}}{V_{max} \cdot \rho_{bulk}} \times D_{Ave} \quad (2.10)$$

$$C_{Resource} = C_{Material} + T_{rate} \times \frac{L_{max}}{V_{max} \cdot \rho_{bulk}} \times D_{Ave} \quad (2.11)$$

$C_{Resource}$	= Total cost of the resource [R/ton].
$C_{Transport}$	= Cost to transport agricultural residue to the plant [R/ton].
T_{Rate}	= Transport rate [R/ton/km].
V_{max}	= Maximum volumetric load that the truck is allowed to transport [m^3].
ρ_{bulk}	= Bulk density of baled agricultural residue [ton/m^3].
D_{Ave}	= Average distance of the agricultural residue from the bio-energy plant as a function of plant capacity (Eq 2.1 to 2.8) [km].

The total cost of resources for each of the four areas is plotted in Figure 2-11 below based on equation 2.11 and the concentration factor for each area given in equation 2.1 to 2.8.

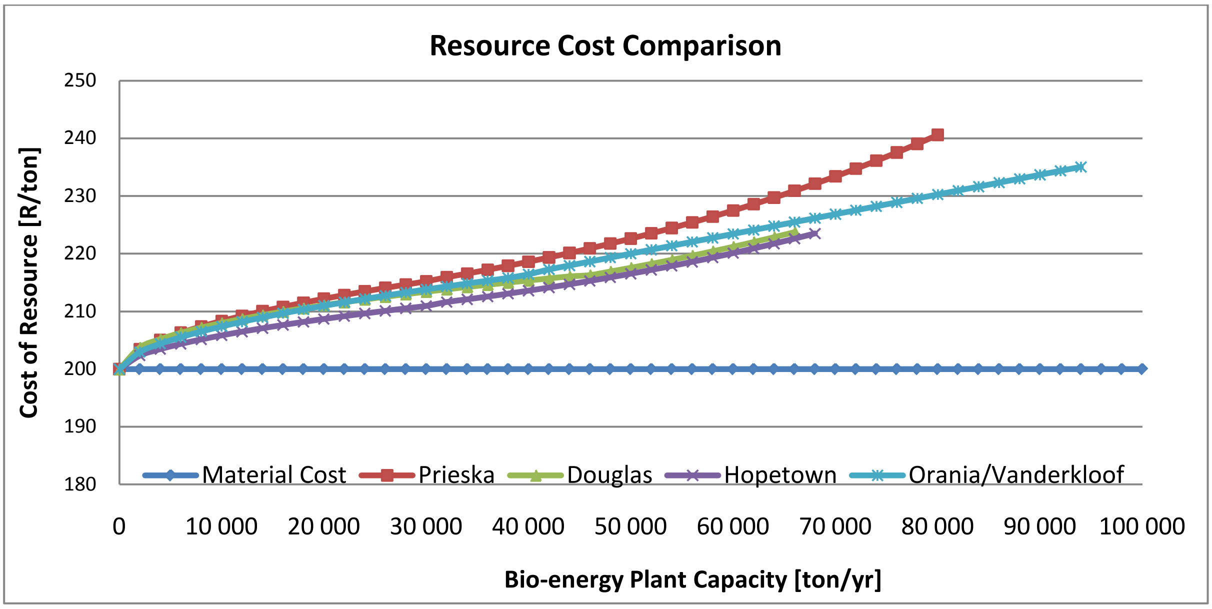


Figure 2-11: Total cost of agricultural residue as for each area

From Figure 2-11 it can be seen that the material cost is independent of the plant capacity while the cost of transportation varies with the plant capacity. The transportation cost increases with the capacity of the plant. The Hopetown agricultural area has the lowest resource cost because of the lower transportation cost. This is mainly a result of the geographical factors and layout of the area.

2.5.2. Energy Balance

An important part of evaluating a renewable energy resource and conversion technology is the final overall energy balance of the product. Thus, all the energy units required to produce one unit of energy product from the resource. Part of this overall energy balance is the energy requirement to transport the material from the field to the bio-energy plant. Once again, the energy inputs required to produce the biomass is taken as zero as it is a waste product in the production of food.

The energy input is mainly in the form of diesel used during transport and the energy used per ton of agricultural residue can be modelled as a function of:

- Concentration factor as a function of plant capacity – D_{Ave};
- The density of the biomass transported – ρ_{bulk};
- The mode of transport used to collect the biomass;
- Diesel consumption – F_{Cons}.

$$F_{Resource} = D_{Ave} \times \frac{F_{Cons}/100}{V_{max} \times \rho_{bulk}} \tag{2.12}$$

$$E_{Resource} = D_{Ave} \times \frac{F_{Cons}/100}{V_{max} \times \rho_{bulk}} \times E_{Diesel} \tag{2.13}$$

$F_{Resource}$ = Fuel usage per ton of resource [L diesel/ton].
F_{Cons} = Fuel consumption of the truck [L/100km]. An average of 55 L/100km was used (Road Freight Association, 2010).
$E_{Resource}$ = Energy input per ton of resource [MJ/ton].
E_{Diesel} = Energy value of diesel [MJ/L].

The average fuel consumption and energy input per ton of agricultural residue transported to the bio-energy plant is shown in Figure 2-12 and Figure 2-13 below.

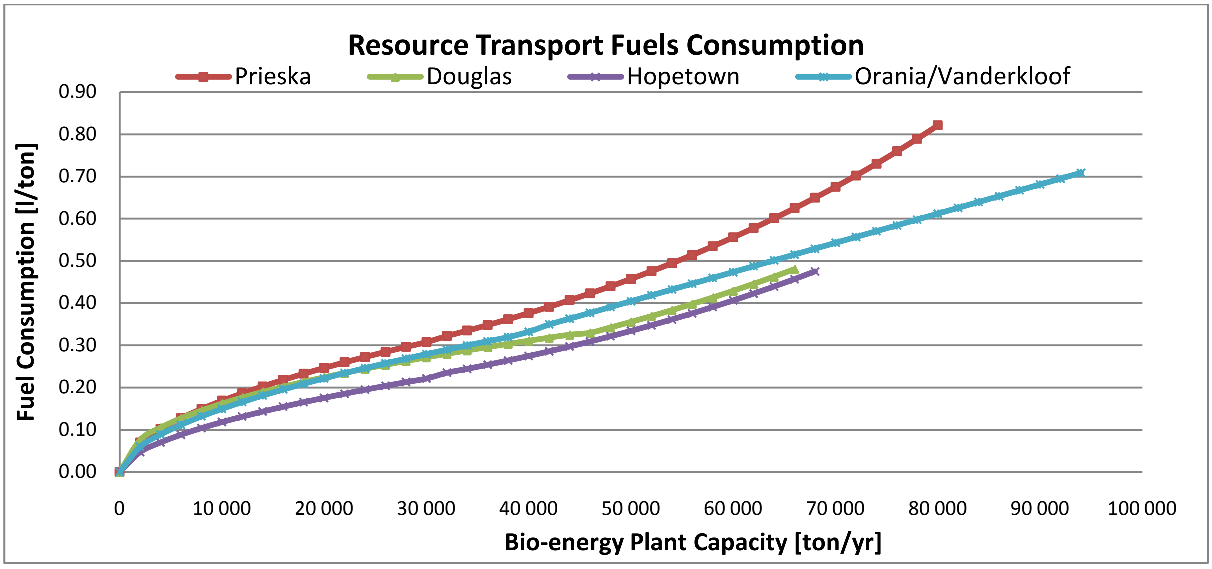


Figure 2-12: Transport fuel consumption per ton of agricultural residue

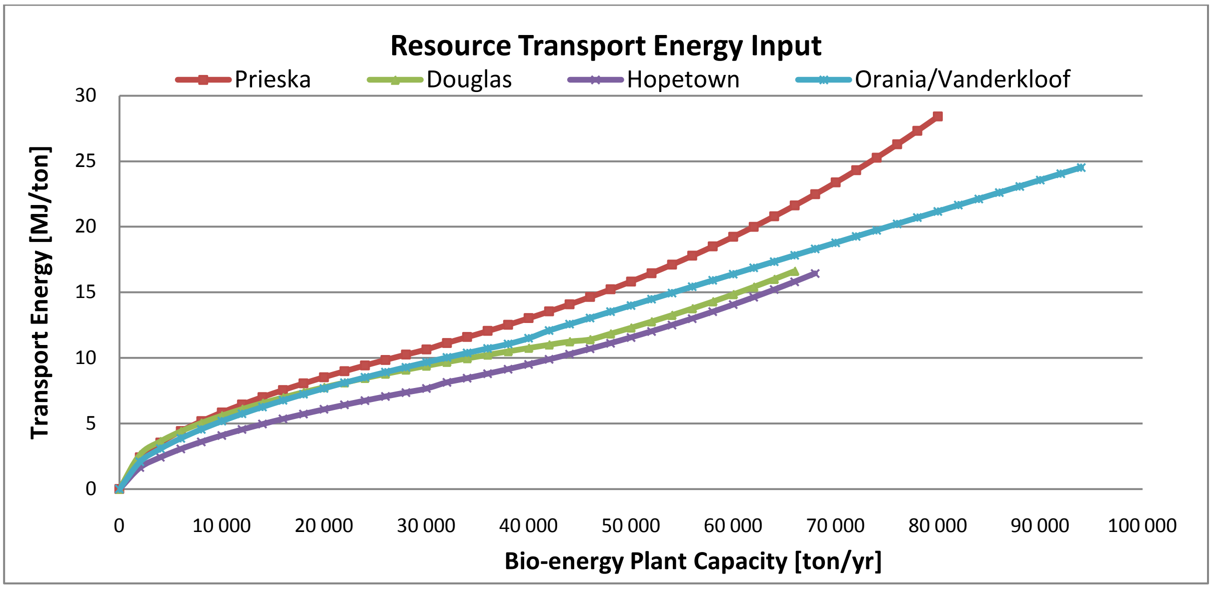


Figure 2-13: Energy input per ton of agricultural residue transported to bio-energy plant

From Figure 2-12 and Figure 2-13 it can be seen that the Hopetown area has the lowest fuel consumption and energy input per ton of agricultural residue transported to the bio-energy plant.

3. BIOMASS CONVERSION TECHNOLOGY

3.1. Overview of Biomass Conversion Technologies

A biomass conversion technology is any technology or process that is used to convert a biomass resource into a more useful form of energy or a higher grade of bio-fuel. As discussed in the previous chapter, there are many different types of biomass available. In this chapter, the main technologies that exist to convert these types of biomass into a more useful form of energy will be discussed briefly in order to select the conversion technologies with the highest potential to convert agricultural residue into a more useful form of energy.

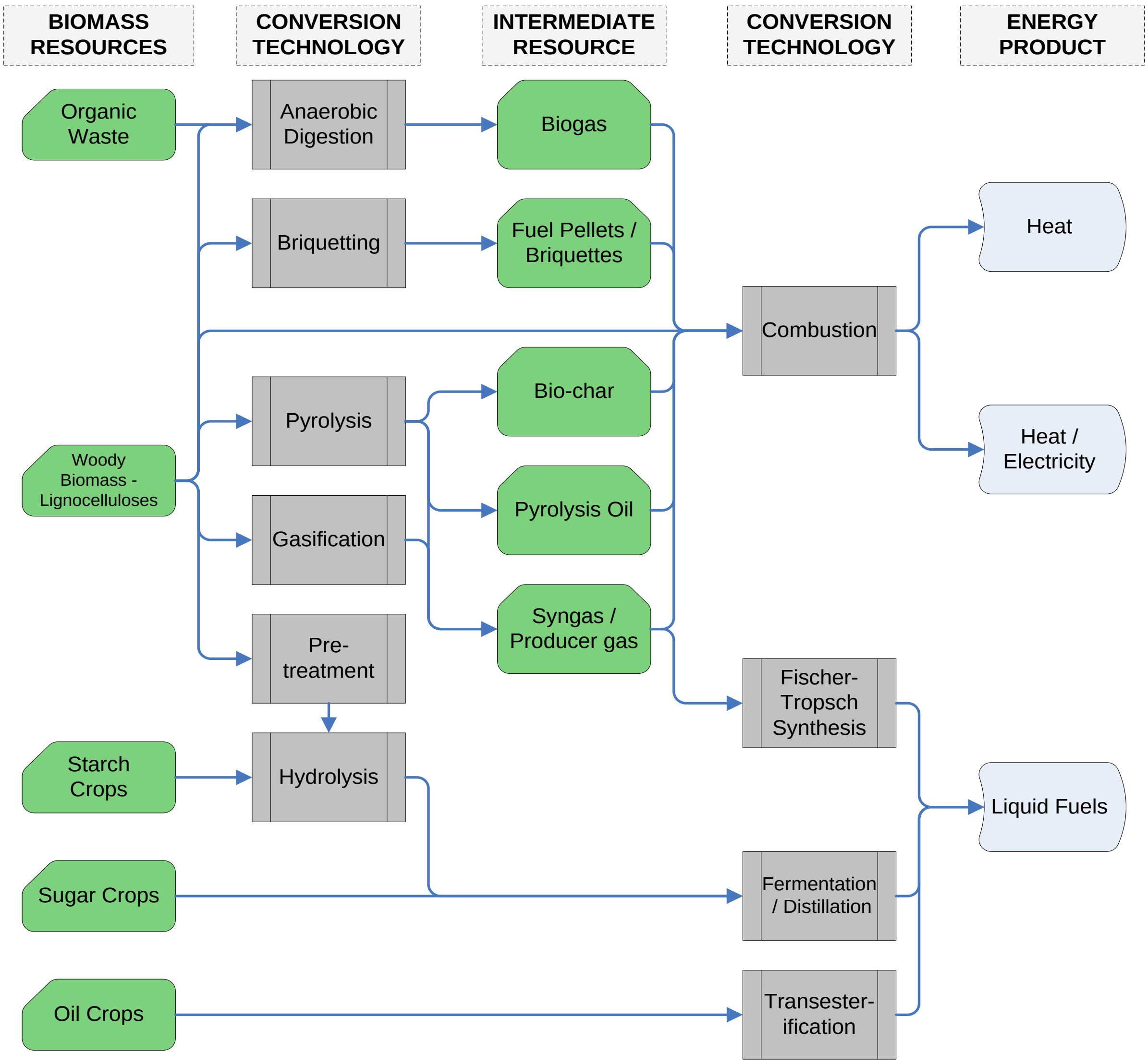


Figure 3-1: Superstructure showing different biomass conversion options

The main types of biomass resources, biomass conversion technologies and energy products with their conversion paths are illustrated with the superstructure in Figure 3-1 above.

3.1.1. Combustion

Combustion of biomass is the oldest, simplest and most common energy technology and is used to convert biomass or fossil fuels into thermal energy that can be used for anything from open fire cooking to ultrahigh pressure boilers for electricity generation. The combustion of woody biomass is widely used in South Africa for cooking and domestic heating purposes, especially in the rural areas where there are no connections to electricity. The efficiency of open flame heating and cooking can be as low as 10%. New low-cost technologies exist that can increase this efficiency to 70-90%. These cooking devices should be made available and distributed throughout the country to promote the sustainable use of biomass in South Africa.

The combustion technologies are based on the exothermic oxidation reaction that takes place when woody biomass is burned as in the reaction below (Huber, et al., 2006).

$C_aH_{4b}O_{2c} + (a+b-c)O_2 \rightarrow aCO_2 + 2bH_2O + \text{heat}$

Depending on the amount of oxygen available and the completion of the reaction, carbon monoxide is also formed in variable amounts. Larger scale combustion takes place in boilers to produce low pressure steam for heating or high pressure steam to drive turbines to generate electricity.

3.1.2. Briquetting

Briquetting is the technology to compress large volumes of low density biomass into fuel pellets or briquettes that has a higher mass and energy density. These fuel pellets are then used as feedstock for combustion processes to convert the biomass into heat or electricity.

Traditionally, briquetting is not classified as a bio-energy technology as it does not convert the biomass into another form of energy. However, in the context of this research project, briquetting is classified as a biomass conversion technology as it converts a biomass resource into a more dense and useful form of energy resource. The most significant value of this technology is in the saving of transport costs and energy when evaluating the conversion efficiency of biomass as a whole.

A typical biomass briquetting plant consists of a material size-reduction step, drying or moisture-control step and a briquetting press.

3.1.3. Pyrolysis

Pyrolysis is the thermal degradation of biomass at high temperatures between 350-600°C in the absence of oxygen. The pyrolysis products are in the form of gasses, bio-oil and charcoal. Different pyrolysis technologies exist to manipulate the preferential production of bio-oil or charcoal.

The three main pyrolysis technologies are slow pyrolysis, vacuum pyrolysis and fast pyrolysis. Slow pyrolysis is the thermal degradation of biomass in the presence of very limited oxygen allowed to enter the reactor to drive the thermal process. Slow pyrolysis is widely used to produce charcoal as this technology produce high yields of charcoal. This technology unfortunately also results in higher concentrations of ash in the charcoal that results from the combustion reaction that takes place with the limited amount of oxygen that is allowed into the reactor.

Fast pyrolysis takes place at higher temperatures between 450-600°C in the absence of oxygen. The pyrolysis reactor is kept free of oxygen by the addition of an inert gas like nitrogen or argon to displace the oxygen (Huber, et al., 2006). Fast pyrolysis produces a high yield of bio-oil compared to slow pyrolysis.

Vacuum pyrolysis takes place under vacuum to ensure that there is no oxygen in the reactor, but is not a very popular technology on industrial scale because of the vacuum that needs to be maintained. The handling of the pyrolysis gasses under vacuum also requires larger equipment which adds to the high cost of a vacuum pyrolysis plant (Gorgens, 2007).

3.1.4. Gasification

Gasification is a thermal technology where carbonaceous materials such as biomass are converted to syngas by a complex combination of pyrolysis, partial oxidation and steam gasification reaction at high temperatures above 800°C (Huber, et al., 2006). Syngas contains mainly CO, CO_2, H_2, CH_4 and small amounts of other impurities such as N_2, NO_x, S, SO_x etc depending on the feedstock. A list of the typical gasification reactions is shown in Table 3-1 below.

Table 3-1: Typical gasification reactions (Huber, et al., 2006)

classification	stoichiometry	enthalpy (kJ/g-mol) ref temp 300 K
pyrolysis	$C_6H_{10}O_5 \rightarrow 5CO + 5H_2 + C$	180
	$C_6H_{10}O_5 \rightarrow 5CO + CH_4 + 3H_2$	300
	$C_6H_{10}O_5 \rightarrow 3CO + CO_2 + 2CH_4 + H_2$	−142
partial oxidation	$C_6H_{10}O_5 + \frac{1}{2} O_2 \rightarrow 6CO + 5H_2$	71
	$C_6H_{10}O_5 + O_2 \rightarrow 5CO + CO_2 + 5H_2$	−213
	$C_6H_{10}O_5 + 2O_2 \rightarrow 3CO + 3CO_2 + 5H_2$	−778
steam gasification	$C_6H_{10}O_5 + H_2O \rightarrow 6CO + 6H_2$	310
	$C_6H_{10}O_5 + 3H_2O \rightarrow 4CO + 2CO_2 + 8H_2$	230
	$C_6H_{10}O_5 + 7H_2O \rightarrow 6CO_2 + 12H_2$	64
water-gas shift	$CO + H_2O \rightarrow CO_2 + H_2$	−41
methanation	$CO + 3H_2 \rightarrow CH_4 + H_2O$	−206

Syngas can be used in many different processes of which combustion, electricity generation and the production of liquid fuels are the most popular. Syngas is combusted in boilers for heat or to generate electricity through steam turbines, it can also be combusted in combined cycle power plants for electricity generation or alternatively be converted into liquid fuels using the Fischer-Tropsch Synthesis technology.

The presence of tar (high molecular weight hydrocarbons) in the syngas produced from biomass is one of the biggest technical challenges for large-scale biomass gasification plants.

3.1.5. Fischer-Tropsch Synthesis

The Fischer-Tropsch synthesis (FTS) technology converts syngas into a range of straight chain hydrocarbons over a Fischer-Tropsch catalyst. The range of hydrocarbons formed include C_1 - C_{50} chains that is governed by the Anderson-Schulz-Flory polymerisation model that can be manipulated by changing the CO/H_2 ratio that is fed into the reactor to produce different products like petrol, diesel, waxes, etc. (Huber, et al., 2006).

The overall FTS reaction is:

$CO + 2H_2 \rightarrow (1/n)C_nH_n + H_2O$ (Huber, et al., 2006).

One of the disadvantages of FTS is that a wide range of products are formed even though the CO/H_2 ratio is optimised for the desired product. This means that further refinement of the product is necessary. This is not a technology that can be developed on a small scale.

3.1.6. Bio-Ethanol Technologies

The production of bio-ethanol is a well established technology, especially ethanol production from sugarcane. Bio-ethanol production from maize is also well established, specifically in the USA even though it receives a lot of criticism based on the overall energy efficiency of the process and also from the food vs. fuel debate. Bio-ethanol from lignocellulose material shows huge potential, but is still under development.

Bio-ethanol can be produced from three different types of feedstock: sugar, starch or lignocellulosic material, each requiring different technologies or process steps to produce bio-ethanol. These technologies are discussed below.

Bio-ethanol from Sugar Based Feedstock

Ethanol is produced by the yeast fermentation of sugars in the absence of oxygen. The fermentation reaction of glucose into ethanol and carbon dioxide is as follows:

$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + CO_2$

Feedstock such as sugarcane and sugar beet can be fermented directly as the feedstock is sugar based. This is also the reason why bio-ethanol production from sugarcane is the most economical, most energy-efficient and also the most established of the bio-ethanol technologies. The energy efficiency of bio-ethanol produced from sugarcane is typically between 8 and 10, thus 8-10 units of energy are produced for every unit of energy input required in the production thereof (Gorgens, 2007).

Bio-ethanol from Starch Based Feedstock

Production of bio-ethanol from a starch based feedstock such as maize or wheat requires an additional hydrolysis or saccharification process step before fermentation as described above. The reason for this is that starch is a polysaccharide consisting of many monosaccharides joint together. In the case of starch, this monosaccharide is glucose. Thus, in order to convert starch into glucose that is fermentable, the polysaccharamide needs to be enzymatically hydrolysed or broken down into its monosaccharamides in a saccharification process.

Traditionally, saccharification and fermentation were achieved in separate reactors mainly because the hydrolysis enzymes and the fermentation yeasts could not perform efficiently in the same reactor under the same conditions. This process is known as Separate Hydrolysis and Fermentation (SHF). Recent developments has seen new enzymes being developed that can hydrolyse starch in the presence of fermenting yeast and under the same optimal process conditions. In fact, the simultaneous fermentation of glucose reduces the glucose concentration in the reactor increasing the hydrolysis reaction rate and improving the overall efficiency of the process. It also decreased the capital cost associated with this process as fewer reactors and controls are required. This process is known as Simultaneous Saccharification and Fermentation (SSF) (Gorgens, 2007).

This technology is well established in the USA where it is heavily subsidised. The biggest technical drawback of this technology producing bio-ethanol from maize is that it has a very poor energy balance of 1.34 J/J (Gorgens, 2007). On an ethical level, there is also criticism against the production of bio-ethanol from starch in that starch is the staple food of the world and the large scale utilisation of starch for bio-fuel will increase the price of food.

Bio-ethanol from Lignocellulose

The commercialisation of bio-ethanol production from lignocellulosic materials is still under development with the biggest challenge being cost reduction.

Lignocellulosic material consists of cellulose, hemicellulose and lignin. Similar to starch, cellulose and hemicellulose are also polysaccharides, but instead of being made up of only glucose, they are made up from five different types of sugars that need to be hydrolysed enzymatically as well as fermented together. This poses unique challenges as the process is much more complex than the saccharisation and fermentation of starch.

The physical structure of lignocellulosic material inhibits digestion of the material that is required in the saccharification and fermentation process and result in very poor conversion efficiencies if a pre-treatment step is not included to break open the material structure to allow better access for the enzymes. There are many pre-treatment options available, but the ones showing the most potential are: wet oxidation, hydrothermal pre-treatment, dilute acid pre-treatment, base treatment and ammonia fibre explosion. These pre-treatment steps are all still under development and research are being focused on improving and optimising the pre-treatment step.

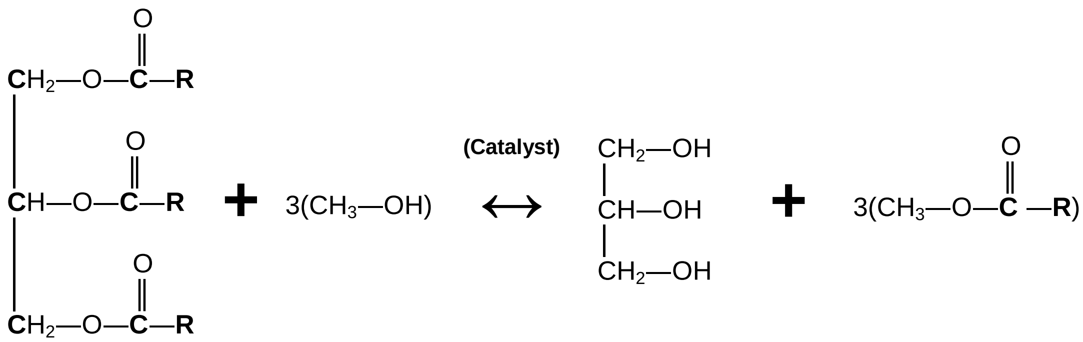
The energy efficiency of bio-ethanol production from lignocellulosic material from energy crops were determined in a study done by the National Renewable Energy Laboratory to be 2.6, and that from agricultural waste is expected to be as high as 5 (Gorgens, 2007).

This technology unfortunately is not yet economically robust and needs further development and optimisation before it can be commercialised on a broad base.

3.1.7. Biodiesel Technologies

Biodiesel can be produced from a variety of fats and oils by a simple transesterification process. There are a few different types of transesterification processes that can be used to produce biodiesel and depending on the type of feedstock used, the most efficient and economical process will be selected.

The typical transesterification reaction is given below. Methanol and a catalyst are added to the triglyceride (bio-oil) to form glycerol and fatty acid methyl esters (bio-diesel).



Triglyceride | 3 x Methanol | Glycerine | 3 x FAME (Biodiesel)

The two most common processes used are the acid and base catalysed transesterification processes where an acid or a base is used as catalyst in the reaction described above. NaOH is usually used as catalyst in the base catalysed process as this process has the advantage of very fast reaction times compared to the acid catalysed process.

A typical biodiesel plant will include the following process steps:

1. Feedstock handling and preparation
2. Oil press to release the oil from the seed crops (if seed crops are used as feedstock)
3. Transesterification reactor
4. Biodiesel, catalyst and glycerine separation
5. Biodiesel washing

3.1.8. Anaerobic Digestion

Biogas is produced as by-product in the anaerobic digestion of biomass by micro-organisms that happen naturally under the right conditions and in the absence of oxygen. When anaerobic digestion is used as a biomass conversion technology, biogas becomes the product and the conditions under which the digestion takes place are manipulated to produce the maximum amount of biogas per kilogram biomass digested. The net overall reaction that describes the conversion of biomass to biogas is given below using Buswell's approach (Stafford, et al., 2007).

$$C_aH_bO_cN_d \; + \; (4a-b-2c-3d)/4H_2O \quad \rightarrow \; C\,H_4 \; + \; (4s-b+2c+3d)/8\,CO_2 + dNH_3$$

Anaerobic digestion is a three-stage process:

1. Hydrolysis is the first step where complex biomass structures are broken down into simpler organic compounds by saprophytic bacteria;
2. Acidification is the second step where these simpler organic compounds are converted into volatile fatty acids by acid forming bacteria;
3. The third step is where methanising bacteria convert these volatile fatty acids into methane.

During these three steps, biogas consisting of methane, carbon dioxide hydrogen, nitrogen, hydrogen sulphide and water vapour is produced.

Many different types of anaerobic digesters like the up-flow anaerobic sludge blanket (UASB) reactor, plug-flow reactor, stirred reactor and the baffled reactor have been developed over the years to produce the maximum biogas for different types of biomass feed. One of the biggest advantages of anaerobic digestion is that it is a simple technology that is efficient and economically viable for small- and large-scale reactors alike.

3.2. High Level Evaluation and Selection of Conversion Technologies

As shown in Figure 3-1, and discussed in the previous section: combustion, briquetting, pyrolysis, gasification, Fischer-Tropsch synthesis, third generation bio-ethanol technologies and anaerobic digestion can be used to convert agricultural residue into a more useful form of energy:

The purpose of the high level evaluation and technology selection is to identify the technologies with the highest potential according to the research objectives and to eliminate the technologies not applicable.

The seven technologies are rated relative to each other on the following questions:

- What is the current status of development of the technology? Still under development, commercialised or mature?
- What is the technical feasibility of the technology? Is it a robust proven technology?
- What is the capital cost per unit energy produced relative to the other technologies?
- Energy efficiency of the technology? Conversion rate of raw feedstock to product?
- Energy balance? Energy input per energy output?
- Can the technology be implemented on a small scale?

Each technology was given a rating relative to the other technologies between 0 and 2, 0 being poor, 1 fair and 2 good. The results are shown in Table 3-2 below.

Table 3-2: High level evaluation of technologies

#	Description	Technology Applicable to Agricultural Residue						
		Combustion	Briquetting	Pyrolysis	Gasification	Bio-ethanol	FTS	Anaerobic Digestion
1	Current Status of Development	2	2	1	1	1	1	2
2	Current Technical Feasibility	2	2	2	2	1	1	2
3	Capital Cost	2	2	1	1	0	0	1
4	Energy Efficiency	1	1	2	2	2	2	0
5	Energy Balance	2	1	2	2	1	1	1
6	Viability of Small Scale Systems	2	2	2	2	0	0	2
		11	10	10	10	5	5	8

According to the high-level evaluation, the four technologies with the highest potential according to the research objectives are combustion, pyrolysis, gasification and briquetting.

Anaerobic digestion was eliminated mainly because of the low energy efficiency, energy balance and high capital cost of the technology based on agricultural residue as feedstock.

Anaerobic digestion has a low energy efficiency because it is a wet technology. Water has to be added to the relatively dry agricultural residue in order to break it down and digest. Agricultural residue is a difficult source of carbon to digest in an anaerobic digester as long digestion times are required to break down the lignin and waxes into digestible volatile fatty acids. Thus the carbon conversion efficiency is low and very large reactors are required, increasing the capital cost of the technology. The energy balance of the technology is also low as large amounts of nutrients have to be added to digest the biomass (Gerardi, 2003). This can however be mitigated by the addition of nutrient-rich manure or sewage to the reactor.

Bio-ethanol production from lingo cellulose materials was eliminated mainly because of the high cost, large scale and current development status. Third generation bio-ethanol technologies are still under development and although there are commercial plants currently being operated, the technology is still very expensive. This technology also requires large-scale plants to use the economy of scale to make it financially viable, thus small-scale plants is not currently feasible.

Fischer-Tropsch synthesis was eliminated mainly because of its high cost, large scale and current state of development. FTS does not use agricultural residue directly as feedstock, but rather the producer gas from the pyrolysis or gasification of agricultural residue to produce liquid fuels. Although FTS is widely used to produce liquid fuels from syngas derived from the gasification of coal, the use of producer gas is still under development. The financial viability of this technology is also based on large economies of scale and small scale application is not financially viable.

3.3. Briquetting of Agricultural Residue

Briquetting of agricultural residue is one of the technologies selected to investigate in more detail. The briquetting process, energy balance and efficiency, capital cost and operating cost are discussed below.

3.3.1. Briquetting Process

A process block flow diagram of a typical briquetting plant is shown in Figure 3-2 below. The briquetting plant consists of: feedstock offloading and storage area, material size reduction, dryer or moisture control, briquetting press and the briquette handling and storage area.

The feedstock offloading and storage area is required for the handling and storage of raw material. As the bales delivered are too heavy to manhandle, this area will include overhead cranes and conveyor systems. One of the main risks associated with the handling and storage of large volumes of dry agricultural residue is fire. The mitigation of fire risk needs to be addressed in the design of this facility.

The two most important factors in the briquetting of agricultural residue are the particle size and moisture content of the material. The first step in processing agricultural residue is to reduce the size of the material. Size reduction is done before drying as the shredded material is dried more effectively. The optimum particle size for briquetting depends on the briquetting equipment used, but studies have shown that the optimum particle size for densification of agricultural residue is between 6 and 8 mm (Grover, et al., 1995). Material size reduction is done by a rotating blade type shredder that is most effective for this application. The shredded material is screened and the oversize material returned to the shredder while the correct size fraction is fed to the moisture control section.

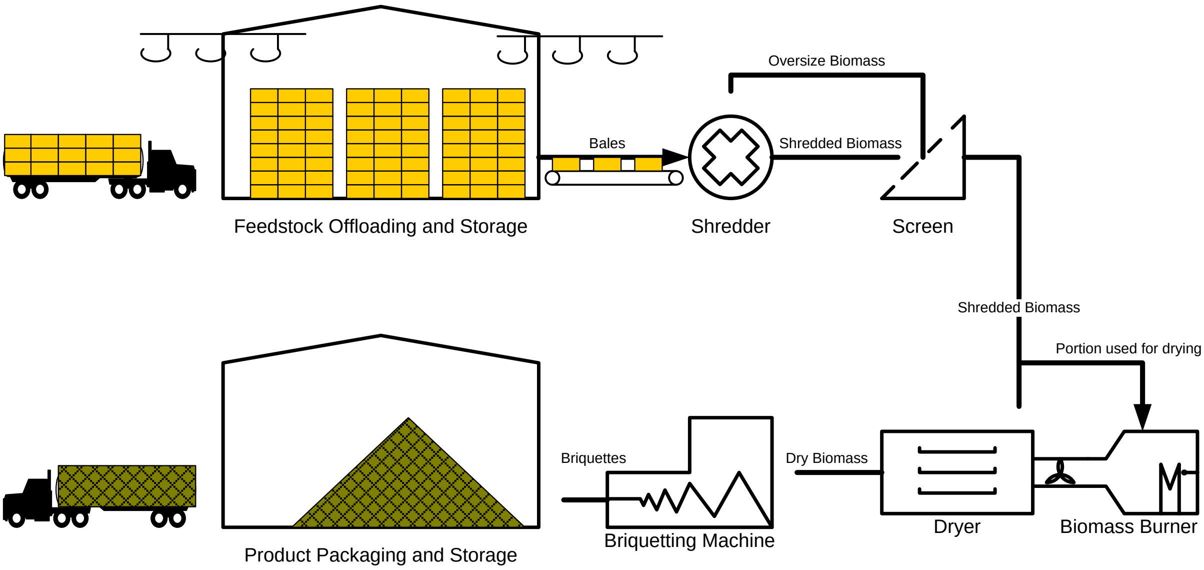


Figure 3-2: Typical agricultural residue briquetting process overview

Fresh agricultural residue generally has a moisture content of between 10 and 20% (Nikolaisen, et al., 1998). Studies by Mani and Tabil have shown that the optimum moisture content for achieving the highest density and most stable briquettes from corn stover is between 5 and 10% measured on a wet basis (Mani, et al., 2006). In order to reduce the moisture from 15 to 7.5%, the shredded material is dried in a rotary drum dryer. A portion of the material is burned in a biomass burner to supply the dryer with heat to dry the rest of the material before briquetting. Biomass is used as heat source as it is available. Although it reduces the conversion efficiency, it increases the energy balance as less fossil fuel is required in the production of the briquettes. The shredded and dried agricultural residue is now ready for briquetting.

The densification of agricultural residue into briquettes is achieved by forcing the individual particles together by applying mechanical pressure to form inter-particle bonds. This process can be assisted by the addition of binders such as molasses or starch (Kaliyan, et al., 2010). However, studies have shown that raw agricultural residue has sufficient natural binders such as lignin and proteins that are expressed during the briquetting process to form stable briquettes without the addition of binders (Kaliyan, et al., 2010).

Fuel briquettes with a specific density between 650 to 950 kg/m^3 and moisture content of 5 to 10% can be produced with the agricultural residue (Mani, et al., 2006). Taking into account the reduced moisture content and the increase in density, the lower heating value of the agricultural residue is increased from 17.2 MJ/kg to 19 MJ/kg and the bulk density increased from 150 kg/m^3 to 680 kg/m^3 depending on the shape and size of the briquettes.

3.3.2. Energy Balance and Efficiency

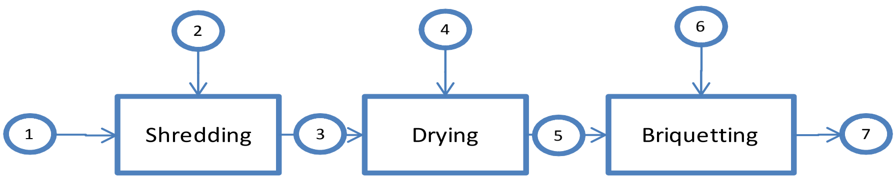
The energy balance and energy efficiency of the process is two different indicators used to evaluate the biomass resource and conversion technology. The energy balance is a measure of the renewable energy product produced divided by the fossil fuel or external energy input required to produce the energy product.

$$EB = \frac{Energy\ Product\ Out}{Fossil\ Fuel\ In} \quad (3.1)$$

The energy efficiency is a measure of the conversion efficiency and is calculated by dividing the energy value of the product by the energy value of the feedstock.

$$\eta_{Eff} = \frac{Energy\ value\ of\ product}{Energy\ value\ of\ feedstock} \quad (3.2)$$

The briquetting process can be divided into three separate process steps namely shredding, drying and briquetting, each step with its own energy balance and efficiency. The energy balance for these processes is shown in Figure 3-3 below.



	Shredding		Drying		Briquetting		Overall
E_{eff}	100.0%		98.9%		100.0%		98.9%
EB	151		N/A		902		128

		Feedstock In	External Energy In	Shredded Feedstock	External Energy In	Dryed Feedstock	External Energy In	Briquettes
Description	**Units**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Energy Value	MJ/ton	17 200	114	17 200	0	18 950	21	18 950
Biomass	ton	1.000	1.000	1.000	1.000	0.898	0.898	0.898
Energy input	MJ	17 200	114	17 200	0	17 013	19	17 013

Figure 3-3: Overall energy balance and efficiency of briquetting process

The external energy input required for the shredding step is between 125 MJ/ton for wheat straw and 103 MJ/ton for corn stover (Bitra, et al., 2009) while the conversion efficiency is taken as 100% with a negligible amount of biomass that is being lost through inefficiencies in the dust removal step of the hammer mill.

The energy balance over the drying step is not calculated as the external energy input is negligible. The energy required for drying is generated from the burning of agricultural residue thus decreasing the conversion efficiency of the drying process but not affecting the energy balance. The energy required to dry the agricultural residue from 15% moisture to 7.5% is calculated as approximately 400 MJ/ton that correspond to approximately 23 kg biomass burned per ton dried with a dryer efficiency of 50%.

The conversion efficiency of the briquetting step is taken as 100% as the biomass losses are negligible. The external energy required to densify the agricultural residue varies between 12 and 30 MJ/ton depending on the extent of densification achieved (Mani, et al., 2006). The energy balance and conversion efficiency calculated over the whole briquetting process is 128:1 and 99.8% respectively.

3.3.3. Capital and Operating Cost

The capital cost of the briquetting plant consists of the pre-treatment (size reduction and drying) cost and the briquetting cost as shown in equation 3.3 below.

$$C_{C.Briq.Plant} = C_{C.PT} + C_{C.Briq} \tag{3.3}$$

The capital cost estimation for the pre-treatment and briquetting sections is based on a study by Sultana (Sultana, et al., 2010) on the production cost of pellets from agricultural biomass and adapted to this application by converting the cost basis from USD_{2010} to R_{2010} versus ton feedstock processed per annum. This adapted costing model is given by equations 3.4 and 3.5 below and the cost is shown in Figure 3-4 below.

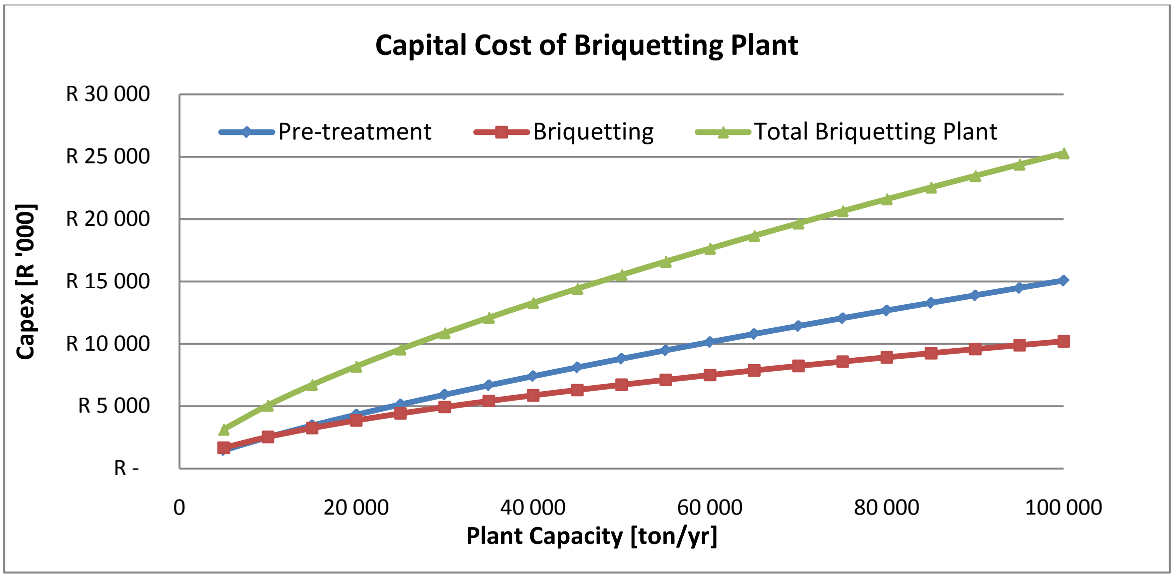


Figure 3-4: Capital cost of the briquetting plant

$$C_{C.PT} = 9875.6 \times Cap^{0.61} \tag{3.4}$$

$$C_{C.PT} = 9875.6 \times Cap^{0.61} \tag{3.5}$$

$C_{C.PT}$ is the capital cost of the pre-treatment steps in Rand.
$C_{C.Briq}$ is the capital cost of the briquetting steps in Rand.
Cap is the plant capacity in ton of agricultural residue processed per year.

Operating cost estimation is very difficult as it varies from area to area based on labour rates, availability of skilled labourers, available infrastructure etc. Thus, direct comparison of operating cost from literature is not always accurate. The typical number of operating labourers required for the operation and maintenance of plants can be compared directly and scaled more accurately from literature. For the purpose of this study, labour requirements given by Bridgwater (Bridgwater, et al., 2002) and Sultana (Sultana, et al., 2010) were used as basis with local labour rates for the operating labour cost estimation.

Operating cost ratios for process plants from Verbaan (Verbaan, 1985) were used to determine the total operating cost from the labour cost. The labour requirement model, assumptions and ratios used for the operating cost comparison can be found in Appendix C. The results are shown in Figure 3-5.

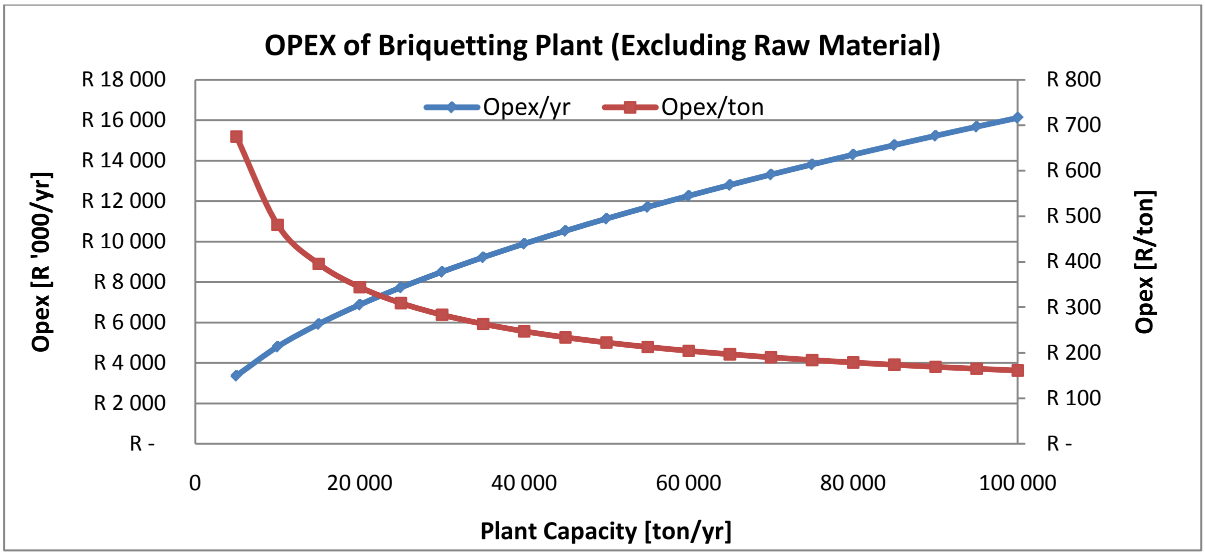


Figure 3-5: Operating cost of the briquetting plant excluding raw material cost

3.4. Direct Combustion of Agricultural Residue

Direct combustion of agricultural residue is one of the technologies selected to investigate in more detail. The combustion and steam cycle process, energy balance and efficiency, capital cost and operating cost are discussed below.

3.4.1. Combustion Process

Many different combustion technologies exist and the selection of the specific technology should be done on a case by case basis as each technology has its advantages and disadvantages. The main factors that influence the technology to be selected are the type of feedstock, the energy product or mix of product required (heat or electricity) and the scale of the installation. Based on agricultural residue as feedstock and electricity as main energy product, grate or fluidised bed combustors that produce steam for electricity generation through a steam turbine is the most appropriate technology and will be further investigated.

A process block flow diagram of an agricultural residue combustion and electricity generation process is shown in Figure 3-6 below. The combustion plant consists of: biomass offloading and storage, pre-treatment step, combustion chamber and boiler, steam cycle (turbine, condenser, and generator).

Although some small scale combustors are designed to combust agricultural residue directly from the field, most combustors require some form of pre-treatment of the biomass before combustion in order to improve combustion efficiency, process control or to control corrosion of the boiler. This pre-treatment can include washing, drying, size reduction and briquetting.

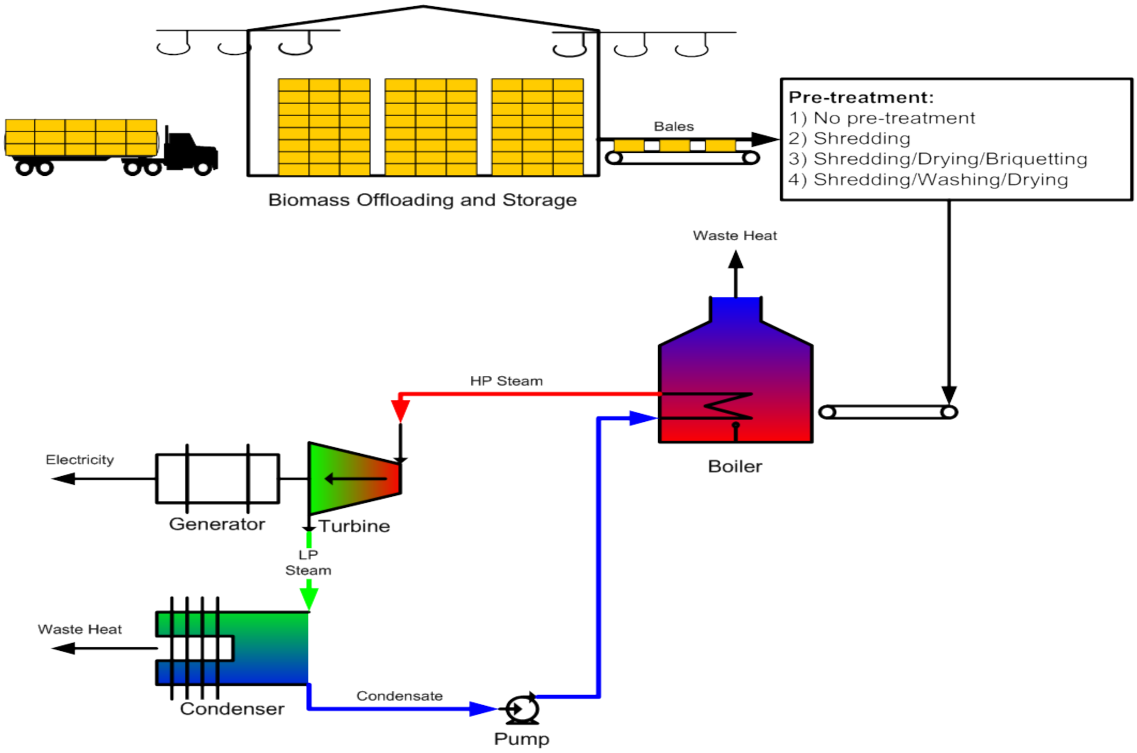


Figure 3-6: Combustion and steam cycle process overview

Agricultural residue is washed at temperatures of between 50 and 60°C to remove chlorides, potassium and other corrosive elements that is present in the straw. The energy losses associated with the washing pre-treatment step is approximately 8% of the energy value of the feedstock, but these losses are recovered through the prolonged life of the boilers (Nikolaisen, et al., 1998).

Drying of the agricultural residue increases the lower heating value of the biomass as well as the combustion efficiency that can be achieved in the combustor. The waste energy from the flue gas or condensers can be used for drying purposes, thus increasing the overall efficiency of the process.

Size reduction is done before briquetting, but also to improve the consistency of the feedstock when feeding it to the combustor, improving control and efficiency of the combustion process.

Biomass briquettes are sometimes preferred as feedstock to combustors as it slows down the combustion rate allowing better temperature control and more complete combustion. The use of briquettes also improves the transport efficiency thus the agricultural residue can be briquetted off-site and transported to a larger scale centralised power plant for combustion.

Grate combustor and fluidised bed combustors differ mainly in the way that the biomass and air is introduced and kept in the combustion chambers to ensure optimum contact between the biomass and oxygen in the air. However, the combustion reactions taking place are the same as shown in Figure 3-7 below.

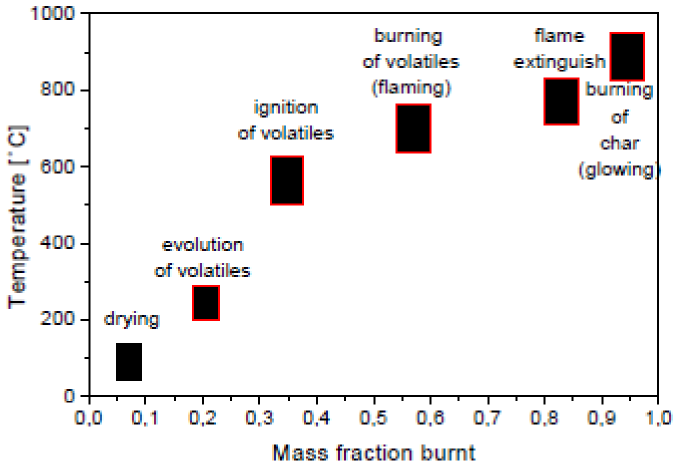


Figure 3-7: Steps taking place during combustion (Werther, et al., 2000)

Firstly the moisture evaporates until the biomass is completely dry. As soon as the moisture has evaporated, the temperature increases and thermal degradation takes place to release the volatile organics from the carbon structure of the biomass. The volatiles ignite and burn and lastly the bio-char starts to burn. The combustion chamber is designed to enhance these reactions and transfer the heat of combustion to the boiler to produce steam. The scale of biomass combustors typically range from a few kilowatts for small farm-scale combustors that produce heat to 20 MW electricity, however a 500 MW thermal biomass combustion plant has been commissioned in Finland (Faaij, 2006). Turbines are used to generate electricity from steam produced in combustion plants. This is an established technology but with relatively low conversion efficiencies between 20-30% for small-scale power plants.

3.4.2. Energy Balance and Efficiency

The overall energy balance and efficiency of a typical combustion plant with steam cycle to generate electricity were evaluated. Briquetting was selected as pre-treatment step before the combustion plant.

The efficiencies and balance done in section 3.3.2 above was used for the briquetting pre-treatment with the exception that waste heat from the combustion and steam cycle were used as energy source for drying of the agricultural waste in order to increase the overall efficiency of the process.

The conversion efficiency of the combustion and steam cycle process varies significantly with the capacity of the plant, thus a model was developed to relate the conversion efficiency with the capacity of the plant. A previous study by Bridgewater showed the conversion efficiency of an agricultural waste combustion plant with steam turbine electricity generation for power plants with generation capacity between 1 and 20 MWe that falls within the same range as the potential for the Greater Gariep agricultural area. The efficiencies determined by Bridgwater given in efficiency vs. generation capacity were used and converted to efficiency vs. feedstock capacity incorporating the pre-treatment as discussed and is shown in Figure 3-8 below (Bridgwater, et al., 2002).

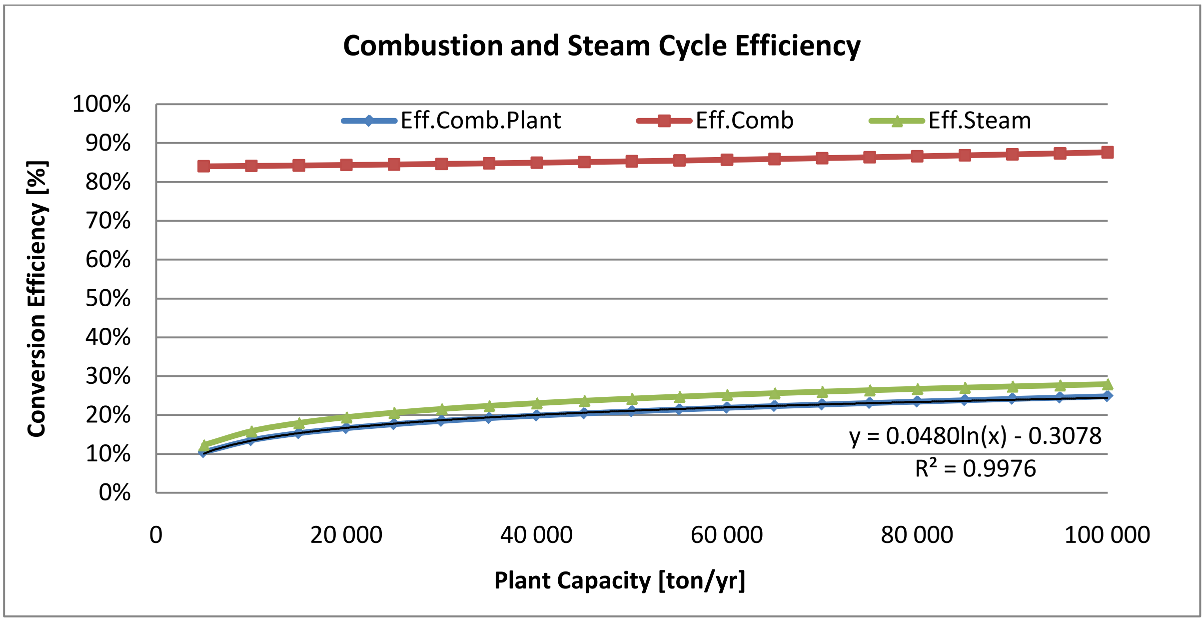
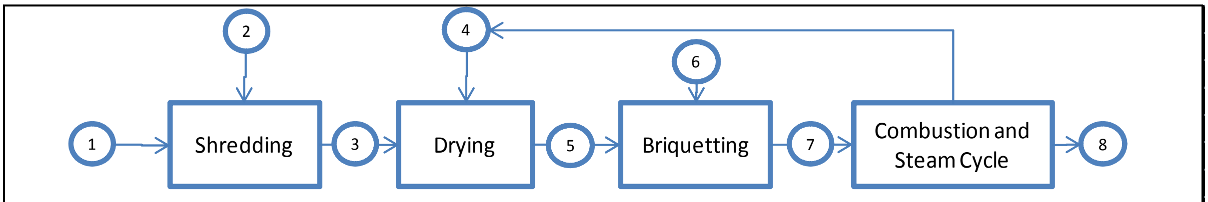


Figure 3-8: Conversion efficiency of a combustion and steam cycle power plant

The normalised energy balance and conversion efficiency of a typical 10 MWe power plant is shown in Figure 3-9 below.



						Pre-Treatment			Overall
E_{eff}	100.0%		101%		100%	101.2%	21.0%		21.3%
EB	151		-		902	131	-		27
		Feedstock In	**External Energy In**	**Shredded Feedstock**	**Waste Heat Recycle**	**Dryed Feedstock**	**External Energy In**	**Feed to Combustion**	**Electricity**
Description	**Units**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Energy Value	MJ/ton	17 200	114	17 200	396	18 950	21	18 950	3 980
Biomass	ton	1.000	1.000	1.000	1.000	0.919	0.919	0.919	0.919
Energy input	MJ	17 200	114	17 200	396	17 414	19	17 414	3 657

Figure 3-9: Energy balance of a typical 10 MWe agricultural residue power plant

Based on these results the conversion efficiency can be modelled as a function of the pre-treatment efficiency that is assumed to be independent of capacity and the efficiency of the combustion and steam cycle process that is dependant on capacity as shown in equation 3.6 below.

$$\eta_{Eff} = \eta_{PT} \times \eta_{Comb.Steam}$$

$$\eta_{Eff} = 1.012 \times [0.0480 \ln(Cap) - 0.3078] \qquad (3.6)$$

3.4.3. Capital and Operating Cost

The capital cost of the combustion plant consists of the pre-treatment (size reduction and drying) cost, the briquetting plant, the combustion cost and the steam cycle cost as shown in equation 3.7 below.

$$C_{C.Comb.Plant} = C_{C.PT} + C_{C.Briq} + C_{C.Comb} + C_{C.Steam} \quad (3.7)$$

The capital cost estimation for the pre-treatment and briquetting sections is the same as in the previous section.

The capital cost estimate for the combustion and steam cycle is based on a study by Bridgwater (Bridgwater, et al., 2002) on the techno-economic comparison of power production by fast pyrolysis, gasification and combustion. The costing models from Bridgwater are available in the reference articles and were based on actual plant costs in $Euro_{2010}$. For the purpose of this study, these models were converted to this application by changing the costing basis to R_{2010} using the SEIFSA escalation table P for plant and equipment cost before installation. Installed costs were assumed to have escalated according to the same ratio as the plant and equipment costs. The costing scale was also adjusted from energy output to ton agricultural residue processed by taking into account the relevant energy conversion efficiencies. These adapted costing models are given in equations 3.8 and 3.9 below and the cost is shown in Figure 3-10 below.

$$C_{C.Comb} = 15209.4 \times (\eta_{PT} \times Cap)^{0.8} \quad (3.8)$$

$$C_{C.Steam} = 7983.2 \times (\eta_{Comb.Plant} \times Cap)^{0.695} \quad (3.9)$$

$C_{C.Comb}$ is the capital cost of the combustion step in R.
η_{PT} is the energy conversion efficiency of the pre-treatment in %.
$\eta_{Comb.Plant}$ is the overall energy conversion efficiency of the combustion plant in %.

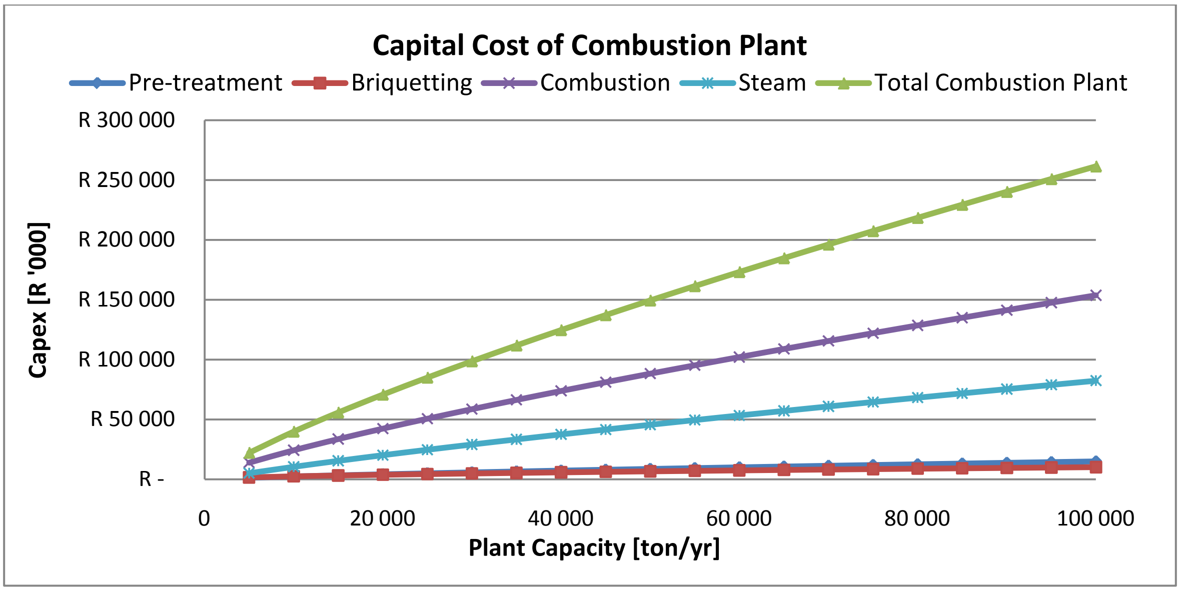


Figure 3-10: Capital cost of the combustion plant

The same method used to estimate the operating cost of the briquetting plant was used for the combustion plant with different labour requirements and ratios. The operating cost of the combustion plant consists of the combined cost for pre-treatment, combustion and the steam cycle with the results shown in Figure 3-11 below.

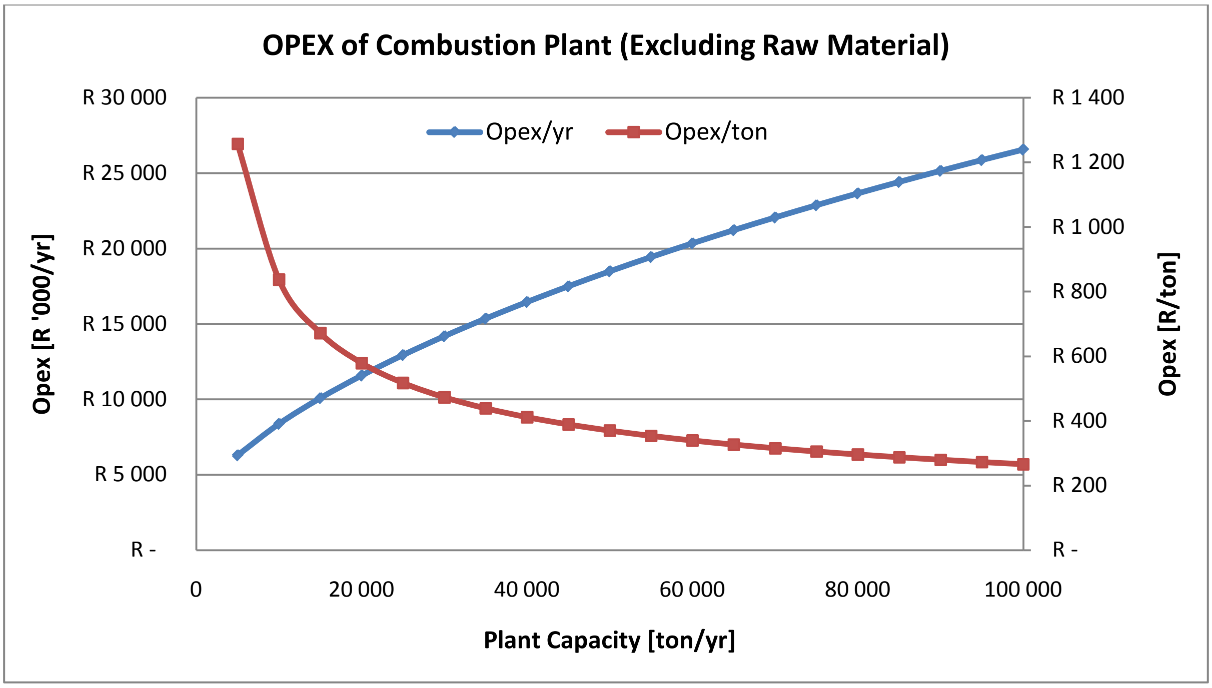


Figure 3-11: Operating cost of the combustion plant

3.5. Pyrolysis of Agricultural Residue

Pyrolysis of agricultural residue is one of the technologies selected to investigate in more detail. The process of fast pyrolysis producing bio-oil for electricity generation with a diesel engine, the energy balance and efficiency, capital cost and operating cost are discussed.

3.5.1. Pyrolysis Process

Fast pyrolysis is the thermal degradation of biomass under operating conditions that favour the production of bio-oil. From Figure 3-12 below it can be seen that the optimum yield of bio-oil (organics) is produced at pyrolysis temperatures between 500 and 550 °C. Another important operating parameter affecting the bio-oil yield is the retention time of the vapours in the reactor. The vapours should be removed from the reactor and cooled down as soon as possible to avoid further cracking of the oil as this will decrease the bio-oil yield and increase the gas production.

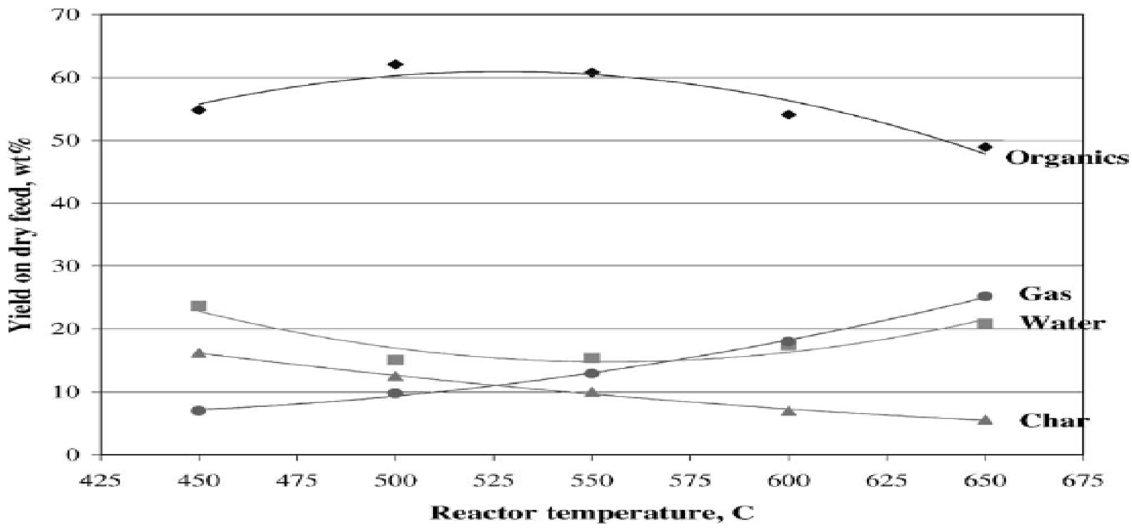


Figure 3-12: Pyrolysis product yield at different temperatures (Bridgwater, 2003).

The proposed process flow diagram for the evaluation is shown in Figure 3-13 below. Pyrolysis temperature of 500°C will be used with predicted pyrolysis product yields of 60%, 15%, 13% and 12% for bio-oil, reaction water, bio-char and gas respectively from Figure 3-12.

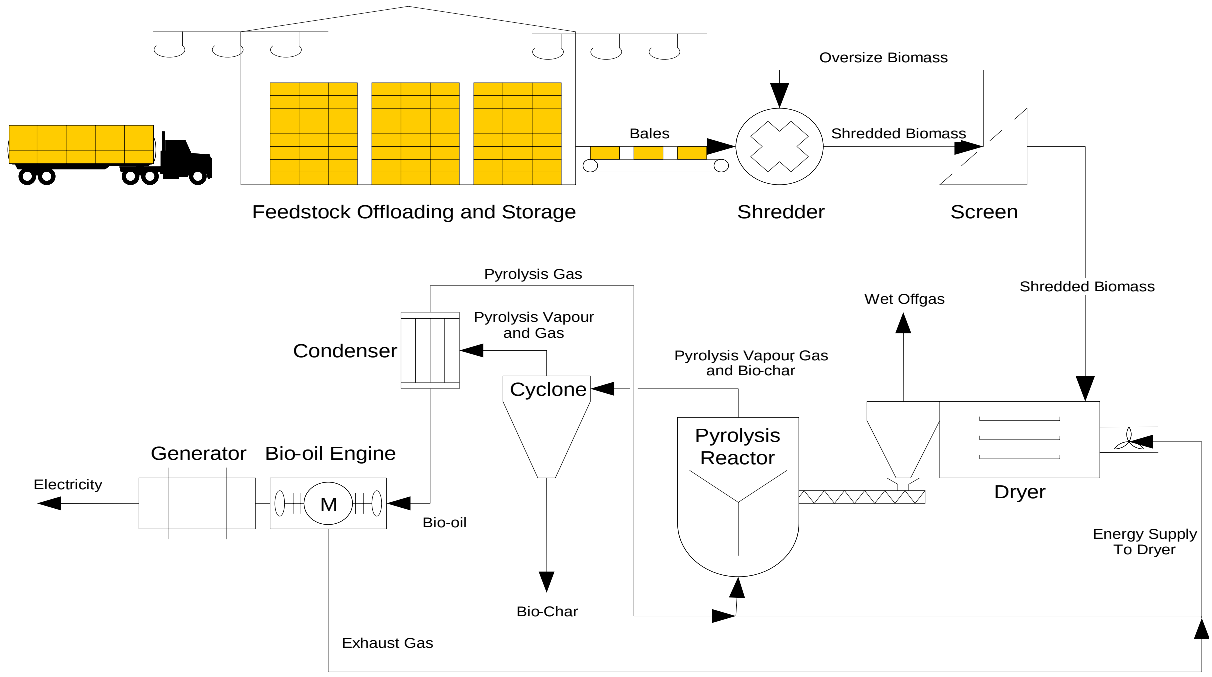


Figure 3-13: Proposed process flow diagram of a fast pyrolysis plant

The proposed pyrolysis plant can be divided into three main sections namely the feedstock storage and pre-treatment, the pyrolysis plant and the electricity generation plant. These three sections can however not operate independently from each other in a decoupled way because of the energy integration between the sections to improve the overall efficiency.

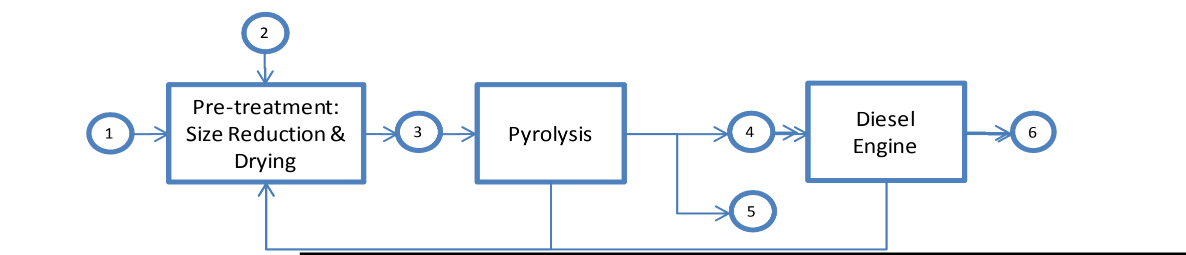
The pre-treatment consists of a shredder for size reduction and dryer to reduce the moisture of the feedstock to below 10%. A mixture of exhaust gas and pyrolysis gas is used to dry the feedstock in order to optimise the energy efficiency. For fast pyrolysis, feedstock particles smaller than 6 mm is preferred as it allows for a quicker reaction time and thus higher bio-oil yields (Bridgwater, 2003).

Different fluidised bed reactors are commonly used for fast pyrolysis as their configuration allows for short retention times and thus higher bio-oil yield and efficiency. The dry biomass particles are fed to the reactor and heats up rapidly in an oxygen starved atmosphere before thermal degradation takes place. The mixture of bio-char, vapour and gas exits the reactor at the top before the bio-char is separated from the vapour and gas in a cyclone. The vapour and gas are then cooled down in a condenser to separate the vapour from the gas.

The bio-oil (condensed vapour) can be stored intermediately before firing it in a bio-oil engine and generator set to produce electricity. There are some technical challenges with using bio-oil as fuel to diesel engines, mainly associated with the consistency of bio-oil, ignition characteristics and char deposits that block the fuel injection system (Bridgwater, et al., 2002).

3.5.2. Energy Balance and Efficiency

The mass balance and energy efficiency of the pyrolysis plant based on the process steps and conditions as discussed in section 3.5.1 is shown in Figure 3-14.



	Pre-Treatment	Pyrolysis Bio-oil	Pyrolysis Bio-char	Pyrolysis Overall	Diesel Engine	Overall Electrical
E_{eff}	101%	64%	23%	86%	41%	26%
EB	153	-	-	-	-	40

Description	Units	Feedstock In 1	External energy input 2	Prepared Feedstock 3	Bio-oil (20% Moisture) 4	Bio-Char 5	Electricity 6
Energy Value	MJ/ton	17 200	114	18 950	16 138	32 971	-
Biomass	ton	1.000	1.000	0.919	0.689	0.119	-
Energy Input	MJ	17 200	114	17 413	11 122	3 939	4 515

Figure 3-14: Energy balance and efficiency projection for a pyrolysis plant.

The energy balance for the pre-treatment is based on the same size reduction and drying steps used for the combustion model and is assumed to be independent of scale. The pyrolysis product fractions of 75%, 13% and 12% for bio-oil (including reaction water), bio-char and gas, and the LHV of the pyrolysis oil is based on the studies of Brigwater (Bridgwater, et al., 2002) and Potgieter (Potgieter, 2004).

The energy efficiency of the diesel engine generator increase with capacity and the model developed by Bridgwater (Bridgwater, et al., 2002) that gives the electrical conversion efficiency of a diesel engine running on bio-oil was modified to include the pre-treatment and pyrolysis process steps to give the overall electricity generation efficiency of the proposed pyrolysis plant as a function of biomass processed per annum as shown in Figure 3-15 and equation 3.10 below.

$$\eta_{pyr} = \eta_{PT} \times \eta_{oil} \times \eta_{Enine}$$

$$\eta_{pyr} = -1.873 \times 10^{-10} \times Cap^2 + 7.136 \times 10^{-5} \times Cap + 24.95 \qquad (3.10)$$

This model does not take into account the energy produced in the form of bio-char, as the bio-char will not be converted to electricity in this plant, but sold as a separate product.

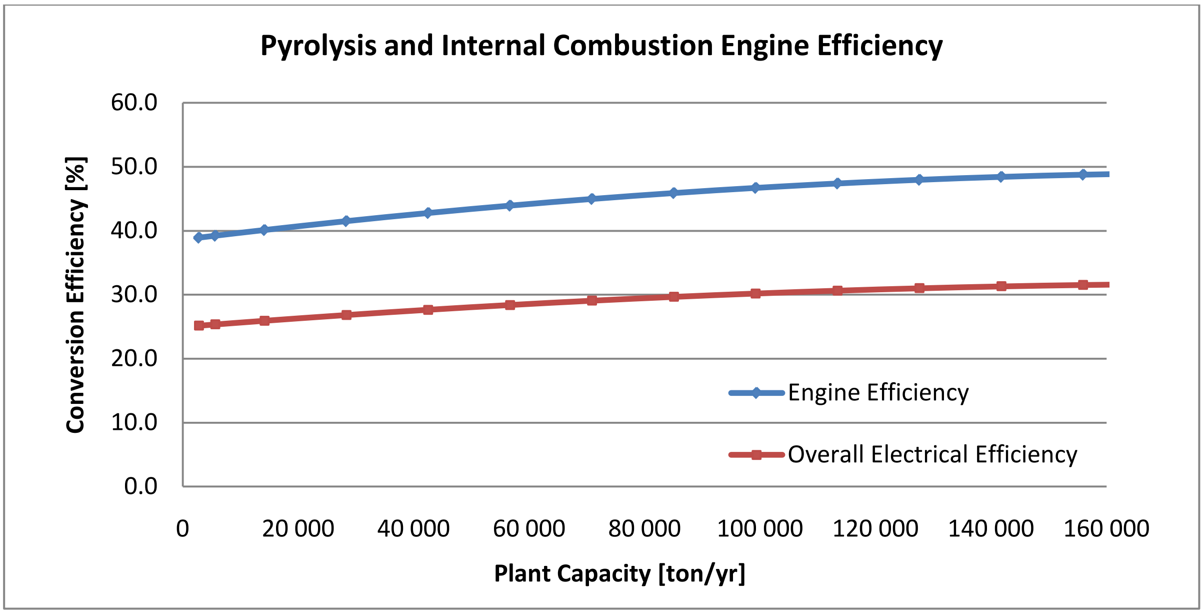


Figure 3-15: Efficiency of the proposed pyrolysis plant

3.5.3. Capital and Operating Cost

The capital cost of the pyrolysis plant consists of the pre-treatment (size reduction and drying) cost, the pyrolysis cost and the liquid fuel internal combustion engine cost as shown in equation 3.11 below.

$$C_{C.Pyr.Plant} = C_{C.PT} + C_{C.Pyr} + C_{C.LEngine} \qquad (3.11)$$

The capital cost estimate for the pyrolysis and internal combustion engine is based on a study by Bridgwater (Bridgwater, et al., 2002) on the techno-economic comparison of power production by fast pyrolysis, gasification and combustion. These costing models were adapted to this study on the same basis as the combustion plant and are given in equations 3.12 and 3.13 below and the cost is shown in Figure 3-16 below.

$$C_{C.Pyr} = 124092.3 \times (Cap)^{0.619} \qquad (3.12)$$

$$C_{C.LEngine} = 8977.6 \times \left(\eta_{Pyr.Plant} \times Cap\right)^{0.954} \qquad (3.13)$$

$C_{C.Pyr}$	is the capital cost of the pyrolysis step in Rand.
$C_{C.LEngine}$	is the capital cost of the internal combustion engine step in Rand.
$\eta_{Pyr.Plant}$	is the overall energy conversion efficiency of the pyrolysis plant.

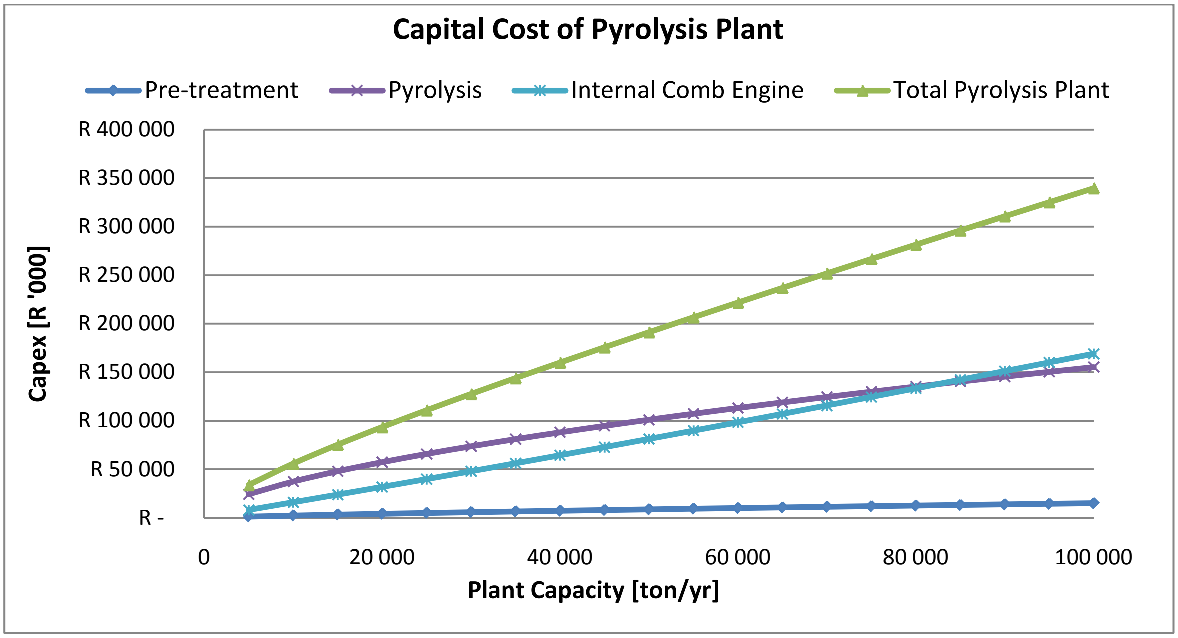


Figure 3-16: Capital cost of the pyrolysis plant

The same method used to estimate the operating cost of the briquetting plant was used for the Pyrolysis plant with different labour requirements and ratios. The operating cost of the pyrolysis plant consists of the combined cost for pre-treatment, pyrolysis and the internal combustion engine with the results shown in Figure 3-17 below.

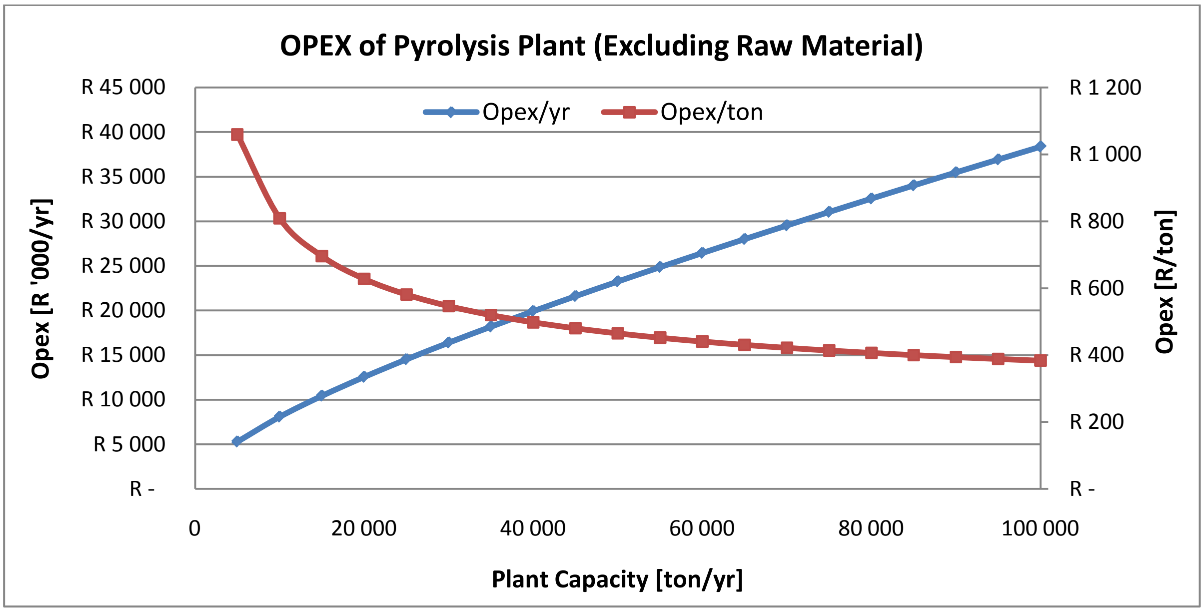


Figure 3-17: Operating cost of the pyrolysis plant

3.6. Gasification of Agricultural Residue

Gasification of agricultural residue is one of the technologies selected to investigate in more detail. The biomass gasification with electricity generation process, energy balance and efficiency, capital cost and operating cost are discussed.

3.6.1. Gasification Process

The overall gasification process can again be divided into three sections namely pre-treatment, gasification and electricity production as shown in Figure 3-18 below.

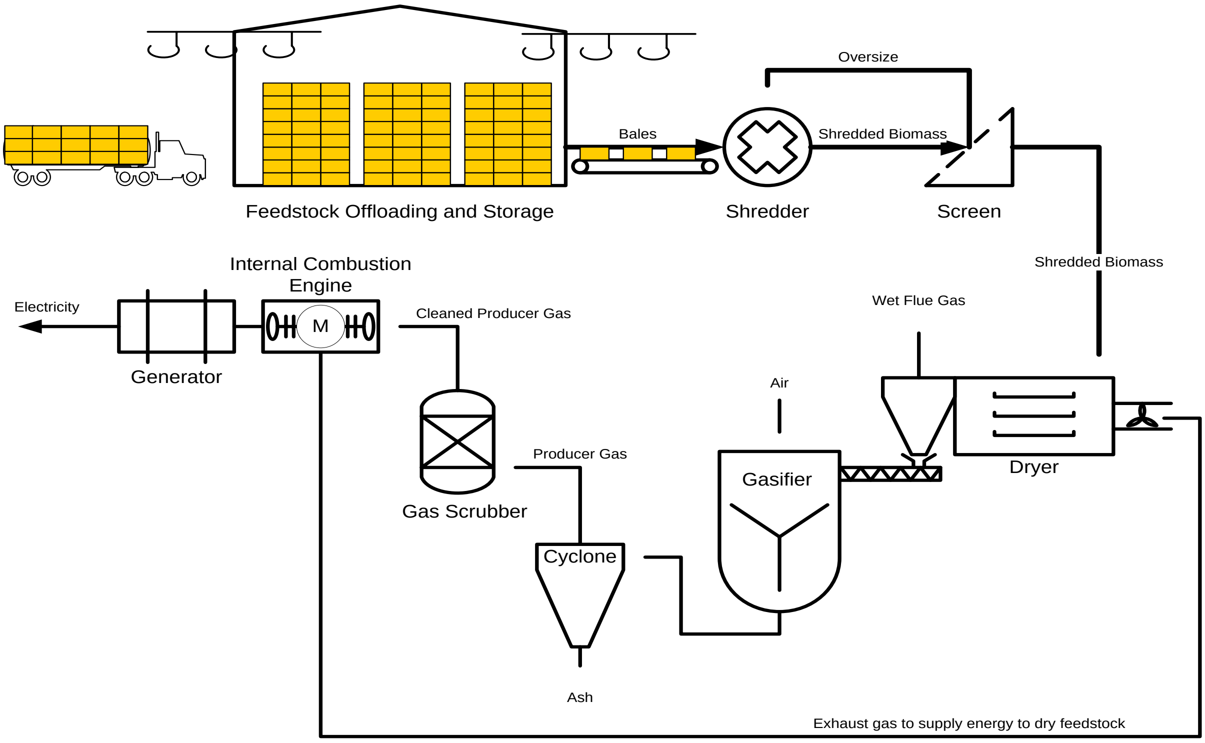


Figure 3-18: Proposed gasification plant with internal combustion engine

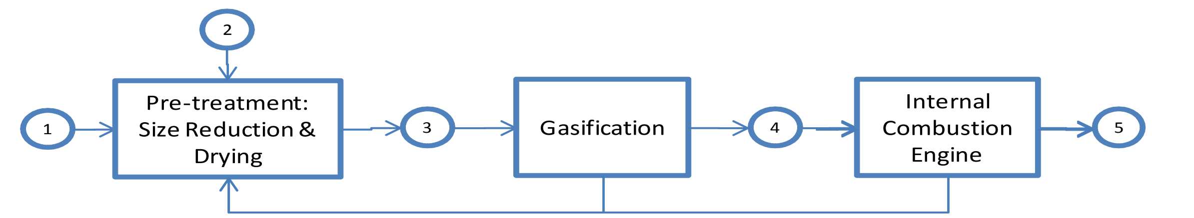
Gasification is more tolerant to feed particle size, but should still preferably be smaller than 30 mm diameter as it affects the reaction rate (Huber, et al., 2006). Drying of the biomass is very important as the moisture lowers the heating value of the biomass and decrease conversion efficiency.

A downdraft gasifier is proposed for this evaluation mainly because of the cleaner producer gas produced from this reactor and also for its small- to medium-size application. Many other types of reactors are available with their own applications, advantages and disadvantages (Huber, et al., 2006). In a downdraft gasifier, the biomass and air enters the gasifier at the top and moves down the reactor to enter at the bottom. A cyclone is used to separate the ash and other particulates from the producer gas. The amount of tar typically produced in a downdraft gasifier is 1 g/Nm^3 compared to 10 g/Nm^3 and 100 g/Nm^3 in a fluidised bed and updraft gasifier respectively (Huber, et al., 2006). Even with this low tar content, it is recommended to clean the gas before using it in an internal combustion engine or gas turbine to prevent charring and particulate build-up inside the equipment.

An internal combustion engine is proposed for this application rather than a combined cycle gas turbine even though the latter is more efficient. An internal combustion engine has the advantage that is can be used in very small-scale applications as well as medium-scale applications and is more tolerant to the producer gas quality and simpler to operate and maintain than a combined cycle gas turbine installation.

3.6.2. Energy Balance and Efficiency

The energy balance and efficiency of the proposed gasification plant is divided into the pre-treatment, gasification and internal combustion engine sections as shown in Figure 3-19.



	Pre-treatment	Gasification	Engine	Overall Electrical
E_{eff}	101%	73%	44%	33%
EB	153	-	-	49

		Feedstock In	External energy input	Prepared Feedstock	Cleaned Producer Gas	Electricity
Description	**Units**	**1**	**2**	**3**	**4**	**5**
Energy Value	MJ/ton	17 200	114	18 950	-	-
Biomass	ton	1.000	1.000	0.919	-	-
Energy Input	MJ	17 200	114	17 415	12 713	5 594

Figure 3-19: Proposed gasification plant energy balance and efficiency

The proposed pre-treatment consists of size reduction and drying, and the same basis as in the previous sections has been used. The exhaust gas from the internal combustion engine is used to dry the feedstock, thus the only external energy required is for the size reduction. The efficiency of the pre-treatment is assumed to be independent of scale thus the energy efficiency and energy balance of the pre-treatment section is 101% and 114:1 respectively.

The energy balance and efficiency model done by Bridgwater (Bridgwater, et al., 2002) was used as basis for gasification section. The model was adjusted for this application and is given in equation 3.14 below.

$$\eta_{Gas} = -5.649 \times 10^{-15} Cap^2 + 3.367 \times 10^{-7} Cap + 0.711 \qquad (3.14)$$

The energy balance and efficiency model for the internal combustion engine used with the pyrolysis plant can be used with the gasification plant as well. This model was adjusted as a function of biomass capacity and also incorporates the gasification plant efficiency as given in equation 3.15 below.

$$\eta_{Engine} = -7.102 \times 10^{-12} \eta_{Gas}^2 Cap^2 + 1.728 \times 10^{-6} \eta_{Gas} Cap + 0.386 \qquad (3.15)$$

The overall efficiency of the proposed gasification process is given in equation 3.16 below and plotted together with the gasification and internal combustion engine efficiencies vs. feedstock processed in Figure 3-20 below.

$$\eta_{Gas.Conv} = \eta_{pt} \times \eta_{Gas} \times \eta_{Engine} \quad (3.16)$$

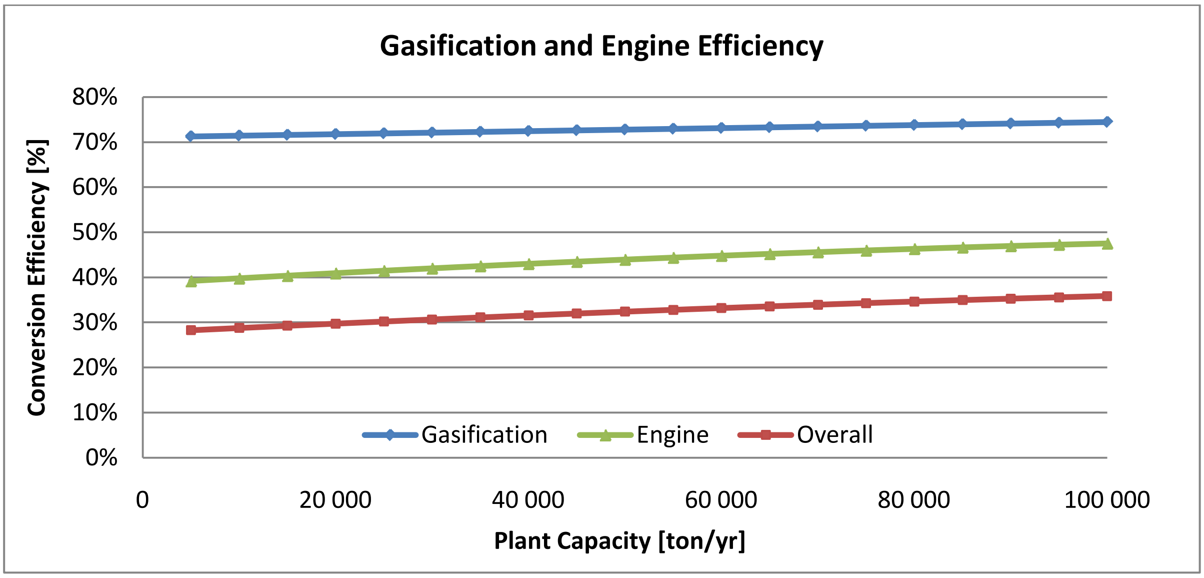


Figure 3-20: Proposed gasification plant efficiency

3.6.3. Capital and Operating Cost

The capital cost of the gasification plant consists of the pre-treatment (size reduction and drying) cost, the gasification cost and the gas fuel internal combustion engine cost as shown in equation 3.17 below.

$$C_{C.Gas.Plant} = C_{C.PT} + C_{C.\mathrm{Gas}} + C_{C.\mathrm{GEngine}} \quad (3.17)$$

The capital cost estimate for the pyrolysis and internal combustion engine is based on a study by Bridgwater (Bridgwater, et al., 2002) on the techno-economic comparison of power production by fast pyrolysis, gasification and combustion. These costing models were adapted to this study on the same basis as the combustion plant and are given in equations 3.18 and 3.19 below and the cost is shown in Figure 3-21 below.

$$C_{C.Gas} = 77980.3 \times (Cap)^{0.698} \quad (3.18)$$

$$C_{C.GEngine} = 8977.6 \times (1.25 \times \eta_{Gas.Plant} \times Cap)^{0.954} \quad (3.19)$$

$C_{C.Gas}$ is the capital cost of the pyrolysis step in Rand.
$C_{C.GEngine}$ is the capital cost of the internal combustion engine step in Rand.
$\eta_{Gas.Plant}$ is the overall energy conversion efficiency of the pyrolysis plant.

The 1.25 factor that were added to equation 3.19 for the internal combustion engine capacity is to compensate for the de-rated power output of internal combustion engines when running on low heating value gas (Bridgwater, et al., 2002).

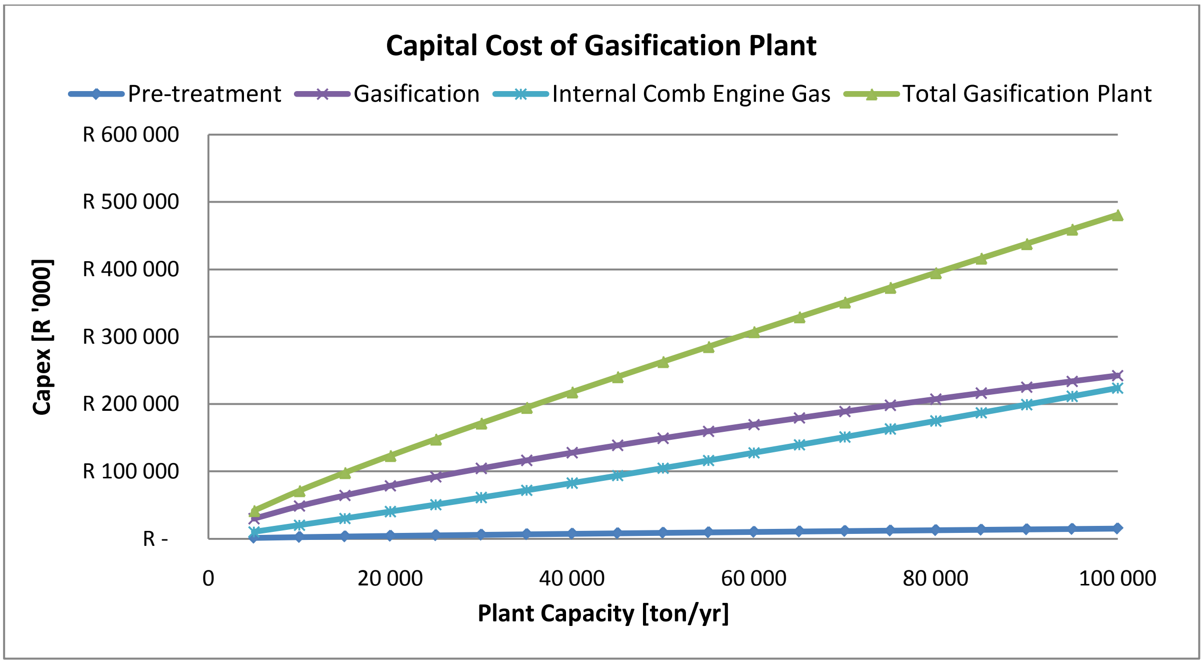


Figure 3-21: Capital cost of gasification plant

The same method used to estimate the operating cost of the briquetting plant was used for the gasification plant with different labour requirements and ratios. The operating cost of the gasification plant consists of the combined cost for pre-treatment, gasification and the internal combustion engine with the results shown in Figure 3-22 below.

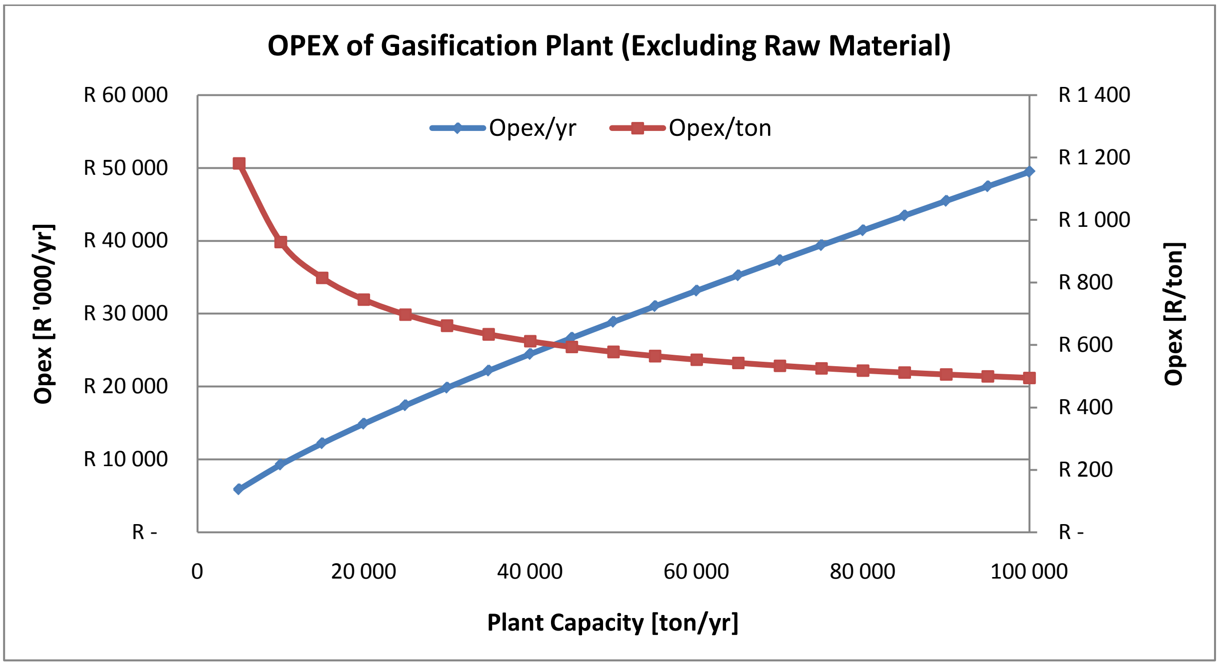


Figure 3-22: Operating cost of the gasification plant

4. ENERGY PRODUCTS

The different energy products produced with the conversion technologies discussed are fuel briquettes, heat, electricity and bio-char. The potential revenue from each is discussed in this section.

4.1. Fuel Briquettes as Renewable Energy Product

The fuel briquettes produced from the agricultural residue can be used locally for cooking and heating purposes. The fuel briquettes are produced in a rural area where there is a high unemployment rate and a large number of people living in informal settlements without connection to the electricity grid. These people are dependant on paraffin, anthracite or firewood for cooking and heat. Thus there is an existing market that can utilise the fuel briquettes locally. This will also reduce the use of firewood and fossil fuels like paraffin and anthracite. One ton of fuel briquettes is equivalent to 0.63 ton of anthracite, thus it can be assumed that the maximum price for one ton of fuel briquettes at the local outlet will be 63% of the cost for one ton of anthracite at the local outlet. Allowing 50% of the selling price at the local outlet for transport, packaging and supply chain mark-up, the price for fuel briquettes used in for this evaluation is R 614.25 per ton.

The fuel briquettes can also be co-fired with coal in conventional boilers. Even with the higher density of the briquettes, the transport cost and energy to transport the biomass to the nearest large scale conventional boiler is too high as there is no existing power plants or industrial activities in close proximity. This option will however be very attractive in Mpumalanga where maize is produced close to existing power stations.

4.2. Electricity as Renewable Energy Product

Electricity that is produced from the agricultural residue can be utilised locally as the agricultural sector is the main electricity consumer in the Greater Gariep agricultural area. Electricity is mainly used for pumping and irrigation purposes. Electricity supply to the grid is also a viable option as the infrastructure is available.

The electricity price available to the agricultural industry in this area varies between R 0.26 /kWh in the low season off-peak time to R 2.26 /kWh in the high season peak time. An electricity price of R 0.75 /kWh was assumed to calculate the base case revenue potential from electricity generation.

4.3. Bio-char as Renewable Energy Product

Bio-char can be used as combustion fuel, fertiliser product or worked back into the soil as sequestrated carbon. The market for bio-char is still developing with the different bio-char products. A bio-char price of R 1 000 per ton was assumed to calculate the base case revenue potential from bio-char.

4.4. Heat as Renewable Energy Product

Low value waste heat is a by-product from the combustion, pyrolysis and gasification plants. This heat can potentially be used for drying of agricultural residue or crops. It is assumed that the waste heat is already being used internally to the process for drying of the feedstock and drying of agricultural crops is only a seasonal requirement, thus there is no revenue potential from the low value heat in the Greater Gariep agricultural area.

There are no other industries in the area that require high quality heat or steam, thus there is no revenue potential from cogeneration to produce steam as heat product.

4.5. Revenue from the Renewable Energy Products

The potential revenue from the conversion technologies was investigated using the energy conversion efficiency of each technology to give the revenue based on the feedstock capacity as shown in Figure 4-1 below.

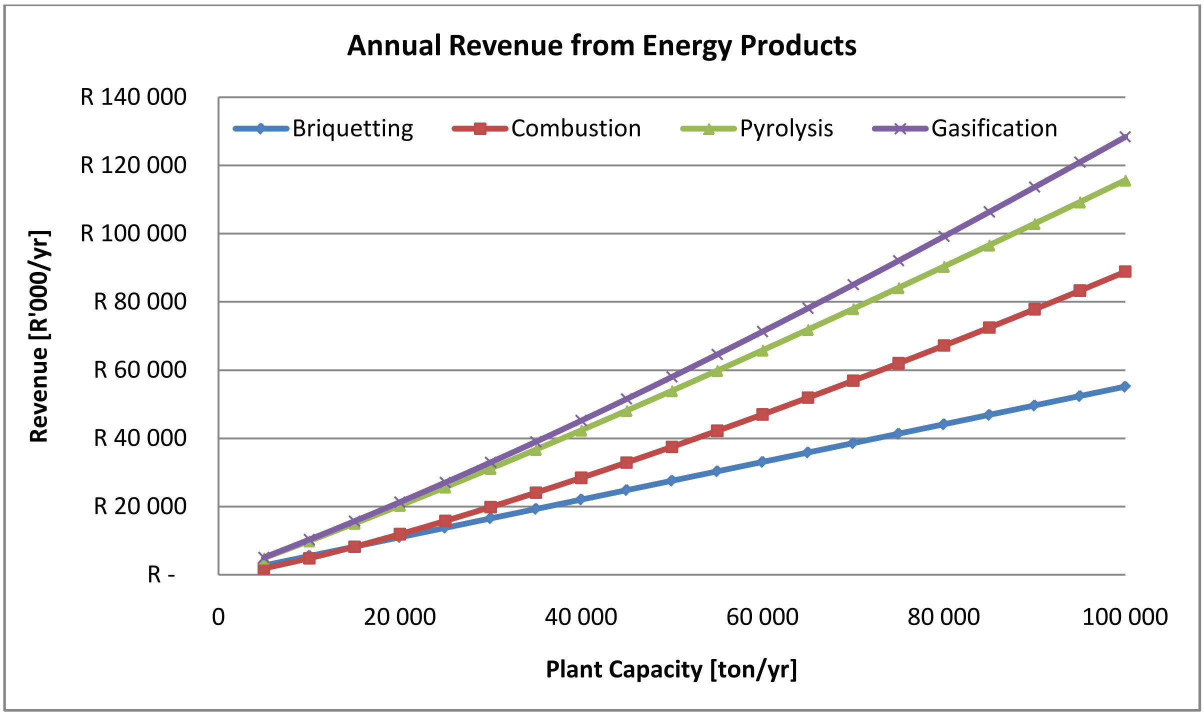


Figure 4-1: Annual revenue from the energy products

5. EVALUATION

An overall energy balance, energy efficiency and financial evaluation of the agricultural areas, conversion technologies and energy products was done in this section in order to select the scenario with the highest potential.

5.1. Overall Energy Balance and Efficiency

Only the Hopetown area and the Orania to Vanderkloof agricultural areas were selected for further evaluation. Hopetown was selected because it has the highest agricultural residue density, while the Orania to Vanderkloof area has been selected because it has the most available agricultural residue.

The overall energy balance is a measure of all the external energy inputs required to produce the energy product output. The battery limits for the overall energy balance was taken next to the field when the agricultural residue bales are loaded onto the truck to where the energy product leaves the boundary of the bio-energy conversion plant.

The overall energy balance for the different conversion technologies in both agricultural areas are shown in Figure 5-1 below and the overall conversion efficiency of the different technologies is given in Figure 5-2.

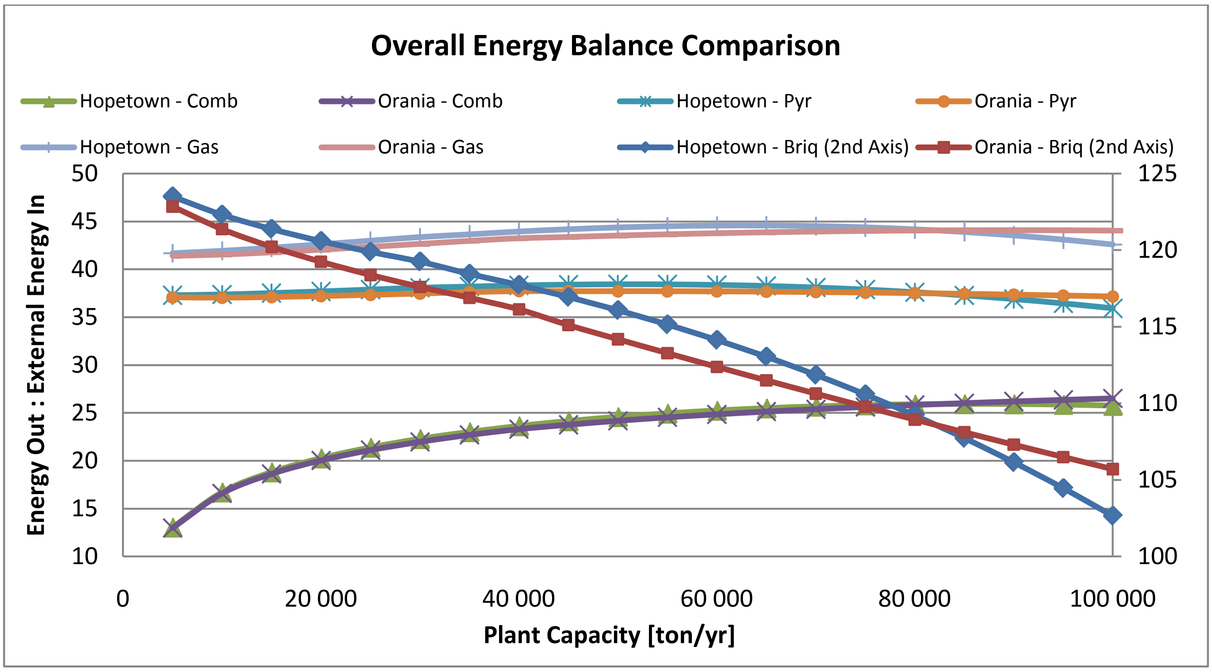


Figure 5-1: Overall energy balance comparison

The energy balance of the briquetting plants is plotted on the secondary axis and is significantly higher than the other technologies with an overall energy balance between 124:1 and 103:1. This is because the energy value of the product fuel briquettes is still in the same form as that of the feedstock, only with a higher density. Thus it is a low grade energy product compared to the electricity produced with the other technologies and should not be compared directly to each other. It can also be seen that the gasification technologies has the highest energy balance varying between 42.0 and 44.6 with the best energy balance of 44.6 being achieved for a 60 000 ton/yr gasification plant in the Hopetown agricultural area. The effect of the increased transport requirements at higher capacity can be seen in the decrease of the overall energy balance at capacities above 60 000 ton/yr.

The energy efficiency of the briquetting plant is not shown as it is assumed to be constant and not vary significantly with capacity. The transport is not included in the energy efficiency comparison as the transport energy required is from external sources and does not impact on the conversion efficiency. Thus the conversion efficiency of the same technology and capacity is the same in both agricultural areas.

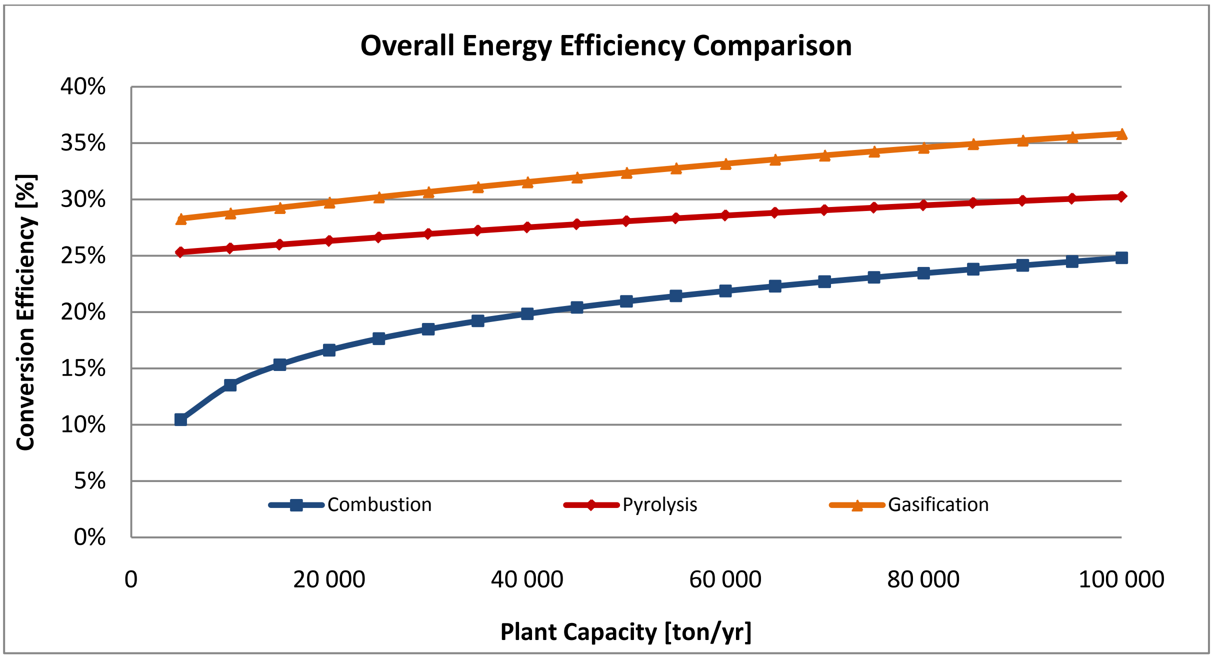


Figure 5-2: Overall energy efficiency comparison

The gasification has the highest energy efficiency compared with combustion and pyrolysis. The overall energy efficiency of a 60 000 ton/year gasification plant is 33.2% compared to 28.6% and 21.9% of a pyrolysis and combustion plant of the same feedstock capacity.

5.2. Financial Evaluation

The internal rate of return (IRR) and net present value (NPV) of each project are used to rate and evaluate the financial profitability of each option. The IRR and NPV calculations are based on a 20 year plant life and a discount rate of 10% was used for the NPV calculations. The annual cash flow is given by:

$$CF = C_{Revenue} - C_{Material} - C_{Transport} - C_{O\&M} \quad (5.1)$$

It was assumed that the cash flow of the first year is the capital cost invested in the plant and that the first revenue will only be realised in year two.

5.2.1. Internal Rate of Return (IRR)

The IRR of the briquetting, combustion, pyrolysis, and gasification plants were evaluated for the Hopetown and Orania to Vanderkloof agricultural areas and are given in Figure 5-3 below.

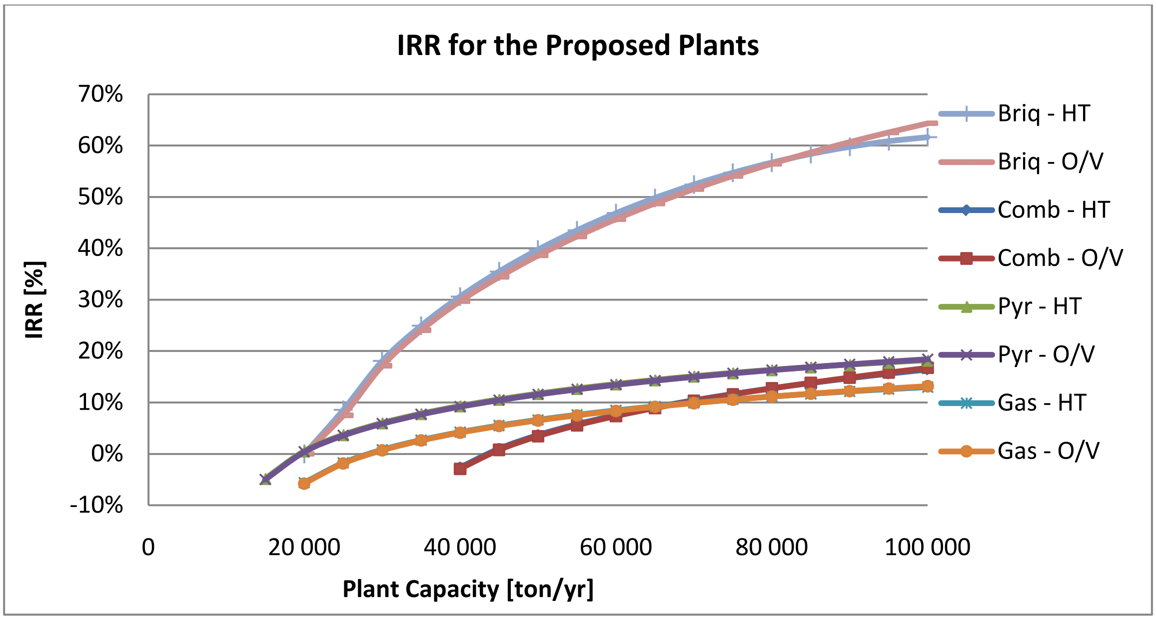


Figure 5-3: IRR of the proposed plants

The IRR results for the briquetting plants are significantly higher than that of the electricity plants. This is misleading as the market for fuel briquettes in the area is limited to domestic use thus the maximum capacity briquetting plant should not be installed without taking into account the high transport cost to distribute the briquettes to other markets.

It can be seen that the advantages of economy of scale achieved in the capital and operating cost outweighs the increased transport cost for the plant capacities investigated as the IRR still increases with increasing capacity for all four conversion technologies. This is also confirmed with the small difference in IRR between the plant located in the Hopetown area and the Orania to Vanderkloof area compared to the difference in IRR for the different technologies.

Based on the IRR results, a small scale briquetting plant that can supply the local market with fuel briquettes is the most profitable followed by the maximum capacity pyrolysis plant that is allowed by the agricultural residue supply.

5.2.2. Net Present Value (NPV)

The NPV of the briquetting, combustion, pyrolysis, and gasification plant was calculated and the results are shown in Figure 5-4 below.

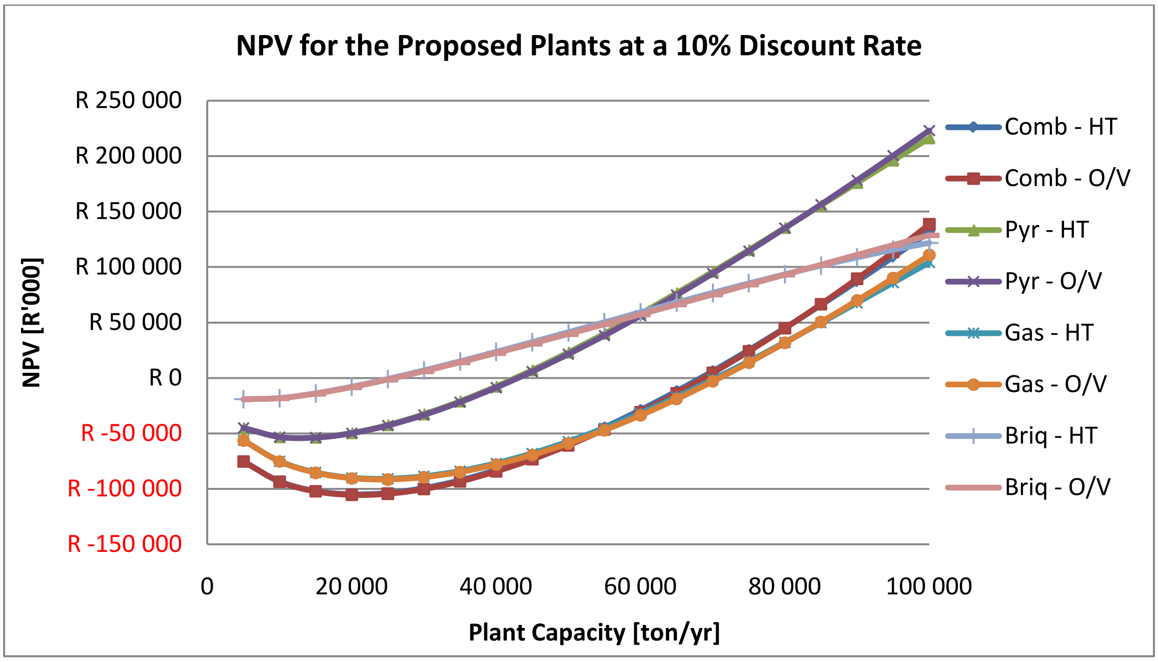


Figure 5-4: NPV results of the proposed plants

According to the NPV results, the small scale briquetting plant and the maximum capacity pyrolysis plant are the most attractive projects. A large scale briquetting plant was not considered because of the limited local demand for fuel briquettes.

Based on the IRR and NPV results, a 30 000 ton/yr briquetting plant located in the Hopetown area as well as a 95 000 ton/yr pyrolysis plant in the Orania to Vanderkloof area were selected as the two most viable options for further investigation.

5.3. Sensitivity and Risk Analysis

The technical risks associated with agricultural residue as a renewable energy feedstock and the associated conversion technologies has been discussed in section 0 and 0 and are well understood. The sensitivity of the models to market fluctuations has not been investigated and poses a major risk to the feasibility of these scenarios.

The market related variables identified for the sensitivity and risk analysis are the accuracy of the capital cost estimation, the raw material price, transport cost, the operating cost estimation and the selling price of fuel briquettes, bio-char and electricity. For the purpose of the sensitivity analysis, each of these variables were varied –10% and +25% from the base case scenario while the others were kept constant and the effect of these variations on the projected IRR and NPV were plotted in Figure 5-5 to Figure 5-8 below.

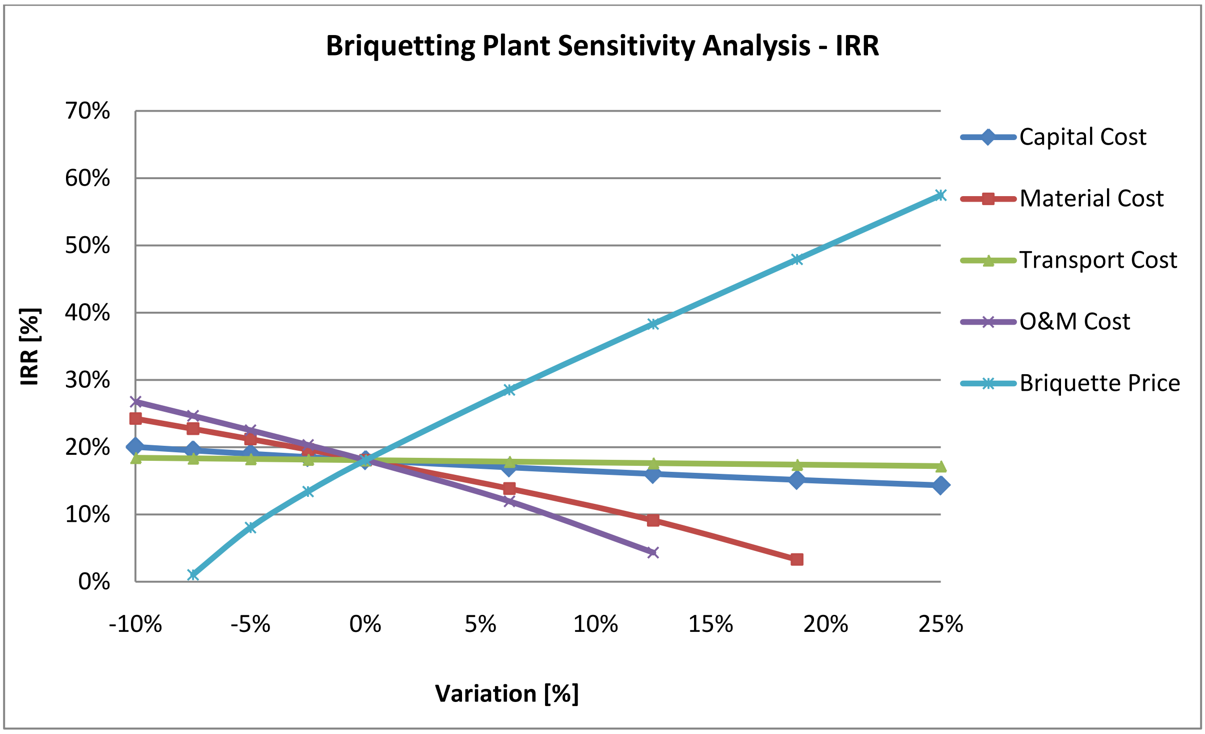


Figure 5-5: IRR sensitivity analysis of the briquetting plant

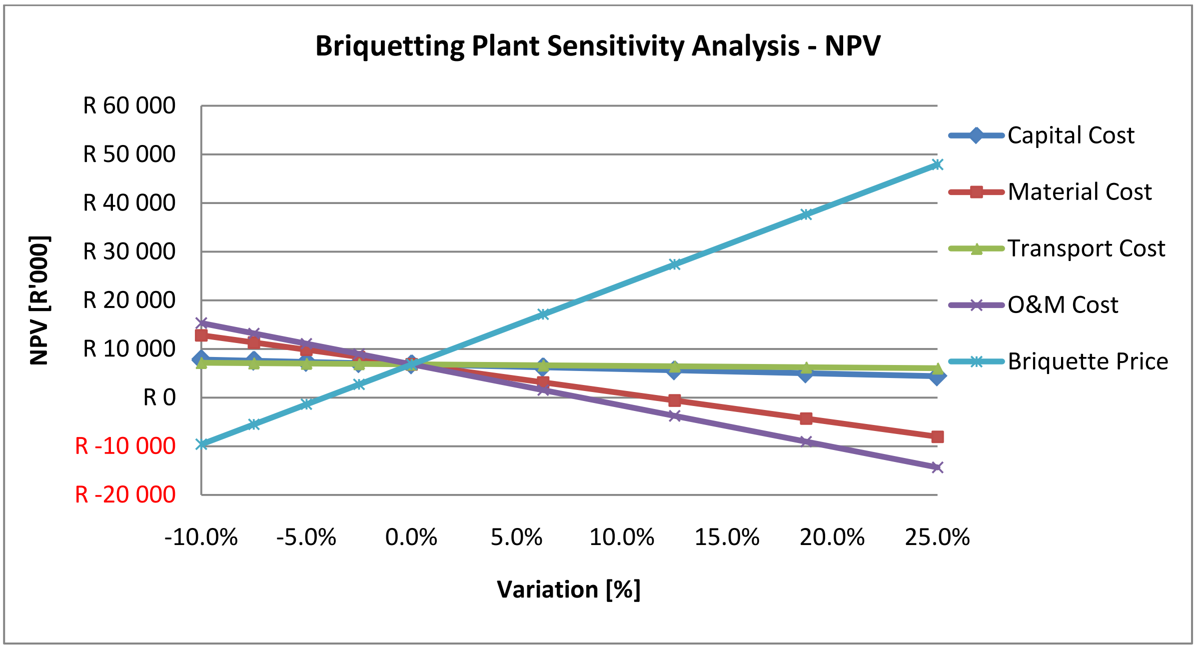


Figure 5-6: NPV sensitivity analysis of the briquetting plant

It can be seen from Figure 5-5 and Figure 5-6 that the financial viability of the briquetting plant is most sensitive to variations in the briquette selling price. Other than the sensitivity to revenue, the operating and maintenance cost of a briquetting plant is also one of the major expenses as reflected in the sensitivity results.

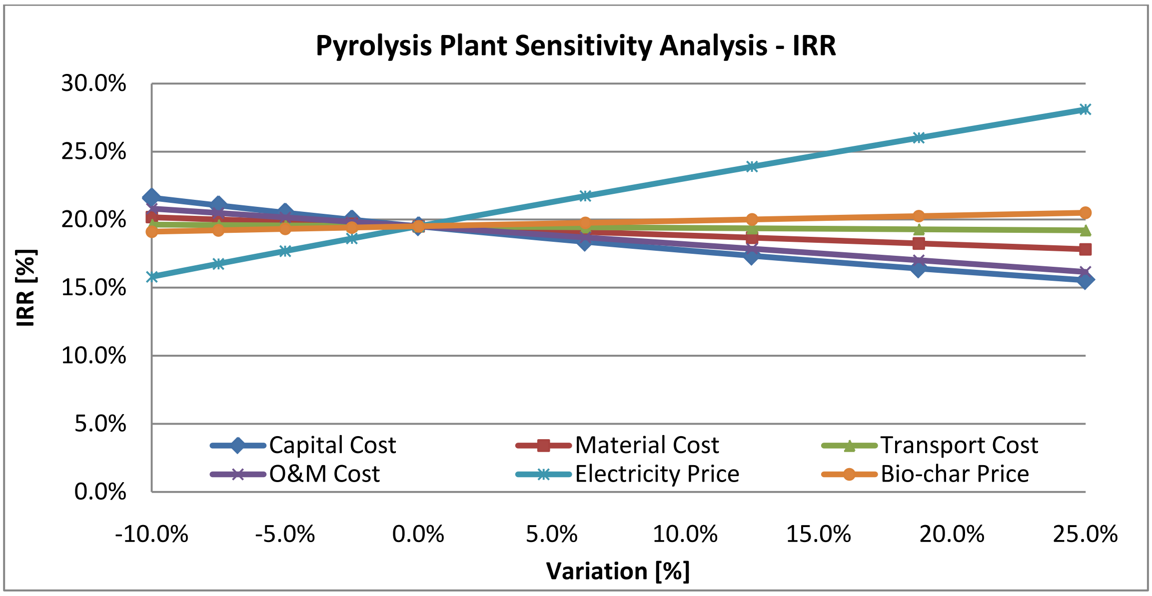


Figure 5-7: IRR sensitivity analysis of the pyrolysis plant

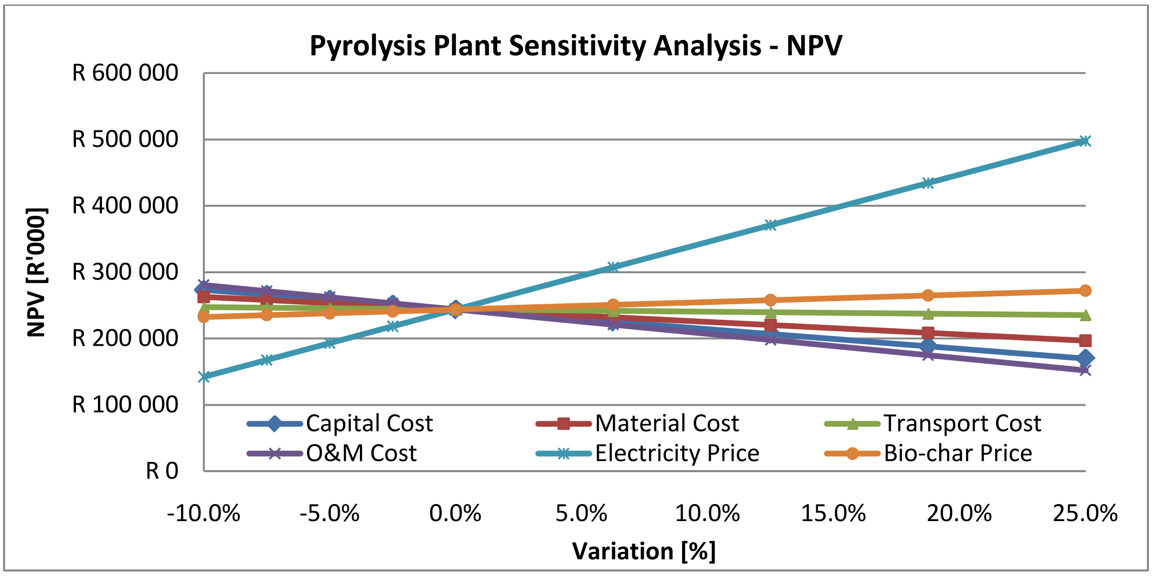


Figure 5-8: NPV sensitivity analysis of the pyrolysis plant

From Figure 5-7 and Figure 5-8 it can be seen that the projected IRR and NPV is most sensitive to variations in the electricity selling price while the other variables poses a much smaller risk.

The sensitivity analysis gives an indication of the model's sensitivity to the change in a single variable at a time. To evaluate the risk associated with variances in all of the variables from the base case scenario, a Monte Carlo simulation were done on the two models to predict the probability of achieving a certain IRR or realising the base case NPV. The Monte Carlo simulations were based on the assumption that the probability of the variance of each variable identified above is distributed evenly over a certain confidence range. A confidence range of –10% to +25% from the base case were used for all of the variables. The simulation was done on a sample of 25 000 random combinations and the results for IRR and NPV for the briquetting plant and pyrolysis plant is shown in Figure 5-9 to Figure 5-12 below.

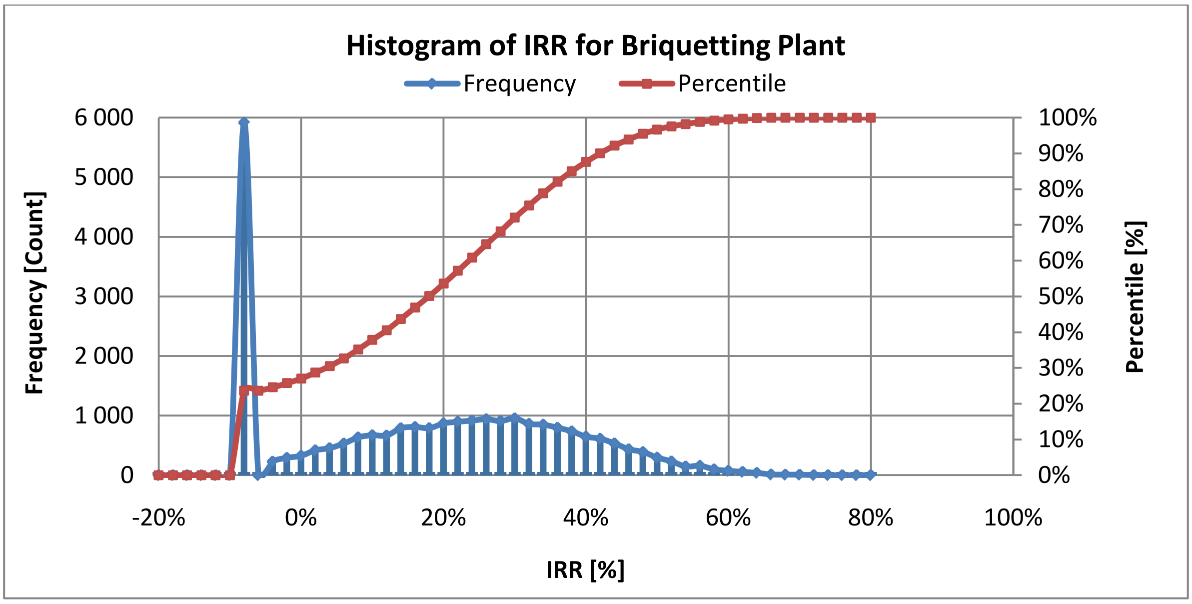


Figure 5-9: IRR histogram from a Monte Carlo simulation on the briquetting plant

The high spike on the left of Figure 5-9 include the number of combinations where the IRR could not be determined for, all of which indicates a negative IRR.

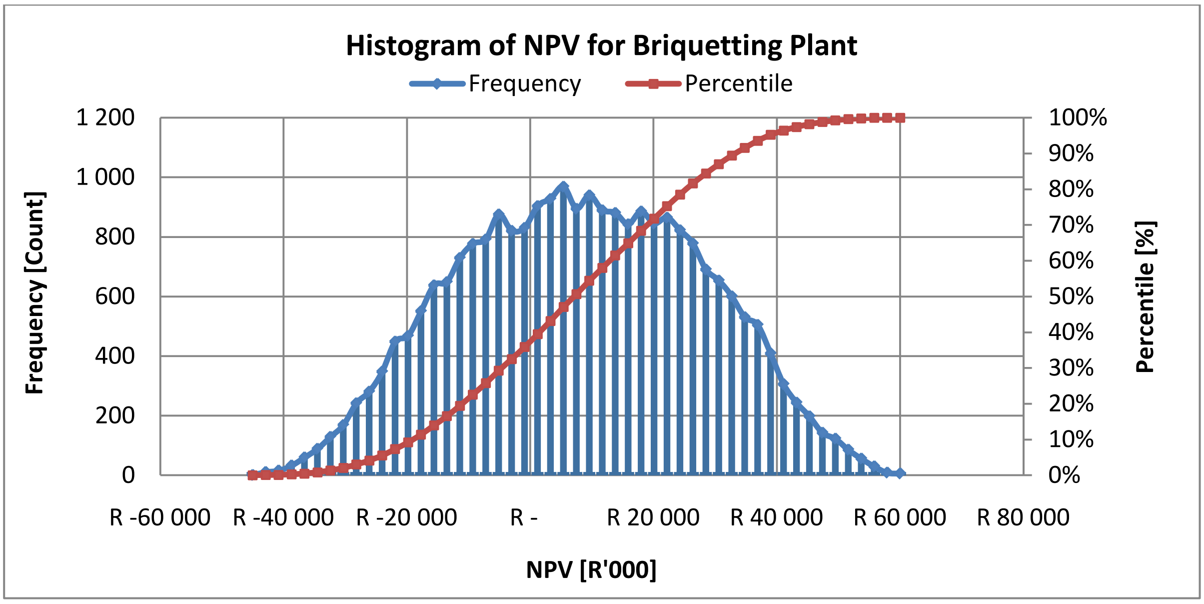


Figure 5-10: NPV histogram from a Monte Carlo simulation on the briquetting plant

From the Monte Carlo risk analysis results in Figure 5-9 and Figure 5-10 it is clear that the briquetting plant is a very high risk investment even though the base case scenario shows attractive results. The probability that the IRR will be lower than the discount rate of 10% is 40% and a 25% probability that the IRR will be negative.

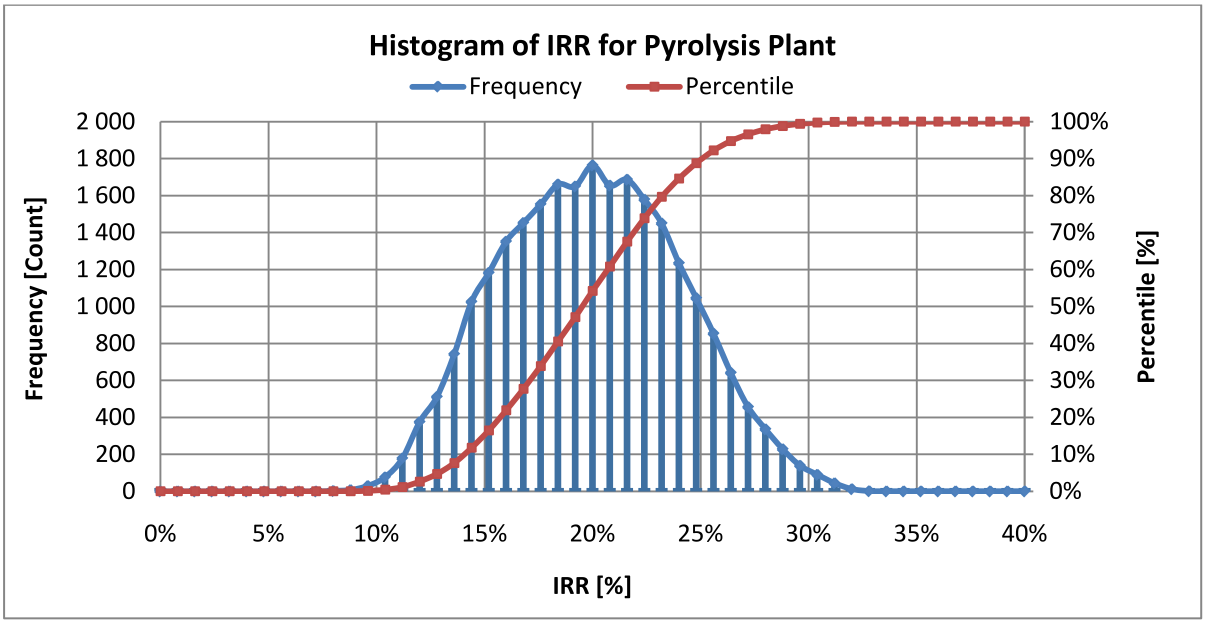


Figure 5-11: IRR histogram from a Monte Carlo simulation on the pyrolysis plant

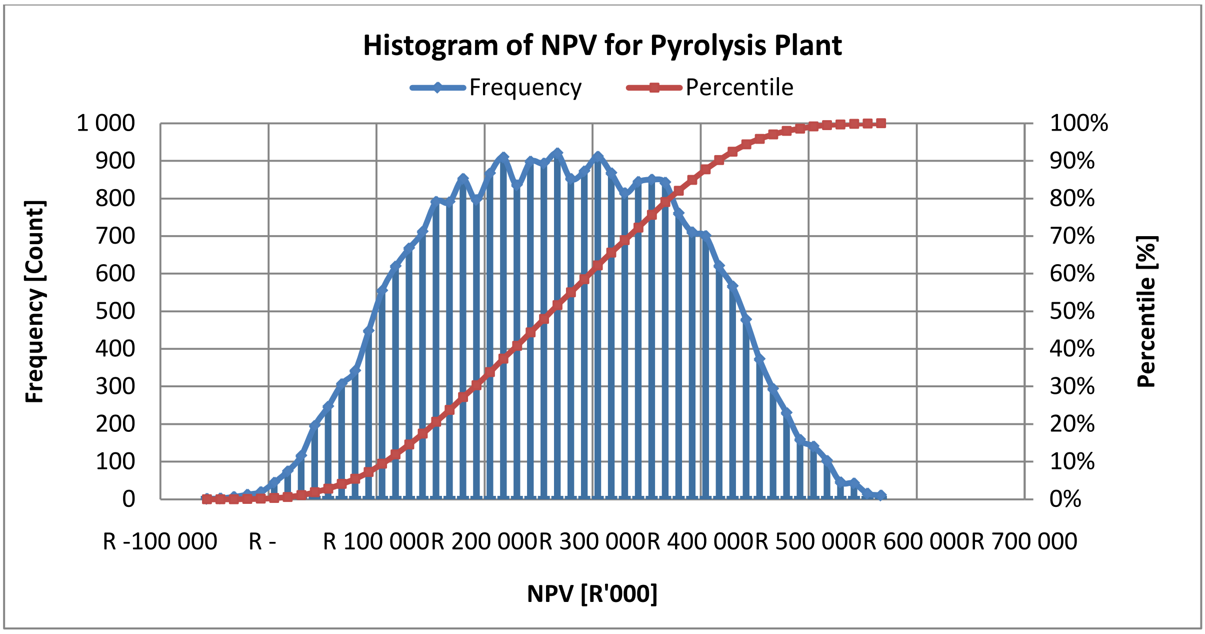


Figure 5-12: NPV histogram from a Monte Carlo simulation on the pyrolysis plant

The Monte Carlo risk analysis results for the pyrolysis plant is very positive and shows that the probability of achieving an IRR and NPV better than the base case scenario is approximately 50% and that there is a 90% probability that an IRR of higher than 14% will be achieved.

Based on the sensitivity and risk analysis results it is clear that the market-related risks associated with the pyrolysis plant is much lower than the risks associated with the briquetting plant.

6. CONCLUSION

An estimated 311 000 ton/yr of agricultural residues are produced and available as a renewable energy resource from the Greater Gariep agricultural area next to the Orange river between Prieska and the Vanderkloof Dam. The energy potential from these residues are 5 362 TJ/yr on a lower heating value basis.

Different technologies are available to convert agricultural residue into a more useful energy product such as fuel briquettes, bio-char or electricity. The high-level evaluation of technologies identified briquetting, combustion, pyrolysis and gasification as the technologies with the highest techno-economic potential for this specific application.

Briquetting of agricultural residue produces fuel briquettes that can be used as fuel for domestic cooking and heating or as fuel to a combustion and steam cycle power plant. The energy balance and efficiency of the briquetting plant is the highest of the technologies investigated, but can not be compared directly with the energy balance and efficiency of technologies that produce electricity as fuel briquettes is a much lower grade of energy product.

Direct combustion of agricultural residue combined with a steam turbine cycle to produce electricity is the technology that requires the smallest capital investment (excluding briquetting), but also has the lowest energy conversion efficiency between 10 and 25%.

Pyrolysis of agricultural residue to produce bio-oil and bio-char combined with an internal combustion engine to convert the bio-oil to electricity is more expensive than the combustion process, but the energy conversion efficiency is higher between 25 and 30%.

Gasification of agricultural residue to produce producer gas that is converted to electricity by an internal combustion engine is the most expensive technology, but also has the highest energy conversion efficiency between 28 and 36%.

The financial evaluation identified the briquetting plant as financially feasible and the most profitable for capacities between 25 000 and 60 000 ton/yr. The local demand for fuel briquettes was identified as the limiting factor and should be determined before continuing with the installation of such a plant. The pyrolysis was identified as financially feasible and the most profitable technology for capacities greater than 60 000 ton/yr.

The sensitivity and risk analysis done on the proposed briquetting plant showed that the financial feasibility is very sensitive to variation in the selling price of fuel briquettes and also the high maintenance cost associated with the briquetting equipment. The risks associated with the market conditions for the briquetting plant is very high.

The proposed pyrolysis plant is very sensitive to variation in the electricity price, but the risks associated with the market conditions for the pyrolysis plant is still very low.

It can be concluded that the utilisation of agricultural residue produced in the Greater Gariep agricultural area is technically and financially viable.

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APPENDIX A – COST ESTIMATION

The models, assumptions and factors used to estimate the operating and capital costs for the different technologies are given in this appendix.

The models and factors used for the capital cost estimations in Section 3 are given in Equations A-1 to A-8 below:

M.Eng Thesis: Agricultural Residue
Great Gariep Agricultural Area
Prieska to Vanderkloof

Capital Cost

Description	Units	Value	Comment
SEIFSA Table P	2000/06	1520.6	Equipment and plant cost (uninstalled)
SEIFSA Table P	2010/06	3069.9	Equipment and plant cost (uninstalled)
R:Eur 2000	R:Eur	6.4	http://www.x-rates.com/d/ZAR/EUR/hist2000.html
F	R/Eur	12.9	Escalation and Currency Factor
R:USD 2010	R/USD	7.0	
LHV	MJ/ton	17200	LHV of untreated AR
Moisture of AR	% WB	15%	

Capital Cost Pre-treatment

$C_{C.PT} = USD*X*(Cap)^{Y}$ (A-1)

X =	288.4	From (Sultana, 2010) modified in *PT Briq Cost* sheet
Y =	0.7746	From (Sultana, 2010) modified in *PT Briq Cost* sheet
USD =	7.0	R/UDS exchange rate 2010

$C_{C.Briq} = USD*X*(Cap)^{Y}$ (A-2)

X =	1410.8	From (Sultana, 2010) modified in *PT Briq Cost* sheet
Y =	0.6029	From (Sultana, 2010) modified in *PT Briq Cost* sheet
USD =	7.0	R/UDS exchange rate 2010

$C_{C.Comb} = F*X*(k*N_{briq}*Cap)^{Y}$ (A-3)

X =	481000	From (Bridgwater, 2002)
Y =	0.8	From (Bridgwater, 2002)
k =	5.454E-04	Modification
N_{briq}	101.2%	Efficiency of PT/Briq

$C_{C.Steam} = F*X*(k*N_{comb.plant}*Cap)^{Y}$ (A-4)

X =	1147000	From (Bridgwater, 2002)
Y =	0.695	From (Bridgwater, 2002)
k =	5.454E-04	Modification
$N_{comb.plant}$		Overall eff of Comb Plant - From tab

$C_{C.Pyr} = F*X*(k*Cap)^{Y}$ (A-5)

X =	40804	From (Bridgwater, 2002)
Y =	0.6194	From (Bridgwater, 2002)
k =	9.703E-02	Modification

$C_{C.LEngine} = F*X*(k*N_{Pyr.plant}*Cap)^{Y}$ (A-6)

X =	903100	From (Bridgwater, 2002)
Y =	0.954	From (Bridgwater, 2002)
k =	5.454E-04	Modification
$N_{Pyr.plant}$	Overall eff of Pyr Plant - From tab	

$C_{C.Gas} = F*X*(k*Cap)^{Y}$ (A-7)

X =	30820	From (Bridgwater, 2002)
Y =	0.6983	From (Bridgwater, 2002)
k =	9.703E-02	Modification

$C_{C.GEngine} = F*X*(k*N_{Gas.plant}*Cap)^{Y}$ (A-8)

X =	821000	From (Bridgwater, 2002)
Y =	0.954	From (Bridgwater, 2002)
k =	6.818E-04	Modification
$N_{Pyr.plant}$	Overall eff of Pyr Plant - From tab	

The results from Equations A-1 to A-8 are shown in Table A- 1 below for each unit operation.

Table A- 1: Capital cost results for the different unit operations.

Capacity Ton/yr	1 $C_{c.PT}$ Rk	2 $C_{c.Briq}$ Rk	3 $C_{c.Comb}$ Rk	4 $C_{c.Steam}$ Rk	5 $C_{c.Pyr}$ Rk	6 $C_{c.LEngine}$ Rk	7 $C_{c.Gas}$ Rk	8 $C_{c.GEngine}$ Rk
5 000	R 1 480	R 1 678	R 14 005	R 6 050	R 24 301	R 8 193	R 29 900	R 10 242
10 000	R 2 532	R 2 548	R 24 384	R 11 937	R 37 332	R 16 077	R 48 516	R 20 178
15 000	R 3 467	R 3 253	R 33 726	R 17 382	R 47 991	R 23 963	R 64 395	R 30 191
20 000	R 4 332	R 3 869	R 42 454	R 22 537	R 57 352	R 31 906	R 78 722	R 40 348
25 000	R 5 149	R 4 427	R 50 752	R 27 476	R 65 852	R 39 925	R 91 995	R 50 669
30 000	R 5 930	R 4 941	R 58 721	R 32 244	R 73 725	R 48 030	R 104 486	R 61 165
35 000	R 6 682	R 5 422	R 66 428	R 36 871	R 81 112	R 56 222	R 116 361	R 71 836
40 000	R 7 411	R 5 877	R 73 917	R 41 379	R 88 105	R 64 502	R 127 733	R 82 680
45 000	R 8 118	R 6 309	R 81 221	R 45 784	R 94 773	R 72 866	R 138 683	R 93 692
50 000	R 8 809	R 6 723	R 88 364	R 50 098	R 101 165	R 81 312	R 149 271	R 104 867
55 000	R 9 484	R 7 121	R 95 365	R 54 331	R 107 317	R 89 835	R 159 544	R 116 197
60 000	R 10 145	R 7 504	R 102 240	R 58 491	R 113 259	R 98 429	R 169 538	R 127 676
65 000	R 10 794	R 7 875	R 109 001	R 62 584	R 119 016	R 107 090	R 179 284	R 139 295
70 000	R 11 432	R 8 235	R 115 658	R 66 617	R 124 607	R 115 813	R 188 806	R 151 045
75 000	R 12 059	R 8 585	R 122 221	R 70 594	R 130 047	R 124 590	R 198 125	R 162 919
80 000	R 12 677	R 8 926	R 128 698	R 74 519	R 135 351	R 133 417	R 207 258	R 174 908
85 000	R 13 287	R 9 258	R 135 093	R 78 396	R 140 530	R 142 286	R 216 221	R 187 002
90 000	R 13 888	R 9 582	R 141 414	R 82 228	R 145 594	R 151 193	R 225 026	R 199 192
95 000	R 14 482	R 9 900	R 147 665	R 86 018	R 150 553	R 160 129	R 233 684	R 211 470
100 000	R 15 069	R 10 211	R 153 850	R 89 768	R 155 413	R 169 090	R 242 206	R 223 826

The assumptions and ratios used to estimate the operating cost of the different unit operations are given in Table A-2 to Table A-9 below.

Table A-2: Operating cost estimation model for the pre-treatment process step

Pre-treatment		
Operating Labour		
L_{PT} = Shifts * Sal * X * (k * Cap)^Y		
X =	6.6	From (Sultana, 2010)
k =	2.27273E-05	Conversion
Y =	0.475	From (Sultana, 2010)
Shifts =	4	rotating 3 shift
Sal =	72000	[R/yr] Cost to company of Operating Personnel
Supervision and Admin	15%	10% - 25% of Operating Labour (Verbaan)
Maintenance	10%	2% - 10% of Fixed Capital Cost (Verbaan)
Overheads	60%	50% - 70% of (Operating Labour+ Sup&Admin+Maint) (Verbaan)
Operating Supplies	1.00%	0.5% - 1% of Fixed Capital Cost (Verbaan)
Utilities	10%	10% - 20% of Total Product Cost (Verbaan)
Insurance and General	0.60%	0.4% - 1% of Fixed Capital Cost (Verbaan)

Table A-3: Operating cost model for the pre-treatment and briquetting process step

Pre-treatment and Briquetting		
Operating Labour		
$L_{PT.Briq}$ = Shifts * Sal * X * (k * Cap)^Y		
X =	11	From (Sultana, 2010)
k =	2.27273E-05	Conversion
Y =	0.475	From (Sultana, 2010)
Shifts =	4	rotating 3 shift
Sal =	72000	[R/yr] Cost to company of Operating Personnel
Supervision and Admin	15%	10% - 25% of Operating Labour (Verbaan, 1985)
Maintenance	10%	2% - 10% of Fixed Capital Cost (Verbaan, 1985)
Overheads	60%	50% - 70% of (Operating Labour+ Sup&Admin+Maint) (Verbaan, 1985)
Operating Supplies	1.00%	0.5% - 1% of Fixed Capital Cost (Verbaan, 1085)
Utilities	10%	10% - 20% of Total Product Cost (Verbaan, 1985)
Insurance and General	0.60%	0.4% - 1% of Fixed Capital Cost (Verbaan, 1985)

Table A-4: Operating cost model for the combustion process step

Combustion		
Operating Labour		
L_{Comb} = Shifts * Sal * (X * ln(k * Cap) + Y) * k * Cap)		
X =	-0.04880	From (Bridgwater, 2002)
k =	0.00055	Conversion
Y =	0.30010	From (Bridgwater, 2002)
Shifts =	4	rotating 3 shift
Sal =	72000	[R/yr] Cost to company of Operating Personnel
Supervision and Admin	15%	10% - 25% of Operating Labour (Verbaan)
Maintenance	4%	2% - 10% of Fixed Capital Cost (Verbaan)
Overheads	60%	50% - 70% of (Operating Labour+ Sup&Admin+Maint) (Verbaan)
Operating Supplies	0.75%	0.5% - 1% of Fixed Capital Cost (Verbaan)
Utilities	10%	10% - 20% of Total Product Cost (Verbaan)
Insurance and General	0.60%	0.4% - 1% of Fixed Capital Cost (Verbaan)

Table A-5: Operating cost model for the steam cycle process step

Steam		
Operating Labour		
L_{Steam} = Shifts*Sal *(X* ln(k * $N_{comb.plant}$ Cap) + Y)*k*$N_{comb.plant}$ *Cap)		
X =	-0.1951	From (Bridgwater, 2002)
k =	5.454E-04	Conversion
Y =	0.9298	From (Bridgwater, 2002)
Shifts =	4	rotating 3 shift
Sal =	72000	[R/yr] Cost to company of Operating Personnel
$N_{comb.plant}$	F(Cap)	From "Comb EB" Tab
Supervision and Admin	15%	10% - 25% of Operating Labour (Verbaan)
Maintenance	4%	2% - 10% of Fixed Capital Cost (Verbaan)
Overheads	60%	50% - 70% of (Operating Labour+ Sup&Admin+Maint) (Verbaan)
Operating Supplies	0.75%	0.5% - 1% of Fixed Capital Cost (Verbaan)
Utilities	10%	10% - 20% of Total Product Cost (Verbaan)
Insurance and General	0.60%	0.4% - 1% of Fixed Capital Cost (Verbaan)

Table A-6: Operating cost model for the pyrolysis process step

Pyrolysis		
Operating Labour		
L_{Pyr} = Shifts * Sal * X * (k * Cap)^Y		
X =	1.04	From (Bridgwater, 2002)
k =	9.7032E-05	Conversion
Y =	0.475	From (Bridgwater, 2002)
Shifts =	4	rotating 3 shift
Sal =	72000	[R/yr] Cost to company of Operating Personnel
Supervision and Admin	15%	10% - 25% of Operating Labour (Verbaan)
Maintenance	4%	2% - 10% of Fixed Capital Cost (Verbaan)
Overheads	60%	50% - 70% of (Operating Labour+ Sup&Admin+Maint) (Verbaan)
Operating Supplies	0.75%	0.5% - 1% of Fixed Capital Cost (Verbaan)
Utilities	10%	10% - 20% of Total Product Cost (Verbaan)
Insurance and General	0.60%	0.4% - 1% of Fixed Capital Cost (Verbaan)

Table A-7: Operating cost model for the internal combustion engine (liquid fuel) process step

Internal Combustion Engine - Liquid		
Operating Labour		
$L_{LEngine}$ = Shifts * Sal * X * (k * $N_{pyr.plant}$ * Cap)^Y		
X =	0.4847	From (Bridgwater, 2002)
k =	0.000545408	Conversion
Y =	0.483	From (Bridgwater, 2002)
Shifts =	4	rotating 3 shift
Sal =	72000	[R/yr] Cost to company of Operating Personnel
Supervision and Admin	15%	10% - 25% of Operating Labour (Verbaan)
Maintenance	4%	2% - 10% of Fixed Capital Cost (Verbaan)
Overheads	60%	50% - 70% of (Operating Labour+ Sup&Admin+Maint) (Verbaan)
Operating Supplies	0.75%	0.5% - 1% of Fixed Capital Cost (Verbaan)
Utilities	10%	10% - 20% of Total Product Cost (Verbaan)
Insurance and General	0.60%	0.4% - 1% of Fixed Capital Cost (Verbaan)

Table A-8: Operating cost model for the gasification process step

Gasification		
Operating Labour		
L_{Gas} = Shifts * Sal * X * (k * Cap)^Y		
X =	1.04	From (Bridgwater, 2002)
k =	9.7032E-05	Conversion
Y =	0.475	From (Bridgwater, 2002)
Shifts =	4	rotating 3 shift
Sal =	72000	[R/yr] Cost to company of Operating Personnel
Supervision and Admin	15%	10% - 25% of Operating Labour (Verbaan)
Maintenance	4%	2% - 10% of Fixed Capital Cost (Verbaan)
Overheads	60%	50% - 70% of (Operating Labour+ Sup&Admin+Maint) (Verbaan)
Operating Supplies	0.75%	0.5% - 1% of Fixed Capital Cost (Verbaan)
Utilities	10%	10% - 20% of Total Product Cost (Verbaan)
Insurance and General	0.60%	0.4% - 1% of Fixed Capital Cost (Verbaan)

Table A-9: Operating cost model for the internal combustion engine (gas fuel) process step

Internal Combustion Engine - Gas		
Operating Labour		
$L_{GEngine}$ = Shifts * Sal * X * (k * $N_{Gas.plant}$ * Cap)^Y		
X =	0.4847	From (Bridgwater, 2002)
k =	0.000545408	Conversion
Y =	0.483	From (Bridgwater, 2002)
Shifts =	4	rotating 3 shift
Sal =	72000	[R/yr] Cost to company of Operating Personnel
Supervision and Admin	15%	10% - 25% of Operating Labour (Verbaan)
Maintenance	4%	2% - 10% of Fixed Capital Cost (Verbaan)
Overheads	60%	50% - 70% of (Operating Labour+ Sup&Admin+Maint) (Verbaan)
Operating Supplies	0.75%	0.5% - 1% of Fixed Capital Cost (Verbaan)
Utilities	10%	10% - 20% of Total Product Cost (Verbaan) (10/15 of OL)
Insurance and General	0.60%	0.4% - 1% of Fixed Capital Cost (Verbaan)

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Table A-10: Operating cost for the complete process plants

	Operating Cost Excluding Raw Materials							
Capacity	**OPEX Briq.Plant**		**OPEX Combustion.Plant**		**OPEX Pyrolysis.Plant**		**OPEX Gasification.Plant**	
[ton/yr]	[Rk/yr]	[R/ton]	[Rk/yr]	[R/ton]	[Rk/yr]	[R/ton]	[Rk/yr]	[R/ton]
5 000	R 3 382	R 676	R 6 294	R 1 259	R 5 300	R 1 060	R 5 909	R 1 182
10 000	R 4 823	R 482	R 8 384	R 838	R 8 094	R 809	R 9 302	R 930
15 000	R 5 946	R 396	R 10 096	R 673	R 10 445	R 696	R 12 229	R 815
20 000	R 6 904	R 345	R 11 598	R 580	R 12 567	R 628	R 14 913	R 746
25 000	R 7 756	R 310	R 12 958	R 518	R 14 543	R 582	R 17 442	R 698
30 000	R 8 534	R 284	R 14 213	R 474	R 16 415	R 547	R 19 864	R 662
35 000	R 9 254	R 264	R 15 385	R 440	R 18 211	R 520	R 22 205	R 634
40 000	R 9 928	R 248	R 16 488	R 412	R 19 947	R 499	R 24 483	R 612
45 000	R 10 566	R 235	R 17 533	R 390	R 21 633	R 481	R 26 712	R 594
50 000	R 11 172	R 223	R 18 528	R 371	R 23 280	R 466	R 28 901	R 578
55 000	R 11 751	R 214	R 19 479	R 354	R 24 893	R 453	R 31 055	R 565
60 000	R 12 308	R 205	R 20 391	R 340	R 26 476	R 441	R 33 181	R 553
65 000	R 12 844	R 198	R 21 267	R 327	R 28 033	R 431	R 35 282	R 543
70 000	R 13 362	R 191	R 22 111	R 316	R 29 568	R 422	R 37 362	R 534
75 000	R 13 864	R 185	R 22 926	R 306	R 31 083	R 414	R 39 422	R 526
80 000	R 14 351	R 179	R 23 713	R 296	R 32 579	R 407	R 41 464	R 518
85 000	R 14 825	R 174	R 24 475	R 288	R 34 058	R 401	R 43 491	R 512
90 000	R 15 287	R 170	R 25 214	R 280	R 35 521	R 395	R 45 503	R 506
95 000	R 15 737	R 166	R 25 930	R 273	R 36 969	R 389	R 47 502	R 500
100 000	R 16 178	R 162	R 26 626	R 266	R 38 402	R 384	R 49 487	R 495

APPENDIX B – SENSITIVITY AND RISK ANALYSIS

The variables and ranges used to evaluate the sensitivity and risks associated with uncertain market conditions are given in Table B-1 and Table B-2 below while the results from the risk analysis are shown in Table B-3 and Table B-4.

Table B-1: Variables used for the sensitivity and risk analysis for the briquetting plant

30 000 ton/yr Briquetting Plant					
Feedstock	30 000 ton/yr				
Fuel Briquettes	26 934 ton/yr				
CPI	4%				
Discount Rate	10%				
Variables to Evaluate					
	Base Case	**Variance**		**Values**	
	R/ton	**Min**	**Max**	**Min**	**Max**
Capital Cost	R 362.38	-10%	25%	R 326.14	R 452.97
Material Cost	R 200.00	-10%	25%	R 180.00	R 250.00
Transport Cost	R 10.95	-10%	25%	R 9.86	R 13.69
O&M Cost	R 284.45	-10%	25%	R 256.01	R 355.57
Briquette Price	R 614.25	-10%	25%	R 552.83	R 767.81

Table B-2: Variables used for the sensitivity and risk analysis for the pyrolysis plant

95 000 ton/yr Pyrolysis Plant						
Feedstock	95 000 ton/yr					
Electricity Produced	136 394 MWh/yr					
Bio-char Produced	11 348 ton/yr					
CPI	4%					
Discount Rate	10%					
Variables to Evaluate						
	Base Case	Variance			Values	
		Min	Max		Min	Max
Capital Cost	R 3 422.78	-10%	25%	[R/ton]	R 3 080.51	R 4 278.48
Material Cost	R 200.00	-10%	25%	[R/ton]	R 180.00	R 250.00
Transport Cost	R 35.39	-10%	25%	[R/ton]	R 31.85	R 44.23
O&M Cost	R 389.14	-10%	25%	[R/ton]	R 350.23	R 486.43
Electricity Price	R 0.75	-10%	25%	[R/kWh]	R 0.68	R 0.94
Bio-char Price	R 1 000.00	-10%	25%	[R/ton]	R 900.00	R 1 250.00

Table B-3: Results from the risk analysis done on the briquetting plant

IRR Simulation				NPV Simulation			
Bracket IRR %	Count Frequency #	Normalised Frequency %	Cumulative %	Bracket NPV [R'000]	Count Frequency #	Normalised Frequency %	Cumulative %
-10%	0	0.00%	0.00%	R -45 000	1	0.00%	0.00%
-8%	5861	23.44%	23.44%	R -42 900	11	0.04%	0.05%
-6%	0	0.00%	23.44%	R -40 800	16	0.06%	0.11%
-5%	146	0.58%	24.03%	R -38 700	33	0.13%	0.24%
-3%	271	1.08%	25.11%	R -36 600	60	0.24%	0.48%
-1%	284	1.14%	26.25%	R -34 500	89	0.36%	0.84%
1%	350	1.40%	27.65%	R -32 400	129	0.52%	1.36%
3%	366	1.46%	29.11%	R -30 300	169	0.68%	2.03%
4%	422	1.69%	30.80%	R -28 200	242	0.97%	3.00%
6%	491	1.96%	32.76%	R -26 100	281	1.12%	4.12%
8%	515	2.06%	34.82%	R -24 000	348	1.39%	5.52%
10%	586	2.34%	37.17%	R -21 900	449	1.80%	7.31%
12%	633	2.53%	39.70%	R -19 800	468	1.87%	9.18%
13%	695	2.78%	42.48%	R -17 700	551	2.20%	11.39%
15%	741	2.96%	45.44%	R -15 600	638	2.55%	13.94%
17%	756	3.02%	48.47%	R -13 500	649	2.60%	16.54%
19%	765	3.06%	51.53%	R -11 400	730	2.92%	19.46%
21%	802	3.21%	54.74%	R -9 300	777	3.11%	22.56%
22%	821	3.28%	58.02%	R -7 200	792	3.17%	25.73%
24%	822	3.29%	61.31%	R -5 100	876	3.50%	29.24%
26%	765	3.06%	64.37%	R -3 000	821	3.28%	32.52%
28%	797	3.19%	67.56%	R -900	831	3.32%	35.84%
30%	827	3.31%	70.86%	R 1 200	904	3.62%	39.46%
31%	821	3.28%	74.15%	R 3 300	928	3.71%	43.17%
33%	788	3.15%	77.30%	R 5 400	969	3.88%	47.05%
35%	732	2.93%	80.23%	R 7 500	895	3.58%	50.63%
37%	696	2.78%	83.01%	R 9 600	940	3.76%	54.39%
39%	623	2.49%	85.50%	R 11 700	890	3.56%	57.95%
40%	634	2.54%	88.04%	R 13 800	881	3.52%	61.47%
42%	544	2.18%	90.22%	R 15 900	843	3.37%	64.84%
44%	467	1.87%	92.08%	R 18 000	886	3.54%	68.39%
46%	413	1.65%	93.74%	R 20 100	845	3.38%	71.77%
48%	354	1.42%	95.15%	R 22 200	865	3.46%	75.23%
49%	290	1.16%	96.31%	R 24 300	823	3.29%	78.52%
51%	225	0.90%	97.21%	R 26 400	778	3.11%	81.63%
53%	193	0.77%	97.98%	R 28 500	691	2.76%	84.40%
55%	133	0.53%	98.52%	R 30 600	654	2.62%	87.01%
57%	116	0.46%	98.98%	R 32 700	601	2.40%	89.42%
58%	90	0.36%	99.34%	R 34 800	531	2.12%	91.54%
60%	50	0.20%	99.54%	R 36 900	505	2.02%	93.56%
62%	45	0.18%	99.72%	R 39 000	409	1.64%	95.20%
64%	25	0.10%	99.82%	R 41 100	306	1.22%	96.42%
66%	20	0.08%	99.90%	R 43 200	244	0.98%	97.40%
67%	15	0.06%	99.96%	R 45 300	198	0.79%	98.19%
69%	6	0.02%	99.98%	R 47 400	143	0.57%	98.76%
71%	2	0.01%	99.99%	R 49 500	123	0.49%	99.25%
73%	1	0.00%	100.00%	R 51 600	86	0.34%	99.60%
75%	1	0.00%	100.00%	R 53 700	56	0.22%	99.82%
76%	0	0.00%	100.00%	R 55 800	30	0.12%	99.94%
78%	0	0.00%	100.00%	R 57 900	9	0.04%	99.98%
80%	0	0.00%	100.00%	R 60 000	6	0.02%	100.00%

Table B-4: Results from the risk analysis done on the pyrolysis plant

IRR Simulation				NPV Simulation			
Bracket IRR %	Count Frequency #	Normalised Frequency %	Cumulative %	Bracket NPV [R'000]	Count Frequency #	Normalised Frequency %	Cumulative %
0%	0	0.00%	0.00%	R -57 000	1	0.00%	0.00%
1%	0	0.00%	0.00%	R -44 520	2	0.01%	0.01%
2%	0	0.00%	0.00%	R -32 040	6	0.02%	0.04%
2%	0	0.00%	0.00%	R -19 560	12	0.05%	0.08%
3%	0	0.00%	0.00%	R -7 080	19	0.08%	0.16%
4%	0	0.00%	0.00%	R 5 400	44	0.18%	0.34%
5%	0	0.00%	0.00%	R 17 880	74	0.30%	0.63%
6%	0	0.00%	0.00%	R 30 360	115	0.46%	1.09%
6%	0	0.00%	0.00%	R 42 840	195	0.78%	1.87%
7%	0	0.00%	0.00%	R 55 320	246	0.98%	2.86%
8%	2	0.01%	0.01%	R 67 800	306	1.22%	4.08%
9%	7	0.03%	0.04%	R 80 280	341	1.36%	5.44%
10%	29	0.12%	0.15%	R 92 760	447	1.79%	7.23%
10%	76	0.30%	0.46%	R 105 240	554	2.22%	9.45%
11%	178	0.71%	1.17%	R 117 720	619	2.48%	11.92%
12%	375	1.50%	2.67%	R 130 200	667	2.67%	14.59%
13%	511	2.04%	4.71%	R 142 680	711	2.84%	17.44%
14%	742	2.97%	7.68%	R 155 160	791	3.16%	20.60%
14%	1025	4.10%	11.78%	R 167 640	790	3.16%	23.76%
15%	1182	4.73%	16.51%	R 180 120	852	3.41%	27.17%
16%	1351	5.40%	21.91%	R 192 600	796	3.18%	30.35%
17%	1452	5.81%	27.72%	R 205 080	866	3.46%	33.82%
18%	1552	6.21%	33.93%	R 217 560	909	3.64%	37.45%
18%	1660	6.64%	40.57%	R 230 040	835	3.34%	40.79%
19%	1649	6.60%	47.16%	R 242 520	898	3.59%	44.38%
20%	1763	7.05%	54.22%	R 255 000	893	3.57%	47.96%
21%	1654	6.62%	60.83%	R 267 480	920	3.68%	51.64%
22%	1686	6.74%	67.58%	R 279 960	852	3.41%	55.04%
22%	1578	6.31%	73.89%	R 292 440	872	3.49%	58.53%
23%	1449	5.80%	79.68%	R 304 920	911	3.64%	62.18%
24%	1234	4.94%	84.62%	R 317 400	867	3.47%	65.64%
25%	1045	4.18%	88.80%	R 329 880	814	3.26%	68.90%
26%	853	3.41%	92.21%	R 342 360	844	3.38%	72.28%
26%	641	2.56%	94.78%	R 354 840	850	3.40%	75.68%
27%	456	1.82%	96.60%	R 367 320	842	3.37%	79.04%
28%	336	1.34%	97.94%	R 379 800	760	3.04%	82.08%
29%	228	0.91%	98.86%	R 392 280	710	2.84%	84.92%
30%	139	0.56%	99.41%	R 404 760	700	2.80%	87.72%
30%	90	0.36%	99.77%	R 417 240	620	2.48%	90.20%
31%	44	0.18%	99.95%	R 429 720	566	2.26%	92.47%
32%	12	0.05%	100.00%	R 442 200	477	1.91%	94.38%
33%	1	0.00%	100.00%	R 454 680	372	1.49%	95.86%
34%	0	0.00%	100.00%	R 467 160	293	1.17%	97.04%
34%	0	0.00%	100.00%	R 479 640	229	0.92%	97.95%
35%	0	0.00%	100.00%	R 492 120	158	0.63%	98.58%
36%	0	0.00%	100.00%	R 504 600	140	0.56%	99.14%
37%	0	0.00%	100.00%	R 517 080	102	0.41%	99.55%
38%	0	0.00%	100.00%	R 529 560	45	0.18%	99.73%
38%	0	0.00%	100.00%	R 542 040	42	0.17%	99.90%
39%	0	0.00%	100.00%	R 554 520	15	0.06%	99.96%
40%	0	0.00%	100.00%	R 567 000	10	0.04%	100.00%