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Presented by

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Assessment of Technical Potential of Agricultural Waste to Bioenergy in Botswana

Defended on 04/09/2018 Before the Following Committee:

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DECLARATION

I **Phumuza Mabuza**, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

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ABSTRACT

The global impact of energy demand and the unstable fuel prices to power national economies have not only affected the industrious countries but all countries and the most hard hit are poor and developing nations. The world is faced with the challenge of adopting the most efficient methods of energy use to preserve the reserves and full scale exploration and clean forms of energy is ongoing. In light of the global efforts an in depth study was conducted to examine the potential of agricultural waste to bioenergy in Botswana. Crop residues and animal waste were assessed for their potential to supply electricity for rural electrification using the Food Agriculture organization Bio Energy and Food Security Appraisal tools and approach.

Agricultural production data for a period averaging 10years was collected from relevant stakeholders in charge or actively involved in production sector. The data was then used to map the amount crop residues available in Borolong, Panda and BMC Lobatse. Trips were made to the areas to inquire and gather information about other uses of the crop residues that remain in the fields after harvest and adjustment were made to cater for such uses and subtract the portion used for other purposes from possible energy pathways. The BEFS Rapid Appraisal method was used to determine the possibility of rural electrification through combustion and gasification. Bio digester was also considered for the supply of heat and electricity using animal waste as a feed stock.

The three areas have the possibility to use animal waste and crop residues to produce electricity for rural electrification. The amount of crop wastes available are sufficient to power gasification and combustion plants and supply over 300 households with electricity in both Borolong and Panda. Nationally the bioethanol potential stands at over 2 million liters annually. If fully exploited Botswana can add bioethanol to its liquid fuels mix and have a blended petrol mandate. From crop residues sorghum straw is the most abundant in Panda and has an annual output of over 75 ‘000tonnes/year.

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Choukran..!

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LIST OF ABBREVIATIONS

BEFS AF	Bioenergy and Food Security Analytical Framework
BEFS	Bioenergy and Food Security
BEFS RA	Bioenergy and Food Security Rapid Appraisal
BEP	Botswana Energy Policy
BITRI	Botswana Institute for Technology & Research Innovation
BVI	Botswana Vaccine Institute.
CSIR	Council for Scientific & Industrial Research
GIT	Gastro Intestinal Track
IEA	International Energy Agency
IRR	Internal Rate of Return
JICA	Japanese International Cooperation Agency
NO_X	Nitrogen Oxides
NPV	Net Present Value
OPEC	Organisation of Petroleum Exporting Countries
RPR	Residue to Product Ratio
SAPP	Southern African Power Pool
SIRDC	Scientific, Industrial Research & Development Centre
BMC	Botswana Meat Commission

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Chapter 1 INTRODUCTION AND SIGNIFICANCE OF RESEARCH

1.1 Introduction

Energy is an important aspect of human life. All activities man engage in demand some form of energy to be either dissipated or gained. Industrialisation is possible today because of energy; quality of life is improved because of it, in today's world almost everything cannot be done without energy to a point where life is meaningless if electricity were to be cut. As we depend solely on energy there are various sources where this energy is derived. The sources are split into two main groups being renewable and non-renewable sources. Non-renewable fuels are not replaceable once used and will eventually get depleted. Examples of this type of sources fossil fuels in the form of crude oil and its by-products, coal and natural gas. Renewable energy sources on the other hand do not get depleted rather they are replaced by the environment through the natural means of reproduction like biofuels and some are naturally in abundance like solar, and wind. The renewables are more desirable over the non-renewables because they do not have high carbon content therefore there is a reduced carbon print in the atmosphere. In the advent of climate change driven by pollution, ozone layer depletion, it is important to use forms of energy that do not contribute to this adverse situation.

The world population is growing exponentially and exponential population growth means an increased energy demand. This turn of events has since caused the depletion of world reserves in petroleum based fuels and their products (Ketlogetswe 2011[a]). In trying to argument the fossil fuels alternative fuels are being researched and the popular fuel has since become the biofuels. Developed nations has maximised their efforts in research on biofuels and they have now gained momentum worldwide

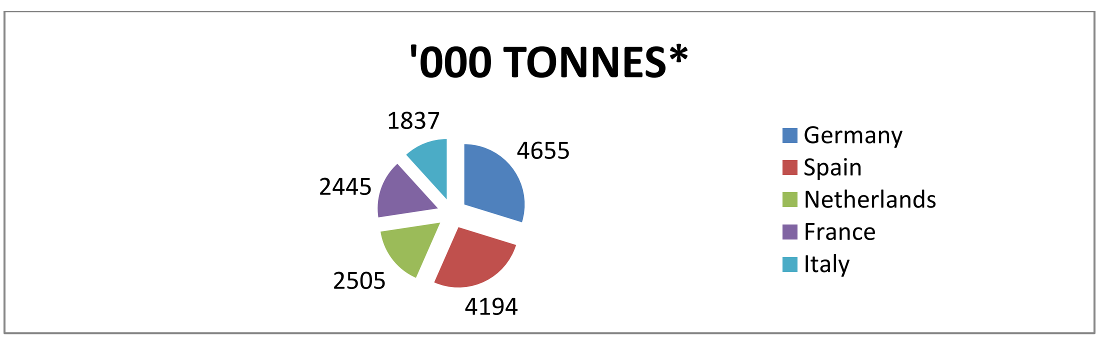

Figure 1.1 2014 EU top 5 biodiesel producers in '000 tonnes (data extracted from European Biodiesel Board, 2015)

Figure 1 shows top biodiesel producers in the European Union. Germany is the highest producer with 4655'000 tonnes as at year 2014. This production capacity was also the highest in the world implying that Germany is also the world's highest biodiesel producer. Another form of biofuels currently pursued is bioethanol. Fig 2 below shows the world regions and their production capacities. South America has the highest capacity mainly from Brazil and uses corn as the primary feedstock while the EU uses mainly rapeseed or canola as substrates for their biofuels.

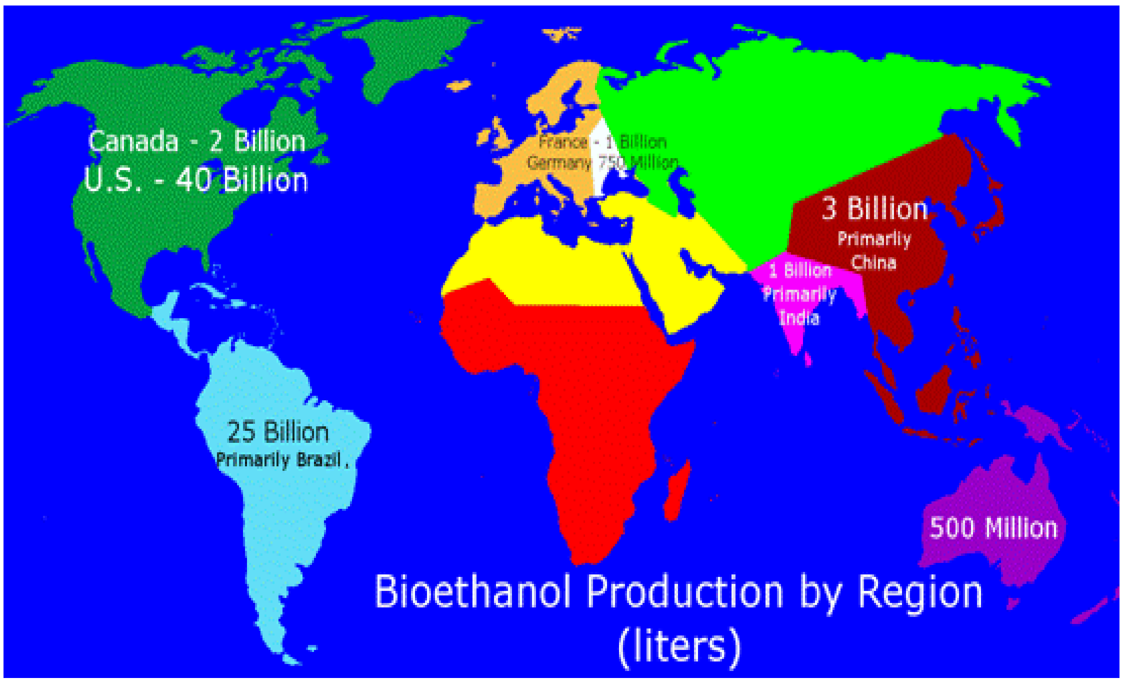

Figure 1.2 Bioethanol production in the world (Adopted from Biofuel.org.uk)

In view of the global happenings Botswana has not been left out, the constant hike in oil prices is challenging for non-oil producing countries (Ketlogetswe 2011[a]). Governments have adopted technologies for alternative fuels to meet their energy demands. According to the Botswana national draft energy policy (2010), Botswana relies on imported energy sources especially petroleum products and electricity, however there is need to promote the use of indigenous energy resources to reduce dependence on imported energy sources. Even on the indigenous resources, more attention is given to the renewable energy sources like biofuels. According to Gao et al (2012) biofuels are viable due to the fact that oil prices are significantly higher than they were in the past and are not likely to fall to those low levels again. In addition to fossils being pricey, they are running out quickly and there is also need for a clean and safe environment and burning fossils have adverse impacts that can result in acid rains, unpredictable weather patterns leading to severe droughts or floods.

In the production of bioenergy supplies there are many types of feed stocks that can be used and examples include energy crops, crop wastes, municipal solid waste, animal waste and any biodegradable material. Primarily the most important aspect in bio energy sources is for them to have higher carbon content (lignocellulosic materials), contain oils or sugars therefore all substrates should contain any of the three important components (Naik et al, 2009).

1.2 Botswana Energy Status

The Republic of Botswana is a landlocked country in Southern Africa bordering Namibia to the west and north, South Africa to the south, Zimbabwe to the north east and meets Zambia at a single point in the north. The country has just over two million inhabitants with a population density of four people per square kilometer (World Bank, 2011). The country has a flat topography and about 70% of it is covered by the Kalahari Desert. Botswana quickly moved from a low income status to a middle income country after its independence from Britain and is considered amongst the fastest growing economies currently with a GDP per capita PPP of about $15915 (IMF 2014). The energy resources of Botswana include coal reserves and renewables (Table 1.1)

Table 1.1 Energy resources in Botswana

Resource	Value(s)	Units
Wind	2.0-3.5	m/s
Forest Biomass	4.8-10.6	Ha/year
Solar Potential	2087670493	Mwh/year
Coal reserves	212.8	Billion Metric Tonnes

As shown in table 1.1 Botswana has huge coal reserves which it relies upon for its electricity generation on coal fired plants. There is about 890 MW installed capacity in total with only 1.3MW being from renewable energy, solar PV specifically while the rest of the plants are thermal powered. Two plants (Morupule A 132MW and B 600MW) are coal fired while the other two are diesel fired (Orapa plant 90MW and Matshelagabedi plant 70MW). Mean annual solar insolation is 24MJ per m2 per day which is very high and presents good prospects for solar energy which is otherwise underutilised. All of the petroleum products are imported into Botswana as the country has no petroleum reserves. The imported petroleum and its associated products are sourced mainly from South Africa which is more economically advanced and has a better improved energy mix in the Sothern African region.

Though the installed capacity is about 800+ the generation capacity is very low leading to consistent electricity shortage and power cuts. The low generation capacity is a result of faulty plants, unscheduled maintenance works and sometimes prolonged scheduled maintenance times. As a result the country depends on electricity imports to meet its growing electricity needs. The South African power utility company Eskom supplies a bigger portion of the electricity imports. In 2008 alone Botswana imported approximately 368MW which was about 67% of its electricity needs for that year and only the remaining 33% was sourced locally. Figure 1 shows the energy sources by type in Botswana, and coal and petroleum are the biggest sources.

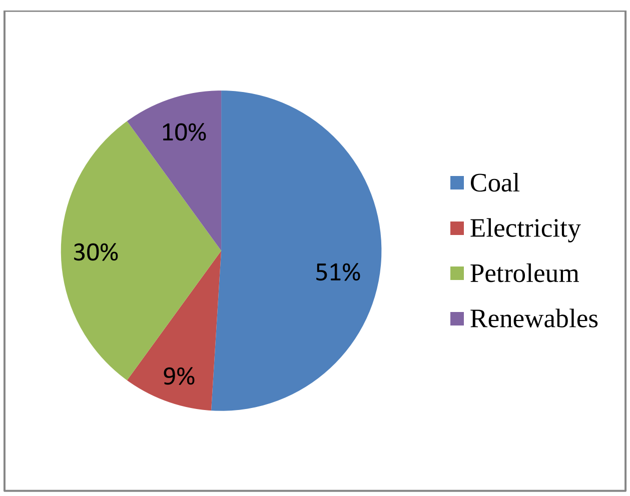

Figure 1.3 Energy Sources by type in Botswana (IEA 2017)

Currently the national electrification rate stands at 62% with 75 % and 57% access in urban and rural areas respectively. The target for national electricity access was 82% by 2016 and 100% by 2030 both from grid electricity and off grid connections. Though the 2016 target was not met BPC (2017) believes it is on track and will ultimately achieve the 2030 target as the nation keep growing its installed and production capacities. The country's energy demand is driven primarily by the residential and transport sector which account for over 70% of the total consumption (Statistics Botswana, 2016). The figure below (figure 1.4) presents the sectors by their percentage composition.

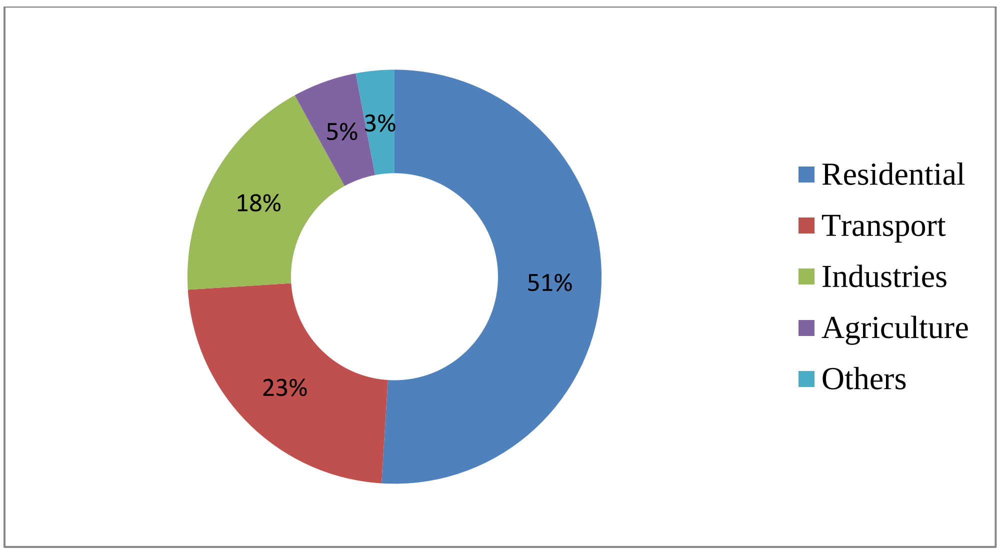

Figure 1.4 Energy Consumption by Sector (Statistics Botswana, 2016)

The increasing energy crisis in Southern Africa does impact Botswana's economic growth plans as it poses a threat to stability and requires concerted efforts at regional & national levels to address the energy challenge. One of the regional interventions was the establishment of the Southern African Power Pool (SAPP). SAPP is a regional electricity body that facilitates the development of competitive energy market and gives users choice electricity supply that is sustainable and environmentally friendly. Table 2 shows the SAPP member states together with their respective utility companies and capacities.

Table 1.2 SAPP member States installed capacities (SAPP, 2016)

Country	Utilllity	Installled Capacity (MW)
Angola	ENE	2 210
Botswana	BPC	892
DRC	SNEL	2 442
Lesotho	LEC	74
Malawi	ESCOM	352
Mozambique	EDM/HCB	2 724
Namibia	NamPower	501
South Africa	Eskom	46 963
Swaziland	SEC	70
Tanzania	TANESCO	1 380
Zambia	ZESCO/CEC/LHPC	2 206
Zimbabwe	ZESA	2 045
TOTAL		61 859

From the table, Swaziland and Lesotho have the lowest installed capacities followed by Malawi and Namibia in that order. These countries do import between 40-70% of their electricity load from other countries on the SAPP.

To improve energy research in Botswana local research organisations have been set like Botswana Institute for Technology & Research Innovation (BITRI) together with universities to research energy solutions for the country. Cooperation agreements with other bodies in the region like Scientific, Industrial Research & Development Centre (SIRDC) of Zimbabwe and the Council for Scientific & Industrial Research (CSIR) of South Africa are also helping to share experiences and approaches to dealing with common problems. The main objectives of these collaborations are to promote and implement high impact regional projects in addition to creating synergy by pooling resources together (Botswana Energy Policy,2015)

Moreover to address the energy difficulties in the country the government has developed strategies to contain the situation by encouraging both energy conservation and energy efficiency by all end-users across the nation. The overall policy goal for the energy sector is to provide an affordable, clean and sustainable energy service that promotes social and economic development (BEP, 2015). This policy is also in tandem with a few sustainable development goals which speak of better access to modern forms of energy which in turn improve education, quality of live and other aspects.

Another avenue that forms the bedrock to pragmatic approach to energy shortage in Botswana is Research and development. Efforts are made to encourage research and development locally though funding is thinly availed. Donor organisations are helping the government undertake some of the R&D projects. For instance the Japanese International Cooperation Agency (JICA) funded a 1.3MW solar plant to be used as a pilot study for solar PV development in the country. The same organisation is also funding a biodiesel development project which is focused on using jatropha seeds. On the same vein this research also contributes to the research and development efforts locally and will be a step further to providing local solutions to local problems.

1.3 Justification/ Socio-Economic Benefits: Importance of Research

Botswana is in pursuit of a green energy status and is exploring all options available at its disposal. Amongst other options it has established the potential to produce biodiesel from Jatropha seeds, ethanol from sweet sorghum and bio-gel (Botswana national draft energy policy 2010). The greatest challenge is that some of the feedstock's like Jatropha are not indigenous plant species and as such more research work is required on the locally and readily available feedstock. Countries are battling with energy sufficiency and security around the world more especially underdeveloped countries of Sub Saharan Africa. Reliable supply of energy is closely linked to the rapid socio-economic growth of every emerging economy in the world today. Lack of reliable energy supply undermines a country's stride towards economic and social advancements. This research has identified feedstock sources, opportunities and impacts for biomass contribution to the energy mix in Botswana. The findings are useful to government, energy planners, policy makers, utilities and international organisations that are engaged in assessing renewable energy technology development. Additionally the inclusion of this waste in the energy mix will greatly reduce the energy poverty in economically disadvantaged citizens as well as reduce carbon emissions in accordance with the Kyoto protocol as biomass is considered carbon neutral.

1.4 Statement of the Problem

The uptake of renewable energy technologies is very low in developing countries. The general population lacks awareness and knowledge about renewable energy because the research and development efforts are very low. Self-sufficiency and self-sustenance in energy issues only becomes a dream if not acted upon. In an effort to increase awareness and promote use of renewable energy this study becomes relevant to argument other indigenous feedstocks that have been added as biodiesel feedstocks in Botswana. The country can realise its vision of being energy reliant in addition to being a centre of solar energy excellence by the year 2020 (Energy draft Policy, 2010). Currently in Botswana the research about energy solutions is very low and as common to other developing countries is not a top notch priority to the government of the day. Funding is very limited to carry out energy projects and a lot of areas are overlooked due to scarcity of funds and resources yet there is so much potential in such areas to address the energy poverty in Botswana especially in rural areas. The current status quo not much has been done in Botswana to include agricultural waste and residues into the total primary energy supply mix of the country yet the resource is available in almost every community and is left to rot in the fields unutilised save for the little that is used for animal feeds. Therefore this research intends to cover this otherwise disregarded area of agricultural waste and bring it to the fore as a possible contributor to the energy supply especially in rural areas where the electricity grid is expensive to expand to.

1.5 Approach to the problem

A good and sustainable solution to any problems encountered by humanity has to be always guided by proper and accurate information. This is to say that the most current information and facts must be analysed in tandem with what is transpiring on the ground at that time guided by what has happened in the past together with future projections. In this instance the solution to the data deficiency and subsequent lack of inclusion of agricultural waste in the energy mix can be resolved by researching on the area and providing well thought out solutions. This particular study is a step towards addressing the problem and more studies of this kind are needed to fully exploit every resource that has potential to improve livelihoods of people more especially if its resources that are carbon neutral and has less carbon emissions.

The primary aim and objective of this study was to investigate the amount of agricultural biomass available for energy (electricity & heat) production in Botswana and establish the most cost effective technologies that can be used to transform this biomass into useful energy. To achieve this primary objective the following specific objectives were necessary to be undertaken;

- Analyse the annual agricultural production figures in Botswana averaging 10years in duration

- Techno-economic analysis of the agricultural waste conversion pathways as per the different BEFS models (gasification, biogas, combustion, transport)

- Analysis of major production centres (Panda, Borolong & BMC) for in house energy supply of the latter area and rural electrification for the former areas

It is worth noting that though the intention is to assess the possibility of waste to energy some limitations do exist. This research work covers only the assessment of agricultural waste from crops and animals available in Botswana. There are other forms of waste available that can be used for energy production like municipal solid waste, food waste from governmental departments and other all kind of waste from industries which is otherwise excluded from this work. The models used in this work deal specifically with crop and animal waste so other kinds are by extension eliminated though they could add to the energy mix also. During the study some of the constraints encountered were;

- Incomplete agricultural production reports which had missing data
- No proper record keeping by farmers on post-harvest use of crop wastes

Over and above the limitations the hypothesis guiding this study was that

- Agricultural waste can contribute significantly to the energy mix of Botswana
- Major agricultural production areas in addition to rural electrification can have their respective in house energy plants running profitably in.

1.6 Thesis layout

This study consists of five main chapters. Chapter one introduces the topic and underlines the background of the study; it gives a brief outline of the status of energy in Botswana. This chapter also gives the problems, justification and approach how the research problem was addressed.

Chapter two sets out the literature review. It presents the global energy situation, history of biofuels in Botswana and closes off by presenting what other researchers have done in the field of biomass assessment together with the various ways in which such can be achieved.

Chapter three outlines the methodology employed for the study. It indicates the data collected, description of the areas studied and outlines in detail the tools, Bio Energy & Food Security Rapid Appraisal criterion and the Analytical frame work.

Chapter four shows the results and discussion. The findings from the study are presented starting with the biogas option for animal waste in Lobatse BMC. The gasification and combustion results are also shown for the two areas (Panda & Borolong) with the corresponding residues and feasible energy outputs.

Lastly chapter five is about conclusions and recommendations for further studies. Major lessons learnt from the study are presented here. The chapter briefly provides answers to the objectives of the study.

Chapter 2 LITERATURE REVIEW

This chapter reviews literature in the area of energy. It presents the global energy scenario then shows how Botswana's renewable energy sector has progressed over the years. Other studies relating to biomass assessment are also presented. The chapter closes off by outlining the techniques for biomass assessment.

2.1 Global Energy Situation

Energy planers and researchers around the world are in tandem agreement that world petroleum reserves are decreasing rapidly, especially crude oil, and that it is only a matter of time before they run out (Shafiee and Topal, 2009). This reduction in reserves comes as a culmination of different factors which have increased demand for energy globally. The factors include world population boom, urbanization, and socio-economic development in addition to industrialisation. The increasing demand, coupled with market forces, has led to rising petroleum costs (Figure 2.1). Though the prices fluctuate a lot in recent years (2010-2016) generally they have been on the rise and oil producing countries (OPEC) and non-oil producing countries (non-OPEC) are affected alike. Other factors, such as the irregularities in supplies and distributions, the challenges of accessing and procuring unconventional fuels, and occasional political instabilities in major supply regions, have caused general uncertainty regarding global reliability in fossil fuels in the coming decades. Projections show that the world will be in an energy crisis by the year 2050 if the current status core remains unchanged. Some researchers and organisations are predicting it to be even sooner than 2050 while others later according to Arranza-Piera et al (2017) these diverging views are only normal and are brought about by differences in methodological approaches when simulating.

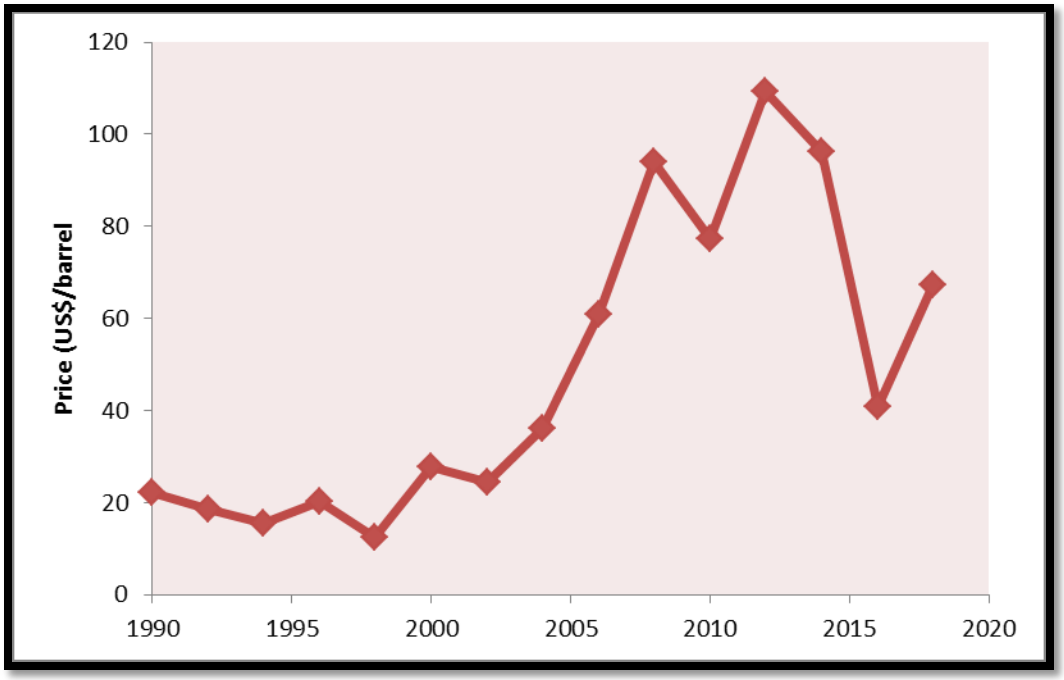

Figure 2.1 Crude oil nominal Prices (World Bank, 2017)

Countries such as the United States and Canada have resorted to fracking and extracting oil from tar sands to avoid expensive means of crude oil extraction through conventional technologies, notwithstanding campaigns against such by environmental groups. In its most recent stunt the United States has opted out of the Paris COP agreement that amongst other things was to govern and regulate carbon emissions thereby meaning it has taken an aggressive stance to deregulate its carbon and steel emissions.

Also, increased use of fossil fuels has implications for global warming. Global warming is directly linked to the production and combustion of fossil fuels (IPCC, 2007) due to the emission of carbon into the atmosphere. In 2015 alone two-thirds of global CO_2 emissions from fossil fuels and industrial processes were generated in China (with 29% share in the global total), the United States (14%), the European Union (EU-28) (10%), India (7%), the Russian Federation (5%) and Japan (3.5%), (Fotolia & Salman 2017). To tackle this situation, several countries/regions are seeking alternative energy futures (IEA, 2013). Indeed, developed and developing countries alike are intensifying their search for alternative fuel sources due to the socio-economic and environmental cost of dependence on fossil fuels. The use of solar, wind, mini-hydro, tides and biomass as alternative energy sources is gaining prominence globally.

In mapping the world energy projections the world is categorised into two groups being membership to Organisation for Economic Cooperation & Development (OECD) or not being a member to such (non-OECD). Within each group further divisions exist according to the geographic groupings (OECD / non-OECD America, Asia, Europe and Africa.) The member states of this organisation are 34 countries and some of the prominent ones include the United States, Canada, Australia, Mexico, South Korea, Germany, and France amongst many others.

The world's greatest energy source by far is fossil fuels in the form of oil, coal and natural gas. These fuels are used for electricity generation and transportation fuels. Most developed and industrious countries have deposits of this resources and high energy intensity. China and the United States have high energy intensities and huge industries that are attributed to both nations having almost all conventional fuels and a robust renewable energy drive to argument their fossil supply. In addition to Russia and Saudi Arabia this four countries combined produce the largest share of oil in the world (43%) from both light and heavy hydrocarbons (REN 21, 2016).

According to the REN 21 (2016) world energy outlooks in 2015 the biggest oil reserves were calculated to be in the Middle East (803 billion barrels), followed by Latin America (329 billion barrels), north America (238 billion barrels), Europe and Asia combined (186 billion barrels). Africa has the lowest reserves (129 billion barrels) centre around West Africa (Nigeria, Ghana, and Cameroon) and North Africa (Algeria, Libya, Egypt & Tunisia). A majority of this African are or have experienced political or economic instability.

Coal and natural gas are other equally important fuel resources to oil. The worldwide proven reserves in 2015 were (1225 tonnes and 23215 cubic litres) of coal and natural gas respectively. IEA (2017) reports that coal as a resource has the largest reserve-to-production ratio for any fossil fuel enough to meet up to 114 years of global production. Coal is widely spread across the world and found in most regions thus making it the most available fossil fuel resource for heat and power generation. Though some countries also use is for transportation it is not on a large scale as the liquefaction technology that converts it into liquid fuels is very expensive (Naik et al, 2010, Gandure 2011). Natural gas is a cleaner fuel as compared to both coal and oil and Chang

(2015) argues that its use worldwide has increased in recent years as it is promoted for environmental friendliness. Natural gas grows faster than both oil and coal, growing by 1.6% p.a. between 2015 and 2035. By sector, the largest contribution to consumption growth comes from the industrial sector (with combusted and non-combusted use together accounting for 45% of growth) followed by power (36%). (BP, 2017) Figures a and b below show the distribution of this fuel reserves across the world.

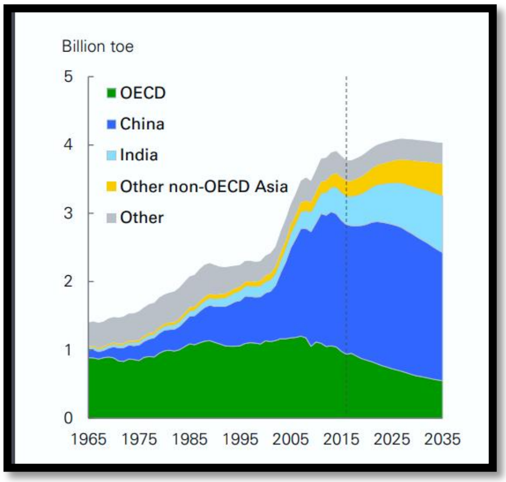

Figure 2.2 Coal Consumption by Region (BP.2017)

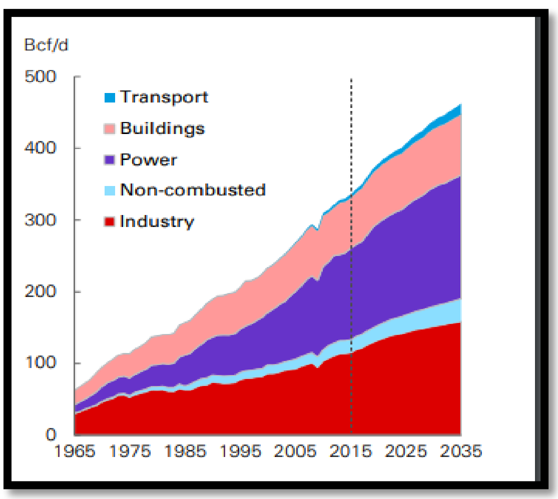

Figure 2.3 Gas Consumption by Sector (BP,2017)

2.2 Renewables & Nuclear Energy

Nuclear energy has for the most part been considered a neutral energy source. It is not considered a fossil neither is it considered renewable. This is so because of the uniqueness of the fuel and the security measures surrounding it. Public acceptance of nuclear has always been questionable and the deadly accidents in Fukushima and then later in Chernobyl has led to most countries re assessing their nuclear energy plans. Most developed nations have pledged to close their nuclear plants a move which Tao et al (2015) argues is it not sustainable as they consider nuclear a strong alternative in the fight against global warming and reduction in carbon emissions. Nuclear is powered by the mineral uranium which is highly radioactive. The World Security Council is discouraging the licensing of new nuclear plants because of fears of nuking and disposal of radioactive waste.

When it comes to the traditional renewable energy forms hydropower is by far the most fully developed and greatest contributor to electricity generation around the world. Renewables in power are projected to be the fastest growing fuel source (7.6% p.a.) and account for 40% of the growth in power generation, causing their share of global power to increase from 7% in 2015 to nearly 20% by 2035. The EU continues to lead the way (figure 4) in terms of the penetration of renewables, with their share of renewables within the power sector reaching almost 40% by 2035 (BP,2017). The strong growth in renewable energy is underpinned by the view that the competitiveness of both solar and wind power improves significantly over the years.

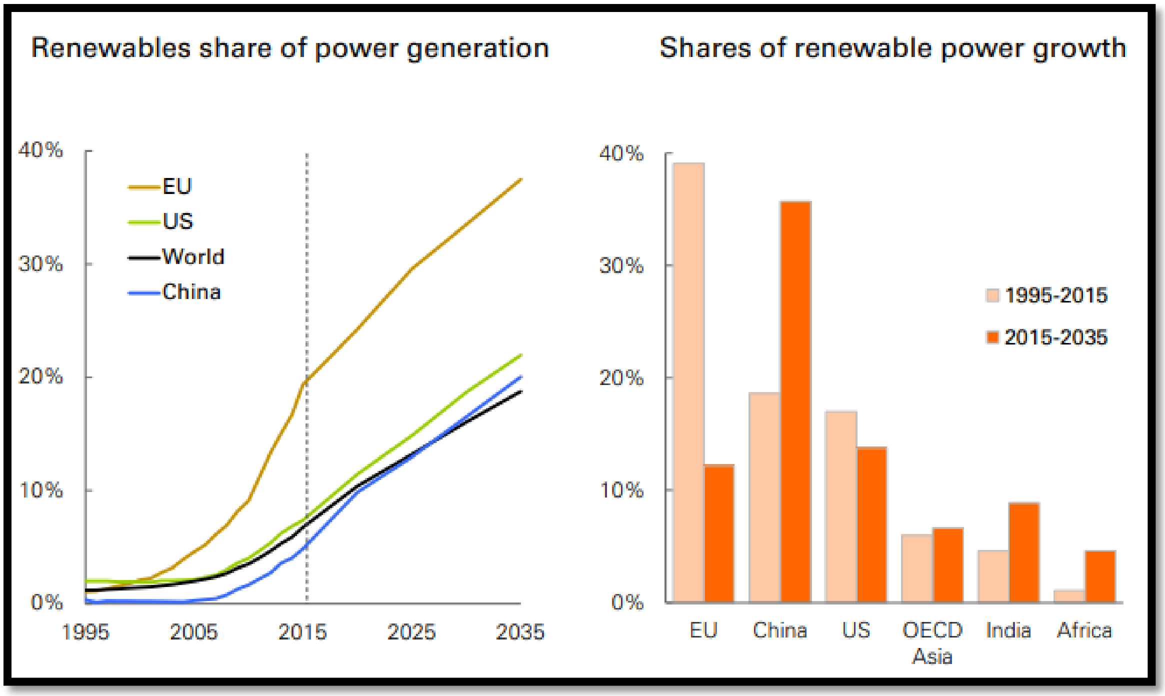

Figure 2.4 Renewable Energy trends in the world (EIA, 2017)

2.3 Other Forms of Energy

Over the years Botswana has relied on energy imports from its neighbouring countries to augment local supply (Energy Affairs Division (EAD, 2010)). Fire wood and liquefied petroleum gas (LPG) are amongst the main sources of energy with wood contributing about 30 and 38 per cent for the country's primary energy and final energy balance respectively (Chimbombi et al 2014). Energy has been mainly sourced from natural resources like wood and animal by-products like dung which Mogotsi (2009) attributes to the majority of the population residing in the rural areas. Of late electricity has increasingly been used as a source of energy and contributes significantly in the energy mix especially on the semi or peri urban centres and towns. The usage of electricity has risen significantly over the years such that the local demand exceeds supply and as such this calls for rationing of electricity in some areas during peak hours (EAD, 2010).

On the transportation sector Botswana has always relied on petroleum fuels with 825.6 million litres being imported from South Africa (Chimbombi et al 2014). Oils Botswana together with its partners, (various filling station outlets) under their respective companies is responsible for the import and distribution of petroleum fuels and lubricants around the country (EAD, 2012). However the amount of fuels imported into the country is worrisome, and possess threats to the national supply should there be problems in South Africa (Ketlogetswe, 2011). Reliance on foreign nations should be reduced by tapping into the indigenous sources for energy supply (Oladiran & Gandure, 2011; Ketlogetswe et al 2011[b]).

2.4 History of biofuels in Botswana

The biofuels industry is still in its infancy in Botswana. Industrially there is not much happening on a large scale and the research in the field is not very much advanced. There is currently one company (Biodiesel Botswana) which produces/ manufactures biodiesel commercially. The company produces about 3'000 litres of biodiesel per month which translates to approximately 36'000 litres annually (Biodiesel Botswana, 2014). The company has various clients locally and across borders with the South African market consuming a larger portion of the process by products. Other forms of biofuels locally available include biogas plants which Chimbombi et al (2014) attributes to the widespread availability of cattle across the country. The government of Botswana through the ministry of minerals energy and water resources has established the potential to produce biofuels and have estimated a 10 percent growth of the gross domestic product (GDP) by diversifying into the biofuels sector. A further 5000 new jobs are also envisaged to be created if the industry booms. Research has established that jatropha has huge potential as a feedstock in Botswana and more efforts has been put towards its cultivation and localisation to increase production. More substrates keep on being investigated and recommended as perfect substitutes, some plant species which have been added to the mix include Sclerocarya birrea (Morula), Tylosema esculentum (Morama) and moretologa (Gandure et al 2011[a], 2011[b], 2012, 2014, Ketlogetswe 2011). Energy farming is an option that is being considered in an effort to improve renewable energy use.

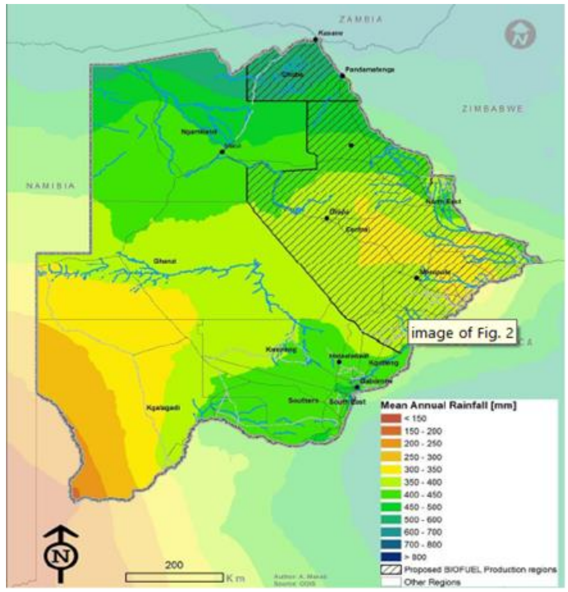

Figure 2.5 Botswana Rainfall Map (Kgathi et al 2012)

From the figure Chobe and Central districts are proposed as biofuels production areas because they receive a considerable amount of rainfall which will boost production. Energy farming is becoming a lucrative business across the world, where small scale farmers grow energy crops and sell to a central production plant. The initiative is also encouraged for Botswana for the cultivation of jatropha (Kgathi et al 2012).

2.5 IMPORTANCE OF USING BIOENERGY

At the fore front of the benefits of using bioenergy is the reduction in greenhouse emissions (Yang et al 2014). The little carbon print emitted from use of renewables helps to address climate change and environmental problems since the process have a complete life cycle;

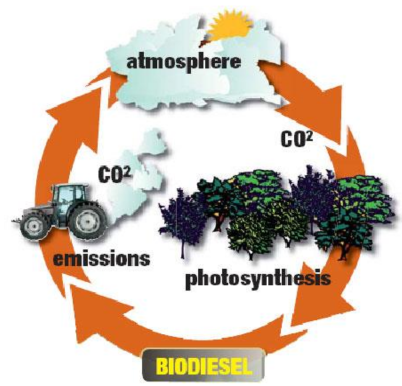

Figure 2.6 the biodiesel life cycle (www.biofuels.coop>archive>lifecycle........./.com**)**

As depicted on the cycle, plants use carbon dioxide in the atmosphere to photosynthesise and produce oils / lipids which are in turn extracted and turned into biodiesel. When burned in tractors or machinery the fumes produced (carbon, sulphur etc.) are released back to the atmosphere and taken up again by plant to repeat the process again. As opposed to petroleum fuels which have a high foot print of greenhouse gases the bad environmental constraints like ozone depletion are reduced significantly by the use of biofuels (Yang et al 2014). The authors also liken the use of biofuels and biodiesel in particular to poverty reduction as the land used to cultivate feedstock crops is mainly in rural areas, therefore local population can be engaged in full time cultivation to sell for fuel production and in the process gain income revenue to improve their living conditions. These sentiments are in agreement with Balat (2011) who also argues that biofuels can increase job creation if commercialised and can empower a lot of women as they are the people who are primarily involved in crop production. Alnuami et al (2014) also report that the production and use of bioenergy strikes a balance between a country's domestic agriculture, economic development and ecological stability. On a technical front specific biofuels like biodiesel is desired because it can be easily blended and used with petroleum diesel. It is compatible with almost all diesel engines and as such can be used directly without the need to modify the engines (Oladiran 2011; Naik et al 2010). Most of European tractor manufacturers like Massey Fergusson (MF), John Deer, Case IH, Deutz-Fahr etc. are able to run directly on biodiesel as western governments encourage their farmers to produce their own fuels. This enables the farmers to run parallel integrated systems (i.e.) have the different farm enterprises feed into one another, for example grow crops, harvest the same crop produce fuel which drives the machinery to perform other tasks around the farm, the by products from the process of making fuel will be fed to the farm animals, which in turn produce manure which is used as humus and aids in crop production (Bender 1999). Due to its relatively high viscosity, over that of petroleum diesel biodiesel can increase engine life because of improved lubrication, its ability to completely burn reduce soot production (Campbell 2008). The solid biofuels are also important and can provide very convenient energy supply to the rural population. Due to relative abundance and accessibility of solid biomass it has since become the fuel of choice to most households who otherwise cannot afford modern forms of energy like cooking gas and electricity. This solid biomass is considered to have carbon neutral emissions as according to Michael (2016) it takes up carbon dioxide as it grows and the same gas it would have absorbed it gives out later when it is burned. Besides being cheap and carbon neutral, biomass can also be densified to increase the energy content. This can be achieved in improved bioenergy supplies by using briquettes and pellets. In the process of briquetting more carbon can be introduced into the biomass substrate to increase the heating value of the fuel.

Not all is glorified with the use of biofuels/energy. There are some negatives which even though are overshadowed by the merits are worth mentioning. Campbell (2008) argues that for biodiesel for instance, the high compression ratios in diesel engines cause an increase in nitrogen oxides (NO_x) emissions. The power output is also reduced when using biodiesel even though it is limited to ± 2 percent which Schneider (2006) reports as insignificant but a reduction nonetheless. The price of modern bioenergy fuels is considerably higher than that of conventional supplies like petroleum or coal. This renders it uncompetitive on the fuels market and governments interventions are required to enable it to be competitive (EAD 2010; Balat 2011). The greatest blow of using bioenergy in the current economic set up is the conflict between food security and energy security. Most professionals caught up in the argument of whether to be energy sufficient or food secure and of late water has been added to the mix and humankind has to find a balance between this food water and energy nexus.

2.6 First Generation Fuels vs Second Generation Fuels

Since there has been a debate about growing crops for food production versus growing crops for fuel production researches have advised on utilising non edible sources as feedstock (Yang et al 2014). According to Yang et al (2014) the edible and non-edible plants are referred to as first and second generation feed stocks respectively. Almost all oil rich or oil producing field crops like sunflower, groundnuts, kola nuts and soya beans are excellent first generation liquid fuel feed stocks. Other crops like maize, cane or sugar cane are not necessarily rich in oils but can still be used in liquid fuel production because they are rich in starch which can also be substituted for oils (Fei Yu et al 2012). Due to land scarcity in most countries the use of second generation feed stocks are encouraged as they will avoid food shortage as more land can be reserved mainly for food production than fuels. Plants or trees like birrea scyreoplata (morula) and tylosema esculentum (morama) have been found to be perfect substrates for liquid biofuels in Botswana (Gandure, etal 2011) and in an effort to be energy reliant more resources which grow naturally and others which are not in competition with food are to be considered. Other researchers have since investigated other crops and or plants like jatropha, which Okullo et al (2011) reports as an oil rich source. The research on feed stocks which do not, compete for land with foods has since led researchers to consider second generation feedstocks which El-Moneim et al (2009) report that some can grow or be grown in areas not suitable for agricultural purposes. Kemausuor et al (2015) believe that instead of focusing completely on new non edible feedstocks rather attention should be accorded to the waste that is generated from food production. The school of thought of these authors is based on growing crops for food production and use the waste thereof for energy production as opposed to using the entire production wholly for energy purposes.

2.7 Biomass Assessment

Biomass features strongly in virtually all the major global energy supply scenarios, as biomass resources are potentially the world largest and most sustainable energy source. Biomass is potentially an infinitely renewable resource comprising 220 oven dry tonnes (odt), or about 4500 exajoules (EJ), of annual primary production; the annual bioenergy potential is about 2900 EJ (approximately 1700 EJ from forests, 850 EJ from grasslands and 350 EJ from agricultural areas) (Rosillo-Cale et al 2008). It can be categorised into three main groups

Table 2.1 Biofuel classification scheme (Rosillo-cale, 2008)

Production Side supply	Common groups	User side demand examples
Direct wood fuels	WOODFUELS	**Solid**; fuel wood (rough chips, saw dust, pellets) charcoal
Indirect wood fuels		**Liquid;** black liquor, methanol, pyrolytic oil
Recovered wood fuels		**Gases;** products from gasification & pyrolysis gases of above fuels
Wood-derived fuels		
Fuel Crops	AGRO FUELS	**Solid;** Straw stalks, husk, baggase, charcoal from same products
Agricultural by products		**Liquid;** ethanol, raw vegetable oil, oil di-ester, methanol pyrolytic oil.
Animal by products		**Gases;** biogas, producer gas, pyrolysis gases from agro fuels.
Agro-Industrial by-products		
Municipal by products	MUNICIPAL BY PRODUCTS	**Solid**; municipal solid waste
		Liquid; sewage sludge
		Gases; landfill gas, sludge gas

The classification of the bioenergy streams differs from region to region and between authors however the one presented above is the most generic and widely accepted all. Depending on which biomass resource is being dealt with quantification can be made to establish availability and energy content. There are many problems associated with measuring or assessing biomass, however Rosillo-cale et al (2008) grouped them into three general groups; the difficulty of physically measuring the biomass, the many different units that are used for these measurements making it difficult to compare/contrast between data sets and the multiple and sometimes sequential uses to which biomass is put. Traditional biomass is an integral part of the informal economy; in most cases data about its usage patterns, availability of lack of it thereof never enters official statistics more especially in developing countries where precise data records is not a priority. These difficulties were also reported by Kemausuor et al (2015) who reported that it was very tedious to collect data for their study on cassava residue assessment. Biomass consumption and supply assessment is different from similar assessment for a similar commercial fuel like kerosene for instance. Kerosene use can be tied down only to use as fuel for heating and lighting while biomass on the other hand provides a range of essential and interrelated needs more especially in developing countries. These benefits include not only energy but also food, fodder, building materials, fencing, medicines and more. Each and every of this benefits need to be looked at carefully and considered as biomass energy should always be looked at in the context of the other benefits that biomass provides, and never just from the point of view of a single sector.

Biomass assessment can be made from different feedstocks however for purposes of this study crop residue and animal waste is being considered. Crop residues are the non-edible plant parts of crops which are left in the field after harvest or after primary processing such as dehusking and/or shelling. In most farming communities, crop residues represent a low cost biomass supply available within a few days/weeks after harvest and before land preparation for the next crop season. Even though most crops produce some form of residue, not all crop residues can be effectively utilized for energy production due to the nature of the residue produced or its composition According to Esteban et al 2010 the residue components are better summarised by Figure 2.7

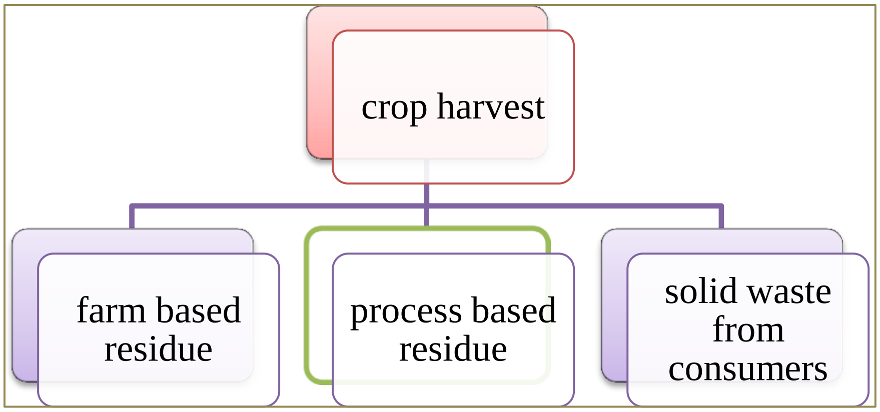

Figure 2.7 Waste path ways (Esteban et al, 2010)

The first stream consists of residues left on the farm and in the immediate vicinity of farm communities. Examples include maize straw, sorghum stalks, millet straw, cassava stems and plantain trunks. These residues are often concentrated on farm plots and available in large quantities. They may also be used on the farm as source of fertiliser or mulching material or as erosion control material. The second stream consists of residues left at primary or secondary processing sites, which may also be on the farm, within the farming community or at a processing facility. These residues include corn cobs, corn husks, rice husks, and cassava peels produced during cassava processing. These residues are often concentrated in one location and available in variable quantities depending on the scale of production. The third pathway consists of residues left at places of consumption, including cassava peels, plantain peels, yam peels, cocoyam peels, and potato peels. These residues, which could also be referred to as process residues, are scattered in homes and restaurants and are available in small quantities. They are difficult and expensive to collect (Kemausuor, 2015; Simon *et al.*, 2010) and often end up in Municipal Solid Waste (MSW) stream. Their collection and disposal often are the responsibility of waste management authorities.

Generally, the straw and stalk from these various crop types are the main source of residues that can be harnessed for use as energy sources. This is to say only two residue pathways (farm based & process based) contribute significant amount of waste. The other stream which consists mainly of peeling of different crop products like potatoes, yam, plantain, cassava and legumes are not considered in the analysis of crop residues for energy generation. The waste/residue from this stream is usually considered when making projections for bio digesters which are fed with MSW or considered in landfill gas production estimates as such caters for MSW specifically (Scheutz et al, 2009).

Studies about biomass assessment in Botswana have not been carried out and this study is the first of its kind to be done in Botswana. Similar studies carried out elsewhere have shown so much potential about energy from agricultural waste. Arranz-Piera et al (2017) established that Ghana can use small farmer cooperatives and use their crop residues to generate electricity sustainably. Though the study was based on Ghana's residue availability lessons can be inferred for other regions and or countries as the study underlined that between 22-54 ten hector clustered farms are sufficient to supply a 1000kWe plant. They also submitted that a combined heat and power plant can be financially viable if the current electricity market in Ghana is improved. In another different study it was reported that since crop residues remain unused in most African communities instead of them being burnt they can rather be used productively. Arranz-Piera (2016) has concluded that tri-generation is possible in most African farming communities so long as the farm lands are clustered and transportation costs are minimal.

BEFS RA approach was used in 2015 to evaluate rural electrification options for Malawi based on the Malawian crop residues availability. Accordingly it was established that Malawi has abundance of sunflower therefore it was the best option for generation of electricity (sunflower-SVO). Other competing options included maize cob and sorghum stalk gasification (Felix et al 2015). In another study Ayamga et al (2014) carried out an assessment for bioethanol production from residues from maize, sorghum, millet and groundnut. After establishing the amount of waste generated from the four crops above they used chemical analysis to determine the composition of each of the various crop waste and then through thermochemical models estimated the amount of bioethanol that can be produced. In the same study regression analysis was used to forecast future growth of bioethanol production basing on the availability of land for agricultural expansion. They used previous production trends (2003-2010) to map the expected growth in production for the period 2010-2022.

In relation to animal waste reported that most sub Saharan countries animals are kept in free range grazing which makes it difficult for collection of waste. In their specific study they submitted that poultry has larger numbers and since they are kept indoors, waste collection and availability is guaranteed. Larger energy content is present in piggery waste as compared to cattle, goats and sheep, this is attributed to the digestive systems of this animals as ruminants digests and releases most of the biogas forming components. Non ruminants on the other hand have higher energy content because of a single tract digestive system (Chimbobmbi, 2009). Though the energy content is generally lower, sizeable quantities of gas can be harvested where waste is available in large quantities like in large abattoirs, dairy pans, horse stables and large piggeries. This idea is also reinforced by Keamousor et al (2014[b]) who are of the view that most free range animals are generally small sized, undernourished and do not excrete a lot of waste.

2.8 Barriers to large scale utilisation of bioenergy

The large-scale utilization of bioenergy still faces many barriers, ranging from socio-economic, cultural and institutional to technical. These barriers have been extensively investigated in the literature and some can be addressed and be solved simply. Other barriers are more complex and cannot be addressed with simple quick fix solutions. Sims (2002) identified some of the barriers as the possible destruction of native forests due to increasing commercial applications of bioenergy. This will destroy the ecosystem of the local areas and cause a disruption to the natural flora and fauna of such places. Soils structure and profile of such areas also faces possible destruction by continuous removal of residues for energy, the process of soil natural enrichment will be disturbed by constant removal of the residues which are otherwise supposed to improve the soil structure and profile. Bhattacharya (2004) sites more economic reasons that affect large scale utilisation. As some biomass sources are low energy intensive transportation costs are likely to be very as more resource has to be ferried across long distances to central places. Other problems include more common arguments like competition for land between food and land, deleterious effects of large-scale dedicated energy plantations on water resources. These barriers should be taken into account when assessing the implications.

2.9 Estimation of Agricultural Residue Potential

In most areas that fall in the semi-arid climatic environment agricultural harvest is usually one season in a year with an exception of some areas where there are two seasons in a year. For areas with one season which is the predominant practice around the world more especially on the subsistence farming sector this residue is therefore available only once in a year. Rosillo-Cale (2008) suggests that for this residue to be availed for energy supply which is otherwise required all year round and not only a certain period of the year the waste must be collected, processed and stored in safe and secure environments where it will not rot, develop mould or be exposed to rodents or termites.

To estimate these residues accurately it is necessary to understand the crop production patterns of the country, region or community where such assessment is being made. In Ghana for instance there are generally two harvest seasons in a year but it is usually for different crops (maize, sorghum, millet around January / February ant the later in the year August/September is mostly legumes and cassava (Mahamat 2015). This being the case a blanket assessment would be problematic as the other season does not have much of the residue that can be used in energy transformation processes. The other competing uses like mulching, industrial use, animal feeds or housing must be quantified accurately and deducted from the energy supply pathway. In addition to data on competing uses the other important aspect in residue estimation is quantification of production or harvest and yield records. The yields or tonnage harvested per area planted is the most critical of all as the residue produced is a function of the yield. Data on yields harvested should be what is measured from the fields or farms from previous years to give more precise and accurate results. Estimations can be used in the absence of recorded data though the accuracy will be affected. The quantity of residue can then be calculated through estimates of the ratio of by-product to crop yields for each specific crop. Equation below is normally used for residue production estimates

$$\boldsymbol{Residue\ estimates} = \frac{\boldsymbol{straw}}{\boldsymbol{grain}} \times \boldsymbol{yield}(\boldsymbol{grain\ production}) \quad \textbf{Equation 1}$$

Other researchers like Keamossur et al (2014) used the weight method otherwise referred to as crop residue index. This technique considers the ratio of the weight of the waste produce as compared to the total consumable crop produced. This method involves measuring out the weight of the waste of a specific crop versus its yield.

2.10 Residue to product ratio (RPR) of agricultural crops

RPR is the gravimetric ratio of the residues to the actual or total harvestable yield of the crop. As discussed above it has an effect on the amount of residue available after harvesting. The RPR is different for every waste component of the crop, for instance maize has about three different waste components (stalk, cobs, and husk) and each has its different PRP that when multiplied with the yield gives an estimate of the amount of the specific waste that can be available. Table below presents energy potentials from both crop and animal residue where RPR has been used.

The estimates given in Table 2.2 are based on the energy content of potentially harvestable residues based on residue production coefficients applied to FAOSTAT data on primary crop and animal production.

Table 2.2 Energy potential from residues (EJ) (adopted from Rosillo-Cale 2007)

	Crop	Forest	Dung	Total
World	24	36	10	70
OECD of which	7	14	2	24
North America	4	9	0.7	14
Europe	3	5	1	9
Asia-Pacific/Oceania	0.8	0.8	0.4	2

The world has about 70 EJ potential of energy that comes from crop, forestry and animal residues. This is a huge potential that can be exploited further and introduced to the world energy mix. The RPR used in estimation of table 1 can be obtained in the process outlined below (adopted from Esteban et al 2010);

- Sampling a crop before harvest: this is normally carried out in random quadrants from a ploughed field. Demarcated areas are randomly sampled and chosen for assessment, after the quadrants are marked the crops enclosed within are then harvested and all plant material taken in for measurement. The grain is separated from the plant and weighed moisture content is also measured as the RPR will be ascribed to certain moisture content.

- Sampling residue after grain harvest: after harvesting the grains the next step is to weigh the waste that emanates from the grain harvested crops, since a single crop may have different waste categories it is important to measure and weigh all the waste per the corresponding categories. Moisture content is also important to be noted for the waste.
- Evaluating straw production in a parcel: this procedure is similar to procedure 2, but in this case the residue is harvested completely and the whole parcel is weighed.

Chapter 3 METHODOLOGY

This chapter presents the processes and procedure followed to carry out this study. A description of the places where the study is made is presented to elucidate on the areas. Thereafter a description of the data collected is given before presenting on the various methods of analysis and assessment that were used for this study.

3.1 Location of study

This study was carried out generally in Botswana with an in-depth focus on major agricultural production areas; (Pandamatenge, Borolong and Lobatse). Two of the three regions are full blown commercial agronomic centres while the other is pastoral farming hub where farmers sell their livestock.

3.1.1 Borolong Farms / South East District

South East district is one of Botswana's major production areas. The district itself is relatively small in size but agricultural production in much higher. The region houses one of the major government owned farms which specialises in sorghum growing. There are other privately owned farms which engage in large scale farming in addition to small scale farmer cooperatives. This region is of interest due to the large scale production and can be a possible area to build an energy conversion unit should one be considered.

3.1.2 Pandamatenge Farms / Chobe District

Pandamatenge is comprised mainly of large scale commercial farms which deal with thousands of acres of land. Due to high cultivation area and higher harvest figures this area also becomes of interest in the energy analysis mix. Considering that it's a commercial area and used a lot of electricity to run the farm operations a standalone electricity generation unit can be a very good investment in this area. The waste from these farms can be used to produce part of the electricity used in the farms and reduce the electricity bill from the grid or fuel costs for the generators.

3.1.3 Lobatse BMC

Livestock waste is one of the major sources of clean energy substrates. Larger quantities of such waste are preferred as there is greater energy potential and continuity of supply. Piggery waste has more energy output as compared to poultry and cattle. In this study Lobatse BMC is of interest because is the country's biggest abattoir and handles a lot of waste from both dead and live animals. The animal waste generated from this establishment can be used to provide energy that is needed to run some operations and ultimately bring about energy savings.

3.2 Research Design

This section of the methodology is meant to provide a detailed scope of the tool used in the assessment of agricultural waste in Botswana. The kind and type of data collected from various stakeholders is also discussed in detail. The Bioenergy and Food Security Rapid Assessment as well as Analytical frame work are outlined together with how they function in the assessment of a countries bioenergy potential.

3.2.1 Primary Data Collection

Botswana is divided into 9 agricultural production zones/regions according to the ministry of Agriculture and Food security. For purposes of this research the entire country data was collected and more focus was given to the three areas of interest. These areas are the busiest in terms of agricultural activity in the country as compared to other regions. A majority of commercial farmers operate from this areas thereby having overall greater production. Agricultural production statistics were collected from the ministry of Agriculture & Food Security through the various offices and officers in the jurisdiction of the areas where they are located. The local agriculture offices in Panda, Mmathethe and Lobatse were consulted to gather production covering a 10 year period. Farmers and other stake holders were also consulted in addition to detailed study on collection, disposal and other uses of agricultural residues.

Where primary data was not available approximations and assumptions were made and such is indicated on the relevant parts of the thesis. Other additional data was gathered from Food and Agriculture Organization Corporate Statistical Database (FAOSTAT), Bank of Botswana, and other ministerial departments like the ministry of Employment, Labour productivity & Skills development, Ministry of Mineral resources, Green technology & Energy Security.

After collection and gathering of the data, statistical analysis was used to treat the data used in subsequent energy calculations and Bioenergy and Food Security (BEFS) models. The (BEFS) approach has been developed by Food and Agriculture Organization (FAO) to support countries in designing and implementing sustainable bioenergy policies and strategies. The approach promotes food and energy security and contributes to agricultural and rural development. It consists of tools and guidance to support countries through the main stages of the bioenergy policy development and implementation process

The models/tools together with the calculations elucidated on the amount/quantity of feedstock available, tentative amounts of more efficient energy that can be produced with the different conversion techniques as well as sizes and financial implications of the plants.

3.2.2 BEFS Rapid Appraisal Assessment

The FAO's Bioenergy and Food Security Rapid Appraisal (BEFS RA) assessment tool was used for the techno-economic assessment for energy generation (heat and power) from crop residue. The analysis followed the BEFS Analytical Framework (BEFS AF) as illustrated in Figure 3.1 below

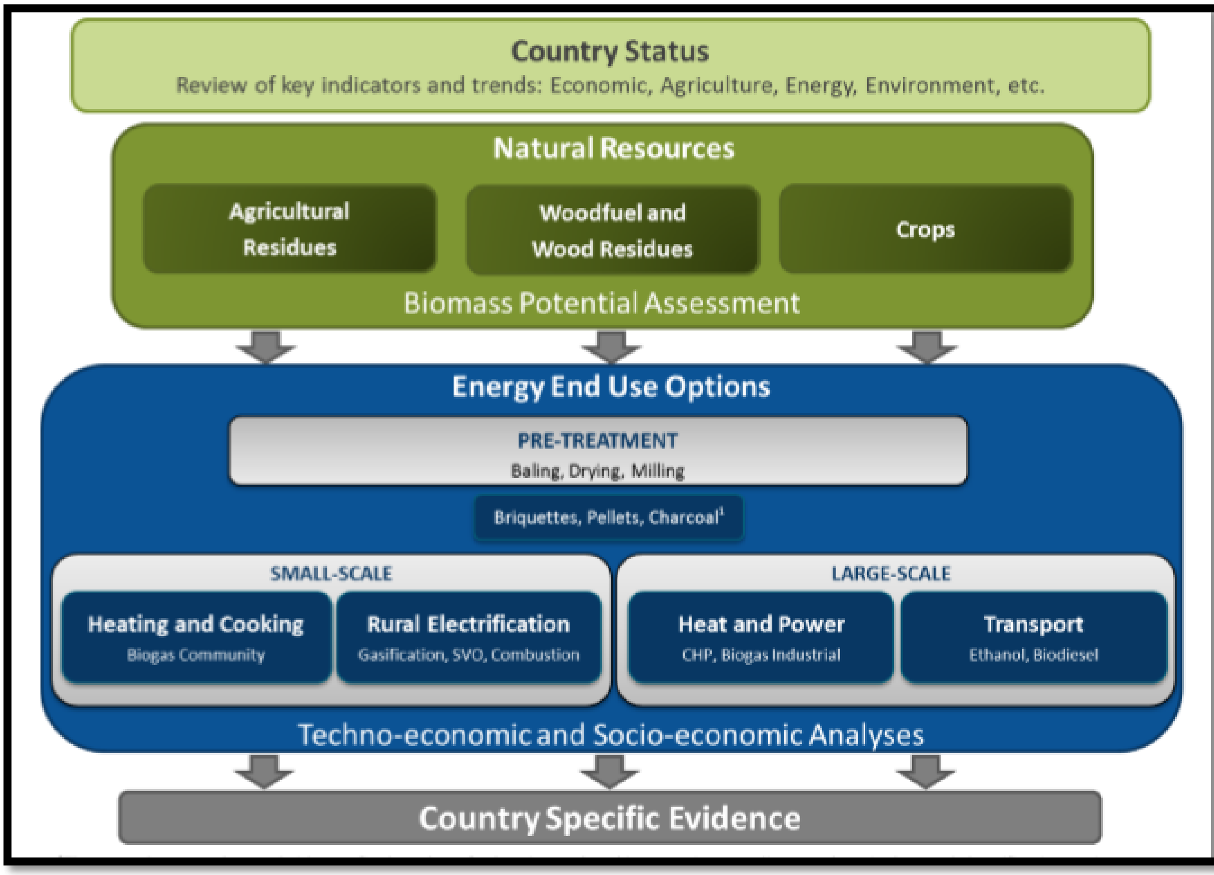

Figure 3.1 BEFS Analytical Framework

The BEFS RA analysis has three main components namely Country Status, Natural Resources and Energy End Use Options. The modules feed into one another therefore are run in that order to obtain a set of results covering the bioenergy pathways identified within the BEFS RA.. The tools used for this study are Country Status Tool, Agricultural Residues Tool, Gasification Tool, Combustion Tool and the Biogas community tool. The BEFS RA however comprises of a couple of other tools which were not considered in this study because of the data limitations as well as waste composition from the Botswana agricultural sector. For instance the transport tool requires sufficient oil crops which are not produced in Botswana.

3.2.3 Country Status tool

The country status tool gives a general overview of the country's context. It presents information about population land cover/land use, state of the economy, socio-economic indicators, food security and energy use. This tool also assesses the energy balance and energy demand situation within a country. Botswana context was analysed using this tool to lay a foundation for other tool which required data processed through the country status tool.

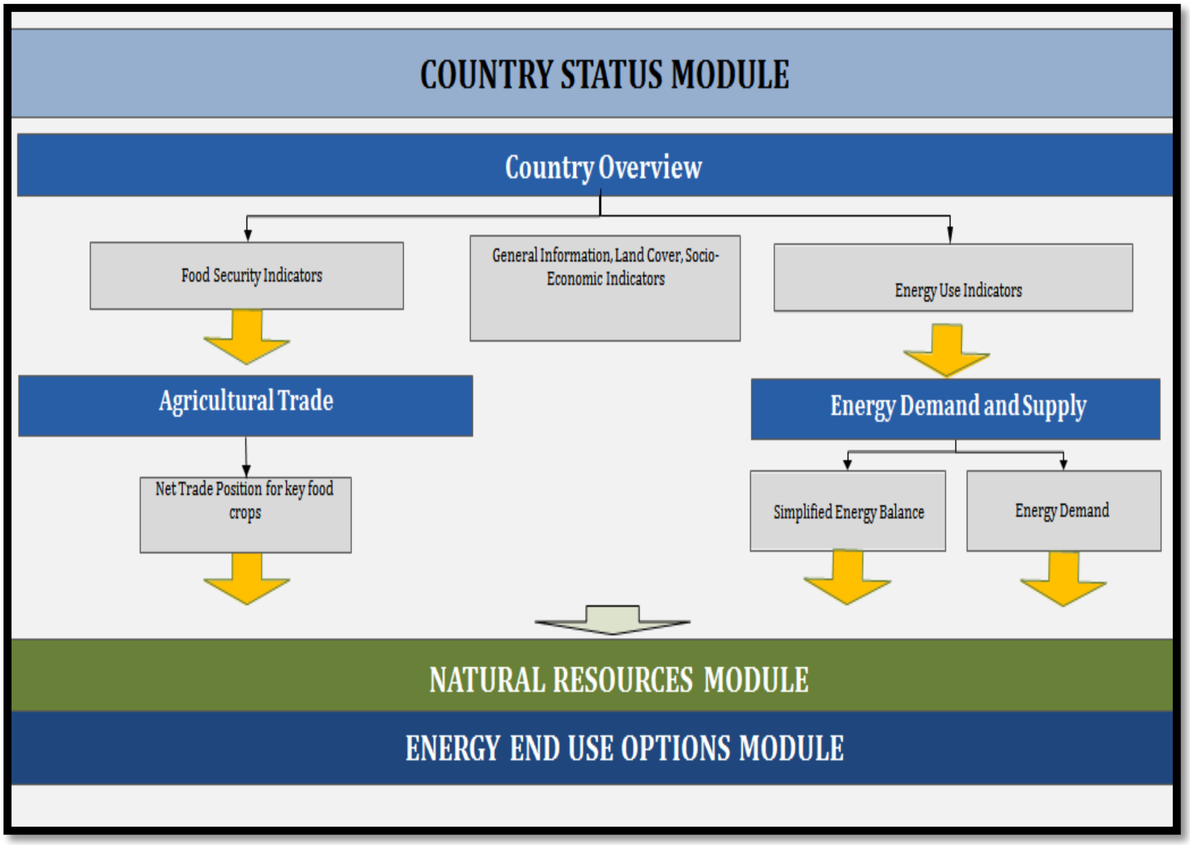

Figure 3.2 Country Status Module (FAO:BEFS RA)

3.2.4 Natural Resource tool

As depicted in Figure 3.2 the country status tool feeds into the natural resource tool, which also feds to the subsequent module being the end use option. The natural resource module has three components being; crop section, this considers crops which are grown and harvested specifically for energy production. The wood fuel & wood residue option considers plantations and wood residue like saw dust for energy production. Lastly the agricultural residue option includes the waste (crop and animal) which is then used for energy production. The portion(s) of the waste being used for other purposes is excluded from this assessment and only the remaining waste is analysed. As this study is centred around using agricultural waste for energy generation this option was used to evaluate crop residue and animal residue in the chosen study areas of Botswana.

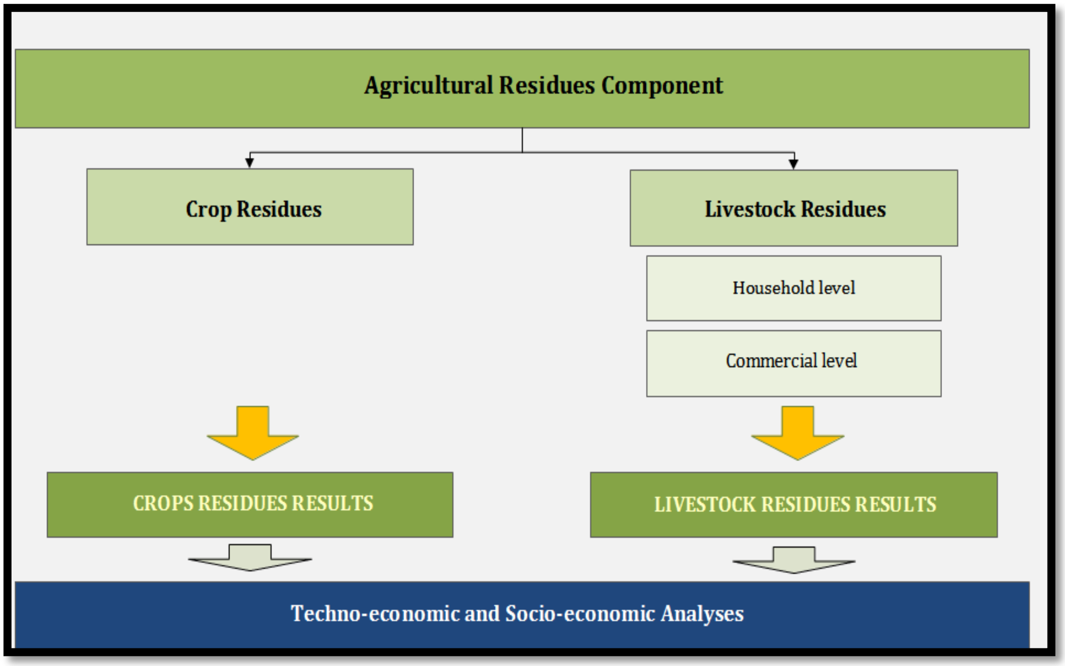

Figure 3.3 Agriculture Residue component

Figure 3.3 shows the residue component, as shown crop and animal residues are analysed on this component. The Borolong and Panada areas were analysed on the crop residue section while Lobatse BMC was analysed on the livestock residue section. It is however worth noting that though the residues may originate from different sources (crop or animal) they eventually combine for techno-economic and socio-economic analysis.

3.2.5 Energy End Use Module

The energy end use option or the techno-economic & socio-economic analysis deals with the associated technology conversion pathways and their economic matrices. It houses three components also being two rural electrification pathways, combustion and gasification then the small scale conversion pathway being bio digestion. All the three conversion pathways were used in this study, and each is discussed below.

3.2.5.1 Combustion Component

The combustion component assumes the working principle of electricity generation that follows the normal Rankine cycle. Heat is supplied from a source and it then heats up water into steam and a turbine produces electricity. Crop residues are considered as the burning fuel in this component and evaluation is made for rural electricity access where it is assumed such residue is available. Figure 3.4 shows a working schematic of a combustion plant which is assumed by this component.

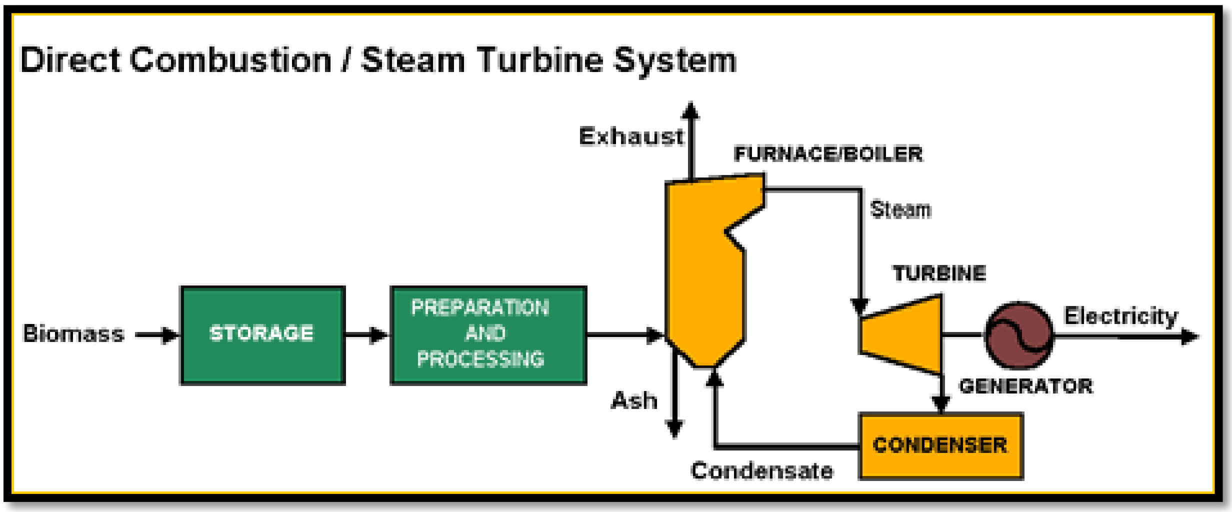

Figure 3.4 Schematic of Combustion

Since there is mostly one cropping season per year the biomass is stored collected and stored for safe keeping. Prior to being burnt it can be processed by carbonising or bailing for easy handling. During combustion, energy is released in the form of heat as well as visible light radiation in the form of glows or flames. The overall biomass combustion process mainly involves four basic stages, that is, drying, devolatilisation, combustion of volatiles and combustion of char all this stages happen in the presence of excess oxygen.

3.2.5.2 Gasification Component

The gasification component evaluates the plant residue for electricity generation assuming the working principles of a gasifier plant. The feedstock (plant residue) is partially combusted resulting in production of combustible gases consisting of Carbon monoxide (CO), Hydrogen

(H_2) and traces of Methane (CH_4). The combustible gases are produced with the aid of a gasifying agent limited oxygen or steam.

Figure 3.5 Biomass Gasification Schematic for Rural Electrification

As depicted on Figure 3.5 feed stocks for gasification can come from a lot of sources like forestry and wood residue and crop residues from the farm or from processing industries. The feedstock is then pre-processed to improve gasification efficiency. Excess moisture is removed and the biomass cut to size before it is introduced to a downdraft gasifier to produce syngas. The syngas is later cleaned and combusted to produce electricity.

3.2.5.3 Bio-Digestion Component

The biogas component of the BEFS RA is used to analyse the amount of animal waste that can be transformed into useable energy. This component can be used both for small scale bio digesters for heat generation only or large scale for both heat and power depending on the availability of animal waste. The waste can be collected from dairy farms, piggeries, poultry farms, feed lots or ranches (Figure 3.6). After collection the waste is then hydrated and allowed to under anaerobic digestion where biogas will be produced. The process of digestion happens in digesters and this component has three options of bio-digesters being the fixed dome, floating drum and tubular digesters.

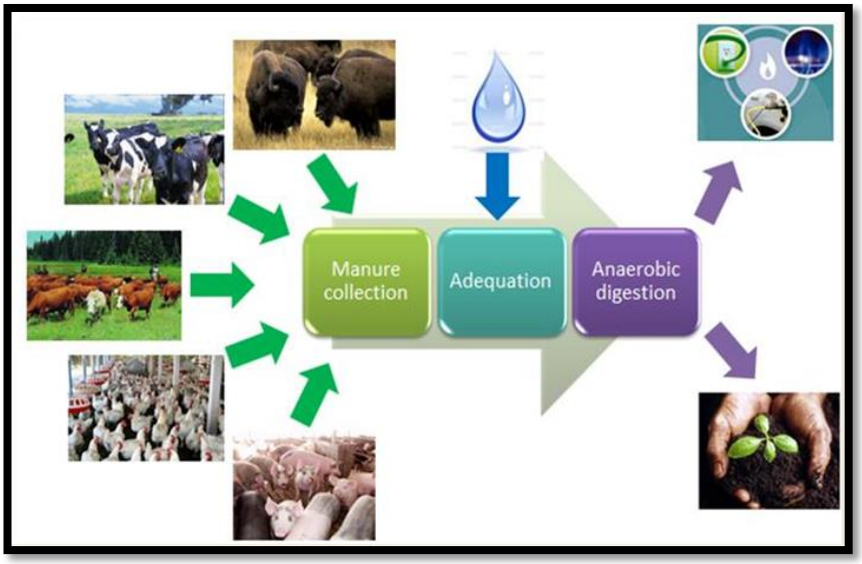

Figure 3.6 Biogas Schematic

Cattle waste from Lobatse BMC was analysed using this component. The waste then breaks down to produce a mixture of gases like methane CH_4, carbon monoxide CO, hydrogen H_2, carbon dioxide CO_2, steam H_2O, nitrogen N_2 and other gases. The higher the quantities of CH_4, CO and H_2 the better the quality of the gas and it is easily combustible.

3.2.6 Analysis of the Three End Use Options (Biogas, Combustion & Gasification)

In order to run the three techno and socio-economic components some data was gathered from the country status tool and other data relating to costs; labour and inputs from relevant government departments. The sequence of running the end use options was as follows;

- Energy demand; the energy demand was based on the consumption and current status of Botswana situation. The country status tool gives an idea of the energy demand which was approximated to be 120 kWh/month.
- Defining the Feed stocks; since this study deals with evaluating crop residue specific residues were defined as reported in the next chapter.

- Defining the price of Electricity; the tool's default values were used to determine the price of electricity.
- Defining Production Costs & Financial Inputs; actual prevailing prices of labour (skilled, semi-skilled and casual) , utilities (water, electricity, fuel) were defined for the tool.
- Defining the transportation costs; the tool defined the transportation costs based on the equation

$$\textit{Transportation cost} = \frac{\textbf{hourly wages}\left(\frac{\$}{\frac{\text{hour}}{\text{person}}}\right) \times \textbf{working time}(\textbf{hours})}{\textbf{transportation distance}(\textbf{km}) \times \textbf{feed stock transport}\left(\frac{\text{tonne}}{\text{person}}\right)} \quad \textbf{Equation 2}$$

3.2.7 Theoretical Potential Calculations

Theoretical potential calculations deals with estimating the amount of residues from crop waste that are available without taking away anything. This implies that the calculations aims to measure how much residues are available in total before removing any other for different reasons, be it use for other purposes like animal feeding, soil fertility, or due to technological hindrances.

3.2.7.1 Crop Waste(s)

From the annual production figures of different crops theoretical and technical energy potential estimates were calculated. Theoretical potential determined the amount of residue available from a crop by using the residue to product ratio. Residue-to-product ratio (RPR) means the ratio by weight of a particular residue generated by a certain crop to the amount of crop harvested. For instance maize has residues like stalk, cobs and husk with each of them having its specific RPR. The theoretical potential was calculated as;

$$ATP = \Sigma^{i}_{n} (C_i \times RPR_i) \quad \textbf{Equation 3}$$

Where, ATP is the annual crop residue potential, C_i is the annual production of crop I and RPR_i is the residue to product ratio of crop *i*. Factor *n* is the total number of residue categories.

After calculating the theoretical potential, it was then adjusted in order to get the technical potential. The recoverability fraction which means the ratio between the residues that realistically can be collected and the total theoretical amount was then used to get the technical potential. In reality not all the biomass may be available for collection due to several inhibiting factors like technology maturity, or some purposefully left for soil fertility. The technical potential was calculated as the product of ATP and recoverability fraction.

3.2.7.2 Animal waste

Livestock waste potentials were estimated based on livestock numbers, average annual manure production per animal and how much of the manure/waste can be accessed and used for energy production (recoverability fraction). Animal waste was estimated using the equation;

$$\mathbf{P_{manure} = \Sigma (P_{live} * Y_{man} * \eta_{rec})} \quad \textbf{Equation 4}$$

Where P_{live} is the number of specific livestock population, Y_{man} is manure produced by one specific livestock per annum and η_{rec} is the recoverability fraction of manure for specific livestock.

Since in this context we considering waste from both dead and live animals some adjustments were made to in the calculation of dead animal waste.

Chapter 4 RESULTS AND DISCUSSIONS

This chapter focuses on the results and findings of the study. Discussions are also made side by side within the chapter. Information collected during the period of this study is analyzed and interpreted. The data is represented in the forms of chart, graphs and tables.

4.1 Country Status

4.1.1 Country overview and Net Trade Position

Botswana has an estimated population of about 2’332’153 as at April 2018 (United Nations, 2018) this is a 15% growth from the previous 2’024’787 reported by Statistics Botswana on their 2011 population census (Statistics Botswana, 2014). More than half of the population resides in urban areas leaving only 47% in rural areas. The majority of rural area dwellers are adults and children who are involved in agricultural sector which contributes a little over 3% to the GDP (WDI, 2018). The Net trade position of Botswana’s main crops (maize, sorghum, pulses) and their respective products indicate that the country is not self-sufficient with these crops.

4.1.2 Total country crop residue energy estimates

Botswana does not have a lot of variety in terms of the crops grown. The main crops grown both by commercial and subsistence farmers are maize and sorghum. A few other crops are also grown and Table 1.1 is representative of such. The crops and their resulting residues are shown and the residue to product ratio (RPR) was used to calculate the amount of each waste category. From the table a total of 1’338’973’041MJ of energy can potentially be recovered from the waste. This is a great amount of energy that is not being utilised at the moment. The energy is equivalent to 22’001’905 litres of bioethanol annually assuming that the conversion efficiency of the process is 35% and the energy content of bioethanol is 21.3MJ/kg. Similarly the amount of biogas that can be produced is approximated at 42’847’137 cubic meters of biogas assuming a digester efficiency of 80% and energy content of 25MJ/kg for biogas. In reality this amounts can be lower depending on a lot of other factors. Maize residues have the greater contribution to the total potential energy.

Table 4.1 Energy potential from crop residues

Crop type	Amount of crop Produced (tonnes)	Residue Type	RPR	Net Calorific Value (MJ/kg)	Theoretical Residue (tonnes)	Energy Potential (GJ)	Energy Potential (MJ)
maize	14572	maize straw	1.59	15.51	23169.48	359358.6348	359358634.8
	14572	maize cob	0.3	15.48	4371.6	67672.368	67672368
	14572	maize husk	0.3	16.63	4371.6	72699.708	72699708
sorghum	21070	sorghum straw	1.99	14.4	41929.3	603781.92	603781920
millet	2306	millet straw	1.99	15.51	4588.94	71174.4594	71174459.4
sunflower	4518	sunflower straw	1.87	14.88	8448.66	125716.0608	125716060.8
pulses	3714	fronds	0.67	15.5	2488.38	38569.89	38569890
Total							**1338973041**

4.2 Agricultural Residue

4.2.1 Animal Residue

The amount of animal waste that was run for this study was based on the statistics of animals that pass through Lobatse BMC. From the ministry of Agriculture & Food Security (MoAFS) records and Statistics Botswana office the number of live animals that BMC has in its jurisdiction is about 1976000 cattle annually. On a daily basis about ±650 cattle are slaughtered and the gastro intestinal track (GTI) contents are cleared and thrown away. Each animal releases about 3-5 litres of blood when slaughtered and part of this blood forms the waste that is washed away and flushed without harnessing the energy in the waste. Part of the blood is collected and used for other purposes like making blood meal or collected by the Botswana Vaccine Institute (BVI) to make serum. When it comes to animal droppings / cow dung since animals are ferried to the abattoir in trucks and rested for 12hrs before slaughter in waiting pans there is manure that can be collected from there in addition to the GTI waste and blood remains. From the Agricultural residue tool an estimation of the manure available for bioenergy is presented (Figure 4.1);

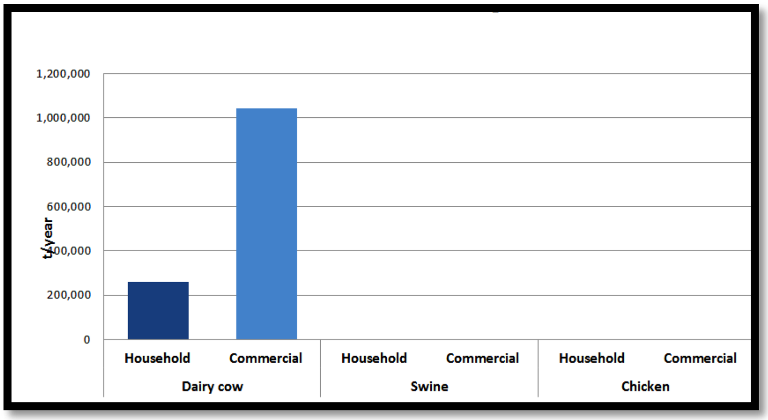

Figure 4.1 Manure generation available for Biogas production

A total of 7158342 metric tonnes of manure can be produced annually as shown in figure above. The input used was that of Dairy cow and other livestock (swine, chicken) were taken to be zero as the focus is only on cattle manure. Dairy cow option was selected on the tool because it is the closest option to beef cattle which is otherwise the true input relevant to the BMC case. It was also assumed that 80% of the cattle come from commercial feedlots (Wall green, GM5 and Better Beef) that supply the BMC with live animals while the other 20% is supplied by private farmers. The default rate of 14.34 kilograms of manure per animal per day adopted in addition to 13.25% of volatile solids in manure. Cattle have a greater manure output per animal per day as compared to swine however; swine does have a greater share of volatile solids in manure. Pigs produce about 1.3kg/head/day of manure with 24% solid volatiles in the manure.

4.2.2 Crop Residue

Crop residues assessment for this study is made for two areas. From the assessment of the crop production figures it is evident Panda has more production as compared to Borolong therefore more waste is generated in Panda. The species planted in both areas are primarily three crops being sorghum, maize and pulses. Panda grows more sorghum than maize and the opposite happens in Borolong. In Panda sorghum straw is the most abundant residue with 75075 tonnes per year, maize straw comes second with 11481t/year lastly follows the pulses with 4962t/year. The crop residues available were then split into two conversion pathways, combustion and gasification (Figure 4.2). Sorghum straw was portioned to 37538t/year being the most contributors for all the residue types. On the energy end use option tools 100% of the residues were evaluated for either option to determine the best conversion pathway.

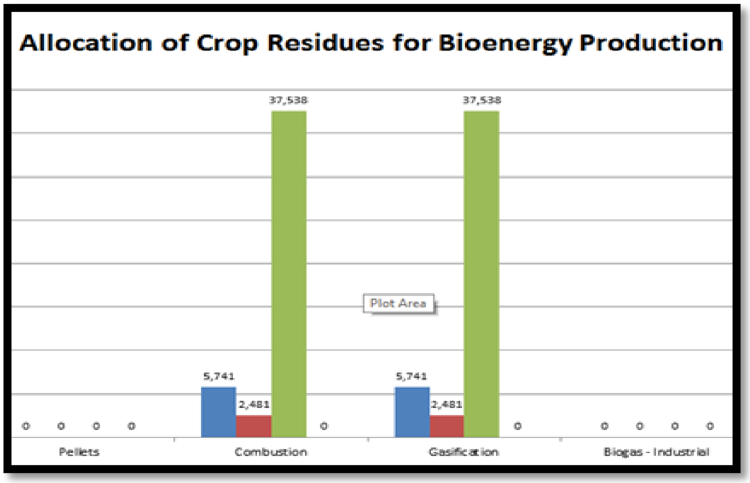

Figure 4.2 Technology pathways for crop residues

4.3 Energy End use option

4.3.1 Biogas community

From the biogas tool, there are three types of digesters that can be simulated and this are fixed dome, floating drum and tubular bio digesters. All this digesters were evaluated and some of the parameters are presented in table below;

Table 4.2 Digester size selection

	Recommended size (m^3)	Number of heads available	Annual biogas production (m^3/year)
Size 1	2	325217	247
Size 2	4	325217	576
Size 3	7	325217	905
Size 4	6	325217	1234

Apart from the digester types another variable that the tool provides is the digester sizing. As shown in the table four sizes were analysed and to make fair comparison the number of animals was split into each share (25%) for each digester size. From all the digester types and sizes the floating drum is the most expensive to construct on a cost per volume basis (US$/$m^3$). Its construction cost ranges from \$0.23 to \$.34 for every m^3. The minimum cost per cubic meter of the floating drum is higher than the maximum cost of both the fixed dome and tubular digester for all the sizes. All the sizes are feasible to be constructed as they all have a positive net present value (NPV) and positive internal rate of return (IRR). The $9m^3$ floating drum digester has the biggest NPV of \$10503 and IRR of 81% making it the worthiest investment for Lobatse BMC. If 100% of the waste available is dedicated to a single plant as opposed to the 25% (4 digesters sharing equally the available waste,Table 4.2) used in this analysis, up to 3000 cubic meters of biogas can be harvested and used productively. This amount of gas can substitute the use of electricity that is used to provide heat in the abattoir. It must be noted that the analysis made by the tool is for the provision of standalone electricity supply however since the abattoir has electricity supply from the grid the biogas plant in this instance can be used to provide primarily heat or alternatively when BMC Lobatse from the grid and only use it as backup in case of power deficiencies. Oladiran (2011) encourages institutions to infuse renewable energy into their energy mixes since there is abundance of resource to make BMC power dependent from an otherwise unutilised resource it better suits the BMC to use such. Even on employment creation biogas can create a good number of jobs that can help alleviate extreme poverty in the less skilled members of the communities where such plants are located. Figure 4.3 presents the comparative results for all digester sizes and types analysed by the tool. The tubular digester has the highest IRR at all sizes going over 200% meaning that if invested upon it will have very quick returns and the investment will be paid off quickly. When it comes to job creation however it has the smallest potential and may not be an ideal solution if the interest of the project developers is more towards socio economic uplifting of the community residents over and above electrification. All the digester types have a higher price on the cost of production for the smallest plant which is above the user defined price of electricity so it not worthy to invest on small plants. For the floating drum even the $4m^3$ size is still costly and it only becomes competitive at bigger sizes.

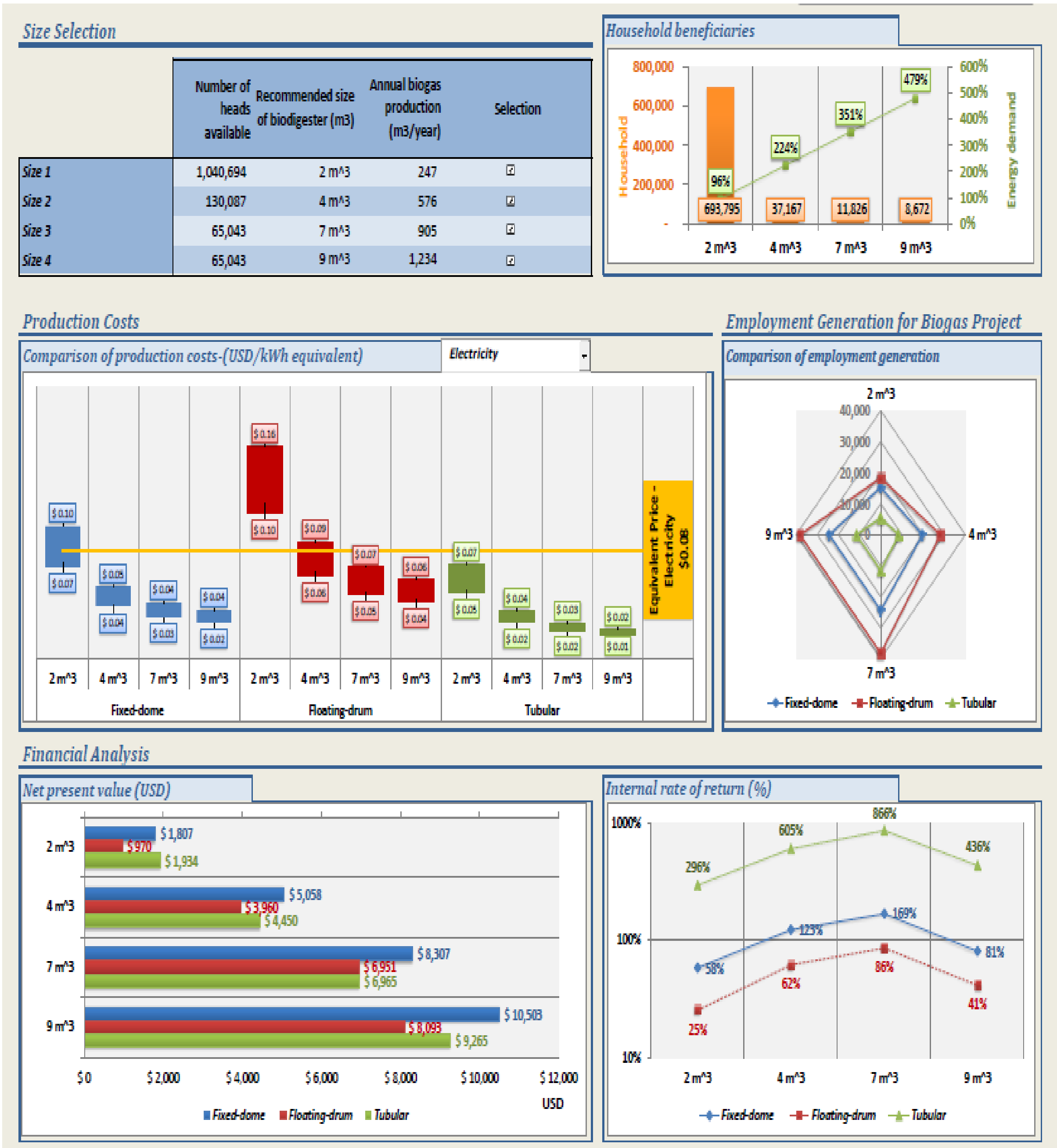

Figure 4.3 Biogas Comparative results

4.3.2 Gasification Tool (Panda)

The gasification tool has 3 inbuilt plant capacities that it runs its simulations based on. It has small (10kW), medium (40kW) and large (100kW) plants that are deemed to be standard plants to produce electricity through gasification. The capacities of these plants are just for reference use and once a project is developed involved stakeholders can decide on a size suitable and relevant to their situation that is not necessarily any of these inbuilt sizes.

4.3.2.1 Sorghum Straw

From the analysis of this residue (sorghum straw) which is the most abundant in the area (75057tonnes/year) it is possible to successfully run all the three plant capacities which are 10kW, 40kW and 100kW plants. The 10kW plant has the smallest net present value and a correspondingly low IRR implying that it is less profitable to invest in such a plant (Figure 4.5 and Figure 4.6). Though somewhat bizarre that a smaller plant has lower returns on investment while a bigger one has higher turnover Tao et al (2012) argues that because of marginal costs of production sometimes larger scales of production are more profitable than smaller scale as it can cost more to produce less.

The production and distribution costs for both the 40kW and 100kW plants range from US$ 0.33 to US$ 0.50 per kWh which is lower than the user defined price of electricity of $0.80. The investment cost of a 40kW plant is $89899 (Figure 4.4) and a total of 46 households can be supplied with electricity and in the process creating about 10 jobs for people living within this community.

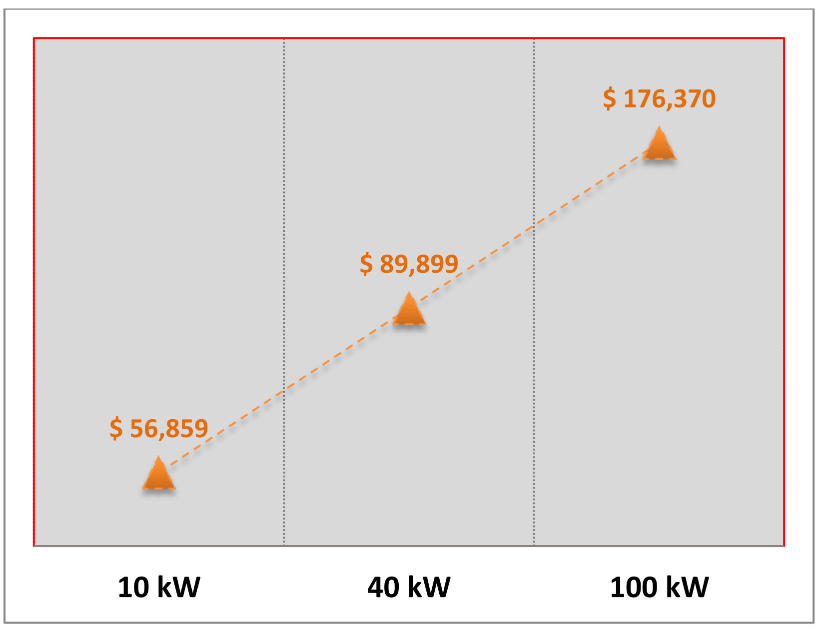

Figure 4.4 Total Investment cost (US$)

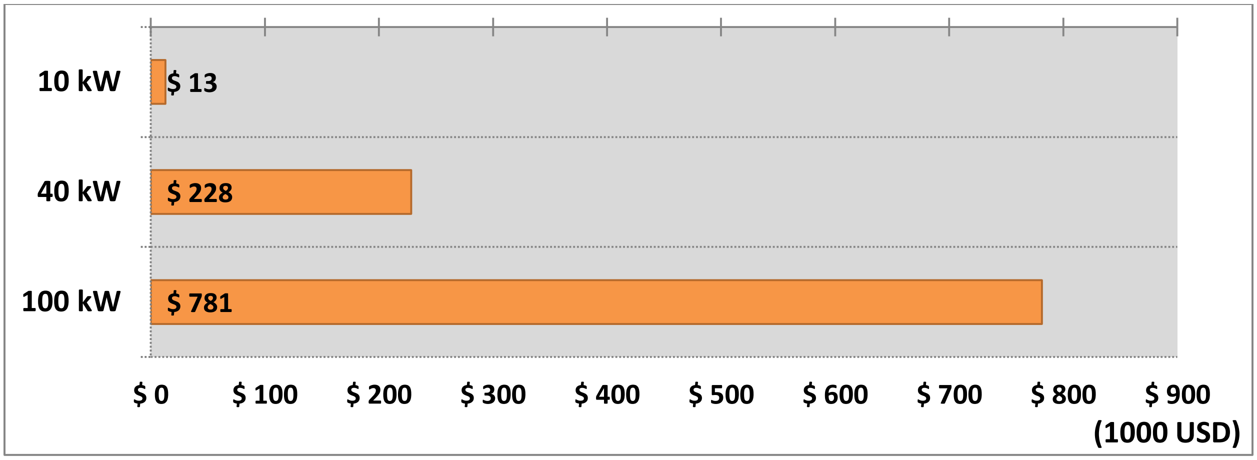

Figure 4.5 Net Present Value for each Plant capacity

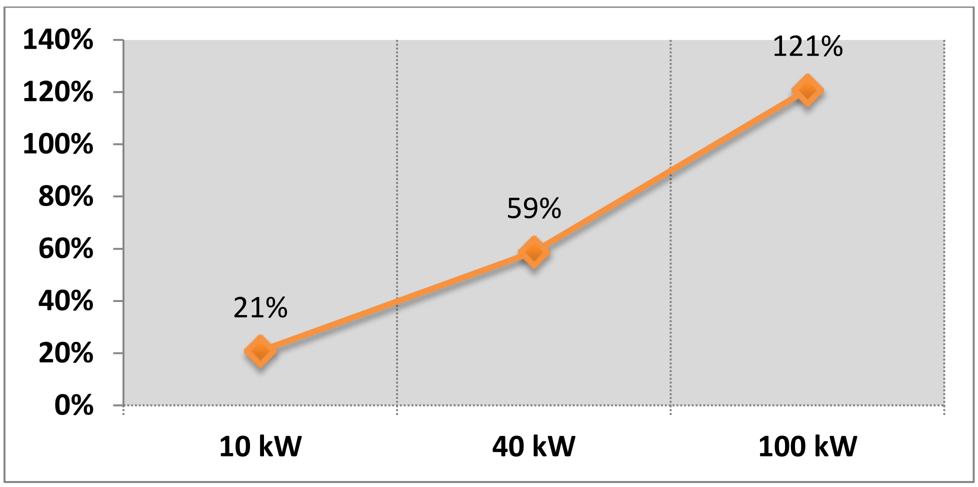

Figure 4.6 IRR for each plant Capacity

4.3.2.2 Pulses fronds

This residue has annual tonnage of 4962t/year. It is a remnant of different types of leguminous plants grown in the area and not particularly from a single source as the other kinds of residues considered in this study. The gasification tool shows that the area required to be tilled to have sufficient residue to run six 40kW plants is 968ha while the two feasible 100kW plants require 2420ha of land to be grown. This estimation on land required is based on the yield of 0.81t/ha for pulses that was defined for this area.

The cost of production and distribution for this residue type is highest on the 10kW plant with a maximum of $0.79/kWh. The other two plant capacities have lower cost and the 100kW plant is the cheapest having a low of $0.34/kWh and a high of $.041/kWh. A maximum of 116 households can be supplied by the biggest plant capacity while only 12 can be supplied by the smallest plant. Financial analysis results show that all this plant capacities are feasible with this residue type. All plant capacities have positive NPV and IRR as shown in the charts below (Figure 4.7, Figure 4.8). Figure 4.9 shows employment creation at each plant capacity.

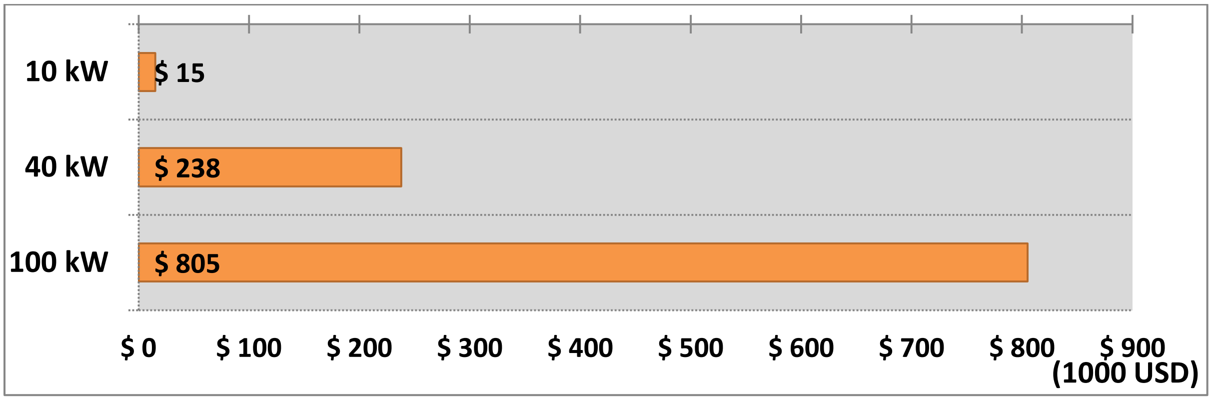

Figure 4.7 NPV for Pulses residues Plants

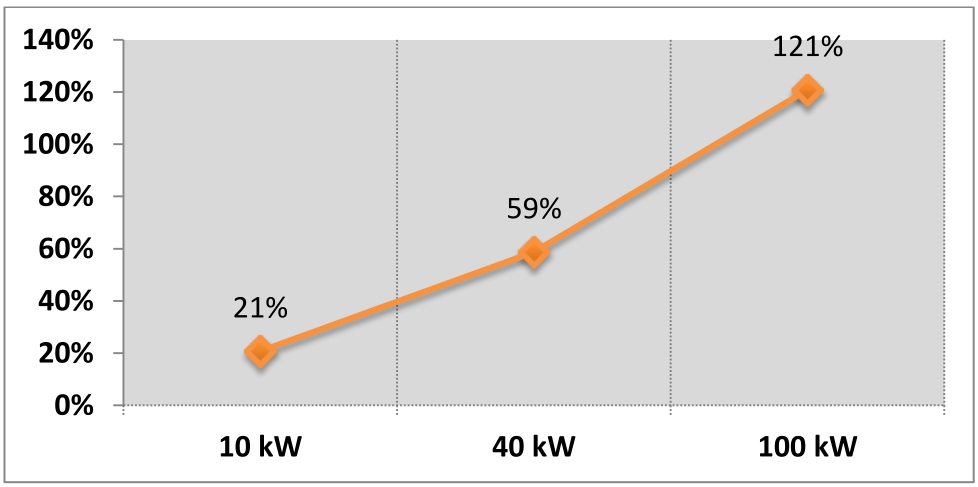

Figure 4.8 IRR for all plant capacities

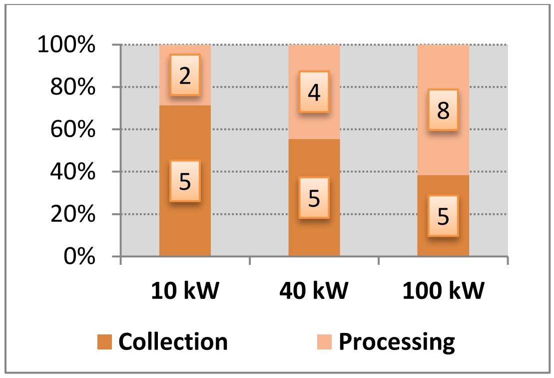

Figure 4.9 Employment creation chart

4.3.2.3 Maize Stalks

The feedstock availability is 11481t/year and it is sufficient to supply the feedstock needed for the three production capacities. The production and distribution costs are lower than the user defined cost of electricity therefore generation from these plants can be bought by consumers as it is at competitive pricing. About 116 households can be supplied by a 100kW plant which has the lowest cost of production and distribution ranging from \$0.26-\$0.32 (Figure 4.11). The biggest of the production cost goes towards labour and miscellaneous costs followed by transportation and storage of the feedstock when depreciation costs are factored out.

A minimum of 7 people can be employed on a 10kW capacity plant (Figure 4.12). The jobs created include labour required to collect and process biomass, as well as produce and distribute electricity. Financially all the plant capacities are feasible all with positive NPV and good standing IRR together with other indicators as shown (Figure 4.10, Figure 4.11). Figure 4.12 and Figure 4.13 present the socio economic indicators being the jobs created and the possible number of households supplied by each plant. The 100kW plant has the biggest jobs and can supply a larger portion of the community. Other plants are not doing bad either considering that there can be more number of smaller plants than big plant.

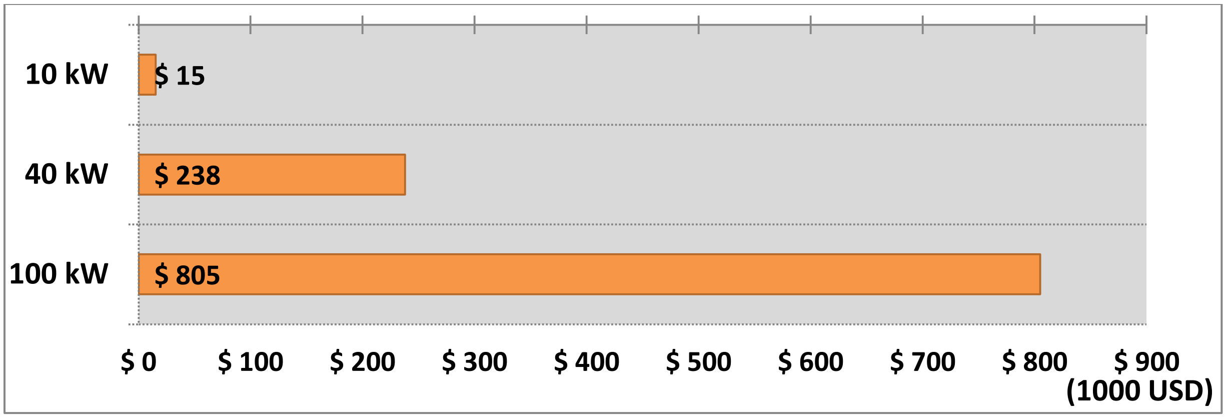

Figure 4.10 NPV for maize stalk residue

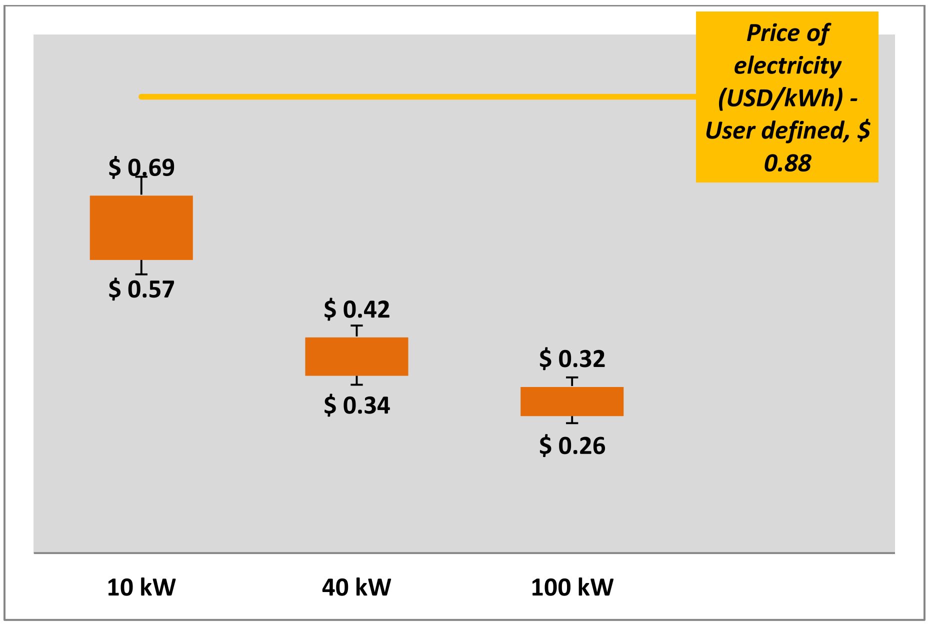

Figure 4.11 Production and Distribution Costs

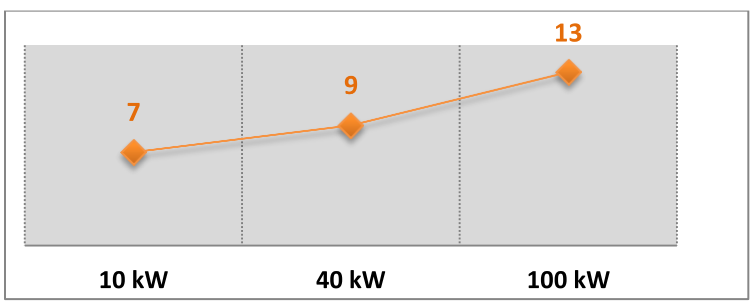

Figure 4.12 Employment creation

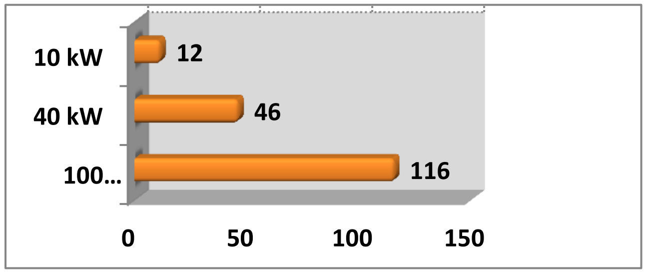

Figure 4.13 Number of households supplied

4.3.3 Combustion Tool (Panda)

Since the analysis of both gasification and combustion was made with 100% availability of potential feedstock for energy the amounts of residue available are equal for all the three types of residues. The combustion tool similarly like the gasification tool has 3 inbuilt plant capacities (10kW, 40kW and 100kW). The plants simulate electricity generation on the general principle of a steam boiler.

4.3.3.1 Sorghum straw

The combustion tool shows that all plant capacities are feasible with this residue. The investment cost for a 10kW plant is $44’466 and can supply 12 households with electricity. The production and distribution cost for this plant is in the margin of $0.44-$0.66 per kilowatt-hour. About 44% of this cost goes towards labour cost and other menial costs.

With a yield of 8.32t/ha for sorghum in this area only 260ha needs to be cultivated in order to have 34 100kW plants running (Figure 4.14). Each individual plant requires about 2’156 tonnes of residues to run efficiently throughout the year. Nineteen jobs can be created from residue collection, production and distribution of electricity. All plant capacities have NPV in good standing together with IRR. The 40kW plant has the highest IRR of 88% and cost of production and distribution is presented in Figure 4.15.

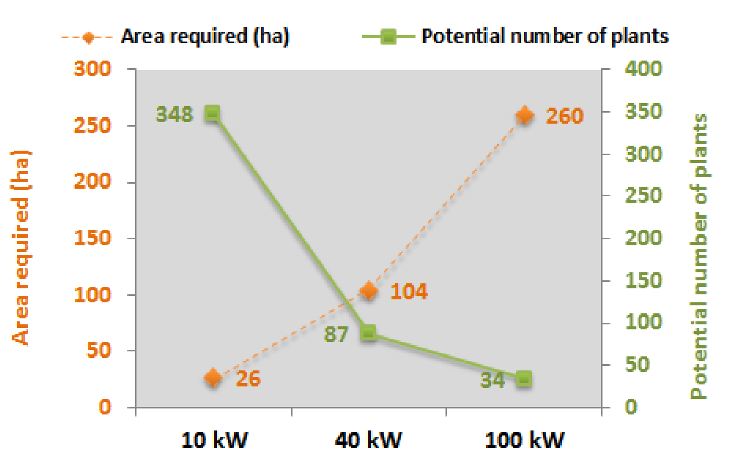

Figure 4.14 Area required Vs potential plants

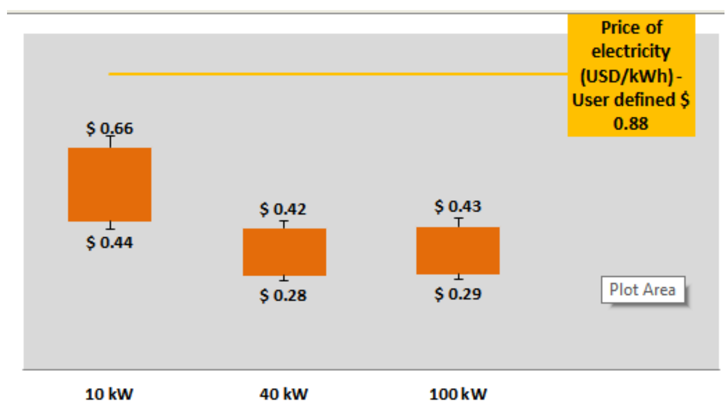

Figure 4.15 Production and distribution costs ($/kWh)

4.3.3.2 Pulses fronds

In the analysis of this residue the number of potential plants has decreased significantly and understandably so because it is the least available type of residue. Only two 100kW plants can be constructed. The number of households however remains unchanged at 12, 46 and 116 households for the 10, 40 and 100 kilowatt plants respectively. Similarly the investment cost also does not change for all plant capacities.

Noticeable changes are observed in terms of NPV and IRR, this residue type has the lowest rates of both indices as compared to the other residues (sorghum straw & maize straw) in this area. The production and distribution costs for 40 and 100 kW plants are similar which is a trend observed only in this residue. The trend has always been that the biggest plant capacity has a lower cost than others. From the total jobs that can be created from this residue a bulk of the labour forces is for collection and processing of the feedstock (Figure 4.16). Only eight technical people are required for the 100kW plant that has a total labour capacity of 226 people and the remaining 218 persons are non-technical.

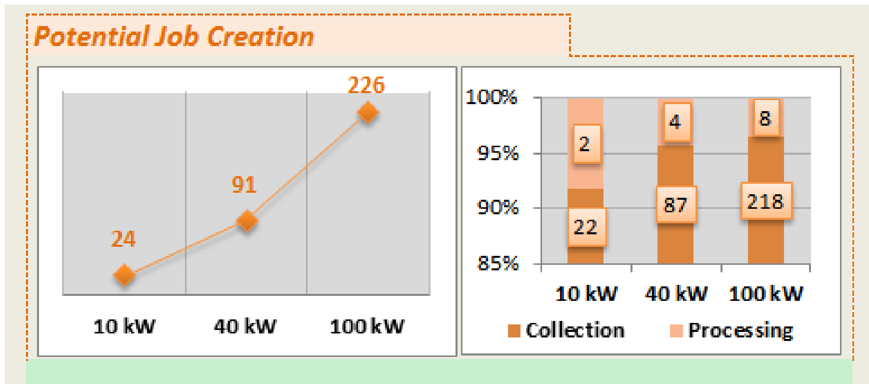

Figure 4.16 Employment creations from Pulses fronds generation plants

4.3.3.3 Maize stalk

The total production and distribution cost of electricity of the 10 kW plant from maize stalk ranges from \$0.47-\$0.70 per kWh is less than the user defined price of electricity which is \$0.88/kWh. Hence, this plant is feasible and attractive for investment. The investment cost of the 10 kW plant still remains unchanged at \$ 44’466 while the 100kW peaks at \$ 45’541

The total amount of feedstock readily available was 11’481 tonne per year. This amount is sufficient for all plant capacities. All the plant capacities are potentially feasible and can be rationed as 224 tonnes, 898 tonnes or 2’244 tonnes annually for all the possible combinations of 10, 40 and 100 kilowatt plants respectively. The feedstock requires an area of 104 hectares to produce 51 units of 10 kW plant. Up to 12 households can be supplied with electricity from this plant. A total of 7 jobs can be created from production and distribution of electricity in addition to collection and processing of feedstock.

The net present value and internal rate of return for all plant capacities are positive therefore, it can concluded that, maize straw residue is feasible for power generation at all plant capacities (Figure 4.17 and Figure 4.18).

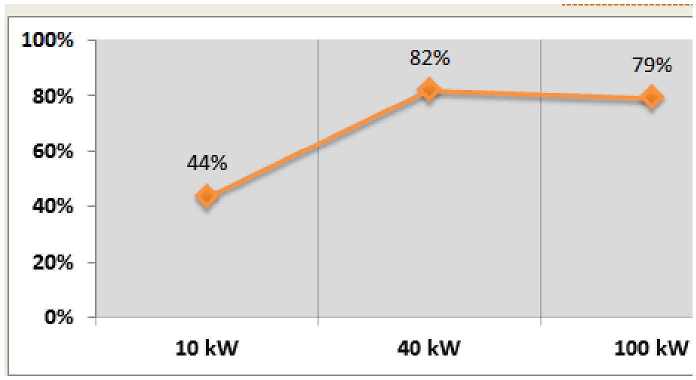

Figure 4.17 IRR of maize residue plants

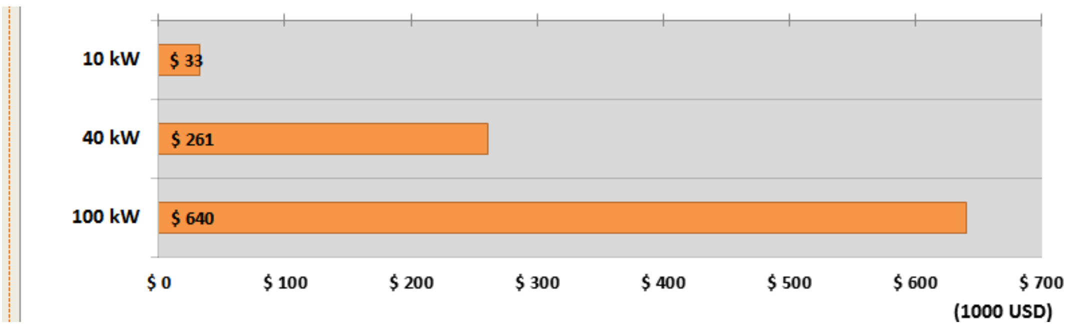

Figure 4.18 NPV of maize residue plants

4.3.4 Gasification and Combustion Tool (Borolong)

4.3.4.1 Maize Straw

In this production area maize residue (straw) in the most abundant residue type at 24’763 tonnes per year with a residue yield of 5.59 tonnes per hector. This amount of residue is sufficient to run all plant capacities for both gasification and combustion.

In the gasification pathway this residue can potentially supply 12 households with the smallest plant capacity and 116 household with the largest capacity. The residue is sufficient to run 107, 26 and 10 kilowatt plants respectively. The costs of production and distribution is highest for the 10kw plant at a high of $0.70/kWh and a single plant requires only 231 tonnes from the overall residue of 24’763 to operate annually. The NPV of all plant capacities is positive and the IRR also in good standing (Figure 4.19 and Figure 4.20). The figures show that the combustion pathway has more present worth and returns on investment for the medium and small plants while the gasification pathway only tops it in the large plant size. This means combustion is likely better technology to use for rural electrification in small and medium plants.

The combustion pathway on the other hand can supply a fewer number of households which is about half of what the gasification pathway can supply. The households supplied are six, twenty three and fifty eight respectively from the smallest to the biggest plant capacity. In terms of job creation however the combustion pathway creates more jobs than the gasification option albeit servicing a smaller portion of the population. The two smaller capacities have more net present worth and higher IRR as compared to the same capacities in the gasification pathway. The production and distribution costs for the 10kW combustion plant ranges from \$0.44-\$ 0.66/kWh and the investment cost is \$42'761.

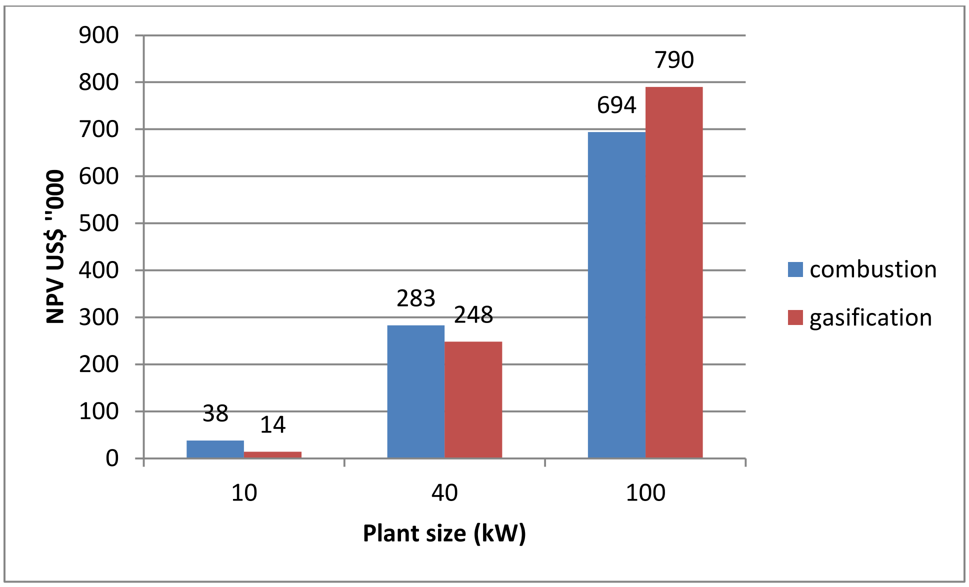

Figure 4.19 Comparison of NPV for both technology options

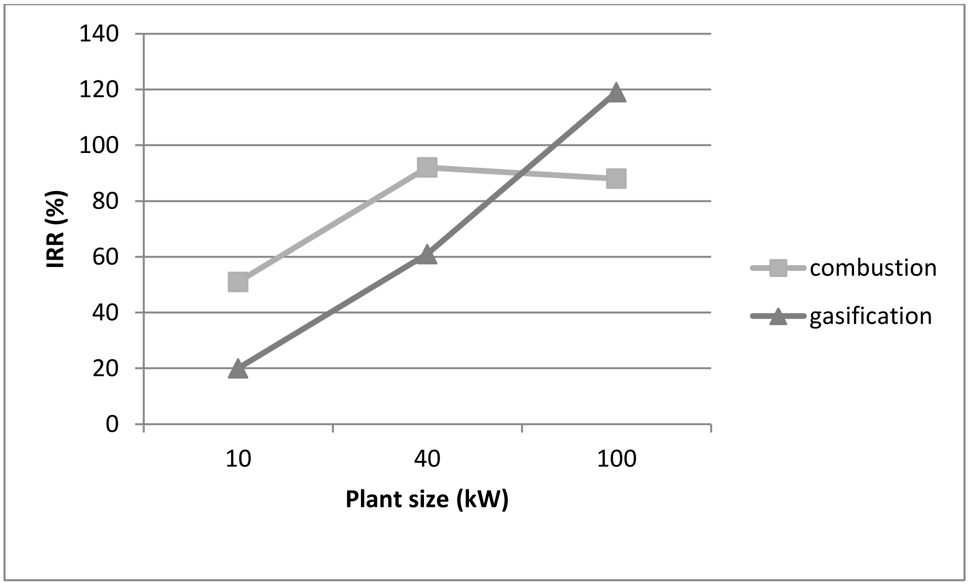

Figure 4.20 IRR for both technology options

4.3.4.2 Sorghum Straw

Sorghum straw is the second most abundant residue available in this area at 12’197 tonnes of residue and a residue to waste yield of 17.39 tonnes per year. Similarly this residue is sufficient to produce power through both combustion and gasification at all plant capacities (Figure 4.22). Though all the plant capacities can be supported, the number of plants that the residue can sustain is lower as compared to the maize residue.

The total number of plants at 10kW capacity that can be supported through combustion is 56 plants (Figure 4.21) which is not a great margin from the plants that gasification can accommodate (42) at the same capacity. Generally combustion pathway of this residue can maintain more plants over the gasification route (14 and 5 plants for 10kW & 100kw over 10 and 4 plants for gasification). Subsequently this implies that more production can be attained through combustion requiring up to 125ha to be cultivated to get enough residue.

The net present value of a small combustion plant is $40’000 and it attracts an IRR of 53% for an investment worth $42’761. This investment cost is the same for all residue types at corresponding sizes. Gasification is more expensive as the small plant cost approximately

$30'000 more. The return rate and NPV are however lower with gasification pathway for the small and medium plant capacities. In terms of job creation combustion has more job opportunities recording three, seven and fourteen posts

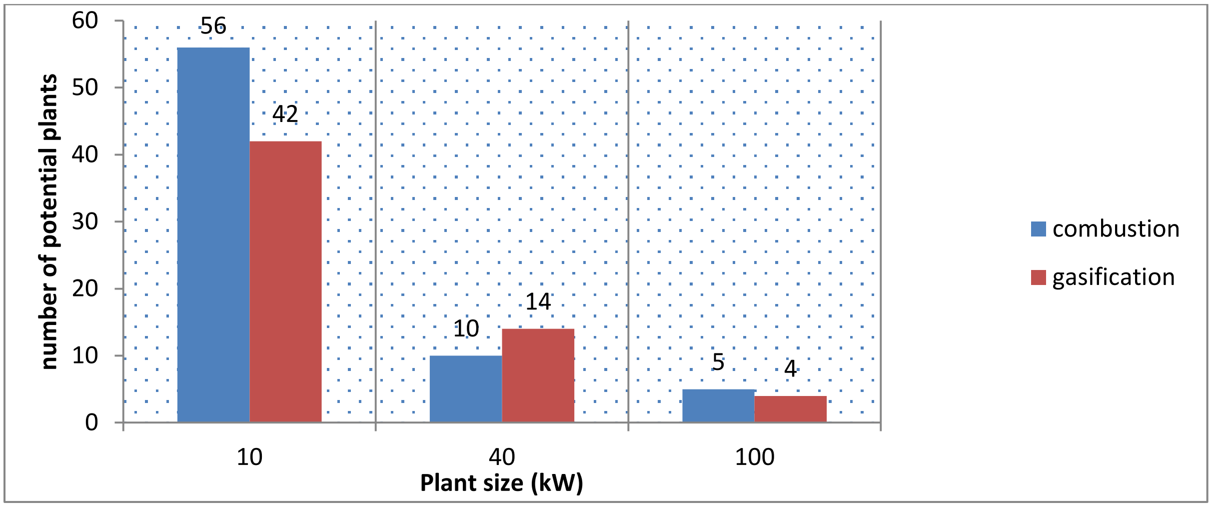

Figure 4.21 Potential number of plants

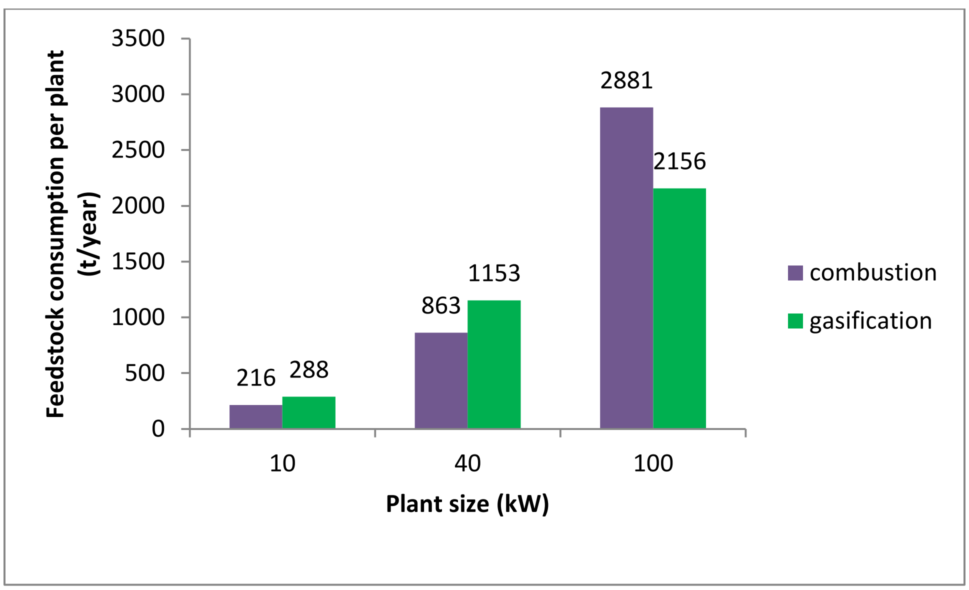

Figure 4.22 Biomass requirement per plant

4.3.4.3 Pulses Fronds

Like in Panda legumes are not produced in large quantities in this production zone. The available residue is 862 tonnes annually at the residue yield of 4.06 tonnes per hector. Considering that it's the smallest amount of residue available it is therefore not sufficient to run all the plant capacities.

In the combustion pathway this residue can only power the 10kW and 40kW plant capacities. There are about four small plants that can be built and only one medium size plant. The medium plant requires 845 tonnes (Figure 4.23) of residues which could be risky to invest in because the margin of error is very small should there be any shortfalls in production then there will not be enough residues. The cost of production and distribution for the small plant is highest at $0.67/kWh and about 44% of this cost goes towards labour and miscellaneous costs. The 10kW which is the ideal option for this residue has a NPV of $38'000 coupled with a 50% rate of return.

The gasification pathway does not have much option for legumes residue. There is not enough feedstock to run the 40kW and 100kW capacities (Figure 4.23). Only three small plants can be built and they individually will require 236 tonnes of residue annually from the 59ha production area that should be planted. The IRR for the feasible plant size is 19% while NPV is $12'000. Distribution and production cost stand at a maximum of $0.72/kWh which is lower than the user defined price of electricity.

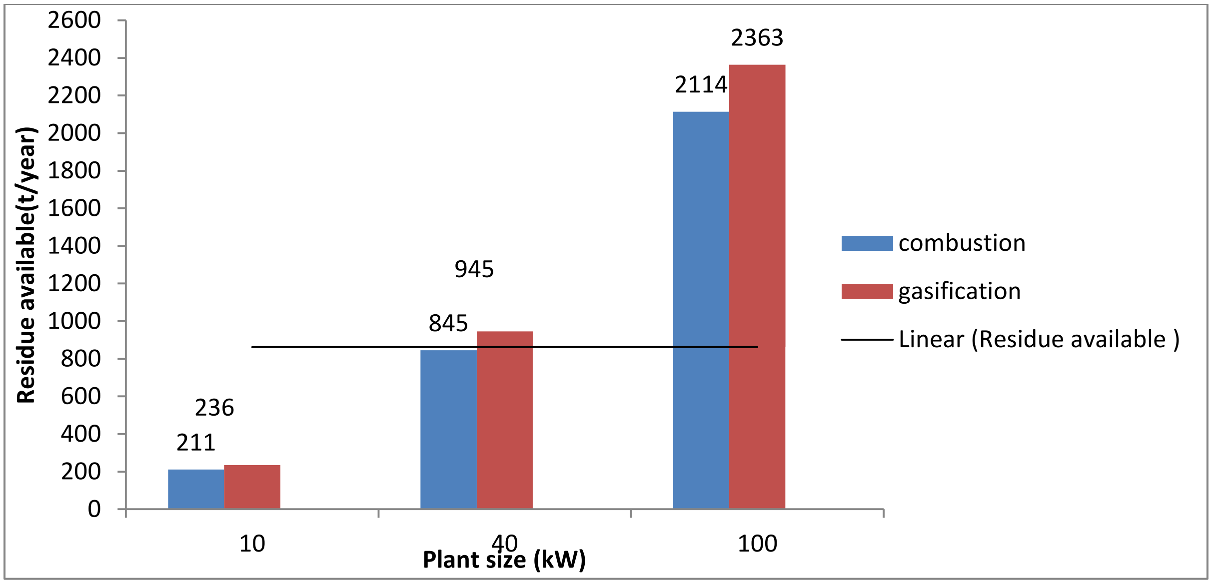

Figure 4.23 Residue available

In the summary of results presented in Figure 4.24 multiple graphs are shown all at once and they show all the residues assessed for the area with the corresponding results for the 3 plant sizes.

From the figure it is evident that pulses residue captured in the tool as soybean straw has the least contribution to socio economic aspects in the form of jobs created and number of households that can be supplied by electricity from combusting the residue. It can supply only 23 households while the other two residues can supply well over 300 households individually. Since the 100kW capacity cannot be supported by this residue it is eliminated resulting fewer jobs and people supplied with electricity.

The net present value is fairly equal with slight differences without any big margins. The value increases from small plant capacities to larger plant capacities at a similar trend for all residues. This trend has been shown by all other technology options (gasification and biogas option) for all the agricultural waste assessed. The IRR also is increasing with increasing plant size.

Maize straw has the highest number of possible plants and correspondingly can supply more households than all the other residues. Distribution and production cost per kWh are competitive for all the residues as it is below the user defined price of electricity used in the assessment.

Figure 4.24 Comparative results of combustion path way

Chapter 5 CONCLUSIONS AND RECOMMENDATIONS

This chapter deals primarily with drawing conclusions and highlighting the major lessons that this study has underscored. The significance and impact of the results obtained is laid out in this section. Additionally recommendations based on the research objectives are made for future works and generally on how to improve the energy sector in Botswana.

5.1 Conclusions

This thesis set out to achieve the aim of investigating the amount of agricultural biomass available for energy (electricity & heat) production in Botswana particularly (Panda, Borolong and BMC Lobatse) and establish the best effective technology that can be used to transform this biomass into useful energy. The specific objectives were to elucidate on;

- Yearly agricultural production figures in Botswana
- Techno-economic analysis of the agricultural waste conversion pathways as per the different BEFS models (gasification, biogas and combustion)
- Analysis of major production centres (Panda farms, NAMPAAD farm & BMC Lobatse) for in house energy supply.

From the data that was collected for the agricultural production statistics of Botswana it can be concluded that there is so much potential to harness energy from the resulting agricultural waste. Though currently no efforts are being made to include agricultural residues in the supply of modern and clean energy Botswana has the potential to supply more than 20% of its energy requirements by the use of residues. Liquid fuels (bioethanol) and electricity can be produced locally. From the crop residue composition Botswana has no possibility to produce biodiesel because a majority of the crops produced have no fats (tri glycerides) that are the basic requirement in the production of biodiesel. Bioethanol on the other hand can be produced from the lignocellulosic residue which widely abundant. Over 22’000’000 litres of bioethanol can be produced annually and this can catapult the country to reach its renewable energy targets, sustainable development goals and adherence to the Kyoto protocol which the county is a signatory of. Bioethanol can be a great addition to the country’s liquid fuel supply and literally raise the levels from the current zero percent blending of bioethanol to a minimum of B5 blending.

The assessment of crop and animal waste in the three areas studied has also proven that the substrates are available in good quantities sufficient to produce sufficient amounts of energy both electricity and heat. The biogas potential is enormous in BMC and can provide adequate heat and power to wean BMC off the national grid and only have the grid as backup should there be any hiccups with production. In case there is no interest to produce electricity independently a biogas bottling plant can be constructed instead. The plant can specialise in the supply of biogas and provide an alternative to the liquefied petroleum gas (LPG) common in most urban and semi urban households. From the tool it can be concluded that the fixed dome digester at the size of $7m^3$ shows the most potential and it is the ideal size to construct

Crop residues are proven to have potential to supply electricity for rural electrification through combustion and gasification. Maize straw and sorghum straw are feasible for power generation at all plant capacities through gasification and combustion in both study areas. Pulse fronds on the other hand are only feasible for all plant capacities only in Panda while they are not enough in Borolong. Though they are considered insufficient they can still be utilised for either conversion path way to add to the other crop residues. The insufficiency is only pronounced because the tools/models do not consider cogeneration which in reality is possible therefore more than one resource can be used for the same generation plant. The electricity cost of production and distribution from the two technologies is very competitive with the prevailing cost of grid connected electricity so technically the development of such projects for rural electrification will bring in revenue attested by their good present net worth and rates of returns. In closing this bioenergy feedstock assessment makes a contribution towards Botswana's bioenergy appraisal and most importantly it considers feed stock that does not compete with food security and there is no competition with food production. If anything the more food security thrives, the more resource there will be for energy production.

5.2 Recommendations

The following recommendation(s) are made

- Due to limitations of the tools it was not possible to include other forms of waste that are not agricultural but can be used for energy production so further studies should be conducted to include such forms of waste and increase the overall contribution of residues to final energy consumption.
- The current study considered only three areas that are centres of mass agricultural production, it is worth extending to the study to other areas which were otherwise not studied in this instance to see if small scale farmers and subsistence farmers produce residue worth considering.

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